International Collaboration in Lunar Exploration

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The U.S. Vision for Space Exploration commits the United States to return astronauts to the moon by 2020 using the Ares I Crew Launch Vehicle and Ares V Cargo Launch Vehicle. Like the Apollo program of the 1960s and 1970s, this effort will require preliminary reconnaissance in the form of robotic landers and probes. Unlike Apollo, some of the data NASA will rely upon to select landing sites and conduct science will be based on international missions as well, including SMART-1, SELENE, and Lunar Reconnaissance Orbiter (LRO). Opportunities for international cooperation on the moon also lie in developing lunar exploration technologies.

The European Space Agency's SMART-1 orbiter (Figure 1) is making the first comprehensive inventory of key chemical elements in the lunar surface. It is also investigating the impact theory of the moon's formation.[1]

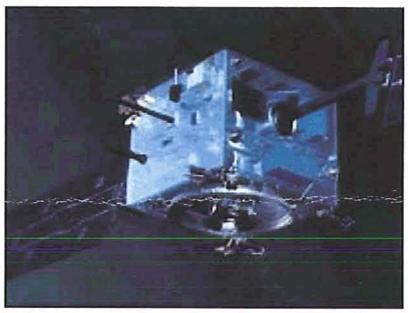

Figure 1. ESA's SMART-1 was used to test solar electric propulsion and other deep-space technologies.

SELENE, the SELenological and ENgineering Explorer (Figure 2), is a Japanese Space Agency (JAXA) lunar orbiter mission. The primary objective of the mission is a global survey of the moon, obtaining data on elemental abundance, mineralogical composition, topography, geology, gravity, and the lunar and solar-terrestrial plasma environments and to develop critical technologies for future lunar exploration, such as lunar polar orbit injection, three-axis attitude stabilization, and thermal control.[2]

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[1] ESA, "SMART-1 Fact Sheet," National Space Science and Data Center (NSSDC) Master Catalog Display, http://www.esa.int/SPECIALS/SMART-1/SEMSDE1A6BD_0.html, Accessed 3 November 2006.
[2] "SELenological and ENgineering Explorer," NSSDC Master Catalog Display, http://nssdc.gsfc.nasa.gov/database/MasterCatalog?sc=SELENE, Accessed 3 November 2006.

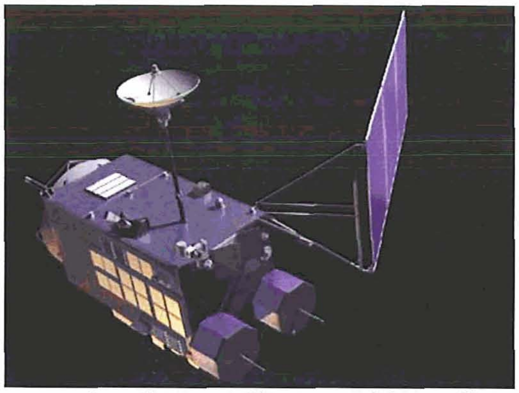
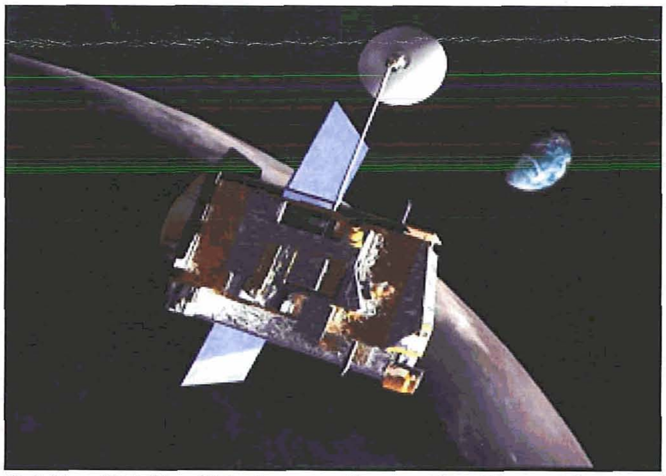


Figure 2. The SELENE orbiter comprises three satellites, an orbiter, a Very Long Baseline Interferometry (VLBI) Radio (VRAD) satellite, and a relay satellite.

Lunar Reconnaissance Orbiter (LRO), the first vehicle to be launched as part of the Lunar Precursor Robotics Program, is a NASA-built vehicle scheduled to reach the moon in October 2008 (Figure 3). LRO will perform many tasks that bear directly upon selecting landing sites for human astronauts later next decade. These studies include characterizing the radiation environment of lunar orbit, studying geodetic global topography, performing high-spatial-resolution hydrogen mapping, mapping temperatures in polar shadowed regions, imaging permanently shadowed surface regions, identifying near-surface water ice in polar cold traps, assessing features for landing sites, and characterizing the polar lighting environment.



Lunar Reconnaissance Orbiter (LRO) will help pave the way for the next human footprints on the moon.

The information gathered from these probes in the next decade will help determine where the next human footprints will be placed on the moon by 2020.

Another potential area for international cooperation on the moon lies in developing exploration technologies. The U.S. lunar exploration strategy, to be released in December 2006, will identify the key technologies needed to work and live on the moon. Among the activities to be detailed in the strategy are conducting lunar science; detecting, extracting, and using lunar resources; and building a permanent outpost (or outposts) on the moon. These technologies will need to be adaptable to the lunar environment, which will be characterized by science learned through international robotic exploration.

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Abstract

The U.S. Vision for Space Exploration commits the United States to return astronauts to the Moon by 2020 using the Ares I Crew Launch Vehicle and Ares V Cargo Launch Vehicle. Like the Apollo program of the 1960s and 1970s, this effort will require preliminary reconnaissance in the form of robotic landers and probes. Unlike Apollo, some of the data the National Aeronautics and Space Administration (NASA) will rely upon to select landing sites and conduct science will be based on international missions as well, including SMART-1, SELENE, and Chandrayaan-1, in addition to NASA's Lunar Reconnaissance Orbiter (LRO) which carries a complement of instruments, with one from an international partner.

The European Space Agency's SMART-1 orbiter made the first comprehensive inventory of key chemical elements in the lunar surface. It also investigated the impact theory of the Moon's formation.[1] SELENE, the SELenological and ENgineering Explorer, is a Japanese Space Agency (JAXA) lunar orbiter mission to perform a global survey of the Moon, obtain data on elemental abundance, mineralogical composition, topography, geology, gravity, and the lunar and solar-terrestrial plasma environments and develop critical technologies for future lunar exploration, such as lunar polar orbit injection, three-axis attitude stabilization, and thermal control.[2] LRO, the first spacecraft to be launched under the Lunar Precursor Robotic Program (LPRP), is a NASA-built vehicle scheduled to reach the Moon in October 2008. LRO will perform many tasks that bear directly upon selecting landing sites for human astronauts later next decade. These studies include characterizing the radiation environment of lunar orbit, studying global topography, performing high-spatial-resolution hydrogen mapping, mapping temperatures in polar shadowed regions, imaging permanently shadowed surface regions, identifying near-surface water ice in polar cold traps, assessing features for landing sites, and characterizing the polar lighting environment.

The information gathered from these probes in the next decade will help determine where the next human footprints will be placed on the Moon by 2020. NASA's Lunar Architecture, unveiled in December 2006, includes assembling a permanent outpost on a crater rim near one of the lunar poles. NASA will determine the final site based on the amount of sunlight and adequacy of the terrain, as well as volatiles and other resources that could facilitate in-situ resource utilization (ISRU). While NASA will maintain the ability to launch from Earth, landing on the Lunar surface and return to the Earth, and extravehicular activity (moon walks), NASA also anticipates leveraging international cooperation for technology development, instrument development, science, and other areas essential for successful lunar exploration.

Opportunities for international cooperation on the Moon also lie in developing lunar exploration technologies. The U.S. Lunar Architecture, released in December 2006, identified the key technologies needed to work and live on the Moon. Among the activities detailed in the strategy are conducting lunar science; detecting, extracting, and using lunar resources; and building a permanent outpost on the Moon. These technologies will need to be adaptable to the lunar environment, which will be characterized by science learned through international robotic exploration.

Introduction

The U.S. Vision for Space Exploration[3] commits the United States to return astronauts to the Moon by 2020 using the Ares I Crew Launch Vehicle and Ares V Cargo Launch Vehicle, setting the stage for the first human footprints on Mars and expansion of human presence into the solar system. The Vision also calls for NASA to "Promote international and commercial participation in exploration."[4] The missions that Europe, India, and other nations are sending to the Moon over the next decade provide an excellent opportunity for fostering cooperation.

Because this new wave of exploration will venture into territory not visited during the Apollo era, preliminary reconnaissance in the form of robotic lunar orbiters and landers will be extremely important. In addition to developing the Ares I and Ares V, NASA's Exploration Systems Mission Directorate has established a Lunar Precursor Robotic Program (LPRP) to send robotic probes to scout potential future landing sites. In addition to NASA's own robotic explorers, data from other nations' probes are essential to characterize the lunar environment and better evaluate potential landing sites. These probes include SMART-1, SELENE, and Chandrayan-1.

Lunar exploration activities are complex, difficult, and expensive. Eventually they may include building a lunar outpost, harnessing solar power for lunar operations, and extracting hydrogen and/or oxygen from the lunar regolith. Because of this complexity and expense, NASA will be looking to the private sector and international partners to help develop these technologies in the coming decades.

I Setting the Stage: NASA's Lunar Architecture Study and the Lunar Precursor Robotic Program

A. Overview of the Lunar Architecture Study

In early 2006 NASA began consulting with hundreds of individuals within government, the private sector, advocacy organizations, and other national space programs to help develop a comprehensive Lunar Architecture Study.[5] Based on those inputs and discussions, NASA sought to:

- Define a series of lunar missions constituting NASA's Lunar campaign, to fulfill the Lunar Exploration elements of the Vision for Space Exploration
- Perform multiple human and robotic missions
- Develop process for future Architecture updates
- Develop a Lunar Architecture Team (LAT) Charter
- Develop a baseline architecture concept and establish a periodic architecture refinement by December 6, 2006
- Baseline the Architecture so that it is tied to overall mission and program objectives

Based on the Architecture Study, NASA identified functional needs and performed a technology analysis to produce a notional concept of operations. The operational concept then set the basis for an Exploration Architecture Requirements Document, which translated the Architecture into concrete, procurable technologies and hardware.

Accompanying the Lunar Architecture Study was NASA's Global Exploration Strategy, which sets forth the justifications for the Architecture, breaking them down into six themes:

- Extending sustained human presence to the Moon.
- Collaborating with international partners.
- Investigating the Moon's usefulness as a unique laboratory.
- Facilitating economic advancement and technological innovations that facilitate space exploration and benefit people here on Earth.
- Preparing for future human and robotic missions to Mars and other destinations.
- Pursuing a vibrant exploration program that will engage and inspire and educate the public, bringing hope to young and old alike.

The U.S. Vision for Space Exploration has mandated that NASA develop launch and initial lunar lander vehicles to get human beings to the Moon in preparation for much longer trips to Mars and to expand human presence in the solar system beyond low Earth orbit. NASA's vehicles include the Ares I Crew Launch Vehicle, Ares V Cargo Launch Vehicle, Orion Crew Exploration Vehicle (CEV), and Lunar Surface Access Module (LSAM).

Ares I, as shown in Figure 1, is a two-stage vehicle that will launch the Orion into Earth orbit for missions to the International Space Station or to rendezvous with the LSAM delivered by the Ares V for missions to the Moon. The Ares I first stage will be a single 5-segment Reusable Solid Rocket Booster (RSRB), which is derived from existing Space Shuttle hardware and uses polybutadiene acrylonitrile (PBAN) propellant. The Ares I upper stage is powered by the J-2X engine, a liquid hydrogen and liquid oxygen-powered engine derivative of the S-II and S-IVB upper stage propulsion used on NASA's Apollo Program Saturn V.

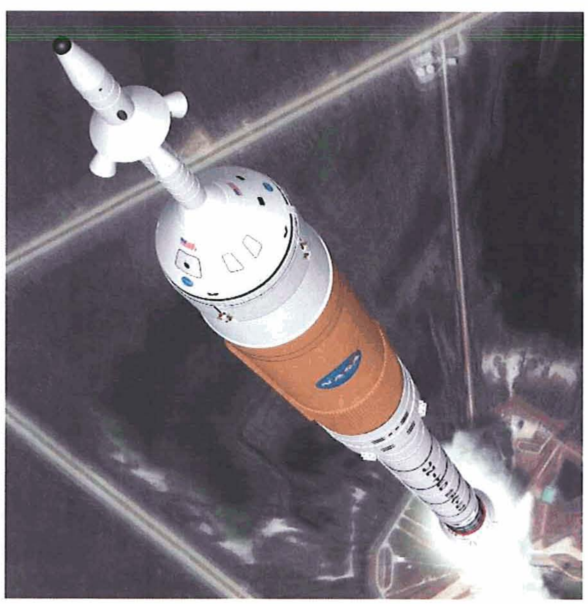

Figure 1. Ares I Crew Launch Vehicle concept. [Use version with logo. See Shelton.]

The Ares V baseline configuration for lunar missions, depicted in Figure 2, consists of two Shuttle-derived 5-segment RSRBs, similar to the Ares I first stage, along with a 33-foot diameter tank delivering liquid oxygen/liquid hydrogen to a cluster of five RS-68 engines. This stack places the Earth Departure Stage (EDS) and LSAM into orbit. The second stage is the Earth Departure Stage, which is powered by a J-2X engine similar to the Ares I upper stage's engine. Once Ares V has reached orbit and the Orion has docked with it, as depicted in Figure 3, the J-2X engine will re-ignite to initiate a trans-lunar injection (TLI) burn to reach lunar orbit.

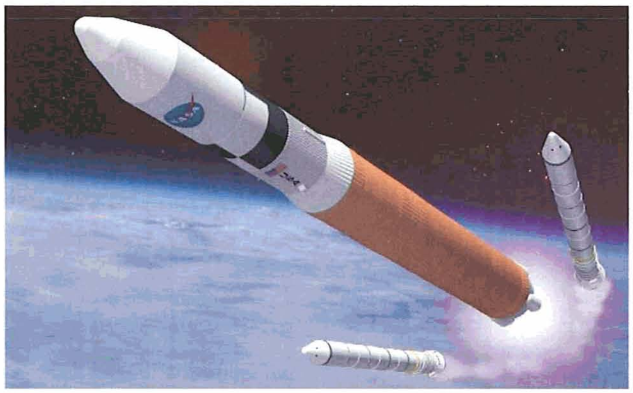

Figure 2. Ares V Cargo Launch Vehicle concept. [Update to logo version. See Shelton.]

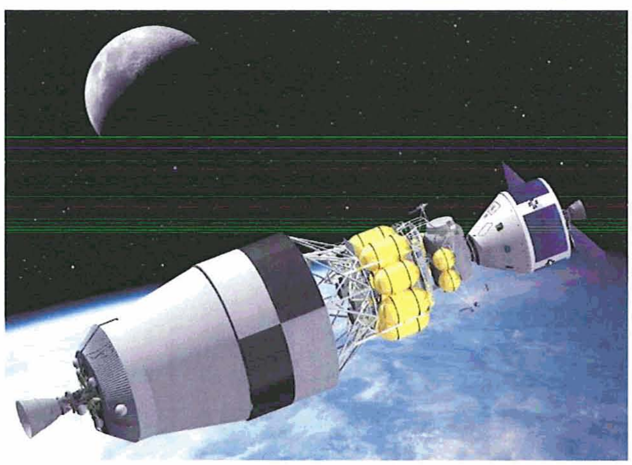

Figure 3. Earth Departure Stage, Lunar Surface Access Module, and Crew Exploration Vehicle ready for trans-lunar injection burn.

B. Lunar Precursor Robotic Program

NASA created the Lunar Precursor Robotic Program (LPRP), a division of the Exploration Systems Mission Directorate, as a complement to its Constellation Program, which is developing the Orion Crew Exploration Vehicle (CEV) and Ares Launch Vehicles. The crew and cargo vehicles being built under the Constellation Program are not dependent on any technical deliverables from the LPRP. However, the landing sites for the Lunar Surface Access Module (LSAM) will depend upon scientific data from the LPRP's first mission, LRO, with its Lunar CRater Observation and Sensing Satellite (LCROSS) secondary payload, the LPRP-2 lander, and other robotic spacecraft, which will be developed in parallel with the crewed exploration vehicles.

Lunar Reconnaissance Orbiter (LRO)

LRO's mission (Figure 4) is to obtain data that will help facilitate humans returning safely to the Moon and staying for extended periods.

Figure 4. Lunar Reconnaissance Orbiter emerges from behind the Moon.

LRO Mission Overview

After launching from Cape Canaveral, Florida on an Atlas launch vehicle, the LRO baseline mission is nominally one Earth year in a 50 km circular, polar orbit around the Moon. This may be followed by an extended mission of up to three years.

The Orbiter will collect information vital to ensuring astronaut safety, including:

- Characterizing the global lunar radiation environment, especially the linear energy transfer (LET) spectra of galactic and solar cosmic rays (particularly above 10 MeV).
- Measuring lunar surface temperatures at spatial scales that provide essential information for future surface operations and exploration.
- Using reflected Lyman sky-glow and starlight that produce sufficient signal for a small UV instrument to see into the Moon's permanently shadowed regions, and determine if frost is present on the surface.
- Providing neutron emission measurements and create maps of the neutron energy over the surface of Moon.
- Providing a precise global lunar topographic model and selenodetic grid that will serve as the foundation of this essential understanding.
- Providing landing site certification and polar illumination. using high-resolution laser imaging for characterizing meter-scale features for potential landing sites and lower-resolution images of the polar regions to determine the lighting conditions.

The end result will be measurements of critical parameters that will help inform the future of human exploration on Moon.

Lunar CRater Observation and Sensing Satellite (LCROSS)

Co-manifested with the LRO spacecraft, the LCROSS mission will advance the Vision for Space Exploration by attempting to identify the presence of water ice at the Moon's South Pole.[6] This mission will use the upper stage of the Atlas launch vehicle to crash a 2,000 kg Kinetic Impactor into the lunar surface (Figure 5). This impact will create nearly a 70-km-high, 1,000-metric-ton plume of lunar ejecta—impacting with more than 200 times the energy of Lunar Prospector (LP)—and will be visible from a number of Lunar-orbital and Earth-based assets.[7] The 1,000 kg Shepherding Spacecraft (S-S/C) flies through the impact plume, telemetering real-time images and searching for water ice in the plume with IR cameras and spectrometers.

LCROSS ready to separate

LCROSS plume developing with

Figure 5. The LCROSS Impactor process.

Another vehicle NASA is developing is the LPRP-2 Medium Lander, which is scheduled to launch early next decade. The second in the series of robotic missions to the moon, the Lander Rim mission will land on the lunar surface to obtain in-situ "ground truth" measurements that will be used to validate environmental models developed from remote sensing, Apollo, and Surveyor data. This first modern mission to the surface of the Moon will serve to certify the site selection for the human lunar outpost, demonstrate technologies that will be used for human landing, and verify predictions of the lunar surface environments. The LPRP-2 mission is currently envisioned as landing along the rim of Shackleton Crater, which is the current baseline destination used by Lunar Architecture. The final landing site will be determined through the lunar outpost site selection process.

A primary objective of the Lander Rim mission will be to collect strategic information from the lunar surface to confirm orbital data obtained by the Lunar Reconnaissance Orbiter (LRO) and international missions such as Chandrayaan-1 and SELENE. These data will be scientifically analyzed to optimize the lunar return architecture and plan for future human activities on the Moon. Proposed measurement objectives for LPRP-2 include (but are not limited to):

- Determining solar illumination over a seasonal cycle.
- Direct measurement of neutron flux and soil hydrogen concentration in sunlit areas for correlation with orbital mapping.
- Characterizing biological radiation response.

- Characterizing the lunar dust and charging environment.

II Leveraging Data from International Robotic Exploration

Optimizing for astronauts' future success and safety on the Moon requires collecting as much data as possible in the near future about potential hazards such as radiation and about the *in-situ* resources that may prove beneficial to explorers who will carry few supplies and limited cargo. To improve its knowledge of potential landing sites, NASA also will rely upon international robotic explorations, including ESA's SMART-1, India's Chandrayaan-1, and Japan's SELENE probes.

A. SMART-1

Mission Profile
SMART-1, which stands for Small Missions for Advanced Research in Technology, was Europe's first venture into ion-electric propulsion. As well as testing new technology, SMART-1 made the first comprehensive inventory of key chemical elements in the lunar surface. It also is investigating the theory that the Moon was formed following the violent collision of a smaller planet with Earth, 4.5 billion years ago. SMART-1 was originally tasked for a six-month orbital exploration, but that time was extended by over a year before the vehicle was deliberately impacted in the *Lacus Excellentiae* region on 3 September 2006.

Instrumentation
SMART-1's instruments included:

- **Electric Propulsion Diagnostic Package (EPDP) and Spacecraft Potential Electron and Dust Experiment (SPEDE)** – Designers of future solar-electric spacecraft want to know how SMART-1's ion engine performs, what side-effects it has, and whether the spacecraft interacts with natural electric and magnetic phenomena in the space around it. The EPDP and SPEDE instruments monitored these effects.[8]
- **Ka-Band TT&C Experiment (KaTE)** – This experiment was designed to demonstrate deep-space telemetry and telecommand communications in the X and Ka bands. The primary purpose of KaTE was to demonstrate the next generation of radio links between the Earth and far-flung spacecraft.
- **Radio-Science Investigations for SMART-1 (RSIS)** – Small changes in SMART-1's motion revealed the precise thrust delivered by the ion engine. RSIS used the Doppler effect to see how the vehicle's speed altered the wavelength using the very short radio waves of KaTE.
- **Laserlink** was a communications experiment providing SMART-1 with a laser optical link to a ground station on Tenerife, in Spain's Canary Islands.
- **On-Board Autonomous Navigation Experiment (OBAN)** – Future spacecraft will be more self-reliant in guiding themselves along pre-defined paths towards distant destinations. OBAN evaluated a computer technique for on-board autonomous navigation using image processing.
- **Advanced Moon micro-Imager Experiment (AMIE)** – This micro-camera provided high-resolution charged-couple device (CCD) images of selected lunar areas. With a resolution of 80 meters per pixel, AMIE searched for the characteristic 1 μm signature of olivine as well as

potential sources of water ice in "cold trap" craters. SMART-1 also mapped potential sites of "eternal night" and "eternal day."[9]

- **SMART-1 InfraRed spectrometer (SIR)** – The SIR mapped mineral composition across the lunar surface at a maximum resolution of 300 m using 256 spectral channels ranging from .9 to 2.6 μm. Using these frequencies, ESA sought to detect exposed materials from the Moon's inner crust and mantle; investigate space weathering and illumination geometry effects; and examine central peaks, walls, rims, and ejecta blankets of large craters.
- **Demo Compact Imaging X-ray Spectrometer (D-CIXS)** – This experiment used both an X-ray spectrometer and a solar X-ray monitor (XSM) to perform high-sensitivity X-ray measurements. This experiment was designed to develop a 50-km-resolution map of the absolute abundances of magnesium, silicon, and aluminum in the lunar regolith by measuring the incident solar spectrum that causes the lunar surface to fluoresce in X-rays.

B. Chandrayaan-1

Mission Profile

Chandrayaan-1 is an Indian Space Research Organization (ISRO) mission designed to orbit the Moon over a two-year period. The spacecraft bus is roughly a 1.5 meter cube with a dry weight of 523 kg. It also will carry a 30 kg probe that will be released from the spacecraft and penetrate the lunar surface. Power is provided by a solar array that generates 750 W and charges lithium ion batteries. A bipropellant propulsion system will transfer Chandrayaan-1 into lunar orbit and maintain attitude. The spacecraft is 3-axis stabilized using attitude control thrusters and reaction wheels (Figure 6). Attitude information is provided by star sensors, accelerometers, and an inertial reference unit. Telecommand communications will be conducted using S-band and science data transmission will occur in X-band.

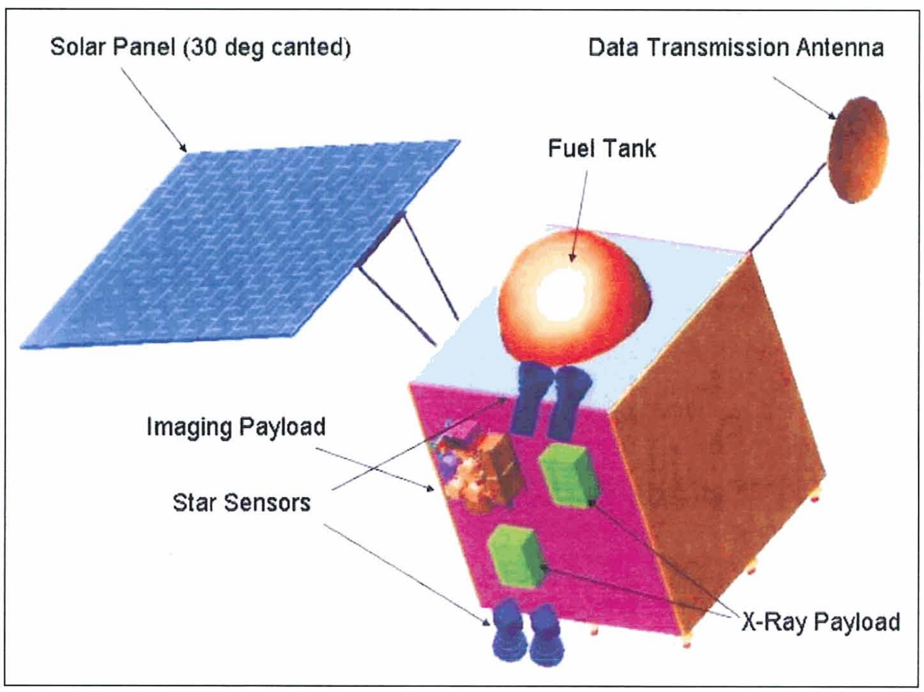

Figure 6. Chandrayaan-1 Configuration.

Instrumentation
Chandrayaan's scientific payload has a mass of 55 kg and contains the following instruments:

- **The Terrain Mapping Camera (TMC)** has 5-meter resolution and a 40 km swath in the panchromatic band and will be used to produce a high-resolution map of the Moon.
- **The Hyper Spectral Imager (HySI)** will perform mineralogical mapping in the 400-900 nm band with a spectral resolution of 15 nm and a spatial resolution of 80 m.
- **The Lunar Laser Ranging Instrument (LLRI)** will determine the surface topography.
- **The X-ray flourescence spectrometer** will have three components:
  - An Imaging X-ray Spectrometer (CIXS) covering 1 - 10 keV with a ground resolution of 10 km, which will be used to map the abundances of Si, Al, Mg, Ca, Fe, and Ti at the surface.
  - A High Energy X-ray/gamma ray spectrometer (HEX) for 10 - 200 keV measurements with ground resolution of about 20 km, which will measure U, Th, 210Pb, 222Rn degassing, and other radioactive elements.
  - A Solar X-ray Monitor (SXM) to detect solar flux in the 2 - 10 keV range, which will monitor the solar flux to normalize the results of CIXS and HEX.
- **The Sub-keV Atom Reflecting Analyzer (SARA)** will map composition using low energy neutral atoms sputtered from the surface.
- **The Moon Mineralogy Mapper (M3),** an imaging spectrometer provided by NASA, is designed to map the Moon's surface mineral composition.
- **A near-infrared spectrometer (SIR-2)** also will map the mineral composition using an infrared grating spectrometer.
- **The Miniature Synthetic Aperture Radar (Mini-SAR)** will perform radar scattering and imaging investigations at the poles in a search for water ice.[10]

This combination of surface-scanning instruments will be vital to identify potentially useful resources on the Moon. While in-situ resource utilization (ISRU) is not a requirement for NASA's proposed outpost, it would facilitate long-term occupation of the site.

C. SELENE

JAXA's SELENE probe, scheduled to launch in 2007, is designed to obtain scientific data regarding element abundance, mineralogical composition, topography, geology, gravity, and the lunar and solar-terrestrial plasma environments and to develop critical technologies for future lunar exploration.[11] The primary objective of the mission is a global survey of the Moon. The mission consists of three satellites, an orbiter containing most of the scientific equipment, a VLBI (Very Long Baseline Interferometry) Radio (VRAD) satellite, and a relay satellite designed to receive a Doppler ranging signal from the orbiter when it is around the far side out of direct contact with the Earth and transmit the signal to Earth to estimate the far-side gravitational field.[12]

Mission Profile
The SELENE launch currently is scheduled for the summer of 2007. SELENE will be launched into a 270 km Earth parking orbit with an inclination of 30.4 degrees. From this orbit, it will conduct a lunar transfer trajectory injection burn. SELENE will be injected into lunar 100 km x

13,000 km, 16-hour polar orbit, 127 hours after launch. The spacecraft will make 6 orbit-transfer maneuvers to lower the orbit to a 2-hour, 100 km circular polar science orbit. During the transition to lower orbit, the relay satellite will be released into a 100 km x 2400 km polar orbit and the VRAD satellite will be released into a 100 x 800 km orbit. The main orbiter will maintain the circular orbit for one year of science operations, using correction burns roughly every two months to maintain the orbit within 30 km of the 100 km nominal orbit.

Spacecraft and Subsystems

The orbiter main bus is box-shaped, roughly 2.1 x 2.1 x 4.8 m, divided into a 2.8-meter-long upper, or mission, module that contains most of the scientific instruments and a 1.2-meter-long lower, or propulsion module (see Figure 7). A solar array wing is mounted on one side of the spacecraft. A 1.3-meter high-gain antenna is mounted on one side 90 degrees from the solar panel. A 12 m magnetometer boom juts out of the top of the spacecraft and four 15 m radar sounder antennas protrude from the top and bottom corners of the mission module. The total launch mass of the spacecraft, including 795 kg of propellant and the two satellites, is 2,885 kg.

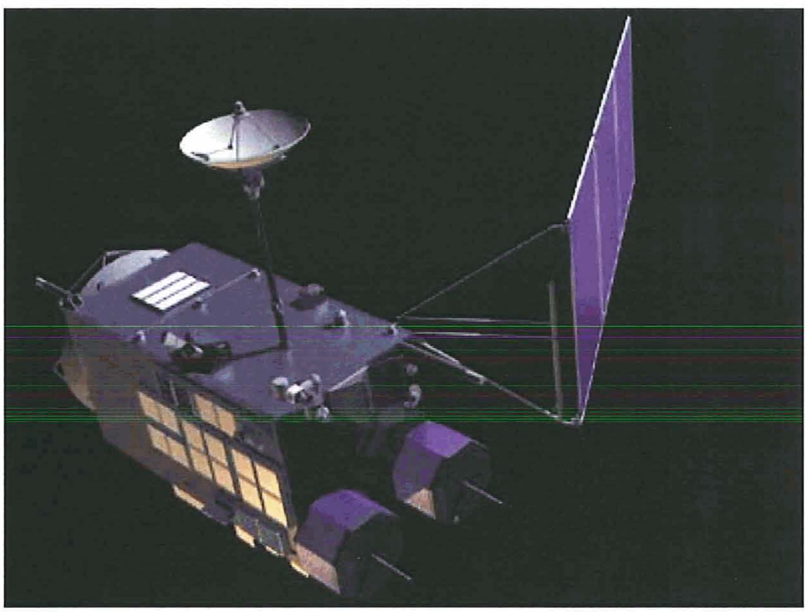

Figure 7. SELENE probe in flight.

Power is supplied by the solar array, consisting of 22 m^2 of GaAs/Ge cells which can generate up to 3,486 W and charges four NiH_2 batteries. Communications are via S- and X-band through the high-gain antenna with a data rate up to 10 Mbps downlink to a 60 m ground dish in X-band, and 40 or 2 kbps S-band downlink. Four S-band omnidirectional antennas are used for command uplink at 1 kbps. Onboard data recording capacity is 10 GB. Thermal control is achieved by radiators, louvers, and heaters.

Instrumentation

The mission module carries 13 instruments for use in science investigations, including:

SELENE

- **X-ray Spectrometer (XRS)** – Identifies surface distribution of major elements such as magnesium, aluminum, silicon, iron, and sodium using X-ray CCD array, with spatial resolution of 20 km.
- **Gamma-ray Spectrometer (GRS)** – GRS uses a highly pure Germanium crystal to map the distribution of potassium, uranium, thorium, and other elements on the lunar surface at a resolution of 120 km.
- **Spectral Profiler (SP)** – Provides continuous spectral profiling from 0.5 to 2.6 μm, at spectral resolutions of 6 to 8nm and spatial resolution of 500 m.
- **Multiband Imager (MI)** – This imager provides spectral coverage ranging from the 0.4 to 1.6 μm, 9 bands at a spectral resolution of 20 to 50 nm and spatial resolution of 20 m.
- **Terrain Camera (TC)** – High-resolution stereo camera providing 10 m spatial resolution.
- **Lunar Radar Sounder (LRS)** – Provides high-frequency radar sounding of the subsurface structure of the Moon and observation of natural radio and plasma waves.
- **Laser Altimeter (LALT)** – Provides 5 m height resolution at a pulse rate of 1 Hz.
- **Lunar Magnetometer (LMAG)** – Magnetic field measurement using flux-gate type magnetometers, accuracy 0.5 nT.
- **Upper atmosphere and Plasma Imager (UPI)** – Provides imaging of the Earth's magnetosphere and aurora from the lunar orbit.
- **Charged Particle Spectrometer (CPS)** – Maps radon and polonium using the ARD (4 to 6.5 MeV for alpha), measurement of high energy particles using the PS instruments (e: 0.3 to 1 MeV, p: 0.1 to 60 MeV, Heavy ion: 2.5 to 370 MeV/n.
- **Plasma energy Angle and Composition Experiment (PACE)** – Provides charged particle energy and composition measurement 5 eV/q to 28keV/q(Ion), 5eV to 17keV(Electron).
- **Radio Science (RS)** – Detects the tenuous lunar ionosphere using S- and X-band carriers.
- **High Definition Television (HDTV)** – Takes pictures and movies of the Earth and the Moon with high-definition television cameras.

Relay Satellite

- **Four-way Doppler measurements by relay satellite and main orbiter transponder (RSAT-1,2)** – Measures far-side gravimetry using four way Doppler measurement from the ground station to Orbiter via Relay Satellite of 2,400 to 100km in altitude.

VRAD Satellite/Relay Satellite

- **Differential VLBI Radio source-1,2 (VRAD-1, 2)** – Provides differential VLBI observation of radio sources on board Relay Satellite and VRAD Satellite from ground radio telescopes, for selenodesy and gravimetry.

Together, these instruments will provide crucial data on the Moon's radiation environment, elemental characteristics and components, and surface geography, all of which will be crucial for ensuring crew safety and productive scientific and resource harvesting activities.

D. Incorporating International Science Data into the Lunar Architecture

NASA's current baseline mission for future lunar exploration would be to place an outpost on the rim of a permanently shadowed crater near a lunar pole. Shackleton Crater near the Lunar South Pole is one such example of a possible location (Figure 8). This particular location may be interesting because concentrations of hydrogen has been remotely detected there and because the site is believed to be in daylight for over 80% of the lunar month, making the outpost supportable by near-continuous solar power.[13] If SMART-1, Chandrayaan-1, or LRO reveal a presence of water ice on the Moon, this water ice could be used, in principle, to manufacture breathing oxygen for a permanent base and hydrogen and oxygen for rocket fuel, in addition to use as water in supporting life. While these future robotic orbiting spacecraft will give us more information about the nature of hydrogen on the Moon, it eventually may take a landed instrument on the surface to provide the ultimate ground-truth of orbitally based measurements.

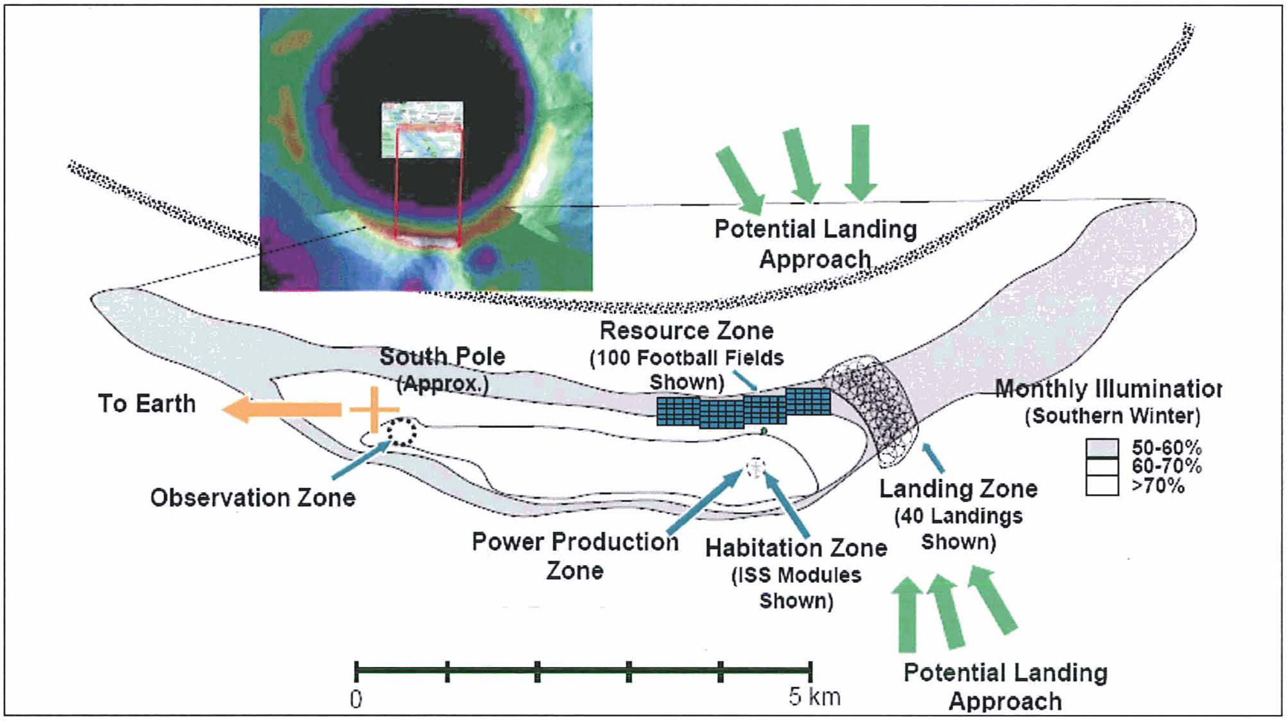

Figure 8. Map of potential landing site on the rim of Shackleton Crater.

ESA's SMART-1 probe already has imaged large areas around the lunar poles, looking for specific regions in which sunlight persists in a near-continuous fashion. Such areas, if located, would be very advantageous for installing solar power infrastructure.[14] SMART-1 has also detected the presence of calcium on the lunar surface, as well as the reflective signatures of aluminum, silicon, and iron.[15] The probe also made many passes over Shackleton Crater, which will enable ESA to develop highly detailed maps of the area, though its ability to find water ice or other volatiles is still uncertain.[16] Finally, SMART-1 already has impacted a dark area of the lunar surface, as the LCROSS vehicle is expected to do in 2008.[17] A preliminary assessment indicates that the impact flash was possibly caused by thermal emission from the impact itself or by the release of spacecraft volatiles, such as the small amount of hydrazine fuel remaining on board.[18]

III Working with International Partners to Develop Human Exploration Technologies

While the U.S. Vision for Space Exploration has mandated that NASA develop initial launch and lunar lander vehicles to get human beings to the Moon, Mars, and beyond, the Vision for Space Exploration policy also requires international cooperation to develop the technologies needed to live and work on the Moon.[19] The baseline architecture described in the previous section will depend on these technologies to grow the lunar base in incremental stages, with the LSAMs leaving cargo and/or useful infrastructure at the base site after every mission, as shown in Figure 9 below.

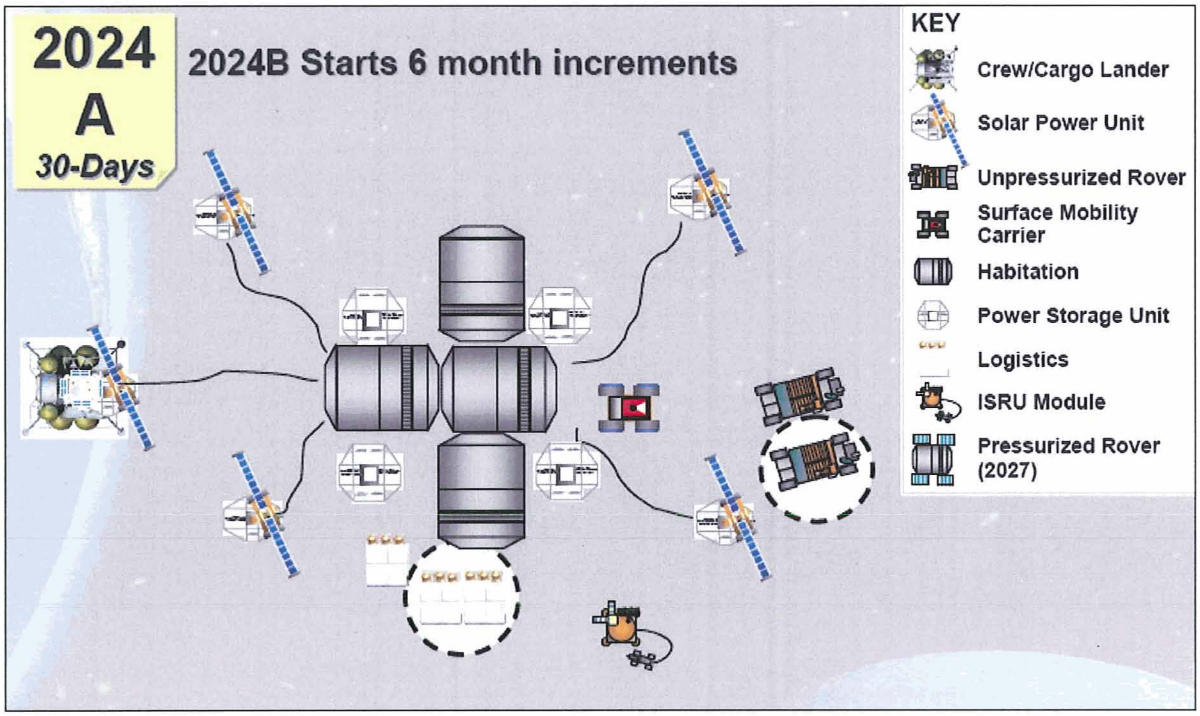

Figure 9. Site map of a notional lunar outpost.

The open nature of NASA's lunar architecture offers many opportunities for other nations to contribute significantly to its technological development. The U.S. also will encourage external parallel development of lunar exploration capabilities. This open architecture opens the lunar infrastructure to potential cost savings and increased capabilities through external cooperation. This cooperation will become increasingly important in the coming years, as NASA Administrator Mike Griffin stated in his recent testimony regarding the agency's budget: "We must seek innovative ways to leverage, to the maximum extent practicable, the investments being made by commercial industry and through international partnerships."[20]

Long-term habitation and exploration on the Moon will require a wide variety of critical technologies, including new, long-duration space suits, power systems, pressurized and unpressurized rover vehicles, regolith digging and processing machinery, logistical resupply, and ISRU processing units. While the U.S. will be developing basic navigation and communication hardware, international or private sector partners could enhance these capabilities through augmented or high-bandwidth communications, such as SELENE's HDTV transmissions.[21]

In addition to high-technology items, lunar explorers will need a variety of low-tech but no less critical items, such as drills, sub-components, instrumentation, scoops, sample handling arms, food, and personal support equipment.

Rather than following the International Space Station model of directing partners' roles in the work, NASA is leaving the option open for other nations to volunteer for work they would like to perform. NASA has taken the first steps to facilitate these partnerships already by holding quarterly meetings with interested nations.[22] As a further step to ensure easier cooperation, NASA is pledging to "make the Moon metric" rather than use Imperial units to make measurement units consistent.[23]

All of these activities, combined with the mission preparation data gathered from space probes, offer many opportunities for international partners to join with NASA in the next phase of lunar exploration, which will be the work of generations to come. NASA's Science Mission and Exploration Systems Mission Directorates look forward to long and fruitful relationships with other nations' space programs, private companies, and academic institutions to make this adventure possible.

Summary

The next phase of lunar exploration will be the work of generations and will require the efforts of many nations working in a variety of capacities. From selecting landing sites to characterizing the lunar environment to developing the technologies needed to survive and thrive on the Moon, the Vision for Space Exploration offers a variety of excellent opportunities for international partnerships.

Nomenclature/Acronyms

Term	Explanation
μm	Micrometer
Al	Aluminum
AMIE	Advanced Moon micro-Imager Experiment
Ca	Calcium
CCD	Charged-Coupled Device
CEV	Crew Exploration Vehicle
CIXS	Imaging X-ray Spectrometer
CPS	Charged Particle Spectrometer
D-CIXS	Demo Compact Imaging X-ray Spectrometer
EDS	(Ares V) Earth Departure Stage
EDUS	(LCROSS) Earth Departure Upper Stage
EPDP	Electric Propulsion Diagnostic Package
ESA	European Space Agency
eV	Electronvolt
Fe	Iron
GaAs/Ge	Gallium Arsenide/Germanium
GB	Gigabytes
GRS	Gamma-Ray Spectrometer
H	Hydrogen

Term	Explanation
HDTV	High-Definition Television
HEX	High Energy X-ray/gamma ray spectrometer
HySI	Hyper Spectral Imager
Hz	Hertz
ISRO	Indian Space Research Organization
ISRU	In-Situ Resource Utilization
ITAR	International Traffic in Arms Regulations
JAXA	Japan Aerospace Exploration Agency
KaTE	Ka-Band TT&C (telemetry, tracking, and control) Experiment
kbps	Kilobits Per Second
keV	Kiloelectronvolt
kg	Kilogram(s)
km	Kilometer(s)
LALT	Laser Altimeter
LAT	Lunar Architecture Team
LET	Linear Energy Transfer
LCROSS	Lunar CRater Observation and Sensing Satellite
LLRI	Lunar Laser Ranging Instrument
LMAG	Lunar Magnetometer
LOI	Lunar Orbit Insertion
LOLA	Lunar Orbiter Laser Altimeter
LRO	Lunar Reconnaissance Orbiter
LPRP	Lunar Precursor Robotics Program
LROC	Lunar Reconnaissance Orbiter Camera
LRS	Lunar Radar Sounder
LSAM	Lunar Surface Access Module
m	Meter(s)
M3	Moon Mineralogy Mapper
Mbps	Megabits Per Second
MeV	Million Electronvolts
Mg	Magnesium
Mini-SAR	Miniature Synthetic Aperture Radar
MI	Multi-band Imager
NASA	National Aeronautics and Space Agency
Ni	Nickel
nm	Nanometer
nT	Tesla
OBAN	On-Board Autonomous Navigation Experiment
PACE	Plasma energy Angle and Composition Experiment
Pb	Lead
PBAN	Polybutadiene Acrylontrile
ppm	Parts Per Million
Rn	Radon
RS	Radio Science

Term	Explanation
RSIS	Radio-Science Investigations for SMART-1
RSRB	Reusable Solid Rocket Booster
SARA	Sub-keV Atom Reflecting Analyzer
SELENE	SELenological and ENgineering Explorer
Si	Silicon
SIR	SMART-1 InfraRed spectrometer
SIR-2	Near-infrared spectrometer (Chandrayaan-1)
SMART-1	European Space Agency Small Missions for Advanced Research in Technology
SP	Spectral Profiler
SPEDE	Spacecraft Potential Electron and Dust Experiment
S-S/C	Shepherding Spacecraft
SXM	Solar X-ray Monitor
TC	Terrain Camera
Th	Thorium
Ti	Titanium
TLI	Trans-Lunar Injection
TMC	Terrain Mapping Camera
U	Uranium
UPI	Upper atmosphere and Plasma Imager
VLBI	Very Long Baseline Interferometry
VRAD	VLBI Radio Satellite
W	Watt(s)
XRS	X-Ray Spectrometer

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