Space and Solar System Exploration

(2000-2010)

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Space and Solar System Exploration in 2004

Rosetta (spacecraft)

Rosetta

Operator	European Space Agency
Major contractors	European Space Agency
Mission type	Comet Orbiter/Lander
Flyby of	Earth, Mars, 2867 Šteins, 21 Lutetia
Satellite of	67P/Churyumov-Gerasimenko
Launch date	March 2, 2004 at 07:17 UTC
Launch vehicle	Ariane 5G+
Mission duration	6 years, 10 months, and 12 days elapsed
Orbital decay	N/A
COSPAR ID	2004-006A

Rosetta is a robotic spacecraft of the European Space Agency on a mission to study the comet 67P/Churyumov-Gerasimenko. Rosetta consists of two main elements: the **Rosetta space probe** and the **Philae lander**. The spacecraft was launched on 2 March 2004 on an

Ariane V rocket and will reach the comet by mid 2014. The space probe is intended to orbit and perform long-term exploration of the comet at close quarters. On 10 November 2014 the Philae lander will attempt to land and perform detailed investigations on the comet's surface. Both the probe and the lander carry a large complement of scientific experiments designed to complete the most detailed study of a comet ever attempted.

The probe is named after the Rosetta Stone, as it is hoped the mission will help unlock the secrets of how our solar system looked before planets formed. The lander is named after the Nile island Philae where an obelisk was found that helped decipher the Rosetta Stone. The spacecraft has already performed two successful asteroid flyby missions on its way to the comet. The craft completed its fly-by of asteroid 2867 Šteins in September 2008 and of 21 Lutetia in July 2010, and is presently functioning and on-target for its final destination as of late 2010.

Mission timeline

This is the planned timeline for the mission after its launch:

- First Earth flyby (March 4, 2005)
- Mars flyby (February 25, 2007)
- Second Earth flyby (November 13, 2007)
- Flyby of asteroid 2867 Šteins (September 5, 2008)
- Third Earth flyby (November 13, 2009)
- Flyby of asteroid 21 Lutetia (July 10, 2010)
- Deep-space hibernation (May 2011 - January 2014)
- Comet approach (January-May 2014)
- Comet mapping / Characterisation (August 2014)
- Landing on the comet (November 2014)
- Escorting the comet around the Sun (November 2014 - December 2015)

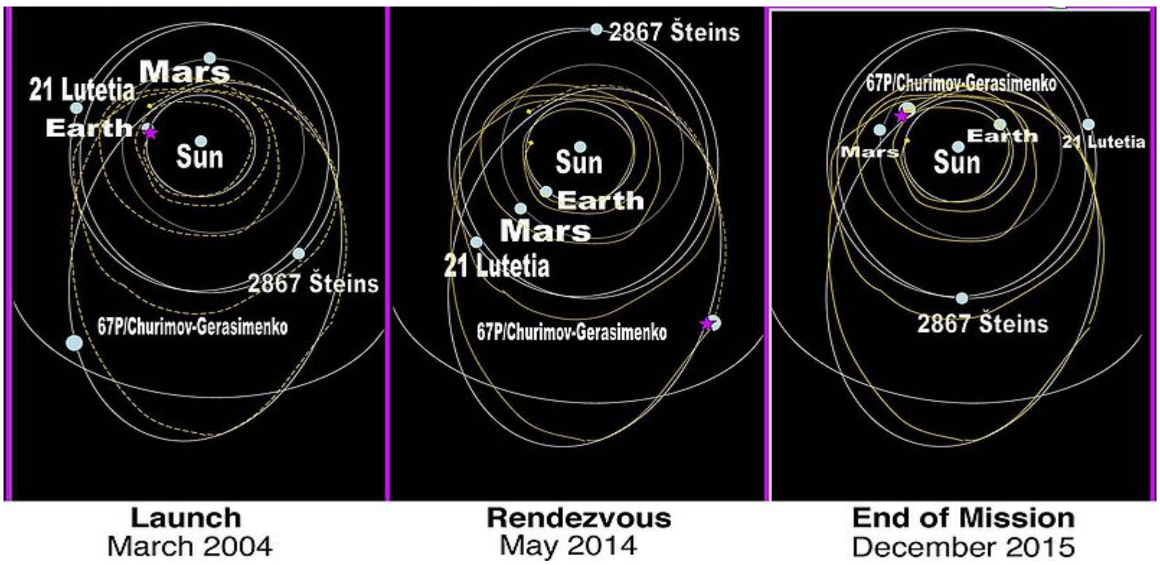
Overview

During the 1986 apparition of the Comet Halley, a number of international space probes were sent to explore the cometary system, most prominent among them being ESA's highly successful Giotto. After the probes returned a treasure-trove of valuable scientific information it was becoming obvious that follow-ons were needed that would shed more light on the complex cometary composition and resolve the newly opened questions.

Both NASA and ESA started cooperatively developing new probes. The NASA project was the Comet Rendezvous Asteroid Flyby or CRAF mission. The ESA project was the follow-on Comet Nucleus Sample Return (CNSR) mission. Both missions were to share the Mariner Mark II spacecraft design, thus minimizing costs. In 1992, after NASA axed CRAF due to budgetary limitations, ESA decided to develop a CRAF-style project on its own. By 1993 it was evident that the ambitious sample return mission was unfeasible with the existing ESA budget, so the mission was redesigned, with the final flight plan resembling the canceled CRAF mission, an asteroid flyby followed by a comet rendezvous with in-situ examination, including a lander.

Rosetta was built in a clean room according to COSPAR rules, but "Sterilisation [was] generally not crucial since comets are usually regarded as objects where you can find prebiotic molecules, that is, molecules that are precursors of life, but not living microorganisms, " according to Gerhard Schwehm, Rosetta's Project Scientist.

It was set to be launched on January 12, 2003 to rendezvous with the comet 46P/Wirtanen in 2011.



Trajectory of the Rosetta Space Probe

However, this plan was abandoned after a failure of the planned launch vehicle Ariane 5 on December 11, 2002. A new plan was formed to target the comet Churyumov-Gerasimenko, with launch on February 26, 2004 and rendezvous in 2014. The larger mass and the resulting increased impact velocity made modification of the landing gear necessary. After two cancelled launch attempts, Rosetta was launched on March 2, 2004 at 7:17 GMT. Besides the changes made to launch time and target, the mission profile remains almost identical.

The first flyby of Earth occurred on March 4, 2005.

On February 25, 2007, the craft was scheduled for a low-altitude bypass of Mars, to correct the trajectory after the first launch in 2003 was delayed by one year. This was not without risk, as the estimated altitude of the flyover manoeuvre was a mere 250 km (155 miles). During that encounter the solar panels could not be used since the craft was in the planet's shadow, where it would not receive any solar light for 15 minutes, causing a dangerous shortage of power. The craft was therefore put into standby mode, with no possibility to communicate, flying on batteries that were originally not designed for this task. This Mars manœuvre was therefore nicknamed "The Billion Dollar Gamble". Fortunately, the flyby was successful and the mission continued as planned.

The second Earth flyby occurred on November 13, 2007.

The spacecraft performed a close flyby of asteroid 2867 Šteins on September 5, 2008. Its onboard cameras were used to fine-tune the trajectory, achieving a minimum separation of less than 800 km (497 miles). Onboard instruments measured the asteroid from August 4 to September 10. Maximum relative speed between the 2 objects during the flyby was 8.6 km/s (19,240 mph).

Rosetta's third and final flyby of Earth happened on November 12, 2009.

The asteroid's orbit was known before Rosetta's launch, from ground-based measurements, to an accuracy of approximately 100 km. Information gathered by the onboard cameras beginning at a distance of 24 million km will be processed at ESA's Operation Center to refine the asteroid's position in its orbit to a few km.

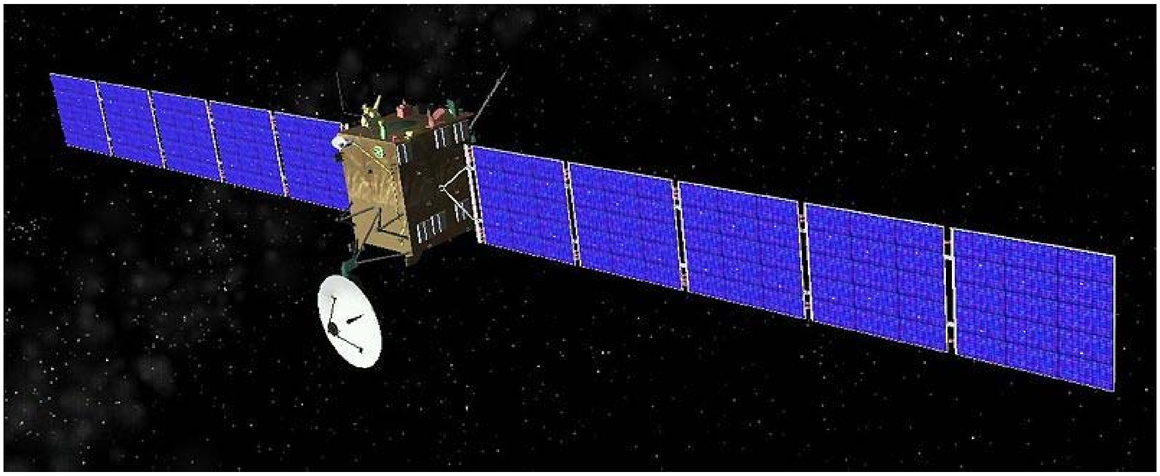
In May 2014, the *Rosetta* craft will enter a slow orbit around the comet and gradually slow down in preparation for releasing a lander that will make contact with the comet itself. The lander, named "Philae", will approach Churyumov-Gerasimenko at relative speed around 1 m/s and on contact with the surface, two harpoons will be fired into the comet to prevent the lander from bouncing off. Additional drills are used to further secure the lander on the comet.

Once attached to the comet, expected to take place in November 2014, the lander will begin its science mission:

- Characterisation of the nucleus
- Determination of the chemical compounds present, including enantiomers
- Study of comet activities and developments over time

The exact surface layout of the comet is currently unknown and the orbiter has been built to map this before detaching the lander. It is anticipated that a suitable landing site can be found, although few specific details exist regarding the surface.

Instruments



Computer model of Rosetta probe

Core

The spectroscopical investigation of the core is done by four instruments.

- **ALICE** (an ultraviolet imaging spectrograph). The UV spectrograph will search for the abundance of noble gas in the comet core, from which the temperature during the comet creation could be estimated. The detection is done by an array of potassium bromide and caesium iodide photocathodes. The 3.1 kg instrument uses 2.9 watts and was produced in the USA, and an improved version is used in the New Horizons.
- **OSIRIS** (Optical, Spectroscopic, and Infrared Remote Imaging System). The camera system has a narrow angle lens (700 mm) and a wide angle lens (140 mm), with a 2048x2048 pixel CCD chip. The instrument was constructed in Germany.
- **VIRTIS** (Visible and Infrared Thermal Imaging Spectrometer). The Visible and IR spectrometer is able to make pictures of the core in the IR and also search for IR spectra of molecules in the coma. The detection is done by a mercury cadmium teluride array for IR and with a CCD chip for the Visible range. The instrument was produced in Italy, and improved versions were used for Dawn and Venus express.
- **MIRO** (Microwave Instrument for the Rosetta Orbiter). The abundance and temperature of volatile substances like water, ammonia and carbon dioxide can be detected by MIRO via their microwave emissions. The 30 cm radio antenna was constructed in Germany, while the rest of the 18.5 kg instrument was provided by the USA.

The interior of the comet is probed by the CONSERT instrument.

- **CONSERT** (Comet Nucleus Sounding Experiment by Radiowave Transmission). The CONSERT experiment is the only experiment on board the ROSETTA mission which will provide information about the deep interior of the comet. The Consert radar will perform tomography of the nucleus by measuring electromagnetic wave propagation between the Philae lander and the Rosetta orbiter through the comet nucleus. This allows it to determine the comet's internal structure and deduce information on its composition. The lander and orbiter electronics were provided by France and both antennas were constructed in Germany.

Gas and particles

- **ROSINA** (Rosetta Orbiter Spectrometer for Ion and Neutral Analysis). The instrument consists a double focus magnetic mass spectrometer DFMS and a reflectron type time of flight mass spectrometer RTOF. The DFMS has a high resolution (can resolve N_2 from CO) for molecules up to 300 amu. The RTOF is highly sensitive for neutral molecules and for ions.
- **MIDAS** (Micro-Imaging Dust Analysis System). The high resolution atomic force microscope will investigate the dust particles which are deposited on a silicone plate.
- **COSIMA** (Cometary Secondary Ion Mass Analyser). COSIMA analyses the composition of dust particles by secondary ion mass spectrometry, after the surface is cleaned by indium ions. It can analyse ions up to a mass of 4000 amu.

Solarwind interaction

- **GIADA** (Grain Impact Analyser and Dust Accumulator)

- **RPC** (Rosetta Plasma Consortium).

Major events and discoveries

2004

- March 2 – ESA's *Rosetta* mission was successfully launched at 07:17 UTC (08:17 Central European Time). The launcher successfully placed its upper stage and payload into an eccentric coast orbit (200 x 4,000 km). About two hours later, at 09:14 UTC, the upper stage ignited its own engine to reach escape velocity in order to leave the Earth’s gravity field and enter heliocentric orbit. The Rosetta probe was released 18 minutes later. ESA’s Operations Centre (ESOC) in Darmstadt, Germany, established contact with the probe shortly after that.

- May 10 – The first and most important deep space maneuver was successfully executed to adjust the course of the space craft, with a reported inaccuracy of 0.05%.

2005

- March 4 – *Rosetta* executed its first planned close flyby of Earth. The Moon and the Earth's magnetic field were used to test and calibrate the instruments on board of the spacecraft. The minimum altitude above the Earth's surface was about 1,954.7 km at 22:09 UTC and images of the space probe passing by were captured by amateur astronomers.
- July 4 – Imaging instruments on board observed the collision between the comet Tempel 1 and the impactor of the Deep Impact mission.

2007

- February 25 – Mars swing-by. Philae's ROMAP (Rosetta Lander Magnetometer and Plasma Monitor) instrument measures the complex Martian magnetic environment, while Rosetta's OSIRIS (Optical, Spectroscopic, and Infrared Remote Imaging System) took various images of the planet using different photographic filters. While in Mars' shadow most of the instruments were turned off the Philae lander was autonomously running on batteries. During this operation the ÇIVA instrument on the lander took pictures of Mars. Among others, both actions were meant to test the spacecraft's instruments. The space craft used the gravity of Mars to change course towards its second Earth flyby in November.
- November 8 – Misidentification of Rosetta space craft as an asteroid (see below).

2008

- September 5 – Flyby of asteroid 2867 Šteins. The spacecraft passed the main-belt asteroid at a distance of 800 km and the relatively slow speed of 8.6 km/s.

2009

- November 13 – Last swingby (gravity assist passage) of Earth. The spacecraft made its closest approach (perigee passage) at 2481 km altitude over 109°E and 8°S - just off the coast of the Indonesian island of Java, at 07:45 UTC.

2010

- March 16 - Observation of the dust tail of the asteroid P/2010 A2. Together with observations of Hubble space telescope it could be confirmed that the P/2010 A2 is not a comet but an asteroid and the tail most likely consists of particles from an impact of an smaller asteroid.
- July 10 - Flew by and photographed the asteroid 21 Lutetia.

Misidentification as an asteroid

In November, 2007, during its second flyby, the Rosetta spacecraft was mistaken for a dangerous near-Earth asteroid and given the designation **2007 VN_{84}**. Based upon images taken by a 0.68 meter telescope of the Catalina Sky Survey, an astronomer 'discovered' the spacecraft and misidentified it as an asteroid about 20 meters in diameter, and performed a trajectory calculation showing that it would make its closest flyby of the Earth at a distance of 5,700 kilometers on November 13, 2007. This extremely close approach (in astronomical terms) led to speculation that 2007 VN_{84} might be at risk of impacting the Earth. However, astronomer Denis Denisenko recognized that the trajectory matched that of the Rosetta probe, which was performing a flyby of Earth en route to its rendezvous with a comet. The Minor Planet Center later confirmed in an editorial release that 2007 VN_{84} was actually the spacecraft.

MESSENGER

MESSENGER

Technicians prepare MESSENGER for transfer to a hazardous processing facility prior to loading the spacecraft's complement of hypergolic propellants.

Operator	NASA
Major contractors	APL
Mission type	Orbiter / Fly-by

Flyby of	Earth, Venus, Mercury
Satellite of	Mercury
Orbital insertion date	2011-03-18 02:14:00 UTC (projected)
Launch date	2004-08-03 06:15:56 UTC (6 years, 167 days ago)
Launch vehicle	Delta II 7925H-9.5
Launch site	Space Launch Complex 17A Cape Canaveral Air Force Station
Mission duration	In Transit
COSPAR ID	2004-030A
Mass	1,093 kg (2,410 lb)
Power	450 W (Solar array / 11 NiH_2 batteries)

The **MErcury Surface, Space ENvironment, GEochemistry and Ranging** (**MESSENGER**) probe is a spacecraft of the United States space agency NASA, launched August 3, 2004 to study the characteristics and environment of Mercury from orbit. Specifically, the mission is to characterize the chemical composition of Mercury's surface, the geological history, the nature of the magnetic field, the size and state of the core, the volatile inventory at the poles, and the nature of Mercury's exosphere and magnetosphere over a nominal orbital mission of one Earth year.

The mission is the first to visit Mercury in over 30 years; the only previous probe to visit Mercury was Mariner 10, which completed its mission in March 1975. The MESSENGER has vastly improved scanning capability, with cameras capable of resolving surface features to 18 m (59 ft) across compared to the 1.6 km (0.99 mi) resolution of the Mariner 10. MESSENGER is an orbital mission, and will spend over a year imaging the entire planet; Mariner 10 was a flyby mission and was only able to observe the one hemisphere that was lit during its flybys.

The contrived acronym MESSENGER was chosen because Mercury was the messenger of the gods according to Roman mythology.

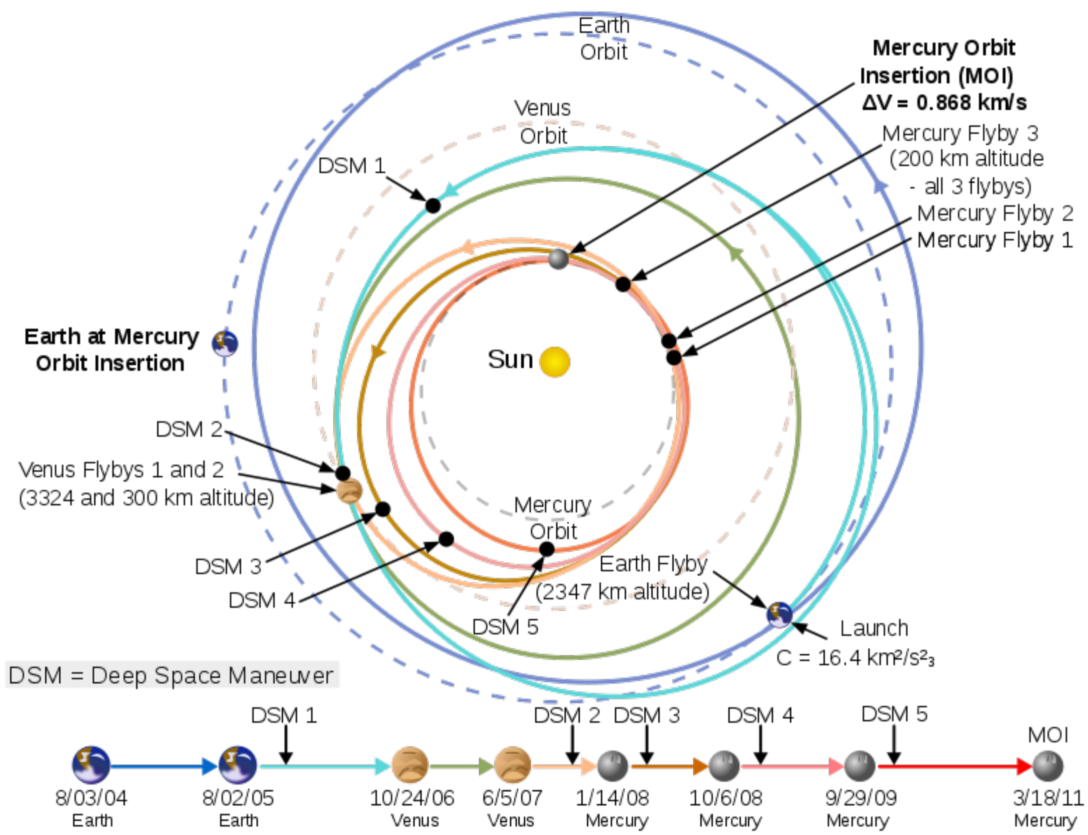
Travel to Mercury

The launch of MESSENGER

The Boeing Delta II rocket carrying MESSENGER lifted off from Cape Canaveral Air Force Station, Florida at 02:15:56 EDT on August 3, 2004. An hour later, NASA confirmed that MESSENGER had successfully separated from the third stage booster and commenced its roundabout route to Mercury.

Travel to Mercury requires an extremely large velocity change, or delta-v, because Mercury lies deeper in the Sun's gravity well; a spacecraft traveling to Mercury is greatly accelerated as it falls toward the Sun, so there must be a mechanism to slow it. Mercury does not have an atmosphere thick enough to aerobrake on arrival. To make the trip feasible, MESSENGER makes extensive use of gravity assist maneuvers. These reduce the amount of rocket fuel needed to slow down, but greatly prolong the trip. For additional fuel savings, the thrust used for insertion into orbit about Mercury will be minimized, resulting in a notably elliptical orbit. Besides the advantage of saving fuel, such an orbit allows the spacecraft to measure solar wind and magnetic fields at a variety of distances from the planet, yet still get close-up measurements and photographs of the surface.

MESSENGER performed a successful Earth swing-by a year after launch, on 2 August 2005, with the closest approach at 19:13 UTC at an altitude of 2,347 kilometers (1,458 statute miles) over central Mongolia. On December 12, 2005, a 524 second long burn (Deep-Space Maneuver or DSM-1) of the large thruster adjusted the trajectory for the upcoming Venus swing-by.



MESSENGER's trajectory

A view of Earth from MESSENGER during its Earth swing-by

MESSENGER made its first flyby of Venus at 08:34 UTC on October 24, 2006 at an altitude of 2,992 kilometers (1,859 mi). A second flyby of Venus was made at 23:08 UTC on June 5, 2007 at an altitude of 338 kilometers (210 mi). On October 17, 2007, Deep-Space Maneuver 2 or DSM-2' was executed successfully, putting MESSENGER on target for its first flyby of Mercury. MESSENGER made a flyby of Mercury on 14 January 2008 (closest approach 200 km above surface of Mercury at 19:04:39 UTC), followed by a second flyby on October 6, 2008. MESSENGER executed one last flyby on September 29, 2009, that further slowed down the spacecraft. Both the second and third flybys were preceded by DSM-3 on 19 March 2008 at 19:30 UTC and DSM-4 on 04 Dececember, 2008 at 20:30 UTC to adjust the velocity of the spacecraft. One last deep space maneuver, DSM-5 was executed on November 24, 2009 at 22:45 UTC to provide the required velocity change for the scheduled Mercury orbit insertion on March 18, 2011, marking the beginning of a year-long orbital mission.

All along the way, numerous trajectory corrections were made to MESSENGER's course. The corrections numbered 35 as of 24, November 2009 and are referred to as TCM or Trajectory Correction Maneuver. TCM which use the large bi-propellant thrusters are also referred to as DSM or Deep Space Maneuver. DSM generally concern major adjustments to the spacecraft's velocity while TCM usually deal with modifying the craft's orientation with respect to the Sun (crucial for thermal management) and targeting aim points for flybys of planets.

During the Earth flyby, MESSENGER imaged the Earth and Moon and used its atmospheric and surface composition spectrometer to look at the Moon. The particle and magnetic field instruments investigated the Earth's magnetosphere.

The spacecraft was originally scheduled to launch during a 12-day window that opened May 11, 2004, but on March 26, 2004, NASA announced that a later launch window starting at July 30, 2004 with a length of 15 days would be used. This was to allow more time for testing and spacecraft processing. This change significantly altered the trajectory of the mission and delayed the arrival at Mercury by two years. The original plan called for three fly-by maneuvers past Venus, with Mercury orbit insertion scheduled for 2009. The new trajectory features one Earth flyby, two Venus flybys, and three Mercury flybys before orbit insertion on March 18, 2011.

The navigation team is led by KinetX, Inc. of Tempe, Arizona. KinetX is the first private company to be responsible for navigation of a NASA deep space mission. In that role, they are responsible for determining all trajectory adjustments throughout the probe's flight through the inner solar system ensuring that MESSENGER arrives at Mercury with the proper velocity for orbit insertion.

Mercury observation plan

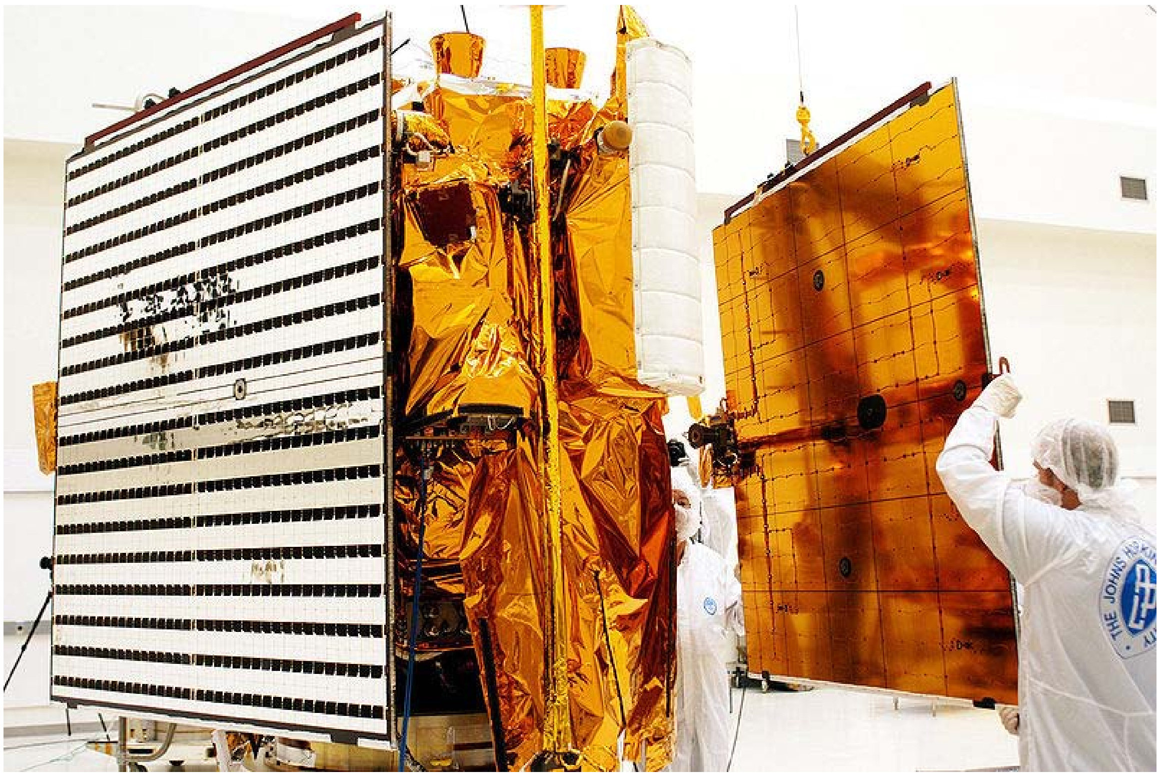
MESSENGER's first image of the side of Mercury which was never seen by Mariner 10, from a distance of about 17,000 miles (27,000 km)

An unidentified patch of black on Mercury

The nominal orbit has a periapsis of 200 km (120 mi) at 60 degrees N latitude, and an apoapsis of 15,193 km (9,440 mi), a period of 12 hours and an inclination of 82.5 degrees. The periapsis will slowly rise due to solar perturbations to over 400 km (250 mi) at the end of 88 days (one Mercury year) at which point it will be readjusted to a 200 km (120 mi), 12 hour orbit via a two burn sequence. Data will be collected from orbit for one Earth year, the nominal end of the primary mission. Global stereo image coverage at 250 meters/pixel resolution is expected. The mission should also yield global composition maps, a 3-D model of Mercury's magnetosphere, topographic profiles of the northern hemisphere, gravity field to degree and order 16, altitude profiles of elemental species, and a characterization of the volatiles in permanently shadowed craters at the poles.

Once there, scientists hope to test a theory that the planet is shrinking, contracting on itself as its core slowly freezes. The probe will look for signs of surface buckling on Mercury's unobserved hemisphere, as well as collect surface composition data on material that may have once spewed out of the planet's interior. The idea that Mercury's surface was somehow shrinking arose when Mariner 10 returned images of great scarps biting deep into the planet's surface. One such scarp, Discovery Rupes, cuts 1.6 km (1 mi) into Mercury's crust.

Spacecraft and subsystems



MESSENGER assembly installation of solar panels Astrotech

MESSENGER was designed and built by the Johns Hopkins University Applied Physics Laboratory (JHU/APL). It is a squat box (1.27 m × 1.42 m × 1.85 m) with a semi-cylindrical thermal shade for protection from the Sun and two solar panel wings extending radially. A 3.6 m (12 ft) magnetometer boom also extends from the craft. The total mass of the spacecraft is 1,093 kg (2,410 lb); 607.8 kg (1,340 lb) of this is propellant (hydrazine and nitrogen tetroxide) and helium. The structure is primarily graphite cyanate ester (GrCE) composite and consists of two vertical panels which support two large fuel tanks and two vertical panels which support the oxidizer tank and plumbing panel. The four vertical panels make up the center column and are bolted at their aft ends to an aluminum adapter. A single top deck panel mounts the LVA (large velocity adjust) thruster, small thrusters, helium and auxiliary fuel tanks, star trackers and battery.

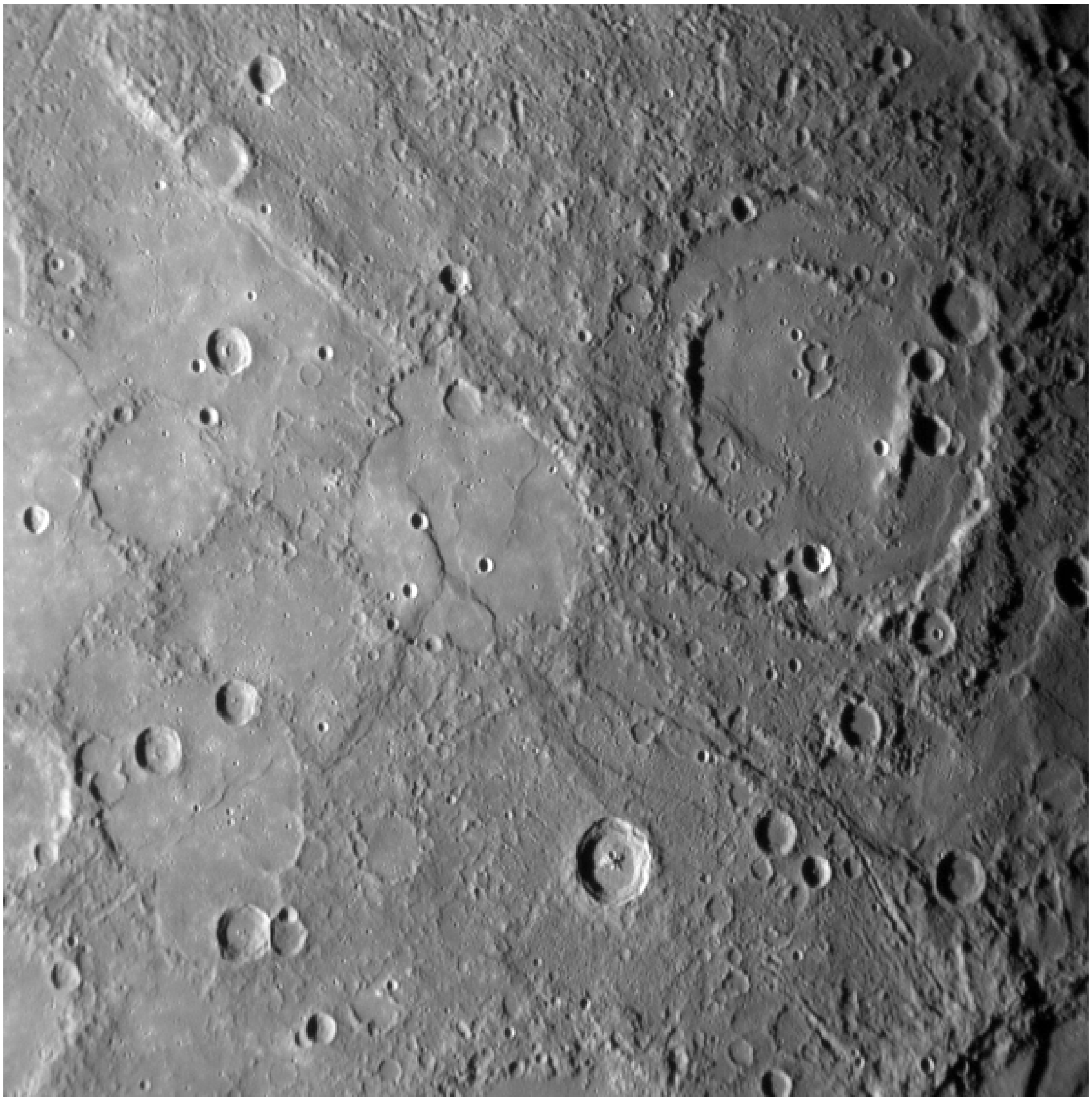
Main propulsion is via the 645 N (145 lb_f), 317 s bipropellant LVA thruster. Four 22 N (4.9 lb_f) monopropellant thrusters provide spacecraft steering during main thruster burns, and ten 4 N (0.9 lb_f) monopropellant thrusters are used for attitude control. There is also a reaction wheel attitude control system. Information for attitude control is provided by star tracking cameras, an inertial measurement unit, and six solar sensors. Power is provided by solar panels which extend beyond the sunshade. They are rotatable to balance panel temperature and power generation and provide a nominal 450 watts in Mercury orbit. The panels are 70 percent optical solar reflectors and 30 percent GaAs/Ge cells. The power is stored in a common-pressure-vessel, 23-ampere-hour nickel hydrogen battery, with 11 vessels and two cells per vessel.

Communications uses two small deep space transponders (SDSTs) operating at X-band. Downlink is through two fixed phased array antenna clusters, and uplink and downlink through medium- and low-gain antennas on the forward and aft sides of the spacecraft. Passive thermal control, primarily a fixed opaque ceramic cloth sunshade, is utilized to maintain operating temperatures near the Sun. Radiators are built into the structure and the orbit is optimized to minimize infrared and visible light heating of the spacecraft from the surface of Mercury. Multilayer insulation, low conductivity couplings, and heaters are also used to maintain temperatures within operating limits.

Five science instruments are mounted externally on the bottom deck of the main body: the Mercury Dual Imaging System (MDIS), Gamma-Ray and Neutron Spectrometer (GRNS), X-ray Spectrometer (XRS), Mercury Laser Altimeter (MLA), and Atmospheric and Surface Composition Spectrometer (MASCS). The Energetic Particle and Plasma Spectrometer (EPPS) is mounted on the side and top deck and the magnetometer (MAG) is at the end of the 3.6 meter boom. Radio Science (RS) experiments will use the existing communications system.

MESSENGER's onboard computer system is based on the Integrated Electronics Module (IEM), a device that combines core avionics in a single box. The spacecraft carries a pair of identical IEMs for backup purposes; both house a 25 megahertz main processor and 10 MHz fault protection processor. All four are radiation-hardened IBM RAD6000 processors, based on the IBM POWER1 CPU architecture (similar to that of older Macintoshes). The RAD computer is slow by current personal computer standards, but is capable of radiation tolerance required on the MESSENGER mission. For data storage, the spacecraft carries two solid-state recorders (one backup) able to store up to one gigabyte each. Its main processor collects, compresses, and stores on the recorder images and other data from MESSENGER's instruments, which can then be sent back to Earth.

Scientific results



An image of part of the previously unseen side of the planet

MESSENGER performed its first Mercury flyby successfully on 14 January 2008, and its second flyby on 6 October 2008, taking pictures with both the wide angle and narrow angle cameras as well as using some of its other sensors. Preliminary image results from this first pass can be viewed at JHUAPL's MESSENGER Science Photos page.

On July 3, 2008, MESSENGER team member Thomas Zurbuchen announced that the probe discovered large amounts of water present in Mercury's exosphere. "Nobody expected that. I don't know a single person that did. We were astonished, just astonished", Zurbuchen stated.

MESSENGER also provided visual evidence of volcanic activity on the surface of Mercury as well as evidence for a liquid planetary core.

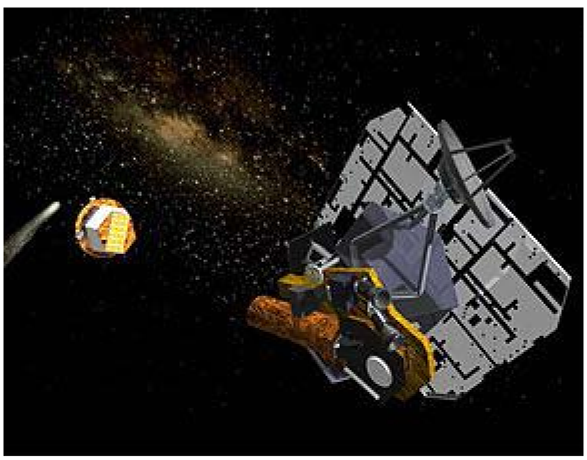
MESSENGER performed its third and last Mercury flyby on September 29, 2009 with the spacecraft coming within 142 mi (229 km) of the planet's surface. The inbound portion of the fly-by seems to have gone as planned, however sometime during the closest approach the spacecraft entered safe mode. Although this had no effect on the trajectory necessary for later orbit insertion it may have resulted in the loss of science data and images that were planned for the outbound leg of the fly-by. The spacecraft had fully recovered by about 7 hours later.

Chapter 2

Space and Solar System Exploration in 2005

Deep Impact (spacecraft)

Deep Impact



Artist's conception of the *Deep Impact* space probe after impactor separation.

Operator	NASA / JPL
Major contractors	Ball Aerospace, JPL
Mission type	Flyby / Impactor
Flyby of	Tempel 1, Hartley 2
Launch date	2005-01-12 18:47:08 UTC (6 years and 2 days ago)
Launch vehicle	Delta II-7925
Launch site	Space Launch Complex 17B

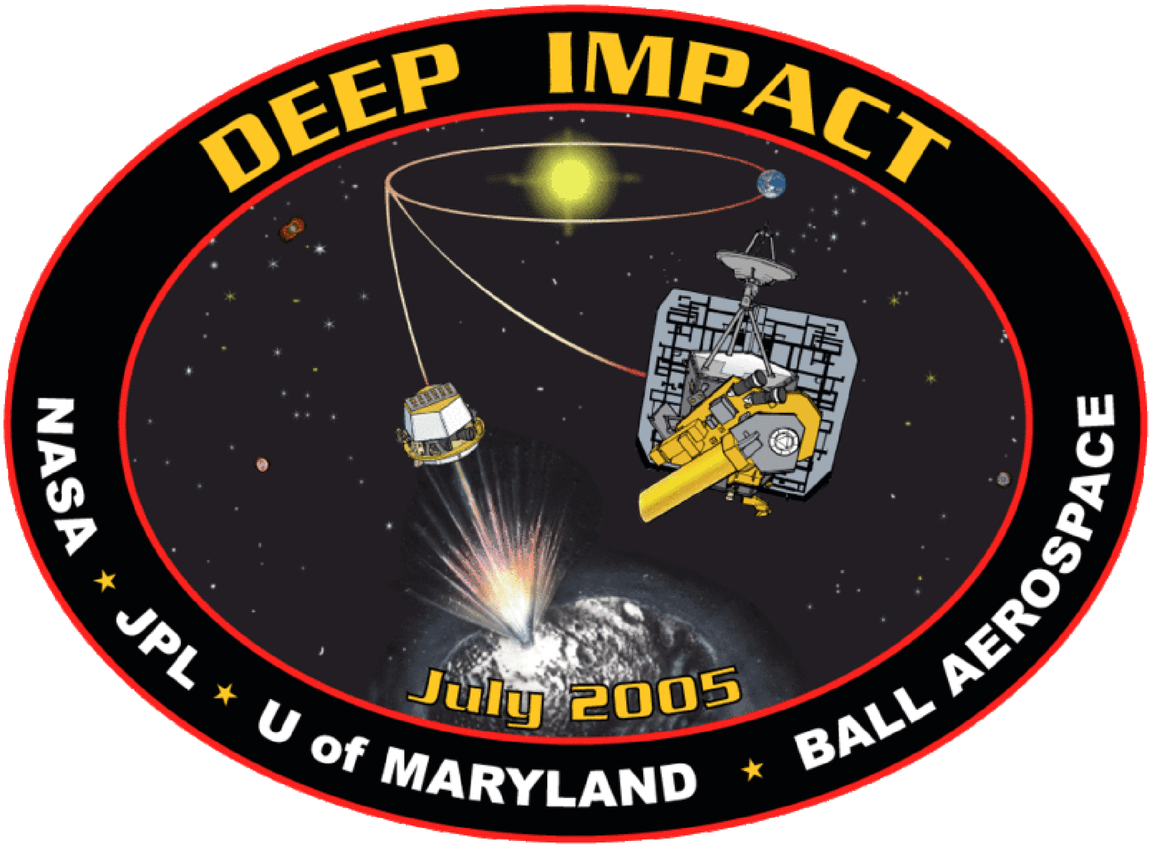
	Cape Canaveral Air Force Station
Mission duration	In Progress (EPOXI) (5 years, 5 months, and 23 days elapsed) Tempel 1 flyby *(completed 2005-07-04)* Hartley 2 flyby *(completed 2010-11-25)*
COSPAR ID	2005-001A
Mass	650 kg (1,433 lb) 370 kg (816 lb) Impactor
Power	620 W (Solar array / NiH2 battery)

Deep Impact is a NASA space probe launched on January 12, 2005. It was designed to study the composition of the comet interior of 9P/Tempel, by releasing an impactor into the comet. At 5:52 UTC on July 4, 2005, the impactor successfully collided with the comet's nucleus. The impact excavated debris from the interior of the nucleus, allowing photographs of the impact crater. The photographs showed the comet to be more dusty and less icy than had been expected. The impact generated a large and bright dust cloud, which unexpectedly obscured the view of the impact crater.

Previous space missions to comets, such as *Giotto* and *Stardust*, were fly-by missions. These missions were only able to photograph and examine the surfaces of cometary nuclei from a distance. The *Deep Impact* mission was the first to eject material from a comet's surface, and the mission garnered large publicity from the media, international scientists, and amateur astronomers.

Upon the completion of its primary mission proposals were made to further utilize the spacecraft. Consequently, *Deep Impact* flew by Earth on December 31, 2007 on its way to an extended mission, designated EPOXI, with a dual purpose to study extrasolar planets and comet Hartley 2.

Scientific goals

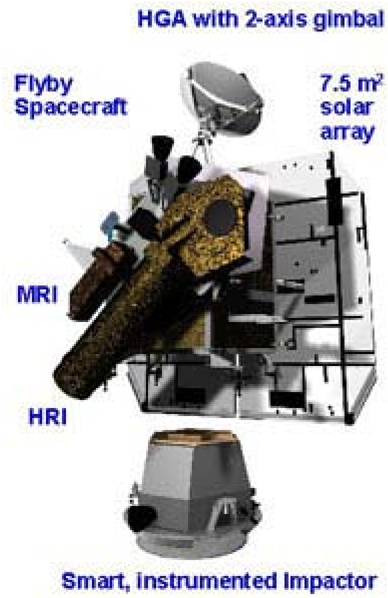


Deep Impact mission patch

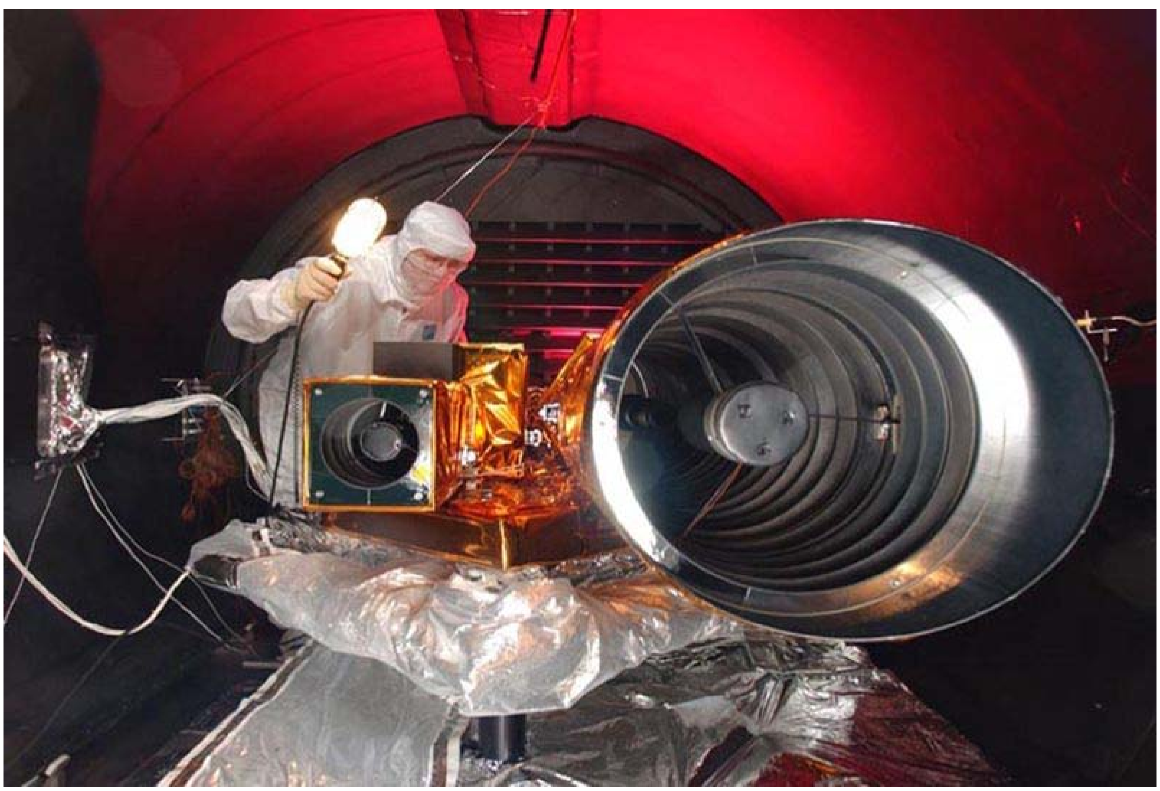
The *Deep Impact* mission was planned to help answer fundamental questions about comets, which included what makes up the composition of the comet's nucleus, what depth the crater would reach from the impact, and where the comet originated in its formation. By observing the composition of the comet, astronomers hoped to determine how comets form based on the differences between the interior and exterior makeup of the comet. Observations of the impact and its aftermath would allow astronomers to attempt to determine the answers to these questions.

The mission's Principal Investigator was Michael A'Hearn, an astronomer at the University of Maryland. He led the science team, which included members from Cornell University, University of Maryland, University of Arizona, Brown University, Belton Space Exploration Initiatives, JPL, University of Hawaii, SAIC, Ball Aerospace, and Max-Planck-Institut für extraterrestrische Physik.

Spacecraft design and instrumentation



Spacecraft overview



Cameras of the flyby spacecraft, HRI at right, MRI at left

The spacecraft consists of two main sections, the 370-kg (815-lb) copper-core "Smart Impactor" that impacted the comet, and the "Flyby" section, which imaged the comet from a safe distance during the encounter with Tempel 1.

The Flyby spacecraft is about 3.2 meters (10.5 ft) long, 1.7 meters (5.6 ft) wide and 2.3 meters (7.5 ft) high. It includes two solar panels, a debris shield, and several science instruments for imaging, infrared spectroscopy, and optical navigation to its destination near the comet. The spacecraft also carried two cameras, the High Resolution Imager (HRI), and the Medium Resolution Imager (MRI). The HRI is an imaging device that combines a visible-light camera with a filter wheel, and an imaging infrared spectrometer called the "Spectral Imaging Module" or SIM that operates on a spectral band from 1.05 to 4.8 micrometres. It has been optimized for observing the comet's nucleus. The MRI is the backup device, and was used primarily for navigation during the final 10-day approach. It also has a filter wheel, with a slightly different set of filters.

The Impactor section of the spacecraft contains an instrument that is optically identical to the MRI, called the Impactor Targeting Sensor (ITS), but without the filter wheel. Its dual purpose was to sense the Impactor's trajectory, which could then be adjusted up to four times between release and impact, and to image the comet from close range. As the Impactor neared the comet's surface, this camera took high-resolution pictures of the nucleus (as good as 0.2 meters (0.7 ft) per pixel) that were transmitted in real-time to the Flyby spacecraft before it and the Impactor were destroyed. The final image taken by the impactor was snapped only 3.7 seconds before impact.

The impactor's payload, dubbed the "Cratering Mass", was 100% copper (impactor 49% copper by mass) to reduce debris interfering with scientific measurements of the impact. Since copper was not expected to be found on a comet, scientists could eliminate copper from the spectrometer reading. Instead of using explosives, it was also cheaper to use copper as the payload.

The name of the mission is shared with the 1998 *Deep Impact* film, in which a comet strikes the Earth. This is coincidental, however, as the scientists behind the mission and the creators of the film devised the name independently of each other at around the same time.

Mission profile

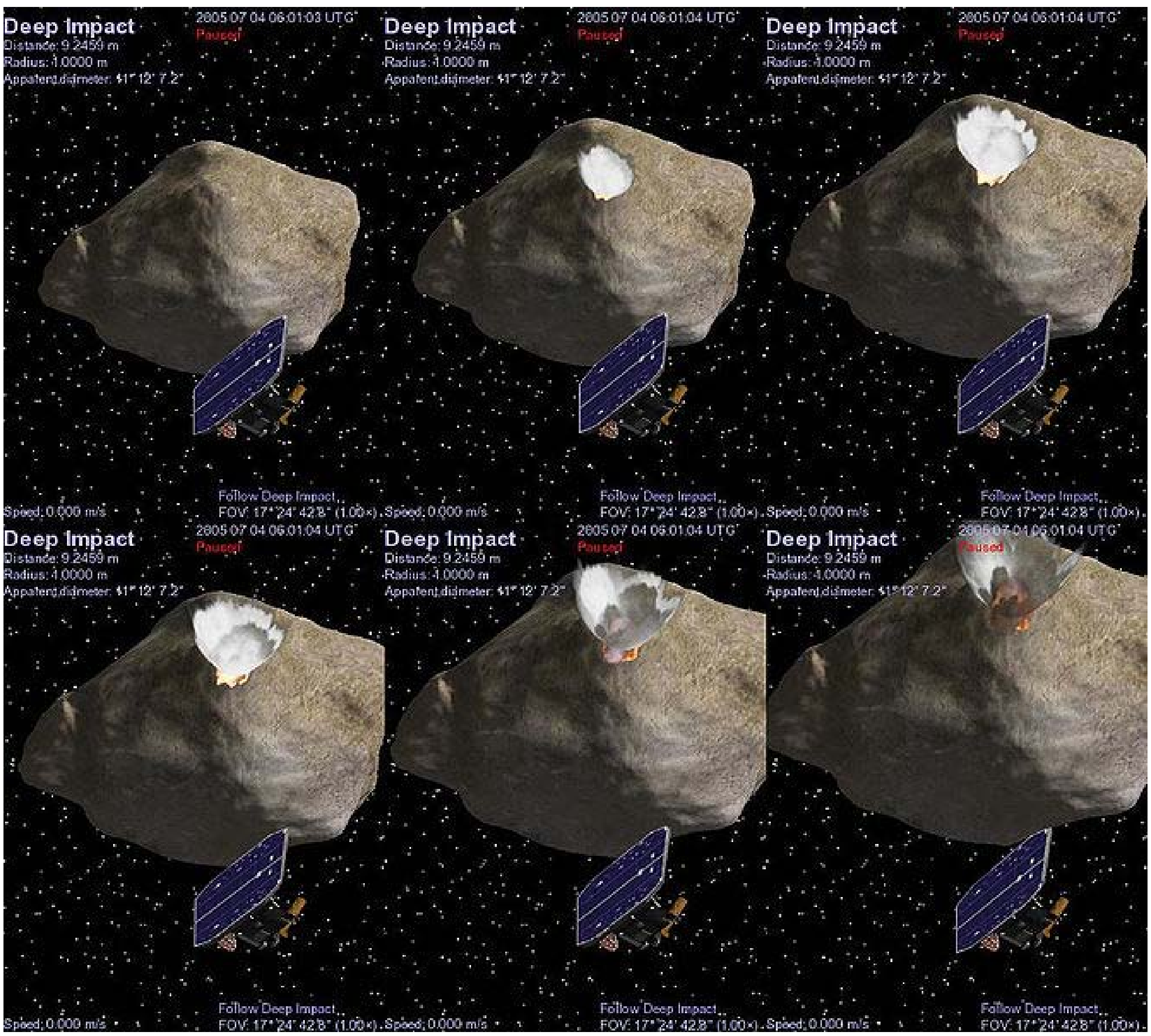
Deep Impact about to be launched with a Delta II rocket

Following its launch on January 12, 2005, the *Deep Impact* spacecraft traveled 429 million kilometers (267 million mi) in 174 days to reach comet 9P/Tempel at a cruising speed of 28.6 km/s (103,000 km/h or 64,000 mph). Once the spacecraft reached the vicinity of the comet on July 3, 2005, it separated into two portions, an impactor and a flyby probe. The impactor used its thrusters to move into the path of the comet, impacting 24 hours later at a relative speed of 10.3 km/s (37,000 km/h or 23,000 mph). The impactor, a 370-kilogram (820-pound) copper projectile, delivered 1.96×10^{10} joules of kinetic energy—the equivalent of 4.7 tons of TNT. Scientists believed that the energy of the high-velocity collision would be sufficient to excavate a crater up to 100 m (328 ft) wide (larger than the bowl of the Roman Colosseum). The size of the crater was still not known one year after the impact.

Just minutes after the impact, the flyby probe passed by the nucleus at a close distance of 500 km (310 mi), taking pictures of the crater position, the ejecta plume, and the entire cometary nucleus. The entire event was photographed by Earth-based telescopes and orbital observatories, including the Hubble, Chandra, Spitzer, and XMM-Newton. The impact was also observed by cameras and spectroscopes on board Europe's *Rosetta* spacecraft, which was about 80 million km (50 million mi) from the comet at the time of impact. *Rosetta* determined the composition of the gas and dust cloud that was kicked up by the impact.

Mission events

Before launch



Simulation: The collision of comet 9P/Tempel and the *Deep Impact* impactor, simulated by Celestia software using pre-impact information. The sun and the earth are on the right side. Note: The Deep Impact itself faces the wrong direction. The solar array should face the sun and the high-gain antenna should point to the earth.

A comet-impact mission was first proposed to NASA in 1996, but at the time, NASA engineers were skeptical that the target could be hit. In 1999, a revised and technologically upgraded mission proposal, dubbed *Deep Impact*, was accepted and funded as part of NASA's Discovery Program of low-cost spacecraft. The two spacecraft (Impactor and Flyby) and the three main instruments were built and integrated by Ball Aerospace & Technologies Corp. in Boulder, Colorado. Developing the software for the spacecraft took 18 months and the application code consisted of 20,000 lines and 19 different application threads. The total cost of developing the spacecraft and completing its mission reached $330 million.

Launch and commissioning phase

The probe was originally scheduled for launch on December 30, 2004, but NASA officials delayed its launch, in order to allow more time for testing the software. It was successfully launched from Cape Canaveral on January 12, 2005 at 1:47 p.m. EST (1847 UTC) by a Delta 2 rocket.

Deep Impact's state of health was uncertain during the first day after launch. Shortly after entering orbit around the Sun and deploying its solar panels, the probe switched itself to safe mode. The cause of the problem was simply an incorrect temperature limit in the fault protection logic for the spacecraft's RCS thruster catalyst beds. The spacecraft's thrusters were used to detumble the spacecraft following third stage separation. NASA subsequently announced that the probe was out of safe mode and healthy.

On February 11, *Deep Impact*'s rockets were fired as planned to correct the spacecraft's course. This correction was so precise that the next planned maneuver for March 31 was canceled. The "commissioning phase" verified that all instruments were activated and checked out. During these tests it was found that the HRI images were not in focus after it underwent a bake-out period. After mission members investigated the problem, on June 9, it was announced that by using image processing software and the mathematical technique of deconvolution, the HRI images could be corrected to restore much of the resolution anticipated.

Cruise phase

Comet 9P/Tempel imaged on April 25 by the Deep Impact spacecraft

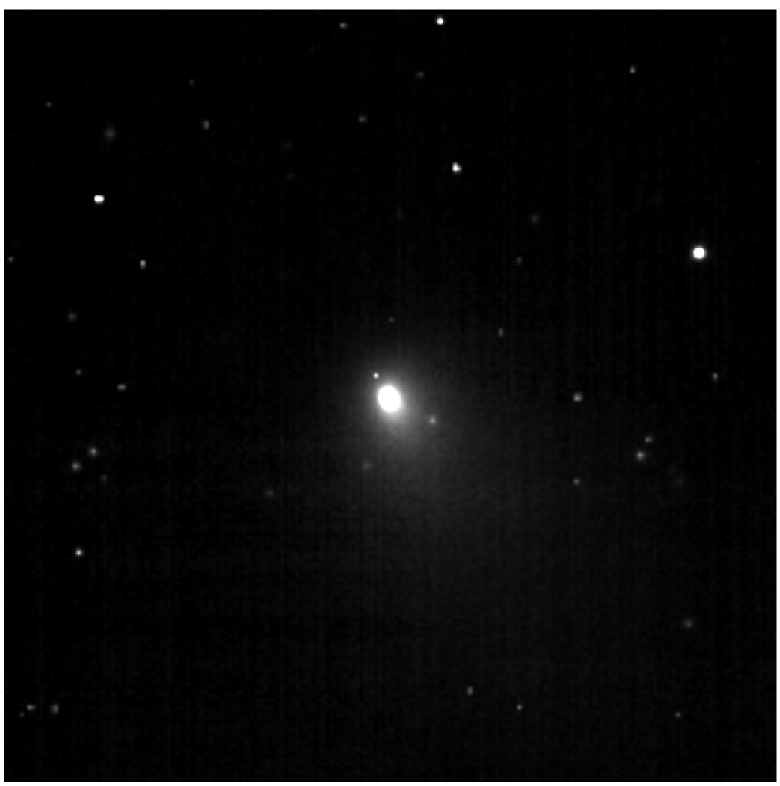
The "cruise phase" began on March 25, immediately after the commissioning phase was completed. This phase continued until about 60 days before the encounter with comet 9P/Tempel. On April 25 the probe acquired the first image of its target at a distance of 64 million km (40 million miles).

On May 4 the spacecraft executed its second trajectory correction maneuver. Burning its rocket engine for 95 seconds, the spacecraft speed was changed by 18.2 km/h (11.3 mph). Rick Grammier, the project manager for the mission at NASA's Jet Propulsion Laboratory, reacted to the maneuver stating that "spacecraft performance has been excellent, and this burn was no different...it was a textbook maneuver that placed us right on the money."

Approach phase

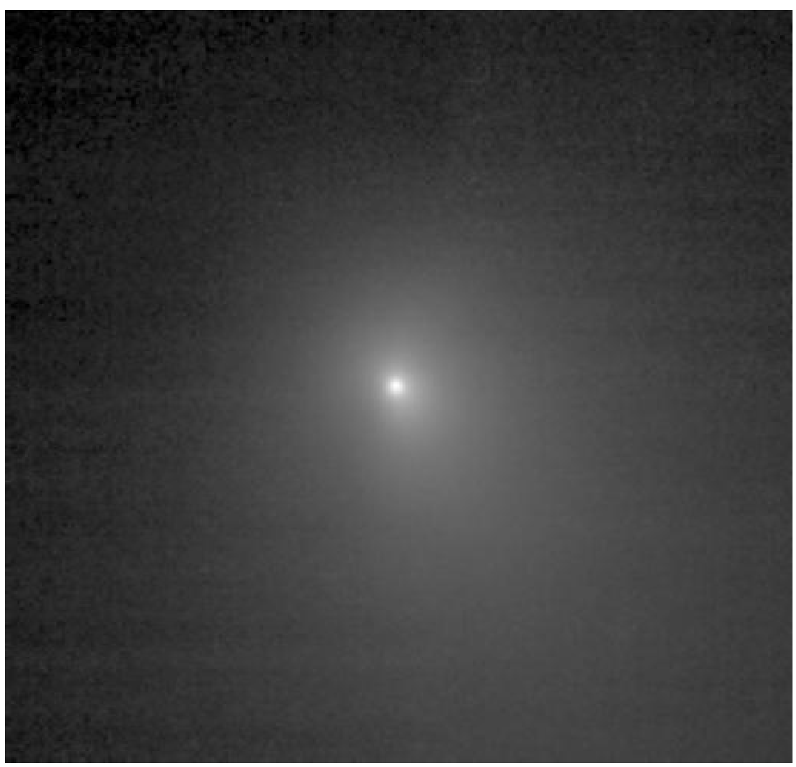
The approach phase extended from 60 days before encounter (May 5) until five days before encounter. Sixty days out was the earliest time that the *Deep Impact* spacecraft was expected to detect the comet with its MRI camera. In fact, the comet was spotted ahead of schedule, 69 days before impact. This milestone marks the beginning of an intensive period of observations to refine knowledge of the comet's orbit and study the comet's rotation, activity, and dust environment.

On June 14 and June 22, Deep Impact observed two outbursts of activity from the comet, the latter being six times larger than the former. The spacecraft studied the images of various distant stars to determine its current trajectory and position. Don Yeomans, a mission co-investigator for JPL pointed out that "it takes 7½ minutes for the signal to get back to Earth, so you cannot joystick this thing. You have to rely on the fact that the Impactor is a smart spacecraft as is the Flyby spacecraft. So you have to build in the intelligence ahead of time and let it do its thing." On June 23, the first of the two final trajectory correct maneuvers (targeting maneuver) was successfully executed. A 6 m/s (13.4 mph) velocity change was needed to adjust the flight path towards the comet and target the impactor at a window in space about 100 kilometers (62 mi) wide.

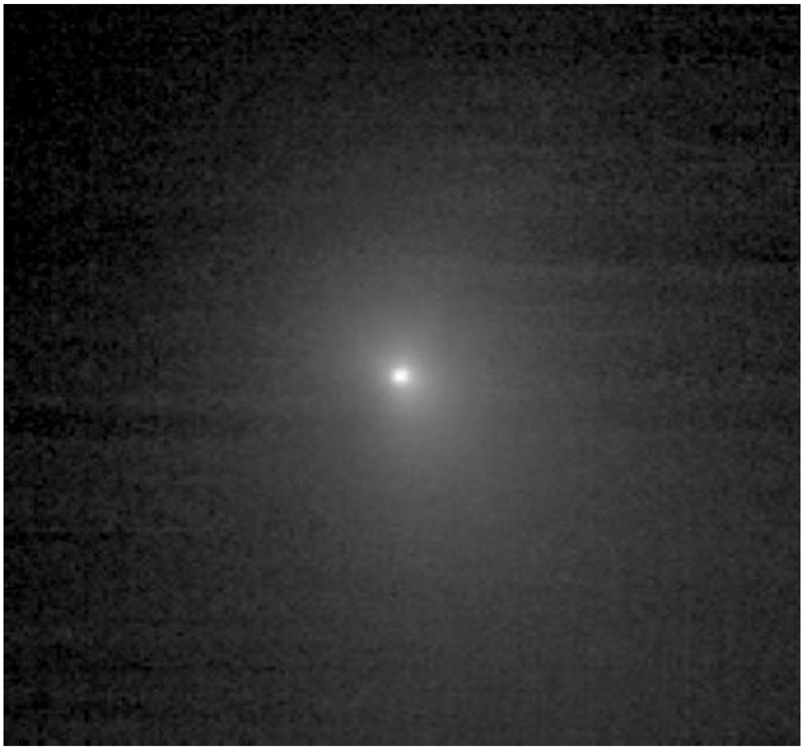


May 30, 2005, 35 days from impact

June 15, 19 days from impact

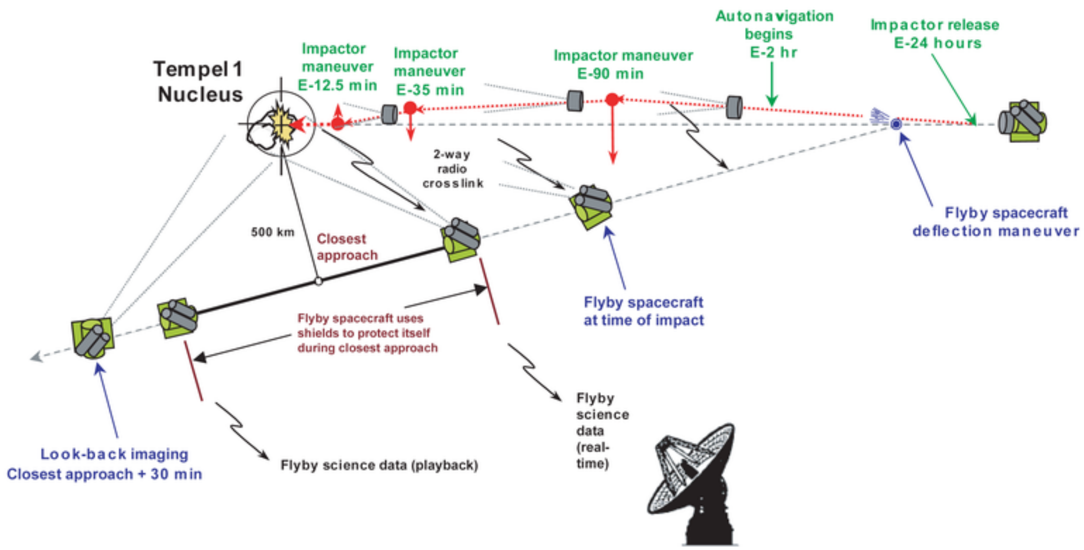


June 21, 13 days from impact



June 27, 7 days from impact, near end of approach phase

Impact phase



Deep Impact comet encounter sequence

Impact phase began nominally on June 29, five days before impact. The impactor successfully separated from the flyby spacecraft at 6:00 (6:07 Ground UTC) July 3 UTC. The first images from the instrumented Impactor were seen two hours after separation.

The flyby spacecraft performed one of two divert maneuvers to avoid damage. A 14-minute burn was executed which slowed down the spacecraft. It was also reported that the communication link between the flyby and the impactor was functioning as expected. The impactor spacecraft executed three correction maneuvers in the final two hours before impact.

The impactor was maneuvered to plant itself in front of the comet, so that 9P/Tempel would collide with it. Impact occurred at 05:45 UTC (05:52 Ground UTC, +/- up to three minutes, one-way light time = 7m 26s) on the morning of July 4, within one second of the expected time for impact.

The impactor returned images as late as three seconds before impact. Most of the data captured was stored on board the flyby spacecraft, which radioed approximately 4,500 images from the HRI, MRI, and ITS cameras to earth over the next few days. The energy from the collision was similar in size to exploding five tons of dynamite and the comet shone six times brighter than normal.

Impact Phase Timeline (NASA)

Results

Mission team members celebrate after the impact with the comet

Mission control did not become aware of the impactor's success until five minutes later at 0157 ET. Once news of a successful impact had taken place, the mission control team members applauded and hugged each other. Don Yeomans confirmed the results for the press, "We hit it just exactly where we wanted to" and JPL Director Charles Elachi stated "The success exceeded our expectations."

In the post-impact briefing at 0100 Pacific Daylight Time (08:00 UTC) on July 4, 2005, the first processed images revealed existing craters on the comet. NASA scientists stated they could not see the new crater that had formed from the impactor, but it was later discovered to be about 100 meters (328 ft) wide and up to 30 meters (98 ft) deep. Lucy McFadden, one of the co-investigators of the impact, stated "We didn't expect the success of one part of the mission [bright dust cloud] to affect a second part [seeing the resultant crater]. But that is part of the fun of science, to meet with the unexpected." Analysis of data from the Swift X-ray telescope showed that the comet continued outgassing from the impact for 13 days, with a peak five days after impact. A total of 5 million kilograms (11 million pounds) of water and between 10 and 25 million kilograms (22 and 55 million pounds) of dust were lost from the impact.

Initial results were surprising as the material excavated by the impact contained more dust and less ice than had been expected. The only models of cometary structure astronomers could positively rule out were the very porous models which had comets as loose aggregates of material. In addition, the material was finer than expected; scientists compared it to talcum powder rather than sand. Other materials found while studying the impact included clays, carbonates, sodium, and crystalline silicates which were found by studying the spectroscopy of the impact. Clays and carbonates usually require liquid water to form and sodium is rare in space. Observations also revealed that the comet was about 75% empty space, and one astronomer compared the outer layers of the comet to the same makeup of a snow bank. Astronomers have expressed interest in more missions to different comets to determine if they share similar compositions or if there are different materials found deeper within comets that were produced at the time of the solar system's formation.

Astronomers determined that the comet had possibly formed in the Uranus and Neptune Oort cloud region of the solar system. Based on its interior chemistry, astronomers were able to determine that a comet which forms farther from the Sun will have greater amounts of ices with low freezing temperatures, such as ethane, which was present in 9P/Tempel. If comets have similar compositions as Tempel, astronomers believe they could have formed in the same region.

Public interest

Media coverage

This image was circulated widely in the media

The impact was a substantial news event reported and discussed online, in print, and on television. There was a genuine suspense because experts held widely differing opinions over the result of the impact. Various experts debated whether the impactor would go straight through the comet and out the other side, would create an impact crater, would open up a hole in the interior of the comet, and other theories. However, twenty-four hours before impact, the flight team at JPL began privately expressing a high level of confidence that, barring any unforeseen technical glitches, the spacecraft would intercept

9P/Tempel. One senior personnel member stated "All we can do now is sit back and wait. Everything we can technically do to ensure impact has been done." In the final minutes as the impactor hit the comet, more than 10,000 people watched the collision on a giant movie screen at Hawaii's Waikiki Beach.

Experts came up with a range of soundbites to summarize the mission to the public. Iwan Williams of Queen Mary, University of London, said "It was like a mosquito hitting a 747. What we've found is that the mosquito didn't splat on the surface; it is actually gone through the windscreen."

One day after the impact Marina Bay, a Russian astrologer, sued NASA for $300 million for the impact which "ruin[ed] the natural balance of forces in the universe." Her lawyer asked the public to volunteer to help in the claim by declaring "The impact changed the magnetic properties of the comet, and this could have affected mobile telephony here on Earth. If your phone went down this morning, ask yourself Why? and then get in touch with us." On August 9, 2005 the Presnensky Court of Moscow ruled against Bay, although she did attempt to appeal the result. One Russian physicist said that the impact had no effect on Earth and "the change to the orbit of the comet after the collision was only about 10 cm (3.9 in)."

Send Your Name To A Comet!

The CD containing the 625,000 names is added to the Impactor

The mission was notable for one of its promotional activities, "Send Your Name To A Comet!". Visitors to the Jet Propulsion Laboratory's website were invited to submit their name between May 2003 and January 2004, and the names gathered—some 625,000 in all—were then burnt onto a mini-CD, which was attached to the impactor. Dr. Don Yeomans, a member of the spacecraft's scientific team, stated "this is an opportunity to become part of an extraordinary space mission ... when the craft is launched in December 2004, yours and the names of your loved-ones can hitch along for the ride and be part of what may be the best space fireworks show in history." The idea was credited with driving interest in the mission.

Reaction from China

Chinese researchers used the *Deep Impact* mission as an opportunity to highlight the efficiency of American science because public support ensured the possibility of funding long-term research. By contrast, "in China, the public usually has no idea what our scientists are doing, and limited funding for the promotion of science weakens people's enthusiasm for research."

Two days after the U.S. mission succeeded in having a probe collide with a comet, China revealed a plan for what it called a "more clever" version of the mission: landing a probe on a small comet or asteroid to push it off course. China will begin the mission after sending a probe to the Moon.

Contributions from amateur astronomers

Deep Impact participation certificate of Maciej Szczepańczyk

Since observing time on large, professional telescopes such as Keck or Hubble is always scarce, the *Deep Impact* scientists called upon "advanced amateur, student, and professional astronomers" to use small telescopes to make long-term observations of the target comet before and after impact. The purpose of these observations was to look for "volatile outgassing, dust coma development and dust production rates, dust tail development, and jet activity and outbursts." By mid-2007, amateur astronomers had submitted over a thousand CCD images of the comet.

One notable amateur observation was by students from schools in Hawaii, working with US and UK scientists, who during the press conference took live images using the Faulkes Automatic Telescope in Hawaii (the students operated the telescope over the

Internet) and were one of the first groups to get images of the impact. One amateur astronomer reported seeing a structureless bright cloud around the comet, and an estimated magnitude 2 increase in brightness after the impact. Another amateur published a map of the crash area from NASA images.

Musical tribute

The *Deep Impact* mission coincided with celebrations in the Los Angeles area marking the 50th anniversary of "Rock Around the Clock" by Bill Haley and His Comets becoming the first rock and roll single to reach No. 1 on the recording sales charts. Within twenty-four hours of the mission's success, a two-minute music video produced by Martin Lewis had been created using images of the impact itself combined with computer animation of the *Deep Impact* probe in flight, interspersed with footage of Bill Haley and His Comets performing in 1955 and the surviving original members of The Comets performing in March 2005. The video was posted to NASA's website for a couple of weeks afterwards.

On July 5, the surviving original members of The Comets (ranging in age from 71 to 84) performed a free concert for hundreds of employees of the Jet Propulsion Laboratory to help them celebrate the mission's success. This event received worldwide press attention. Later, in February 2006, the International Astronomical Union citation that officially named asteroid 79896 Billhaley included a reference to the JPL concert.

Extended mission

Deep Impact is now on an extended mission designated EPOXI (Extrasolar Planet Observation and Deep Impact Extended Investigation) to visit other comets, after being put to sleep in 2005 upon completion of the Tempel 1 mission.

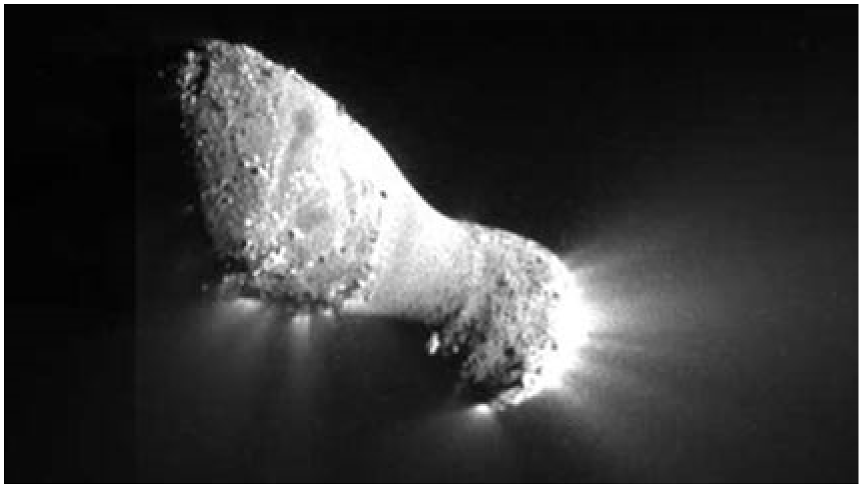
Flyby of Comet Boethin

Its first extended visit was to do a flyby of Comet Boethin, but with some complications. On July 21, 2005 *Deep Impact* executed a trajectory correction maneuver that allows the spacecraft to use Earth's gravity to begin a new mission in a path towards another comet.

The original plan was for a December 5, 2008 flyby of Comet Boethin, coming within 700 kilometers (435 miles) of the comet. Michael A'Hearn, the *Deep Impact* team leader, explained "We propose to direct the spacecraft for a flyby of Comet Boethin to investigate whether the results found at Comet Tempel 1 are unique or are also found on other comets." The $40 million mission would provide about half of the information as the collision of Tempel 1 but at a fraction of the cost. *Deep Impact* would use its spectrometer to study the comet's surface composition and its telescope for viewing the surface features.

However, as the Earth gravity assist approached, astronomers were unable to locate Comet Boethin, which may have broken up into pieces too faint to be observed. Consequently, its orbit could not be calculated with sufficient precision to permit a flyby.

Flyby of Comet Hartley 2

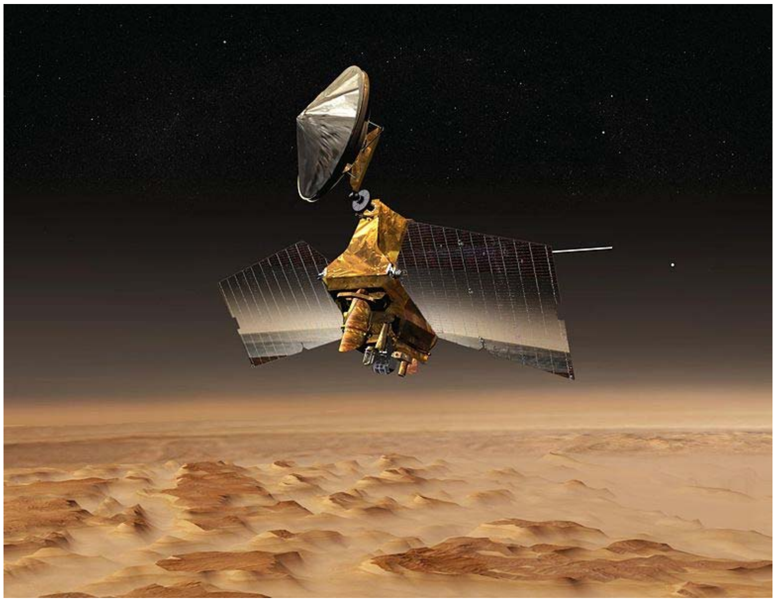


Comet Hartley 2 on November 4, 2010

JPL team targeted *Deep Impact* toward Comet Hartley 2. However, this would require an extra two years of travel for *Deep Impact*. On May 28, 2010, a burn of 11.3 seconds was conducted, to enable the June 27 Earth fly-by to be optimized for the transit to Hartley 2 and fly-by on November 4. The velocity change was 0.1 metres per second (0.22 mph).

On November 4, the Deep Impact extended mission (EPOXI) returned images from comet Hartley 2. EPOXI came within 700 kilometers (430 mi) of the comet, returning detailed photographs of the "peanut" shaped cometary nucleus and several bright jets. The probe's medium-resolution instrument captured the photographs.

Mars Reconnaissance Orbiter

Mars Reconnaissance Orbiter	
 Conceptual image depicting the Mars Reconnaissance Orbiter in an elliptical low-planet orbit around Mars	
Operator	NASA / JPL
Major contractors	Lockheed Martin Space Systems University of Arizona Applied Physics Laboratory Italian Space Agency Malin Space Science Systems,
Mission type	Orbiter
Satellite of	Mars
Orbital insertion date	2006-03-10 21:24:00 UTC
Launch date	2005-08-12 11:43:00 UTC
Carrier rocket	Atlas V-401
Launch site	Space Launch Complex 41 Cape Canaveral Air Force Station
Mission duration	Primary mission: >2 years

	elapsed: 5 years, 5 months, and 5 days
COSPAR ID	2005-029A
Mass	2,180 kilograms (4,800 lb) fueled 1,031 kilograms (2,270 lb) dry
Power	1,000.0 W

Mars Reconnaissance Orbiter (MRO) is a NASA multipurpose spacecraft designed to conduct reconnaissance and exploration of Mars from orbit. As MRO entered orbit it joined five other spacecraft in orbit of or on the planet including: *Mars Global Surveyor*, *Mars Express*, *Mars Odyssey*, and two *Mars Exploration Rovers*; a then record for most spacecraft operational in Mars vicinity. The US$720 million spacecraft was built by Lockheed Martin under the supervision of the Jet Propulsion Laboratory. It was launched August 12, 2005, and attained Martian orbit on March 10, 2006. In November 2006, after five months of aerobraking, it entered its final science orbit and began its primary science phase.

MRO contains a host of scientific instruments such as cameras, spectrometers, and radar, which are used to analyze the landforms, stratigraphy, minerals, and ice of Mars. It paves the way for future spacecraft by monitoring daily weather and surface conditions, studying potential landing sites, and hosting a new telecommunications system. MRO's telecommunications system will transfer more data back to Earth than all previous interplanetary missions combined, and MRO will serve as a highly capable relay satellite for future missions.

The mission is managed by the Jet Propulsion Laboratory, at California Institute of Technology, Pasadena, California, for the NASA Science Mission Directorate, Washington, D.C.

Pre-launch

MRO was one of two missions being considered for the 2003 Mars launch window; however, during the proposal process the orbiter lost against what became known as the Mars Exploration Rovers. The orbiter mission was rescheduled for launch in 2005, and NASA announced its final name, *Mars Reconnaissance Orbiter*, on October 26, 2000.

MRO is modeled after NASA's highly successful *Mars Global Surveyor* to conduct surveillance of Mars from orbit. Early specifications of the satellite included a large camera to take high resolution pictures of Mars. In this regard, Jim Garvin, the Mars exploration program scientist for NASA, proclaimed that MRO would be a "microscope in orbit". The satellite was also to include a visible-near-infrared spectrograph.

On October 3, 2001, NASA chose Lockheed Martin as the primary contractor for the spacecraft's fabrication. By the end of 2001 all of the mission's instruments were selected.

There were no major setbacks during MRO's construction, and the spacecraft was moved to John F. Kennedy Space Center on May 1, 2005 to prepare it for launch.

Mission objectives

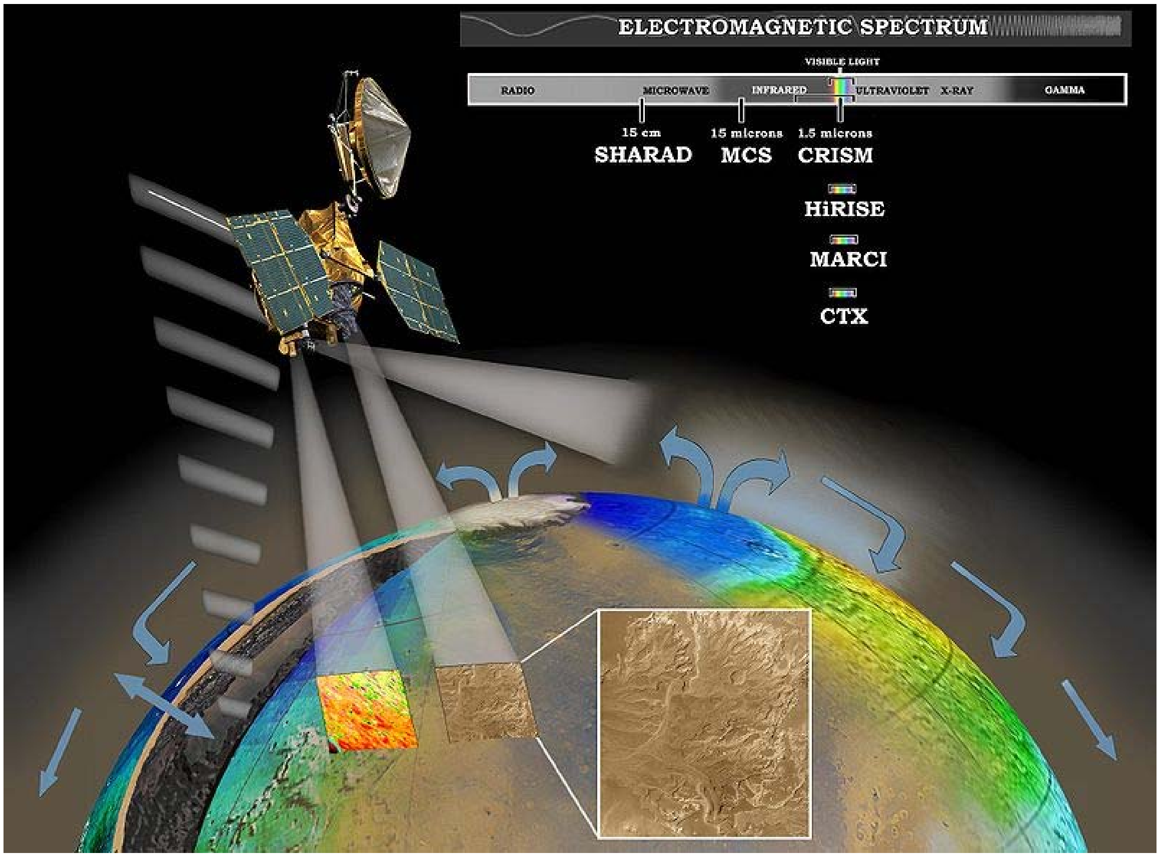


Diagram of instrumentation aboard MRO

MRO science operations were initially scheduled to last two Earth years, from November 2006 to November 2008. One of the mission's main goals is to map the Martian landscape with its high-resolution cameras in order to choose landing sites for future surface missions. The MRO played an important role in choosing the landing site of the Phoenix Lander, which explored the Martian Arctic in Green Valley. The initial site chosen by scientists was imaged with the HiRISE camera and found to be littered with boulders. After analysis with HiRISE and the Mars Odyssey's THEMIS a new site was chosen. *Mars Science Laboratory*, a highly maneuverable rover, will also have its landing site inspected. The MRO will also provide critical navigation data during their landings and act as a telecommunications relay.

MRO is using its on-board scientific equipment to study the Martian climate, weather, atmosphere, and geology, and to search for signs of water in the polar caps and underground. In addition, MRO is looking for the remains of the previously lost Mars Polar Lander and Beagle 2 spacecraft, and serves as the first step in setting up an internet protocol network for the planets in our solar system. After its main science operations are completed, the probe's extended mission is to be the communication and navigation system for landers and rover probes.

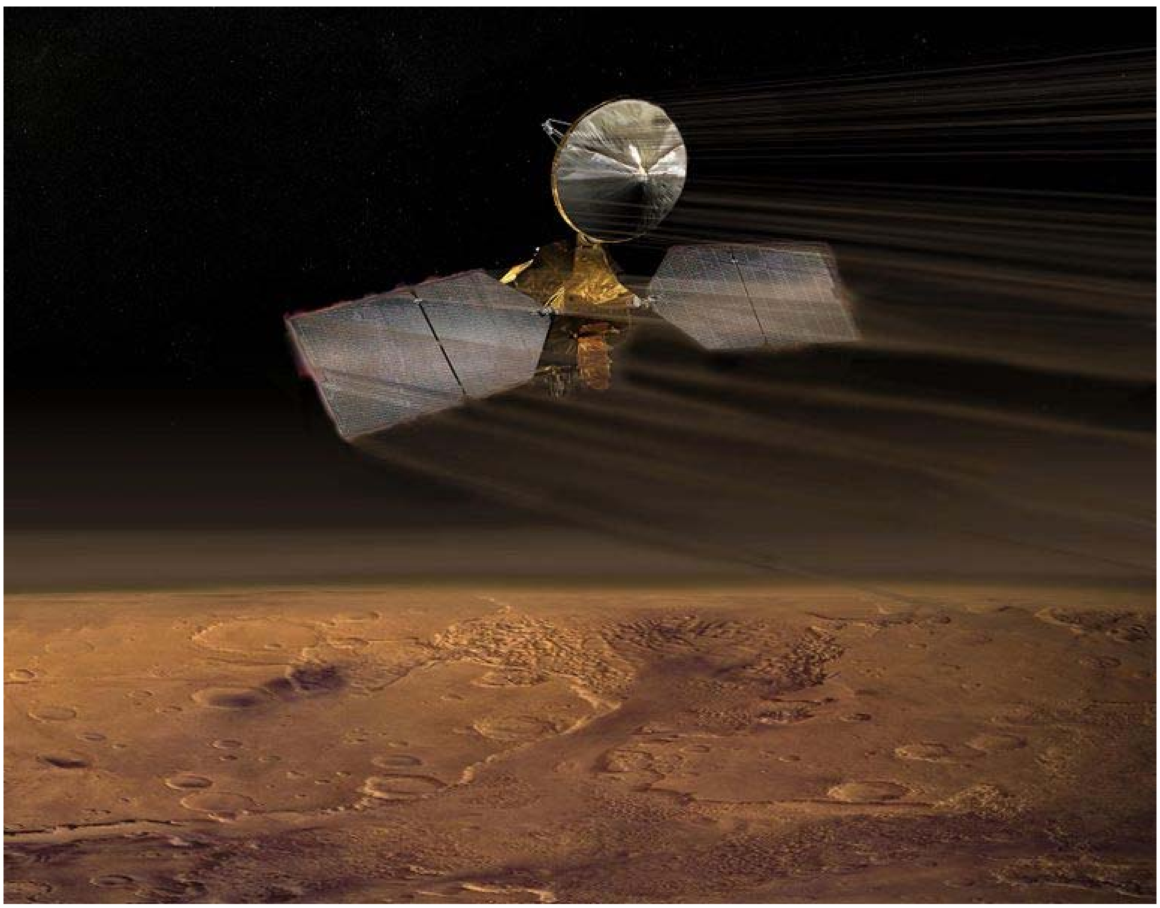
Launch and orbital insertion

Launch of Atlas V carrying the Mars Reconnaissance Orbiter, 11:43:00 UTC August 12, 2005

On August 12, 2005, MRO was launched aboard an Atlas V-401 rocket from Space Launch Complex 41 at Cape Canaveral Air Force Station. The Centaur upper stage of the rocket completed its burns over a fifty-six minute period and placed MRO in interplanetary transfer orbit towards Mars.

MRO cruised through interplanetary space for seven and a half months before reaching Mars. While en route most of the scientific instruments and experiments were tested and calibrated. To ensure proper orbital insertion upon reaching Mars, four trajectory correction maneuvers were planned and a fifth emergency maneuver was discussed. However, only three trajectory correction maneuvers were necessary, saving fuel for MRO's extended mission.

MRO began orbital insertion by approaching Mars on March 10, 2006, and passing above its southern hemisphere at an altitude of 370–400 km (190 mi). All six of MRO's main engines burned for 27 minutes to slow the probe from ~2,900 m/s to ~1,900 m/s (6,500 mph to 4,250 mph). The helium pressurization tank was colder than expected, which reduced the pressure in the fuel tank by about 21 kPa (3 psi). The reduced pressure caused the engine thrust to be diminished by 2%, but MRO automatically compensated by extending the burn time by 33 seconds.



Artwork of MRO aerobraking

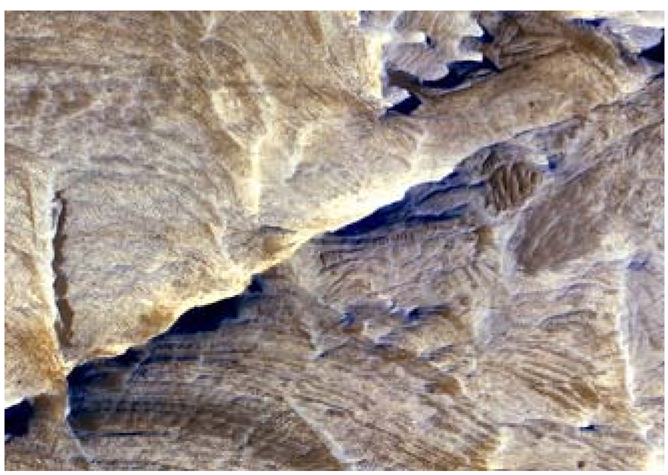
Completion of the orbital insertion placed the orbiter in a highly elliptical polar orbit with a period of approximately 35.5 hours. Shortly after insertion, the periapsis – the point in the orbit closest to Mars – was 3,806 km from the planet's center (426 km from its surface). The apoapsis – the point in the orbit farthest from Mars – was 47,972 km from the planet's center (44,500 km from its surface).

On March 30, 2006, MRO began the process of aerobraking, a three-step procedure that cuts in half the fuel needed to achieve a lower, more circular orbit with a shorter period. First, during its first five orbits of the planet (one Earth week), MRO used its thrusters to drop the periapsis of its orbit into aerobraking altitude. This altitude depends on the thickness of the atmosphere because Martian atmospheric density changes with its seasons. Second, while using its thrusters to make minor corrections to its periapsis altitude, MRO maintained aerobraking altitude for 445 planetary orbits (about 5 Earth months) to reduce the apoapsis of the orbit to 450 km (280 mi). This was done in such a way so as to not heat the spacecraft too much, but also dip enough into the atmosphere to slow the spacecraft down. After the process was complete, MRO used its thrusters to move its periapsis out of the edge of the Martian atmosphere, August 30, 2006.

In September 2006 MRO fired its thrusters twice more to fine-tune its final, nearly circular orbit approximately 250 to 316 km (155 to 196 mi) above the Martian surface. The SHARAD dipole antennas were deployed on September 16. All of the scientific instruments were tested and most were turned off prior to the solar conjunction which occurred from October 7, 2006 to November 6, 2006. After the conjunction ended the "primary science phase" began.

On November 17, 2006 NASA announced the successful test of the MRO as an orbital communications relay. Using the NASA rover "Spirit" as the point of origin for the transmission, the MRO acted as a relay for transmitting data back to Earth.

Events and discoveries



Tectonic fractures within the Candor Chasma region of Valles Marineris, Mars, retain ridge-like shapes as the surrounding bedrock erodes away. This points to past episodes of fluid alteration along the fractures and reveals clues into past fluid flow and geochemical conditions below the surface.

On September 29, 2006, MRO took its first high resolution image from its science orbit. This image is said to resolve items as small as 90 cm (3 feet) in diameter.

On October 6, 2006, NASA released detailed pictures from the MRO of Victoria crater along with the Opportunity rover on the rim above it.

In November 2006, problems began to surface in the operation of two MRO spacecraft instruments. A stepping mechanism in the Mars Climate Sounder (MCS) skipped on multiple occasions resulting in a field of view that is slightly out of position. By December normal operations of the instrument was suspended, although a mitigation strategy allows the instrument to continue making most of its intended observations. Also, an increase in noise and resulting bad pixels has been observed in several CCDs of the High Resolution Imaging Science Experiment (HiRISE). Operation of this camera with a longer warm-up time has alleviated the issue. However, the cause is still unknown and may return.

HiRISE continues to return images which have enabled discoveries regarding the geology of Mars. Foremost among these is the announcement of banded terrain observations indicating the presence and action of liquid carbon dioxide or water on the surface of Mars in its recent geological past. HiRISE was able to photograph the *Phoenix* lander during its parachuted descent to Vastitas Borealis on May 25, 2008.

The orbiter continued to experience recurring problems in 2009, including four spontaneous resets, culminating in a four-month shut-down of the space craft from August to December. While engineers have not determined the cause of the recurrent resets, they have created new software to help troubleshoot the problem should it recur.

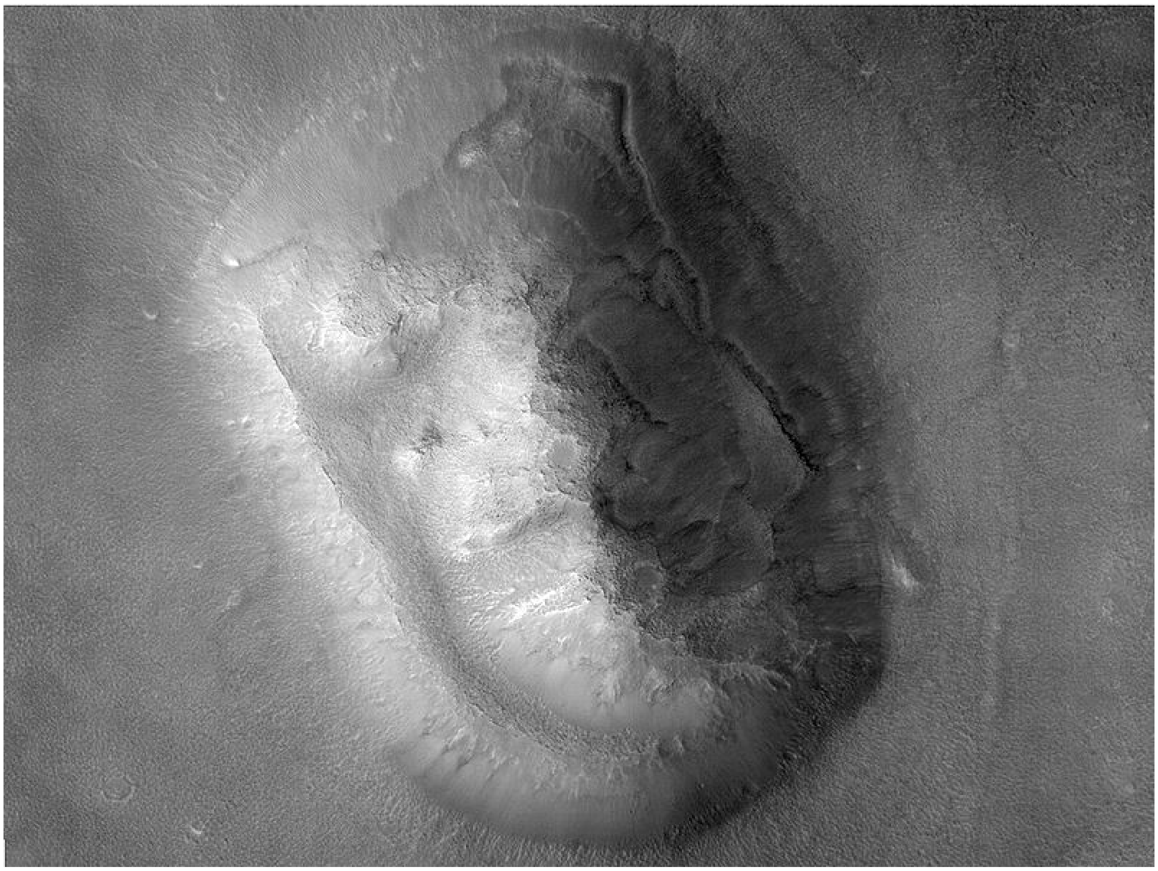
Instruments

Three cameras, two spectrometers and a radar are included on the orbiter along with two "science-facility instruments", which use data from engineering subsystems to collect science data. Three technology experiments will test and demonstrate new equipment for future missions. It is expected MRO will obtain about 5,000 images a year.

HiRISE (camera)

HiRISE camera structure

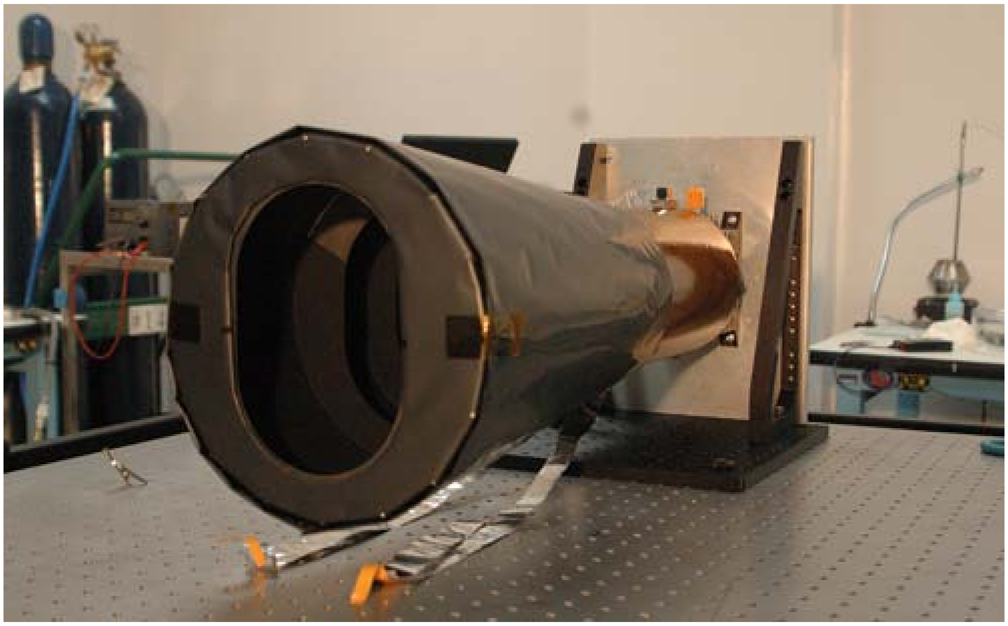
The High Resolution Imaging Science Experiment camera is a 0.5 m reflecting telescope, the largest ever carried on a deep space mission, and has a resolution of 1 microradian (μrad), or 0.3 m from an altitude of 300 km. In comparison, satellite images of Earth are generally available with a resolution of 0.5 m, and satellite images on Google Maps are available to 1 m. HiRISE collects images in three color bands, 400 to 600 nm (blue-green or B-G), 550 to 850 nm (red) and 800 to 1,000 nm (near infrared or NIR).



HiRISE image of the 'face' at Cydonia Mesa

Red color images are 20,264 pixels across (6 km wide), and B-G and NIR are 4,048 pixels across (1.2 km wide). HiRISE's on-board computer reads these lines in time with the orbiter's ground speed, and images are potentially unlimited in length. Practically however, their length is limited by the computer's 28 Gigabit (Gb) memory capacity, and the nominal maximum size is 20,000 × 40,000 pixels (800 megapixels) and 4,000 × 40,000 pixels (160 megapixels) for B-G and NIR images. Each 16.4 Gb image is compressed to 5 Gb before transmission and release to the general public on the HiRISE website in JPEG 2000 format. To facilitate the mapping of potential landing sites, HiRISE can produce stereo pairs of images from which topography can be calculated to an accuracy of 0.25 m. HiRISE was built by Ball Aerospace & Technologies Corp.

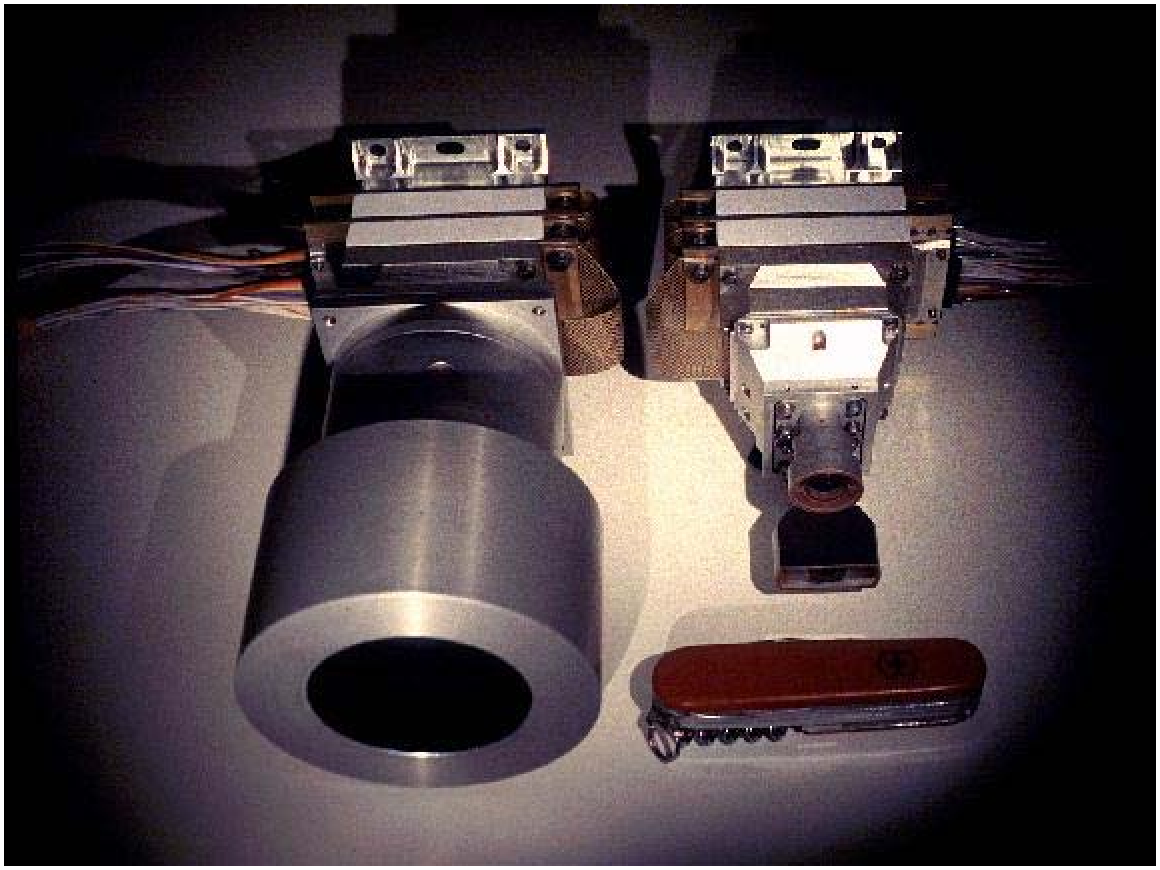
CTX (camera)



Context (CTX) Camera

The Context Camera (CTX) provides grayscale images (500 to 800 nm) with a pixel resolution of 6 m. CTX is designed to provide context maps for the targeted observations of HiRISE and CRISM, and is also used to mosaic large areas of Mars, monitor a number of locations for changes over time, and to acquire stereo (3D) coverage of key regions and potential future landing sites. The optics of CTX consist of a 350 mm focal length Maksutov Cassegrain telescope with a 5,064 pixel wide line array CCD. The instrument takes pictures 30 km (19 mi) wide and has enough internal memory to store an image 160 km long before loading it into the main computer. The camera was built (and is operated by) Malin Space Science Systems.

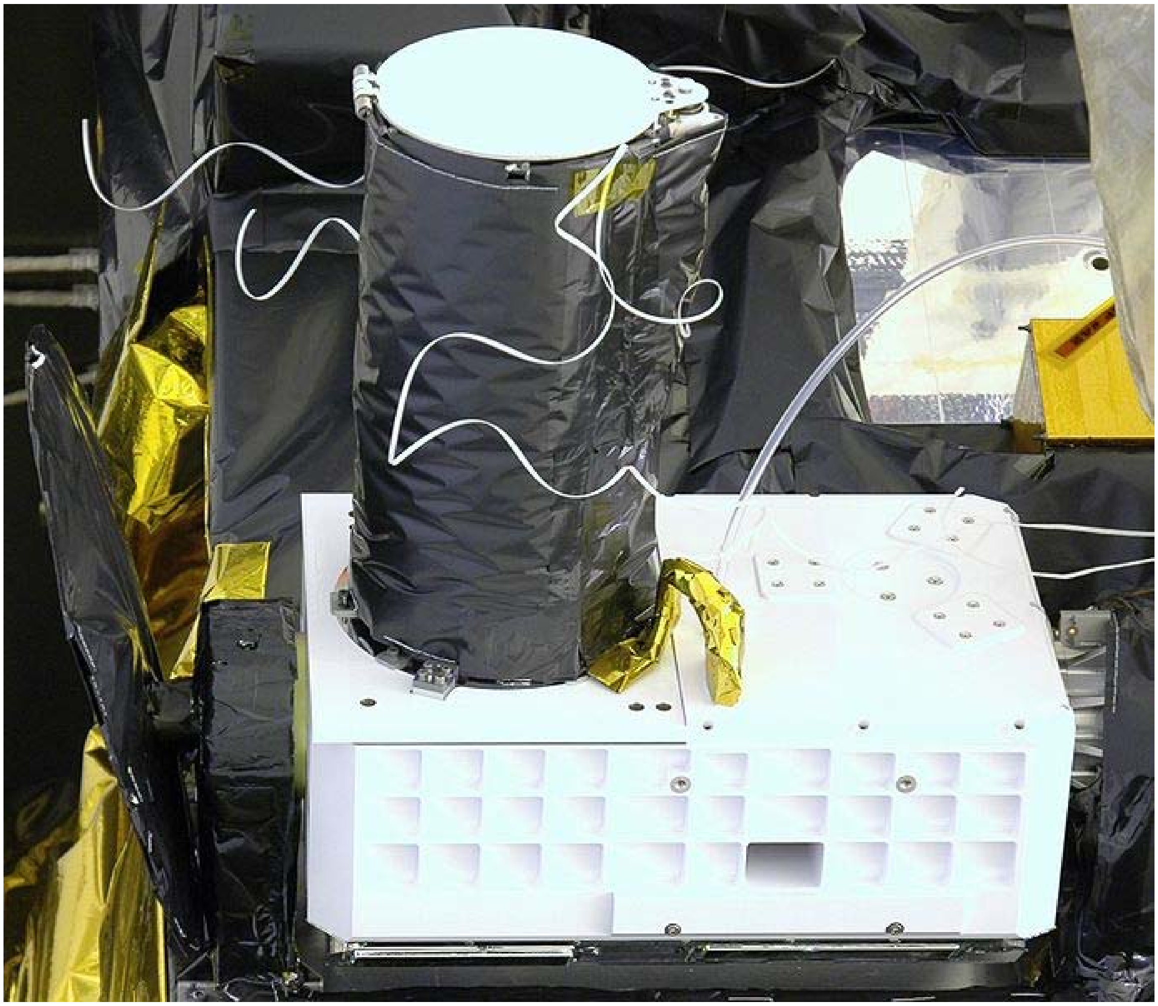
MARCI (camera)



Mars Color Imager

The Mars Color Imager (MARCI) is a wide-angle, low-resolution camera that views the surface of Mars in five visible and two ultraviolet bands. Each day, MARCI collects about 84 images and produces a global map with pixel resolutions of 1 to 10 km. This map provides a daily weather report for Mars, helps to characterize its seasonal and annual variations, and maps the presence of water vapor and ozone in its atmosphere. The camera was built (and is operated by) Malin Space Science Systems.

CRISM (spectrometer)



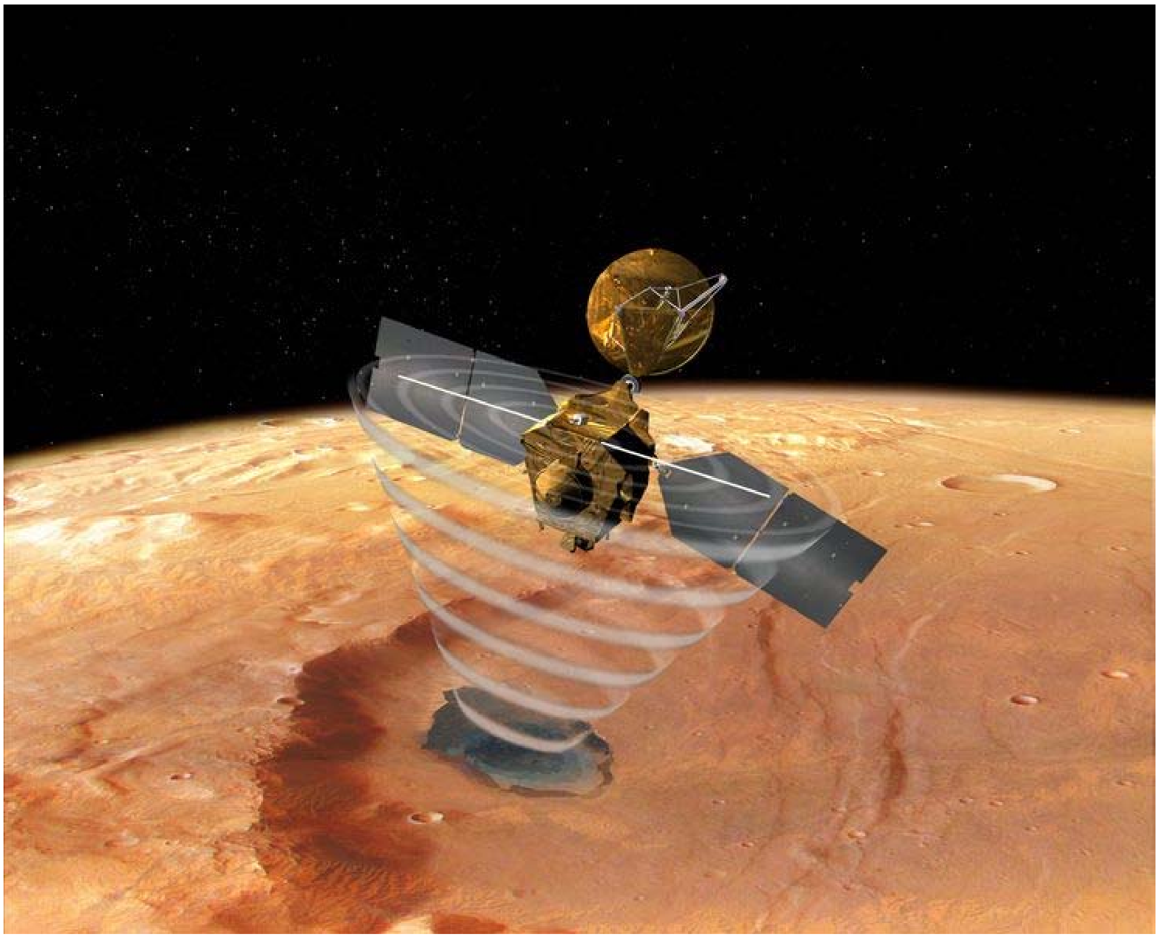
CRISM Instrument

The Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) instrument is a visible and near infrared (VNIR) spectrometer that is used to produce detailed maps of the surface mineralogy of Mars. It operates from 370 to 3920 nm, measures the spectrum in 544 channels (each 6.55 nm wide), and has a resolution of 18 m (59 ft) at an altitude of 300 km (190 mi). CRISM is being used to identify minerals and chemicals indicative of the past or present existence of water on the surface of Mars. These materials include iron, oxides, phyllosilicates, and carbonates, which have characteristic patterns in their visible-infrared energy.

MCS (spectrometer)

The Mars Climate Sounder (MCS) is a spectrometer with one visible/near infrared channel (0.3 to 3.0 μm) and eight far infrared (12 to 50 μm) channels. These channels were selected to measure temperature, pressure, water vapor and dust levels. MCS observes the atmosphere on the horizon of Mars (as viewed from MRO) by breaking it up into vertical slices and taking measurements within each slice in 5 km (3 mi) increments. These measurements are assembled into daily global weather maps to show the basic variables of Martian weather: temperature, pressure, humidity and dust density.

SHARAD (radar)



An artist's concept of MRO using SHARAD to "look" under the surface of Mars

MRO's Shallow Subsurface Radar (SHARAD) experiment is designed to probe the internal structure of the Martian polar ice caps. It also gathers planet-wide information about underground layers of ice, rock and possibly liquid water that might be accessible from the surface. SHARAD uses HF radio waves between 15 and 25 MHz, a range that allows it to resolve layers as thin as 7 m (23 ft) to a maximum depth of 1 km (0.6 mi). It has a horizontal resolution of 0.3 to 3 km (0.2 to 1.9 mi). SHARAD is designed to operate in conjunction with the Mars Express MARSIS, which has lower resolution but penetrates to a much greater depth. Both SHARAD and MARSIS were made by the Italian Space Agency.

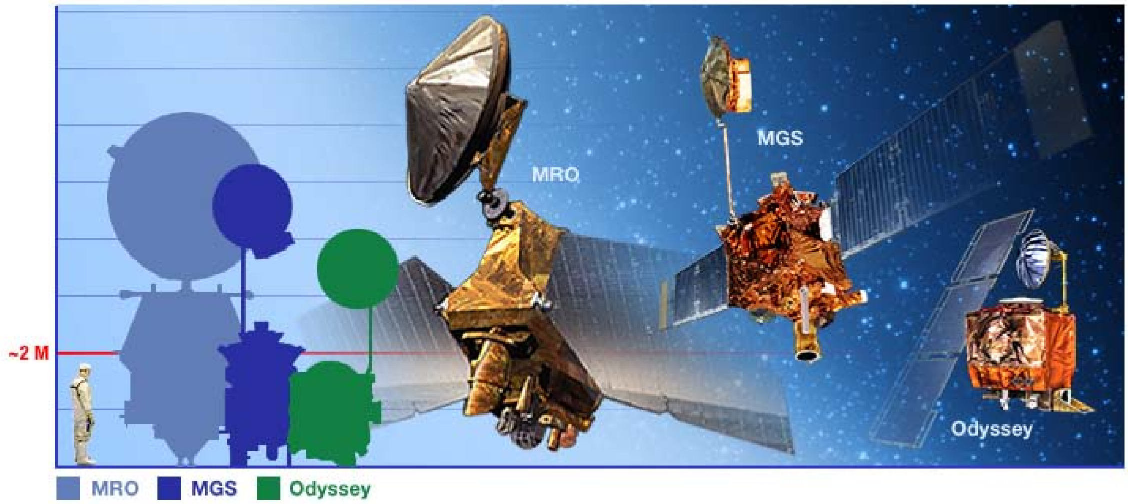
Engineering instruments

In addition to its imaging equipment, MRO carries a variety of engineering instruments. The Gravity Field Investigation Package measures variations in the Martian gravitational field through variations in the spacecraft's velocity. Velocity changes are detected by measuring doppler shifts in MRO's radio signals received on Earth. The package also includes sensitive on-board accelerometers used to deduce the *in situ* atmospheric density of Mars during aerobraking.

The Electra is a UHF software defined radio designed to communicate with other spacecraft as they approach, land, and operate on Mars. In addition to protocol controlled inter-spacecraft data links of 1 kbit/s to 2 Mbit/s, Electra also provides Doppler data collection, open loop recording and a highly accurate timing service based on a 5e-13 USO. Doppler information for approaching vehicles can be used for final descent targeting or descent and landing trajectory recreation. Doppler information on landed vehicles will also enable scientists to accurately determine the surface location of Mars landers and rovers. The two MER spacecraft currently on Mars utilize an earlier generation UHF relay radio providing similar functions through the Mars Odyssey orbiter. The Electra radio has used the MER spacecraft to prove its functionality but it is not scheduled to provide formal relay services until the 2008 arrival of the Phoenix Mars lander. Because the Electra radio is software defined down to the modem level, new modulation, coding or protocol functions can be added or updated while the MRO spacecraft is in orbit around Mars.

The Optical Navigation Camera images the Martian moons, Phobos and Deimos, against background stars to precisely determine MRO's orbit. Although moon imaging is not mission critical, it was included as a technology test for future orbiting and landing of spacecraft. The Optical Navigation Camera was tested successfully in February and March 2006.

Engineering data



Size comparison of MRO with predecessors

Structure

Workers at Lockheed Martin Space Systems in Denver assembled the spacecraft structure and attached the instruments. Instruments were constructed at the Jet Propulsion Laboratory, the University of Arizona Lunar and Planetary Laboratory in Tucson, Arizona, Johns Hopkins University Applied Physics Laboratory in Laurel, Maryland, the Italian Space Agency in Rome, and Malin Space Science Systems in San Diego, California. The total cost of the spacecraft was $720 million USD.

The structure is made of mostly carbon composites and aluminum-honeycombed plates. The titanium fuel tank takes up most of the volume and mass of the spacecraft and provides most of its structural integrity. The spacecraft's total mass is less than 2,180 kg (4,806 lb) with an unfueled dry mass less than 1,031 kg (2,273 lb).

Power systems

The Mars Reconnaissance Orbiter solar panel

MRO gets all of its electrical power from two solar panels, each of which can move independently around two axes (up-down, or left-right rotation). Each solar panel measures 5.35 × 2.53 m and has 9.5 m^2 (102 ft^2) covered with 3,744 individual photovoltaic cells. Its high-efficiency triple junction solar cells are able to convert more than 26% of the sun's energy directly into electricity and are connected together to produce a total output of 32 volts. At Mars, the two panels produce 1,000 watts of power; in contrast, the panels would generate 3,000 watts in a comparable Earth orbit by being closer to the Sun.

MRO has two nickel-hydrogen rechargeable batteries used to power the spacecraft when it is not facing the sun. Each battery has an energy storage capacity of 50 ampere-hours (180 kC). The full range of the batteries cannot be used due to voltage constraints on the spacecraft, but allows the operators to extend the battery life—a valuable capability, given that battery drain is one of the most common causes of long-term satellite failure. Planners anticipate that only 40% of the batteries' capacities will be required during the lifetime of the spacecraft.

Electronic systems

MRO's main computer is a 133 MHz, 10.4 million transistor, 32-bit, RAD750 processor. This processor is a radiation-hardened version of a PowerPC 750 or G3 processor with a specially-built motherboard. The RAD750 is a successor to the RAD6000. This processor may seem underpowered in comparison to a modern PC processor, but it is extremely reliable, resilient, and can function in solar flare-ravaged deep space. The operating system software is VxWorks and has extensive fault protection protocols and monitoring.

Data is stored in a 160 Gb (20 GB) flash memory module consisting of over 700 memory chips, each with a 256 Mbit capacity. This memory capacity is not actually that large considering the amount of data to be acquired; for example, a single image from the HiRISE camera can be as large as 28 Gb.

Attitude determination

In order to determine the spacecraft's orbit and facilitate maneuvers, sixteen sun sensors – eight primaries and eight backups – are placed around the spacecraft to calibrate solar direction relative to the orbiter's frame. Two star trackers, digital cameras used to map the position of catalogued stars, provide NASA with full, three-axis knowledge of the spacecraft orientation and attitude. A primary and backup Miniature Inertial Measurement Unit (MIMU), provided by Honeywell, measures changes to the spacecraft attitude as well as any non-gravitationally induced changes to its linear velocity. Each MIMU is a combination of three accelerometers and three ring-laser gyroscopes. These systems are all critically important to MRO, as it must be able to point its camera to a very high precision in order to take the high-quality pictures that the mission requires. It has also been specifically designed to minimize any vibrations on the spacecraft, so as to allow its instruments to take images without any distortions caused by vibrations.

Telecommunications system

MRO High Gain Antenna installation

The Telecom Subsystem on MRO is the best digital communication system sent into deep space so far and for the first time using capacity achieving turbo-codes. It consists of a very large (3 meter) antenna, which is used to transmit data through the Deep Space Network via X-band frequencies at 8 GHz, and it demonstrates the use of the K_a band at 32 GHz for higher data rates. Maximum transmission speed from Mars is projected to be as high as 6 Mbit/s, a rate ten times higher than previous Mars orbiters. The spacecraft carries two 100-watt X-band amplifiers (one of which is a backup), one 35-watt Ka-band amplifier, and two Small Deep Space Transponders (SDSTs).

Two smaller low-gain antennas are also present for lower-rate communication during emergencies and special events, such as launch and Mars Orbit Insertion. These antennas do not have focusing dishes and can transmit and receive from any direction. They are an important backup system to ensure that MRO can always be reached, even if its main antenna is pointed away from the Earth.

The Ka-band subsystem is used for demonstration purposes. Due to lack of spectrum at 8.41 GHz X-band, future high-rate deep space missions will use 32 GHz Ka-band. NASA Deep Space Network (DSN) has implemented Ka-band receiving capabilities at all three of its complexes (Goldstone, Canberra and Madrid) over its 34-m beam-waveguide (BWG) antenna subnet. MRO Ka-band demonstration will demonstrate viability of Ka-band for deep space operations. During the cruise phase, spacecraft Ka-band telemetry was tracked 36 times by these antennas proving DSN Ka-band reception functionality at all the antennas. During the primary science phase, Ka-band demonstration is assigned two passes a week for Ka-band demonstration purposes. The success of Ka-band during cruise also makes it a viable backup for the X-band subsystem on MRO.

Propulsion and attitude control

Data comparison chart

The spacecraft uses a 1,175 L (310 US gal) fuel tank filled with 1187 kg (2617 lb) of hydrazine monopropellant. Fuel pressure is regulated by adding pressurized helium gas from an external tank. Seventy percent of the fuel was used for orbital insertion.

MRO has twenty rocket engine thrusters on board. Six large thrusters each produce 170 N (38 lbf) of thrust for a total of 1,020 N (230 lbf) meant mainly for orbital insertion.

These thrusters were originally designed for the Mars Surveyor 2001 Lander. Six medium thrusters each produce 22 N (5 lbf) of thrust for trajectory correction maneuvers and attitude control during orbit insertion. Finally, eight small thrusters each produce 0.9 N (0.2 lbf) of thrust for attitude control during normal operations.

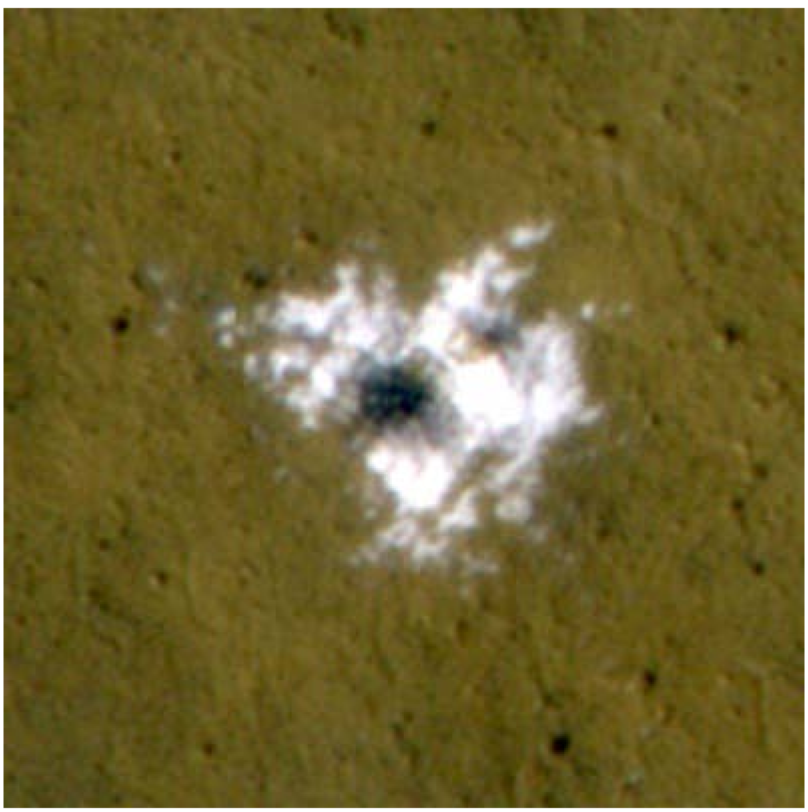
Four reaction wheels are also used for precise attitude control during activities requiring a highly stable platform, such as high-resolution imaging, in which even small motions can cause blurring of the image. Each wheel is used for one axis of motion. The fourth (skewed) wheel is a backup in case one of the other three wheels fails. Each wheel weighs 10 kg (22 lb) and can be spun as fast as 100 Hz or 6,000 rpm.

Discoveries and photographs

Water ice in ice cap measured

Results, published in 2009, of radar measurements of the North Polar ice cap determined that the volume of water ice in the cap is 821,000 cubic kilometers (197,000 cubic miles). That's equal to 30% of the Earth's Greenland ice sheet.

Ice exposed in new craters



Bright part is water ice that has been exposed by impact. The ice was identified using CRISM on the MRO.

Impressive research, reported in the journal Science in September 2009, has showed that some new craters on Mars show exposed, pure, water ice. After a time, the ice disappears, evaporating into the atmosphere. The ice is only a few feet deep. The ice was confirmed with the Compact Imaging Spectrometer (CRISM) onboard the Mars Reconnaissance Orbiter (MRO). The ice was found in a total of 5 locations. Three of the locations are in the Cebrenia quadrangle. These locations are 55.57° N, 150.62° E; 43.28° N, 176.9° E; and 45° N, 164.5° E. Two others are in the Diacria quadrangle: 46.7° N, 176.8° E and 46.33° N, 176.9° E. This discovery proves that future colonists on Mars will be able to obtain water from a wide variety of locations. The ice can be dug up, melted, then taken apart to provide fresh oxygen and hydrogen for rocket fuel. Hydrogen is the powerful fuel used by the space shuttle main engines.

Lobate debris aprons

Lobate Debris Apron in Phlegra Montes, Cebrenia quadrangle. The debris apron is probably mostly ice with a thin covering of rock debris, so it could be a source of water for future Martian colonists. Scale bar is 500 meters long.

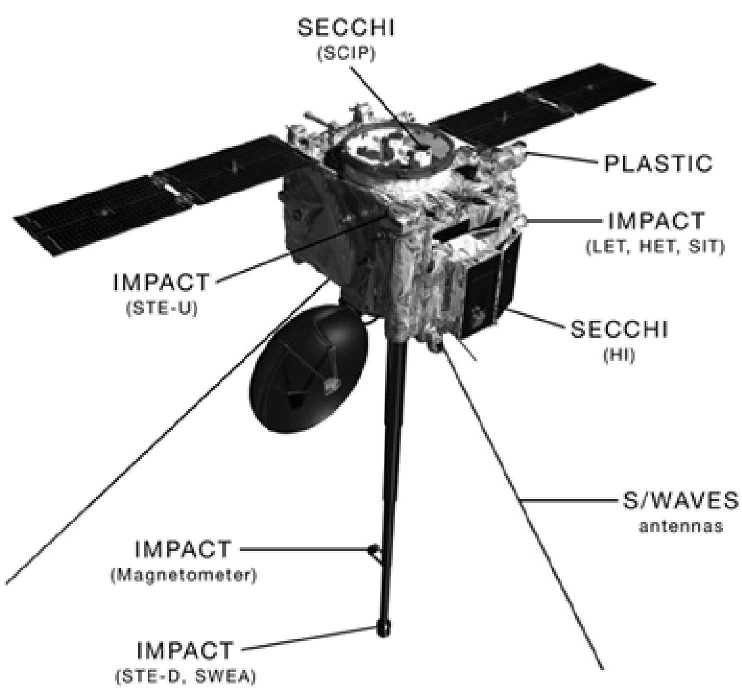
One of the most important discoveries made by the Mars Reconnaissance Orbiter was that features called Lobate Debris Aprons (LDA's) contain large amounts of water ice. Of interest from the days of the Viking Orbiters, these LDA's are piles of material surrounding cliffs. They have a convex topography and a gentle slope; this suggests flow away from the steep source cliff. In addition, lobate debris aprons can show surface lineations just as rock glaciers on the Earth. The Shallow Radar on the Mars Reconnaissance Orbiter has provided strong evidence that the LDAs in Hellas Planitia are glaciers that are covered with a thin layer of rocks. Radar from the Mars Reconnaissance Orbiter gave a strong reflection from the top and base of LDAs, meaning that pure water ice made up the balk of the formation (between the two reflections). Based on the experiments of the Phoenix lander and the studies of the Mars Odyssey from orbit, frozen water is known to exist a just under the surface of Mars in the far north and south (high latitudes). The discovery of water ice in LDA's demonstrates that water is found at even lower latitudes. Future colonists on Mars will be able to tap into these ice deposits, instead of having to travel to much higher latitudes. Another major advantage of LDA's over other sources of Martian water is that they can easily be detected and mapped from orbit. Lobate Debris Aprons are shown below from the Phlegra Montes which are at a latitude of 38.2 degrees north. The Phoenix lander set down at about 68 degrees north latitude, so the discovery of water ice in LDA's greatly expands the range of easily available water on Mars. It is far easier to land a spaceship near the equator of Mars, so the closer water is available to the equator the better it will be for future colonists.

Chapter 3

Space and Solar System Exploration in 2006

STEREO

STEREO



One of two STEREO spacecraft

Operator	NASA
Major contractors	Johns Hopkins University Applied Physics Laboratory
Mission type	Orbiter

Satellite of	Sun
Launch date	2006-10-26, 00:52:00 UTC
Carrier rocket	Delta II 7925-10L
Launch site	Space Launch Complex 17-B Cape Canaveral Air Force Station
Mission duration	>3 years 4 years, 2 months, and 20 days
COSPAR ID	2006-047
Mass	620 kg
Power	475.0 W
Orbital elements	
Orbital period	**STEREO A**: 346 days **STEREO B**: 388 days
Instruments	
Main instruments	Sun Earth Connection Coronal and Heliospheric Investigation (SECCHI): • Extreme UltraViolet Imager (EUVI) • Inner Coronagraph (COR1) • Outer Coronagraph (COR2) • Heliospheric Imager (HI) • Sungrazing Comets

STEREO (**S**olar **TE**rrestrial **RE**lations **O**bservatory) is a solar observation mission. Two nearly identical spacecraft were launched into orbits that cause them to respectively pull further ahead of and fall gradually behind the Earth. This will enable stereoscopic imaging of the Sun and solar phenomena, such as coronal mass ejections.

Mission profile

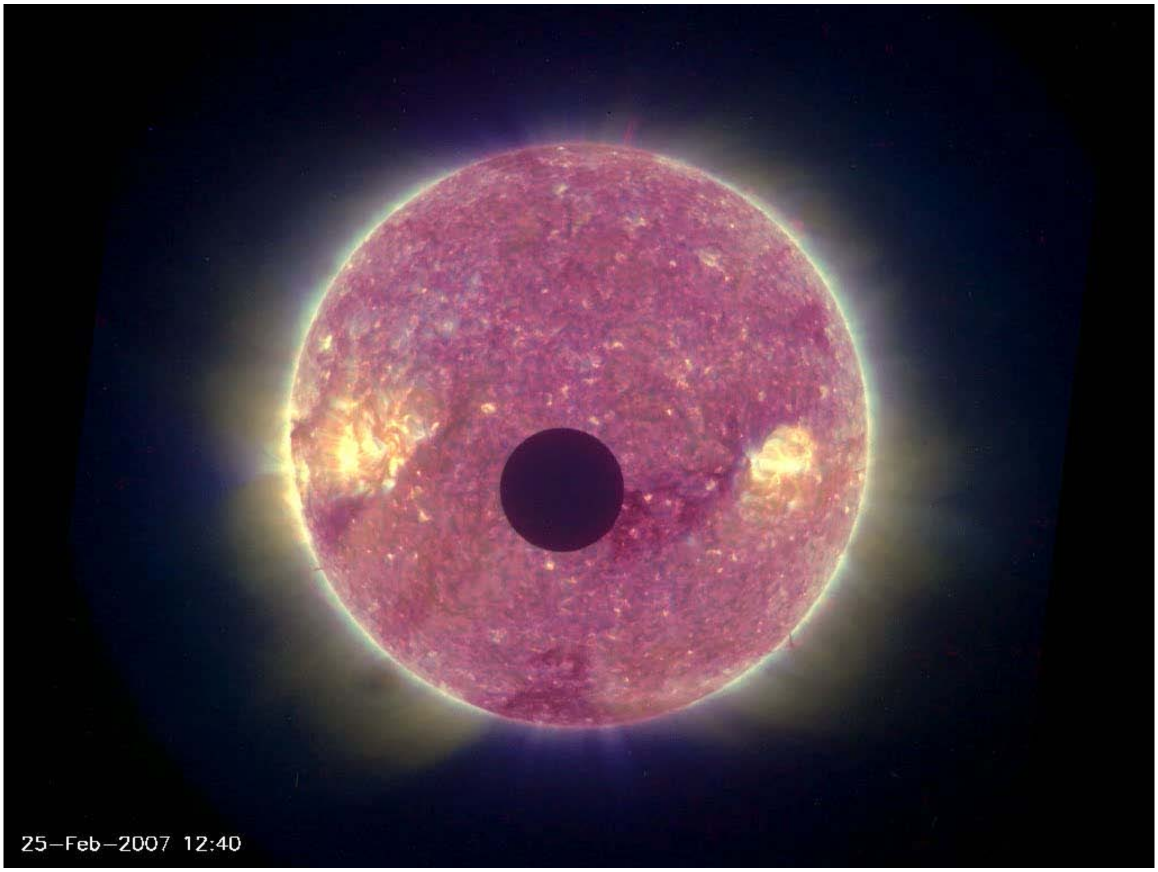
Launch of the STEREO spacecraft atop a Delta II (7925-10L) rocket, 00:52 GMT on 26 October 2006

The two STEREO spacecraft were launched at 0052 UTC on October 26, 2006 from Launch Pad 17B at the Cape Canaveral Air Force Station in Florida on a Delta II 7925-10L launcher into highly elliptical geocentric orbits. The apogee reached the Moon's orbit. On December 15, 2006, on the fifth orbit, the pair swung by the Moon for a gravitational slingshot. Because the two spacecraft were in slightly different orbits, the "ahead" (A) spacecraft was ejected to a heliocentric orbit inside Earth's orbit while the "behind" (B) spacecraft remained temporarily in a high earth orbit. The B spacecraft encountered the Moon again on the same orbital revolution on January 21, 2007, ejecting itself from earth orbit in the opposite direction from spacecraft A. Spacecraft B entered a heliocentric orbit outside the Earth's orbit. Spacecraft A will take 347 days to complete one revolution of the sun and Spacecraft B will take 387 days. The A spacecraft/sun/earth angle will increase at 21.650 deg/year. The B spacecraft/sun/earth angle will change -21.999 degrees per year. Their current locations are shown here.

Because the A spacecraft is moving faster than B, they are separating from each other and A is orbiting closer to the sun than B. This means stereoscopic pairs of images will soon be impossible for human eyes to fuse, which is a STEREO paradox. as human brain can preceive three dimensional vision for the human eye separation angle, which is usually less than a few degrees, while STEREO spacecraft are separated up to 180 degrees as seen from the Sun. At the end of March 2007, the stereoscopic parallax was 1/50, but by June 2007 it was already 1/25. "Ideal" stereoscopic parallax is 1/30 and below 1/10 fusion is difficult even for experts. Already the east and west edges of the sun were becoming difficult, because one eye would see further around the sun than the other. The middle of the solar disc and up towards the poles will be fused stereoscopically after the edges become impossible. The A images, from the satellite closer to the sun, are bigger than B. Magnification must be corrected before stereoscopic fusion by human eyes is possible. Of course the mission does not depend on 3D vision to be useful and mathematical reduction of STEREO image data will continue.

Over time, the STEREO spacecraft will continue to separate from each other at a combined rate of approximately 44 degrees per year. There are no *final* positions for the spacecraft. They achieved 90 degrees separation on January 24, 2009, a condition known as quadrature. This is of interest because the mass ejections seen from the side on the limb by one spacecraft can potentially be observed by the *in situ* particle experiments of the other spacecraft. As they pass through Earth's Lagrangian points L_4 and L_5 (in late 2009), they will search for Lagrangian (trojan) asteroids. On February 6, 2011, the two spacecraft will be exactly 180 degrees apart from each other, allowing the entire Sun to be seen for the first time. Even as the angle increases, the addition of an Earth-based view, e.g. from the Solar Dynamics Observatory, will still provide full-Sun observations for several years. In 2015, contact will be lost for several months when the spacecraft pass behind the Sun. After this, they can continue to be operated after rolling by 180 degrees to point the high gain antenna at Earth. They will then start to approach Earth again, with closest approach sometime in 2023. They will not be recaptured into Earth orbit.

Science instrumentation



A lunar transit of the sun captured during calibration of Stereo B's Ultra Violet imaging cameras. The Moon appears much smaller than it does seen from Earth, because the spacecraft-Moon separation was several times greater than the Earth-Moon distance.

Each of the spacecraft carries cameras, particle experiments and radio detectors in four instrument packages:

- **Sun Earth Connection Coronal and Heliospheric Investigation (SECCHI)** - SECCHI has five cameras: an extreme ultraviolet imager (EUVI) and two white-light coronagraphs (collectively known as the Sun Centered Instrument Package or SCIP), which image the solar disk and the inner and outer corona, plus two heliospheric imagers (called the HI), which image the space between Sun and Earth. The purpose of SECCHI is to study the 3-D evolution of Coronal Mass Ejections through their full journey from the Sun's surface through the corona and interplanetary medium to their impact at Earth.
- **In-situ Measurements of Particles and CME Transients (IMPACT)** - IMPACT will study energetic particles, the three-dimensional distribution of solar wind electrons and interplanetary magnetic field.

- **PLAsma and SupraThermal Ion Composition (PLASTIC)** - PLASTIC will study the plasma characteristics of protons, alpha particles and heavy ions.
- **STEREO/WAVES (SWAVES)** - SWAVES is a radio burst tracker that will study radio disturbances traveling from the Sun to the orbit of Earth.

Spacecraft subsystems

- **Structure**

Launch weight including propellants was 1364 pounds (620 kg).

- **Propulsion and attitude control**

3-axis control

- **Attitude determination** - Each STEREO spacecraft has a primary and a backup Miniature Inertial Measurement Unit (MIMU), provided by Honeywell, which measure changes to the spacecraft attitude. Each MIMU is equipped with three ring laser gyroscopes to detect angular changes. Additional attitude information is provided by the Star Tracker and the SECCHI Guide Telescope.
- **Power**

475 Watts from solar panels.

- **Telecommunications**

Data downlink: 720 kilobits per second.

- **Flight computers**

STEREO's onboard computer systems are based on the Integrated Electronics Module (IEM), a device that combines core avionics in a single box. Each single-string spacecraft carries two 25 megahertz RAD6000 CPUs: one for Command/Data-handling, and one for Guidance-and-Control. Both are radiation hardened RAD6000 processors, based on IBM POWER CPUs (predecessor of the PowerPC chip found in older Macintoshes). The computers, slow by current personal computer standards, are typical for the radiation requirements needed on the STEREO mission.

- **Data handling**

For data storage, each spacecraft carries a solid state recorder able to store up to one gigabyte each. Its main processor collects and stores on the recorder images and other data from STEREO's instruments, which can then be sent back to Earth.

New Horizons

New Horizons

Operator	NASA
Major contractors	APL, SwRI
Mission type	Flyby
Flyby of	APL, Jupiter, Pluto, Charon, Hydra, Nix
Flyby date	2015-07-14 (projected)
Launch date	2006-01-19 19:00:00 UTC (4 years, 11 months, and 29 days elapsed)
Launch vehicle	Atlas V 551
Launch site	Launch Complex 41 Cape Canaveral Air Force Station
Mission duration	In transit (Pluto) (4 years, 11 months, and 29 days elapsed) APL flyby *(completed 2006-06-13)* Jupiter flyby *(completed 2007-02-28)*
COSPAR ID	2006-001A

Homepage	pluto.jhuapl.edu
Mass	478 kg (1,050 lb)
Power	228 W (RTG)
	Orbital elements
Inclination	negligible As of 2010

New Horizons mission logo

New Horizons on the launchpad

New Horizons is a NASA robotic spacecraft mission currently en route to the dwarf planet Pluto. It is expected to be the first spacecraft to fly by and study Pluto and its moons, Charon, Nix, and Hydra. NASA may also approve flybys of one or more other Kuiper belt objects.

New Horizons was launched on January 19, 2006, directly into an Earth-and-solar-escape trajectory. It had an Earth-relative velocity of about 16.26 km/s (58,536 km/h; 36,373 mph) after its last engine shut down. Thus, it left Earth at the fastest launch speed ever recorded for a man-made object. *New Horizons* flew by Jupiter on February 28, 2007, and the orbit of Saturn on June 8, 2008; it is projected to arrive at Pluto on July 14, 2015, after which it will continue into the Kuiper belt.

Background

New Horizons is the first mission in NASA's New Frontiers mission category, larger and more expensive than Discovery missions but smaller than the Flagship Program. The cost of the mission (including spacecraft and instrument development, launch vehicle, mission operations, data analysis, and education/public outreach) is approximately $650 million over 15 years (from 2001 to 2016). An earlier proposed Pluto mission – Pluto Kuiper Express – was cancelled by NASA in 2000 for budgetary reasons.

The *New Horizons* craft was built primarily by Southwest Research Institute (SwRI) and the Johns Hopkins Applied Physics Laboratory (APL). The mission's principal investigator is Alan Stern (NASA Associate Administrator, formerly of the Southwest Research Institute).

Overall control, after separation from the launch vehicle, is performed at Mission Operations Center (MOC) at the Applied Physics Laboratory. The science instruments are operated at the Clyde Tombaugh Science Operations Center (T-SOC) in Boulder, Colorado. Navigation, which is not real-time, is performed at various contractor facilities; KinetX is the lead on the New Horizons navigation team and is responsible for planning trajectory adjustments as the spacecraft speeds toward the outer Solar System.

New Horizons was originally planned as a voyage to what was then the only unexplored planet in the Solar System. When the spacecraft was launched, Pluto was still classified as a planet, later to be reclassified as a dwarf planet by the International Astronomical Union (IAU). However, some members of the New Horizons team, including Alan Stern, disagree with the IAU definition and therefore still describe Pluto as the ninth planet. Pluto's newly-discovered satellites, Nix and Hydra, also have a connection with the spacecraft: the first letters of their names, **N** and **H**, are the initials of "New Horizons". The moons' discoverers chose these names for this reason, in addition to Nix and Hydra's relationship to the mythological Pluto.

In addition to the scientific equipment, there are several cultural artifacts traveling with the spacecraft. These include a collection of 434,738 names stored on a compact disc, a piece of Scaled Composites, *SpaceShipOne*, and an American flag, along with other mementos. One of the trim weights on the spacecraft is a Florida state quarter.

In homage to the discovery of the dwarf planet the probe will visit, approximately one ounce of the ashes of Pluto discoverer Clyde Tombaugh are aboard the spacecraft, while one of the science packages (a dust counter) is named after Venetia Burney, who as a child was responsible for naming the dwarf planet.

Launch

New Horizons at lift-off

The launch of *New Horizons* was originally scheduled for January 11, 2006, but was initially delayed until January 17 to allow for borescope inspections of the Atlas rocket's kerosene tank. Further delays related to low cloud ceiling conditions downrange, and high winds and technical difficulties - unrelated to the rocket itself - prevented launch for a further two days. The probe finally lifted off from Pad 41 at Cape Canaveral Air Force Station, Florida, directly south of Space Shuttle Launch Complex 39, at 14:00 EST on January 19, 2006.

Space Launch Complex 41 during *New Horizons* launch

The Centaur second stage reignited at 14:30 EST (19:30 UTC), successfully sending the probe out of Earth orbit. *New Horizons* took only nine hours to reach the Moon's orbit, passing lunar orbit before midnight EST that day.

Although there were backup launch opportunities in February 2006 and February 2007, only the first 23 days of the 2006 window permitted the Jupiter fly-by. Any launch outside that period would have forced the spacecraft to fly a slower trajectory directly to Pluto, delaying its encounter by 2–4 years.

The craft was launched by a Lockheed Martin Atlas V 551 rocket, with a Boeing Star 48B third stage added to increase the heliocentric (escape) speed. This was the first launch of the 551 configuration of the Atlas V, as well as the first Atlas V launch with an additional third stage (Atlas V rockets usually do not have a third stage). Previous flights had used none, two, or three solid boosters, but never five. This puts the Atlas V 551 take-off thrust, at well over 2,000,000 lbf (9 MN), past the Delta IV-Heavy. The major part of this thrust is supplied by the Russian RD-180 engine, providing 4.152 MN (933,000 lbf). The Delta IV-H remains the larger vehicle, at over 1,600,000 lb (726,000 kg) compared to 1,260,000 lb (572,000 kg) of the AV-010. The Atlas V rocket had earlier been slightly damaged when Hurricane Wilma swept across Florida on October 24, 2005. One of the solid rocket boosters was hit by a door. The booster was replaced with an identical unit, rather than inspecting and requalifying the original.

New Horizons probe launched from Cape Canaveral on January 19, 2006

The Star 48B third stage is also on a hyperbolic solar system escape trajectory, and reached Jupiter before the *New Horizons* spacecraft. So did two small de-spin masses, the "yo-yo masses", released from the stage. However, since they are not in controlled flight, they did not receive the correct gravity assist, and will only pass within 200,000,000 km (120,000,000 mi) of Pluto.

New Horizons is often erroneously given the title of *Fastest Spacecraft Ever Launched,* when in fact the Helios probes are the holders of that title. To be more specific *New Horizons* achieved the highest launch velocity and thus left Earth faster than any other spacecraft to date. It is also the first spacecraft launched directly into a solar escape trajectory, which requires an approximate velocity of 16.5 km/s (36,900 mph), plus losses, all to be provided by the launcher. However, it will not be the fastest spacecraft to leave the solar system. This record is held by *Voyager 1*, currently travelling at 17.145 km/s (38,400 mph) relative to the Sun. *Voyager 1* attained greater hyperbolic excess velocity from Jupiter and Saturn gravitational slingshots than *New Horizons*. Other spacecraft, such as *Helios 1* & *2*, can also be measured as the fastest objects, due to their orbital velocity relative to the Sun at perihelion. However, because they remain in solar orbit, their orbital energy relative to the Sun is lower than the five probes, and three other third stages on hyperbolic trajectories, including *New Horizons*, that achieved solar escape velocity, as the Sun has a much deeper gravitational well than Earth.

Trajectory corrections and instrument testing

On January 28 and January 30, 2006, mission controllers guided the probe through its first trajectory correction maneuver (TCM), which was divided into two parts (TCM-1A and TCM-1B). The total velocity change of these two corrections was about 18 meters per second. TCM-1 was accurate enough to permit the cancellation of TCM-2, the second of three originally scheduled corrections.

During the week of February 20, controllers conducted initial in-flight tests of three onboard scientific instruments, the Alice ultraviolet imaging spectrometer, the PEPSSI plasma-sensor, and the LORRI long-range visible-spectrum camera. No scientific measurements or images were taken, but instrument electronics, and in the case of Alice, some electromechanical systems were shown to be functioning correctly.

On March 9 at 1700 UTC, controllers performed TCM-3, the last of three scheduled course corrections. The engines burned for 76 seconds, adjusting the spacecraft's velocity by about 1.16 meters per second.

On June 30, 2010 on 7:49 EDT, mission controllers executed a fourth TCM on *New Horizons* that lasted 35.6 seconds.

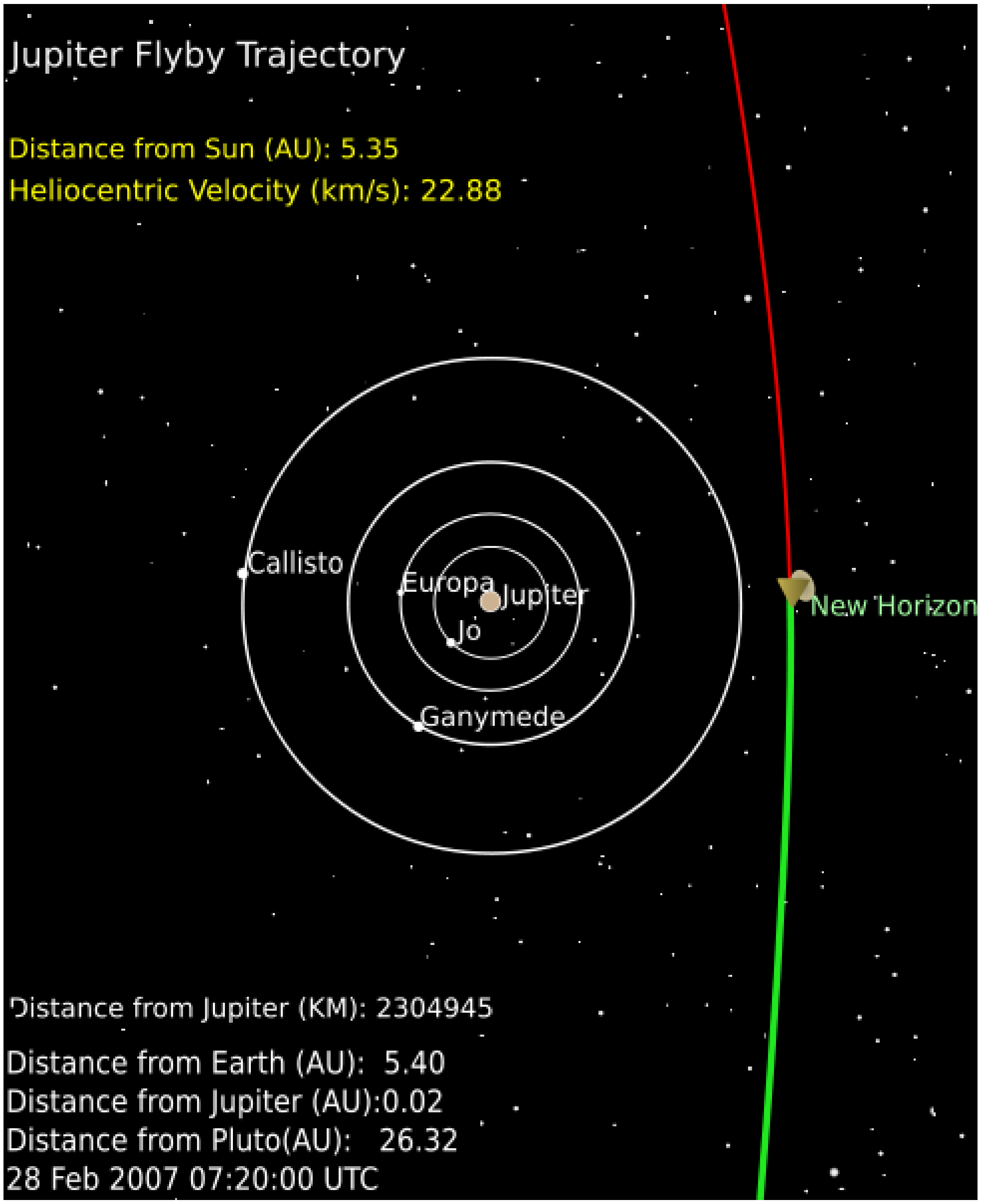
Passing Mars orbit and asteroid flyby

On April 7, 2006 at 10:00 UTC, the spacecraft passed the orbit of Mars, moving at roughly 21 km/s away from the Sun at a solar distance of 243 million kilometers.

New Horizons made a distant flyby of the small asteroid 132524 APL (previously known by its provisional designation, 2002 JF_{56}), at a distance of 101,867 km at 04:05 UTC on June 13, 2006. The best current estimate of the asteroid's diameter is approximately 2.3 kilometers, and the spectra obtained by *New Horizons* showed that APL is an S-type asteroid.

The spacecraft successfully tracked the asteroid over June 10 – June 12, 2006. This allowed the mission team to test the spacecraft's ability to track rapidly moving objects. Images were obtained through the Ralph telescope.

Jupiter gravity assist



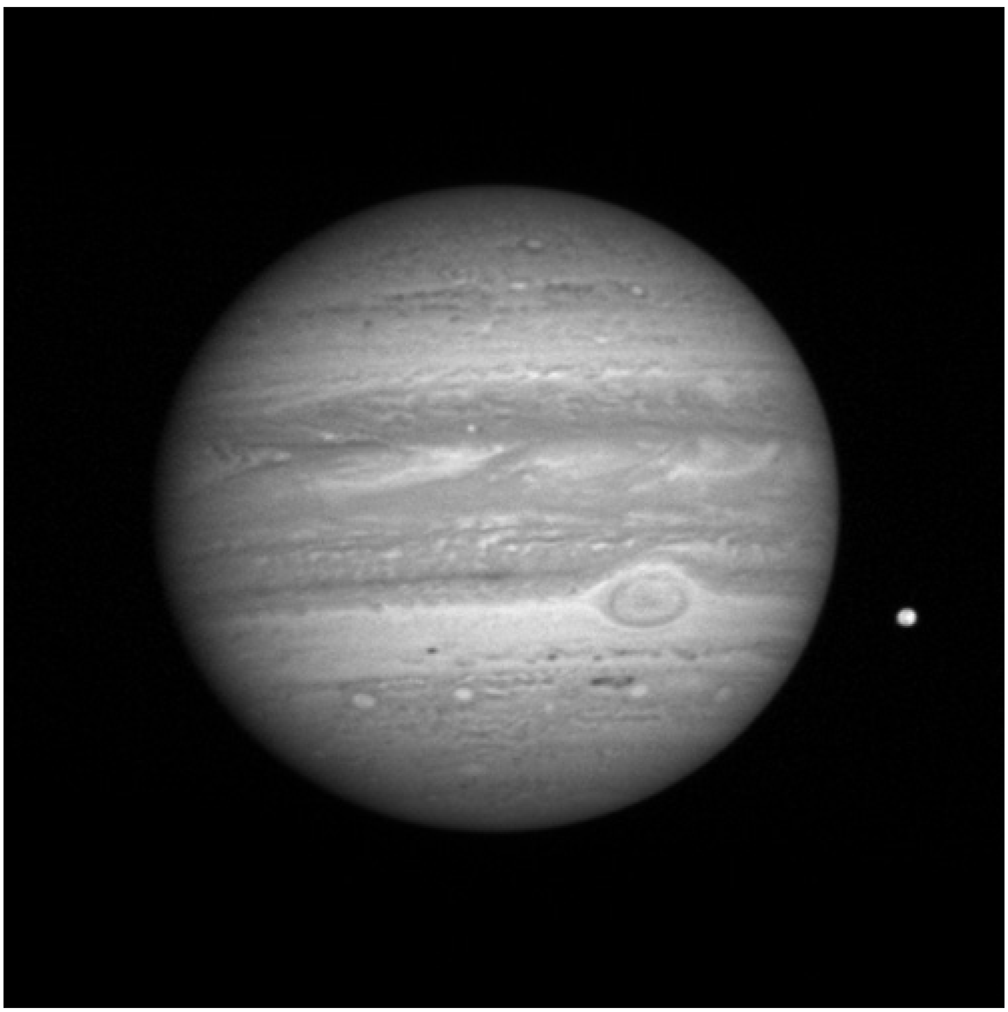
New Horizons at periapsis with Jupiter on February 28, 2007

New Horizons' Long Range Reconnaissance Imager (LORRI) took its first photographs of Jupiter on September 4, 2006. The spacecraft began further study of the Jovian system in December 2006.

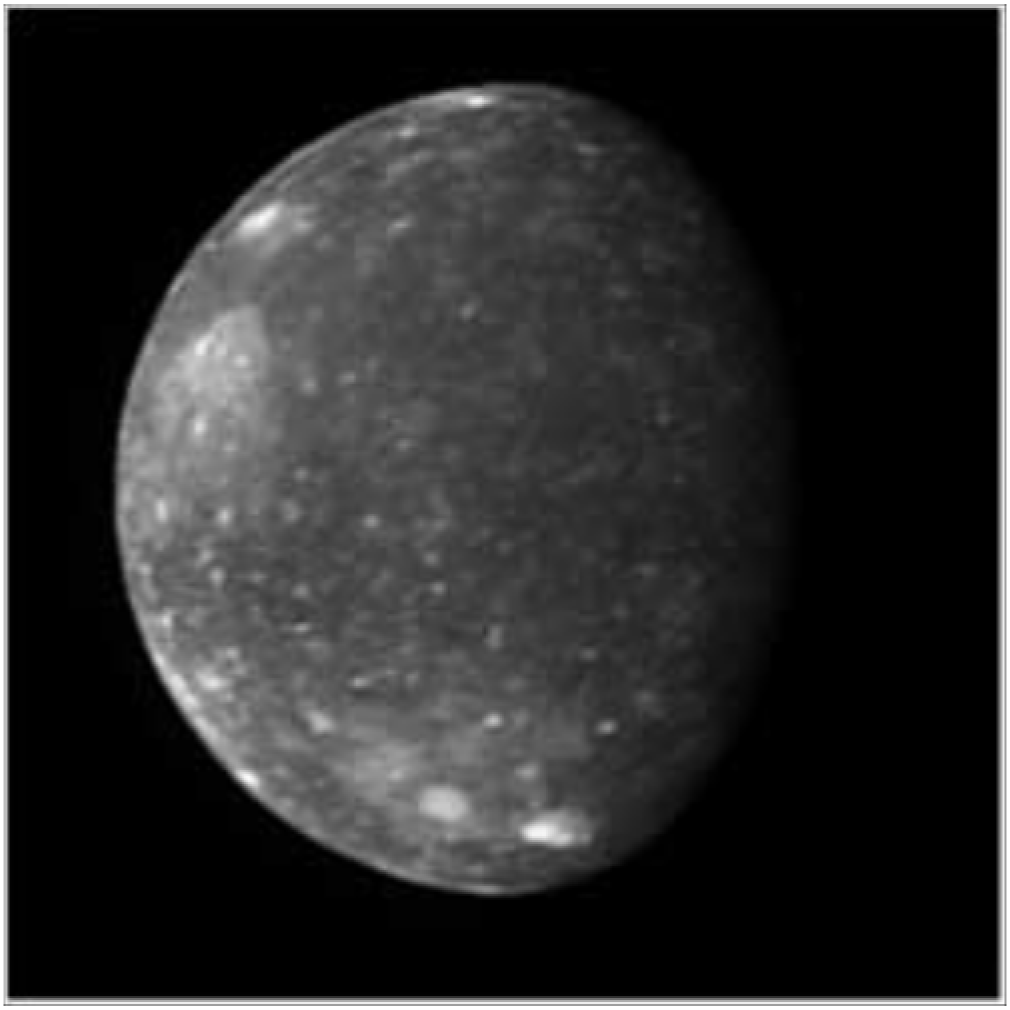
New Horizons received a Jupiter gravity assist with a closest approach at 5:43:40 UTC (12:43:40am EST) on February 28, 2007. It passed through the Jupiter system at 21 km/s (47,000 mph) relative to Jupiter (23 km/s (51,000 mph) relative to the Sun). The flyby increased *New Horizons'* speed away from the Sun by nearly 4 km/s (8,900 mph), putting the spacecraft on a faster trajectory to Pluto, about 2.5 degrees out of the plane of the Earth's orbit (the "ecliptic"). As of November, 2009, the gravitational attraction of the Sun has slowed down the spacecraft to about 16.656 km/s (37,260 mph). *New Horizons* was the first probe launched directly toward Jupiter since the Ulysses probe in 1990.

While at Jupiter, *New Horizons'* instruments made refined measurements of the orbits of Jupiter's inner moons, particularly Amalthea. The probe's cameras measured volcanoes on Io and studied all four Galilean moons in detail, as well as long distance studies of the outer moons Himalia and Elara. Imaging of the Jovian system began on September 4, 2006. The craft also studied Jupiter's Little Red Spot and the planet's magnetosphere and tenuous ring system.

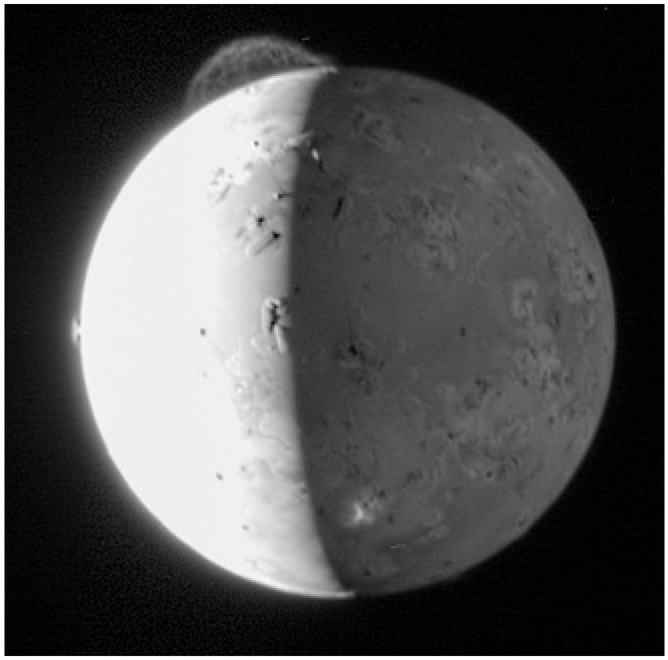
Jovian system imaged by New Horizons



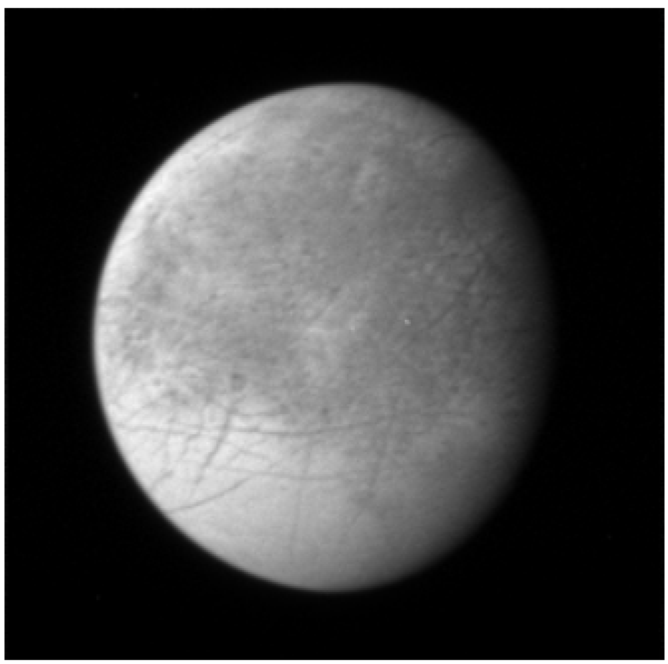
Jupiter and its moon Io imaged by *New Horizons* during flyby



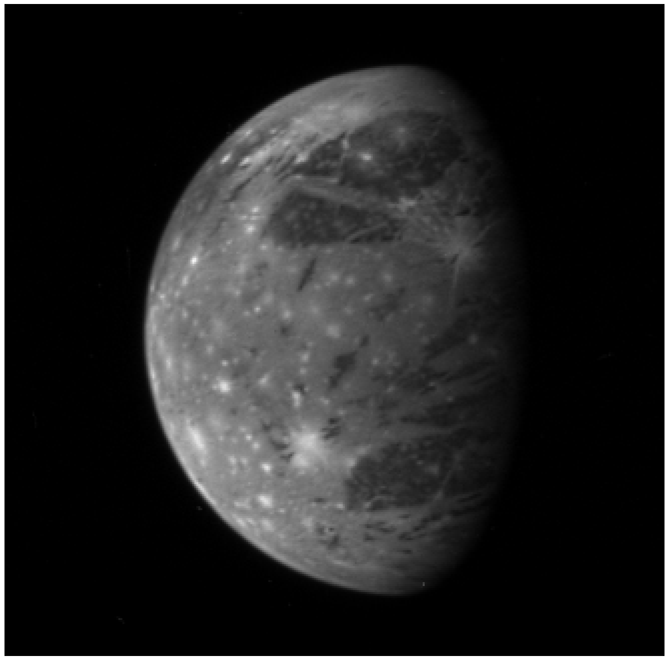
Callisto imaged by *New Horizons* during flyby



Io imaged by *New Horizons* during flyby

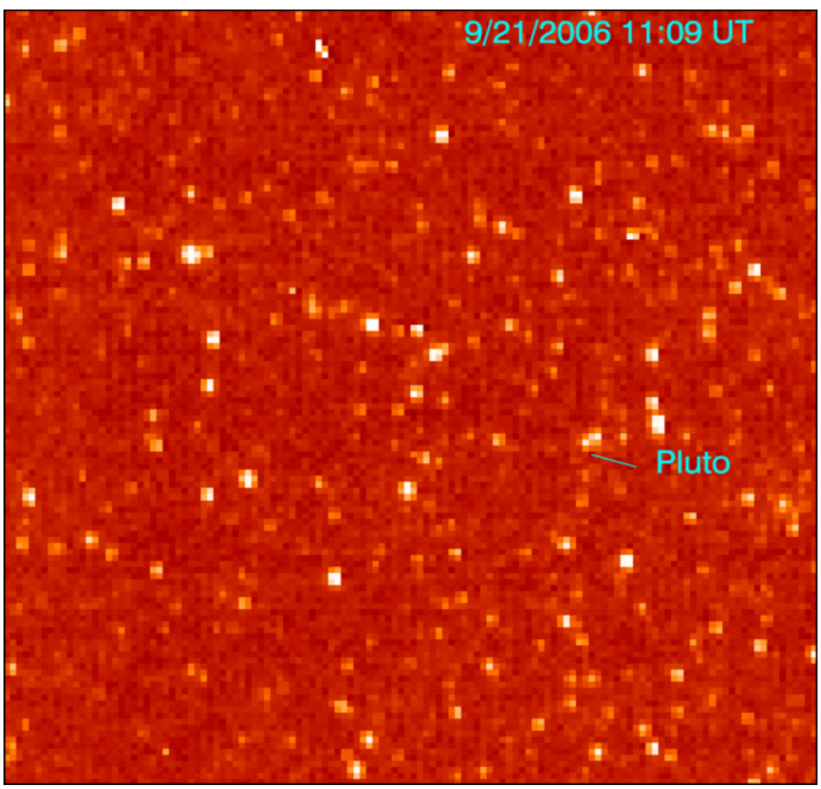


Europa imaged by *New Horizons* during flyby



Ganymede imaged by *New Horizons* during flyby

Pluto approach



First Pluto sighting from *New Horizons* (September 21–24, 2006)

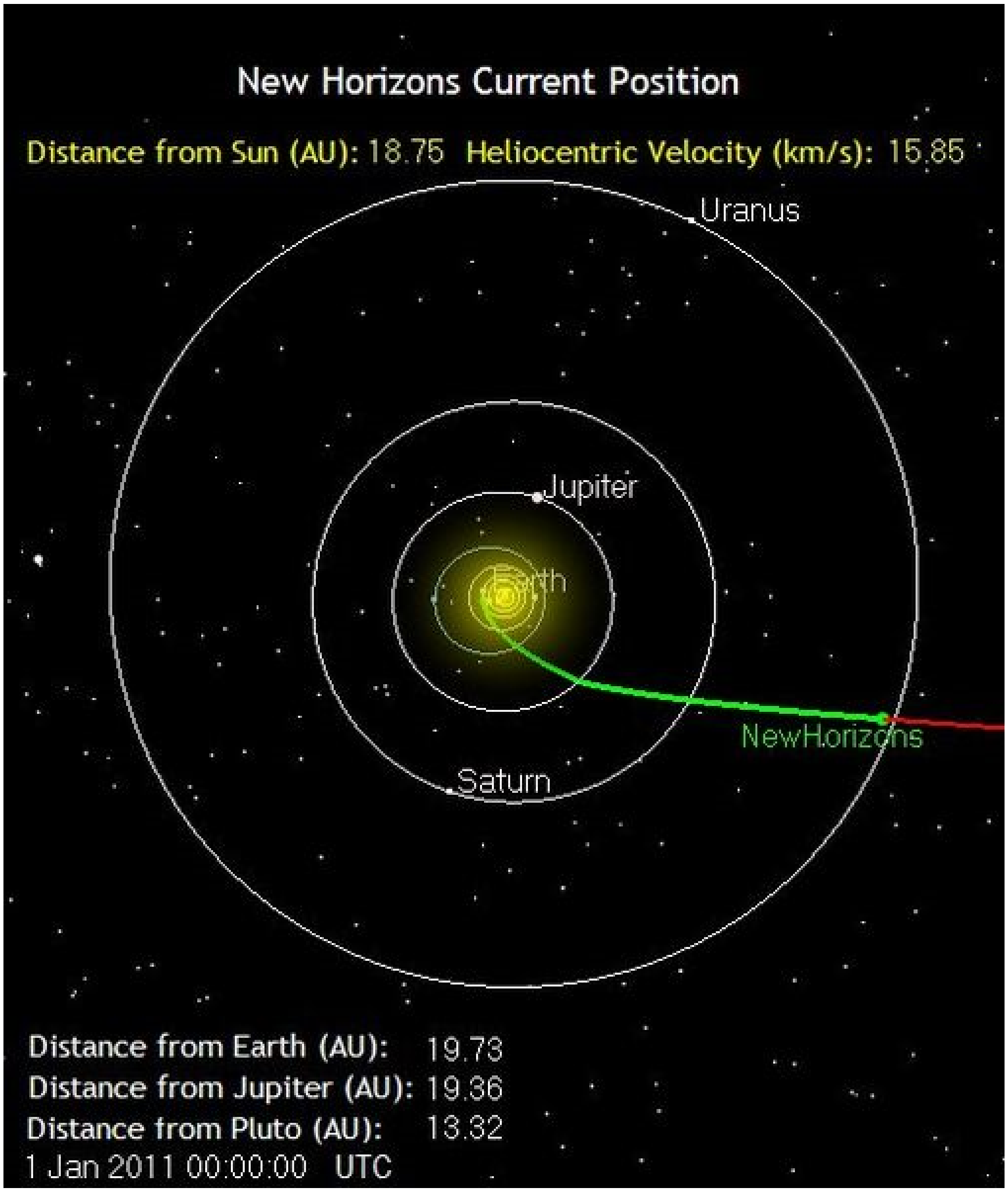
The first images of Pluto from *New Horizons* were created between September 21–24, 2006, during a test of the LORRI. They were released on November 28. The images, taken from a distance of approximately 4.2 billion kilometers (2.6 billion miles), confirmed the spacecraft's ability to track distant targets, critical for maneuvering toward Pluto and other Kuiper belt objects.

It is planned for *New Horizons* to fly within 10,000 km (6,200 mi) of Pluto in 2015. *New Horizons* will have a relative velocity of 13.78 km/s at closest approach, and will come as close as 27,000 km (17,000 mi) to Charon, although these parameters may be changed during flight.

Kuiper belt mission

After passing by Pluto, *New Horizons* will continue further into the Kuiper belt. Mission planners are now searching for one or more additional Kuiper belt objects (KBOs) on the order of 50–100 km (31–62 mi) in diameter for flybys similar to the spacecraft's Plutonian encounter. As maneuvering capability is limited, this phase of the mission is contingent on finding suitable KBOs close to *New Horizons'*s flight path, ruling out any possibility for a planned flyby of Eris, a trans-Neptunian object comparable in size to Pluto. The available region, being fairly close to the plane of the Milky Way and thus difficult to survey for dim objects, is one that has not been well-covered by previous KBO search efforts.

Key mission dates



Position of *New Horizons* (as of January 1st, 2011, 0h UTC)

- June 8, 2001 — New Horizons picked by NASA over a competing design, POSSE (Pluto and Outer Solar System Explorer).
- June 13, 2005 — Spacecraft departed APL for final testing at Goddard Space Flight Center (GSFC).
- September 24, 2005 — Spacecraft shipped to Cape Canaveral, through Andrews Air Force Base, aboard a C-17 Globemaster III cargo aircraft.
- December 17, 2005 — Transported from Hazardous Servicing Facility to Vertical Integration Facility at Space Launch Complex 41.

- January 11, 2006 — Primary launch window opened. Launch delayed for further testing.
- January 16, 2006 — Atlas V launcher, serial number AV-010, rolled out onto pad.
- January 17, 2006 — First day launch attempts scrubbed because of unacceptable weather conditions (high winds).
- January 18, 2006 — Second launch attempt scrubbed because of morning power outage at the Applied Physics Laboratory.
- January 19, 2006 — **Successful launch** at 14:00 EST (19:00 UTC) after brief delay due to cloud cover.
- April 7, 2006 — The probe passed Mars' orbit.
- Early May, 2006 — The probe entered the asteroid belt.
- June 13, 2006 — The probe passed closest to the asteroid 132524 APL in the Belt at about 101,867 km at 04:05 UTC. Pictures were taken.
- Late October, 2006 — The probe left the asteroid belt.
- November 28, 2006 — First faint image of Pluto taken from a distance released.
- January 8, 2007 — Start of Jupiter encounter.
- January 10, 2007 — Long distance observations of outer moon Callirrhoe as a navigation exercise.
- February 28, 2007 — Jupiter flyby. Closest approach occurred at 05:43:40 UTC at 2.305 million km, 21.219 km/s.
- March 5, 2007 — End of Jupiter encounter phase.
- June 8, 2008 — The probe passed Saturn's orbit.
- December 29, 2009 — The probe became closer to Pluto than to Earth
- March 8, 2010 - Distant flyby of 83982 Crantor
- October 17, 2010 — As of 4.25 UTC, half the mission time between launch and closest approach had elapsed, with 1731 days, 8 hours and 25 minutes remaining to closest approach and having elapsed since launch.

Planned

- March 18, 2011 — The probe will pass Uranus' orbit.
- August 24, 2014 — The probe will pass Neptune's orbit.
- July 14, 2015 — Flyby of Pluto around 11:47 UTC at 13,695 km, 13.78 km/s.
- July 14, 2015 — Flyby of Charon, Hydra and Nix around 12:01 UTC at 29,473 km, 13.87 km/s.
- 2016-2020 — Possible flyby of one or more Kuiper belt objects (KBOs).
- 2029 — The probe will leave the solar system.

Spacecraft subsystems

The spacecraft is comparable in size and general shape to a grand piano and has been compared to a "piano glued to a sports-car-sized satellite dish". As a point of departure, the team took inspiration from the Ulysses spacecraft, which also carried an RTG and dish on a box-in-box structure through the outer Solar System. Many subsystems and components have flight heritage from APL's CONTOUR spacecraft, which in turn had heritage from APL's TIMED spacecraft.

Structural

The spacecraft's body forms a triangle, almost 2.5 feet (0.76 m) thick. (The *Pioneer*s had hexagonal bodies, while the *Voyager*s, *Galileo*, and *Cassini-Huygens* had decagonal, hollow bodies.) A 7075 aluminium alloy tube forms the main structural column, between the launch vehicle adapter ring at the "rear," and the 2.1 m radio dish antenna affixed to the "front" flat side. The titanium fuel tank is in this tube. The radioisotope thermoelectric generator, or RTG attaches with a 4-sided titanium mount resembling a grey pyramid or stepstool. Titanium provides strength and thermal isolation. The rest of the triangle is primarily sandwich panels of thin aluminum facesheet (less than $^1⁄_{64}$ in or 0.40 mm) bonded to aluminum honeycomb core.

New Horizons in its assembly hall

The structure is larger than strictly necessary, with empty space inside. The structure is designed to act as shielding, reducing electronics errors caused by radiation from the RTG. Also, the mass distribution required for a spinning spacecraft demands a wider triangle.

Propulsion and attitude control

New Horizons has both spin-stabilized (cruise) and three-axis stabilized (science) modes, controlled entirely with hydrazine monopropellant. 77 kg (170 lb) of hydrazine provides a delta-v capability of over 290 m/s (649 mph) after launch. Helium is used as a pressurant, with an elastomeric diaphragm assisting expulsion. The spacecraft's on-orbit mass including fuel will be over 470 kg (1,036 lb) for a Jupiter flyby trajectory, but would have been only 445 kg (981 lb) for a direct flight to Pluto. This would have meant less fuel for later Kuiper belt operations and is caused by the launch vehicle performance limitations for a direct-to-Pluto flight.

There are 16 thrusters on *New Horizons*: four 4.4 N (1.0 lbf) and twelve 0.9 N (0.2 lbf) plumbed into redundant branches. The larger thrusters are used primarily for trajectory corrections, and the small ones (previously used on *Cassini* and the *Voyager* spacecraft) are used primarily for attitude control and spinup/spindown maneuvers. Two star cameras (from Galileo Avionica) are used for fine attitude control. They are mounted on the face of the spacecraft and provide attitude information while in spinning or in 3-axis mode. Between star camera readings, knowledge is provided by dual redundant Miniature Inertial Measurement Unit (MIMU) from Honeywell. Each unit contains three solid-state gyroscopes and three accelerometers. Two Adcole Sun sensors provide coarse attitude control. One detects angle to the Sun, while the other measures spin rate and clocking.

Power

A cylindrical radioisotope thermoelectric generator, or RTG, protrudes from one vertex in the plane of the triangle. The RTG will provide about 240 W, 30 V DC at launch, and is predicted to drop approximately 5% every 4 years, decaying to 200 W by the encounter with the Plutonian system in 2015. The RTG, model "GPHS-RTG," was originally a spare from the Cassini mission. The RTG contains 11 kg (24 lb) of plutonium-238 oxide pellets. Each pellet is clad in iridium, then encased in a graphite shell. It was developed by the U.S. Department of Energy.

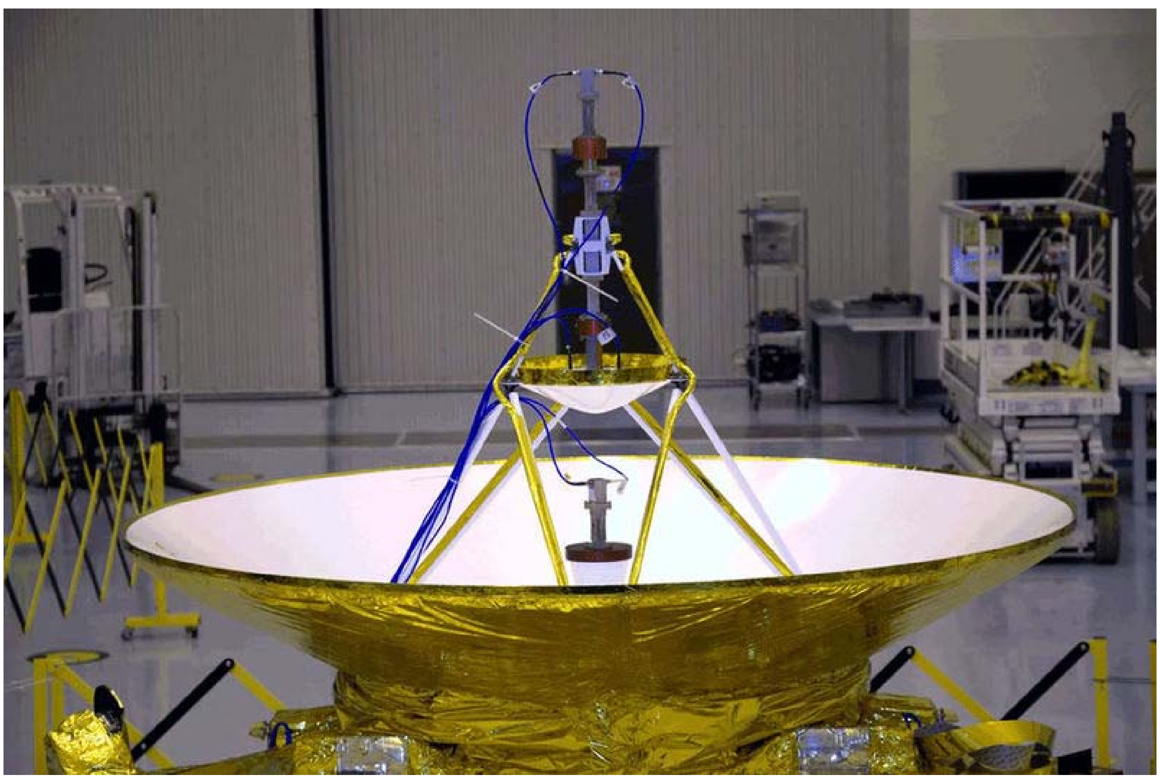
The use of a plutonium RTG battery resulted in minor demonstrations some days before launch by about 30 anti-nuclear protesters. The amount of radioactive plutonium in the RTG is 10.9 kg, about one-third the amount on-board the Cassini-Huygens probe when it launched in 1997. That launch was protested by over 300 people. The United States Department of Energy estimated the chances of a launch accident that would release radiation into the atmosphere at 1 in 350 and monitored the launch as it always does when RTGs are involved. It was believed that a worst-case scenario of total dispersal of on-board plutonium would spread the equivalent radiation of 80% the average annual dosage in North America from background radiation over an area with a radius of 65 miles (105 km), with cleanup costing anywhere from $241 million – $1.2 billion USD per square mile. at the Materials and Fuels Complex (formerly Argonne West), a part of the Idaho National Laboratory in Bingham County, near the town of Arco and the city of Idaho Falls. The plutonium was produced at Los Alamos National Laboratory in New Mexico. Less than the original design goal was produced, due to delays at the United

States Department of Energy, including security activities, which held up production. The mission parameters and observation sequence had to be modified for the reduced wattage; still, not all instruments can operate simultaneously. The Department of Energy transferred the space battery program from Ohio to Argonne in 2002 because of security concerns. There are no onboard batteries. RTG output is relatively predictable; load transients are handled by a capacitor bank and fast circuit breakers.

Thermal

Internally, the structure is painted black. This equalizes temperature by radiative heat transfer. Overall, the spacecraft is thoroughly blanketed to retain heat. Unlike the Pioneers and Voyagers, the radio dish is also enclosed in blankets which extend to the body. The heat from the RTG also adds warmth to the spacecraft in the outer solar system. In the inner solar system, the spacecraft must prevent overheating. Electronic activity is limited, power is diverted to shunts with attached radiators, and louvers are opened to radiate excess heat. Then, when the spacecraft is cruising inactively in the cold outer solar system, the louvers are closed, and the shunt regulator reroutes power to electric heaters.

Telecommunications



Antennas of *New Horizons* (HGA, MGA and LGA)

Communication with the spacecraft is via X band.

At Pluto's distance a rate of approximately 1,000 bits per second is expected. The craft had a communication rate of 38 kbit/s at Jupiter.

The 70 m Deep Space Network (DSN) dishes will be used to relay data beyond Jupiter.

Besides the low bandwidth, Pluto's distance also causes a (one way) latency of about 4.5 hours.

The spacecraft uses dual redundant transmitters and receivers, and either right- or left-hand circular polarization. The downlink signal is amplified by dual redundant 12-watt TWTAs (traveling-wave tube amplifiers) mounted on the body under the dish.

The receivers are new, low-power designs. The system can be controlled to power both TWTAs at the same time, and transmit a dual-polarized downlink signal to the DSN that could almost double the downlink rate. Initial tests with the DSN in this dual-polarized mode have been successful, and an effort to make the DSN polarization-combining technique operational is underway.

In addition to the high-gain antenna, there are two low-gain antennas and a medium-gain dish. The high-gain dish has a Cassegrain layout, composite construction, and a 2.1 meter diameter (providing well over 40 dB of gain, and a half-power beam width of about a degree). The prime-focus, medium-gain antenna, with a 0.3 meter aperture and 10-degree half-power beamwidth, is mounted to the back of the high-gain antenna's secondary reflector. The forward low-gain antenna is stacked atop the feed of the medium-gain antenna. The aft low-gain antenna is mounted within the launch adapter at the rear of the spacecraft. This antenna was only used for early mission phases near Earth, just after launch and for emergencies if the spacecraft had lost attitude control.

To save mission costs, the spacecraft will be in "hibernation" between Jupiter and Pluto. It will awaken once per year, for 50 days, for equipment checkout and trajectory tracking. The rest of the time, the spacecraft will be in a slow spin, sending a beacon tone which will be checked once per week. Depending on frequency, the beacon indicates normal operation, or one of seven fault modes. New Horizons is the first mission to use the DSN's beacon tone system operationally, the system having been flight-tested by the DS1 mission.

Data handling

New Horizons will record scientific instrument data to its solid-state buffer at each encounter, then transmit the data to Earth. Data storage is done on two low-power solid-state recorders (one primary, one backup) holding up to 8 gigabytes each. Because of the extreme distance from Pluto and the Kuiper belt, only one buffer load at those encounters can be saved. This is because *New Horizons* will have left the vicinity of Pluto (or future target object) by the time it takes to transmit the buffer load back to Earth.

Part of the reason for the delay between the gathering and transmission of data is because all of the *New Horizons* instrumentation is body-mounted. In order for the cameras to record data, the entire probe must turn, and the one-degree-wide beam of the high-gain antenna will almost certainly not be pointing toward Earth. Previous spacecraft, such as the Voyager program probes, had a rotatable instrumentation platform (a "scan platform") that could take measurements from virtually any angle without losing radio contact with Earth. *New Horizons'* elimination of excess mechanisms was implemented to save weight, shorten the schedule, and improve reliability to achieve a 15+-year lifetime.

(The *Voyager 2* spacecraft experienced platform jamming at Saturn; the demands of long time exposures at Uranus led to modifications of the probe to rotate the entire probe instead to achieve the time exposure photos at Uranus and Neptune, similar to how *New Horizons* will rotate.)

Chapter 4

Space and Solar System Exploration in 2007

Dawn (spacecraft)

Dawn

Artist's concept of *Dawn* with Vesta (left) & Ceres (right) (the proximity of Vesta to Ceres is not to scale.)

Operator	NASA
Major contractors	Orbital Sciences, JPL, UCLA
Mission type	Flyby / Orbiter
Flyby of	Mars
Satellite of	Vesta, Ceres
Orbital insertion date	Vesta: July 2011 (projected) Ceres: February 2015 (projected)
Launch date	2007-09-27 11:34:00 UTC

	(3 years, 141 days ago)
Launch vehicle	Delta II 7925H
Launch site	Space Launch Complex 17B Cape Canaveral Air Force Station
Mission duration	In Transit Mars flyby *(completed 2009-02-04)*
COSPAR ID	2007-043A
Mass	1,250 kg (2,800 lb)
Power	1000 W (Solar array)
Orbital elements	
Eccentricity	~ circular
Inclination	Polar

Dawn is a robotic spacecraft sent by NASA on a space exploration mission to the two most massive members of the asteroid belt: Vesta and the dwarf planet Ceres. Launched on September 27, 2007, *Dawn* is scheduled to explore Vesta between 2011 and 2012, and Ceres in 2015. It will be the first spacecraft to visit either body.

Dawn is innovative in that it will be the first spacecraft to enter into orbit around a celestial body, study it, and then re-embark under powered flight to proceed to a second target. All previous multi-target study missions—such as the Voyager program—have involved rapid planetary flybys.

The Dawn mission to Vesta and Ceres is managed by NASA's Jet Propulsion Laboratory, a division of the California Institute of Technology in Pasadena, for NASA's Science Mission Directorate, Washington.

Launch

Dawn was scheduled to launch from pad 17-B at the Cape Canaveral Air Force Station on a Delta 7925-H rocket. On April 10, 2007, *Dawn* arrived at the Astrotech Space Operations subsidiary of SPACEHAB, Inc. in Titusville, Florida, where it was prepared for launch. Launch was originally scheduled for June 20, but was delayed until June 30 due to delays with part deliveries. A broken crane at the launch pad, used to raise the solid rocket boosters, delayed the launch for a week, until July 7, but on June 15 the second stage was successfully hoisted into position. A mishap at the Astrotech Space

Operations facility, involving slight damage to one of the solar arrays, did not have an effect on the launch date; however, bad weather caused the launch to slip to July 8. Range tracking problems then delayed the launch to July 9, and then July 15, before the launch was delayed further to avoid knock-on delays with the Phoenix mission to Mars, which was successfully launched on August 4.

A Delta II launching *Dawn* from CCAFS SLC-17

Launch of *Dawn* was then rescheduled for September 26, 2007, then September 27, due to bad weather delaying fueling of the second stage, the same problem which had earlier delayed the July 7 launch attempt. The launch window extended from 07:20 – 07:49 EDT (11:20 – 11:49 GMT). During the final built-in hold at T-4 minutes, a ship entered the exclusion area offshore, the sea strip where the rocket boosters were likely to fall after separation. The ship was commanded to leave the area, then the launch had to wait for the end of a collision avoidance window with the International Space Station. The spacecraft launched at 07:34 EDT from pad 17-B on a Delta II launch vehicle.

The launch rocket propelled *Dawn* to 11.46 kilometers per second (25,600 miles per hour) relative to earth. Thereafter *Dawn's* ion thrusters took over.

Status

After initial checkout, during which the ion thrusters accumulated more than 11 days of thrust, *Dawn* began long-term cruise propulsion on December 17, 2007. On October 31, 2008, *Dawn* completed its first thrusting phase to send it on to Mars for a gravity assist flyby in February 2009. During this first interplanetary cruise phase *Dawn* spent 270 days, or 85% of this phase using its thrusters. It expended less than 72 kilograms (158 pounds) of xenon propellant for a total change in velocity of 1.81 kilometers per second (4050 miles per hour). On November 20, 2008, *Dawn* performed its first trajectory correction maneuver (TCM1), firing its number 1 thruster for 2 hours, 11 minutes. Following *Dawn's* solar conjunction, an originally scheduled course correction maneuver in January 2009 was determined not necessary.

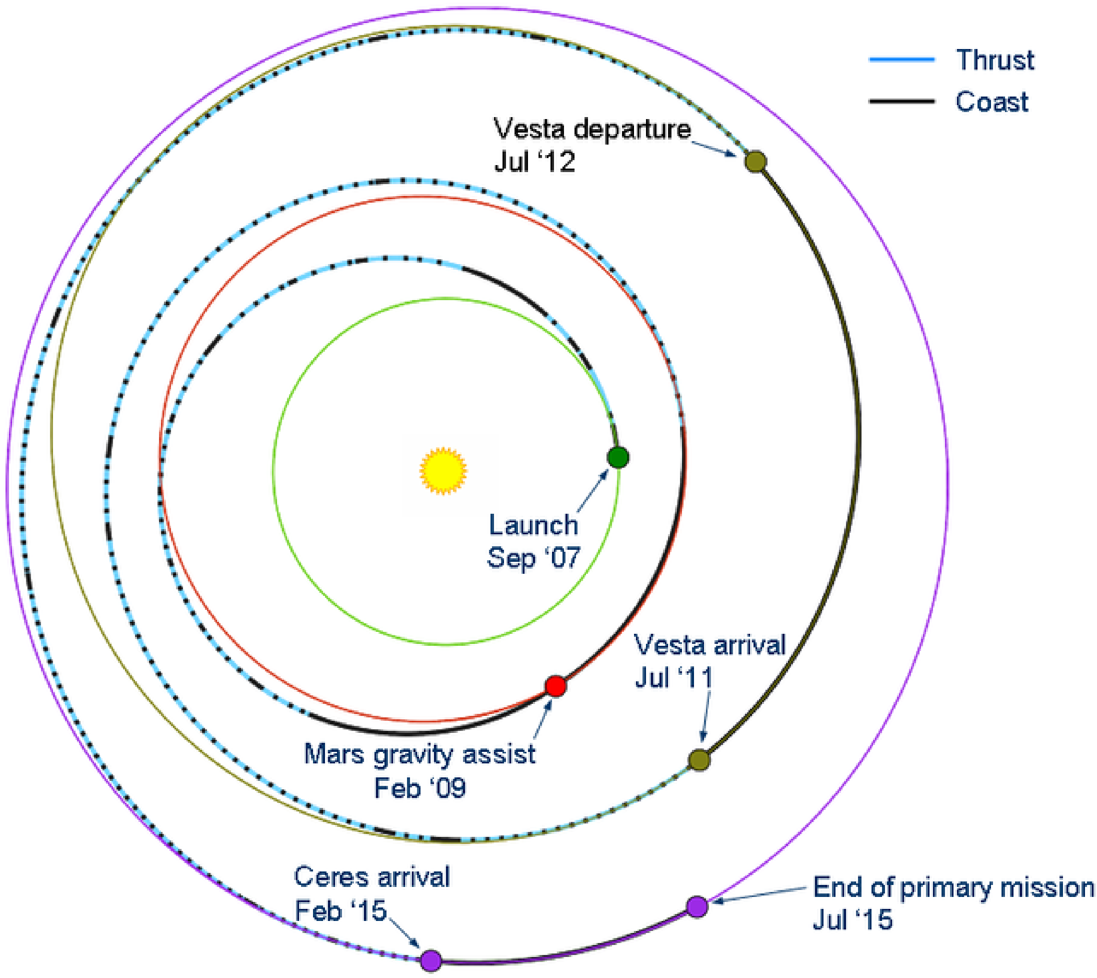
Dawn made its closest approach (549 km) to Mars on February 17, 2009 during a successful gravity assist. On this day the spacecraft placed itself in safe mode resulting in some data acquisition loss. The spacecraft was reported to be back in full operation two days later with no impact to the subsequent mission. The root cause of the event was reported to be a software programming error.

Mission

The mission's goal is to characterize the conditions and processes of the solar system's earliest epoch by investigating in detail two of the largest protoplanets remaining intact since their formation. Ceres and Vesta have many contrasting characteristics that are thought to have resulted from them forming in two different regions of the early solar system; Peter Thomas of Cornell University has proposed that Ceres has a differentiated interior; its oblateness appears too small for an undifferentiated body, which indicates that it consists of a rocky core overlain with an icy mantle. There is a large collection of potential samples from Vesta accessible to scientists, in the form of over 200 HED meteorites, giving insight into Vestian geologic history and structure. Vesta is thought to consist of a metallic iron–nickel core, an overlying rocky olivine mantle, with a surface crust.

Using two redundant framing cameras, a visual and infared spectrometer, and a Gamma Ray and Neutron Spectrometer, *Dawn* will take pictures and measure the chemical composition of Ceres and Vesta.

To cruise from Earth to its targets it will travel in a long outward spiral. The estimated chronology is as follows:



Planned flight trajectory

- September 27, 2007: launch
- February 17, 2009: Mars gravity assist
- July 2011: Vesta arrival
- July 2012: Vesta departure
- February 2015: Ceres arrival
- July 2015: End of primary operations

NASA posts the current location of *Dawn* on the web.

An extended mission following the completion of the Ceres study is also possible, although unlikely, as greater return is expected by spending the available time at Vesta and Ceres. Although 2 Pallas would have been a feasible extended target for the originally scheduled launch date, launch delays have meant that this may no longer be the case. Fuel was also not specifically allocated to break orbit from Ceres, and will depend upon the details of the flight reaching Ceres.

Mission team

The *Dawn* mission team is led by UCLA space scientist and *Dawn* Principal Investigator Christopher T. Russell. NASA's Jet Propulsion Laboratory provided overall planning and management of the mission, the flight system and scientific payload development, and provided the Ion Propulsion System. Orbital Sciences Corporation provided the spacecraft, which constituted the company's first interplanetary mission. The Max Planck Institute for Solar System Research and the German Aerospace Center (DLR) provided the framing cameras, the Italian Space Agency provided the mapping spectrometer, and the DOE Los Alamos National Laboratory provided the gamma ray and neutron spectrometer.

Motivation

Dawn waits for encapsulation at its launch pad on July 1, 2007

Dawn is intended to study two large bodies in the asteroid belt in order to answer questions about the formation of the solar system.

Ceres and Vesta were chosen as two contrasting protoplanets, the first one apparently "wet" (that is, icy) and the other "dry" (or rocky), whose accretion was terminated by the formation of Jupiter. They provide a bridge in our understanding between the formation of rocky planets and the icy bodies of our solar system, and under what conditions a rocky planet can hold water.

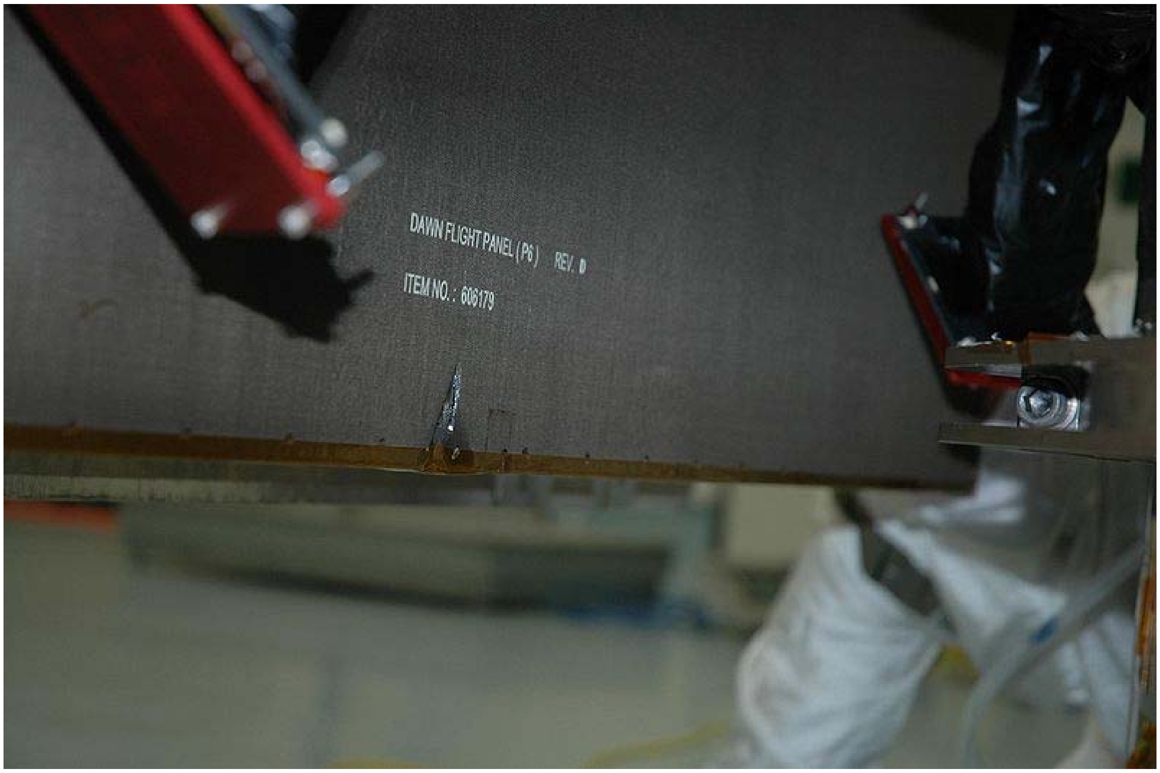
The IAU adopted a new definition of planet on August 24, 2006, and thus, if the IAU's definition stands and the spacecraft experiences no delays, *Dawn* will become the first mission to study a dwarf planet, arriving at Ceres five months prior to the arrival of *New Horizons* at Pluto.

Ceres is a dwarf planet whose mass comprises about one-third of the total mass of the bodies in the asteroid belt and whose spectral characteristics suggest a composition similar to that of a water-rich carbonaceous chondrite. Smaller Vesta, a water-poor achondritic asteroid, has experienced significant heating and differentiation. It shows signs of a metallic core, a Mars-like density and lunar-like basaltic flows.

Both bodies formed very early in the history of the solar system, thereby retaining a record of events and processes from the time of the formation of the terrestrial planets. Radionuclide dating of pieces of meteorites thought to come from Vesta suggests that Vesta differentiated quickly, in only three million years. Thermal evolution studies suggest that Ceres must have formed a little later, more than three million years after the formation of CAIs (the oldest known objects of Solar System origin).

Moreover, Vesta is the source of many smaller objects in the solar system. Most (but not all) V-type near-Earth asteroids, and some outer main-belt asteroids have spectra similar to Vesta and are known as *vestoids*. Five percent of the found meteoritic samples on Earth, the Howardite Eucrite Diogenite ("HED") meteorites, are thought to be the result of a collision or collisions with Vesta.

Mission cancellations and reinstatements



The slightly damaged solar array (NASA)

The status of the *Dawn* mission has changed several times. In December 2003, the project was first cancelled, and then reinstated in February 2004. In October 2005, work on *Dawn* was placed in "stand down" mode. In January 2006, *Dawn's* "stand down" was discussed in the press as "indefinitely postponed", even though NASA had announced no new decisions regarding the mission's status. On March 2, 2006, *Dawn* was publicly, but not formally canceled by NASA headquarters.

The spacecraft's manufacturer Orbital Sciences Corporation appealed the decision and offered to build the spacecraft at cost, forgoing any profit in order to gain experience in a new market field. NASA then put the cancellation under review, and on March 27, 2006, it was announced that the mission would not be canceled after all. In the last week of September 2006, the *Dawn* mission instrument payload integration reached a full functional status.

Propulsion system

The *Dawn* spacecraft is propelled by three DS1 heritage xenon ion thrusters (firing only one at a time). They have a specific impulse of 3,100 s and produce a thrust of 90 mN. The whole spacecraft, including the ion propulsion thrusters, is powered by a 10 kW triple-junction photovoltaic solar array. To get to Vesta, *Dawn* is allocated 275 kg

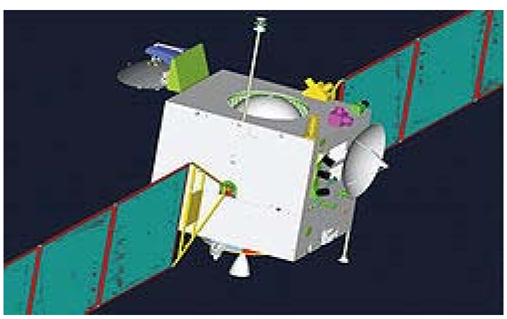
(606 lb) Xe, with another 110 kg (243 lb) to reach Ceres, out of a total capacity of 425 kg (937 pounds) of on-board propellant. All in all, it will perform a velocity change of over 10 km/s, far more than any other spacecraft has done after being propelled by its launch rocket. *Dawn* is NASA's first purely exploratory mission to use ion propulsion engines.

The *Dawn* microchip

Onboard *Dawn* is a small computer microchip bearing the names of more than 360,000 space enthusiasts. The names were submitted online as part of a public outreach effort between September 2005 and November 4, 2006. The microchip (about the size of a nickel) was installed above the forward ion thruster, underneath the spacecraft's High Gain Antenna, on May 17, 2007. More than one microchip was made, with a back-up copy on display at the *2007 Open House* at the Jet Propulsion Laboratory in Pasadena, California.

Chang'e 1

Chang'e 1



Operator	China National Space Administration (CNSA)
Mission type	Orbiter / impactor
Satellite of	The moon
Launch date	2007-10-24, 10:05:04.602 UTC
Carrier rocket	Long March 3A
Launch site	Xichang Satellite Launch Center, Launch Pad 3 Xichang, The People's Republic of China

Mission duration	2009-03-01, 08:13:10 UTC 1 year, 4 months, 4 days, 22 hours and 7 minutes
COSPAR ID	2007-051A
Homepage	CLEP
Mass	2,350 kg
	Orbital elements
Inclination	~64°
Apoapsis	~200 km
Periapsis	~200 km
Orbital period	~127 minutes

Chang'e 1 (pronounced *chang-uh*; simplified Chinese: 嫦娥一号; traditional Chinese: 嫦娥一號; pinyin: *Cháng'é yī hào*) was an unmanned Chinese lunar-orbiting spacecraft, part of the first phase of the Chinese Lunar Exploration Program. The spacecraft was named after the Chinese moon goddess, Chang'e.

Chang'e 1 was launched on 24 October 2007 at 10:05:04 UTC from Xichang Satellite Launch Center. It left lunar transfer orbit on 31 October and entered lunar orbit on 5 November. The first picture of the Moon was relayed on 26 November 2007. On 12 November 2008, a map of the entire lunar surface was released, produced from data collected by Chang'e 1 between November 2007 and July 2008.

The mission was scheduled to continue for a year, but was later extended and the spacecraft operated until 1 March 2009, when it was taken out of orbit. It impacted the surface of the Moon at 08:13 UTC. Data gathered by Chang'e 1 was able to create the most accurate and highest resolution 3-D map ever created of the lunar surface. Its sister orbital probe Chang'e 2 was launched on the first of October 2010.

Objectives

The Chang'e 1 mission had four major goals:

1. Obtaining three-dimensional images of the landforms and geological structures of the lunar surface, so as to provide a reference for planned future soft landings. The orbit of Chang'e 1 around the Moon was designed to provide complete coverage, including areas near the north and south poles not covered by previous missions.

2. 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 (potassium (K), thorium (Th), uranium (U), oxygen (O), silicon (Si), magnesium (Mg), aluminum (Al), calcium (Ca), tellurium (Te), titanium (Ti), sodium (Na), manganese (Mn), chromium (Cr), and lanthanum (La)), compared with the 10 elements (K, U, Th, Fe (iron), Ti, O, Si, Al, Mg, and Ca) previously probed by NASA's Lunar Prospector.
3. Probing the features of the lunar soil and assessing its depth, as well as the amount of helium-3 (^3He) present.
4. 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.

In addition, the lunar probe engineering system, composed of five major systems – the satellite system, the launch vehicle system, the launch site system, the monitoring and control system and the ground application system – accomplished five goals:

- Researching, developing and launching China's first lunar probe
- Mastering the basic technology of placing satellites in lunar orbit
- Conducting China's first scientific exploration of the Moon
- Initially forming a lunar probe space engineering system
- Accumulating experience for the later phases of China's lunar exploration program

Mission

The launch of Chang'e 1 at Xichang Satellite Launch Center

According to the schedule, detailed design of the first program milestone was completed by September 2004. Research and development of a prototype probe and relevant testing of the probe were finished before the end of 2005. Design, manufacture, general assembly, test and ground experiments of the lunar orbiter were finished before December 2006.

Originally scheduled for April 2007, the launch was postponed until October as this was "a better time for sending a satellite into the moon's orbit". Chang'e 1 was launched by a Long March 3A rocket at 10:05 GMT on October 24, 2007 from Xichang Satellite Launch Center in Sichuan Province.

After liftoff, Chang'e 1 made three orbits around the Earth, a burn at perigee extending the orbit's apogee further each time, until a final translunar injection burn placed it on course for the Moon on October 31, 2007. Another burn placed it in a polar orbit around the Moon, with burns at the perilune of the first three orbits decreasing the apolune until it entered a final circular orbit. Lunar orbit insertion was achieved on the November 5, 2007. To mark this occasion, the probe transmitted 30 classical Chinese songs and musical pieces, including "My Motherland", "The Song of the Yangtze River", and "High Mountains and Flowing Water".

The probe was remotely controlled from stations at Qingdao and Kashgar. As well as Chinese facilities, the ESA Maspalomas Tracking Station was used to transmit signals to and from the probe.

The first pictures of the Moon were relayed on November 26, 2007. The probe was designed to orbit the Moon for one year, but operations were later extended, and it remained in lunar orbit until March 1, 2009.

End of mission

On 1 March 2009, at 08:13:10 UTC, Chang'e 1 crashed onto the surface of the Moon, ending its mission. According to the State Administration of Science, Technology and Industry for National Defense (China), this was a planned and controlled impact. Impact point was 1°30′S 52°22′E / 1.50°S 52.36°E. During its orbital mission the probe transmitted 1,400 gigabits or 175 gigabytes (GB) of data.

Design and instrumentation

The Chang'e 1 spacecraft had a mass of 2,350 kg, with a 130 kg payload, carrying 24 instruments including a Charge-coupled device (CCD) stereo camera, microprobe instruments, and a high-energy solar particle detector.

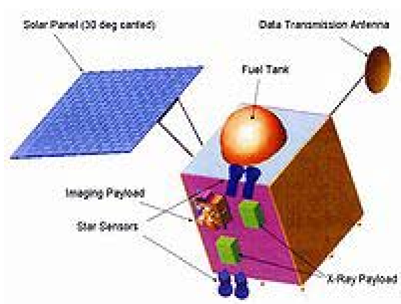
- Stereo camera with an optical resolution of 120 m and spectrometer imager operating at wavelengths of 0.48 μm to 0.96 μm.
- Laser altimeter with 1064 nm, 150 mJ laser, a range resolution of 1 m and a spot size of 300 m.
- Imaging spectrometer
- Gamma and X-ray spectrometer working in an energy range 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 MeV.

Chapter 5

Space and Solar System Exploration in 2008

Chandrayaan-1

Chandrayaan-1



Configuration of Chandrayaan-1 that lift off on the PSLV-C11

Operator	Indian Space Research Organisation
Mission type	Orbiter
Satellite of	Moon
Orbital insertion date	12 November 2008
Orbits	3400 orbits around the Moon.
Launch date	22 October 2008 00:52 UTC
Launch vehicle	PSLV-C11
Launch site	SDSC, Sriharikota

Mission duration	Intended: 2 years Achieved: 312 days
COSPAR ID	2008-052A
Homepage	Chandrayaan-1
Mass	1,380 kg (3,042 lb)
	Orbital elements
Eccentricity	near circular
Inclination	polar
Apoapsis	initial 7,500 km (4,660 mi), final 100 km (62 mi), final (wef 19 May 2009) 200 km (124 mi)
Periapsis	initial 500 km (311 mi), final 100 km (62 mi), final (wef 19 May 2009) 200 km (124 mi)

Chandrayaan-1 (Sanskrit: चंद्रयान-१, lit: moon vehicle) was India's first unmanned lunar probe. It was launched by the Indian Space Research Organisation in October 2008, and operated until August 2009. The mission included a lunar orbiter and an impactor. India launched the spacecraft with a modified version of the PSLV, PSLV C11 on 22 October 2008 from Satish Dhawan Space Centre, Sriharikota, Nellore District, Andhra Pradesh, about 80 km north of Chennai, at 06:22 IST (00:52 UTC). Former prime minister Atal Bihari Vajpayee announced the project on course in his Independence Day speech on 15 August 2003. The mission was a major boost to India's space program, as India researched and developed its own technology in order to explore the Moon. The vehicle was successfully inserted into lunar orbit on 8 November 2008.

On 14 November 2008, the Moon Impact Probe separated from the Chandrayaan orbiter at 20:06 and struck the south pole in a controlled manner, making India the fourth country to place its flag on the Moon. The probe impacted near Shackleton Crater at 20:31 ejecting underground soil that could be analysed for the presence of lunar water ice.

The estimated cost for the project was ₹386 crore (US$80 million).

The remote sensing lunar satellite had a mass of 1,380 kilograms (3,042 lb) at launch and 675 kilograms (1,488 lb) in lunar orbit. It carried high resolution remote sensing equipment for visible, near infrared, and soft and hard X-ray frequencies. Over a two-year period, it was intended to survey the lunar surface to produce a complete map of its chemical characteristics and three-dimensional topography. The polar regions are of special interest as they might contain ice. The lunar mission carries five ISRO payloads and six payloads from other space agencies including NASA, ESA, and the Bulgarian Aerospace Agency, which were carried free of cost.

After suffering from several technical issues including failure of the star sensors and poor thermal shielding, Chandrayaan stopped sending radio signals at 1:30 AM IST on 29 August 2009 shortly after which, the ISRO officially declared the mission over. Chandrayaan operated for 312 days as opposed to the intended two years but the mission achieved 95 percent of its planned objectives. Among its many achievements was the discovery of the widespread presence of water molecules in lunar soil.

Objectives

The stated scientific objectives of the mission were:

- to design, develop, launch and orbit a spacecraft around the Moon using an Indian-made launch vehicle
- to conduct scientific experiments using instruments on the spacecraft which would yield data:
  - for the 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
  - for 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, and thorium
  - to increase the scientific knowledge
  - to test the impact of a sub-satellite (Moon Impact Probe — MIP) on the surface on the Moon as a fore-runner to future soft-landing missions

Specifications

Mass
: 1,380 kg at launch, 675 kg at lunar orbit, and 523 kg after releasing the impactor.

Dimensions
: Cuboid in shape of approximately 1.5 m

Communications
: X band, 0.7 m diameter dual gimballed parabolic antenna for payload data transmission. The Telemetry, Tracking & Command (TTC) communication operates in S band frequency.

Power
: The spacecraft is mainly powered by its solar array, which includes one solar panel covering a total area of 2.15 x 1.8 m generating 750 W of peak power, which is stored in a 36 A·h lithium-ion battery for use during eclipses.

Propulsion

The spacecraft uses a bipropellant integrated propulsion system to reach lunar orbit as well as orbit and altitude maintenance while orbiting the Moon. The power plant consists of one 440 N engine and eight 22 N thrusters. Fuel and oxidizer are stored in two tanks of 390 litres each.

Navigation and control

The craft is 3-axis stabilized with two star sensors, gyros and four reaction wheels. The craft carries dual redundant bus management units for attitude control, sensor processing, antenna orientation, etc.

Specific areas of study

- High-resolution mineralogical and chemical imaging of the permanently shadowed north- and south-polar regions
- Searching for surface or sub-surface lunar water-ice, especially at the lunar poles
- Identification of chemicals in lunar highland rocks
- Chemical stratigraphy of the lunar crust by remote sensing of the central uplands of large lunar craters, and of the South Pole Aitken Region (SPAR), an expected site of interior material
- Mapping the height variation of features of the lunar surface
- Observation of X-ray spectrum greater than 10 keV and stereographic coverage of most of the Moon's surface with 5 m resolution
- Providing new insights in understanding the Moon's origin and evolution

Payloads

The scientific payload had a total mass of 90 kg and contained five Indian instruments and six foreign instruments.

Indian Payloads

- **TMC** or the **Terrain Mapping Camera** is a CCD camera with 5 m resolution and a 40 km swath in the panchromatic band and was used to produce a high-resolution map of the Moon. The aim of this instrument was to completely map the topography of the Moon. The camera works in the visible region of the electromagnetic spectrum and captures black and white stereo images. When used in conjunction with data from Lunar Laser Ranging Instrument (LLRI), it can help in better understanding of the lunar gravitational field as well. TMC was built by the ISRO's Space Applications Centre (SAC) at Ahmedabad. The TMC was successfully tested on 29 October 2008 through a set of commands issued from ISTRAC.

- **HySI** or **Hyper Spectral Imager** performed 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 by sending pulses of infrared laser light towards the lunar surface and detecting the reflected portion of that light. It operated continuously and collected 10 measurements per second on both the day and night sides of the Moon. It was successfully tested on 16 November 2008.

- **HEX** is a **High Energy aj/gamma x-ray spectrometer** for 30 – 200 keV measurements with ground resolution of 40 km, the HEX measured U, Th, ^{210}Pb, ^{222}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. It was ejected at 20:00 hours IST on 14 November 2008. The Moon Impact Probe successfully crash landed at the lunar south pole at 20:31 hours IST on 14 November 2008. It carried with it a picture of the Indian flag. India is now the fourth nation to place a flag on the Moon after the Soviet Union, United States and Japan.

Payload from other countries

- **C1XS** or **X-ray fluorescence spectrometer** covering 1- 10 keV, mapped the abundance of Mg, Al, Si, Ca, Ti, and Fe at the surface with a ground resolution of 25 km, and monitored solar flux. This payload results from collaboration between Rutherford Appleton laboratory, U.K, ESA and ISRO. It was activated on 23 November 2008.

- **SARA**, **The Sub-keV Atom Reflecting Analyser** from the ESA mapped mineral composition using low energy neutral atoms emitted from the surface.

- **M^3**, the **Moon Mineralogy Mapper** from Brown University and JPL (funded by NASA) is an imaging spectrometer designed to map the surface mineral composition. It was activated on 17 December 2008.

- **SIR-2**, A near infrared spectrometer from ESA, built at the Max Planck Institute for Solar System Research, Polish Academy of Science and University of Bergen, also maped the mineral composition using an infrared grating spectrometer. The instrument is similar to that of the Smart-1 SIR. It was activated on 19 November 2008 and scientific observations were successfully started on 20 November 2008.

- **miniSAR**, designed, built and tested for NASA by a large team that includes the Naval Air Warfare Center, Johns Hopkins University Applied Physics Laboratory, Sandia National Laboratories, Raytheon and Northrop Grumman; it is the active Synthetic Aperture Radar system to search for lunar polar ice. The instrument transmitted right polarised radiation with a frequency of 2.5 GHz and monitored scattered left and right polarised radiation. The Fresnel reflectivity and the circular polarisation ratio (CPR) are the key parameters deduced from these measurements. Ice shows the Coherent Backscatter Opposition Effect which results in an enhancement of reflections and CPR, so that water content of the Moon's polar regions can be estimated.

- **RADOM-7**, **Radiation Dose Monitor Experiment** from the Bulgarian Academy of Sciences maps the radiation environment around the Moon. It was successfully tested on 16 November 2008.

Space flight

Chandrayaan-1 was launched on 22 October 2008 at 6.22 am IST from Satish Dhawan Space Centre using the ISRO's 44.4 metre tall four-stage PSLV launch rocket. Chandrayaan-1 was sent to the Moon in a series of orbit-increasing manoeuvres around the Earth over a period of 21 days as opposed to launching the craft on a direct trajectory to the Moon. At launch the spacecraft was inserted into geostationary transfer orbit (GTO) with an apogee of 22,860 km and a perigee of 255 km. The apogee was increased with a series of five orbit burns conducted over a period of 13 days after launch.

For the duration of the mission, ISRO's telemetry, tracking and command network (ISTRAC) at Peenya in Bangalore, tracked and controlled Chandrayaan-1. Scientists from India, Europe, and the U.S. conducted a high-level review of Chandrayaan-1 on 29 January 2009 after the spacecraft completed its first 100 days in space.

Earth orbit burns

First orbit burn

The first orbit-raising manoeuvre of Chandrayaan-1 spacecraft was performed at 09:00 hrs IST on 23 October 2008 when the spacecraft’s 440 Newton Liquid Engine was fired for about 18 minutes by commanding the spacecraft from Spacecraft Control Centre (SCC) at ISRO Telemetry, Tracking and Command Network (ISTRAC) at Peenya, Bangalore. With this Chandrayaan-1’s apogee was raised to 37,900 km, and its perigee to 305 km. In this orbit, Chandrayaan-1 spacecraft took about 11 hours to go around the Earth once.

Second orbit burn

The second orbit-raising manoeuvre of Chandrayaan-1 spacecraft was carried out on 25 October 2008 at 05:48 IST when the spacecraft’s engine was fired for about 16 minutes, raising its apogee to 74,715 km, and its perigee to 336 km, thus completing 20 percent of its journey. In this orbit, Chandrayaan-1 spacecraft took about twenty-five and a half hours to go round the Earth once. This is the first time an Indian spacecraft has gone beyond the 36,000 km high geostationary orbit and reached an altitude more than twice that height.

Third orbit burn

The third orbit raising manoeuvre was initiated on 26 October 2008 at 07:08 IST when the spacecraft's engine was fired for about nine and a half minutes. With this its apogee was raised to 164,600 km, and the perigee to 348 km. In this orbit, Chandrayaan-1 took about 73 hours to go around the Earth once.

Fourth orbit burn

The fourth orbit-raising maneuver took place on 29 October 2008 at 07:38 IST when the spacecraft's engine was fired for about three minutes, raising its apogee to 267,000 km and the perigee to 465 km. This extended its orbit to a distance more than half the way to the Moon. In this orbit, the spacecraft took about six days to go around the Earth once.

Final orbit burn

The fifth and final orbit raising manoeuvre was carried out on 4 November 2008 04:56 am IST when the spacecraft's engine was fired for about two and a half minutes resulting in Chandrayaan-1 entering the Lunar Transfer Trajectory with an apogee of about 380,000 km.

Lunar orbit insertion

Chandrayaan-1 successfully completed the lunar orbit insertion operation on 8 Nov 2008 at 16:51 IST. This manoeuvre involved firing of the liquid engine for 817 seconds (about thirteen and half minutes) when the spacecraft passed within 500 km from the Moon. The satellite was placed in an elliptical orbit that passed over the polar regions of the Moon, with 7502 km aposelene (point farthest away from the Moon) and 504 km periselene (nearest to the Moon). The orbital period was estimated to be around 11 hours. With the successful completion of this operation, India became the fifth nation to put a vehicle in lunar orbit.

First orbit reduction

First Lunar Orbit Reduction Manoeuvre of Chandrayaan-1 was carried out successfully on 9 November 2008 at 20:03 IST. During this, the engine of the spacecraft was fired for about 57 seconds. This reduced the periselene from 504 km to 200 km while aposelene remained unchanged at 7,502 km. In this elliptical orbit, Chandrayaan-1 took about ten and a half hours to circle the Moon once.

Second orbit reduction

This manoeuvre, which resulted in steep decrease in Chandrayaan-1's aposelene from 7,502 km to 255 km and its periselene from 200 km to 187 km, was carried out on 10 November 2008 at 21:58 IST. During this manoeuvre, the engine was fired for about

866 seconds (about fourteen and half minutes). Chandrayaan-1 took two hours and 16 minutes to go around the Moon once in this orbit.

Third orbit reduction

Third Lunar Orbit Reduction was carried out by firing the on board engine for 31 seconds on 11 November 2008 at 18:30 IST. This reduced the periselene from 187 km to 101 km, while the aposelene remained constant at 255 km. In this orbit Chandrayaan-1 took two hours and 9 minutes to go around the Moon once.

Final orbit

Chandrayaan-1 spacecraft was successfully placed into a mission-specific lunar polar orbit of 100 km above the lunar surface on 12 November 2008. In the final orbit reduction manoeuvre, Chandrayaan-1's aposelene was reduced from 255 km to 100 km while the periselene was reduced from 101 km to 100 km. In this orbit, Chandrayaan-1 takes about two hours to go around the Moon once. Two of the 11 payloads – the Terrain Mapping Camera (TMC) and the Radiation Dose Monitor (RADOM) – have already been successfully switched on. The TMC successfully acquired images of both the Earth and the Moon.

Impact of the MIP on the lunar surface

The Moon Impact Probe (MIP) crash-landed on the lunar surface on 14 November 2008, 15:01 UTC (20:31 Indian Standard Time (IST)) near the crater Shackleton at the south pole. The MIP was one of eleven scientific instruments (payloads) on board Chandrayaan-1.

The MIP separated from Chandrayaan at 100 km from lunar surface and began its nosedive at 14:36 UTC (20:06 IST). going into free fall for thirty minutes. As it fell, it kept sending information back to the mother satellite which, in turn, beamed the information back to Earth. The altimeter then also began recording measurements to prepare for a rover to land on the lunar surface during a second Moon mission - planned for 2012.

Following the successful deployment of the MIP, the other scientific instruments were turned on, starting the next phase of the mission.

After scientific analyses of the received data from the MIP, the Indian Space Research Organisation confirmed the presence of water in the lunar soil and published the finding in a press conference addressed by its then Chairman Sri. G. Madhavan Nair.

Rise of spacecraft's temperature

ISRO had reported on 25 November 2008 that Chandrayaan-1's temperature had risen above normal to 50 °C, scientists said that it was caused by higher than normal temperatures in lunar orbit. The temperature was brought down by about 10 °C by rotating the spacecraft about 20 degrees and switching off some of the instruments. Subsequently ISRO reported on 27 November 2008 that the spacecraft was operating under normal temperature conditions. In subsequent reports ISRO says, since the spacecraft was still recording higher than normal temperatures, it would be running only one instrument at a time until January 2009 when lunar orbital temperature conditions are said to stabilise. The spacecraft was experiencing high temperature because of radiation from the Sun and infrared radiation reflected by the Moon.

Mapping of minerals

The mineral content on the lunar surface was mapped with the Moon Mineralogy Mapper (M^3), a NASA instrument on board the orbiter. The presence of iron was reiterated and changes in rock and mineral composition have been identified. The Oriental Basin region of the Moon was mapped, and it indicates abundance of iron-bearing minerals such as pyroxene.

Mapping of Apollo landing sites

ISRO claims that the landing sites of the Apollo Moon missions have been mapped by the orbiter using multiple payloads. Six of the sites have been mapped including that of Apollo 11, the first mission that brought humans on the Moon.

Images acquisition

The craft completed 3000 orbits acquiring 70000 images of the lunar surface, which many in ISRO believe is quite a record compared to the lunar flights of other nations. ISRO officials estimated that if more than 40,000 images have been transmitted by Chandrayaan's cameras in 75 days, it worked out to nearly 535 images being sent daily. They were first transmitted to Indian Deep Space Network at Byalalu near Bangalore, from where they were flashed to ISRO's Telemetry Tracking And Command Network (ISTRAC) at Bangalore.

Some of these images have a resolution of up to 5 metres, providing a sharp and clear picture of the Moon's surface, while many images sent by some of the other missions had a 100-metre resolution.

On 26 November, the indigenous Terrain Mapping Camera, which was first activated on 29 October 2008, acquired images of peaks and craters. This came as a surprise to ISRO officials because the Moon consists mostly of craters.

Detection of X-Ray signals

The X-ray signatures of aluminium, magnesium and silicon were picked up by the C1XS X-ray camera. The signals were picked up during a solar flare that caused an X-ray fluorescence phenomenon. The flare that caused the fluorescence was within the lowest C1XS sensitivity range.

Full Earth image

On 25 March 2009 Chandrayaan beamed back its first images of the Earth in its entirety. These images were taken with the TMC. Previous imaging was done on only part of the Earth. The new images show Asia, parts of Africa and Australia with India being in the center.

Chapter 6

Space and Solar System Exploration in 2009

Lunar Reconnaissance Orbiter

Lunar Reconnaissance Orbiter

LRO spacecraft, artist's rendering

Operator	NASA/Goddard Space Flight Center
Mission type	Orbiter
Satellite of	Earth's Moon
Orbits	30–70 km polar orbit, extended mission 30–216 km
Launch date	18 June 2009 21:32:00 UTC
Launch vehicle	Atlas V 401
Launch site	Space Launch Complex 41 Cape Canaveral Air Force Station
Mission duration	one year, extended mission of up to five years elapsed: 1 year, 6 months, and 29 days

COSPAR ID	2009-031A
Mass	1,846 kg
Power	1,850 W

The **Lunar Reconnaissance Orbiter** (**LRO**) is a NASA robotic spacecraft currently (as of April 2010) orbiting the Moon on a low 50 km polar mapping orbit. The LRO mission is a precursor to future manned missions to the moon by NASA. To this end a detailed mapping program will identify safe landing sites, locate potential resources on the moon, characterize the radiation environment, and demonstrate new technology.

The probe will make a 3-D map of the Moon's surface and has provided some of the first images of Apollo equipment left on the Moon. The first images from LRO were published on 2 July 2009, showing a region in the lunar highlands south of Mare Nubium (*Sea of Clouds*).

Launched on 18 June 2009, in conjunction with the Lunar Crater Observation and Sensing Satellite (LCROSS), as the vanguard of NASA's Lunar Precursor Robotic Program, this is the first United States mission to the Moon in over ten years. LRO and LCROSS are the first missions launched as part of the United States's Vision for Space Exploration program.

The total cost of the mission is reported as US$583 million, of which $504 million pertains to the main LRO probe and $79 million to the LCROSS satellite.

Mission

Developed at NASA's Goddard Space Flight Center, LRO is a large (1,900 kg) and sophisticated spacecraft planned to fly in a lunar polar orbit for a mission of one Earth year. An optional extended phase of the mission (up to five years) could provide a communications relay for future lunar ground missions, such as a Moon lander or rover.

After completing a preliminary design review in February 2006 and a critical design review in November 2006, the LRO was shipped from Goddard Space Flight Center to Cape Canaveral Air Force Station on 11 February 2009. Launch was planned for October 2008, but this slid to April as the spacecraft underwent testing in a thermal vacuum chamber. Launch was rescheduled for June 17, 2009 because of the delay in a priority military launch, and happened one day later, on June 18. The one-day delay was to allow the Space Shuttle Endeavour a chance to lift off for mission STS-127 following a hydrogen fuel leak that canceled an earlier planned launch.

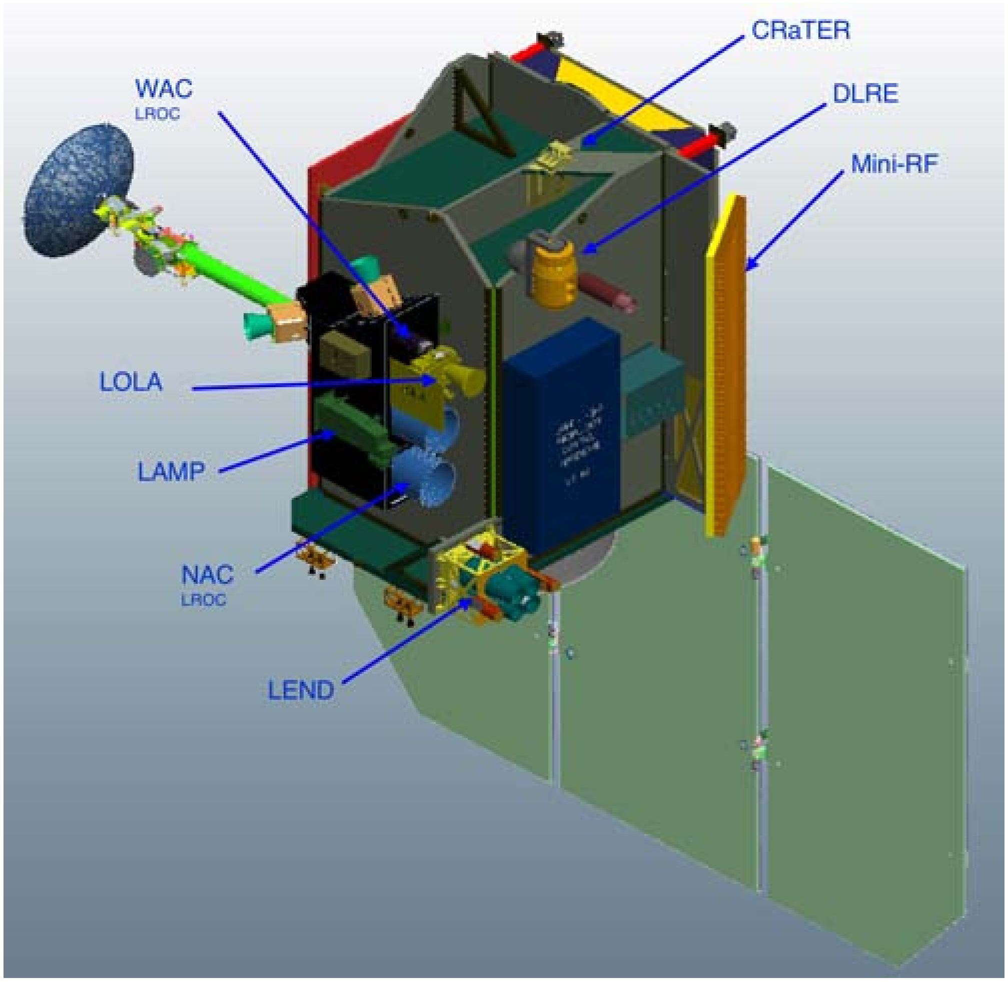
Areas of investigation will include:

- Selenodetic global topography.
- Characterization of deep space radiation in lunar orbit.

- The lunar polar regions, including possible water ice deposits and the lighting environment. The lunar polar regions experience temperatures of −223 °C (−369.4 °F) and may be able to hold water ice.
- High-resolution mapping (max 0.5 metres (1.6 ft)) to assist in the selection and characterization of future landing sites.

In addition, LRO has provided some of the first images of leftover Apollo equipment on the Moon.

Payload



Onboard instruments

The orbiter carries a complement of six instruments and one technology demonstration:

- **CRaTER**—The primary goal of the **C**osmic **Ra**y **T**elescope for the **E**ffects of **R**adiation is to characterize the global lunar radiation environment and its biological impacts.

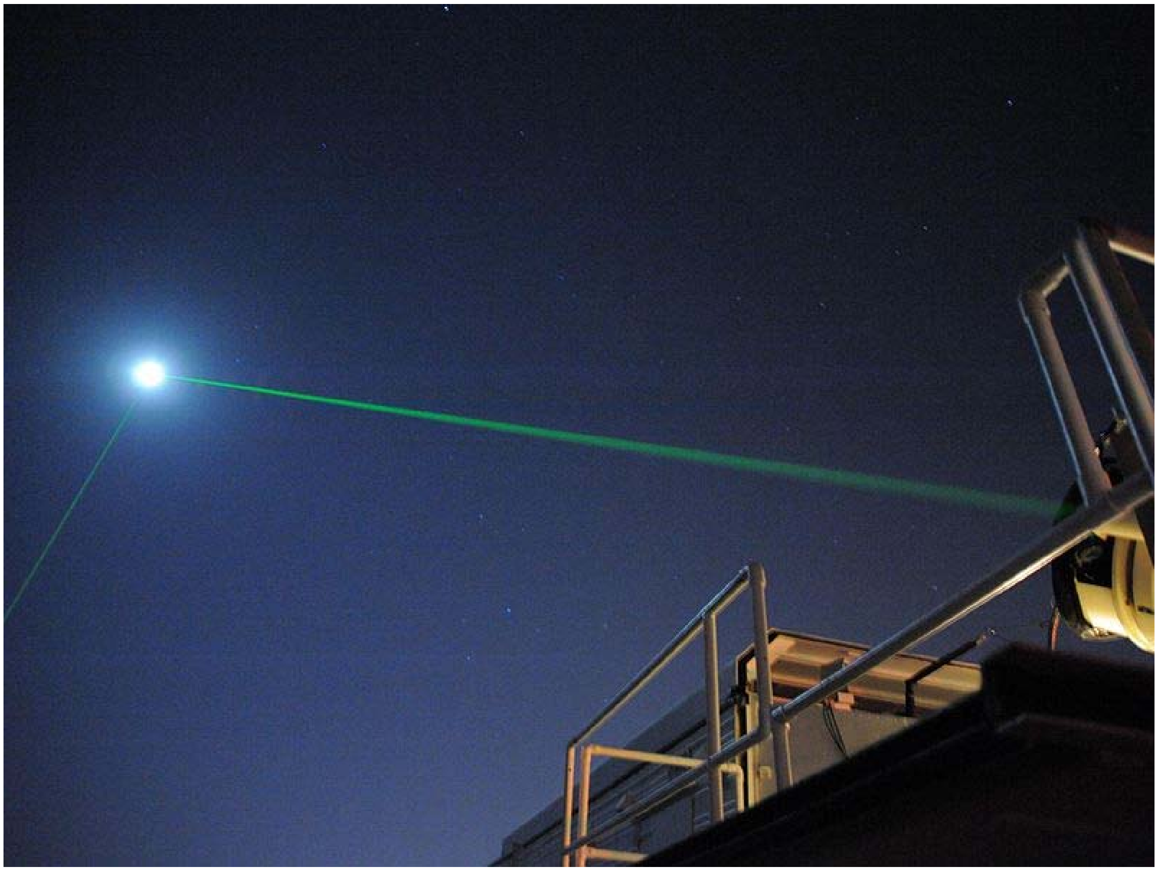
- **DLRE**—The **D**iviner **L**unar **R**adiometer **E**xperiment will measure lunar surface thermal emission to provide information for future surface operations and exploration.
- **LAMP**—The **L**yman-**A**lpha **M**apping **P**roject will peer into permanently shadowed craters in search of water ice, seeing by the ultraviolet light from stars and the interplanetary medium.
- **LEND**—The **L**unar **E**xploration **N**eutron **D**etector will provide measurements, create maps, and detect possible near-surface water ice deposits.
- **LOLA**—The **L**unar **O**rbiter **L**aser **A**ltimeter investigation will provide a precise global lunar topographic model and geodetic grid.
- **LROC**—The **L**unar **R**econnaissance **O**rbiter **C**amera 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). LROC will fly several times over the historic Apollo lunar landing sites at 31 miles (50 km) altitude; with the camera's high resolution, the lunar rovers and Lunar Module descent stages and their respective shadows will be clearly visible, along with other equipment previously left on the Moon. The mission will return approximately 70–100 Terabytes of image data. It is expected that this photography will boost public acknowledgement of the validity of the landings, and further discredit Apollo conspiracy theories.
- **Mini-RF**—The **Mini**ature **R**adio **F**requency radar will demonstrate new lightweight SAR and communications technologies and locate potential water-ice.

Names to the Moon

The microchip panel containing 1.6 million names

Prior to the LRO's launch, NASA gave members of the public the opportunity to have their names placed in a microchip on the LRO. The deadline for this opportunity was 31 July 2008. About 1.6 million names were submitted.

Mission progress



In this image, the lower of the two green beams is from the Lunar Reconnaissance Orbiter's dedicated tracker.

On June 23, 2009, the Lunar Reconnaissance Orbiter entered into orbit around the Moon after a four and a half day journey from the Earth. When launched, the spacecraft was aimed at a point ahead of the Moon's position. A mid-course correction was required during the trip in order for the spacecraft to correctly enter Lunar orbit. Once the spacecraft reached the far side of the Moon, its rocket motor was fired in order for it to be captured by the Moon's gravity into an elliptical lunar orbit. A series of four rocket burns over the next four days put the satellite into its commissioning phase orbit where each instrument was brought online and tested. On September 15, 2009, the spacecraft started its primary mission by orbiting the Moon at about 50 kilometers (31 mi) for one year.

On August 21, 2009, the spacecraft, along with the Chandrayaan-1, was used to perform a Bistatic radar experiment to detect the presence of water ice on the lunar surface. In this experiment, Chandrayaan transmitted radar pulses which, after reflection from the surface, were picked up by the receivers of LRO and in a different angle by the Chandrayaan. Both receivers, Mini-RF in LRO and Mini-SAR in Chandrayaan, are similar in nature. They were pointed at the Erlanger crater for four minutes during which the observations were made.

NASA's LCROSS mission culminated with two lunar impacts at approximately 4:30 a.m. PDT on October 9. The goal of the impact was the search for water in the Cabeus crater near the Moon's south pole, and preliminary results indicated the presence of both water and hydroxyl, an ion related to water.

On December 17, 2010, the topographic map of the Moon based on data gathered by the LOLA instrument was released to the public. This is the most accurate topographic map of the Moon to date.

Chapter 7

Solar Dynamics Observatory

Solar Dynamics Observatory

Operator	NASA / Goddard Space Flight Center
Mission type	Orbiter
Satellite of	Earth
Launch date	2010-02-11 15:23:00 UTC
Carrier rocket	Atlas V 401
Launch site	Space Launch Complex 41 Cape Canaveral Air Force Station
Mission duration	5 - 10 years elapsed: 11 months, and 3 days
COSPAR ID	2010-005A
Mass	payload: 290 kg (640 lb) fuel: 1,400 kg (3,100 lb) total: 3,100 kg (6,800 lb)

Orbital elements	
Regime	Geosynchronous orbit
Inclination	28°
Longitude	102° W
Instruments	
Spectral band	<.1 nm
Data rate	130 Mbps on the 26 GHz K_a band 150 million bits/second

The **Solar Dynamics Observatory (SDO)** is a NASA mission which will observe the Sun for over five years. Launched on February 11, 2010, the observatory is part of the Living With a Star (LWS) program. The goal of the LWS program is to develop the scientific understanding necessary to effectively address those aspects of the connected Sun–Earth system that directly affect life and society. SDO's goal is to understand the Sun's influence on Earth and near-Earth space by studying the solar atmosphere on small scales of space and time and in many wavelengths simultaneously. SDO will investigate how the Sun's magnetic field is generated and structured, how this stored magnetic energy is converted and released into the heliosphere and geospace in the form of solar wind, energetic particles, and variations in the solar irradiance.

General

The SDO spacecraft was assembled and tested at NASA's Goddard Space Flight Center in Greenbelt, Maryland, and launched on February 11, 2010, from Cape Canaveral Air Force Station. The primary mission is scheduled to last five years and three months, with expendables expected to last for ten years. Some consider SDO to be a follow-on mission to the Solar and Heliospheric Observatory (SOHO).

SDO is a 3-axis stabilized spacecraft, with two solar arrays, and two high-gain antennas. The spacecraft includes three instruments: the Extreme Ultraviolet Variability Experiment (EVE) built in partnership with the University of Colorado at Boulder's Laboratory for Atmospheric and Space Physics (LASP), the Helioseismic and Magnetic Imager (HMI) built in partnership with Stanford University, and the Atmospheric Imaging Assembly (AIA) built in partnership with the Lockheed Martin Solar & Astrophysics Laboratory. Data which is collected by the craft will be made available as soon as possible, after it is received.

Helioseismic and Magnetic Imager

The Helioseismic and Magnetic Imager (HMI), led from Stanford University in Stanford, California, studies solar variability and characterizes the Sun's interior and the various components of magnetic activity. HMI produces data to determine the interior sources and mechanisms of solar variability and how the physical processes inside the Sun are related to surface magnetic field and activity. It also produces data to enable estimates of the coronal magnetic field for studies of variability in the extended solar atmosphere. HMI observations will enable establishing the relationships between the internal dynamics and magnetic activity in order to understand solar variability and its effects. HMI will take high-resolution measurements of the longitudinal and vector magnetic field over the entire visible disk thus extending the capabilities of the SOHO's MDI instrument.

Extreme Ultraviolet Variability Experiment

Extreme Ultraviolet Variability Experiment logo

The Extreme Ultraviolet Variability Experiment (EVE), will measure the Sun's extreme ultraviolet irradiance with improved spectral resolution, "temporal cadence", accuracy, and precision over preceding measurements made by TIMED SEE, SOHO, and SORCE XPS. The instrument incorporates physics-based models in order to further scientific understanding of the relationship between solar EUV variations and magnetic variation changes in the Sun.

The Sun's output of energetic extreme ultraviolet photons is primarily what heats the Earth's upper atmosphere and creates the ionosphere. Solar EUV radiation output undergoes constant changes, both moment to moment and over the Sun's 11-year solar cycle, and these changes are important to understand because they have a significant impact on atmospheric heating, satellite drag, and communications system degradation, including disruption of the Global Positioning System.

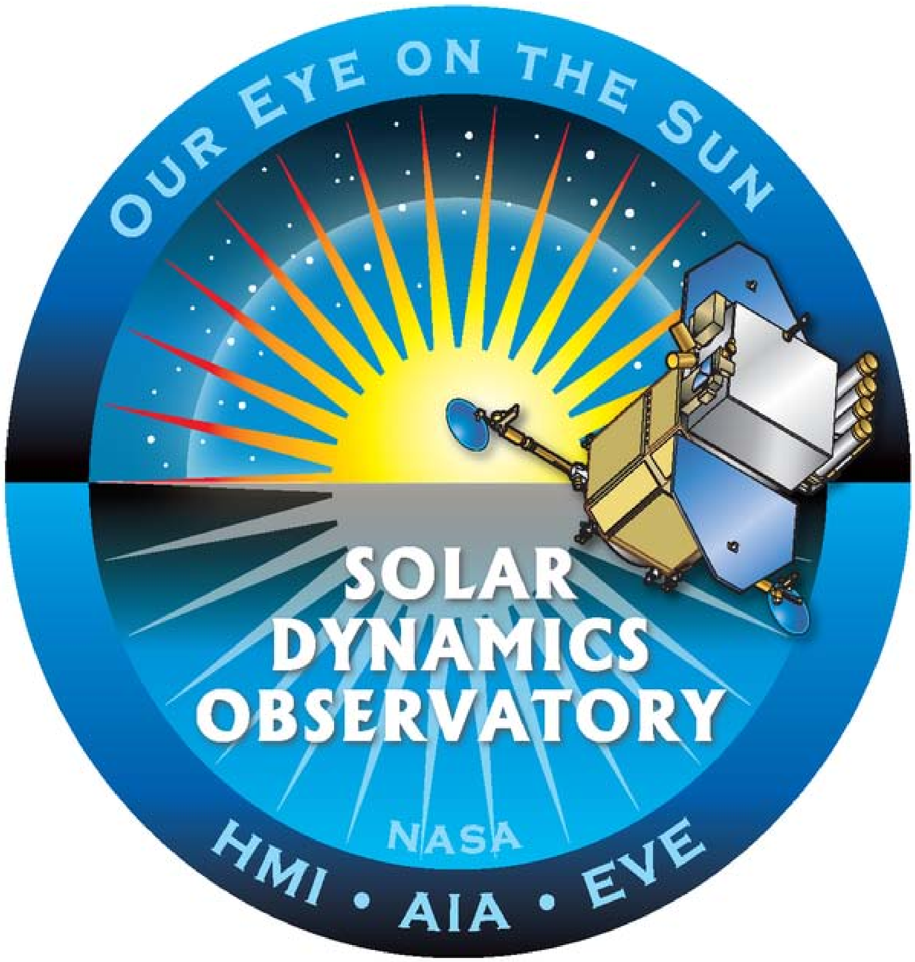
The EVE instrument package was built by the University of Colorado at Boulder's Laboratory for Atmospheric and Space Physics, with Dr. Tom Woods as Principal Investigator, and was delivered to Goddard Space Flight Center on September 7, 2007. The instrument provides improvements of up to 70 percent in spectral resolution measurements in the wavelengths below 30nm, and a 30 percent improvement in "time cadence" by taking measurements every 10 seconds over a 100 percent duty cycle.

Atmospheric Imaging Assembly

The Atmospheric Imaging Assembly (AIA), led from the Lockheed Martin Solar and Astrophysics Laboratory (LMSAL), provides full-disk imaging of the Sun in ten white light, ultraviolet and extreme ultraviolet (EUV) band passes at high spatial and temporal resolution. The four telescopes that provided the individual light feeds for the instrument were designed and built at the Smithsonian Astrophysical Observatory (SAO).

AIA Wavelength Channel	Region of solar atmosphere	Characteristic Temperature
White Light	Photosphere	5000 K
170 nm	Temperature minimum, photosphere	5000 K
160 nm	Transition region & photosphere	10^5 & 5000 K
30.4 nm	Chromosphere & transition region	50,000 K
17.1 nm	Quiet corona, upper transition region	6.3×10^5 K
19.3 nm	Corona & hot flare plasma	1.2×10^6 & $2x10^7$ K
21.1 nm	Active region corona	2×10^6 K
33.5 nm	Active region corona	2.5×10^6 K
9.4 nm	Flaring regions	6.3×10^6 K
13.1 nm	Flaring regions	4×10^5, 10^7 & 1.6×10^7 K

Communications



The insignia of the SDO

SDO will down-link science data (K-band) from its two onboard high-gain antennas, and telemetry (S-band) from its two onboard omnidirectional antennas. The ground station consists of two dedicated (redundant) 18-meter radio antennas in White Sands Missile Range, New Mexico, constructed specifically for SDO. Mission controllers will operate the spacecraft remotely from the Mission Operations Center at NASA's Goddard Space Flight Center. The combined data rate will be about 130 Mbit/s (150 Mbit/s with overhead, or 300 Msymbols/s with rate 1/2 convolutional encoding), and the craft will generate approximately 1.5 terabytes of data per day, beaming back 150 million bits of data every second (The equivalent of about 380 full length movies).

Launch

The launch Thursday, 11 February 2010 15:23:00 UTC (10:23 a.m. EST)

Attempt	Planned	Result	Turnaround	Reason	Decision point	Weather go %	Notes
1	10 Feb 2010, 3:26:00 pm	Scrubbed	---	Weather (high winds)	10 Feb 2010, 11:26 am(T-3:59, immediately after T-4:00 hold)	40%	window 10:26 to 11:26a EST, attempts made at

						10:26, 10:56 and 11:26
2	11 Feb 2010, 3:23:00 pm	Success	0 days, 23 hours, 57 minutes		60%	Window: 10:23 to 11:23a EST

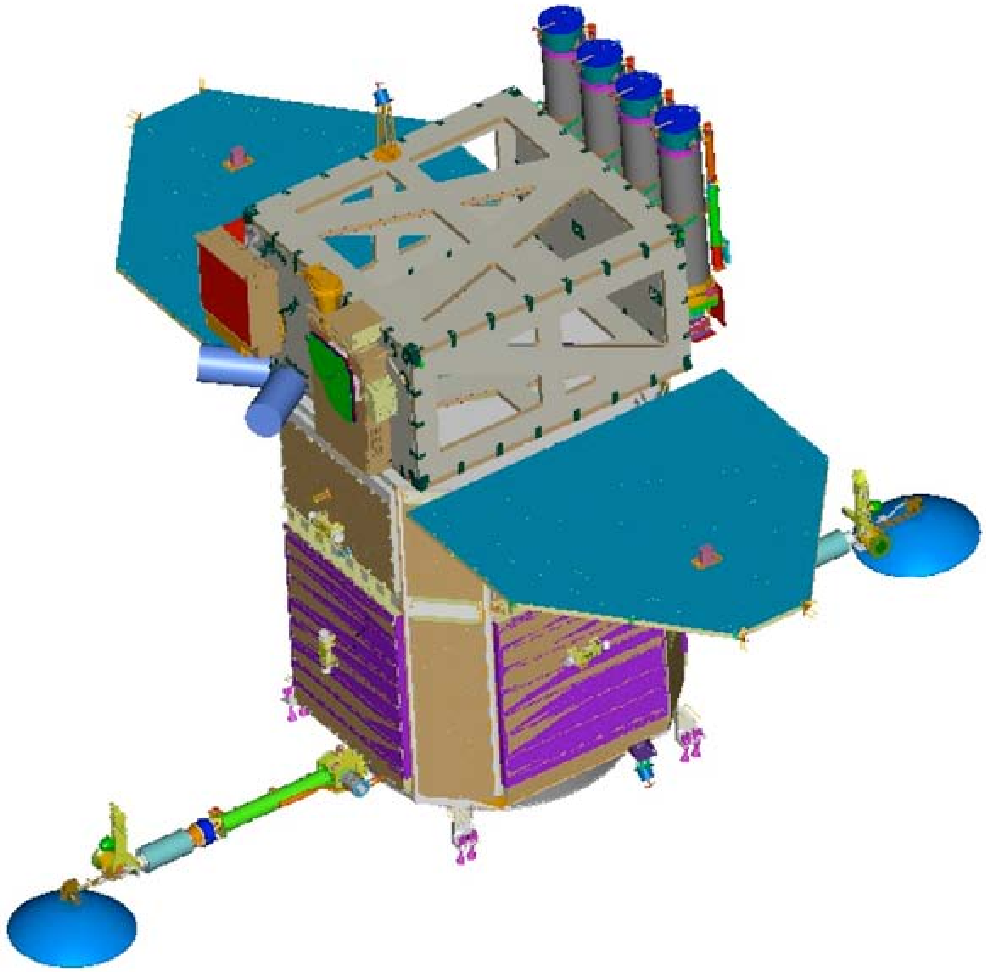
NASA's Launch Services Program at Kennedy Space Center managed the payload integration and launch. The SDO launched from Cape Canaveral Air Force Station Space Launch Complex 41, utilizing an Atlas V-401 rocket with a RD-180 powered Common Core Booster, which has been developed to meet the Evolved Expendable Launch Vehicle (EELV) program requirements.

Orbit

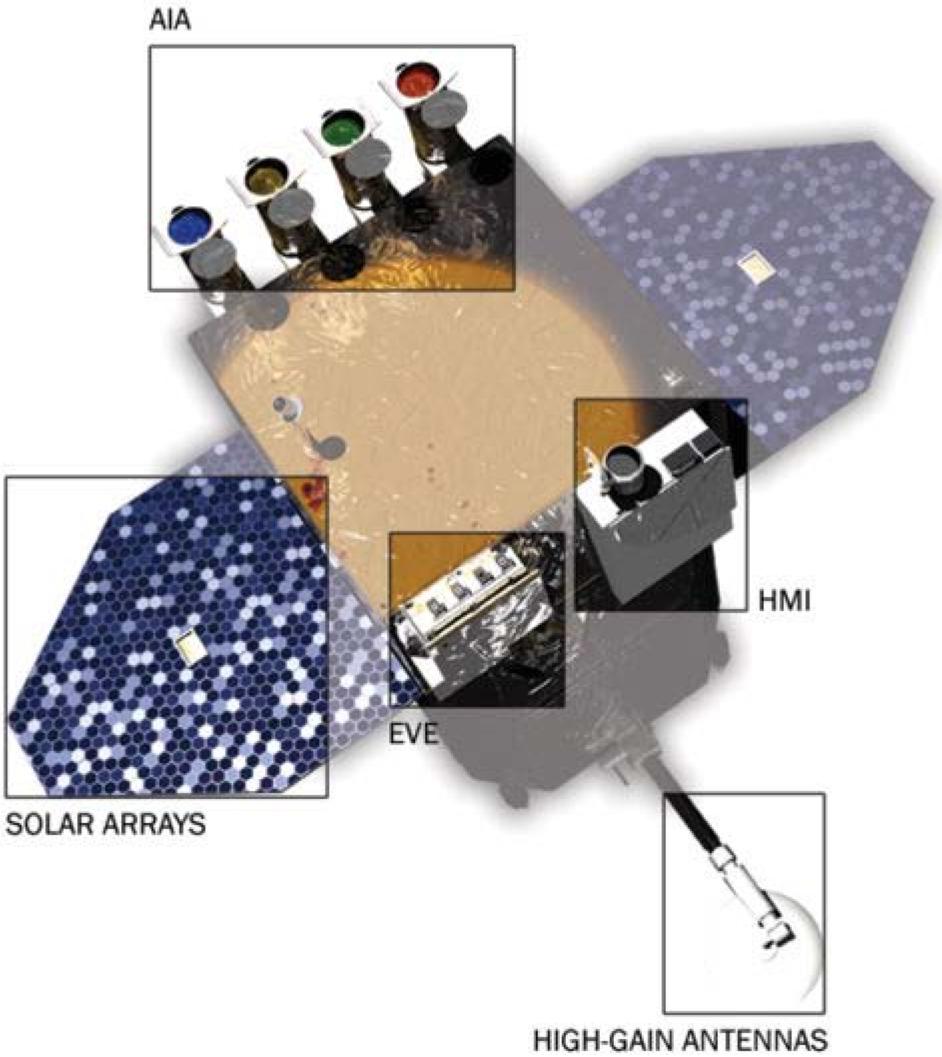
After launch, the spacecraft was placed into an orbit around the earth with an initial perigee of about 2,500 kilometres (1,600 mi). SDO will undergo a series of orbit-raising maneuvers which will adjust its orbit until the spacecraft reaches its planned circular, geosynchronous orbit at an altitude of 36,000 kilometres (22,000 mi), at 102° W longitude, inclined at 28.5°.

Camilla Corona

Camilla Corona SDO is a rubber chicken and mission mascot for NASA's Solar Dynamics Observatory (SDO). She is part of the Education and public outreach team and assists with various functions to help educate the public, mainly children, about the SDO mission, facts about the sun and space weather. Camilla also assists in cross-informing about other NASA missions and space related projects. Camilla Corona SDO uses social media to interact with fans.

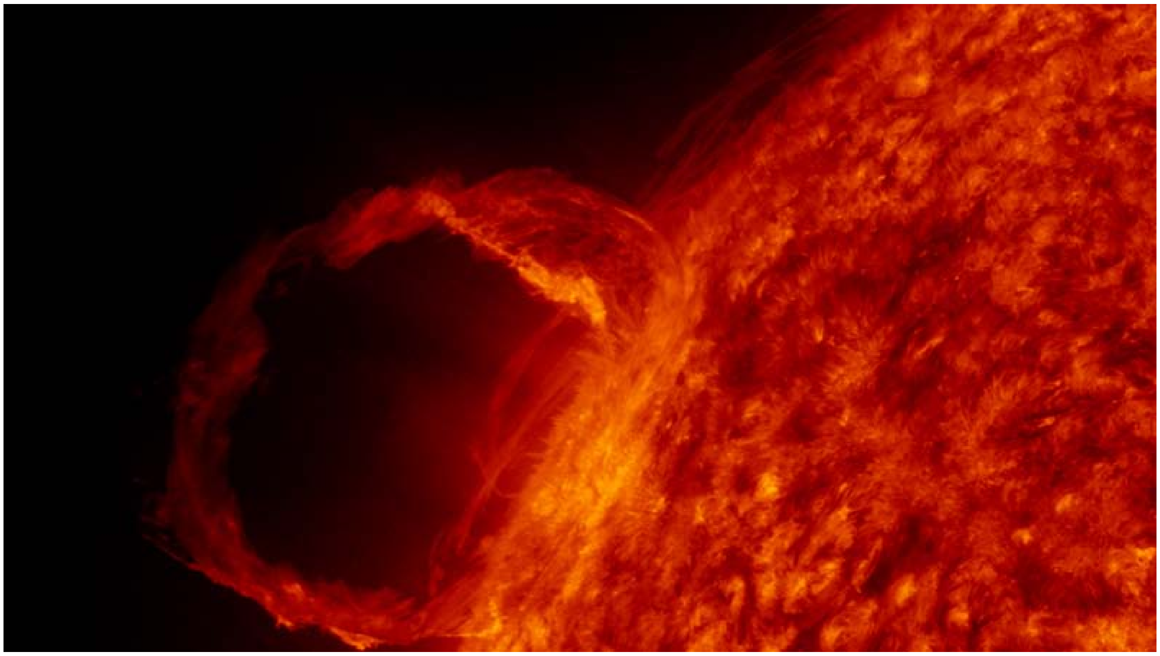


SDO 3-D schematic



SDO Instruments

SDO ready to be placed on Atlas rocket for launch



First light image from the SDO showing a solar flare

Chapter 8

Akatsuki (spacecraft)

Akatsuki	
Operator	Japan Aerospace Exploration Agency (JAXA)
Mission type	Orbiter
Satellite of	Venus
Orbital insertion date	2010-12-06 23:49:00 UTC (anticipated)
Launch date	2010-05-20 21:58:22 UTC
Carrier rocket	H-IIA 202
Launch site	Tanegashima Space Center Tanegashima, Japan
Mission duration	~2 years elapsed: 7 months, and 28 days
COSPAR ID	2010-020D
Mass	320 kg (710 lb)
Power	1,200 W
Orbital elements	
Eccentricity	0.992
Inclination	172 degrees
Apoapsis	79,000 km (49,000 mi)
Periapsis	300 km (190 mi)

Orbital period	30 hours

Akatsuki (あかつき, 暁?, literally "dawn"), formerly known as the **Venus Climate Orbiter (VCO)** and **Planet-C**, is a Japanese unmanned spacecraft which was intended to explore Venus. It was launched aboard an H-IIA 202 rocket on 20 May 2010, after being delayed because of weather from its initial 18 May scheduled target. The total launch mass of the spacecraft including propellant was 480 kg, 34 kg out of this was scientific instruments. The mission reached Venus on 7 December 2010 (JST) but failed to enter orbit around the planet. It had been intended to conduct scientific research for two or more years from an elliptical orbit ranging from 300 km to 80,000 km from Venus.

Akatsuki is Japan's first planetary exploration mission since the Nozomi probe, which was launched in 1998 but failed to go into a Mars orbit in 2003 as planned.

Design

The mass of the spacecraft is 640 kg (1,400 lb), including 320 kg (710 lb) of propellants and 34 kg (75 lb) of scientific instruments.

The main bus is a 1.6 m x 1.6 m x 1.25 m box with two solar arrays, each with an area of 1.4 m^2 (15 sq ft). The solar array panels provide over 1,200 watts of power in Venus orbit.

Propulsion is provided by a 500 newton (N) bi-propellant, hydrazine / nitrogen tetroxide orbital maneuvering engine and 12 mono-propellant hydrazine reaction control thrusters, eight with 23 N thrust and four with 3 N.

Communications is via a 8 GHZ X-band 20 W transponder using the 1.6 m slot array high gain dish antenna used for most telemetry data. Akatsuki also has a pair of medium gain horn antennas mounted on turntables and two low gain antennas for command uplink. The medium gain horn antennas will be used for housekeeping data downlink when the high gain antenna is not facing Earth.

Instruments

The scientific payload consists of six instruments including a Lightning and airglow camera (LAC), an ultraviolet imager (UVI), a longwave infrared camera (LIR), a 1-µm camera (IR1), a 2-µm camera (IR2), and the radio science (RS) experiment. The five cameras will explore Venus in wavelengths from ultraviolet to the mid-infrared.

The LAC will look for lightning in the visible wavelengths of 552 to 777 nanometers. The LIR will study the structure of high-altitude clouds at a wavelength where they emit heat (10 microns). The UVI will study the distribution of specific atmospheric gases such as sulfur dioxide in ultraviolet wavelengths (293 to 365 nanometers). The IR1 will peer through semi-transparent windows in Venus' atmosphere to see heat radiation emitted from Venus' surface rocks (0.9 to 1.01 microns) and will help researchers to spot active volcanoes, if they exist. The IR2 will peer through semi-transparent windows in Venus' atmosphere to see heat radiation emitted from the lower reaches of the atmosphere (1.65 to 2.32 microns). The last science instrument - Akatsuki's radio dish, will be used to actively probe the atmosphere.

Mission

Planned investigations include surface imaging with an infrared camera and experiments designed to confirm the presence of lightning and to determine whether volcanism occurs on the surface.

The budget for this mission is ¥13 billion (US$110 million) for the satellite and ¥12 billion (US$100 million) for the launch.

Public relations

There was a public relations campaign held between October 2009 and January 2010 by The Planetary Society and JAXA, to allow individuals to send their name and a message aboard *Akatsuki*. Names and messages were printed in fine letters on an aluminum plate and placed aboard *Akatsuki*. 260,214 people submitted names and messages for the mission. Around 90 aluminum plates were created for the spacecraft, including three aluminum plates in which the images of the Vocaloid Hatsune Miku and her super deformed figure Hachune Miku were printed.

Operation

Launch

The launch of Akatsuki

Akatsuki left the Sagamihara Campus on 17 March 2010, and arrived at the Tanegashima Space Center's Spacecraft Test and Assembly Building 2 on 19 March. On 4 May, *Akatsuki* was encapsulated inside the large payload fairing of the H-IIA rocket that launched the spacecraft, along with the IKAROS solar sail, on a 6-month journey to Venus. On 9 May, the payload fairing was transported to the Tanegashima Space Center's Vehicle Assembly Building, where the fairing was mated to the H-IIA launch vehicle itself. The spacecraft was launched on May 20, 2010 at 21:58:22 (UTC) from the Tanegashima Space Center.

Orbit insertion failure

Akatsuki was planned to initiate orbit insertion operations by igniting the orbital maneuvering engine at 23:49:00 on 6 December UTC. The burn was supposed to continue for 12 minutes, to an initial orbit of 180,000 – 200,000 km apoapsis / 550 km periapsis / 4 days orbital period around Venus.

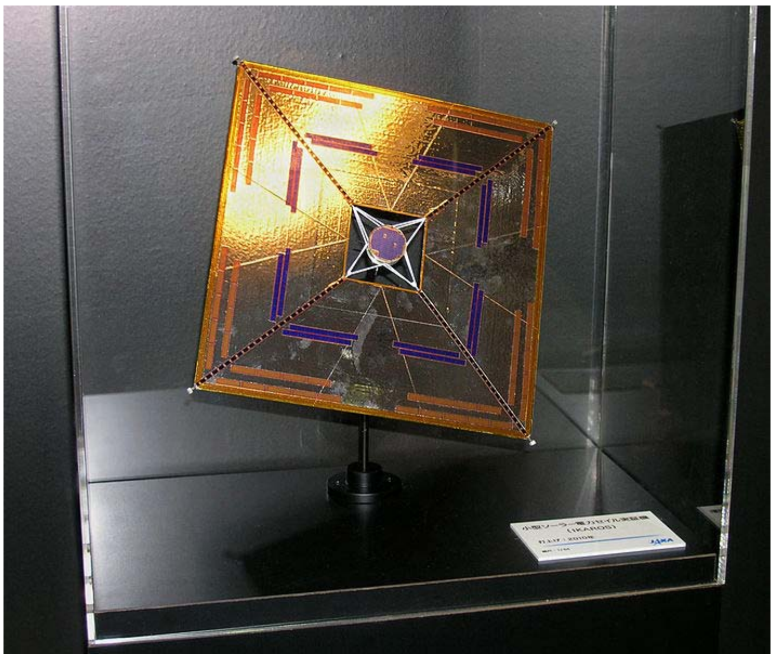
The orbit insertion maneuver was confirmed to have started on time. But after the expected blackout due to occultation by Venus, the communication with the probe did not recover as planned. The probe was found to be in safe-hold mode, spin-stabilized state with 10 minutes per rotation. Due to the low communication speed through low-gain antenna, it took a while to determine the state of probe. JAXA stated on December 8, that the probe's orbital insertion maneuver has failed. At a press conference on 10 December, officials reported that Akatsuki's engines fired for less than 3 minutes far short of what was required to enter into Venus orbit.

JAXA is developing plans to attempt another orbital insertion burn when the probe returns to Venus in 6 years. This requires placing the probe into a hibernation state to prolong its life beyond the original 4.5 year design. JAXA expressed some confidence in keeping the probe operational, pointing to reduced battery wear, since the probe is orbiting the Sun instead of its intended Venusian orbit.

Chapter 9

IKAROS

IKAROS



Model of the IKAROS spacecraft, not to scale.

Operator	JAXA
Flyby of	Venus
Satellite of	The Sun
Orbital insertion date	2010-05-21
Launch date	2010-05-20 21:58:22 UTC
Carrier rocket	H-IIA 202
Launch site	Tanegashima Space Center Tanegashima, Japan

Mission duration	~0.5 years elapsed: 7 months, and 27 days
COSPAR ID	2010-020E
Mass	315 kg

IKAROS (**Interplanetary Kite-craft Accelerated by Radiation Of the Sun**) is a Japan Aerospace Exploration Agency experimental spacecraft. The spacecraft was launched on 21 May 2010 aboard an H-IIA rocket, together with *Akatsuki* (Venus Climate Orbiter) and four other small spacecraft. IKAROS is the first spacecraft to successfully demonstrate solar-sail technology in interplanetary space.

On December 8, 2010, IKAROS passed by Venus at about 80,000 km distance, completing the planned mission successfully, and entered extended operation phase.

Purpose

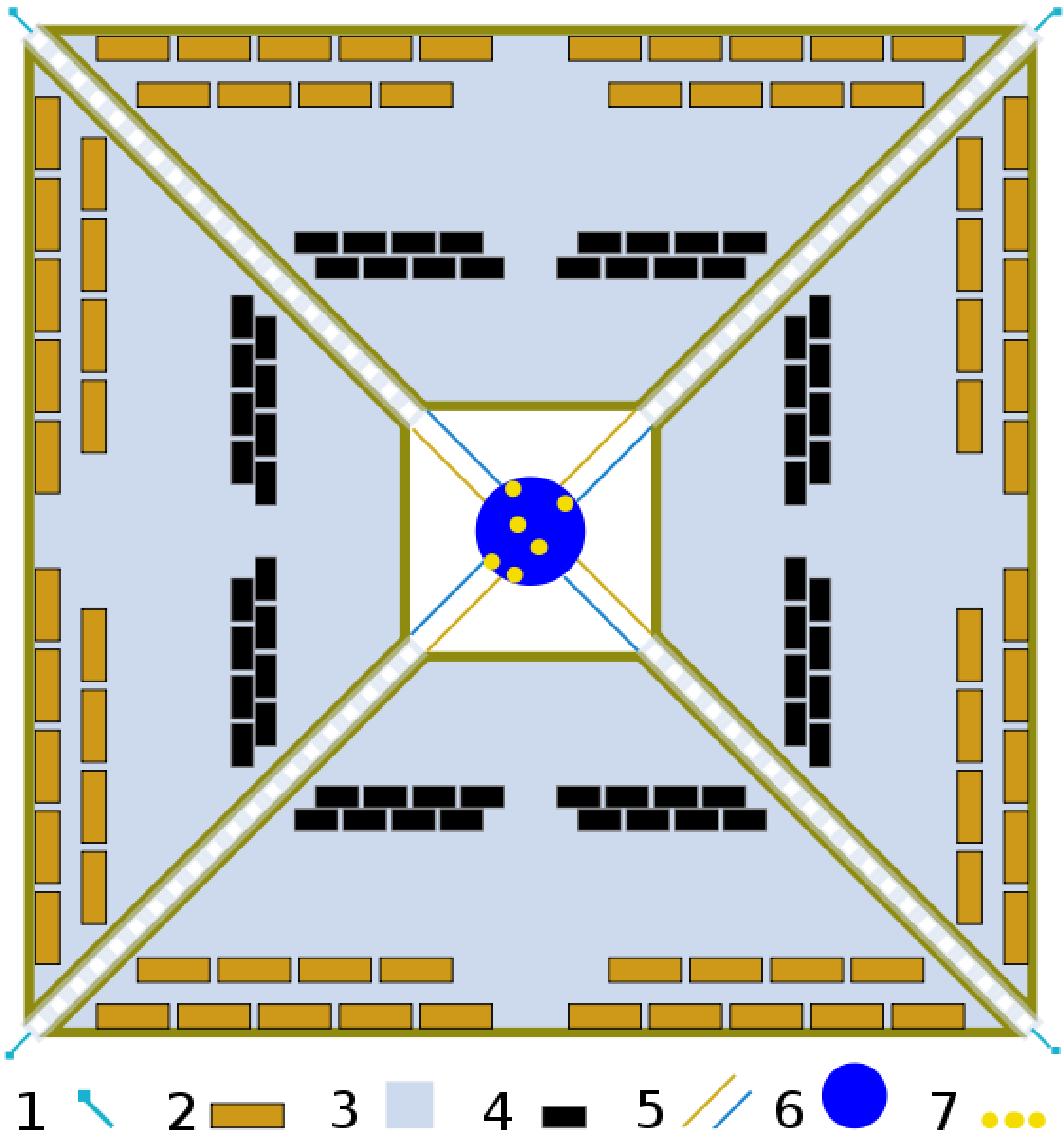
The IKAROS probe is the world's first spacecraft to use solar sailing as the main propulsion. It plans to demonstrate four key technologies (comments in parentheses refer to figure):

1. Deployment and control of a large, thin solar sail membrane (gray areas numbered 3)
2. Thin-film solar cells integrated into the sail to power the payload (black rectangles numbered 4)
3. Measurement of acceleration due to radiation pressure on the solar sail
4. Attitude control via variable reflectance liquid crystal panels (orange rectangles numbered 2)

The sail finished deploying on 10 June 2010, and is currently being tested. The final two items will be tested during the remaining six month voyage to Venus.

The mission also includes investigations of aspects of interplanetary space, such as the gamma-ray burst, solar wind and cosmic dust.

Design



IKAROS sail schematic diagram:
1 (blue square on a line) Tip mass 0.5 kg, 1 of 4
2 (orange rectangle) Liquid crystal device, 1 of 80
3 (blue square) Membrane 7.5 μm thick, 20 metres diameter
4 (black rectangle) Solar cells 25 μm thick
5 (yellow and blue lines) Tethers
6 (blue disc) Main body
7 (yellow dots) Instruments

The square sail, deployed via a spinning motion using 0.5 kg tip masses (1 in key at right), is 20 m (66 ft) on the diagonal and is made of a 7.5-micrometre (0.0075 mm) thick sheet of polyimide (3 in key at right). A thin-film solar array is embedded in the sail (4 in key at right). PowerFilm, Inc. provided the thin-film solar array. Eighty blocks of LCD panels are embedded in the sail, whose reflectance can be adjusted for attitude control (2 in key at right). The sail also contains eight dust counters on the opposite face as part of the science payload.

Mission

IKAROS was successfully launched together with *Akatsuki* (the Venus Climate Orbiter) aboard an H-IIA rocket from the Tanegashima Space Center on 21 May 2010.

IKAROS spun at 20–25 revolutions per minute and finished unfurling its sail on 11 June 2010. The craft contains two tiny ejectable cameras, DCAM1 and DCAM2. DCAM2 was used to visualise the sail after deployment on 14 July 2010.

On 9 July, JAXA confirmed that IKAROS is being accelerated by its solar sail.

If successful, IKAROS is to be followed by a 50 m (160 ft) sail, intended to journey to Jupiter and the Trojan asteroids, later in the decade.

Chapter 10

STS-131

STS-131

Mission insignia

Mission statistics

Mission name	STS-131
Space shuttle	*Discovery*
Launch pad	39A
Launch date	5 April 2010 06:21:22 EDT (10:21:22 UTC)
Landing	20 April 2010, 09:08:35 EDT (13:08:35 UTC)
Mission duration	15 days 2 hours, 47 min, 11 seconds
Number of orbits	238
Orbital altitude	Insertion: 122 nautical miles (226 km) Rendezvous: 185 nautical miles (343 km)

Orbital inclination	51.6 degrees
Distance traveled	6,232,235 miles (10,029,810 km)

Docking

Docking date	7 April 2010 07:44 UTC
Undocking date	17 April 2010 12:52 UTC
Time docked	10 days, 5 hours, 8 minutes

Crew photo

Seated: James Dutton (left) Alan Poindexter (right), Standing (l-r): Rick Mastracchio, Stephanie Wilson, Dorothy Metcalf-Lindenburger, Naoko Yamazaki (JAXA) and Clayton Anderson

Related missions

Previous mission	**Subsequent mission**
 STS-130	 STS-132

STS-131 (ISS assembly flight **19A**) was a Space Shuttle mission to the International Space Station (ISS). Space Shuttle *Discovery* launched on 5 April 2010 at 6:22 AM from Kennedy Space Center's launch pad 39A and landed at 9:08 AM on 20 April 2010 on runway 33 at the Kennedy Space Center's Shuttle Landing Facility. The mission marked the longest flight for space shuttle *Discovery*.

The primary payload was a Multi-Purpose Logistics Module loaded with supplies and equipment for the International Space Station. The mission also removed and replaced an ammonia tank assembly outside the station on the S1 truss. The mission also included several on-board payloads; this mission had the most payloads since STS-107.

Crew

Position	Astronaut
Commander	Alan Poindexter Second spaceflight
Pilot	James Dutton First spaceflight
Mission Specialist 1	Richard Mastracchio Third spaceflight EV1
Mission Specialist Educator 2	Dorothy M. Metcalf-Lindenburger First spaceflight Flight Engineer/Intra-vehicular officer
Mission Specialist 3	Stephanie Wilson Third spaceflight Lead robotics officer
Mission Specialist 4	Naoko Yamazaki, JAXA First spaceflight Load master
Mission Specialist 5	Clayton Anderson Second spaceflight EV2

Notes:

- This was the final Space Shuttle mission with a seven person crew.
- This was the final Space Shuttle mission that contains one or more "rookie" astronauts; the missions after this will have all-veteran crews.
- STS-131 was only the third mission in the Space Shuttle program to carry three female astronauts. Missions STS-40 and STS-96 were the first and the second.
- STS-131 marked the first time that two Japanese astronauts, Naoko Yamazaki from the shuttle crew, and Soichi Noguchi on the ISS, were in space together.
- With three female crew members arriving on-board *Discovery* and Expedition 23 Flight Engineer Tracy Caldwell Dyson on the ISS, the STS-131 mission marked the first time that four women were in space at one time.
- Although Naoko Yamazaki is not the last non-U.S. astronaut, she was the last Japanese astronaut to fly on the space shuttle.

Mission parameters

- **Mass:**
  - Shuttle liftoff weight: 4,521,749 pounds (2,051,031 kg)
  - Orbiter liftoff: 266,864 pounds (121,047 kg)
  - Orbiter landing: 224,957 pounds (102,039 kg)
- **Perigee:** 200 miles (320 km)
- **Apogee:** 215 miles (346 km)
- **Inclination:** 51.6
- **Period:** 90 min

Mission payload

Location	Cargo	Mass
Bays 1-2	Orbiter Docking System EMU 3008 / EMU 3017	1,800 kilograms (4,000 lb) ~260 kilograms (570 lb)
Bay 4P	Shuttle Power Distribution Unit (SPDU)	~18 kilograms (40 lb)
Bay 7S	ROEU 751A umbilical	127 kilograms (280 lb)
Bays 7-12	Leonardo (MPLM FM-1)	12,371 kilograms (27,270 lb)
Bay 13	Lightweight MPESS Carrier (LMC)	1,764 kilograms (3,890 lb)
Starboard Sill	Orbiter Boom Sensor System	382 kilograms (840 lb)
Port Sill	Canadarm	410 kilograms (900 lb)
	Total:	**15,332 kilograms (33,800 lb)**

Multi-Purpose Logistics Module *Leonardo*

The primary payload of STS-131 was the Multi-Purpose Logistics Module (MPLM) *Leonardo*. The MPLM was filled with food and science supplies for the International Space Station (ISS). The MPLM also carried the third and final Minus Eighty Degree Laboratory Freezer for ISS (MELFI), Window Orbital Research Facility (WORF), one Crew Quarters Rack, the Muscle Atrophy Resistive Exercise (MARES) rack, Resupply Stowage Racks (RSRs), as well as Resupply Stowage Platforms (RSPs).

Lightweight Multi-Purpose Equipment Support Structure Carrier

The Lightweight Multi-Purpose Equipment Support Structure Carrier (LMC) carried a refurbished Ammonia Tank Assembly (ATA) to the ISS. The refurbished ATA was removed from the Space Station and returned for use on this mission during STS-128. It was swapped with an empty tank which will ride home on the LMC.

TriDAR

This mission was the second flight of the TriDAR, a 3D dual-sensing laser camera, intended for potential use as an autonomous rendezvous and docking sensor. TriDAR provides guidance information that can be used to guide a vehicle during rendezvous and docking operations in space. TriDAR does not rely on any reference markers, such as reflectors, positioned on the target spacecraft. To achieve this, it relies on a laser based 3D sensor and a thermal imager. Geometric information contained in successive 3D images is matched against the known shape of the target object to calculate its position and orientation in real-time. The TriDAR tracked the ISS position and orientation from the shuttle during docking, undocking, and flyaround operations.

Mission background

The mission marks:

- 162nd American manned space flight
- 131st shuttle mission since STS-1
- 38th flight of *Discovery*
- 33rd shuttle mission to the ISS
- 106th post-*Challenger* mission
- 18th post-*Columbia* mission
- 35th night launch of a shuttle, 22nd night launch from launch pad 39A
- 2nd "descending node" entry since 2003

Shuttle processing

Space Shuttle *Discovery* was moved from its hangar in the Orbiter Processing Facility (OPF) 3 to the nearby Vehicle Assembly Building on 22 February 2010. The rollover was completed around 10:30 EST. According to NASA, the rollover occurred a day earlier than announced to take advantage of favorable weather in advance of poor conditions forecasted on the next day.

An earlier plan to move *Discovery* into the VAB on 12 February 2010 was delayed because of cold weather at the Kennedy Space Center. For the rollover, temperatures in the Vehicle Assembly Building (VAB) had to be above 45 °F (7 °C) for more than twelve hours because *Discovery* was not attached to any heating purges to protect its systems from potential damage from the cold.

Space shuttle *Discovery* began its trip, known as the rollout, to launch pad 39A at 23:58 EST on 2 March 2010. The complete shuttle stack and mobile launch platform were secured to the launch pad 39A structure at 6:49 EST on 3 March 2010. The 3.4 mi (5.5 km) trek took 6 hours 51 minutes to complete. The rollout was delayed 24 hours by the threat of lightning from a passing cold front. That weather moved away, and the stiff wind gusts blowing on Florida's Space Coast on the next day were not a factor for the rollout. Ahead of the rollout, engineers noticed some damage caused by birds to the External Tank (ET-135), which was repaired inside the VAB. Birds had managed to reach the tank, and pecked away at the Thermal Protection System (TPS) foam.

Space Shuttle *Discovery* rolls toward the Vehicle Assembly Building

Space Shuttle *Discovery* at Launch Pad 39A

International Space Station (bottom right) passes over the Cape 15 minutes prior to launch.

Mission timeline

April 5 (Flight Day 1 - Launch)

Space Shuttle *Discovery* lifted off successfully at 06:21 EDT. After the eight and a half minute ride to space, *Discovery's* seven person crew began configuring the orbiter from a launch vehicle to an orbital vehicle. Commander Alan Poindexter and pilot Jim Dutton, with help from mission specialist 2 Dorothy Metcalf-Lindenburger, also performed a series of engine firings or burns to adjust their speed and refine their path to the International Space Station. While the engine burns were going on, the rest of the crew opened the payload bay doors, set up the computers and K_u band antenna. The antenna suffered a failure during normal checkout and setup on orbit. Due to the failure, the normal downlink of imagery of the external tank was not completed. The crew onboard will monitor the inspections of the thermal protection system (TPS) in real time and will note any spots of interest and let the ground know while downlinking the imagery after docking. The dish antenna also serves as a radar antenna, measuring the distance to the space station.

The failed K_u band dish antenna

Discovery lifts off Launch Pad 39A

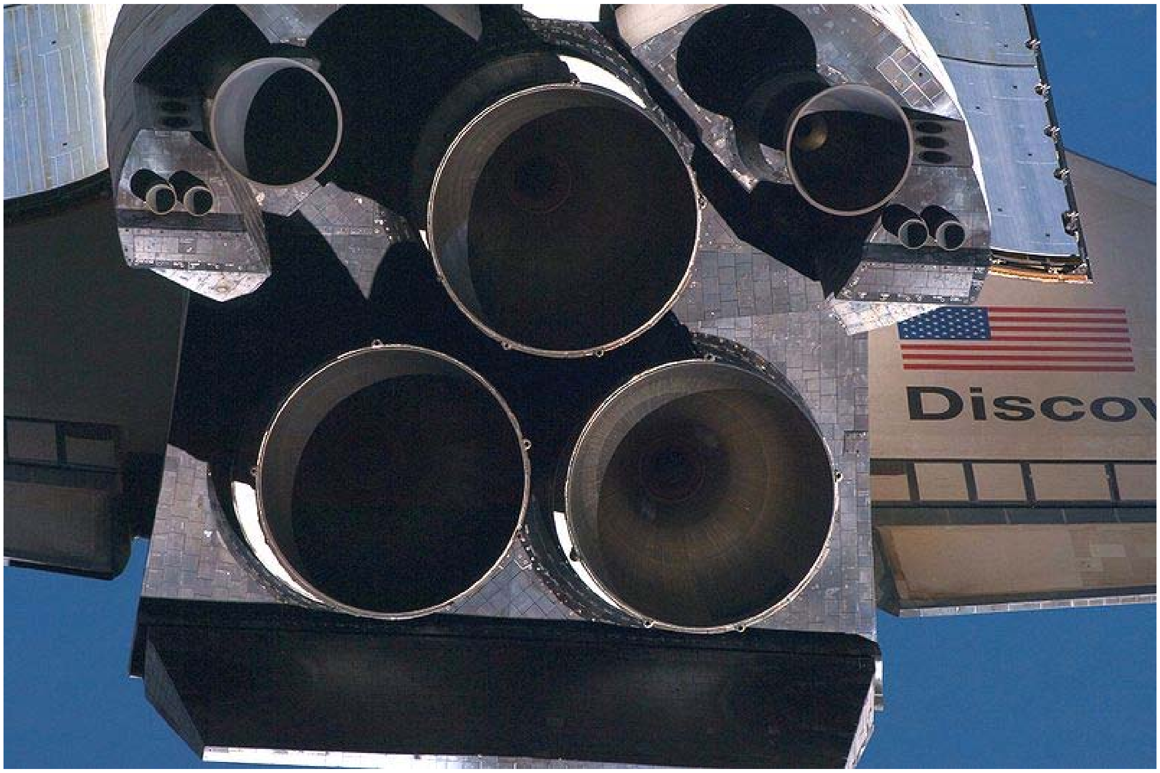
Space Shuttle Discovery launches from Kennedy Space Center, April 5, 2010

April 6 (Flight Day 2 - Inspections)

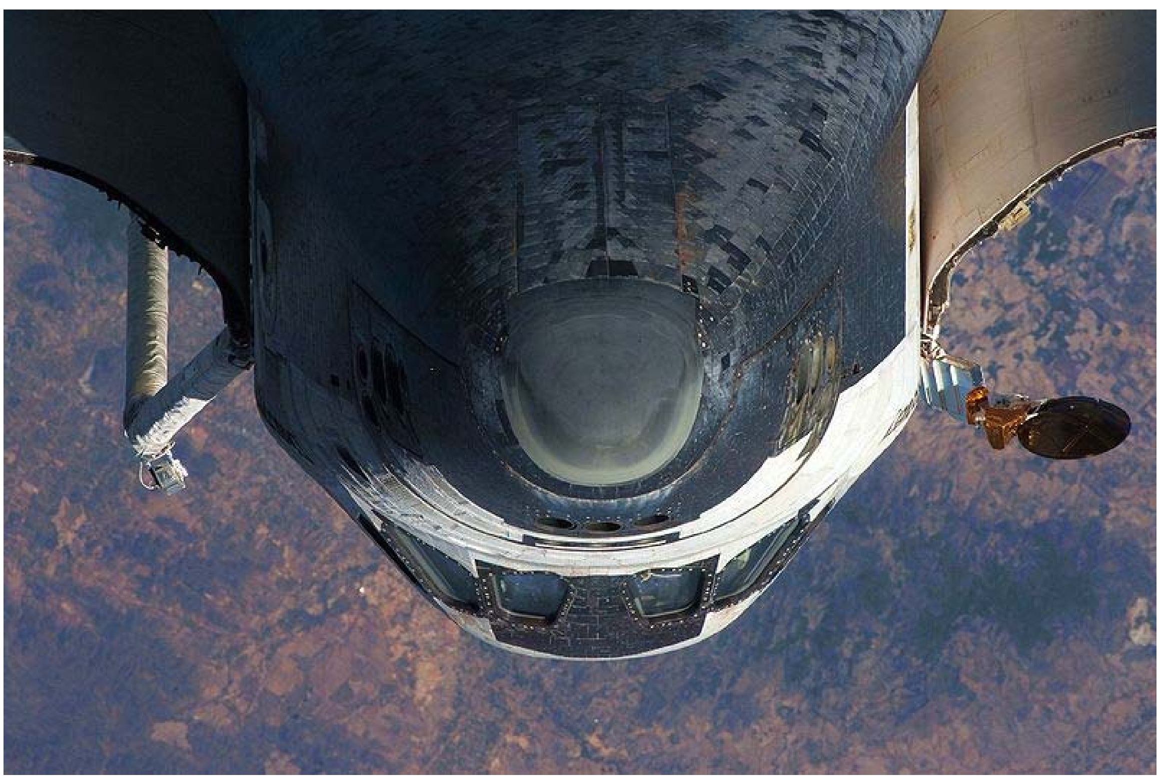
The seven person crew of STS-131 was awakened to begin their first full day in space on Flight Day 2. Due to the lack of K_u-band communication, changes to the crews daily plan were read up for them to write out. After their post sleep activities, commander Alan Poindexter and pilot Jim Dutton fired *Discovery*'s Orbital Maneuvering System (OMS) engines to correct and further refine the shuttle's path to the ISS. Astronauts Naoko Yamazaki and Dorothy Metcalf-Lindenburger began activating and checking out the Shuttle Remote Manipulator System (SRMS) also known as the Canadarm. While Metcalf-Lindenburger and Yamazaki were working with Canadarm, Stephanie Wilson was getting equipment together and set up to record the inspections of the shuttle's heat shield. The inspections were recorded so they could be downlinked to the ground once docked to the ISS. Once all that work was done, commander Poindexter and pilot Dutton joined Metcalf-Lindenburger, Yamazaki, and Wilson to conduct the inspection of the shuttle's heat shield. While the inspection was going on, Rick Mastracchio and Clayton Anderson were on the mid-deck of *Discovery* checking out the Extravehicular Mobility Units (EMU) and getting them ready for their three spacewalks. The last portion of the crew day was spent preparing and checking out all of the tools used during rendezvous.

April 7 (Flight Day 3 - Docking)

Space shuttle *Discovery* successfully docked with the space station at 07:44 UTC (03:44 EDT) on 7 April 2010 as the two spacecraft sailed 220 miles above the Caribbean. The crew performed six successful engine firings to set up the on-time docking. Prior to docking commander Poindexter guided *Discovery* through the standard Rendezvous Pitch Maneuver (RPM). Station commander Oleg Kotov and flight engineer T.J. Creamer took more than 350 photos of *Discovery's* heat shield. Once *Discovery* docked to the International Space Station (ISS), a series of leak checks were done on both sides of the hatch by the shuttle and station crews. The hatches between the two vehicles were opened at 09:11 UTC (05:11 EDT), which was 30 minutes earlier than planned. Once the hatches were opened the STS-131 crew got a safety briefing from the station crew, then began to transfer items that would be needed for later in the day and early on flight day 4. Two items that were transferred were the two EMUs that will be used for the three spacewalks. The crew also completed a grapple of the Orbiter Boom Sensor System (OBSS) with the Space Station Remote Manipulator System (SSRMS) also known as Canadarm2. Once the OBSS was grappled it was unberthed from the starboard sill of the space shuttle payload bay, and handed off to the SRMS. Throughout the day, after docking to the station, the shuttle crew began downlinking all of the inspection video from flight day 2, and launch imagery and video.



Aft portion of Discovery, including the three main engines, during the RPM



View of the underside of the crew cabin of Discovery during the RPM

Discovery approaches the Space Station for docking

Kibo, photographed by a crew member while Discovery was docked with the station

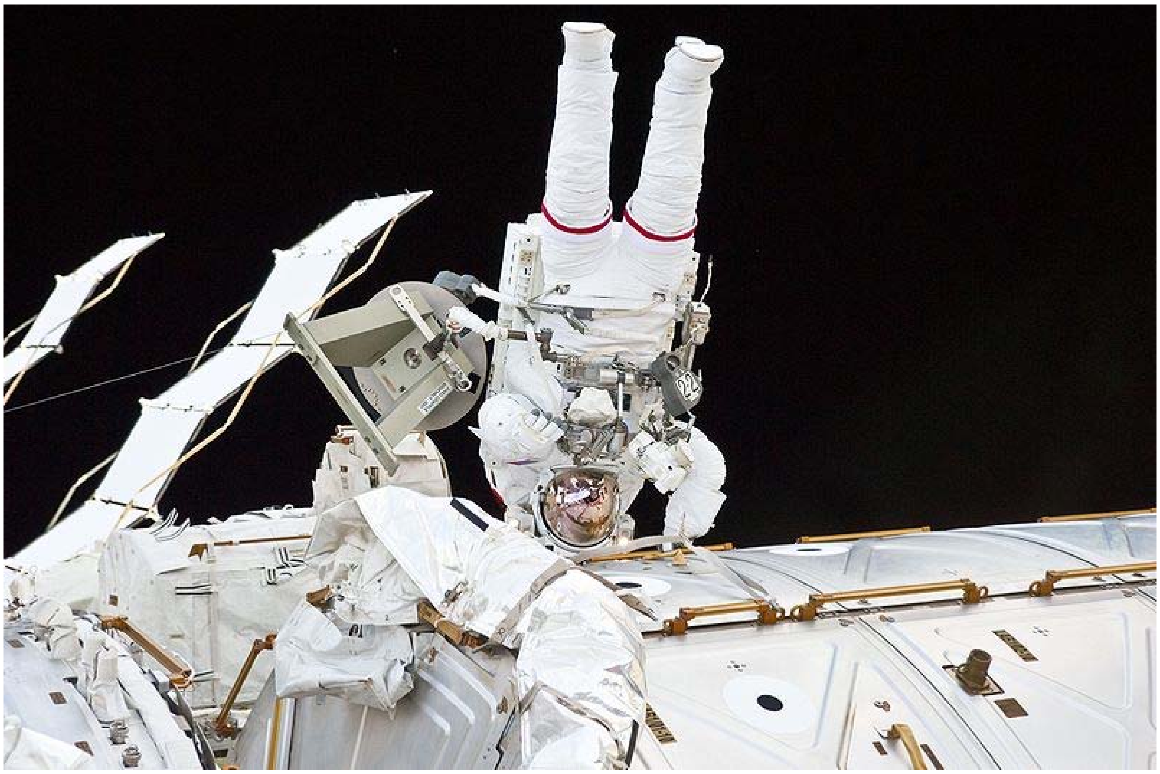
April 8 (Flight Day 4 - MPLM ingress)

On flight day 4 Stephanie Wilson and Naoko Yamazaki grappled and berthed the Multi-purpose Logistics Module (MPLM) *Leonardo*. The MPLM was berthed to the station at 04:24 UTC (00:24 EDT). The hatches were opened by station flight engineer Soichi Noguchi and shuttle mission specialist Clayton Anderson at 11:58 UTC (07:58 EDT). The joint STS-131/Expedition 23 crews began transferring cargo from the MPLM, with the first item being a Rate Gyro Assembly (RGA) which will be replaced on the first spacewalk of the mission. During flight day 4 commander Alan Poindexter did several in-flight interviews. Commander Poindexter was joined by mission specialists Rick Mastracchio and Stephanie Wilson. The interviews were with the Tom Joyner Radio Show, WVIT-TV and Fox News Radio. At the end of the day Mastracchio and Anderson entered the Quest airlock and begin breathing pure oxygen for an hour, while the atmospheric pressure inside the airlock was lowered to 10.2 psi. This procedure is known as the pre-breathe protocol and is done before every spacewalk, to purge nitrogen from the blood stream and prevent the decompression sickness.

April 9 (Flight Day 5 - EVA 1)

Flight day 5 saw the completion of the first spacewalk by Rick Mastracchio and Clayton Anderson. The pair released the new ammonia tank assembly for transfer to station for installation on a later spacewalk. They also removed an experiment from outside on the

Kibo Exposed Facility, replaced a Rate Gyro Assembly (RGA) and performed several get-ahead tasks. The spacewalking pair was assisted by the SSRMS which was operated by pilot Jim Dutton and mission specialist Stephanie Wilson. While the spacewalk was going on, Naoko Yamazaki was assisted by commander Alan Poindexter, and the Expedition 23 crew to move several of the large science racks from the MPLM *Leonardo* to their new location on the ISS.



Mastracchio during EVA 1

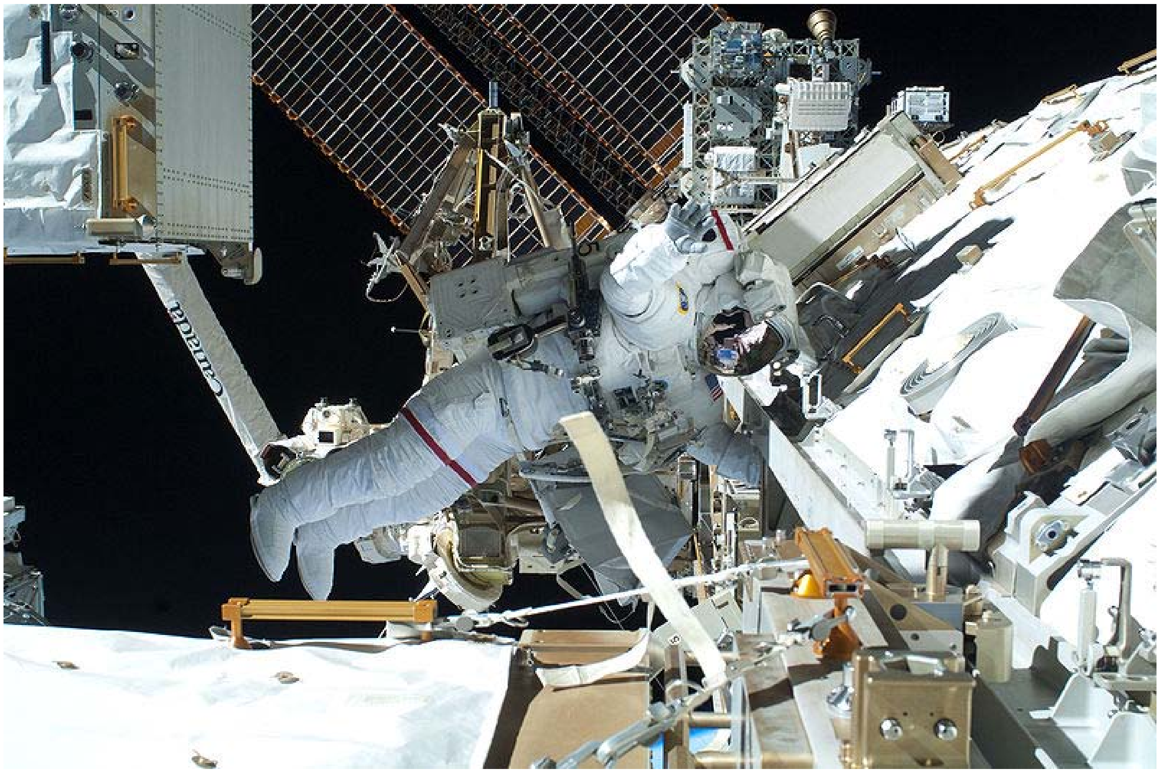
April 10 (Flight Day 6 - Transfers)

Flight day 6 was dedicated to transferring supplies from the MPLM *Leonardo* and the space shuttle mid-deck. The crews transferred the Windows Observational Research Facility (WORF) to the Destiny lab. Mission specialist Naoko Yamazaki, along with flight engineer Soichi Noguchi also transferred the Express Rack 7 (ER7) to its final location. During the crews morning, a smoke alarm sounded in the Russian segment of the station, which prompted the joint crew to move into emergency procedures. However the alarm was false and was cleared within a couple of minutes and all normal work resumed. Mission specialists Clay Anderson, Rick Mastracchio and Stephanie Wilson conducted in-flight interviews with Nebraska Public Radio, CBS Newspath and Radio Network and KETV-TV in Omaha, Nebraska. Later in the day commander Alan Poindexter, pilot Jim Dutton and mission specialist Dorothy Metcalf-Lindenburger talked with students at the Naval Postgraduate School in Monterey, California. At the end of the crews work day, the joint crew got together and reviewed the procedures for the second spacewalk. After the procedures review spacewalkers Clay Anderson and Rick Mastracchio entered the Quest airlock, closed the hatch and lowered the inside pressure to 10.2 psi. The pair also breathed pure oxygen for an hour while the pressure was being lowered.

Dorothy Metcalf-Lindenburger inside the MPLM Leonardo

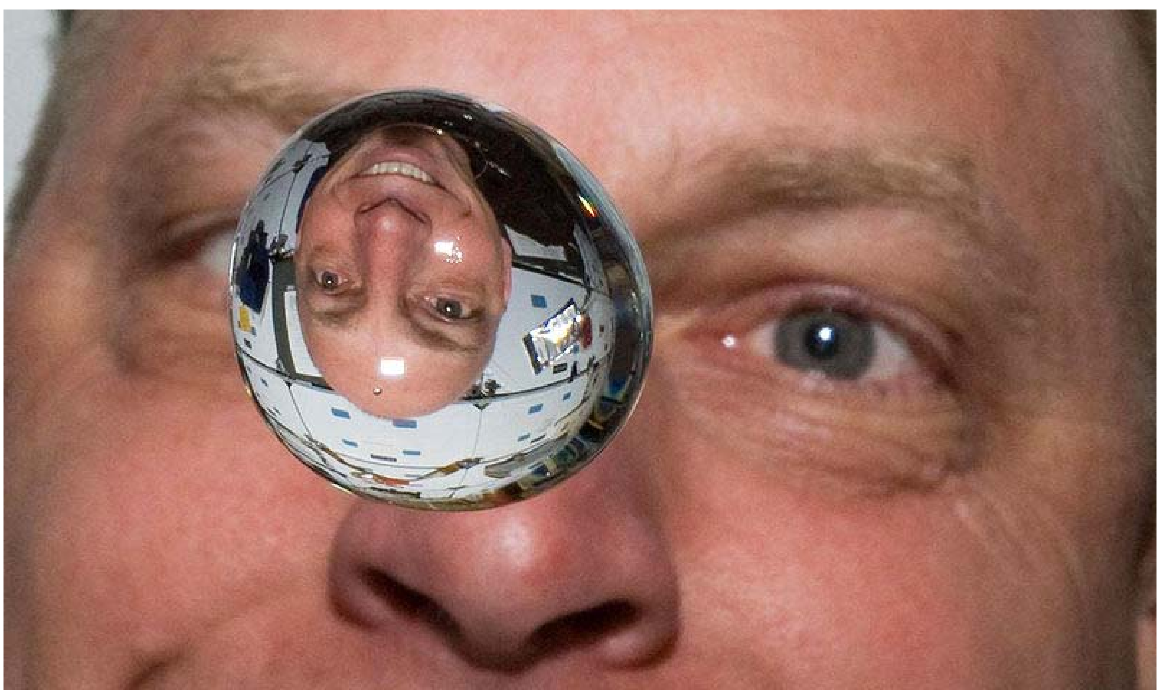
April 11 (Flight Day 7 - EVA 2)

On flight day 7 astronauts Clay Anderson and Rick Mastracchio performed their second spacewalk of the STS-131 mission. Mastracchio and Anderson exited the airlock at 05:30 UTC, a full 45 minutes ahead of the planned time, and spent 7 hours and 26 minutes outside the ISS. The pair removed the old Ammonia Tank Assembly (ATA) from the S1 truss and installed the new ATA. Anderson and Mastracchio ran into a small problem when one of the four bolts that holds the tank in place wouldn't turn. They loosened the other three and tried them all again and the fourth bolt was successfully tightened. The two spacewalkers helped guide the SSRMS to temporarily stow the old ATA on the truss structure. The new ATA had its electrical connections made, but the fluid connections were deferred until the third spacewalk since the EVA was behind the time-line. Mastracchio and Anderson also installed two radiator grapple fixture stowage beams on the P1 truss. While Anderson and Mastracchio were outside, members of the STS-131 crew continued transferring items from space shuttle *Discovery*'s mid-deck and the MPLM *Leonardo*. Overall, the crew had completed about half of the transfer work.



Mastracchio during EVA 2

April 12 (Flight Day 8 - Off duty)



Astronaut Clayton Anderson playing with a water bubble

The joint STS-131/Expedition 23 crews had the morning off on flight day 8. After their morning off the crews continued their transfer activities, which are more than seventy percent complete. The crews also conducted several PAO events, including VIP events with Roscosmos, Russian president Dmitry Medvedev, RSC Energia, the Japanese Aerospace Exploration Agency (JAXA), Japanese students, astronaut Mamoru Mohri, and Japanese dignitaries. Later commander Alan Poindexter, pilot Jim Dutton and mission specialists Dorothy Metcalf-Lindenburger and Stephanie Wilson participated in an in-flight interview with several American media outlets including Fox News, ABC World News and MSNBC. While the PAO events were going on, Rick Mastracchio and Clay Anderson were preparing the spacesuits and tools they will use for the third and final spacewalk. Later in the day the pair will have a procedures review with other members of the ISS and shuttle crews. After the review, they will enter the airlock, close the hatch and lower the pressure to 10.2 psi and breathe pure oxygen for their campout.

April 13 (Flight Day 9 - EVA 3)

On flight day 9, Rick Mastracchio and Clay Anderson completed the third and final spacewalk of the STS-131 mission. Their tasks included hooking up the ammonia and nitrogen lines to the new Ammonia Tank Assembly (ATA), installing the old ATA in the shuttle's payload bay, retrieving some Micro-Meteoroid Orbital Debris (MMOD) shields, bolting a grapple bar (which had been removed from the old ATA) onto the new ATA, and preparation of some cables on the Z1 truss and tools to be used during STS-132. During the installation of the old ATA in *Discovery'*s payload bay, the spacewalkers had some problems securing a bolt on the ATA to the LMC. The spacewalk took 6 hours and 24 minutes, bringing the total EVA time to 20 hours and 19 minutes. While the EVA was going on, commander Alan Poindexter and mission specialist Naoko Yamazaki continued transferring items from the MPLM to the ISS. Transfer is more than seventy-five percent complete.

Mastracchio & Anderson working in Discovery's aft payload bay during EVA 3

Clayton Anderson during EVA 3

April 14 (Flight Day 10 - Final transfers/off duty)

The crew of STS-131 continued with transfer activities on the morning of flight day 10. The morning was devoted largely to transferring items to the MPLM *Leonardo*. There are only a few items awaiting transfer to space shuttle *Discovery*'s mid-deck left. The crew enjoyed an hour long mid-day meal with the Expedition 23 crew. The entire joint crew took part in a crew photo, which was followed by a joint crew news conference with U.S., Russian and Japanese media. Later in the day commander Alan Poindexter, mission specialists Dorothy Metcalf-Lindenburger, Stephanie Wilson and Clayton Anderson took time out to talk with students from Eastern Guilford High School in Gibsonville, North Carolina and with third and fourth graders from that school district. The majority of the crews afternoon was spent off duty.

S131E010080

Naoko Yamazaki eats a snack in the Kibo laboratory

STS-131 and Expedition 23 crew members gather for a group portrait

April 15 (Flight Day 11 - MPLM unberthing)

On flight day 11 the MPLM *Leonardo*s hatches were closed at 07:38 UTC (03:38 EDT) and the MPLM was unberthed from the nadir or earth facing port of the Harmony node at 20:24 UTC (16:24 EDT). It was placed in a low hover, about 3 feet (0.91 m) above shuttle *Discovery'*s payload bay. This was done because the MPLM was unberthed from *Harmony* later than planned. The delay in unberthing was caused by a set of bolts on the Common Berthing Mechanism (CBM) getting stuck due to a broken pin. The crew will finish putting *Leonardo* in the payload bay on flight day 12, prior to the docked late inspection. The crews conducted some transfer operations between the ISS and shuttle mid-deck, which brings the overall transfer operations to ninety-four percent complete for the mission.

April 16 (Flight Day 12 - Late inspection)

The MPLM *Leonardo* secured in Discovery's payload bay

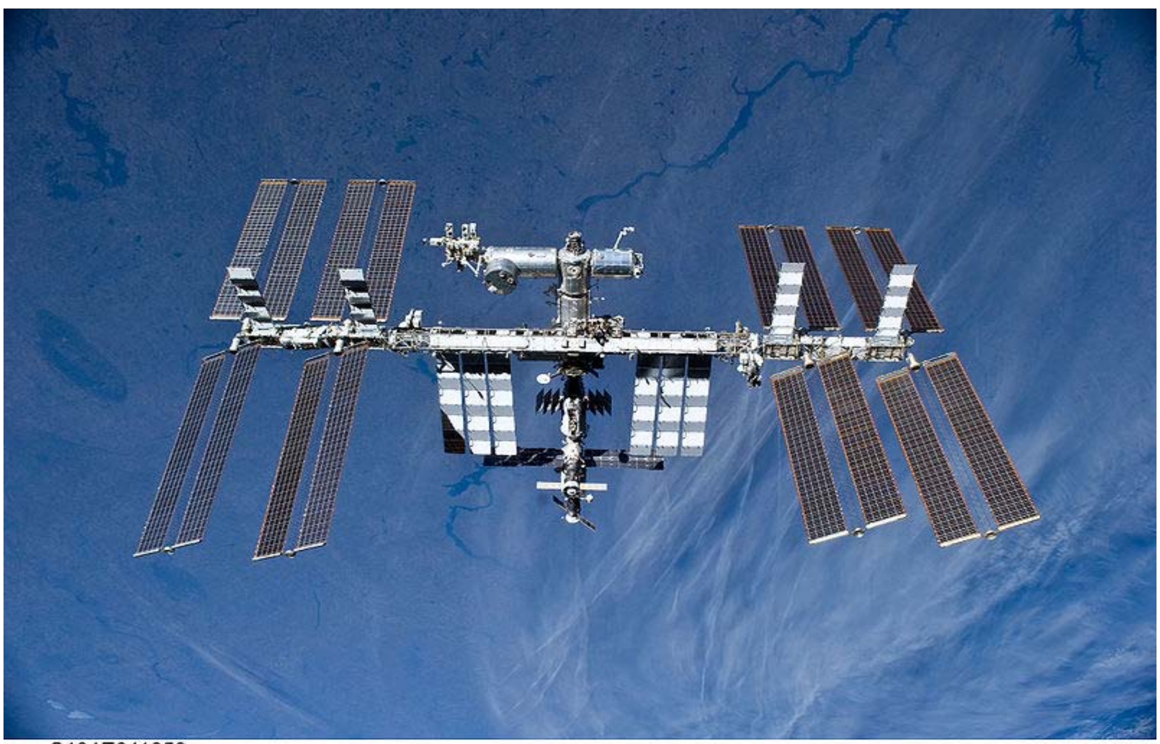
On flight day 12, the crew of space shuttle *Discovery* secured the MPLM *Leonardo* in the payload bay for return to earth. Mission specialist Dorothy Metcalf-Lindenburger activated the latches to secure *Leonardo* in the payload bay at 07:15 UTC (03:15 EDT). After *Leonardo* was secured, Metcalf-Lindenburger, pilot Jim Dutton began the late inspection of *Discovery'*s heat shield. The pair were joined by commander Alan Poindexter and mission specialist Naoko Yamazaki to complete the inspection of the shuttle's Reinforced Carbon-Carbon (RCC) panels on the wings and nose and the heat-resistant tiles. The scan which takes about 7 hours was completed 3 hours ahead of schedule, and was done while still docked to the International Space Station (ISS) due to the loss of the shuttles K_u-Band antenna.

April 17 (Flight Day 13 - Undocking)

Space Shuttle *Discovery* successfully undocked from the International Space Station (ISS) at 12:52 UTC (08:52 EDT). *Discovery* was docked to the ISS for 10 days, 5 hours and 8 minutes. After *Discovery* departed from the ISS, pilot Jim Dutton took control of the shuttle and performed a fly around of the space station. The undocking was preceded by a farewell ceremony, where shuttle commander Alan Poindexter and station commander Oleg Kotov said farewells on behalf of their crews. After undocking the shuttle crew stowed the Orbiter Boom Sensor System (OBSS) and the Shuttle Remote Manipulator System (SRMS) since they will not be needed for the rest of the flight. The crew was also informed that *Discovery's* heat shield was cleared for re-entry in to Earth's atmosphere.

Discovery separates from the Space Station

The underside of *Discovery* soon after post-undocking relative separation



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ISS seen from *Discovery* after undocking

April 18 (Flight Day 14 - Landing prep)

On flight day 14, the crew of space shuttle *Discovery* began their final preparations for landing. The crew packed and stowed away items they no longer need for the rest of the flight. Throughout the day commander Alan Poindexter and pilot Jim Dutton completed a series of checkouts of flight systems. These checks include 2 firings of the Reaction Control System (RCS) jets and a test of the Flight Control System (FCS). Once those checkouts were complete the pair began doing communications checkouts with the Merritt Island tracking station and tracking stations at the White Sands Space Harbor in New Mexico and Dryden Flight Research Center at Edwards Air Force Base. The crew also took time out of their day to conduct an in-flight interview with WBZ-AM in Boston, Massachusetts, the Associated Press and KEZI-TV in Eugene, Oregon.

April 19 (Flight day 15 - First landing opportunity)

The crew of STS-131 awoke for flight day 15 and began their deorbit preparations. These preparations include closing the payload bay doors, activating the Flash Evaporator System (FES) and getting into their Advanced Crew Escape Suits (ACES). The crew got as far as "fluid loading", where the crew consumes a set quantity of fluids to counteract the effects of gravity, in their deorbit preps. The crew was informed of the one orbit wave off about one hour prior to the deorbit burn. After the crew was told of the wave off, they held in their procedures to see if they would be given a go for the second landing opportunity. However, they were not given a go for the second chance and the crew began backing out of their deorbit preps. Both landing chances were waved off due to bad weather at the Kennedy Space Center.

April 20 (Flight day 16 - Landing)

Space shuttle Discovery landed at 09:08 EDT (13:08 UTC) on runway 33 at Florida's Kennedy Space Center following a two-week mission in space.

Discovery lands on runnaway 33 at KSC ending the STS-131 mission

Crew on the tarmac

Flyover cities during the landing

Spacewalks

At least three spacewalks were planned for this mission. The main objectives for the three EVAs were as follows:

EVA	Spacewalkers	Start (UTC)	End (UTC)	Duration
EVA 1	Rick Mastracchio Clayton Anderson	9 April 05:31	9 April 11:58	6 hours 27 minutes
	The crew inside used the station's robotic arm to remove a new ammonia tank from shuttle's payload bay and temporarily stow it on the station. The spacewalkers then retrieved a seed experiment from outside the Japanese laboratory, installed a grapple bar to the new ammonia tank on the station's truss and replaced a failed gyroscope that is part of the station's navigation system, along with several get-ahead tasks.			
EVA 2	Mastracchio Anderson	11 April 05:30	11 April 12:56	7 hours 26 minutes
	Crew members, using the station's arm, removed an empty ammonia tank from the station's truss and temporarily stowed it on an equipment cart. The			

	new tank was then installed and electrical connections were made to it. The station's arm then temporarily stowed the old tank on another part of the station's structure until the mission's third spacewalk.			
	Mastracchio Anderson	13 April 06:14	13 April 12:36	6 hours 24 minutes
EVA 3	Using the station's arm, the crew moved the old tank into the shuttle's payload bay for return to Earth. The spacewalkers also removed a grapple bar from the old ammonia tank and attached it to the new one. The pair then relocated a foot restraint and some tools and prepared some cables for the STS-132 mission.			

Wake-up calls

NASA began a tradition of playing music to astronauts during the Gemini program, which was first used to wake up a flight crew during Apollo 15. Each track is specially chosen, often by their families, and usually has a special meaning to an individual member of the crew, or is applicable to their daily activities.

Flight Day	Song	Artist	Played for
Day 2	"Find Us Faithful"	Steve Green	Clay Anderson
Day 3	"I Will Rise"	Chris Tomlin	Jim Dutton
Day 4	"Hato to Shōnen" (The Pigeons and a Boy)	Joe Hisaishi	Naoko Yamazaki
Day 5	"Defying Gravity"	Idina Menzel & Kristen Chenoweth	Dorothy Metcalf-Lindenburger
Day 6	"We Weren't Born to Follow"	Bon Jovi	Rick Mastracchio
Day 7	"Stairway To The Stars"	Ella Fitzgerald	Stephanie Wilson
Day 8	"Because We Believe"	Andrea Bocelli	Alan Poindexter
Day 9	"Galileo"	Indigo Girls	Dorothy Metcalf-Lindenburger
Day 10	"The Miracle of Flight"	Mike Hyden	Clay Anderson
Day 11	"The Earth in the Color of Lapis Lazuli"	Seiko Matsuda	Naoko Yamazaki
Day 12	Opening theme to Stargate SG-1	Joel Goldsmith	Rick Mastracchio
Day 13	"Joy"	Newsboys	Jim Dutton
Day 14	"What A Wonderful World"	Louis Armstrong	Stephanie Wilson
Day 15	"Star Spangled Banner"		Alan Poindexter

Day 16	"On The Road Again"	Willie Nelson	The entire crew

Chapter 11

STS-132

STS-132

Mission insignia

Mission statistics

Mission name	STS-132
Space shuttle	*Atlantis*
Launch pad	39A
Launch date	14 May 2010, 14:20 EDT (18:20 UTC)
Landing	26 May 2010, 08:49:18 EDT (12:49 UTC)
Mission duration	11days 18hours 29minutes 09seconds
Number of orbits	186
Orbital altitude	Insertion: 122 nautical miles (226 km) Rendezvous: 190 nautical miles (350 km)

Orbital inclination	51.6 degrees
Distance traveled	4,879,978 miles (7,853,563 km)
	Docking
Docking date	16 May 2010, 14:28 UTC
Undocking date	23 May 2010, 15:22 UTC
Time docked	7 days 1 hour 1 minute

Crew photo

Sitting: Ken Ham (center), Garrett Reisman (left), Stephen Bowen (Right),

Standing: Michael Good, Tony Antonelli, Piers Sellers

Related missions

Previous mission	**Subsequent mission**
 STS-131	 STS-133

STS-132 (ISS assembly flight **ULF4**) was the most recent Space Shuttle mission, which docked with the International Space Station on 16 May 2010. It was launched from the Kennedy Space Center on 14 May 2010. The primary payload was the Russian *Rassvet* Mini-Research Module along with an Integrated Cargo Carrier-Vertical Light Deployable (ICC-VLD). Space Shuttle *Atlantis* landed at the Kennedy Space Center on 26 May 2010.

STS-132 is scheduled to be the final flight of *Atlantis* provided that the STS-335/STS-135 Launch On Need rescue mission is not flown.

Crew

Position	Crewmember
Commander	Kenneth Ham Second spaceflight
Pilot	Dominic A. "Tony" Antonelli Second spaceflight
Mission Specialist 1	Garrett Reisman Second spaceflight EV1
Mission Specialist 2	Michael T. Good Second spaceflight Flight Engineer/EV3
Mission Specialist 3	Stephen G. Bowen Second spaceflight EV2
Mission Specialist 4	Piers Sellers Third spaceflight Loadmaster/Lead robotics officer

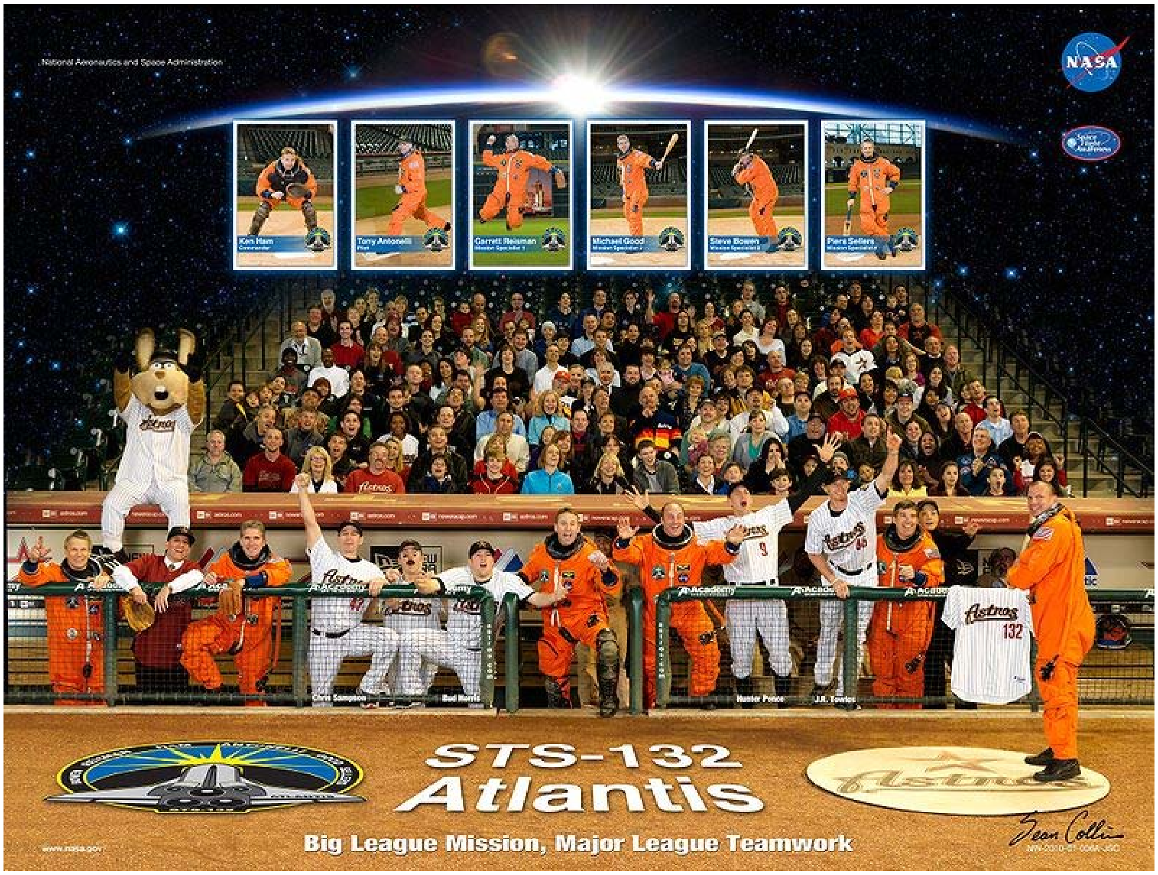
On 11 August 2009, Karen Nyberg was replaced by Michael Good as Mission Specialist 1 due to a temporary medical condition.

Crew seat assignments

Seats 1–4 are on the Flight Deck. Seats 5–7 are on the Middeck.

Seat	Launch	Landing
S1	Kenneth Ham	Kenneth Ham
S2	Dominic Antonelli	Dominic Antonelli
S3	Garrett Reisman	Piers Sellers
S4	Michael Good	Michael Good
S5	Stephen Bowen	Stephen Bowen
S6	Piers Sellers	Garrett Reisman

Mission parameters



Mission poster

- **Mass:**
    - *Shuttle liftoff weight:* 4,519,769 pounds (2,050,133 kg)
    - *Orbiter/payload liftoff weight:* 263,100 pounds (119,300 kg)
    - *Orbiter/payload landing weight:* 209,491 pounds (95,024 kg)
    - *Payload weight:* 26,615 pounds (12,072 kg)
- **Perigee:** 208 miles (335 km)
- **Apogee:** 223 miles (359 km)
- **Inclination:** 51.6°
- **Period:** 91 min

Mission payload

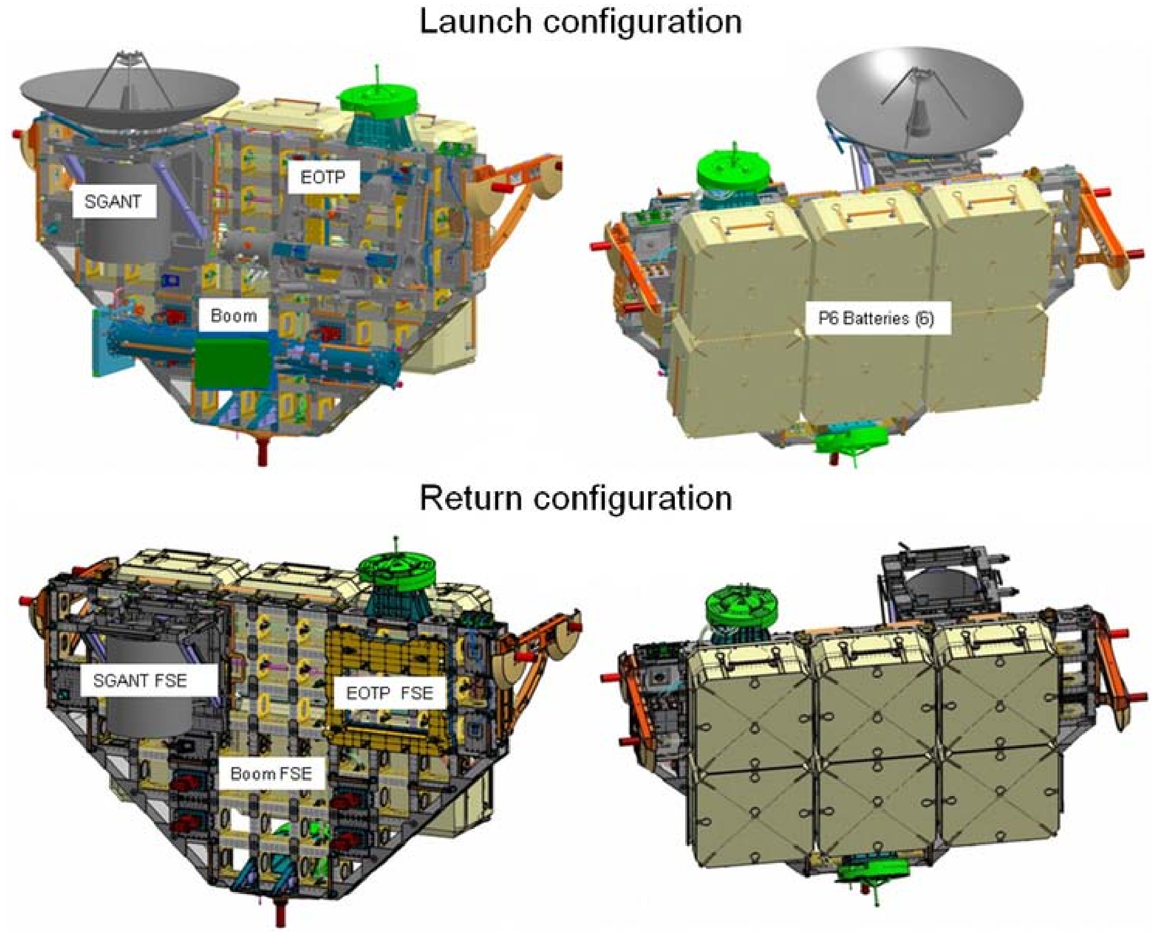
Location	Cargo	Mass
Bays 1-2	Orbiter Docking System EMU 3004 / EMU 3011 / EMU 3018	1,800 kilograms (4,000 lb) ~390 kilograms (860 lb)
Bay 3P	Shuttle Power Distribution Unit (SPDU)	~17 kilograms (37 lb)
Bay 5P	Power & Data Grapple Fixture (PDGF)	~71 kilograms (160 lb)
Bays 6-7	ICC-VLD carrier -6 Battery ORUs -SGANT antenna -EOTP platform	1,913 kilograms (4,220 lb) 1,020 kilograms (2,200 lb) 293 kilograms (650 lb) 191 kilograms (420 lb)
Bay 10P	ROEU 755 umbilical	90 kilograms (200 lb)
Bays 9-13	Rassvet Mini-Research Module 1 -Nauka Airlock -Nauka Radiator -ERA Elbow Joint -ERA Work Platform	6,295 kilograms (13,880 lb) 900 kilograms (2,000 lb) 570 kilograms (1,300 lb) 150 kilograms (330 lb) 100 kilograms (220 lb)
Starboard Sill	Orbiter Boom Sensor System	382 kilograms (840 lb)
Port Sill	Canadarm	410 kilograms (900 lb)
	Total:	**14,592 kilograms (32,170 lb)**

Mini-Research Module 1 (MRM 1)

STS-132 carried the Russian Rassvet Mini-Research Module 1 to the International Space Station. *Rassvet* means "dawn" in Russian. The module was built by Russian aerospace company Energia. Rassvet arrived at the Kennedy Space Center (KSC) aboard an Antonov 124 cargo plane on 17 December 2009 at about 13:00 EST. After it was unloaded from the Antonov, the module was transported to an Astrotech processing bay in Cape Canaveral to undergo preparations for launch.

An airlock and radiation heat exchanger to be used for outfitting the Russian *Nauka* Module (to be launched in 2012), a spare elbow part of the European Robotic Arm (ERA) and a portable work platform for science hardware for performing experiments in outer space were externally mounted on Rassvet in its launch configuration. Russian and US cargo to be delivered will also be accommodated inside the module. The volume for cargo and science inside MRM1 is 5 cubic meters. Rassvet was outfitted with ISS standard grapple fixtures that allowed the module to be unloaded from the payload bay of *Atlantis* using the station's robotic arm.

Integrated Cargo Carrier-Vertical Light Deployable (ICC-VLD)



ICC-VLD launch and return configurations

Also on board *Atlantis* will be the Integrated Cargo Carrier-Vertical Light Deployable (ICC-VLD) pallet holding a Ku-band Space to Ground Antenna (SGANT), SGANT boom assembly, Enhanced Orbital replacement Unit (ORU) Temporary Platform (EOTP) for the Canadian Dextre robotic arm extension, Video and Power Grapple fixtures (PVGF) and six new battery ORUs. The six new batteries will replace older ones on the P6 truss of the ISS. The old batteries will be placed on the ICC-VLD pallet for return to Earth. The EOTP was built by MacDonald, Dettwiler and Associates Ltd. (MDA) of Brampton, Ontario, Canada, for NASA.

The ICC pallet is constructed of aluminum. It is approximately 8 feet (2.4 m) long, 13 feet (4.0 m) wide and 10 inches thick. The empty weight of the pallet is 2,645 pounds. The total weight of ICC–VLD and the ORUs is approximately 8,330 pounds. ICC-VLD return mass is 2,933 kilograms (6,470 lb).

The ICC-VLD will be berthed in the center of the payload bay for both launch and reentry.

Other items

In addition to the standard Official Flight Kit (OFK) flown inside a locker on the mid-deck, two Light Weight Tool Stowage Assemblies were modified to fly memorabilia and then were stowed to the left and right of Atlantis' airlock in the shuttle's payload bay.

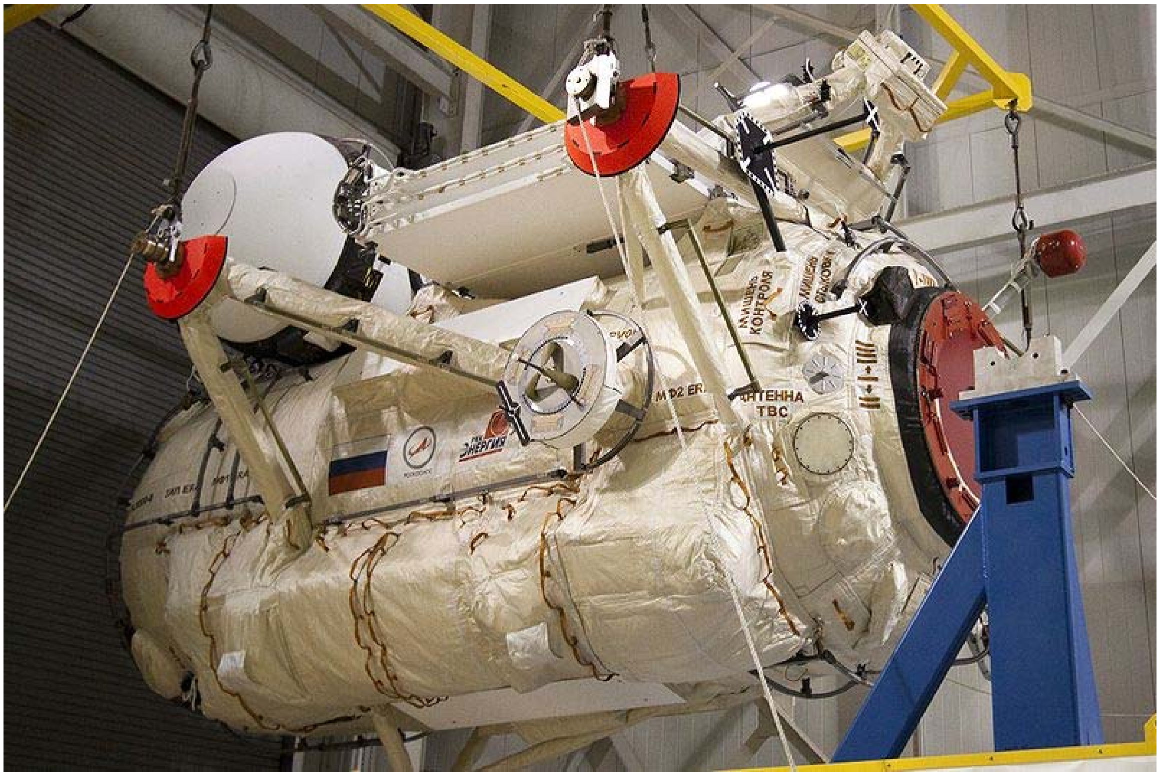
A compact disk (CD) containing the digital copies of all entries submitted to NASA's Space Shuttle Program Commemorative Patch Contest will be flown aboard *Atlantis*. The contest was organized the Space Shuttle Program to mark the end of the shuttle era. The winning patch was designed by Mr. Blake Dumesnil of Hamilton Sundstrand, Johnson Space Center. A panel of NASA judges who included shuttle program manager John Shannon, Leroy Cain and three other shuttle program managers including former astronaut John Casper, selected the winning patch from a pool of 85 entries by NASA employees and contractors.

Seventeen handcrafted beads made by nine different artists across North America will be on board Atlantis' STS-132 mission. NASA teamed up with Beads of Courage, Inc. an approved public charity to bring hope and inspiration to children coping with serious illnesses through the Beads in Space project. The Beads in Space project is the idea of Jamie Newton, an employee at the Marshall Space Flight Center in Huntsville, Alabama. The 17 beads weigh eight ounces and were selected after a contest organized by Beads of Courage that attracted 54 beads.

On board *Atlantis* will be a 4-inch long wood sample of Sir Isaac Newton's apple tree. The piece from the original tree that supposedly inspired Newton's theory of gravity, along with a picture of Newton, will be taken into orbit by astronaut Piers Sellers. The wood is part of the collection of the Royal Society archives in London, and will be returned there following the flight.

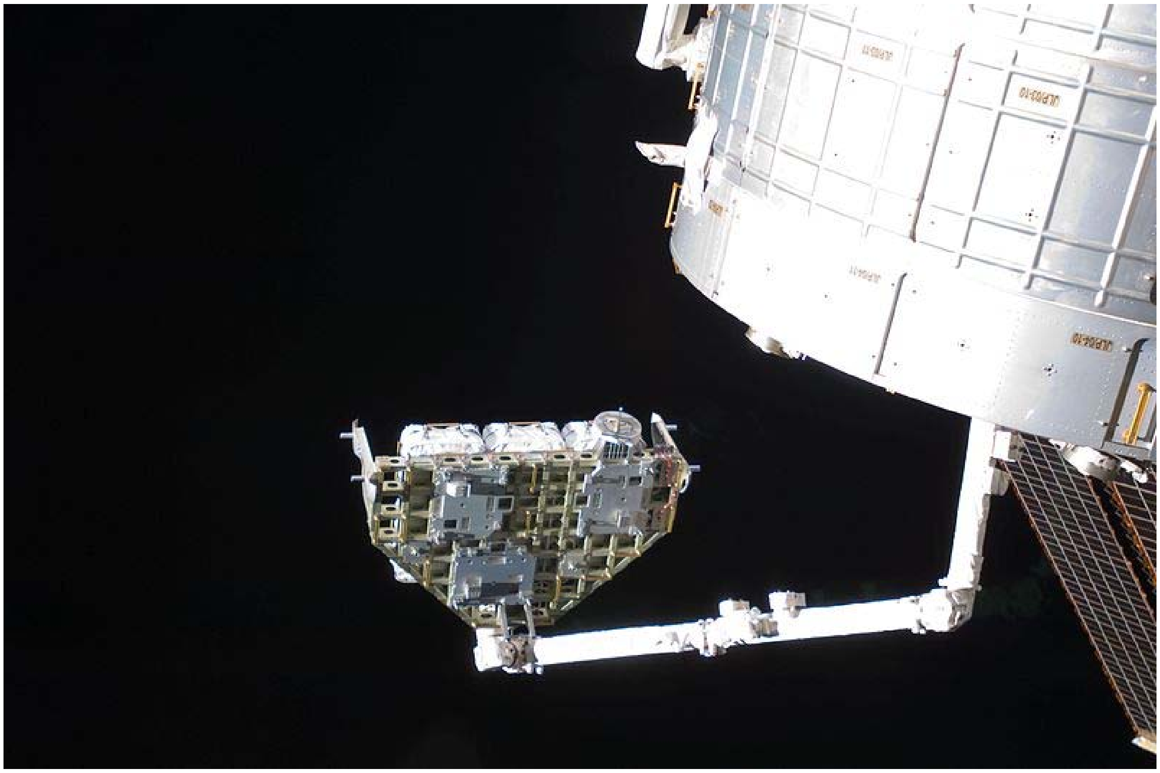
A flag from Clarkson University, Potsdam, New York, will fly on board shuttle *Atlantis*. It will be there in honor of STS-132 lead shuttle flight director, Michael L. Sarafin, who is an alumnus of the Clarkson University.

A comprehensive list of STS-132 items that will be carried aboard Atlantis and their descriptions can be found in the Official Flight Kit.



MRM 1 in the Space Station Processing Facility (SSPF) at Kennedy Space Center

MRM 1 in the Astrotech payload processing facility



ICC-VLD was first carried on STS-127 in July 2009.

Winner of the Space Shuttle Program Commemorative Patch Contest

Mission background

Atlantis heads into space while a pair of F-15E Strike Eagle jets patrolled the skies over Kennedy Space Center.

The mission marked:

- 163rd American manned space flight
- 132nd shuttle mission since STS-1
- 32nd flight of *Atlantis*
- 34th shuttle mission to the ISS
- 11th flight of *Atlantis* to the ISS

- 3rd shuttle flight in 2010
- 107th post-*Challenger* mission
- 19th post-*Columbia* mission

NASA arranged a Tweetup to cover the launch of the STS-132 mission. 150 people attended the event from more than 30 US states, the District of Columbia, Puerto Rico, Belgium, the Netherlands, New Zealand and the United Kingdom. The Tweetup participants met with shuttle technicians, managers, engineers and astronauts, took a tour of the Kennedy Space Center and viewed the launch of *Atlantis*.

Mission experiments

Atlantis crew worked with several short-term experiments during their mission. The shuttle transported new long-term experiments to the ISS. At the end of the mission, *Atlantis* returned some of the completed experiments from the ISS.

Short-term experiments include:

- *Micro-2*: Researchers from Rensselaer Polytechnic Institute sent microorganisms to investigate new ways of preventing the formation and spread of clusters of bacteria (biofilms), that could pose a threat to the health of astronauts. After the shuttle landed, the resulting biofilms were examined to see how their growth and development were impacted by microgravity.
- *Hypersole*: Hypersole is a Canadian research project that plans to investigate sudden changes in skin sensitivity experienced by some astronauts in space. The researchers hope to understand more about how the skin sensitivity of the soles of the feet affect the human balance. Three STS-132 crew members participated in identical trials before the launch and immediately upon landing. The trials will also be repeated on five astronauts scheduled to fly on STS-133 and STS-134 missions. Project findings are expected to add significant knowledge to existing studies of aging and to be beneficial for the elderly and people who suffer from balance problems.
- *Shuttle Ionospheric Modification with Pulsed Localized Exhaust Experiments (SIMPLEX)* - STS-132 crew performed the SIMPLEX burn on Flight Day 12. The experiment investigates plasma turbulence driven by shuttle exhaust in the ionosphere using ground-based radars. The processes by which chemical releases can produce plasma turbulence are quantified with the SIMPLEX measurements. Plasma turbulence can affect military navigation and communications using radio systems. They can also be used to promote communications by opening radio channels at abnormally high frequencies.

Shuttle processing

ET 136 arrives at the Vehicle Assembly Building

Atlantis leaves behind OPF-1 on its move to the Vehicle Assembly Building

Space Shuttle *Atlantis* at Launch Pad 39A

The external tank (ET 136) built to help launch *Atlantis* began its 900-mile (1,400 km), six-day journey across the Gulf of Mexico from NASA's Michoud Assembly Facility in New Orleans, Louisiana, on 24 February 2010. ET 136 measures 154 feet (47 m) long and 28 feet (8.5 m) in diameter. The solid rocket booster retrieval ship Liberty Star, towed the ET in the enclosed barge Pegasus. After docking in the turn basin at the Kennedy Space Center, the tank was offloaded and driven to the Vehicle Assembly Building (VAB) on 1 March 2010.

On 29 March 2010, workers attached ET 136 to its solid rocket boosters. A crane lifted the ET into high bay No. 1 inside the VAB. The day-long process was completed around 18:00 EDT as the tank was bolted to the Atlantis's twin solid rocket boosters.

Atlantis rolled out of its processing bay (OPF-1) around 07:00 EDT on 13 April 2010. The shuttle entered the VAB around 11:00 EDT for attachment to its external tank and solid rocket boosters. Given that this is potentially Atlantis' final rollover for a mission, the shuttle stopped for several hours en route to the VAB allowing engineers and technicians to pose for photographs with the orbiter. The rollover occurred exactly 25 years after *Atlantis* first arrived at the Kennedy Space Center after a cross-country trip from the shuttle factory in Palmdale, California. The path to rollover was without any incidents of major concern, with only 22 Interim Problem Reports (IPRs) noted during *Atlantis'* flow since returning from the STS-129 mission in November 2009.

The transport canister containing the STS-132 payload arrived at Pad 39A on 15 April 2010 ahead of *Atlantis'* rollover to the launch pad. The canister is shaped like the shuttle's 60-foot (18 m)-long payload bay. Packed inside it was MRM1 and the cargo-carrying pallet ICC-VLD.

Space shuttle *Atlantis* began its trip, known as the rollout, to launch pad 39A at 23:31 EDT on 21 April 2010. The complete shuttle stack and mobile launch platform were secured to the launch pad 39A structure at 6:03 EDT on 22 April 2010. The 3.4 mi (5.5 kilometres (3.4 mi)) trek took 6 hours and 32 minutes to complete. The rollout was originally planned for 19 April 2010 evening, but wet weather and thunder storms on the Space Coast caused several delays.

STS-132's payload was installed in the shuttle's cargo bay on 25 April 2010.

Pad engineers preparing *Atlantis* had noticed paint peeling from shuttle's main payload, the MRM-1 module. Although the problem was declared to have no impact on the operation of MRM-1, it holds a potential threat of releasing debris on orbit. Engineers also noted MRM-1 cycled its Fire and Smoke detector self test several times. Similar events occurred during *Atlantis'* STS-129 mission in November 2009 when Shuttle and Station crew were awakened consecutive nights by false depressurization and fire alarms that originated from the MRM-2 (Poisk) module.

The agency wide Flight Readiness Review (FRR) was held at KSC in Florida on 5 May 2010 to discuss Atlantis' launch preparations. At the end of the review, top NASA managers made the decision to officially set the launch for 14 May 2010 at 14:20 EDT. NASA held a post news conference to brief about the results of the FRR. The briefing was broadcasted on NASA TV and was attended by NASA's Associate Administrator for Space Operations, William Gerstenmaier, Space Shuttle Program Manager John Shannon and Space Shuttle Launch Director, Michael Leinbach. Mr. Shannon mentioned that (1) ceramic inserts around Atlantis' windows and forward rocket pod were tested after an insert loosened during Discovery's re-entry on STS-131, posing a potential impact threat. The inserts had been re-installed on to *Atlantis* using a thicker braided cord to reduce the chances of a backing out. (2) Engineers had reviewed work to confirm that all systems on Atlantis' Ku-band antenna were in place. The testing had been provoked after the failure of that communication system during STS-131. Mr. Leinbach also acknowledged the skills and experience of the engineering teams and thanked the engineers who had successfully resolved hypergolic loading issues. Hypergolics are chemicals that ignite when they come in contact with each other. The propellants are used in the reaction control system that steers the shuttle in space.

A booster rocket segment that first flew 25 years ago on Atlantis' maiden flight STS-51-J will also help to fly STS-132. The aft dome on the left solid rocket booster will lift off to support Atlantis' STS-132 mission first launched STS-51-J on 3 October 1985. Including STS-132, 18 of Atlantis' 32 flights are represented by the boosters' segments.

Launch preparations

Technicians prepare to close Atlantis' payload bay doors for launch

Atlantis' astronauts traveled from Johnson Space Center, Houston to the KSC launch site on 10 May 2010 to prepare for the launch. The crew arriving in four T-38 jets landed on the Shuttle Landing Facility around 18:49 EDT.

The official countdown to liftoff started on 11 May 2010 after the countdown clocks at KSC were activated at 16:00 EDT, ticking backward from the T-43 hour mark.

Program managers completed the L-2 Mission Management Team (MMT) meeting on 12 May 2010. At the end of the 18 minute long meeting management team officially cleared

Atlantis for launch. NASA held a pre-launch news conference to reveal the outcomes of the MMT and to brief the press on the upcoming launch. The news conference was attended by Chair, pre-launch mission management team, Mike Moses, Mike Leinbach and STS-132 weather officer, Todd McNamara. The weather officer spoke of a favorable launch weather forecast due to a high pressure weather pattern and despite a low cloud ceiling, calling a 70 percent chance of favorable conditions at launch time. He further elaborated on the predicted weather conditions at the Transoceanic Abort Landing (TAL) sites: Zaragoza and Moron in Spain, and Istres, France, in case of an emergency.

The Space Shuttle Program MMT met at 04:15 EDT on 14 May 2010 and gave a go to begin loading shuttle *Atlantis'* ET with liquid oxygen and liquid hydrogen. The fuel tanking operation began on time at 04:55 EDT and was completed within three hours at 07:56 EDT with replenishment fuel being added throughout the countdown.

Crew preparations for the launch day began at 05:00 EDT following an eight hour overnight sleep. An hour later they completed their final medical check ups. Crew suiting began around 10:00 EDT and the astronauts departed for the launch pad at 10:30 EDT. At around 11:00 EDT, first Commander Ham ingressed the shuttle first and strapped into his seat followed by pilot Antonelli, mission specialists Bowen, Sellers, Reisman and Good in order. Inside the orbiter, all six astronauts performed checks with ground controllers to verify that communications links work properly. With all astronauts onboard, Atlantis' hatch was closed and latched for the flight. Inside the White Room, the closeout crew finished their job by pressurizing the crew cabin and checking for leaks before leaving the pad.

Launch day countdown procedures went without any major problems however *Atlantis* encountered two minor issues. The Final Inspection Team looking for ice & frost buildup on the ET had spotted a small stress fracture on an umbilical strut. Later during the post-launch news conference, chair of NASA's pre-launch mission management team, Mike Moses said that it was not unusual. Engineers also resolved any concerns about a ball bearing found near the shuttle's payload bay days earlier. The bearing was determined to likely be from a camera system, and was ultimately ruled out as a concern.

Mission timeline

May 14 (Flight Day 1 – Launch)

Space Shuttle *Atlantis* launches from Kennedy Space Center, 14 May 2010

Launch of the Space Shuttle *Atlantis* occurred on time at 18:20 UTC with launch commentator George Diller's words upon launch being "liftoff of space shuttle *Atlantis*, reaching the crest of its historic achievements in space". Powered flight conformed to the standard timeline, with main engine cutoff (MECO) occurring at eight minutes and 32 seconds Mission Elapsed Time (MET). The ET-136 separated from the shuttle another 15 seconds later at 8:47 MET. A further boost from the Orbital Maneuvering System (OMS) engines was not required due to the nominal MECO and *Atlantis* settled into its planned preliminary orbit. A subsequent NC-1 engine firing of about 26 seconds adjusted the orbital path of the shuttle to the International Space Station (ISS), by altering the shuttle's velocity by about 41 ft/s (12 m/s).

NASA held a post launch news conference with Bill Gerstenmaier, Alexey Krasnov, chief of Piloted Programs Directorate, Russian Federal Space Agency, Mike Moses and Mike Leinbach. During the conference Gerstenmaier made mention of a piece of space junk that may add a bit more complexity to Atlantis' planned arrival at the ISS.

More than 39,000 guests that included Television host David Letterman, astronaut Buzz Aldrin, and former NASA administrator Mike Griffin witnessed the launch. Russian deputy prime minister, Sergei Ivanov and the head of the Russian Space Federal Agency Anatoly Perminov were also present at KSC.

Once in orbit the crew opened the payload bay doors, activated the radiators and deployed the Ku band antenna successfully. They also completed checkout of orbiter's Shuttle Remote Manipulator System (SRMS). The crew was also successful in down-linking all imagery from Atlantis' umbilical well cameras and crew video of the ET for review by imagery experts in the ground. Preliminary inspections showed that ET 136 was very clean and had performed well during the ascent with only a few foam liberation incidents visible.

May 15 (Flight Day 2 – TPS survey)

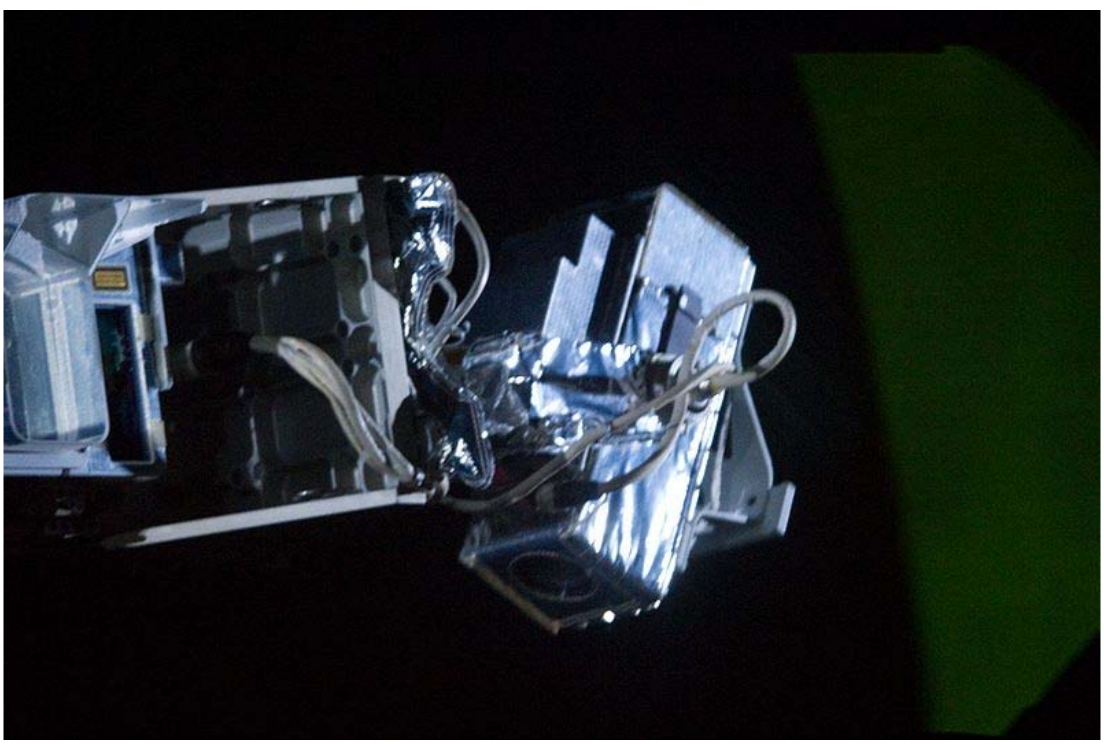
Atlantis' cargo bay and its vertical stabilizer

The crew members aboard *Atlantis* began their first full day in space at 08:20 UTC. The day was primarily devoted to inspecting *Atlantis's* thermal protection system using the shuttle's robotic arm and the Orbiter Boom Sensor System (OBSS) to look for any signs of launch damage. Before the thermal protection checkout began, the crew encountered a problem with the Laser Dynamic Range Imager (LDRI) and the Intensified TV Camera (ITVC) because of a snagged cable in that system's pan and tilt unit. As a result, mission control decided to switch to the less-capable backup sensor system: sensor package 2, a laser camera and a digital camera mounted near the end of the OBSS. Sensor package 2 requires an additional light source such as daylight, has a resolution of a few millimeters and can scan at about 2.5 inches per second. The crew followed "late inspection" procedures for surveying and images of the right wing, the nose cap and much of the left wing were sent to the ground for detailed analysis.

Commander Kenneth Ham installed the centerline camera in the Orbiter Docking System (ODS) to help him during Atlantis' approach to the ISS. Down on the shuttle's middeck, Good and Bowen spent several hours checking out spacesuits and preparing them for transfer to the station. Reisman spent much of his day working with Antonelli and Ham on the TPS survey. He also managed to spend some time helping with the suit and spacewalk equipment checkouts. The crew also performed the ODS ring extension that will connect the shuttle's docking port to the station's Harmony module. The last portion of the crew day was spent preparing and checking out all of the tools used during rendezvous.

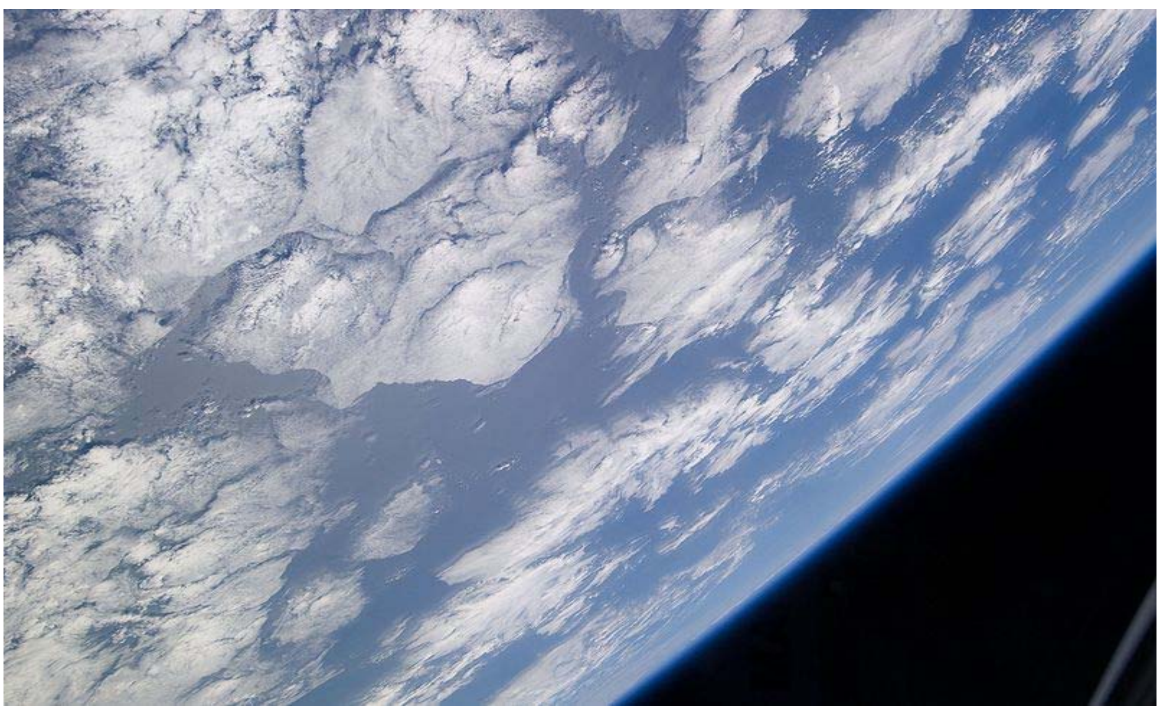
Two course correction burns were also be performed on Flight Day 2. The first 10 second NC-2 burn was performed using the right-hand OMS engine, changing the shuttle's speed by 8 ft/s (2.4 m/s). The burn raised both the apogee and perigee of shuttle's orbit by 1-mile (1.6 km). Atlantis' reaction control jets were again fired for a second time to execute the eight second NC-3 burn which changed the shuttle's velocity by about 2 ft/s (0.61 m/s).

Mission Control managers determined that the ISS will not need an avoidance maneuver to avoid a piece of orbital debris. Updated tracking information showed that the ISS and debris won't pass close enough the next day to require any action.



Snagged cable in the sensor package pan and tilt unit

Garrett "Big G" Reisman in the middeck of *Atlantis*



Blue and White part of Earth as photographed by a crew member

Tony Antonelli

May 16 (Flight Day 3 – Docking)

Atlantis docked to the ISS

The STS-132 crew began their day at 07:20 UTC and prepared to dock with the ISS. Commander Ken Ham performed a series of rendezvous burns (NH, NC4 and TI) to boost the orbit of *Atlantis* to match with that of the ISS. The major one minute 24 seconds long orbit raising maneuver, NH burn changed Atlantis' velocity by 132 feet per second and placed the shuttle into a new 212 by 145 miles (233 km) orbit. A 63 second circularization burn, known as NC4, next boosted *Atlantis* into a 214 by 210-mile (340 km) orbit. At 11:40 UTC with about 9 miles (14 km) separating the shuttle and the ISS, commander Ken Ham performed the final 12-second terminal initiation (TI) burn firing the left OMS engine of *Atlantis*.

By 13:26 UTC with Ken Ham at the controls Ham was flying the shuttle from the aft flight deck, *Atlantis* positioned beneath the ISS and began the 360-degree flip rendezvous pitch maneuver (RPM). As the shuttle's underside rotated into view, three ISS crew members, Oleg Kotov using a camera with 400mm lens, Timothy Creamer and Soichi Noguchi having two 800mm lens cameras took 398 photographs of Atlantis' belly as part of post-launch inspections of the thermal protection system.

Atlantis docked with the ISS Pressurized Mating Adapter-2 at 14:28 UTC as the two orbited 220 miles (350 km) over the South Pacific Ocean. After docking, the ISS was reoriented by the small vernier thrusters on *Atlantis* to minimize the risk of Micro-

Meteoroid Orbital Debris (MMOD) impacts upon the Shuttle. A series of leak checks were done on both sides of the hatch by the shuttle and station crews were done before the hatches were opened at 16:18 UTC. After a brief welcoming ceremony by the station crew, Atlantis' astronauts got the standard station safety briefing. Then the crew got to work with initial transfers of equipment and supplies. Spacesuits were among the first items to go to the ISS. Station crew member Noguchi also transferred high-priority JAXA experiments to the Kibo Module.

Sellers and Expedition 23/24 astronaut Tracy Caldwell Dyson got to work on their joint task to relocate the ICC-VLD cargo pallet. The duo used the station's robotic arm to transfer the pallet from *Atlantis* to the station's mobile base system to prepare for the spacewalks.

In preparation for next day's spacewalk, all Atlantis' crew members gathered for an hour-long spacewalk procedure review. Mission Specialists Reisman and Bowen spent the night in the Quest airlock as part of the overnight "campout" procedure to help them get prepared for the spacewalk. The crewlock was depressurized from 14.7 to 10.2 psi. The depressurization is required to avoid formation of nitrogen bubbles in astronaut's blood in the vacuum of space.

Flying above the Atlantic coast of Spain and the Gulf of Cadiz *Atlantis* approaches the ISS for docking.

Underside of *Atlantis* is revealed during the RPM

May 17 (Flight Day 4 – EVA 1)

Reisman takes a self portrait during EVA 1

After the wakeup call went to awaken the crew, mission control CAPCOM Shannon Lucid informed them that no detailed flight inspection would be required on the next day. However, the crew were requested to utilize that time to do inspections on various sections of *Atlantis* that were not done on Flight Day 2.

Flight day 4 saw mission specialists Garret Reisman and Steve Bowen perform the first of three planned spacewalks. The pair installed a spare Space To Ground Antenna (SGANT), a new enhanced tool platform for the Special Purpose Dexterous Manipulator (SPDM) also known as Dextre and released torque on the six new batteries for the Port 6 (P6) truss segment.

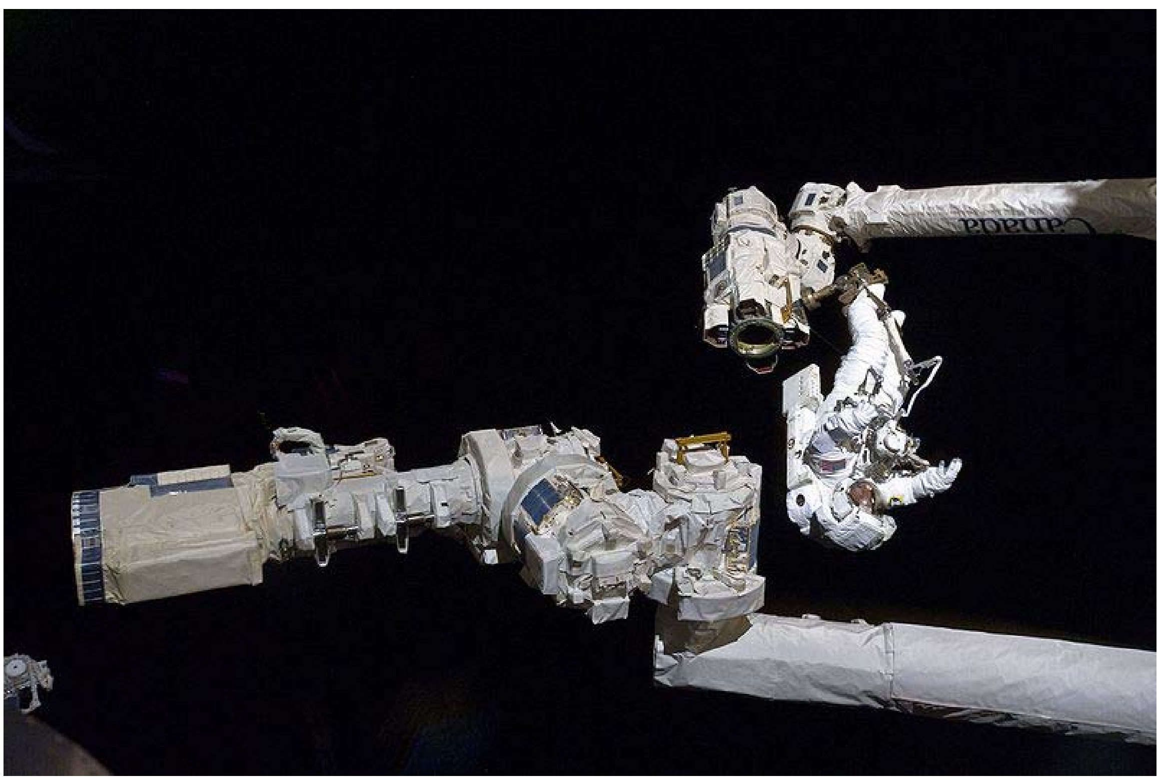
Expedition 23 Flight Engineer Creamer helped the duo with the suit-up preparations. Mike Good joined STS 132 Pilot Antonelli, the intravehicular officer, to assist during the spacewalk. Mission Specialist Sellers and station Flight Engineer Caldwell Dyson operated the robotic arm. Throughout EVA 1, Commander Ken Ham oversaw the extravehicular activities.

During the spacewalk, several problems were encountered, the first of which was during installation of the SGANT. A slight gap was observed between the antenna dish and its mounting pole. The spacewalkers were given a go to loosen the bolts and use a higher torque setting, which managed to get the gap to a smaller amount. The launch locks were left on the SGANT to allow engineers on the ground to determine if the gap is acceptable or if more troubleshooting will be needed. The second problem occurred during the installation of the SGANT, and was related to the Command and Control (CNC) computers. During installation, when Steve Bowen removed a cover from a connector the prime CNC computer detected an error and shut down. The cap is a special cap which allows the circuit for that connector to be closed, when it was opened sensor detected the error. The shut down of the CNC, cause a brief 2 minute loss of communications. The safeing of the computer also stopped the Canadarm2 and for a reconfiguration of the cameras being used during the spacewalk by both the robotic arm operators and the ground.

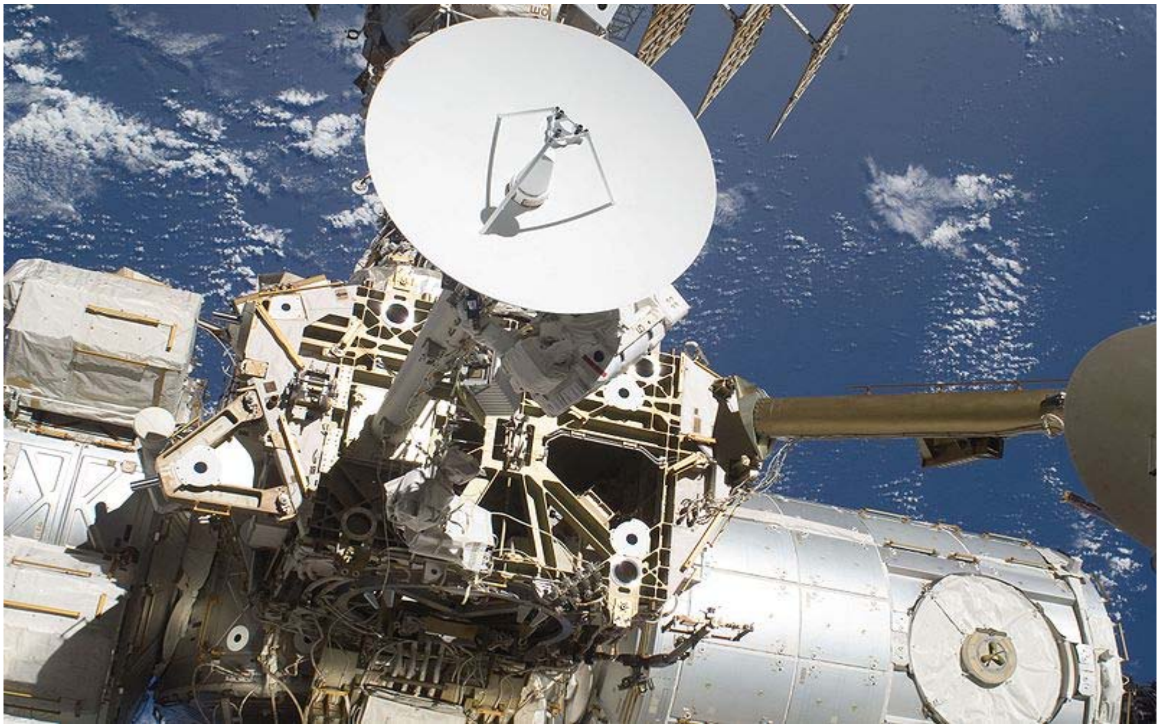
The spacewalk ended at 19:19 UTC after Reisman and Bowen took inventory of the tools they brought with them outside and made their way back into the Quest airlock. EVA 1 was the 237th conducted by U.S. astronauts, the second for Reisman and the fourth for Bowen. It was also the 144th in support of International ISS assembly and maintenance. For EVA 1, lead spacewalker Reisman had a spacesuit with no stripes. Bowen' spacesuit was marked with a red stripe.

Shuttle’s arm also successfully grappled the MRM-1 module in Atlantis' cargo bay in preparation of its next day berthing to the Zarya service module.

Reisman during EVA 1



Garrett Reisman anchored to a Canadarm2 mobile foot restraint during EVA 1



Stephen Bowen works on the installation of the Ku band antenna system.

May 18 (Flight Day 5 - MRM1 installation)

Atlantis docked with the ISS moving southeast across the skies of Tampa, FL

On Flight Day 5 crew focused on the addition of the MRM-1 module to the space station. Commander Ken Ham and pilot Tony Antonelli maneuvered Atlantis' robotic arm to unberth MRM-1 from the shuttle's payload bay at 09:49 UTC and handed it off to the station Canadarm2 at 10:14 UTC. Mission specialists Garrett Reisman and Piers Sellers, working from inside station's Cupola, then maneuvered the Canadarm2 arm to deliver MRM-1 to its new position, the Earth-facing port of the Zarya service module. The docking occurred at 12:20 UTC when the shuttle-station stack was flying above Argentina. Following the successful docking, Sellers reported to the mission control that during the docking, he did not see the expected "capture 1" confirmation signal popping up in his laptop to which CAPCOM Steve Swanson replied "And station, that error's expected. The reason you didn't get 'contact 1' is because Garrett did too good of a job flying. He went right down the middle and got a hole in one"

Expedition 23 Commander Oleg Kotov also monitored the activities from the Russian segment as the MRM-1 engaged into its automated docking sequence for the final attachment to the Zarya module. The berthing marked the first time that the Russian automated docking system has been used along with the station's robotic arm.

At 17:20 UTC, shuttle crew Ham, Reisman, Sellers, and station crew Kotov, Skvortsov and Caldwell Dyson gathered in space station's Harmony module to talk with reporters from MSNBC, Fox News and CNN. The two crews answered questions related to their stay in orbit, medical experiments being conducted at ISS, spacewalking experience and the Gulf of Mexico oil spill.

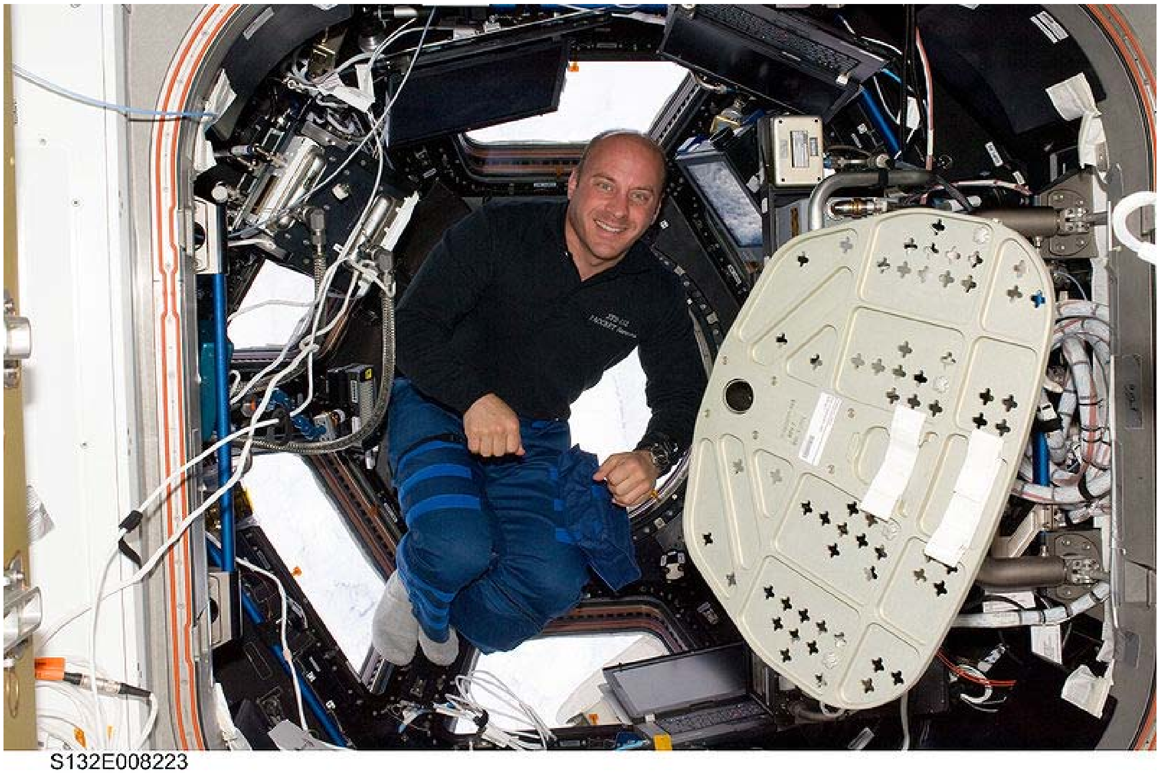
After mid day, Reisman and Sellers used Canadarm2 to unberth OBSS from the sill of Atlantis' cargo bay and handed it off to the shuttle's robotic arm, operated by Ham and Antonelli.

Mission specialists Bowen and Good prepared for next day's EVA 2. Earlier on the day, they configured the tools and prepared their spacesuits. At the end of the workday, Atlantis' crew along with three station crew members met for an hour-long spacewalk procedures review.

At 21:45 UTC, Good and Bowen began their "camp out" inside the Quest airlock with pressure reduced to 10.2 psi.

Canadarm2 transfers MRM-1 to the Earth-facing port of the Zarya module

Canadarm2 attaches MRM-1 to the Zarya module



Garrett Reisman inside the Cupola

May 19 (Flight Day 6 - EVA 2)

Mike Good during EVA 2

The primary task on the mission's second spacewalk, EVA 2 was to remove and replace batteries on the station's port 6 truss. The spacewalk, got under way at 10:38 UTC, more than 25 minutes ahead of the scheduled start that already had been moved up 30 minutes.

Lead spacewalker Bowen's first task was to remove a cable snag in the OBSS's pan and tilt mechanism. Bowen looped a tie wrap on two cables to relieve the snag and completed that task in less than 30 minutes, while Good began work with the batteries. Although the initial plan call was to replace three batteries, the two astronauts managed to replace an additional fourth battery during EVA 2. The batteries Bowen and Good replaced were launched in November 2000. After the battery work and cleanup of the area, Bowen and Good moved on to the new backup Ku band antenna on the Z1 truss. They tightened bolts holding its dish to its boom, closing a gap left there after EVA 1. Good performed a wiggle test and confirmed that two spacewalkers did not see any signs of motion in the antenna-mast interface. They then removed the antenna's launch locks, leaving the antenna ready to operate.

During EVA 2, commander Ken Ham provided photo and television support, and pilot Tony Antonelli served as the spacewalk choreographer. ISS crew member Tracy Caldwell Dyson also assisted with spacewalk preparations. EVA 2 marked the 238th conducted by U.S. astronauts, the fifth for Bowen and the third for Good. It was also the 145th in support of International Space Station assembly and maintenance.

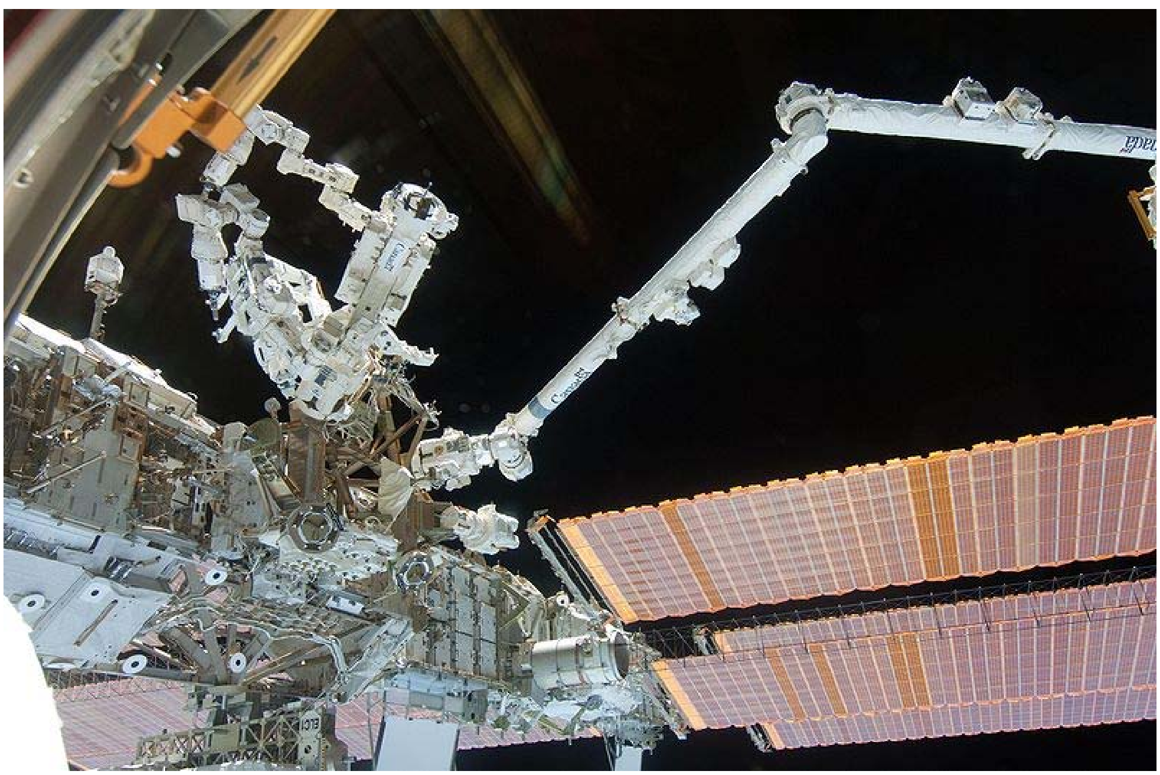
May 20 (Flight Day 7 - MRM-1 initial checks, transfers and off duty)

Good, Bowen and Reisman pose for a photo with an Extravehicular Mobility Unit (EMU).

On Flight Day 7 the crew spent a few hours of off duty time in the afternoon, but otherwise, they largely focused on preparations for EVA 3. Earlier on the day, at 10:52 UTC, following leak checks, ISS Expedition 23 commander Oleg Kotov and flight engineer Alexander Skvortsov opened the hatch to the MRM-1 module. They wore eye and breathing protection as a standard precaution when entering a new module. Kotov reported that some metal filings were drifting inside the new module as unpacking activities gathered pace although initially he reported the interior of MRM-1 looked clean. Flight controllers both in Houston and in Moscow were working with the crew to develop a technique for safely removing the floating debris.

At 12:25 UTC, shuttle crew members, Ken Ham, Tony Antonelli, Piers Sellers and ISS flight engineer Tracy Caldwell Dyson talked with the Associated Press, Fox News Radio, and CBS News. Ham also joined in with past and present members of Mission Control to recognize Lonnie J. Schmitt as the first flight controller to reach his 100th shuttle mission.

During the day, Ham, Antonelli and Sellers transferred equipment, supplies and experiments between *Atlantis* and the ISS. Mission specialists Mike Good and Garrett Reisman prepared for their spacewalk (EVA 3), configuring tools and preparing suits and the airlock. Ham, Antonelli and Sellers also joined them to review the procedures. As part of the "campout" procedure, the two spacewalkers spent the night in the Quest airlock with its pressure reduced to 10.2 psi.



View of a section of ISS as photographed by a STS-132 crew member

Garrett Reisman inside the Quest airlock

The aft section of Atlantis while docked with the Station

May 21 (Flight Day 8 - EVA 3)

On flight day 8, Mike Good and Garret Reisman completed the third and final spacewalk of the STS-132 mission. The pair connected a pair of ammonia jumpers on the P4/P5 truss segment before continuing on out to the end of the P6 truss. Once at the P6 truss, Good and Reisman completed the battery swap by removing and replacing the final 2 batteries and retrieving the temporarily stowed old battery on the truss. Once that task was complete, Good and Reisman moved to *Atlantis'*s payload bay where they removed a grapple fixture and took it to the Quest airlock. The pair then moved on to fix some insulation on the Dextre robot and stowed some tools in an external toolbox on the Z1 truss. Pilot Tony Antonelli choreographed the spacewalk from inside the shuttle.

While the spacewalk was going on, commander Ken Ham and mission specialist Steve Bowen completed some more of the transfer work for the mission.

Good (left) and Reisman look through the aft flight deck windows of Atlantis during EVA 3.

Good during EVA 3

ISS023E047841

Reisman participates in EVA 3

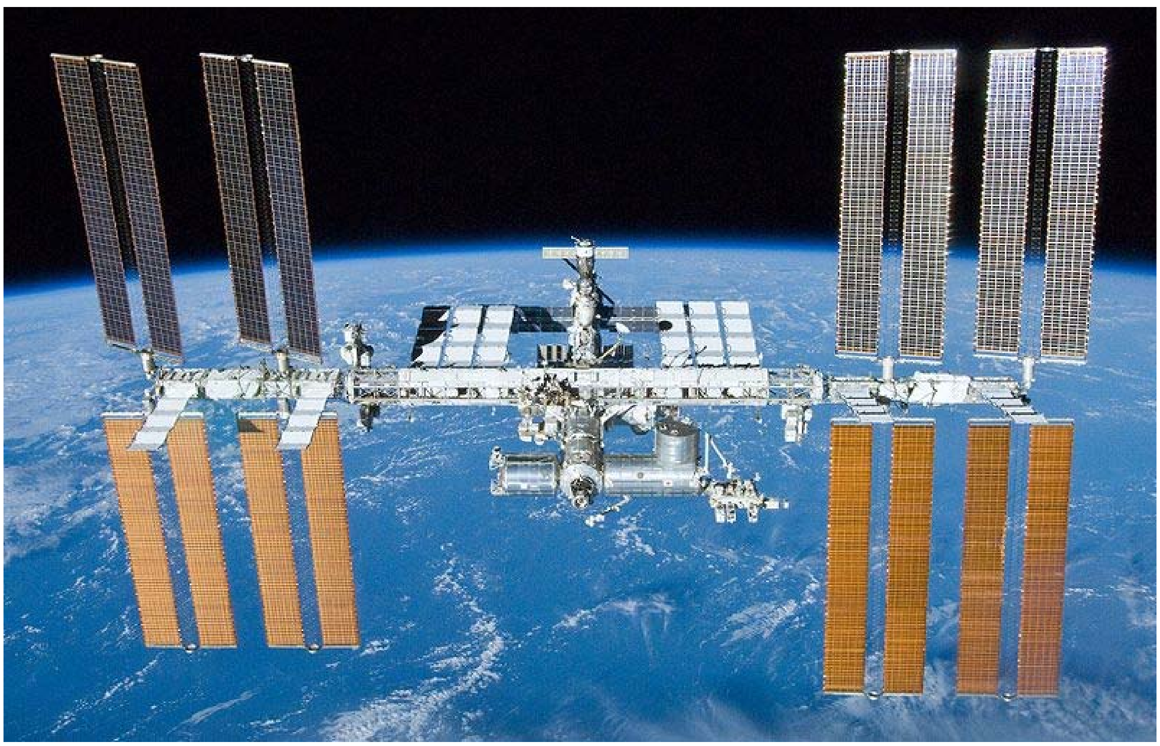
May 22 (Flight day 9 - Off duty)

ISS023E050361

STS-132 Crew and Tracy Caldwell-Dyson during the educational event

Flight day 9 saw the shuttle crew enjoying some off duty time during the crews afternoon. In the morning, the entire crew participated in some transfer activities and orbiter maintenance. The ICC-VLD was also berthed back in space shuttle *Atlantis* payload bay, having completed its tasks for this mission. The SSRMS or Canadarm2 was used to install it back in the payload bay and was operated by mission specialists Piers Sellers, Garrett Reisman and space station flight engineer Tracy Caldwell Dyson. The ICC-VLD moving operations began just after 4:30 a.m. EDT, and was completed at 5:50 a.m. EDT. The shuttle crew and Caldwell Dyson also answered some questions from elementary and middle school students around the U.S. Students from 12 NASA Explorer Schools had submitted their questions earlier by video. The combined shuttle-station crew also shared a joint meal before the shuttle crew enjoyed two and a half hours of off-duty time starting at 11:05 a.m. EDT.

May 23 (Flight day 10 - Undocking)



Newly upgraded ISS seen from the shuttle after undocking.

On flight day 10, the joint STS-132/Expedition 23 crews awoke to begin the final hours of the joint docked mission. The crews completed the final time sensitive transfers of the mission, which included scientific research samples that need to be kept cold. Once those transfers were completed, the two crews held a joint crew news conference and took a crew photo and later prior to hatch closure the crews held a farewell ceremony to say goodbye to one another. After the ceremony the hatches between the space shuttle *Atlantis* and the International Space Station (ISS) were closed and a leak check was performed to ensure all the hatches were sealed properly. The space shuttle undocked from the ISS at 15:22 UTC, a little more than 2 hours after the hatches were closed. At the time of undocking the two spacecrafts were sailing 220 miles (350 km) above the Southern Ocean southwest of Perth, Australia. The shuttle guided by pilot Tony Antonelli backed away from ISS to a distance of about 400 feet (120 m), at which time Antonelli began conducting a fly around of the space station, so that crew members on both the ISS and shuttle could get photos of both vehicles. Once the fly around was complete the shuttle crew conducted two separation burns to move away and in front of the space station.

STS-132 (blue shirts) and Expedition 23 crew members pose for a group portrait on the ISS.

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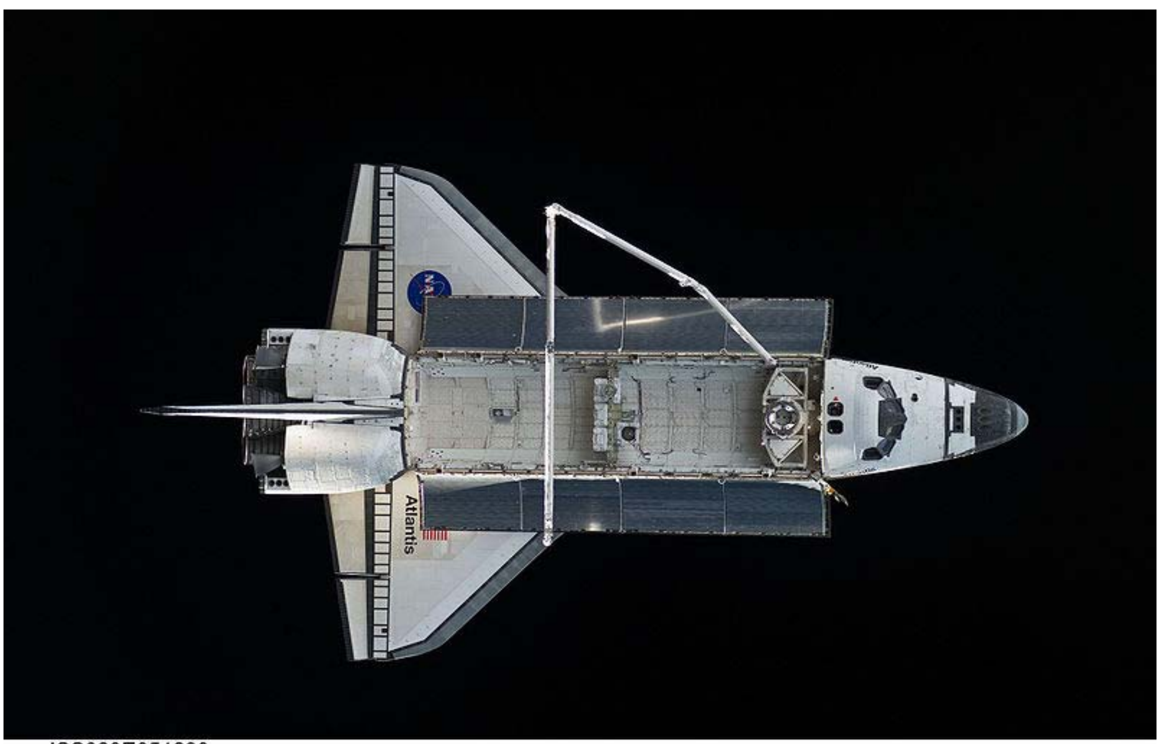
Ham and Kotov shake hands at the farewell ceremony



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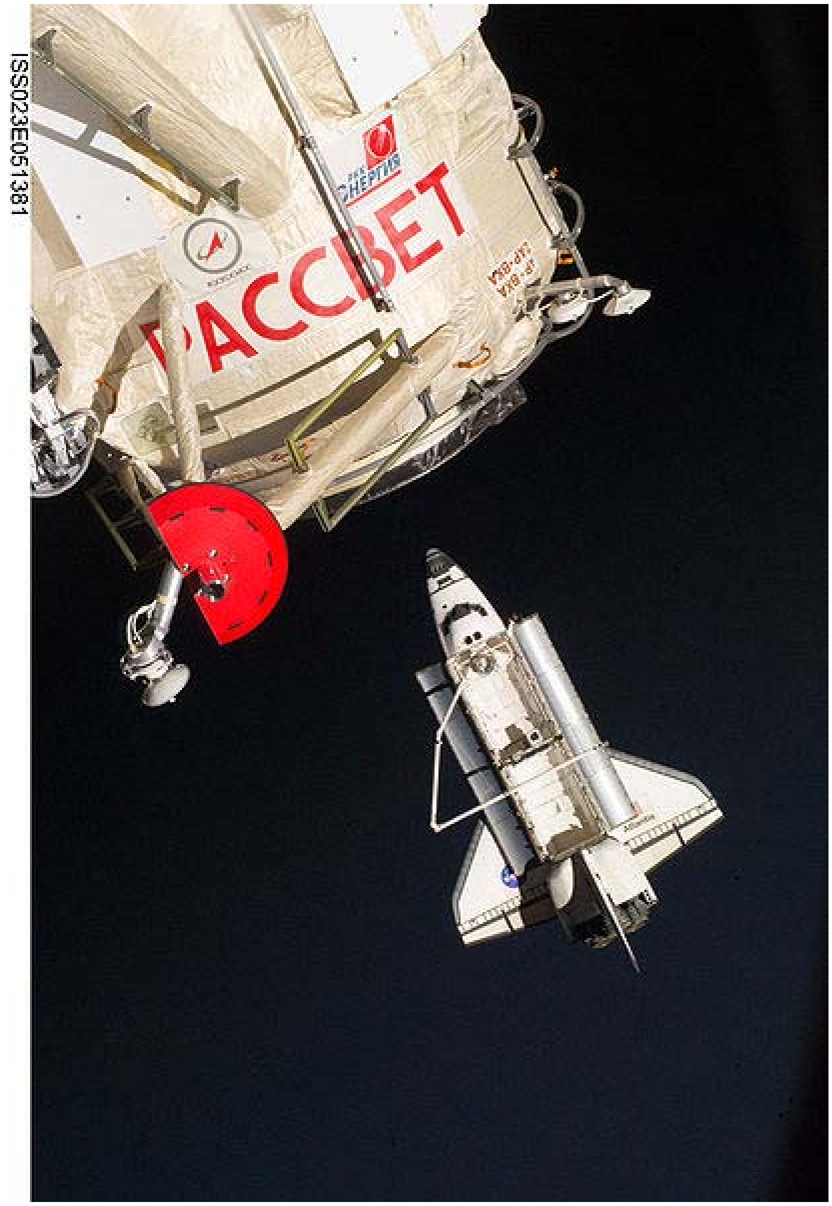
Departing Atlantis as photographed by a station crew member



Atlantis separates from the ISS after undocking

May 24 (Flight day 11 - Late inspection)

The crew of space shuttle *Atlantis* awoke on flight day 11 and after a couple of hours of personal time, begun the late inspection of the shuttles wing leading edges and nose cap. The crew worked through the time line and finished the scans about two and a half hours ahead of schedule. By 09:50 UTC they had finished their look at the right wing, by 10:52 UTC the nose cap survey was complete and the left wing survey was finished at 11:17 UTC. The TPS survey was done using the shuttle arm and its OBSS extension. While the scans were going on, some of the crew was stowing items that were no longer needed or were transferred right before undocking. Spacewalkers Mike Good and Steve Bowen cleaned up and stowed their spacesuits for landing. The latter part of the crews day was spent with some off duty time.

May 25 (Flight day 12 - Landing prep)

Atlantis astronauts devoted flight day 12 to get ready to return home. The crew executed standard day-before-landing activities. Commander Ham, Pilot Antonelli and Mission Specialist Good began the flight control system (FCS) hot-fire checkout at about 1:40 a.m. EDT, operating the rudder and flaps that will control Atlantis' flight through the atmosphere to the KSC runway. That complete, Ham and Antonelli fired each of the shuttle's 44 attitude control thrusters that orient Atlantis in space as it descends from orbit and through the upper atmosphere. Both those tests were completed successfully.

All STS-132 crew members worked at various times throughout the day to stow items in the cabin to prepare for landing. They also gathered for a 30-minute deorbit briefing at 5:40 a.m. EDT. Immediately afterward the crew talked with representatives of The Colbert Report, ABC Radio Network and WEWS-TV of Cleveland, Ohio.

Late in their day, mission specialists Reisman and Sellers stowed the Ku-band antenna in Atlantis' cargo bay.

May 26 (Flight day 13 - Re-entry and Landing)

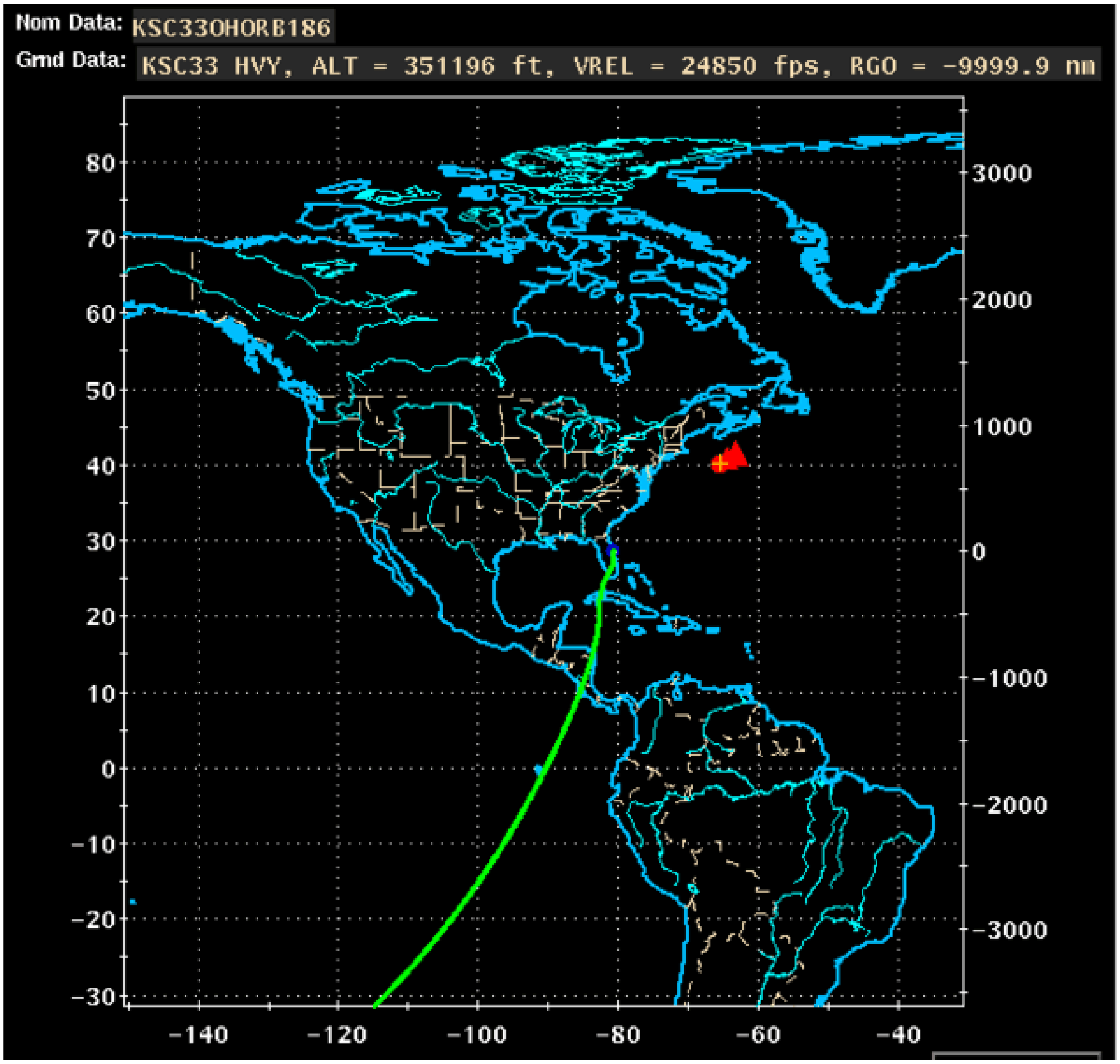
STS-132 ends as Space Shuttle *Atlantis* landed on May 26, 2010, at Kennedy Space Center's Shuttle Landing Facility.

The STS-132 crew awoke at 12:20 EDT (4:20 UTC). At about 7:40 UTC, the astronauts began deorbit preparations and closed the payload bay doors at 9:01 UTC. The deorbit burn initiated at 11:42 UTC 220 miles (350 km) above Indonesia for a landing at KSC and terminated at 11:45. At an altitude of 400,000 feet (120,000 m) and a speed of Mach 25, Atlantis began re-entry at 12:16. At about 12:23 UTC, Atlantis began its s-rolls to bleed off speed and energy during re-entry. At about 12:29, the shuttle was more than 40 miles (64 km) above Earth and 2,000 miles (3,200 km) from KSC traveling at Mach 22. At 12:34, Atlantis was about 180,000 feet (55,000 m) and altitude traveling at about 9,200 mph and was 600 miles (970 km) from the runway. At about the same time, the shuttle was experiencing maximum re-entry heating conditions peaking at about 2,900 degrees Fahrenheit, lasting about two minutes. At 12:39, long-range cameras at KSC spotted the shuttle gliding towards the runway at an altitude of 16 miles (26 km) and a distance of 77 miles (124 km) from KSC. At 12:44, commander Ken Ham took manual control of the orbiter for landing as it glided through the 50,000-foot (15,000 m) mark.

Atlantis landed on runway 33, on its main wheels at 08:48:11 EDT (12:48:11 UTC) at KSC. The nose wheel touched down 10 seconds later, at 08:48:21 EDT (12:48:11 UTC), with the vehicle coming to a stop at 08:49:18 EDT (12:49:18 UTC). The entire mission lasted 11 days, 18 hours, 29 minutes, and 9 seconds, during which time the space shuttle traveled 7,724,851 kilometres (4,800,000 mi).

The six astronauts headed to Houston on May 27. A welcome ceremony for the crew was held on the same day at 5 p.m. EDT at Ellington Field's NASA Hangar 276.

Atlantis reaches OPF-1 after landing



Long-range ground track

Atlantis approaches Runway 33

Crew pause for a post-landing photo opportunity on the tarmac

Spacewalks

Three spacewalks were conducted to replace six aging batteries and to stage spare components outside the station, including a secondary Ku-band antenna and spares for the Canadian Dextre robotic arm extension.

EVA	Spacewalkers	Start (UTC)	End (UTC)	Duration
EVA 1	Garrett Reisman Steve Bowen	17 May 11:54	17 May 19:19	7 hours 25 minutes
	Reisman and Bowen installed a spare space-to-ground Ku-band antenna on the station's truss, or backbone. They then installed a new tool platform on Dextre. The spacewalkers also broke the torque on bolts holding batteries in place on the truss, in preparation for their removal and replacement on the second and third spacewalks.			
EVA 2	Steve Bowen Michael Good	19 May 10:38	19 May 17:47	7 hours 9 minutes
	Bowen and Good removed and replaced four of the six batteries on the port truss to store electricity from the solar arrays on that truss. The used batteries will be installed on the cargo carrier for return to Earth on Atlantis. They also fixed a snagged cable on the Orbiter Boom Sensor System. The final task was to re-torque the bolts on the SGANT and then remove the launch locks and tether that were helping hold it in place.			
EVA 3	Michael Good Garrett Reisman	21 May 10:27	21 May 17:13	6 hours 46 minutes
	Good and Reisman first connected a liquid ammonia jumper hose. They then installed the final two new batteries on the truss and put the old batteries on the carrier. Next, they retrieved a grapple fixture from Atlantis' payload bay and brought it inside the station to be modified for future installation on the Zarya module. The pair also stowed some tools in an external toolbox outside the airlock for future spacewalks.			

Mission insignia

The STS-132 mission patch was designed by NASA artist Sean Collins working with astronaut Garrett Reisman. The patch shows *Atlantis* flying towards a sunset landing, with the names of the STS-132 astronauts around the border.

STS-132 mission decal

During the standard post-flight inspection of Atlantis, a United Space Alliance inspector found a STS-132 mission decal accompanied by an inscription, "*The first, last flight of Atlantis left Earth on 14 May 2010 from Pad 39A*" together with the crew's signatures. The worker had found it tucked away on the upper side of Locker A-16 while scanning the area with a mirror. Moreover, he said the note must have been written on orbit since otherwise, the crew would have had to stand on their heads.

Wake-up calls

NASA began a tradition of playing music to astronauts during the Gemini program, which was first used to wake up a flight crew during Apollo 15. Each track is specially chosen, often by their families, and usually has a special meaning to an individual member of the crew, or is applicable to their daily activities.

Flight Day	Song	Artist	Played for
Day 2	"You're My Home"	Billy Joel	Kenneth Ham
Day 3	"Sweet Home Alabama"	Lynyrd Skynyrd	Dominic A. "Tony" Antonelli
Day 4	"Alive Again"	Matt Maher	Michael T. Good
Day 5	"Macho Man"	Village People	Garrett Reisman
Day 6	"Start Me Up"	The Rolling Stones	Piers Sellers
Day 7	"Welcome to the Working Week"	Elvis Costello	Steve Bowen
Day 8	"Travelin' Light"	JJ Cale	Piers Sellers
Day 9	"Shine"	Matt Redman	Michael T. Good
Day 10	"These Are Days"	10,000 Maniacs	Dominic A. "Tony" Antonelli
Day 11	"Theme from Wallace and Gromit"	Julian Nott	Steve Bowen
Day 12	"Empire State of Mind"	Jay-Z	Garrett Reisman
Day 13	"Supermassive Black Hole"	Muse	Kenneth Ham

Chapter 12

Picard (Satellite) and Chang'e 2

Picard

	Picard
Launch date	June 15, 2010

PICARD is a satellite dedicated to the simultaneous measurement of the absolute total and spectral solar irradiance, the diameter and solar shape, and to the Sun's interior probing by the helioseismology method. These measurements obtained throughout the mission will allow study of their variations as a function of solar activity. It launched, along with the Prisma spacecraft, on June 15, 2010 on a Dnepr-1 launcher from Dombarovskiy Cosmodrome, near Yasny, Russia.

Objectives

The objectives of the PICARD mission are to improve our knowledge of:

- the functioning of our star through new observations,
- the influence of the solar activity on the climate of the Earth.

History

The PICARD mission was named after the French astronomer of the 17th century Jean Picard (1620–1682) who achieved the first accurate measurements of the solar diameter. These measurements are especially important as they were made during a period when the solar activity was minimum characterized by a sun nearly without sunspots between 1645 and 1710. This period was found by Gustav Spörer using sunspots observations gathered in Europe and this period is now named Maunder minimum. By comparing the diameter during the Maunder minimum and the diameter when the sun was active a variation has been found, leading to the still unanswered question "Are diameter and activity linked?". During this period in Europe, there was an unusually cold climate.

Platform

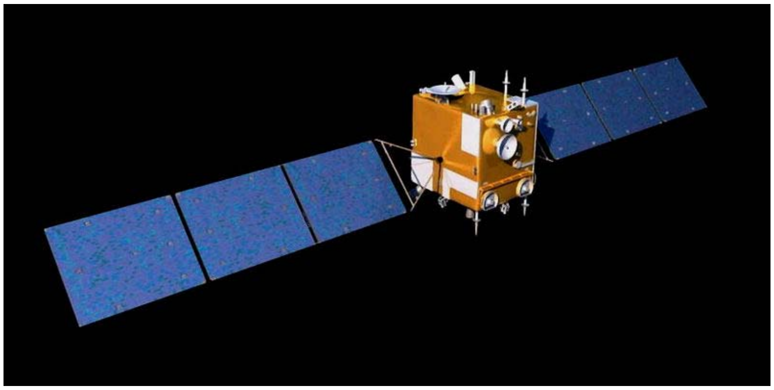
PICARD will use the MYRIADE microsatellite platform, developed by CNES to use as much as possible common equipments. This platform was designed for a total mass of about 120 kg mass at launch. Its attitude in space is maintained by using a star sensor, solar sensors, a magnetometer, gyrometers, several magnetic rods and reaction wheels. If an orbit control and orbit manoeuvres are needed, a hydrazine system may be used. The on-board management is centralised, and uses a 10 MIPS microprocessor T805. A mass memory is available for the data storage. The telemetry and telecommand use CCSDS standard.

Payload

The PICARD payload is composed of the following instruments:

- **SOVAP** (SOlar VAriability PICARD): composed of a differential radiometer and a bolometric sensor to measure the total solar irradiance (previously called solar constant),
- **PREMOS** (PREcision MOnitor Sensor): a set of 3 photometers to study the ozone formation and destruction, and to perform helioseismologic observations, and a differential radiometer to measure the total solar irradiance.
- **SODISM** (SOlar Diameter Imager and Surface Mapper): an imaging telescope accurately pointed and a CCD which allows to measure the solar diameter and shape with an accuracy of a few milliarc second, and to perform helioseismologic observations to probe the solar interior.

Chang'e 2

Chang'e 2	
	
Operator	CNSA
Mission type	Orbiter / impactor
Satellite of	The Moon
Launch date	2010-10-01, 10:59:57 UTC
Carrier rocket	Long March 3C
Launch site	Xichang Satellite Launch Center Xichang, Sichuan, China
Mission duration	> 6 months elapsed: 3 months, and 16 days
COSPAR ID	2010-050A
Mass	2,500 to 2,600 kg (5,500 to 5,700 lb)
Orbital elements	
Apoapsis	100 km (62 mi)
Periapsis	15 km (9.3 mi)
Instruments	
Main instruments	Charge-Coupled Device (CCD) improved stereo camera Laser altimeter Gamma/X-ray Spectrometers Microwave Detector

Spatial resolution	10 meter at 100 km altitude and 1.5 meter at 15 km altitude

Chang'e 2, is a Chinese un-manned lunar probe that was launched on 1 October 2010. It is a follow-on to the Chang'e 1 lunar probe launched in 2007 and is part of the first phase of the Chinese Lunar Exploration Program. The probe will conduct research at a 100-kilometer-high lunar orbit as a preparation for a soft landing by Chang'e 3. Chang'e 2 is similar to Chang'e 1 with some improvements, including a better camera with a resolution of one meter. It is named after a legendary Chinese goddess of the moon. The total expenditure for the Chang'e 2 mission is approximately CN¥900 million, or US$134 million.

Description

Chang'e 2 is similar to the Chang'e 1 mission, but has important differences. While Chang'e 1 operated in a 200-kilometer orbit, Chang'e 2 is flying at only 100 kilometers, leading to better quality and resolution of the science data. Chang'e 2 also has a higher resolution camera.

Some other key differences between Chang'e 1 and Chang'e 2, as summarized by Qian Huang of the Shanghai Astronomical Observatory and Yong-Chun Zheng of the NAOC:

- Chang'e 2 will have a shorter Earth to Moon cruise of 5 days rather than 12 days. The launch rocket has two more boosters to accomplish this more direct route to the Moon.
- The laser altimeter's footprint will be smaller, and will achieve 5-meter vertical accuracy in estimate of the Moon's radius. It will also pulse more frequently, five times per second rather than just 1 time per second.
- The main camera's spatial resolution will be 10 meters rather than 120 meters.
- Late in the mission, the orbit will be lowered to an elliptical one with the same apolune (100 kilometers) but a perilune of only 15 kilometers
- Tracking will be performed with new X-band radio capability.

Zheng also remarked that "The mission goals of CE-2 will be focused into the high resolution image for the future landing site of CE-3 lunar lander and rover. The key technology about soft landing on the Moon will be tested in the CE-2 mission. The success of CE-2 will provide important technical basis for the successful implementation of China's future lunar exploration."

Launch

Chang'e 2 spacecraft was launched on 1 October 2010 at 10:59:57 UTC, aboard a Long March 3C rocket from Xichang Satellite Launch Center in Xichang, Sichuan. The spacecraft entered an orbit with a perigee of 200 kilometers and apogee of 380,000 kilometers and separated from the carrier rocket as planned. It was the first time that a Chinese lunar probe directly entered the earth-moon transfer orbit without orbiting the earth first. After the launch, Chang'e 2 was expected to arrive at its lunar orbit in about 112 hours (about 4 days and 16 hours), much faster than the 12 days taken by Chang'e 1. Later, the probe was to lower its orbit to 100 km (62 mi) and have a lower point of only 15 km (9.3 mi). Chang'e 2 entered its 100 km working orbit on 9 October 2010 after three successful brakings. On 8 November 2010, China announced the success of all missions of Chang'e 2 and published moon surface images with resolution up to 1.3 metres.

Significance

The launch of the probe coincided with the National Day of the People's Republic of China, on October 1, in a symbolic celebration of the country's 61st anniversary.