



Active Space Exploration Missions

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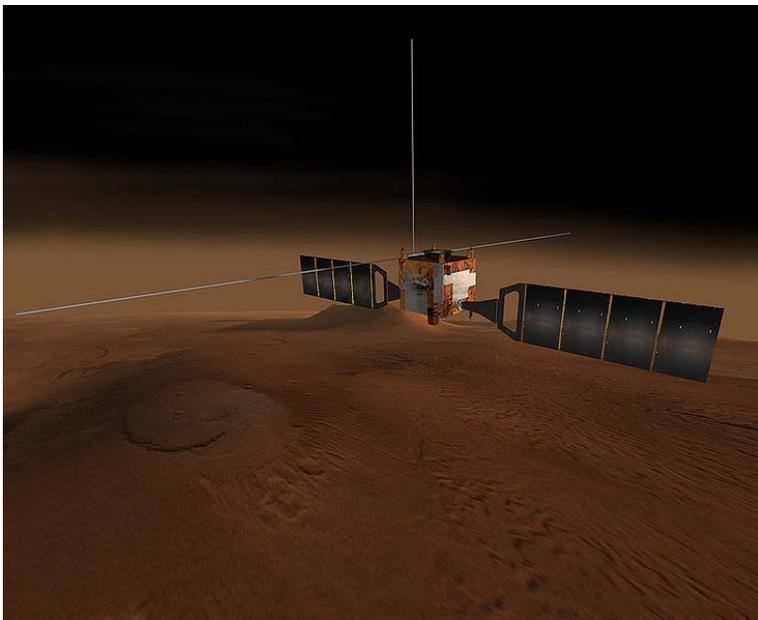
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Chapter- 1

Mars Express

Mars Express



CG image of Mars Express

Operator	ESA
Mission type	Orbiter + Lander
Satellite of	Mars
Orbital insertion date	December 25, 2003
Launch date	June 2, 2003
Launch vehicle	Soyuz-FG/Fregat
COSPAR ID	2003-022A
Mass	1123 (666 + 457 fuel) kg

Power 460 W (Mars)

Orbital elements

Eccentricity 0.943

Inclination 86.3°

Apoapsis 10,107 km

Periapsis 298 km

Orbital period 7.5 hr

Mars Express is a space exploration mission being conducted by the European Space Agency (ESA). The Mars Express mission is exploring the planet Mars, and is the first planetary mission attempted by the agency. "Express" originally referred to the speed and efficiency with which the spacecraft was designed and built. However "Express" also describes the spacecraft's relatively short interplanetary voyage, a result of being launched when the orbits of Earth and Mars brought them closer than they had been in about 60,000 years.

Mars Express consists of two parts, the *Mars Express Orbiter* and the *Beagle 2*, a lander designed to perform exobiology and geochemistry research. Although the lander failed to land safely on the Martian surface, the Orbiter has been successfully performing scientific measurements since early 2004, namely, high-resolution imaging and mineralogical mapping of the surface, radar sounding of the subsurface structure down to the permafrost, precise determination of the atmospheric circulation and composition, and study of the interaction of the atmosphere with the interplanetary medium.

Due to the valuable science return and the highly flexible mission profile, *Mars Express* has been granted four mission extensions, the latest until December 31, 2012.

Some of the instruments on the orbiter, including the camera systems and some spectrometers, reuse designs from the failed launch of the Russian Mars 96 mission in 1996 (European countries had provided much of the instrumentation and financing for that unsuccessful mission). The basic design of Mars Express is based on ESA's Rosetta mission, on which a considerable sum was spent on development. The same design was also used for the *Venus Express* mission in order to increase reliability and reduce development cost and time.

Mission profile and timeline overview

Mission overview

The Mars Express mission is dedicated to the orbital (and originally in-situ) study of the interior, subsurface, surface and atmosphere, and environment of the planet Mars. The

scientific objectives of the Mars Express mission represent an attempt to fulfil in part the lost scientific goals of the Russian Mars-96 mission, complemented by exobiology research with Beagle-2. Mars exploration is crucial for a better understanding of the Earth from the perspective of comparative planetology.

The spacecraft originally carried seven scientific instruments, a small lander, a lander relay and a Visual Monitoring Camera, all designed to contribute to solving the mystery of Mars' missing water. All of the instruments take measurements of the surface, atmosphere and interplanetary media, from the main spacecraft in polar orbit, which will allow it to gradually cover the whole planet.

The overall Mars Express budget excluding the lander is €150 million (roughly US\$185 million).

Spacecraft construction

The prime contractor for the construction of Mars Express Orbiter was EADS Astrium Satellites.

Mission preparation

In the years preceding the launch of a spacecraft numerous teams of experts distributed over the contributing companies and organisations prepared the space and ground segments. Each of these teams focussed on the area of its responsibility and interfacing as required. A major additional requirement raised for the Launch and Early Orbit Phase (LEOP) and all critical operational phases was that it was not enough merely to interface; the teams had to be integrated into one Mission Control Team. All the different experts had to work together in an operational environment and the interaction and interfaces between all elements of the system (software, hardware and human) had to run smoothly for this to happen:

- the flight operations procedures had to be written and validated down to the smallest detail;
- the control system had to be validated;
- system Validation Tests (SVTs) with the satellite had to be performed to demonstrate the correct interfacing of the ground and space segments;
- mission Readiness Test with the Ground Stations had to be performed;
- a Simulations Campaign was run.

Launch

The spacecraft was launched on June 2, 2003 at 23:45 local time (17:45 UT, 1:45 p.m. EDT) from Baikonur Cosmodrome in Kazakhstan, using a Soyuz-FG/Fregat rocket. The Mars Express and Fregat booster were initially put into a 200 km Earth parking orbit, then the Fregat was fired again at 19:14 UT to put the spacecraft into a Mars transfer orbit. The Fregat and Mars Express separated at approximately 19:17 UT. The solar

panels were then deployed and a trajectory correction maneuver was performed on June 4 to aim Mars Express towards Mars and allow the Fregat booster to coast into interplanetary space.

Near earth commissioning phase

The Near Earth Commissioning phase extended from the separation of the spacecraft from the launcher upper stage until the completion of the initial check out of the orbiter and payload. It included the solar array deployment, the initial attitude acquisition, the declamping of the Beagle-2 spin-up mechanism, the injection error correction manoeuvre and the first commissioning of the spacecraft and payload (final commissioning of payload took place after Mars Orbit Insertion). The payload was checked out one instrument at a time. This phase lasted about one month.

The interplanetary cruise phase

This five month phase lasted from the end of the Near Earth Commissioning phase until one month prior to the Mars capture manoeuvre and included trajectory correction manoeuvres and payloads calibration. The payload was mostly switched off during the cruise phase, with the exception of some intermediate check-outs. Although it was originally meant to be a "quiet cruise" phase, It soon became obvious that this "cruise" would be indeed very busy. There were star Tracker problems, a power wiring problem, extra manoeuvres, and on the 28th of October, the spacecraft was hit by one of the largest solar flares ever recorded.

Lander jettison

The Beagle 2 lander was released on December 19 at 8:31 UTC (9:31 CET) on a ballistic cruise towards the surface. It entered Mars' atmosphere on the morning of December 25. Landing was expected to occur at about 02:45 UT on December 25 (9:45 p.m. EST December 24). However, after repeated attempts to contact the lander failed using the Mars Express craft and the NASA Mars Odyssey orbiter, it was declared lost on February 6, 2004, by the Beagle 2 Management Board. On February 11, ESA announced an inquiry would be held into the failure of *Beagle 2*.

Orbit insertion

Mars Express arrived at Mars after a 400 million km journey and course corrections in September and in December 2003.

On December 20 Mars Express fired a short thruster burst to put it into position to orbit the planet. The Mars Express Orbiter then fired its main engine and went into a highly elliptical initial-capture orbit of 250 km × 150,000 km with an inclination of 25 degrees on December 25 at 03:00 UT (10:00 p.m., December 24 EST).

First evaluation of the orbital insertion showed that the orbiter had reached its first milestone at Mars. The orbit was later adjusted by four more main engine firings to the desired 259 km × 11,560 km near-polar (86 degree inclination) orbit with a period of 7.5 hours. Near periapsis the top deck is pointed down towards the Martian surface and near apoapsis the high gain antenna will be pointed towards Earth for uplink and downlink.

After 100 days the apoapsis was lowered to 10,107 km and periapsis raised to 298 km to give an orbital period of 6.7 hours.

MARSIS deployment

On May 4, 2005, *Mars Express* deployed the first of its two 20-metre-long radar booms for its MARSIS (Mars Advanced Radar for Subsurface and Ionosphere Sounding) experiment. At first the boom didn't lock fully into place; however, exposing it to sunlight for a few minutes on May 10 fixed the glitch. The second 20 m boom was successfully deployed on June 14. Both 20 m booms were needed to create a 40 m dipole antenna for MARSIS to work; a less crucial 7-meter-long monopole antenna was deployed on June 17. The radar booms were originally scheduled to be deployed in April 2004, but this was delayed out of fear that the deployment could damage the spacecraft through a whiplash effect. Due to the delay it was decided to split the four week commissioning phase in two parts, with two weeks running up to July 4 and another two weeks in December 2005.

The deployment of the booms was a critical and highly complex task requiring effective inter-agency cooperation ESA, NASA, Industry and public Universities.

Nominal science observations began during July 2005.

Operations of the spacecraft

Operations for Mars Express are carried out by a multinational team of engineers from ESA's Operation Centre (ESOC) in Darmstadt. The team began preparations for the mission about 3 to 4 years prior to the actual launch. This involved preparing the ground segment and the operational procedures for the whole mission.

The Mission Control Team is composed of the Flight Control Team, Flight Dynamics Team, Ground Operations Managers, Software Support and Ground Facilities Engineers. All of these are located at ESOC but there are additionally external teams, such as the Project and Industry Support teams, who designed and built the spacecraft. The Flight Control Team consists of:

- The Spacecraft Operations Manager
- Eight Operations Engineers
- Three Mission Planners
- One Spacecraft Analyst
- Five Spacecraft controllers

The team build-up, headed by the Spacecraft Operations Manager, started about 4 years before launch. He was required to recruit a suitable team of engineers that could handle the varying tasks involved in the mission. For Mars Express the engineers came from various other missions. Most of them had been involved with Earth orbiting satellites.

Routine phase: Science return

Since orbit insertion Mars Express has been progressively fulfilling its original scientific goals. Nominally the spacecraft points to Mars while acquiring science and then slews to earth-pointing to downlink the data, although some instruments like Marsis or Radio Science might be operated while spacecraft is earth-pointing.

Mars Express Spacecraft Orbiter and subsystems

Structure

The Mars Express Orbiter is a cube-shaped spacecraft with two solar panel wings extending from opposite sides. The launch mass of 1123 kg includes a main bus with 113 kg of payload, the 60 kg lander, and 457 kg of propellant. The main body is 1.5 m × 1.8 m × 1.4 m in size, with an aluminium honeycomb structure covered by an aluminum skin. The solar panels measure about 12 m tip-to-tip. Two 20 m long wire dipole antennas extend from opposite side faces perpendicular to the solar panels as part of the radar sounder.

Propulsion

The Soyuz/Fregat launcher provided most of the thrust Mars Express needed to reach Mars. The final stage of the Fregat was jettisoned once the probe was safely on a course for Mars. The spacecraft's on-board means of propulsion was used to slow the probe for Mars orbit insertion and subsequently for orbit corrections.

The body is built around the main propulsion system, which consists of a bipropellant 400 N main engine. The two 267-liter propellant tanks have a total capacity of 595 kg. Approximately 370 kg are needed for the nominal mission. Pressurized helium from a 35 liter tank is used to force fuel into the engine. Trajectory corrections will be made using a set of eight 10 N thrusters, one attached to each corner of the spacecraft bus. The spacecraft configuration is optimized for a Soyuz/Fregat, and was fully compatible with a Delta II launch vehicle.

Power

Spacecraft power is provided by the solar panels which contain 11.42 square meters of silicon cells. The originally planned power was to be 660 W at 1.5 AU but a faulty connection has reduced the amount of power available by 30%, to about 460 W. This loss of power is not expected to significantly impact the science return of the mission. Power is stored in three lithium-ion batteries with a total capacity of 64.8 Ah for use during

eclipses. The power is fully regulated at 28 V. During routine phase, the spacecraft's power consumption is in the interval 450 W - 550 W.

Avionics

Attitude control (3-axis stabilization) is achieved using two 3-axis inertial measurement units, a set of two star cameras and two Sun sensors, gyroscopes, accelerometers, and four 12 N·m·s reaction wheels. Pointing accuracy is 0.04 degree with respect to the inertial reference frame and 0.8 degree with respect to the Mars orbital frame. Three on-board systems help Mars Express maintain a very precise pointing accuracy, which is essential to allow the spacecraft to communicate with a 35-metre and 70-metre dish on Earth up to 400 million kilometres away.

Communications

The communications subsystem is composed of 3 antennas: A 1.7 m diameter parabolic dish high-gain antenna and two omnidirectional antennas. The first one provide links (Telecommands uplink and Telemetry downlink) in both X-band (7.1 GHz) and S-band (2.1 GHz) and is used during nominal science phase around Mars. The low gain antennas are used during Launch and early operations to Mars and for eventual contingencies once in orbit. Two Mars lander relay UHF antennas are mounted on the top face for communication with the Beagle 2.

Earth Stations

Although communications with Earth were originally scheduled to take place with the ESA 35-meter wide Ground Station in New Norcia (Australia) New Norcia Station, the mission profile of progressive enhancement and science return flexibility have triggered the use of the newest ESA ESTRACK Ground Station in Cebreros Station, Madrid, Spain.

In addition, further agreements with NASA Deep Space Network have made possible the use of American stations for nominal mission planning, thus increasing complexity but with a clear positive impact in scientific returns.

This inter-agency cooperation has proven effective, flexible and enriching for both sides. On the technical side, it has been made possible (among other reasons) thanks to the adoption of both Agencies of the Standards for Space Communications defined in CCSDS

Thermal

Thermal control is maintained through the use of radiators, multi-layer insulation, and actively controlled heaters. The spacecraft must provide a benign environment for the instruments and on-board equipment. Two instruments, PFS and OMEGA, have infrared detectors that need to be kept at very low temperatures (about -180 °C). The sensors on

the camera (HRSC) also need to be kept cool. But the rest of the instruments and on-board equipment function best at room temperatures (10-20 °C).

The spacecraft is covered in gold-plated aluminium-tin alloy thermal blankets to maintain a temperature of 10-20 °C inside the spacecraft. The instruments that operate at low temperatures to be kept cold are thermally insulated from this relatively high internal temperature, and emit excess heat into space using attached radiators.

Control Unit and Data storage

The spacecraft is run by two Control and Data management Units with 12 gigabits of solid state mass memory for storage of data and housekeeping information for transmission. The on-board computers control all aspects of the spacecraft functioning including switching instruments on and off, assessing the spacecraft orientation in space and issuing commands to change it.

Another key aspect of the Mars Express mission is the Mars Express AI Tool (MEXAR2). The primary purpose of the AI tool is the scheduling of when to download various parts of the collected scientific data back to Earth, a process which used to take ground controllers a significant amount of time. The new AI tool saves operator time, optimizes bandwidth use on the DSN, prevents data loss, and allows better use of the DSN for other space operations as well. The AI decides how to manage the spacecraft's 12 gigabits of storage memory, when the DSN will be available and not be in use by another mission, how to make the best use of the DSN bandwidth allocated to it, and when the spacecraft will be oriented properly to transmit back to Earth.

Lander



The *Beagle 2* lander component of Mars Express, as it would have appeared on the Martian surface.

The *Beagle 2* lander objectives were to characterize the landing site geology, mineralogy, and geochemistry, the physical properties of the atmosphere and surface layers, collect data on Martian meteorology and climatology, and search for possible signatures of life.

However, the landing attempt was unsuccessful and the lander was declared lost. A Commission of Inquiry on *Beagle 2* identified four possible causes, including insufficiently strong airbags and problems with parts of the landing system colliding, but was unable to reach any firm conclusions.

Mars Express instruments

The scientific objectives of the Mars Express Payload are to obtain global high-resolution photo-geology (10 m resolution), mineralogical mapping (100 m resolution) and mapping of the atmospheric composition, study the subsurface structure, the global atmospheric circulation, and the interaction between the atmosphere and the subsurface, and the atmosphere and the interplanetary medium. The total mass budgeted for the science payload is 116 kg.

- **Visible and Infrared Mineralogical Mapping Spectrometer (OMEGA)**(Observatoire pour la Minéralogie, l'Eau, les Glaces et l'Activité) - France - Determines mineral composition of the surface up to 100 m resolution. Is mounted inside pointing out the top face. Instrument mass: 28.6 kg
- **Ultraviolet and Infrared Atmospheric Spectrometer (SPICAM)** - France - Assesses elemental composition of the atmosphere. Is mounted inside pointing out the top face. Instrument mass: 4.7 kg
- **Sub-Surface Sounding Radar Altimeter (MARSIS)** - Italy - A radar altimeter used to assess composition of sub-surface aimed at search for frozen water. Is mounted in the body and is nadir pointing, and also incorporates the two 20 m antennas. Instrument mass: 13.7 kg
- **Planetary Fourier Spectrometer (PFS)** - Italy - Makes observations of atmospheric temperature and pressure (observations suspended in September 2005). Is mounted inside pointing out the top face, currently working. Instrument mass: 30.8 kg
- **Analyzer of Space Plasmas and Energetic Atoms (ASPERA)** - Sweden - Investigates interactions between upper atmosphere and solar wind. Is mounted on the top face. Instrument mass: 7.9 kg
- **High Resolution Stereo Camera (HRSC)**- Germany - Produces color images with up to 2 m resolution. Is mounted inside the spacecraft body, aimed through the top face of the spacecraft, which is nadir pointing during Mars operations. Instrument mass: 20.4 kg
- **Mars Express Lander Communications (MELACOM)** - UK - Allows Mars Express to act as a communication relay for landers on the Martian surface. (Has been tested with Mars Exploration Rovers, and was used to support the landing of NASA's Phoenix mission)
- **Mars Radio Science Experiment (MaRS)** - Uses radio signals to investigate atmosphere, surface, subsurface, gravity and solar corona density during solar conjunctions. It uses the communications subsystem itself.
- A small camera to monitor the lander ejection, VMC.

- More on Payload

Scientific discoveries and important events

For more than 5000 orbits, Mars Express Payload instruments have been nominally and regularly operated. HRSC camera has been consistently mapping the Martian surface with unprecedented resolution and has taken dozens of breath-taking pictures.

2004

- January 23

ESA announced the discovery of water ice in the South Polar ice cap, using data taken on January 18 with the OMEGA instrument.

- January 28

Mars Express Orbiter reaches final science orbit around Mars.

- March 17

Orbiter detects polar ice caps that contain 85% highly carbon dioxide (CO₂) ice and 15% water ice.

- March 30

A press release announces that the orbiter has detected methane in the Martian atmosphere. Although the amount is small, about 10 parts in a thousand million, it has excited scientists ask about its source. Since methane is removed from the Martian "air" very fast, there needs to be a current source that releases fresh methane still today. Because one of the possible sources could be microbial life, it is planned to verify the reliability of this data and especially watch for difference in the concentration in various places on Mars. It is hoped that the source of this gas can be discovered by finding its location of release.

- April 28

ESA announced that the deployment of the boom carrying the radar based MARSIS antenna was delayed. It described concerns with the motion of the boom during deployment, which can cause the spacecraft to be struck by elements of it. Further investigations are planned to make sure that this will not happen.

- July 15

Scientists working with the PFS instrument announced that they tentatively discovered the spectral features of the compound ammonia in the Martian

atmosphere. Just like methane discovered earlier (see above), ammonia breaks down rapidly in Mars' atmosphere and needs to be constantly replenished. This points towards the existence of active life or geological activity; two contending phenomena whose presence so far have remained undetected.

2005

- In 2005, ESA scientists reported that the OMEGA (Visible and Infrared Mineralogical Mapping Spectrometer)(Observatoire pour la Minéralogie, l'Eau, les Glaces et l'Activité) instrument data indicates the presence of hydrated sulphates, silicates and various rock-forming minerals.

- February 8

The delayed deployment of the MARSIS antenna has been given a green light by ESA. It is planned to take place in early May 2005.

- May 5

The first boom of the MARSIS antenna was successfully deployed. At first, there was no indication of any problems, but later it was discovered that one segment of the boom did not lock. The deployment of the second boom was delayed to allow for further analysis of the problem.

- May 11

Using the Sun's heat to expand the segments of the MARSIS antenna, the last segment locked in successfully.

- June 14

The second boom was deployed, and on June 16 ESA announced it was a success.

- June 22

ESA announces that MARSIS is fully operational and will soon begin acquiring data. This comes after the deployment of the third boom on June 17, and a successful transmission test on June 19.

2006

- September 21

ESA's Mars Express High Resolution Stereo Camera (HRSC) has obtained images of the Cydonia region, the location of the famous "Face on Mars". The massif became famous in a photo taken in 1976 by the American Viking 1

Orbiter. The image recorded with a ground resolution of approximately 13.7 metres per pixel.

- September 26

The Mars Express spacecraft has emerged from an unusually demanding eclipse season introducing a special, ultra-low-power mode nicknamed 'Sumo' - an innovative configuration aimed at saving the power necessary to ensure spacecraft survival.

This mode was developed through tight teamwork between ESOC mission controllers, principal investigators, industry and mission management.

- October

In October 2006 the Mars Express spacecraft has encountered a superior solar conjunction (alignment of Earth-Sun-Mars Express). The angle Sun-Earth-MEX reached a minimum on 23-Oct at 0.39 deg. at a distance of 2.66 AU. Operational measures were undertaken to minimize the impact of the link degradation, since the higher density of electrons in the solar plasma heavily impacts the radio frequency signal. More on

- December

Following the loss of NASA JPL Mars spacecraft Mars Global Surveyor (MGS), Mars Express team was requested to perform actions in the hopes of visually identifying the American spacecraft. Based on last ephemeris of MGS provided by JPL, the on-board high definition HRSC camera swept a region of the MGS orbit. Two attempts were made to find the craft, both unsuccessful.

2007

- January

First agreements with NASA-SPL undertaken for the support of Mars Express on the landing of the American lander Phoenix in May 2008

- February

The small camera VMC (used only once to monitor the lander ejection) has been recommissioned and first steps had been taken to offer students the possibility to participate in a campaign "Command Mars Express Spacecraft and take your own picture of Mars".

- February 23

As result of the important science return, the Science Program Committee (SPC) has granted a mission extension until May 2009 to Mars Express.

- June 28

The High Resolution Stereo Camera (HRSC) has produced dramatic images of key tectonic features in Aeolis Mensae.

2008

The Mars Express Team was the winner of the Sir Arthur Clarke Award for Best Team Achievement.

2009

- February 4

The ESA's Science Programme Committee has extended the operations of Mars Express until December 31, 2009.

- October 7

ESA's Science Programme Committee has approved the extension of mission operations for Mars Express until 31 December 2012.

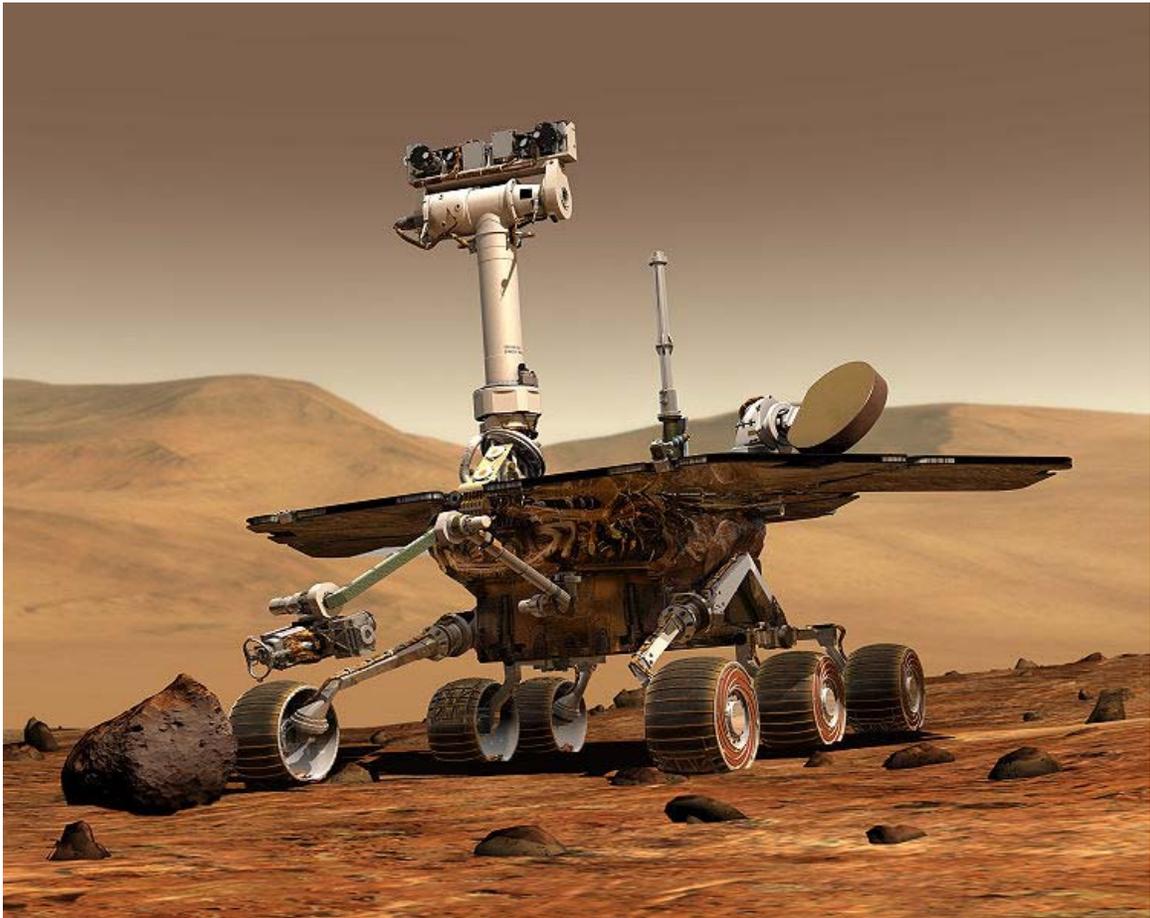
2010

- March 5

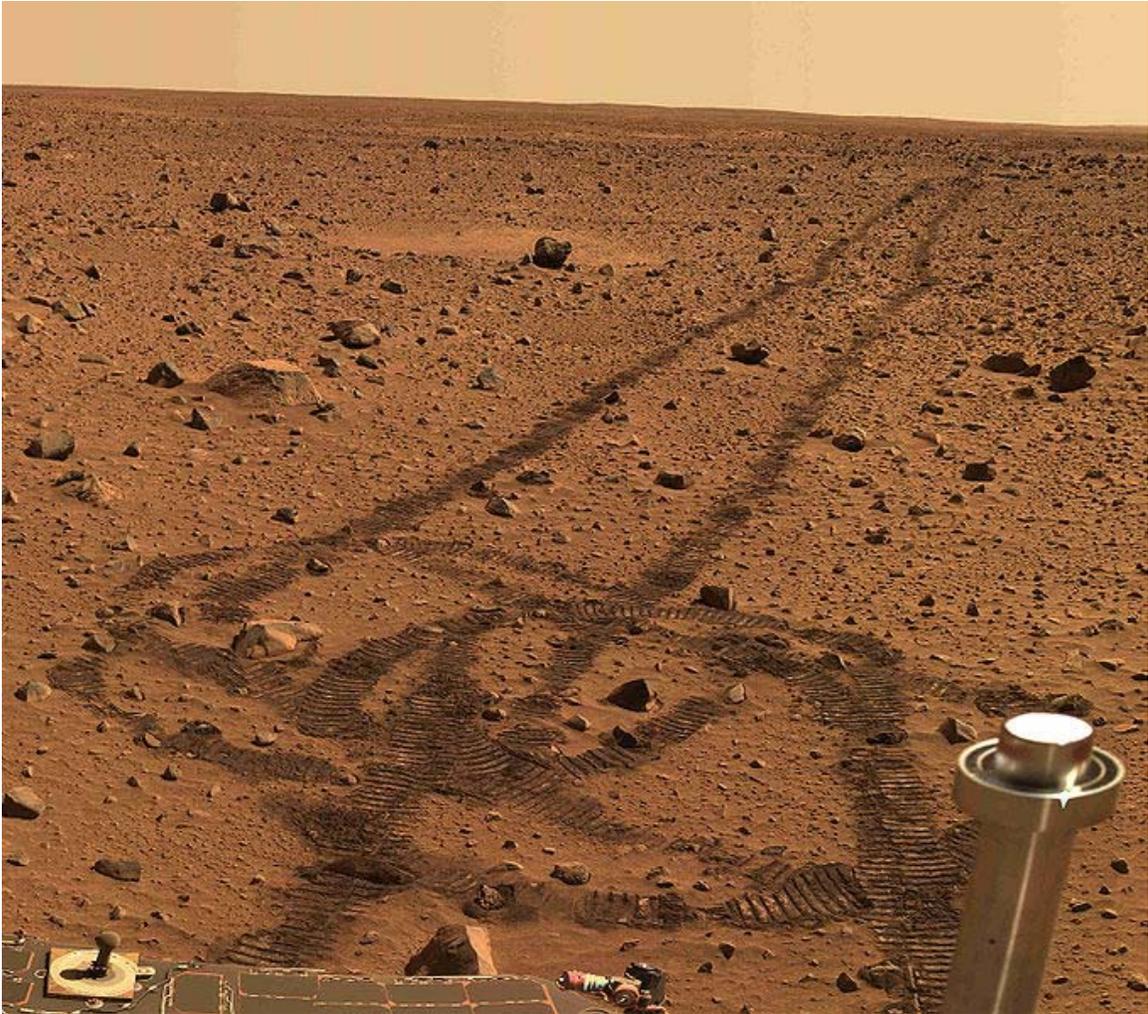
Flyby of Phobos to try to measure Phobos' gravity

Chapter- 2

Mars Exploration Rover



Artist's conception of rover on Mars



Part of a panorama taken by the Spirit rover in 2004

NASA's **Mars Exploration Rover Mission (MER)** is an ongoing robotic space mission involving two rovers, *Spirit and Opportunity*, exploring the planet Mars. It began in 2003 with the sending of the two rovers — MER-A *Spirit* and MER-B *Opportunity* — to explore the Martian surface and geology.

The mission's scientific objective was to search for and characterize a wide range of rocks and soils that hold clues to past water activity on Mars. The mission is part of NASA's Mars Exploration Program, which includes three previous successful landers: the two Viking program landers in 1976 and Mars Pathfinder probe in 1997.

The total cost of building, launching, landing and operating the rovers on the surface for the initial 90-Martian-day (sol) primary mission was US\$820 million. Since the rovers have continued to function beyond their initial 90 sol primary mission, they have each received five mission extensions. The fifth mission extension was granted in October 2007, and runs to the end of 2009. The total cost of the first four mission extensions was \$104 million, and the fifth mission extension is expected to cost at least \$20 million.

In July 2007, during the fourth mission extension, Martian dust storms blocked sunlight to the rovers and threatened the ability of the craft to gather energy through their solar panels, causing engineers to fear that one or both of them might be permanently disabled. However, the dust storms lifted, allowing them to resume operations.

On May 1, 2009, during its fifth mission extension, *Spirit* became stuck in soft soil on Mars. After nearly nine months of attempts to get the rover back on track, including using test rovers on Earth, NASA announced on January 26, 2010 that *Spirit* was being retasked as a stationary science platform. This mode will enable *Spirit* to assist scientists in ways that a mobile platform could not, such as detecting "wobbles" in the planet's rotation that would indicate a liquid core.

In recognition of the vast amount of scientific information amassed by both rovers, two asteroids have been named in their honor: 37452 Spirit and 39382 Opportunity. The mission is managed for NASA by the Jet Propulsion Laboratory, which designed, built, and is operating the rovers.

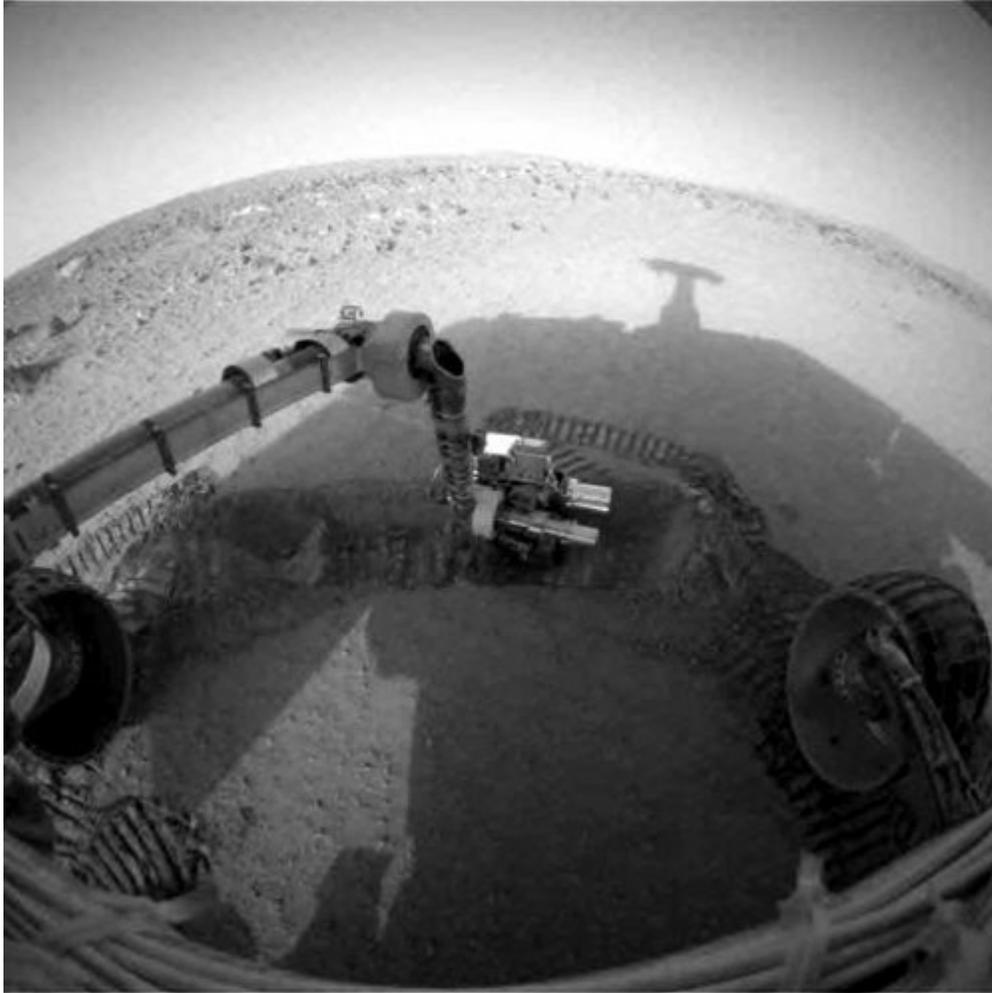
Objectives

The scientific objectives of the Mars Exploration Rover mission are to:

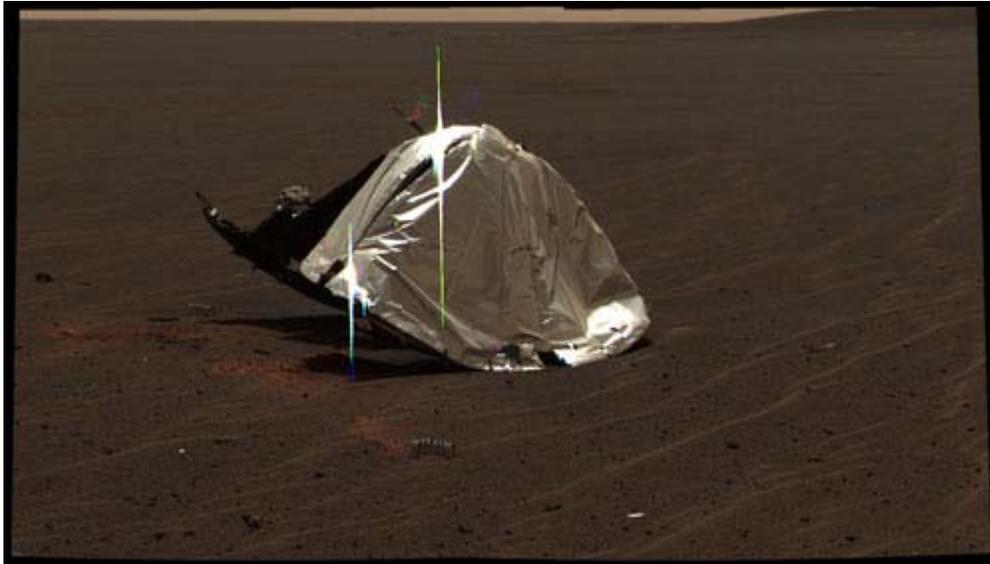
- Search for and characterize a variety of rocks and soils that hold clues to past water activity. In particular, samples sought include those that have minerals deposited by water-related processes such as precipitation, evaporation, sedimentary cementation, or hydrothermal activity.
- Determine the distribution and composition of minerals, rocks, and soils surrounding the landing sites.
- Determine what geologic processes have shaped the local terrain and influenced the chemistry. Such processes could include water or wind erosion, sedimentation, hydrothermal mechanisms, volcanism, and cratering.
- Perform calibration and validation of surface observations made by Mars Reconnaissance Orbiter instruments. This will help determine the accuracy and effectiveness of various instruments that survey Martian geology from orbit.
- Search for iron-containing minerals, and to identify and quantify relative amounts of specific mineral types that contain water or were formed in water, such as iron-bearing carbonates.
- Characterize the mineralogy and textures of rocks and soils to determine the processes that created them.
- Search for geological clues to the environmental conditions that existed when liquid water was present.
- Assess whether those environments were conducive to life.

During the next two decades, NASA will conduct several missions to address whether life ever existed on Mars. The search begins with determining whether the Martian environment was ever suitable for life. Life, as humans understand it, requires water, so the history of water on Mars is critical to finding out if the Martian environment was ever

conducive to life. Although the Mars Exploration Rovers do not have the ability to detect life directly, they offer important information on the habitability of the environment in the planet's history



NASA's Mars Exploration Rover *Spirit* casts a shadow over the trench that the rover is examining with tools on its robotic arm. *Spirit* took this image with its front hazard-avoidance camera on February 21, 2004, during the rover's 48th martian day, or sol 48.



Opportunity's discarded heat shield

History

On January 21, 2004, the Deep Space Network lost contact with *Spirit*, for reasons originally thought to be related to a thunderstorm over Australia. The rover transmitted a message with no data, but later that day missed another communications session with the Mars Global Surveyor. The next day, JPL received a beep from the rover, indicating that it was in fault mode. On January 23, the flight team succeeded in making the rover send. The fault was believed to have been caused by an error in the rover's flash memory subsystem. The rover did not perform any scientific activities for ten days, while engineers updated its software and ran tests. The problem was corrected by reformatting *Spirit's* flash memory and using a software patch to avoid memory overload; *Opportunity* was also upgraded with the patch as a precaution. *Spirit* returned to full scientific operations by February 5.

On March 23, 2004, a news conference was held announcing "major discoveries" of evidence of past liquid water on the Martian surface. A delegation of scientists showed pictures and data revealing a stratified pattern and cross bedding in the rocks of the outcrop inside a crater in Meridiani Planum, landing site of MER-B, *Opportunity*. This suggested that water once flowed in the region. The irregular distribution of chlorine and bromine also suggests that the place was once the shoreline of a salty sea, now evaporated.

On April 8, 2004, NASA announced that it was extending the mission life of the rovers from three to eight months. It immediately provided additional funding of US \$15 million through September, and \$2.8 million per month for continuing operations. Later that month, *Opportunity* arrived at Endurance crater, taking about five days to drive the 200 meters. NASA announced on September 22 that it was extending the mission life of the rovers for another six months. *Opportunity* was to leave Endurance crater, visit its

discarded heat shield, and proceed to Victoria crater. *Spirit* was to attempt to climb to the top of the Columbia Hills.

With the two rovers still functioning well, NASA later announced another 18 month extension of the mission to September 2006. *Opportunity* was to visit the "Etched Terrain" and *Spirit* was to climb a rocky slope toward the top of Husband Hill. On August 21, 2005, *Spirit* reached the summit of Husband Hill after 581 sols and a journey of 4.81 kilometers (2.99 mi).



Spirit's "postcard" view from the summit of Husband Hill: a windswept plateau strewn with rocks, small exposures of outcrop, and sand dunes. The view is to the north, looking down upon the "Tennessee Valley". This approximate true-color composite spans about 90 degrees and consists of eighteen frames captured by the rover's panoramic camera.

Spirit celebrated its one Martian year anniversary (669 sols or 687 Earth days) on November 20, 2005. *Opportunity* celebrated its anniversary on December 12, 2005. At the beginning of the mission, it was expected that the rovers would not survive much longer than 90 Martian days. The Columbia Hills were "just a dream", according to rover driver Chris Leger. *Spirit* explored the semicircular rock formation known as Home Plate. It is a layered rock outcrop that puzzles and excites scientists. It is thought that its rocks are explosive volcanic deposits, though other possibilities exist, including impact deposits or sediment borne by wind or water.

Spirit's front right wheel ceased working on March 13, 2006, while the rover was moving itself to McCool Hill. Its drivers attempted to drag the dead wheel behind Spirit, but this only worked until reaching an impassable sandy area on the lower slopes. Drivers directed *Spirit* to a smaller sloped feature, dubbed "Low Ridge Haven", where it spent the long Martian winter, waiting for spring and increased solar power levels suitable for driving. That September, *Opportunity* reached the rim of Victoria crater, and Spaceflight Now reported that NASA had extended mission for the two rovers through September

2007. On February 6, 2007, *Opportunity* became the first spacecraft to traverse ten kilometers (10,000 meters) on the surface of Mars.

Opportunity was poised to enter Victoria Crater from its perch on the rim of Duck Bay on June 28, 2007, but due to extensive dust storms, it was indefinitely delayed until the dust had cleared and power returned to safe levels. Two months later, *Spirit* and *Opportunity* resumed driving after hunkering down during raging dust storms that limited solar power to a level that nearly caused the permanent failure of both rovers.

On October 1, 2007, both *Spirit* and *Opportunity* entered their fifth mission extension that could possibly extend operations into 2009, allowing the rovers to have spent five years exploring the Martian surface, pending their continued survival.

On August 26, 2008, *Opportunity* began its three-day climb out of Victoria crater amidst concerns that power spikes, similar to those seen on *Spirit* before the failure of its right-front wheel, might prevent it from ever being able to leave the crater if a wheel failed. Project scientist Bruce Banerdt also said, "We've done everything we entered Victoria Crater to do and more." *Opportunity* will return to the plains in order to characterize Meridiani Planum's vast diversity of rocks—some of which may have been blasted out of craters such as Victoria. The rover had been exploring Victoria Crater since September 11, 2007. As of January 2009, the two rovers had collectively sent back 250,000 images and traveled over 21 kilometers (13 mi).

After driving about 3.2 kilometers (2 mi) since it left Victoria crater, *Opportunity* first saw the rim of Endeavour crater on March 7, 2009. It passed the 10-mile mark (16 kilometers) along the way on sol 1897. Meanwhile, at Gusev crater, *Spirit* was dug in deep into the Martian sand, much as *Opportunity* was at Purgatory Dune in 2005.

On January 3 and January 24, 2010, *Spirit* and *Opportunity* marked six years on Mars, respectively. On January 26, NASA announced that *Spirit* will be used as a stationary research platform after several months of unsuccessful attempts to free the rover from soft sand.

NASA announced on March 24, 2010, that *Opportunity*, which has an estimated remaining drive distance of 12 km to Endeavour Crater, has traveled over 20 km since the start of its mission. Each rover was designed with a mission driving distance goal of just 600 meters. One week later, they announced that *Spirit* may have gone into hibernation for the Martian winter and might not wake up again for months.

On September 8, 2010, it was announced that *Opportunity* had reached the halfway point of the 19-kilometer journey between Victoria crater and Endeavour crater.

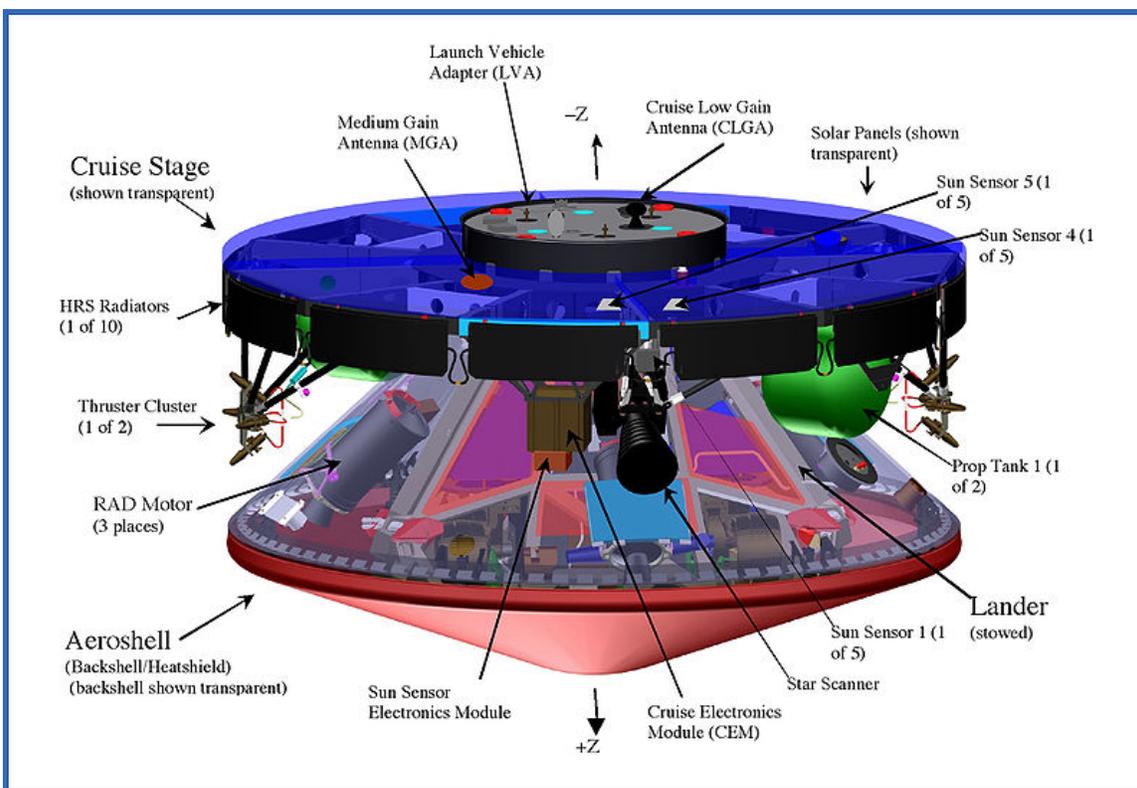
Spacecraft design



Delta II Heavy lifting off with MER-A on June 10, 2003



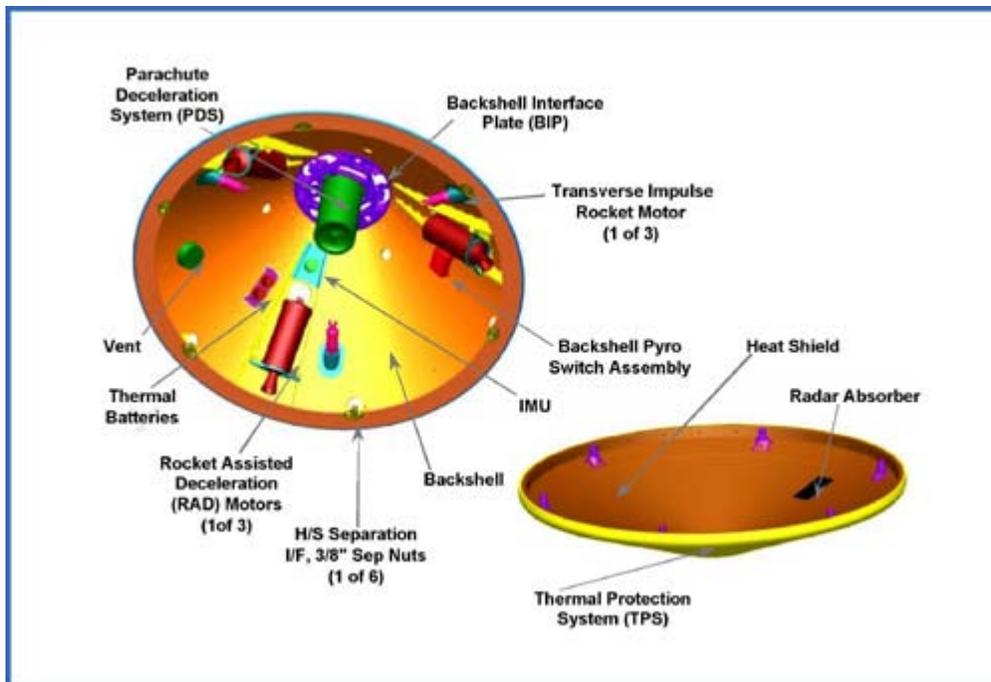
Delta II Heavy (7925H-9.5) lifting off from pad 17-B carrying MER-B



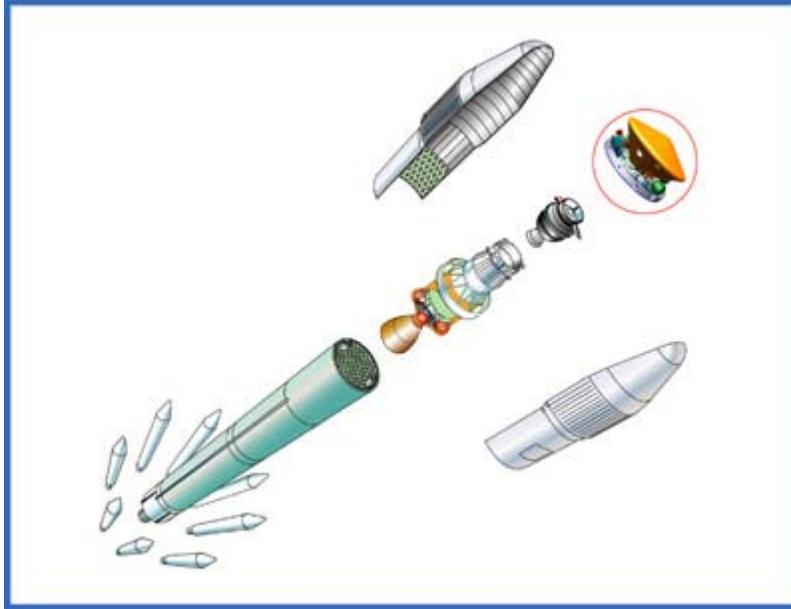
MER cruise stage diagram (Courtesy NASA/JPL-Caltech)



Cruise stage of *Opportunity* rover



Overview of the Mars Exploration Rover aeroshell



MER launch configuration, break apart illustration

The Mars Exploration Rover was designed to be stowed in the nose of a Delta II rocket. Each spacecraft consists of several components:

- Rover: 185 kg (408 lb)
- Lander: 348 kg (767 lb)
- Backshell / Parachute: 209 kg (461 lb)
- Heat Shield: 78 kg (172 lb)
- Cruise Stage: 193 kg (425 lb)
- Propellant: 50 kg (110 lb)
- Instruments: 5 kg (11 lb)

Total mass is 1,063 kg (2,343 lb).

Cruise stage

The cruise stage is the component of the spacecraft that is used for travel from Earth to Mars. It is very similar to the Mars Pathfinder in design and is approximately 2.65 meters (8.7 ft) in diameter and 1.6 m (5.2 ft) tall, including the entry vehicle (see below).

The primary structure is aluminium with an outer ring of ribs covered by the solar panels, which are about 2.65 m (8.7 ft) in diameter. Divided into five sections, the solar arrays can provide up to 600 watts of power near Earth and 300 W at Mars.

Heaters and multi-layer insulation keep the electronics "warm". A freon system removes heat from the flight computer and communications hardware inside the rover so they do not overheat. Cruise avionics systems allow the flight computer to interface with other electronics, such as the sun sensors, star scanner and heaters.

Navigation

The star scanner (with a backup system) and sun sensor allowed the spacecraft to know its orientation in space by analyzing the position of the Sun and other stars in relation to itself. Sometimes the craft could be slightly off course; this was expected, given the 500 million kilometer (320 million mile) journey. Thus navigators planned up to six trajectory correction maneuvers, along with health checks.

To ensure the spacecraft arrived at Mars in the right place for its landing, two light-weight, aluminium-lined tanks carried about 31 kg (about 68 lb) of hydrazine propellant. Along with cruise guidance and control systems, the propellant allowed navigators to keep the spacecraft on course. Burns and pulse firings of the propellant allowed three types of maneuvers:

- An axial burn uses pairs of thrusters to change spacecraft velocity;
- A lateral burn uses two "thruster clusters" (four thrusters per cluster) to move the spacecraft "sideways" through seconds-long pulses;
- Pulse mode firing uses coupled thruster pairs for spacecraft precession maneuvers (turns).

Communication

The spacecraft used a high-frequency X band radio wavelength to communicate, which allowed for less power and smaller antennas than many older craft, which used S band.

Navigators sent commands through two antennas on the cruise stage: a **cruise low-gain antenna** mounted inside the inner ring, and a **cruise medium-gain antenna** in the outer ring. The low-gain antenna was used close to Earth. It is omni-directional, so the transmission power that reached Earth fell faster with increasing distance. As the craft moved closer to Mars, the Sun and Earth moved closer in the sky as viewed from the craft, so less energy reached Earth. The spacecraft then switched to the medium-gain antenna, which directed the same amount of transmission power into a tighter beam toward Earth.

During flight, the spacecraft was spin-stabilized with a spin rate of two revolutions per minute (rpm). Periodic updates kept antennas pointed toward Earth and solar panels toward the Sun.

Aeroshell

The aeroshell maintained a protective covering for the lander during the seven month voyage to Mars. Together with the lander and the rover, it constituted the "entry vehicle". Its main purpose was to protect the lander and the rover inside it from the intense heat of entry into the thin Martian atmosphere. It was based on the Mars Pathfinder and Mars Viking designs.

Parts

The aeroshell was made of two main parts: a heat shield and a backshell. The heat shield was flat and brownish, and protected the lander and rover during entry into the Martian atmosphere and acted as the first aerobrake for the spacecraft. The backshell was large, cone-shaped and painted white. It carried the parachute and several components used in later stages of entry, descent, and landing, including:

- A parachute (stowed at the top of the backshell);
- The backshell electronics and batteries that fire off pyrotechnic devices like separation nuts, rockets and the parachute mortar;
- A Litton LN-200 Inertial Measurement Unit (IMU), which monitors and reports the orientation of the backshell as it swings under the parachute;
- Three large solid rocket motors called RAD rockets (Rocket Assisted Descent), each providing about a ton of force (10 kilonewtons) for about 4 seconds;
- Three small solid rockets called TIRS (mounted so that they aim horizontally out the sides of the backshell) that provide a small horizontal kick to the backshell to help orient the backshell more vertically during the main RAD rocket burn.

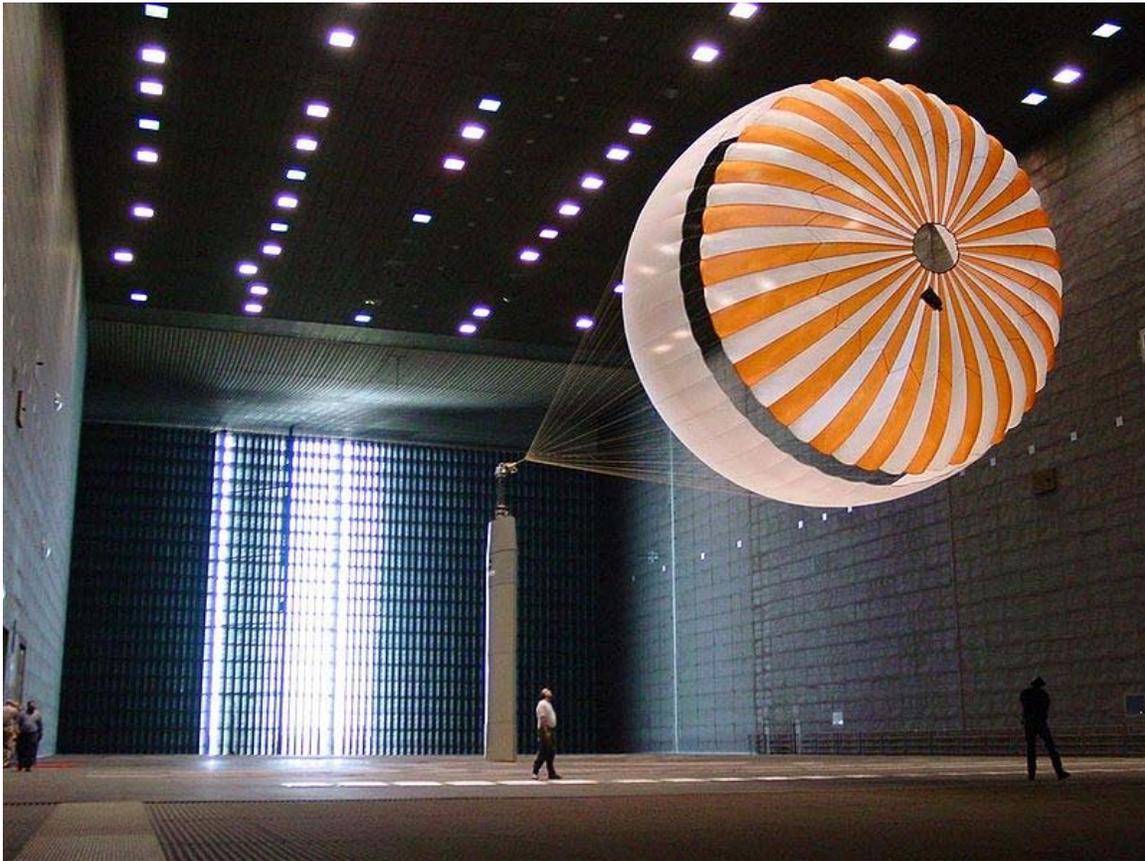
Composition

Built by the Lockheed Martin Astronautics Co. in Denver, Colorado, the aeroshell is made of an aluminium honeycomb structure sandwiched between graphite-epoxy face sheets. The outside of the aeroshell is covered with a layer of phenolic honeycomb. This honeycomb is filled with an ablative material (also called an "ablator"), that dissipates heat generated by atmospheric friction.

The ablator itself is a unique blend of cork wood, binder and many tiny silica glass spheres. It was invented for the heat shields flown on the Viking Mars lander missions. A similar technology was used in the first US manned space missions Mercury, Gemini and Apollo. It was specially formulated to react chemically with the Martian atmosphere during entry and carry heat away, leaving a hot wake of gas behind the vehicle. The vehicle slowed from 19000 km/h (about 12000 mph) to about 1600 km/h (1000 mph) in about a minute, producing about 60 m/s² (6 g) of acceleration on the lander and rover.

The backshell and heat shield are made of the same materials, but the heat shield has a thicker, 1/2 inch (12.7 mm), layer of the ablator. Instead of being painted, the backshell was covered with a very thin aluminized PET film blanket to protect it from the cold of deep space. The blanket vaporized during entry into the Martian atmosphere.

Parachute



Mars Exploration Rover's parachute test

The parachute helped slow the spacecraft during entry, descent, and landing. It is located in the backshell.

Design

The 2003 parachute design was part of a long-term Mars parachute technology development effort and is based on the designs and experience of the Viking and Pathfinder missions. The parachute for this mission is 40% larger than Pathfinder's because the largest load for the Mars Exploration Rover is 80 to 85 kilonewtons (kN) or 18,000 to 19,000 lbf (85 kN) when the parachute fully inflates. By comparison, Pathfinder's inflation loads were approximately 35 kN (about 8,000 lbf). The parachute was designed and constructed in South Windsor, Connecticut by Pioneer Aerospace, the company that also designed the parachute for the *Stardust* mission.

Composition

The parachute is made of two durable, lightweight fabrics: polyester and nylon. A triple bridle made of Kevlar connects the parachute to the backshell.

The amount of space available on the spacecraft for the parachute is so small that the parachute had to be pressure-packed. Before launch, a team tightly folded the 48 suspension lines, three bridle lines, and the parachute. The parachute team loaded the parachute in a special structure that then applied a heavy weight to the parachute package several times. Before placing the parachute into the backshell, the parachute was heat set to sterilize it.

Connected systems



Descent is halted by retrorockets and lander is dropped 10m (30 ft) to the surface in this computer generated impression.

Zylon Bridles: After the parachute was deployed at an altitude of about 10 km (6 miles) above the surface, the heatshield was released using 6 separation nuts and push-off springs. The lander then separated from the backshell and "rappelled" down a metal tape on a centrifugal braking system built into one of the lander petals. The slow descent down the metal tape placed the lander in position at the end of another bridle (tether), made of a nearly 20 m (65 ft) long braided Zylon.

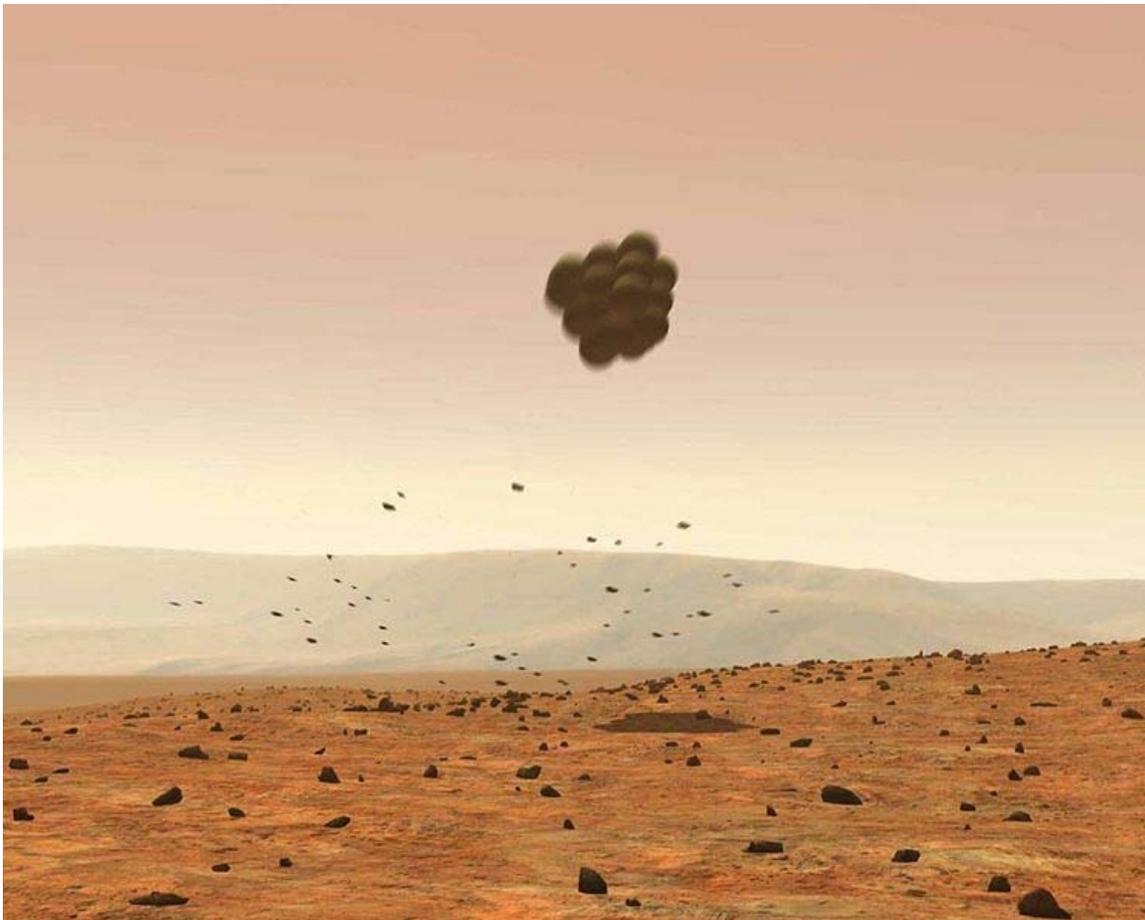
Zylon is an advanced fiber material, similar to Kevlar, that is sewn in a webbing pattern (like shoelace material) to make it stronger. The Zylon bridle provides space for airbag deployment, distance from the solid rocket motor exhaust stream, and increased stability.

The bridle incorporates an electrical harness that allows the firing of the solid rockets from the backshell as well as provides data from the backshell inertial measurement unit (which measures rate and tilt of the spacecraft) to the flight computer in the rover.

Rocket assisted descent (RAD) motors: Because the atmospheric density of Mars is less than 1% of Earth's, the parachute alone could not slow down the Mars Exploration Rover enough to ensure a safe, low landing speed. The spacecraft descent was assisted by rockets that brought the spacecraft to a dead stop 10–15 m (30–50 ft) above the Martian surface.

Radar altimeter unit: A radar altimeter unit was used to determine the distance to the Martian surface. The radar's antenna is mounted at one of the lower corners of the lander tetrahedron. When the radar measurement showed the lander was the correct distance above the surface, the Zylon bridle was cut, releasing the lander from the parachute and backshell so that it was free and clear for landing. The radar data also enabled the timing sequence on airbag inflation and backshell RAD rocket firing.

Airbags



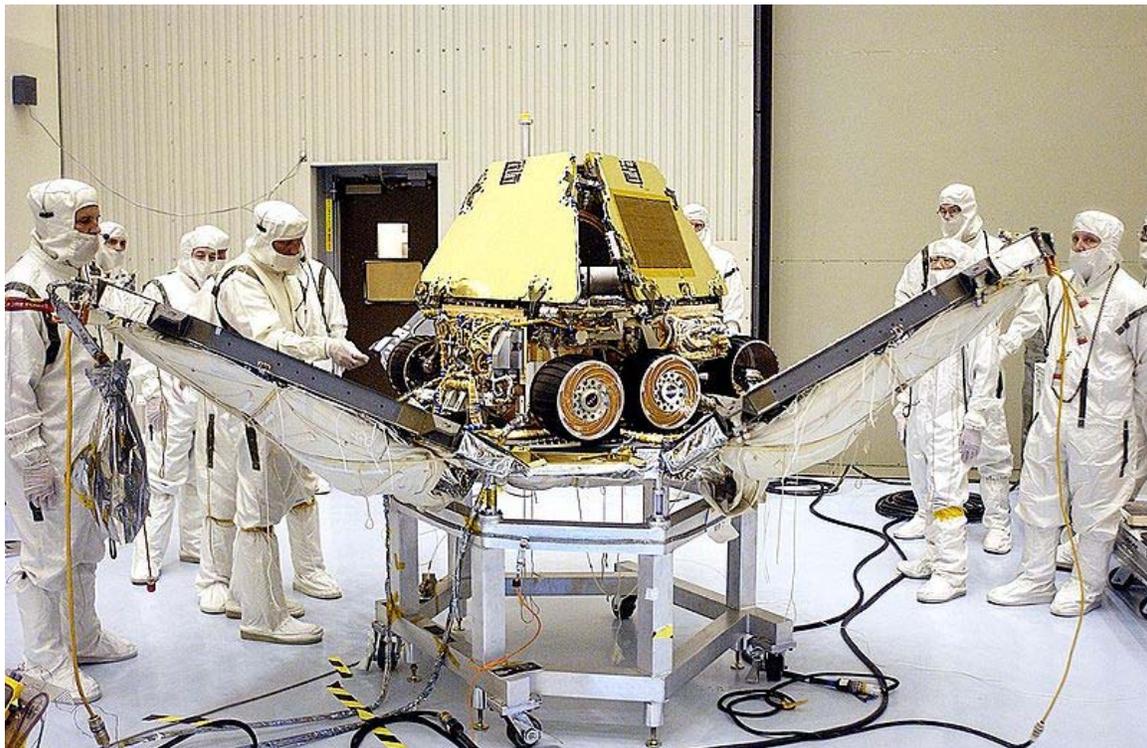
Artist's concept of inflated airbags

Airbags used in the Mars Exploration Rover mission are the same type that Mars Pathfinder used in 1997. They had to be strong enough to cushion the spacecraft if it landed on rocks or rough terrain and allow it to bounce across Mars' surface at freeway speeds after landing. The airbags had to be inflated seconds before touchdown and deflated once safely on the ground.

The airbags were made of Vectran, like those on Pathfinder. Vectran has almost twice the strength of other synthetic materials, such as Kevlar, and performs better in cold temperatures. Six 100 denier (10 mg/m) layers of Vectran protected one or two inner bladders of Vectran in 200 denier (20 mg/m). Using 100 denier (10 mg/m) leaves more fabric in the outer layers where it is needed, because there are more threads in the weave.

Each rover used four airbags with six lobes each, all of which were connected. Connection was important, since it helped abate some of the landing forces by keeping the bag system flexible and responsive to ground pressure. The airbags were not attached directly to the rover, but were held to it by ropes crisscrossing the bag structure. The ropes gave the bags shape, making inflation easier. While in flight, the bags were stowed along with three gas generators that are used for inflation.

Lander



MER lander petals opening (Courtesy NASA/JPL-Caltech)

The spacecraft lander is a protective "shell" that houses the rover, and together with the airbags, protects it from the forces of impact.

The lander is a tetrahedron shape, whose sides open like petals. It is strong and light, and made of beams and sheets. The beams consist of layers of graphite fiber woven into a fabric that is lighter than aluminium and more rigid than steel. Titanium fittings are glued and fitted onto the beams to allow it to be bolted together. The rover was held inside the lander by bolts and special nuts that were released after landing with small explosives.

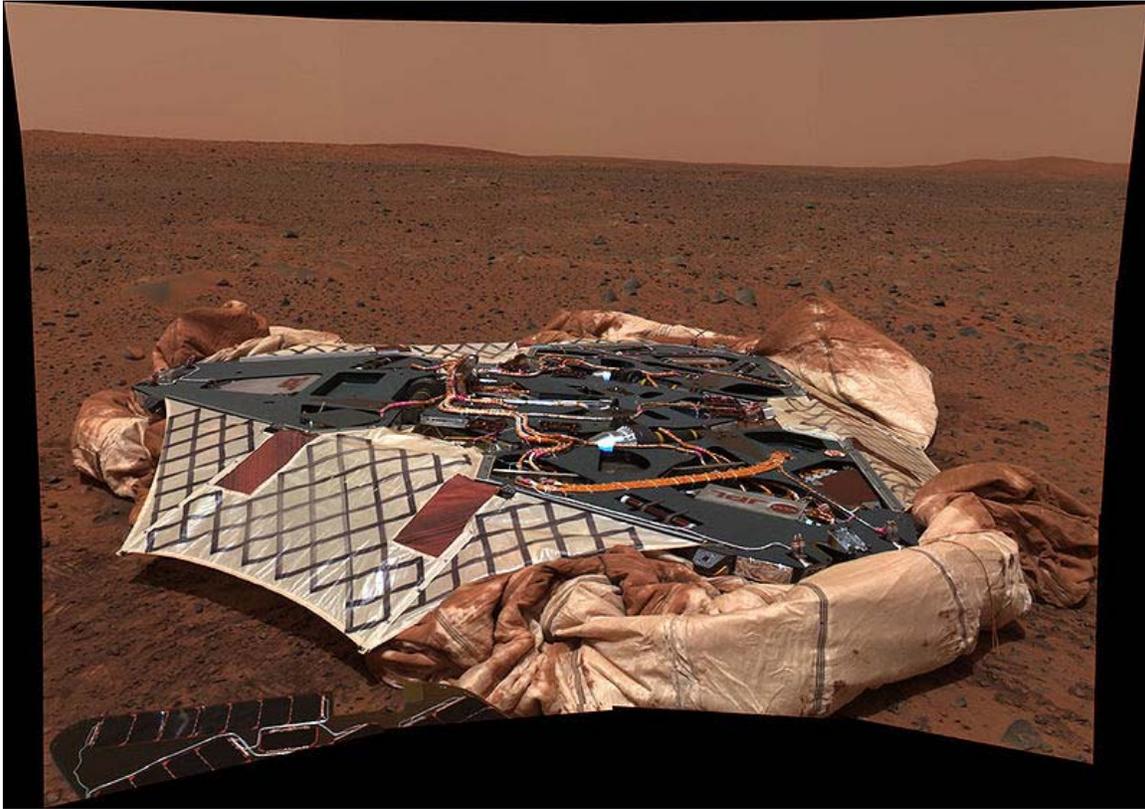
Uprighting

After the lander stopped bouncing and rolling on the ground, it came to rest on the base of the tetrahedron or one of its sides. The sides then opened to make the base horizontal and the rover upright. The sides are connected to the base by hinges, each of which has a motor strong enough to lift the lander. The rover plus lander has a mass of about 533 kilograms (1,175 pounds). The rover alone weighs about 185 kg (408 lb). The gravity on Mars is about 38% of Earth's, so the motor does not need to be as powerful as it would on Earth.

The rover contains accelerometers to detect which way is down (toward the surface of Mars) by measuring the pull of gravity. The rover computer then commanded the correct lander petal to open to place the rover upright. Once the base petal was down and the rover was upright, the other two petals were opened.

The petals initially opened to an equally flat position, so all sides of the lander were straight and level. The petal motors are strong enough so that if two of the petals come to rest on rocks, the base with the rover would be held in place like a bridge above the ground. The base will hold at a level even with the height of the petals resting on rocks, making a straight flat surface throughout the length of the open, flattened lander. The flight team on Earth could then send commands to the rover to adjust the petals and create a safe path for the rover to drive off the lander and onto the Martian surface without dropping off a steep rock.

Moving the payload onto Mars



Spirit's lander on Mars

The moving of the rover off the lander is called the egress phase of the mission. The rover must avoid having its wheels caught in the airbag material or falling off a sharp incline. To help this, a retraction system on the petals slowly drags the airbags toward the lander before the petals open. Small ramps on the petals fan out to fill spaces between the petals. They cover uneven terrain, rock obstacles, and airbag material, and form a circular area from which the rover can drive off in more directions. They also lower the step that the rover must climb down. They are nicknamed "batwings", and are made of Vectran cloth.

About three hours were allotted to retract the airbags and deploy the lander petals.

Rover design



Mars Exploration Rover vs. Sojourner rover (Courtesy NASA/JPL-Caltech)

The rovers are six-wheeled, solar-powered robots that stand 1.5 m (4.9 ft) high, 2.3 m (7.5 ft) wide and 1.6 m (5.2 ft) long. They weigh 180 kg (400 lb), 35 kg (80 lb) of which is the wheel and suspension system.

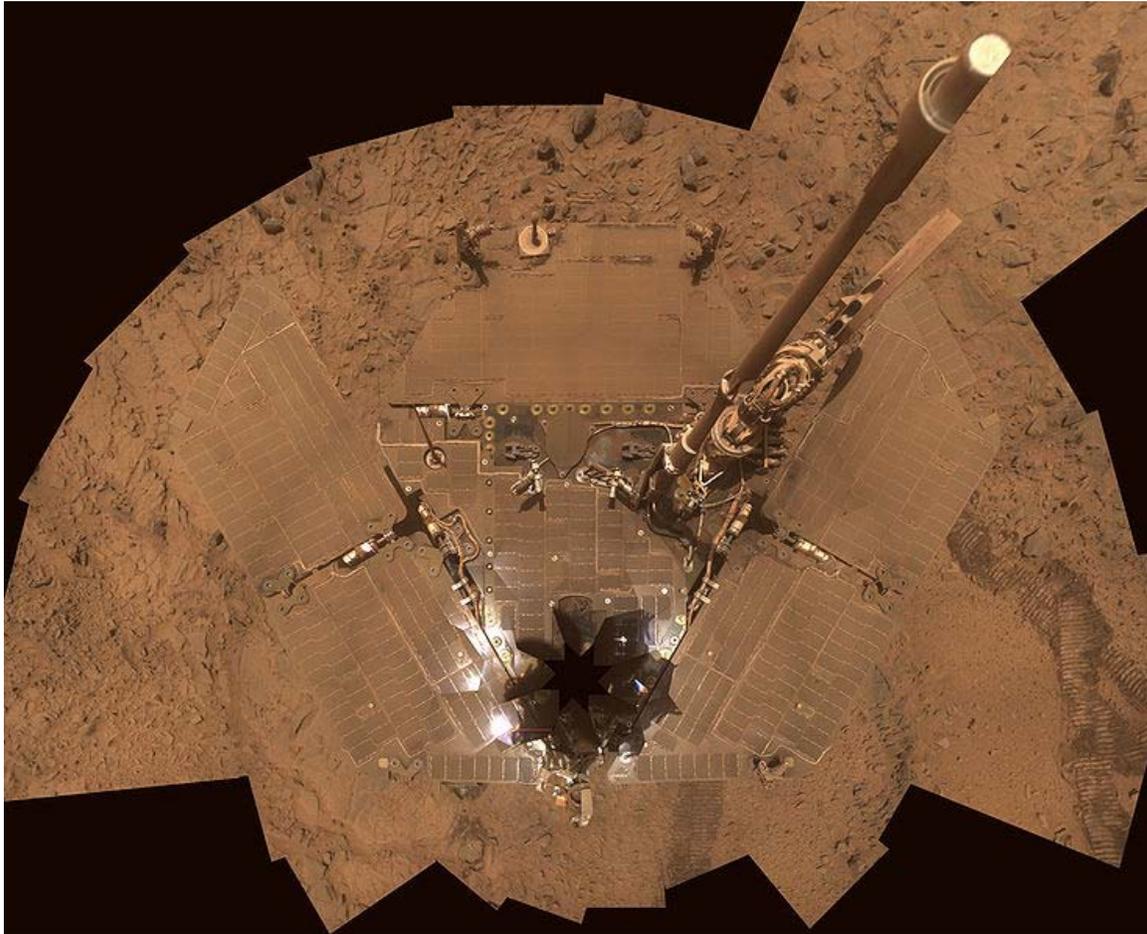
Drive system

Each rover has six wheels mounted on a rocker-bogie suspension system that ensures wheels remain on the ground while driving over rough terrain. The design reduces the range of motion of the rover body by half, and allows the rover to go over obstacles or through holes that are more than a wheel diameter (250 mm or 10 inches) in size. Each wheel also has cleats, providing grip for climbing in soft sand and scrambling over rocks.

Each wheel has its own motor. The two front and two rear wheels each have individual steering motors. This allows the vehicle to turn in place, a full revolution, and to swerve and curve, making arching turns. The rover is designed to withstand a tilt of 45 degrees in any direction without overturning. However, the rover is programmed through its "fault protection limits" in its hazard avoidance software to avoid exceeding tilts of 30 degrees.

Each rover can spin one of its front wheels in place to grind deep into the terrain. It is to remain motionless while the digging wheel is spinning. The rovers have a top speed on flat hard ground of 50 mm/s (2 in/s). The average speed is 10 mm/s, because its hazard avoidance software causes it to stop every 10 seconds for 20 seconds to observe and understand the terrain into which it has driven.

Power and electronic systems



Circular projection showing MER-A *Spirit's* solar panels covered in dust in October 2007 on Mars. Unexpected Cleaning events have periodically increased power.

When fully illuminated, the rover triplejunction solar arrays generate about 140 watts for up to four hours per Martian day (sol). The rover needs about 100 watts to drive. Its power system includes two rechargeable lithium ion batteries weighing 7.15 kg (16 pounds) each, that provide energy when the sun is not shining, especially at night. Over time, the batteries will degrade and will not be able to recharge to full capacity.

For comparison, the future Mars Science Laboratory's power system is composed of a Multi-Mission Radioisotope Thermoelectric Generator (MMRTG) produced by Boeing. The MMRTG is designed to provide 125W of electrical power at the start of the mission,

falling to 100W after 14 years of service. It will be used to power the MSL's many systems and instruments. Solar panels were also considered for the MSL, but RTGs provide constant power, regardless of the time of day, and thus the versatility to work in dark environments and high latitudes where solar energy is not readily available. The MSL will generate 2.5 kilowatt hours per day, compared to the Mars Exploration Rovers, which can generate about 0.6 kilowatt hours per day.

It was thought that by the end of the 90-sol mission, the capability of the solar arrays to generate power would likely be reduced to about 50 watts. This was due to anticipated dust coverage on the solar arrays, and the change in season. Over three Earth years later, however, the rovers' power supplies hovered between 300 watt-hours and 900 watt-hours per day, depending on dust coverage. Cleaning events (dust removal by wind) have occurred more often than NASA expected, keeping the arrays relatively free of dust and extending the life of the mission. During a 2007 global dust storm on Mars, both rovers experienced some of the lowest power of the mission; *Opportunity* dipped to 128 watt-hours. In November 2008, Spirit had overtaken this low-energy record with a production of 89 watt-hours, due to dust storms in the region of Gusev crater.

The rovers run a VxWorks embedded operating system on a radiation-hardened 20 MHz RAD6000 CPU with 128 MB of DRAM with error detection and correction and 3 MB of EEPROM. Each rover also has 256 MB of flash memory. To survive during the various mission phases, the rover's vital instruments must stay within a temperature of $-40\text{ }^{\circ}\text{C}$ to $+40\text{ }^{\circ}\text{C}$ ($-40\text{ }^{\circ}\text{F}$ to $104\text{ }^{\circ}\text{F}$). At night, the rovers are heated by eight radioisotope heater units (RHU), which each continuously generate 1 W of thermal energy from the decay of radioisotopes, along with electrical heaters that operate only when necessary. A sputtered gold film and a layer of silica aerogel are used for insulation.

Communication

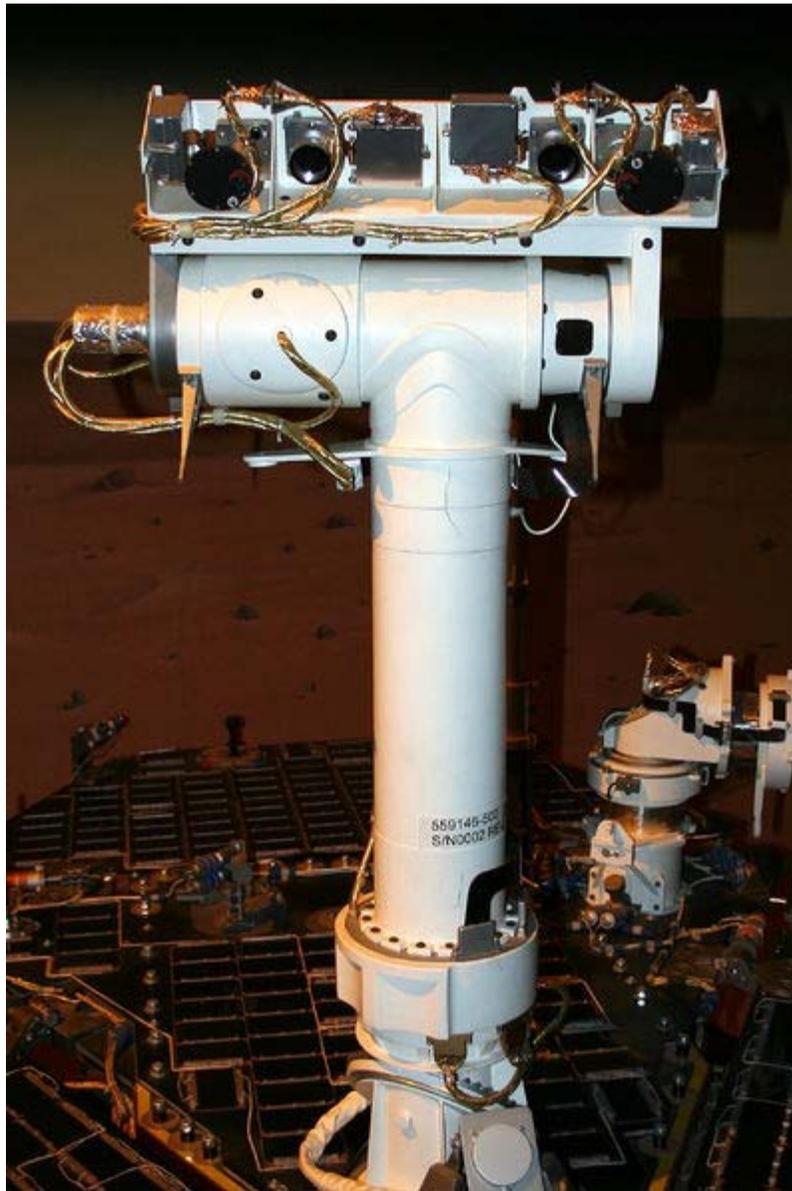
The rover has a low-gain and a high-gain antenna. The low-gain antenna is omnidirectional, and transmits data at a low rate to Deep Space Network (DSN) antennas on Earth. The high-gain antenna is directional and steerable, and can transmit data to Earth at a higher rate. The rovers also use the low-gain antennas to communicate with spacecraft orbiting Mars, the Mars Odyssey and (before its failure) the Mars Global Surveyor. The orbiters relay data from and to Earth; most data to Earth is relayed through Odyssey. The orbiters are closer to the rovers than the antennas on Earth, and have a view of Earth for much longer than the rovers. The orbiters communicate with the rovers using UHF antennas, which have shorter range than the low and high-gain antennas. One UHF antenna is on the rover, and one is on a petal of the lander to aid in gaining information during the critical landing event.

The rovers have a total of 9 cameras, which produce 1024-pixel by 1024-pixel images at 12 bits per pixel, but most navigation camera images and image thumbnails are truncated to 8 bits per pixel to conserve memory and transmission time. All images are then compressed using ICER before being stored and sent to Earth. Navigation, thumbnail, and many other image types are compressed to approximately 0.8 to 1.1 bits/pixel. Lower

bit rates (less than 0.5 bit/pixel) are used for certain wavelengths of multi-color panoramic images.

ICER is based on wavelets, and was designed specifically for deep-space applications. It produces progressive compression, both lossless and lossy, and incorporates an error-containment scheme to limit the effects of data loss on the deep-space channel. It outperforms the lossy JPEG image compressor and the lossless Rice compressor used by the Mars Pathfinder mission.

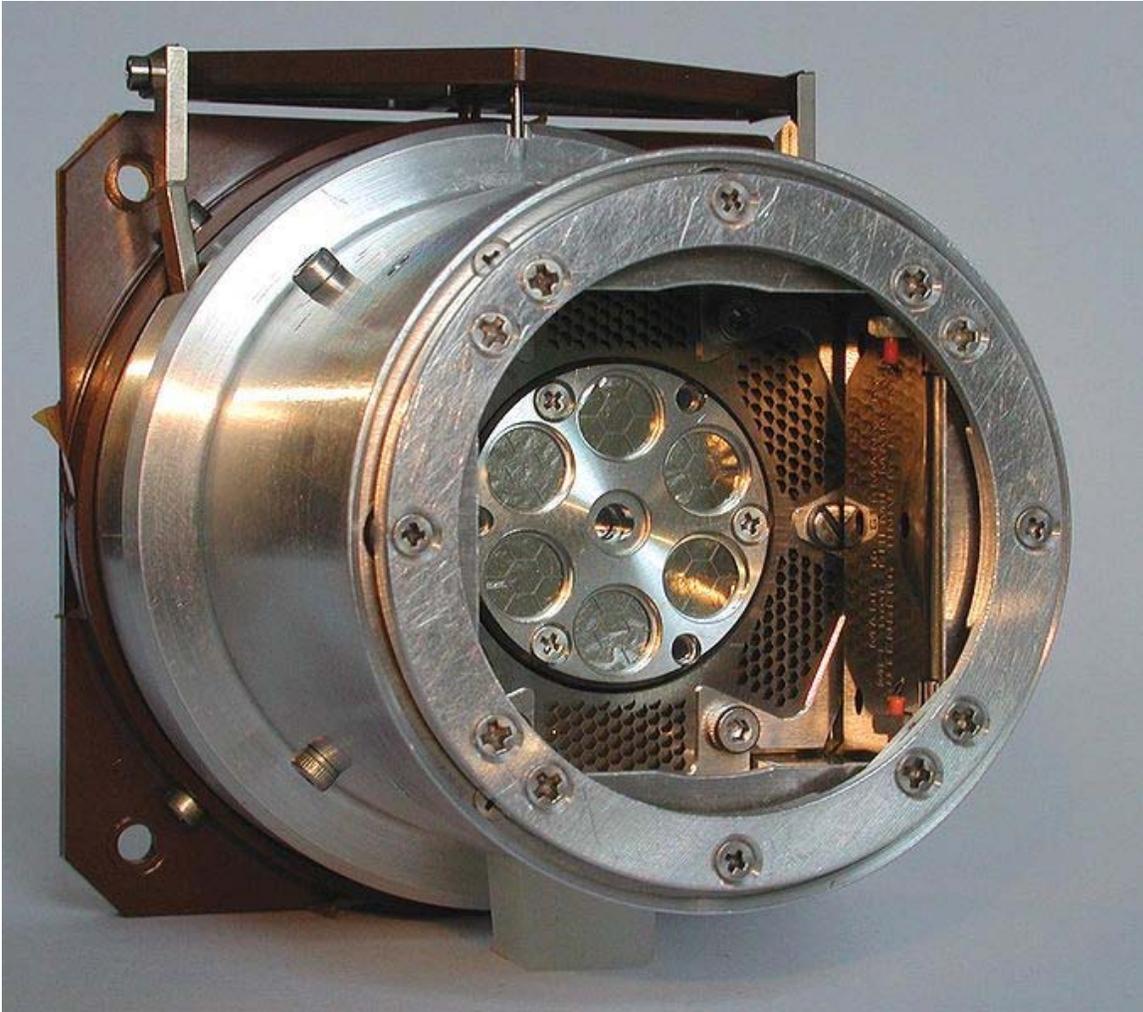
Scientific instrumentation



Panoramic Camera (Pancam)



Rock Abrasion Tool (RAT)



Alpha particle X-Ray Spectrometer (APXS) (Courtesy NASA/JPL-Caltech)

The rover has various instruments. Three are mounted on one assembly:

- Panoramic Camera (Pancam), for determining the texture, color, mineralogy, and structure of the local terrain.
- Navigation Camera (Navcam), that has higher field of view but lower resolution and is monochromatic, for navigation and driving.
- A mirror for the Miniature Thermal Emission Spectrometer (Mini-TES), which identifies promising rocks and soils for closer examination, and determines the processes that formed them. It was built by Arizona State University.

The cameras are mounted 1.5 meters high on the Pancam Mast Assembly. One motor turns the assembly horizontally a whole revolution. Another points the cameras vertically, at most straight up or down. A third motor points the Mini-TES, up to 30° above the horizon and 50° below. The assembly was built by Ball Aerospace & Technologies Corp., Boulder, Colorado, as was the High-Gain Antenna Gimbal (HGAG).

Four monochromatic hazard cameras (Hazcams) are mounted on the rover's body, two in front and two behind.

The instrument deployment device (IDD), also called the rover arm, holds the following:

- Mössbauer spectrometer (MB) MIMOS II, developed by Dr. Göstar Klingelhöfer at the Johannes Gutenberg University in Mainz, Germany, is used for close-up investigations of the mineralogy of iron-bearing rocks and soils.
- Alpha Particle X-Ray Spectrometer (APXS), developed by the Max Planck Institute for Chemistry in Mainz, Germany, is used for close-up analysis of the abundances of elements that make up rocks and soils.
- Magnets, for collecting magnetic dust particles, developed by Jens Martin Knudsen's group at the Niels Bohr Institute, Copenhagen. The particles are analyzed by the Mössbauer Spectrometer and X-ray Spectrometer to help determine the ratio of magnetic particles to non-magnetic particles and the composition of magnetic minerals in airborne dust and rocks that have been ground by the Rock Abrasion Tool. There are also magnets on the front of the rover, which are studied extensively by the Mössbauer spectrometer.
- Microscopic Imager (MI) for obtaining close-up, high-resolution images of rocks and soils. Development was led by Ken Herkenhoff's team at the USGS Astrogeology Research Program.
- Rock Abrasion Tool (RAT), developed by Honeybee Robotics, for removing dusty and weathered rock surfaces and exposing fresh material for examination by instruments on-board.

The robotic arm is able to place instruments directly up against rock and soil targets of interest.

Naming of Spirit and Opportunity

The *Spirit* and *Opportunity* rovers were named through a student essay competition. The winning entry was by Sofi Collis, a third-grade Russian-American student from Arizona.

I used to live in an orphanage. It was dark and cold and lonely. At night, I looked up at the sparkly sky and felt better. I dreamed I could fly there. In America, I can make all my dreams come true. Thank you for the 'Spirit' and the 'Opportunity.'

— Sofi Collis, age 9

Prior to this, during the development and building of the rovers, they were known as MER-1 (*Opportunity*) and MER-2 (*Spirit*). Internally, NASA also uses the mission designations MER-A (*Spirit*) and MER-B (*Opportunity*) based on the order of landing on Mars (*Spirit* first then *Opportunity*).

Test rovers



Rover team members simulate *Spirit* in a Martian sandtrap

The Jet Propulsion Laboratory maintains a pair of rovers at its location in Pasadena for testing and modeling of situations on Mars. One test rover, weighing approximately 180 kilograms (400 lb), is fully instrumented and nearly identical to *Spirit* and *Opportunity*. Another test version is identical in size and drive characteristics but does not include all instruments. It weighs in at 80 kilograms (180 lb), much closer to the weight of *Spirit* and *Opportunity* in the reduced gravity of Mars. These rovers were used in 2009 for a simulation of the incident in which *Spirit* became trapped in soft soil.

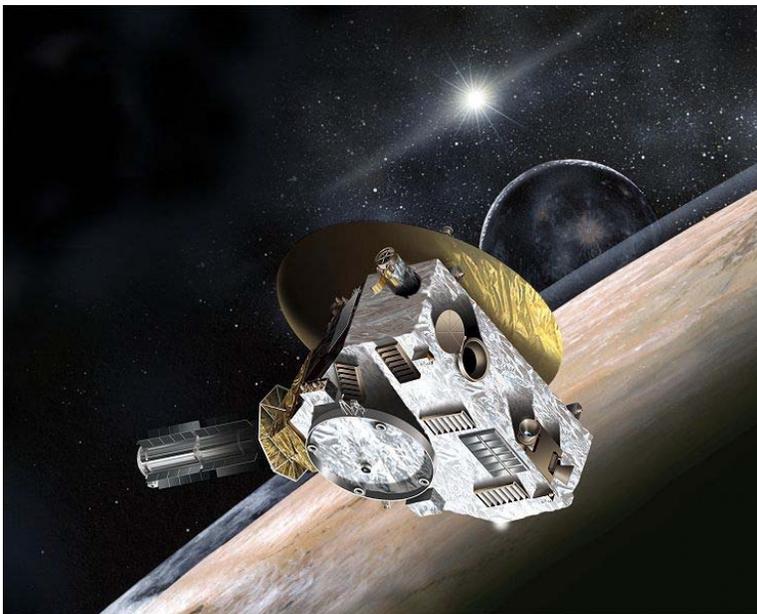
SAP

The NASA team uses a software application called *SAP* to view images collected from the rover, and to plan its daily activities. There is a version available to the public called Maestro.

Chapter- 3

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 26 days elapsed)
Launch vehicle	Atlas V 551
Launch site	Launch Complex 41

Cape Canaveral Air Force Station

In transit (Pluto)

(4 years, 11 months, and 26 days elapsed)

Mission duration

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 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 on the launchpad

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.

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.

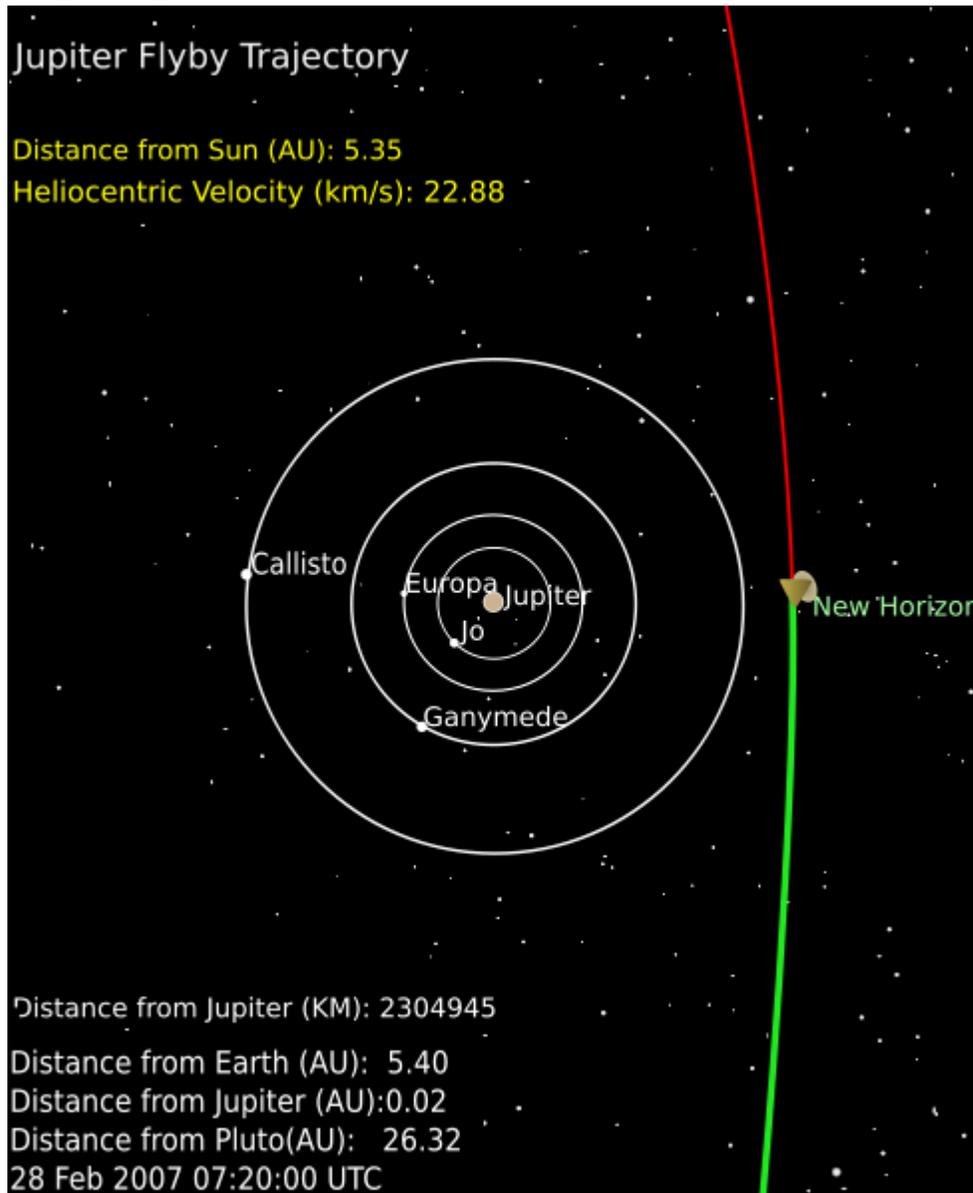
Passing Mars orbit and asteroid flyby

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 JF₅₆), 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



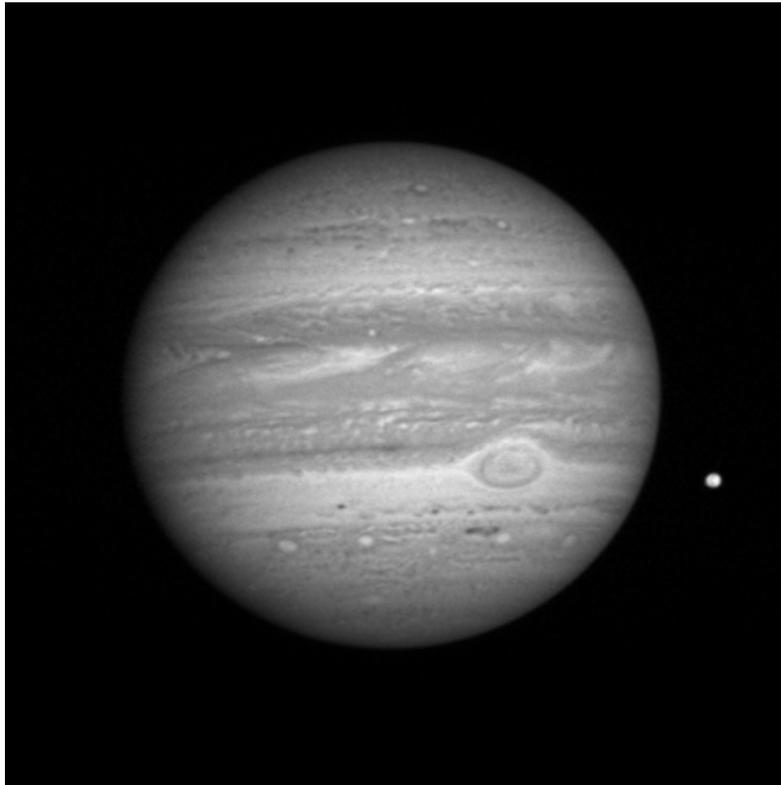
New Horizons at periapsis with Jupiter on February 28, 2007

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.

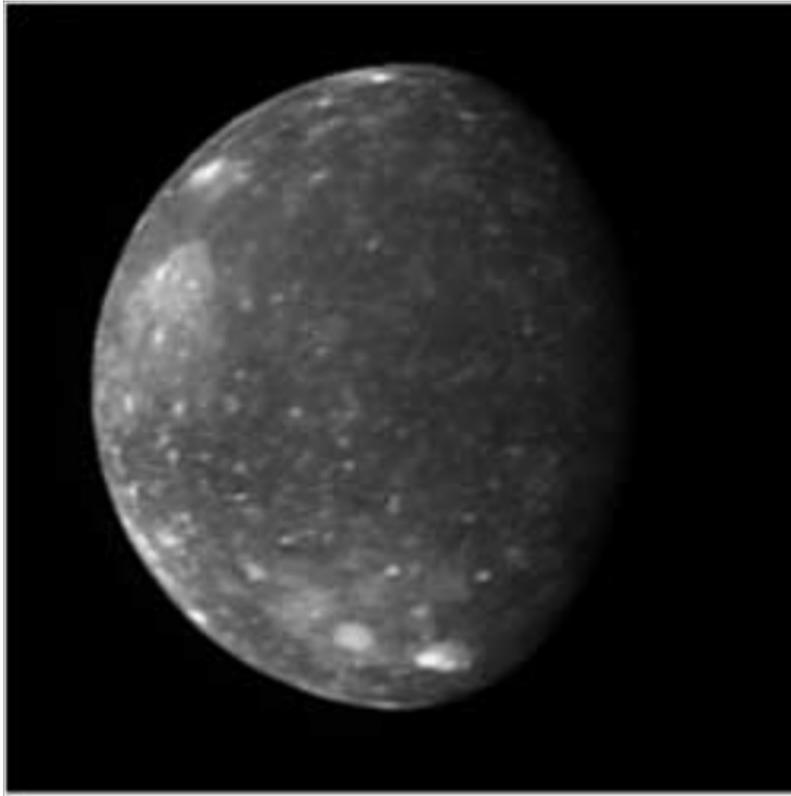
New Horizons received a Jupiter gravity assist with a closest approach at 5:43:40 UTC (12:43:40am EST) on February 28, 2007. It passed through the Jupiter system at 21 km/s (47,000 mph) relative to Jupiter (23 km/s (51,000 mph) relative to the Sun). The flyby increased *New Horizons'* speed away from 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.

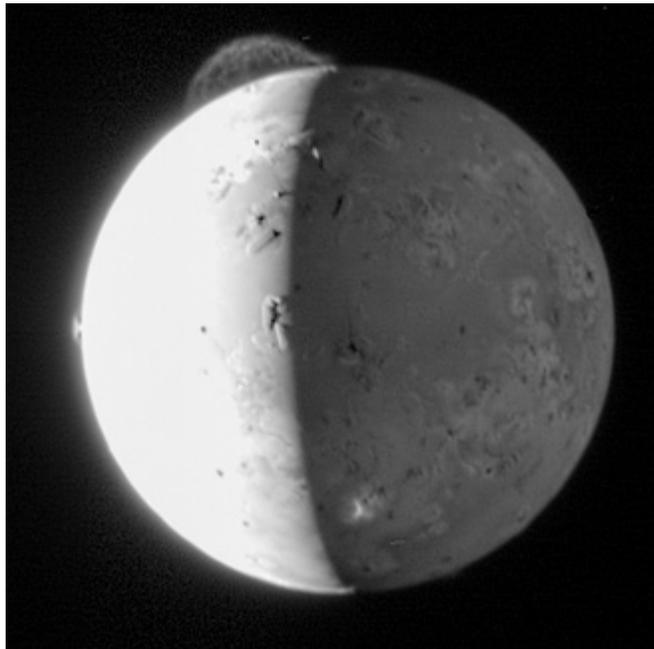
Jovian system imaged by New Horizons



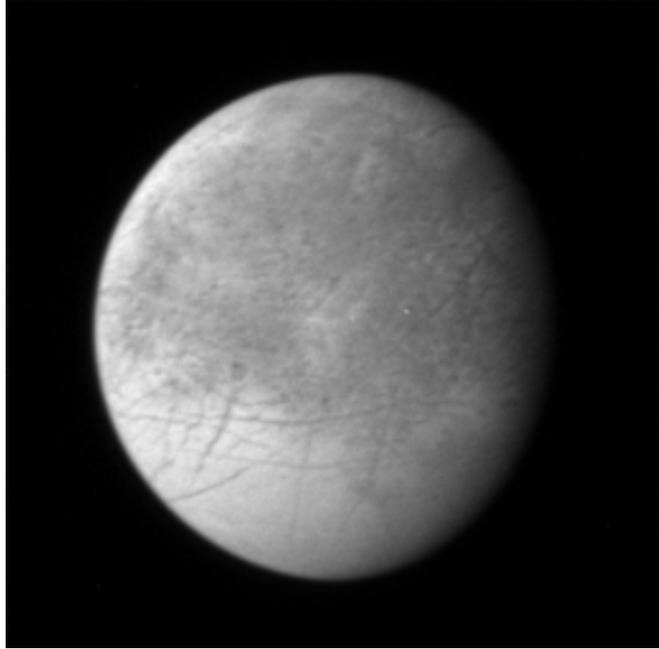
Jupiter and its moon Io imaged by *New Horizons* during flyby



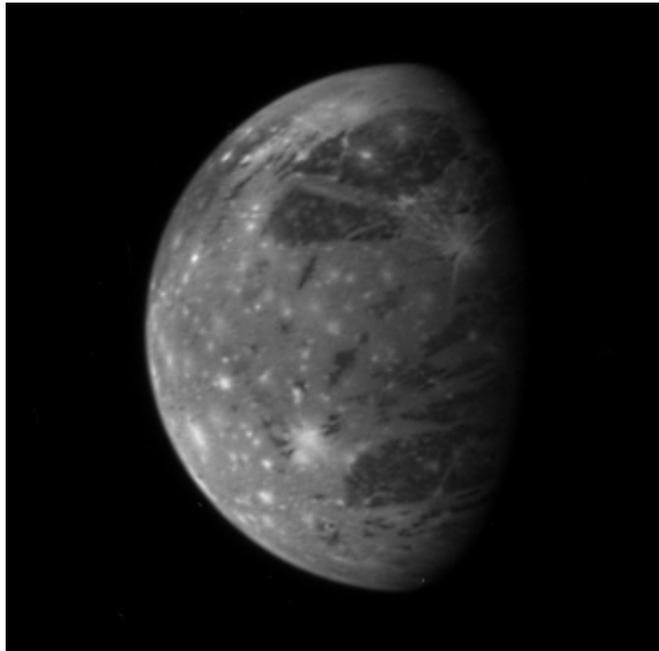
Callisto imaged by *New Horizons* during flyby



Io imaged by *New Horizons* during flyby

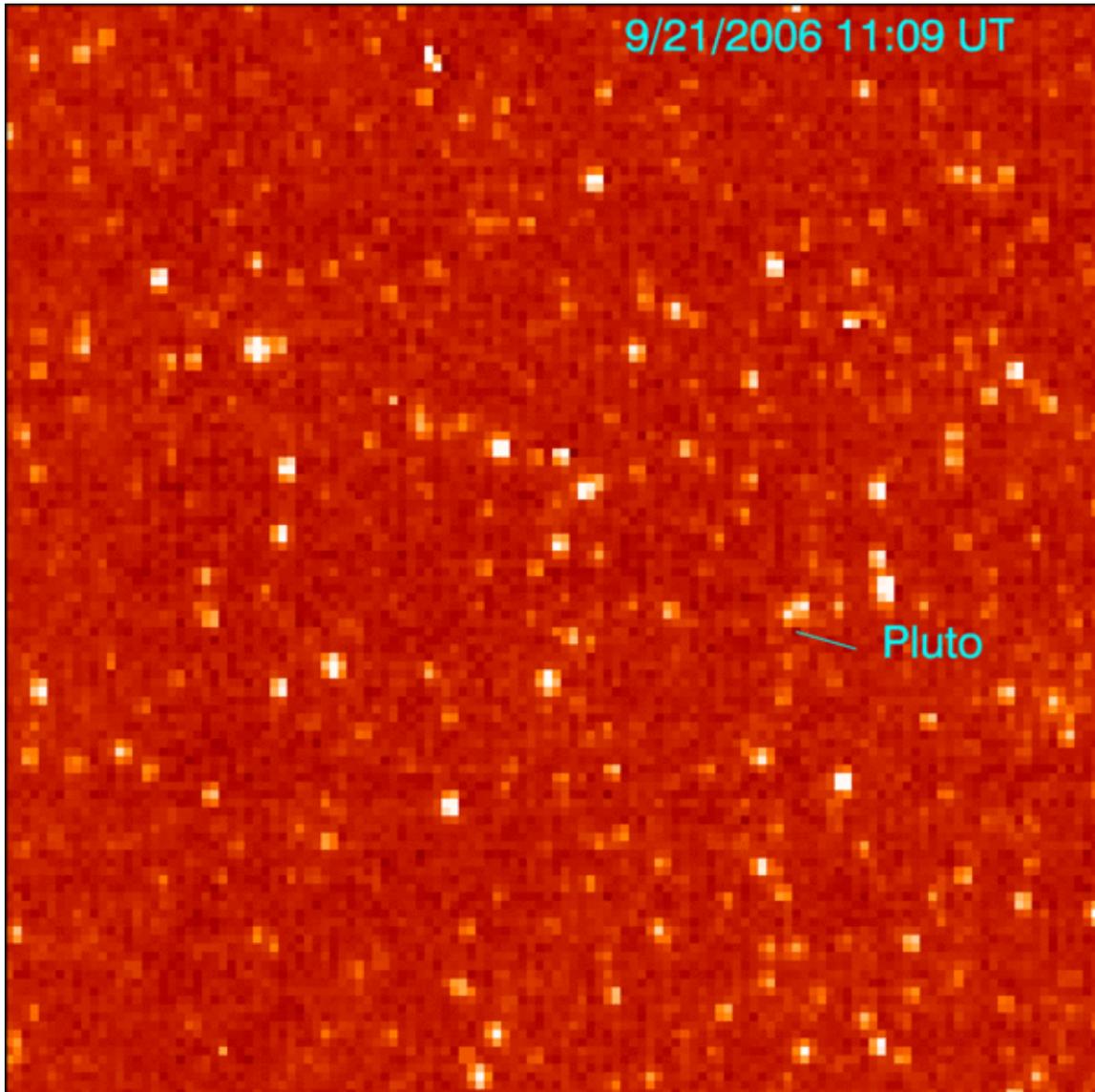


Europa imaged by *New Horizons* during flyby



Ganymede imaged by *New Horizons* during flyby

Pluto approach



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

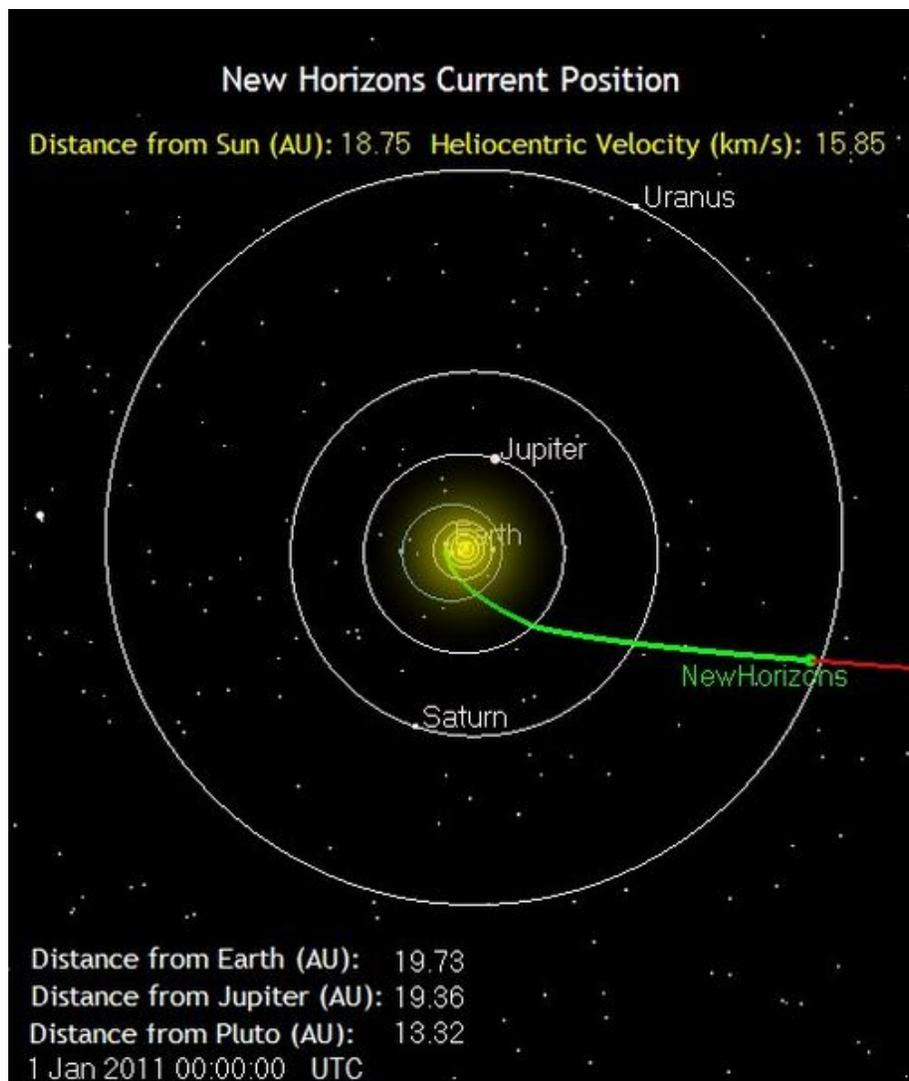
The first images of Pluto from *New Horizons* were created between September 21–24, 2006, during a test of the LORRI. They were released on November 28. The images, taken from a distance of approximately 4.2 billion kilometers (2.6 billion miles), confirmed the spacecraft's ability to track distant targets, 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 *Pioneers* had hexagonal bodies, while the *Voyagers*, *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 $\frac{1}{64}$ 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.)

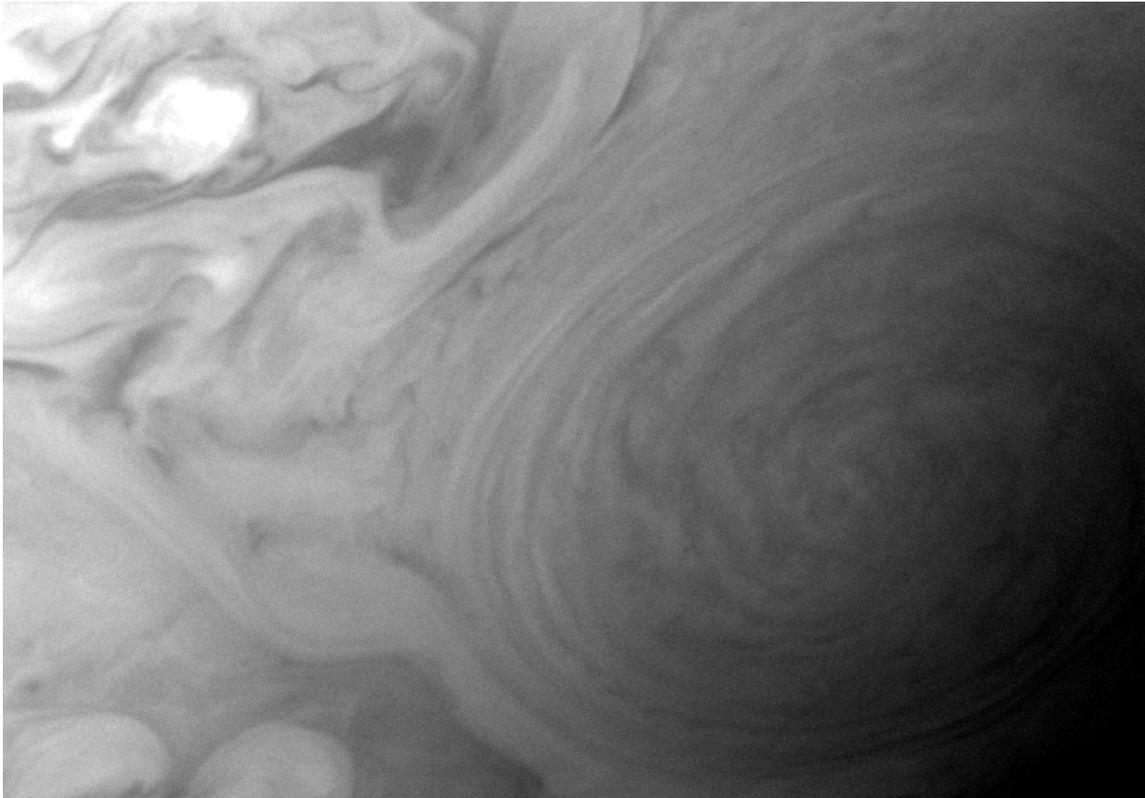
Flight computer

The spacecraft carries two computer systems, the Command and Data Handling system and the Guidance and Control processor. Each of the two systems is duplicated for redundancy, giving a total of four computers. The processor used is the Mongoose-V, a 12 MHz radiation-hardened version of the MIPS R3000 CPU. Multiple clocks and timing routines are implemented in hardware and software to help prevent faults and downtime.

To conserve heat and mass, spacecraft and instrument electronics are housed together in IEMs (Integrated Electronics Modules). There are two redundant IEMs. Including other functions such as instrument and radio electronics, each IEM contains 9 boards.

On March 19, 2007 the Command and Data Handling computer experienced an uncorrectable memory error and rebooted itself, causing the spacecraft to go into safe mode. The craft fully recovered within two days, with some data loss on Jupiter's magnetotail. No impact on the subsequent mission is expected.

Mission science



Enhanced view of Jupiter's "Little Red Spot" by the *New Horizons* space probe

The spacecraft carries seven scientific instruments. Total mass is 31 kg; rated power is 21 watts (though not all instruments operate simultaneously).

Long Range Reconnaissance Imager (LORRI)

A visible-light, high-resolution CCD imager with a 208.3 mm (8.20 in) aperture and 1024×1024 monochromatic CCD. Resolution is 5 microradians (approximately one arcsecond). The CCD is chilled far below freezing by a passive radiator on the antisolar face of the spacecraft. This temperature differential requires insulation, and isolation from the rest of the structure. The Ritchey-Chretien mirrors and metering structure are made of silicon carbide, to boost stiffness, reduce weight, and prevent warping at low temperatures. The optical elements sit in a composite light shield, and mount with titanium and fiberglass for thermal isolation. Overall mass is 8.6 kg, with the Optical tube assembly (OTA) weighing about 5.6 kg, for one of the largest silicon-carbide telescopes yet flown.

Pluto Exploration Remote Sensing Investigation (PERSI)

This consists of two instruments: The **Ralph** telescope, 6 centimeters in aperture, with two separate channels: a visible-light CCD imager (MVIC- Multispectral Visible Imaging Camera) with broadband and color channels, and a near-infrared imaging spectrometer, LEISA (Linear Etalon Imaging Spectral Array). LEISA is

derived from a similar instrument on the EO-1 mission. The second instrument is an ultraviolet imaging spectrometer, **Alice**. Alice resolves 1,024 wavelength bands in the far and extreme ultraviolet (from 180 to 50 nanometers), over 32 view fields. Its goal is to view the atmospheric makeup of Pluto. This Alice is derived from an Alice on the Rosetta mission. Ralph, designed afterwards, was named after Alice's husband on *The Honeymooners*. Ralph and Alice are names, not acronyms.

Plasma and high energy particle spectrometer suite (PAM)

Two instruments, consisting of **SWAP** (Solar Wind At Pluto), a toroidal electrostatic analyzer and retarding potential analyzer, and **PEPSSI** (Pluto Energetic Particle Spectrometer Science Investigation), a time of flight ion and electron sensor. SWAP measures particles of up to 6.5 keV, PEPSSI goes up to 1 MeV. Because of the tenuous solar wind at Pluto's distance, the SWAP instrument has the largest aperture of any such instrument ever flown.

Radio Science Experiment (REX)

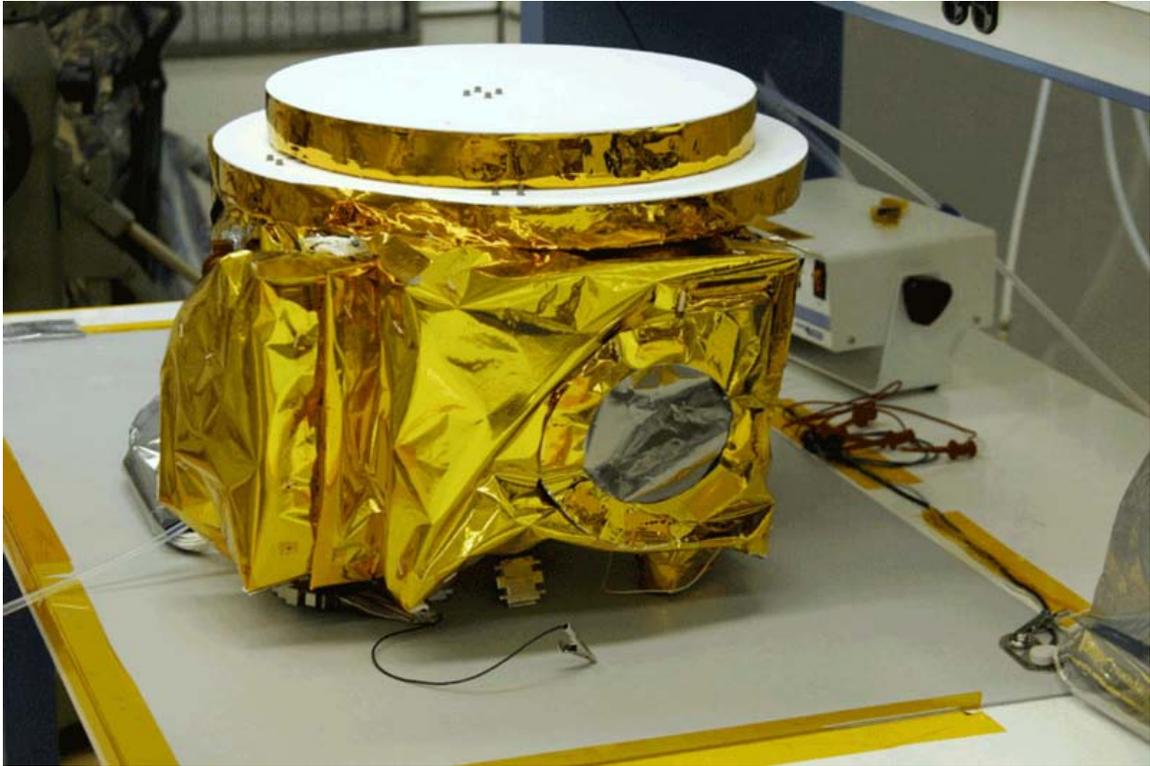
REX will use an ultrastable crystal oscillator (essentially a calibrated crystal in a miniature oven) and some additional electronics to conduct radio science investigations using the communications channels. These are small enough to fit on a single card. Since there are two redundant communications subsystems, there are two, identical REX circuit boards.



New Horizon's image of Jupiter's Himalia

Venetia Burney Student Dust Counter (VBSDC)

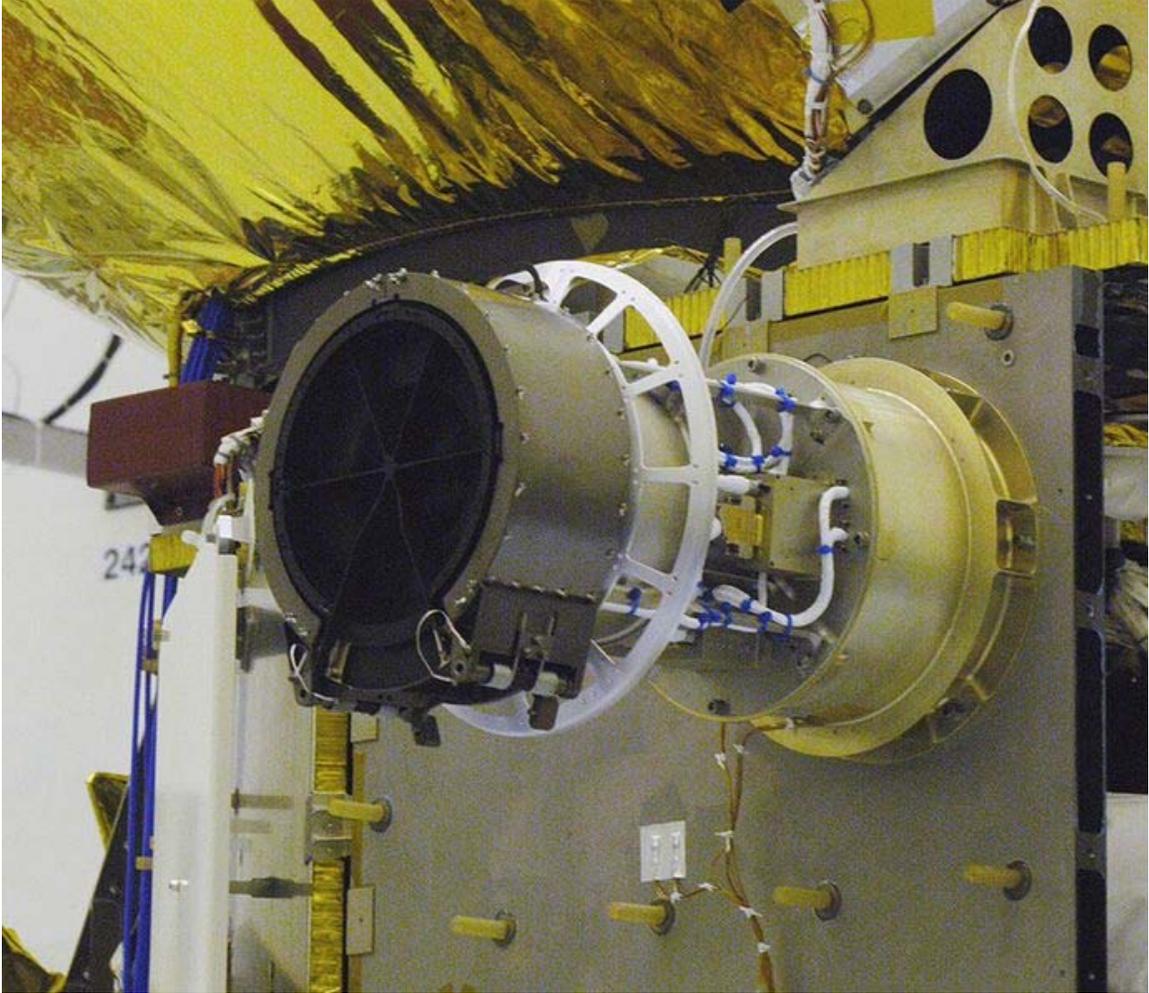
Built by students at the University of Colorado at Boulder, the **Student Dust Counter** will operate continuously through the trajectory to make dust measurements. It consists of a detector panel, about 18 by 12 inches (460 × 300 mm), mounted on the antisolar face of the spacecraft (the ram direction), and an electronics box within the spacecraft. The detector contains fourteen PVDF panels, twelve science and two reference, which generate voltage when impacted. Effective collecting area is 0.125 m². No dust counter has operated past the orbit of Uranus; models of dust in the outer solar system, especially the Kuiper belt, are speculative. VBSDC is always turned on measuring the masses of the interplanetary and interstellar dust particles (in the range of nano and pico grams) as they collide with the PVDF panels mounted on the New Horizons spacecraft. The measured data shall greatly contribute to our understanding of the dust spectra of our own solar system. We can then compare our dust spectra with those observed via telescope of other stars, and that would give us new clues as to where earth like planets can be found in our universe. The dust counter is named for Venetia Burney, who first suggested the name "Pluto" at the age of 11. An interesting thirteen minute short film about VBSDC garnered an Emmy award for student achievement in 2006.



Ralph



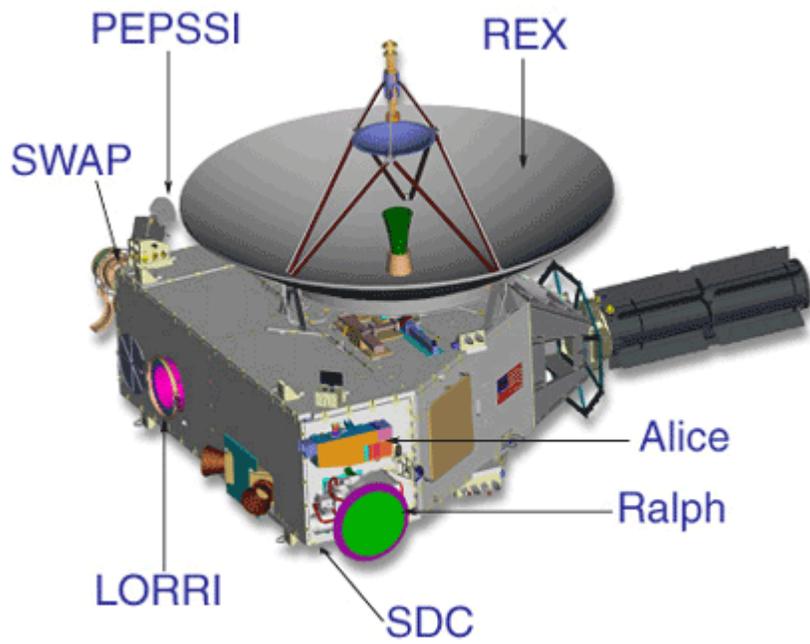
LORRI



SWAP

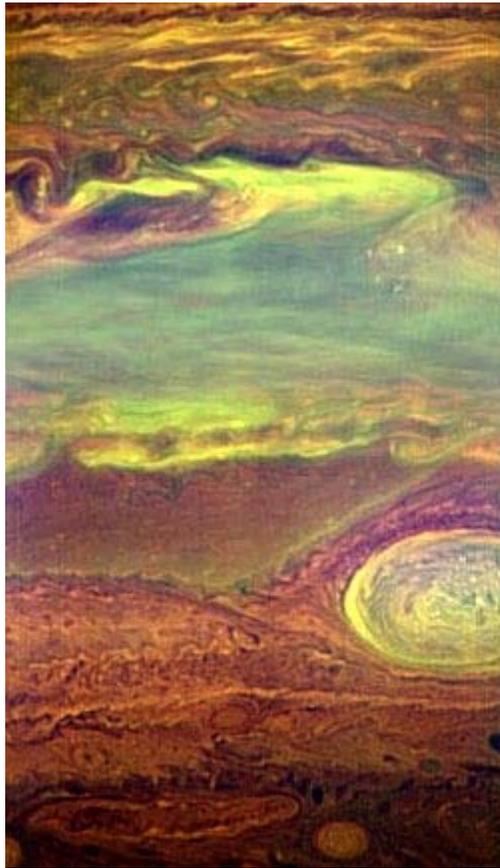


VBSDC



Instrument Locations

Jupiter observations



Jupiter through infrared camera

The flyby came within about 32 Jovian radii (3 Gm) of Jupiter and was the center of a 4-month intensive observation campaign. Jupiter is an interesting, ever-changing target, observed intermittently since the end of the Galileo mission. *New Horizons* also has instruments built using the latest technology, especially in the area of cameras. They are much improved over Galileo's cameras, which were evolved versions of Voyager cameras which, in turn, were evolved Mariner cameras. The Jupiter encounter also served as a shakedown and dress rehearsal for the Pluto encounter. Because of the much shorter distance from Jupiter to Earth, the communications link can transmit multiple loadings of the memory buffer. The mission will actually return more data from Jupiter than Pluto. Imaging of Jupiter began on September 4, 2006, after which several images were taken.

The primary encounter goals included Jovian cloud dynamics, which were greatly reduced from the Galileo observation program, and particle readings from the magnetotail of the Jovian magnetosphere. The spacecraft trajectory coincidentally flew down the magnetotail for months. *New Horizons* also examined the Jovian nightside for aurorae and lightning.

New Horizons also provided the first close-up examination of Oval BA, a storm feature that has informally become known as the "Little Red Spot", since the storm turned red. It was still a white spot when *Cassini* flew by.

Jovian moons

The major (Galilean) moons were in poor position. The aim point of the gravity-assist maneuver meant the spacecraft passed millions of kilometers from any of the Galilean moons. Still, the *New Horizons* instruments were intended for small, dim targets, so they were scientifically useful on large, distant moons. LORRI searched for volcanoes and plumes on Io. The infrared capabilities of LEISA searched for chemical compositions (including Europa ice dopants), and nightside temperatures (including hotspots on Io). The ultraviolet resolution of Alice searched for aurorae and atmospheres, including the Io torus.

Minor moons such as Amalthea had their orbit solutions refined. The cameras determined their position, acting as "reverse optical navigation".

Pluto flyby



Computer-generated view from the spacecraft during flyby of Pluto (right) showing its moon, Charon (left).

Observations of Pluto, with LORRI plus Ralph, will begin about 6 months prior to closest approach. The targets will be only a few pixels across. This should detect any rings or any additional moons (eventually down to 2 kilometers diameter), for avoidance and targeting maneuvers, and observation scheduling. 70 days out, resolution will exceed the Hubble Space Telescope's resolution, lasting another two weeks after the flyby. Long-range imaging will include 40 km (25 mi) mapping of Pluto and Charon 3.2 days out. This is half the rotation period of Pluto-Charon and will allow imaging of the side of both bodies that will be facing away from the spacecraft at closest approach. Coverage will repeat twice per day, to search for changes due to snows or cryovolcanism. Still, due to Pluto's tilt and rotation, a portion of the northern hemisphere will be in shadow at all times.

During the flyby, LORRI should be able to obtain select images with resolution as high as 50 m/px (if closest distance is around 10,000 km), and MVIC should obtain 4-color global dayside maps at 1.6 km resolution. LORRI and MVIC will attempt to overlap their respective coverage areas to form stereo pairs. LEISA will obtain hyperspectral near-infrared maps at 7 km/px globally and 0.6 km/pixel for selected areas. Meanwhile, Alice will characterize the atmosphere, both by emissions of atmospheric molecules (airglow), and by dimming of background stars as they pass behind Pluto (occultation).



A simulated view of New Horizons passing Pluto and Charon when it arrives in 2015

During and after closest approach, SWAP and PEPSSI will sample the high atmosphere and its effects on the solar wind. VBSDC will search for dust, inferring meteoroid collision rates and any invisible rings. REX will perform active and passive radio science. Ground stations on Earth will transmit a powerful radio signal as *New Horizons* passes behind Pluto's disk, then emerges on the other side. The communications dish will

measure the disappearance and reappearance of the signal. The results will resolve Pluto's diameter (by their timing) and atmospheric density and composition (by their weakening and strengthening pattern). (Alice can perform similar occultations, using sunlight instead of radio beacons.) Previous missions had the spacecraft transmit through the atmosphere, to Earth ("downlink"). Low power and extreme distance means New Horizons will be the first such "uplink" mission. Pluto's mass and mass distribution will be evaluated by their tug on the spacecraft. As the spacecraft speeds up and slows down, the radio signal will experience a Doppler shift. The Doppler shift will be measured by comparison with the ultrastable oscillator in the communications electronics.

Reflected sunlight from Charon will allow some imaging observations of the nightside. Backlighting by the Sun will highlight any rings or atmospheric hazes. REX will perform radiometry of the nightside.

Initial, highly-compressed images will be transmitted within days. The science team will select the best images for public release. Uncompressed images will take about nine months to transmit, depending on Deep Space Network traffic. It may turn out, however, that fewer months will be needed. The spacecraft link is proving stronger than expected, and it is possible that both downlink channels may be ganged together to nearly double the data rate.

Primary objectives (required)

- Characterize the global geology and morphology of Pluto and Charon
- Map chemical compositions of Pluto and Charon surfaces
- Characterize the neutral (non-ionized) atmosphere of Pluto and its escape rate

Loss of any of these objectives will constitute a failure of the mission.

Secondary objectives (expected)

- Characterize the time variability of Pluto's surface and atmosphere
- Image select Pluto and Charon areas in stereo
- Map the terminators (day/night border) of Pluto and Charon with high resolution
- Map the chemical compositions of select Pluto and Charon areas with high resolution
- Characterize Pluto's ionosphere, and its interaction with the solar wind
- Search for neutral species such as H₂, hydrocarbons, HCN and other nitriles in the atmosphere
- Search for any Charon atmosphere
- Determine bolometric bond albedos for Pluto and Charon
- Map surface temperatures of Pluto and Charon

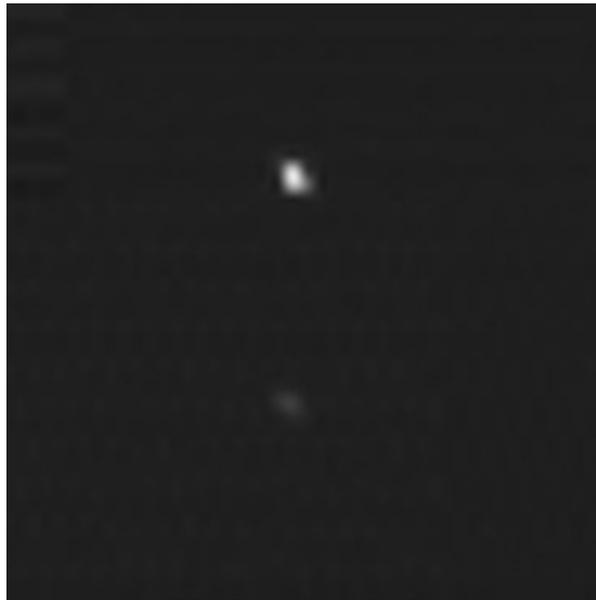
It is expected, but not demanded, that most of these objectives will be met.

Tertiary objectives (desired)

- Characterize the energetic particle environment at Pluto and Charon
- Refine bulk parameters (radii, masses) and orbits of Pluto and Charon
- Search for additional moons, and any rings

These objectives may be attempted, though they may be skipped in favor of the above objectives. An objective to measure any magnetic field of Pluto was dropped. A magnetometer instrument could not be implemented within a reasonable mass budget and schedule, and SWAP and PEPSSI could do an indirect job detecting some magnetic field around Pluto.

Asteroid belt



The 2.5 kilometer-wide asteroid 132524 APL, photographed by the *New Horizons* probe

Because of the need to conserve fuel for possible encounters with Kuiper belt objects subsequent to the Pluto flyby, intentional encounters with objects in the asteroid belt were not planned. Subsequent to launch, the *New Horizons* team scanned the spacecraft's trajectory to determine if any asteroids would, by chance, be close enough for observation. In May 2006 it was discovered that *New Horizons* would pass close to the tiny asteroid 132524 APL on June 13, 2006. Closest approach occurred at 4:05 UTC at a distance of 101,867 kilometers. The asteroid was imaged by Ralph (use of LORRI at that time was not possible due to proximity to sun), which gave the team a chance to exercise Ralph's capabilities, and make observations of the asteroid's composition as well as light and phase curves. The asteroid was estimated to be 2.5 kilometers in diameter.

Neptune trojans

Other possible targets are Neptune trojans. The probe's trajectory to Pluto passes near Neptune's trailing Lagrange point ("L₅"), which may host hundreds of bodies in 1:1

resonance with the planet (the first one, 2008 LC₁₈, was discovered in 2008). If any Neptune trojans are found to be close enough to be studied, observations may be planned. However, spacecraft passage near this Lagrange point comes shortly before the Pluto encounter. Depending on where the object is along the spacecraft trajectory, *New Horizons* may not have significant downlink bandwidth, and thus free memory, for trojan encounter data.

Kuiper belt objects

New Horizons is designed to fly past one or more Kuiper belt objects (KBOs) after passing Pluto. Because the flight path is determined by the Pluto flyby, with only minimal hydrazine remaining, objects must be found within a cone, extending from Pluto, of less than a degree's width, within 55 AU. Past 55 AU, the communications link becomes too weak, and the RTG wattage will have decayed significantly enough to hinder observations. Desirable KBOs will be well over 50 km in diameter, neutral in color (to compare with the reddish Pluto), and, if possible, possess a moon. Because the population of KBOs appears quite large, multiple objects may qualify. Large ground telescopes, such as Pan-STARRS and later the Large Synoptic Survey Telescope, will find suitable objects up until the Pluto flyby; the Pluto aim point, plus some thruster firing, will then determine the subsequent trajectory. KBO flyby observations will be similar to those at Pluto, but reduced due to lower light, power, and bandwidth.

Heliosphere

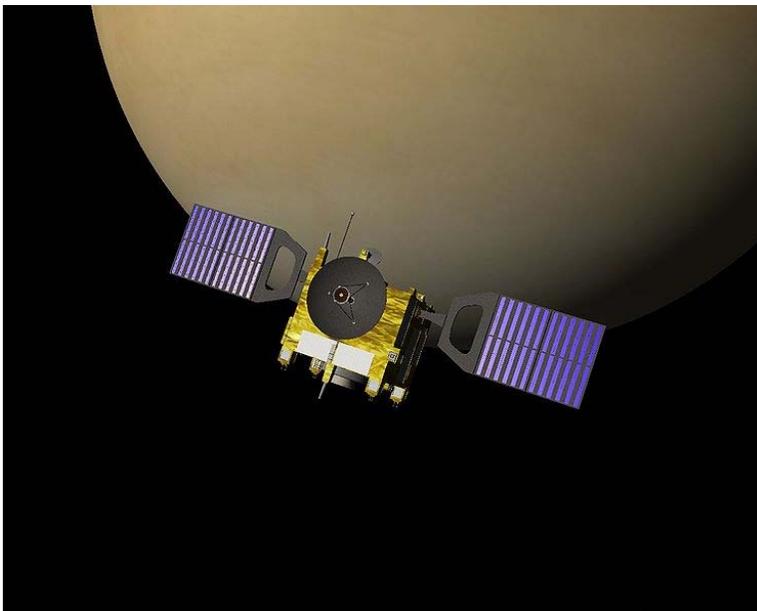
Provided it survives that far out, *New Horizons* is likely to follow the Voyager probes in exploring the outer heliosphere and mapping the heliosheath and heliopause.

Even though it was launched far faster than any outward probe before it, *New Horizons* will never overtake *Voyager 1* as the most distant man-made object from Earth. Close fly-bys of Saturn and Titan gave *Voyager 1* a massive advantage with its extra gravity assist. When *New Horizons* reaches the distance of 100 AU, it will be travelling at about 13 km/s, around 4 km/s slower than *Voyager 1* at that distance.

Chapter- 4

Venus Express

Venus Express



Operator	ESA
Major contractors	EADS Astrium, Toulouse, France, leading a team of 25 subcontractors from 14 European countries.
Mission type	Orbiter
Satellite of	Venus
Launch date	9 November 2005 03:33:34 UTC
Launch vehicle	Soyuz-FG/Fregat
Mission duration	150 days enroute; 1,000 days in orbit 5 years, 2 months, and 4 days elapsed

COSPAR ID 2005-045A

Mass 1,270 kg

Orbital elements

Semimajor axis 39,468.195 km

Eccentricity 0.8403

Inclination 89.99 deg

Orbital period 24 h

Venus Express (*VEX*) is the first Venus exploration mission of the European Space Agency. Launched in November 2005, it arrived at Venus in April 2006 and has been continuously sending back science data from its polar orbit around Venus. Equipped with seven science instruments, the main objective of the mission is the long term observation of the Venusian atmosphere. The observation over such long periods of time has never been done in previous missions to Venus, and is key to a better understanding of the atmospheric dynamics. It is hoped that such studies can contribute to an understanding of atmospheric dynamics in general, while also contributing to an understanding of climate change on Earth. The mission is currently funded by ESA through 31 December 2012.

History

The mission was proposed in 2001 to reuse the design of the *Mars Express* mission. However, some mission characteristics led to design changes: primarily in the areas of thermal control, communications and electrical power. For example, since Mars is approximately twice as far from the Sun as Venus is, the radiant heating of the spacecraft will be four times greater for *Venus Express* than *Mars Express*. Also, the ionizing radiation environment will be harsher. On the other hand, the more intense illumination of the solar panels will result in more generated photovoltaic power. The *Venus Express* mission also uses some spare instruments developed for the *Rosetta* spacecraft. The mission was proposed by a consortium led by D. Titov (Germany), E. Lellouch (France) and F. Taylor (United Kingdom).

The launch window for *Venus Express* was open from 26 October to 23 November 2005, with the launch initially set for 26 October 4:43 UTC. However, problems with the insulation from the Fregat upper stage led to a two week launch delay to inspect and clear out the small insulation debris that migrated on the spacecraft. It was eventually launched by a Soyuz-FG/Fregat rocket from the Baikonur Cosmodrome in Kazakhstan on 9 November 2005 at 03:33:34 UTC into a parking Earth orbit and 1 h 36 min after launch put into its transfer orbit to Venus. A first trajectory correction maneuver was successfully performed on 11 November 2005. It arrived at Venus on 11 April 2006, after approximately 150 days of journey, and fired its main engine between 07:10 and 08:00 Universal Time (UTC) to reduce its velocity so that it could be captured by Venusian

gravity into a nine day orbit. The burn was monitored from ESA's Control Centre, ESOC, in Darmstadt, Germany.

Seven further orbit control maneuvers, two with the main engine and five with the thrusters, were required for *Venus Express* to reach its final operational 24-hour orbit around Venus.

Venus Express entered its target orbit at apocentre on 7 May 2006 at 13:31 UTC, when the spacecraft was at 151 million kilometres from Earth. Now the spacecraft is running on an ellipse substantially closer to the planet than during the initial orbit. The orbit now ranges between 66,000 and 250 kilometres over Venus and it is polar. The pericentre is located almost above the North pole (80° North latitude), and it takes 24 hours for the spacecraft to travel around the planet.

Venus Express is studying the Venusian atmosphere and clouds in detail, the plasma environment and the surface characteristics of Venus from orbit. It will also make global maps of the Venusian surface temperatures. Its nominal mission was originally planned to last for 500 Earth days (approximately two Venusian sidereal days), but the mission has been extended twice: first on 28 February 2007 until early May 2009; then on 4 February 2009 until 31 December 2009; and then on 7 October 2009 until 31 December 2012. On-board resources are sized for an additional 500 Earth days.

Venus Express is outfitted mostly with spare parts and designs from the *Mars Express* and *Rosetta* missions, but has been adapted to cope with the high radiation and thermal environment surrounding Venus.

Instruments

ASPERA-4: An acronym for "Analyzer of Space Plasmas and Energetic Atoms," ASPERA-4 will investigate the interaction between the solar wind and the Venusian atmosphere, determine the impact of plasma processes on the atmosphere, determine global distribution of plasma and neutral gas, study energetic neutral atoms, ions and electrons, and analyze other aspects of the near Venus environment. ASPERA-4 is a re-use of the ASPERA-3 design used on *Mars Express*, but adapted for the harsher near-Venus environment.

VMC: The Venus Monitoring Camera is a wide-angle, multi-channel CCD. The VMC is designed for global imaging of the planet. It operates in the visible, ultraviolet, and near infrared spectral ranges, and maps surface brightness distribution searching for volcanic activity, monitoring airglow, studying the distribution of unknown ultraviolet absorbing phenomenon at the cloud-tops, and making other science observations. It is derived in part by the *Mars Express* High Resolution Stereo Camera (HRSC) and the *Rosetta* Optical, Spectroscopic and Infrared Remote Imaging System (OSIRIS). The camera includes an FPGA to pre-process image data, reducing the amount transmitted to Earth. The consortium of institutions responsible for the VMC includes the Max Planck Institute for Solar System Research, the Institute of Planetary Research at the German Aerospace

Center and the Institute of Computer and Communication Network Engineering at Technische Universität Braunschweig.

Magnetometer

MAG: The magnetometer is designed to measure the strength of Venus's magnetic field and the direction of it as affected by the solar wind and Venus itself. It will be able to map the magnetosheath, magnetotail, ionosphere, and magnetic barrier in high resolution in three-dimensions, aid ASPERA-4 in the study of the interaction of the solar wind with the atmosphere of Venus, identify the boundaries between plasma regions, and carry planetary observations as well (such as for lightning). MAG is derived from the *Rosetta* lander's ROMAP instrument.

Spectrometer

PFS: The "Planetary Fourier Spectrometer" operates in the infrared between the 0.9 μm and 45 μm wavelength range and is designed to perform vertical optical sounding of the Venus atmosphere. It will perform global, long-term monitoring of the three-dimensional temperature field in the lower atmosphere (cloud level up to 100 kilometers).

Furthermore it will search for minor atmospheric constituents that may be present, but have not yet been detected, analyze atmospheric aerosols, and investigate surface to atmosphere exchange processes. The design is based on a spectrometer on *Mars Express*, but modified for optimal performance for the *Venus Express* mission.

SPICAV: Short for "Spectroscopy for Investigation of Characteristics of the Atmosphere of Venus," SPICAV is an imaging spectrometer that will be used for analyzing radiation in the infrared and ultraviolet wavelengths. It is derived from the *SPICAM* instrument flown on *Mars Express*. However, SPICAV has an additional channel known as **SOIR** (Solar Occultation at Infrared) that will be used to observe the Sun through Venus's atmosphere in the infrared.

VIRTIS: VIRTIS (Visible and Infrared Thermal Imaging Spectrometer) is an imaging spectrometer that observes in the near-ultraviolet, visible, and infrared parts of the electromagnetic spectrum. It will analyze all layers of the atmosphere, surface temperature and surface/atmosphere interaction phenomena.

Radio science

VeRa: Venus Radio Science is a radio sounding experiment that will transmit radio waves from the spacecraft and pass them through the atmosphere or reflect them off the surface. These radio waves will be received by a ground station on Earth for analysis of the ionosphere, atmosphere and surface of Venus. It is derived from the Radio Science Investigation instrument flown on *Rosetta*.

Science

Climate of Venus

Venus is the most Earth-like planet in our solar system. Starting out in the early planetary system with similar sizes and chemical compositions, the history of the two planets have diverged in spectacular fashion. It is hoped that the *Venus Express* mission can contribute not only to an in-depth understanding of how the Venusian atmosphere is structured, but also to an understanding of the changes that led to the current greenhouse atmospheric conditions. Such an understanding may contribute to the study of climate change in on Earth.

Search for life on Earth

Venus Express is used also to observe signs of life on Earth from Venus orbit. In the pictures, Earth is less than one pixel in size, which mimics observations of Earth-sized planets in other solar systems. These observations are then used to develop methods for habitability studies of extra-solar planets.

Important events and discoveries

- 3 August 2005: *Venus Express* completed its final phase of testing at Astrium Intespace facility in Toulouse, France. It flew on a Antonov An-124 cargo aircraft via Moscow, before arriving at Baikonur on 7 August.
- 7 August 2005: *Venus Express* arrived at the airport of the Baikonur Cosmodrome.
- 16 August 2005: First flight verification test completed.
- 22 August 2005: Integrated System Test-3.
- 30 August 2005: Last Major System Test Successfully Started.
- 5 September 2005: Electrical Testing Successful.
- 21 September 2005: FRR (Fuelling Readiness Review) Ongoing.
- 12 October 2005: Mating to the Fregat upper stage completed.
- 21 October 2005: Contamination detected inside the fairing — launch on hold.
- 5 November 2005: Arrival at launch pad.
- 9 November 2005: Launch from Baikonur Cosmodrome at 03:33:34 UTC.
- 11 November 2005: First trajectory correction maneuver successfully performed.
- 17 February 2006: The main engine is fired successfully in a dress rehearsal for the arrival maneuver.
- 24 February 2006: Second trajectory correction maneuver successfully performed.
- 29 March 2006: Third trajectory correction maneuver successfully performed - on target for 11 April orbit insertion.
- 7 April 2006: Command stack for orbit insertion maneuver is loaded on the spacecraft.
- 11 April 2006: The Venus Orbit Insertion (VOI) is completed successfully, according to the following timeline:

	spacecraft time (UTC)	ground receive time (UTC)
Liquid Settling Phase start	07:07:56	07:14:41
VOI main engine start	07:10:29	07:17:14
pericentre passage	07:36:35	
eclipse start	07:37:46	
occultation start	07:38:30	07:45:15
occultation end	07:48:29	07:55:14
eclipse end	07:55:11	
VOI burn end	08:00:42	08:07:28

Period of this orbit is nine days.

- 13 April 2006: First images of Venus from *Venus Express* released.
- 20 April 2006: Apocentre Lowering Manoeuvre #1 performed. Orbital period is now 40 hours.
- 23 April 2006: Apocentre Lowering Manoeuvre #2 performed. Orbital period is now approx 25 hours 43 minutes.
- 26 April 2006: Apocentre Lowering Manoeuvre #3 is slight fix to previous ALM.
- 7 May 2006: *Venus Express* entered its target orbit at apocentre at 13:31 UTC
- 14 December 2006: First temperature map of the southern hemisphere.
- 27 February 2007: ESA agrees to fund mission extension until May 2009.
- 19 September 2007: End of the nominal mission (500 Earth days) - Start of mission extension.
- 27 November 2007: The scientific journal *Nature* publishes a series of papers giving the initial findings. It finds evidence for past oceans. It confirms the presence of lightning on Venus and that it is more common on Venus than it is on Earth. It also reports the discovery that a huge double atmospheric vortex exists at the south pole of the planet.
- 20 May 2008: The detection by the VIRTIS instrument on *Venus Express* of hydroxyl (OH) in the atmosphere of Venus is reported in the May 2008 issue of *Astronomy and Astrophysics*.
- 4 February 2009: ESA agrees to fund mission extension until 31 December 2009.
- 7 October 2009: ESA agrees to fund the mission through 31 December 2012.

Chapter- 5

Mars Reconnaissance Orbiter

Mars Reconnaissance Orbiter



Conceptual image depicting the Mars Reconnaissance Orbiter in an elliptical low-planet orbit around Mars

Operator	NASA / JPL Lockheed Martin Space Systems University of Arizona
Major contractors	Applied Physics Laboratory Italian Space Agency Malin Space Science Systems,
Mission type	Orbiter
Satellite of	Mars
Orbital insertion	2006-03-10 21:24:00 UTC

date

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 and 5 months
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.

Springs in Vernal Crater, as seen by HIRISE. Springs are thought to be one of the best places to look for life because molten rock may have kept the area warm enough to support life. Also, fossils can be easily preserved by minerals found in association with hot springs.

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

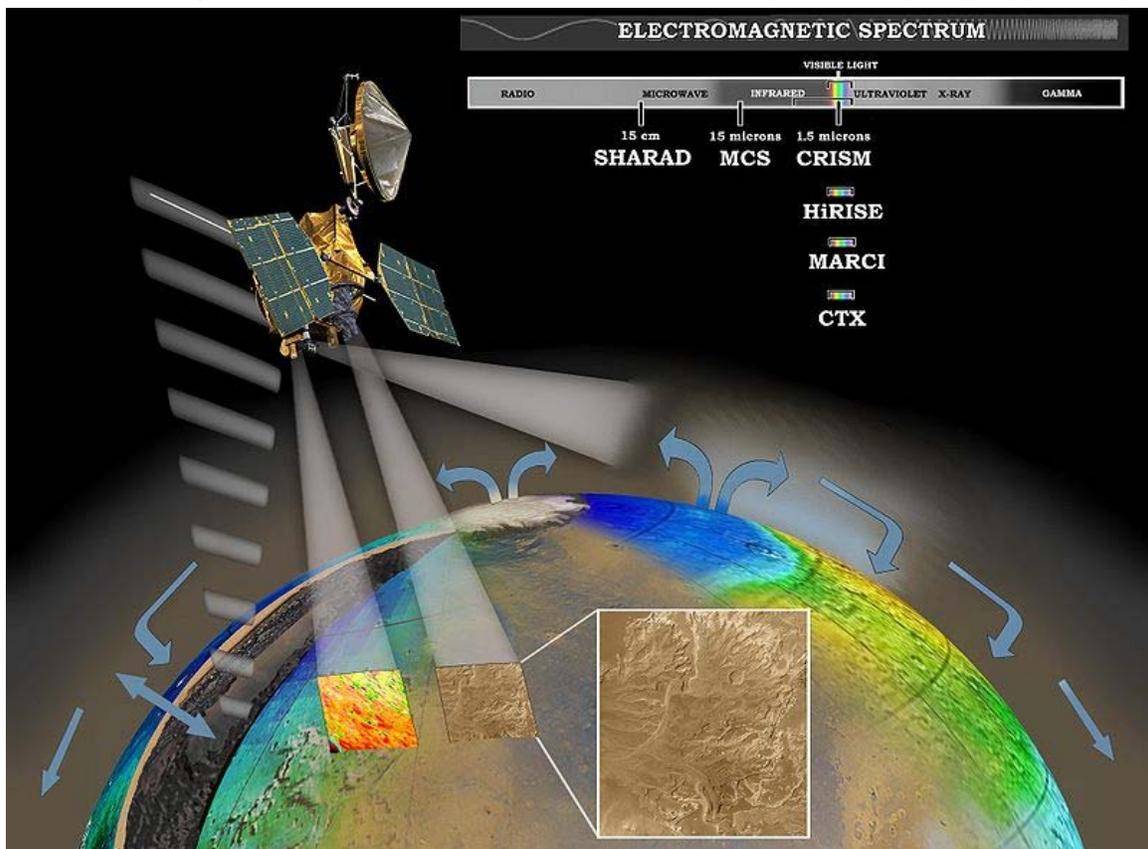


Diagram of instrumentation aboard MRO

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

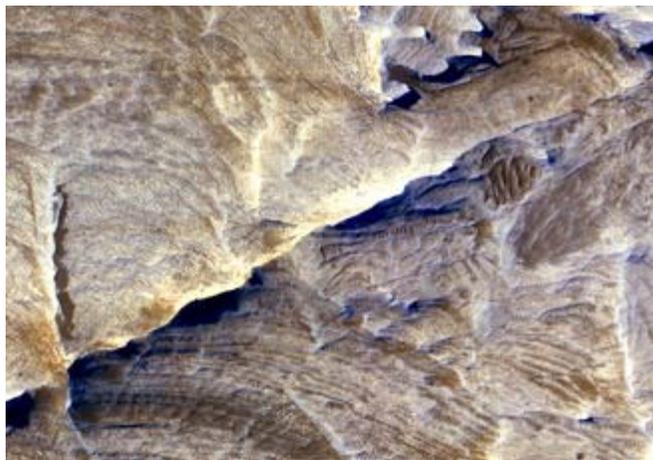
Completion of the orbital insertion placed the orbiter in a highly elliptical polar orbit with a period of approximately 35.5 hours. Shortly after insertion, the periapsis – the point in the orbit closest to Mars – was 3,806 km from the planet's center (426 km from its surface). The apoapsis – the point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

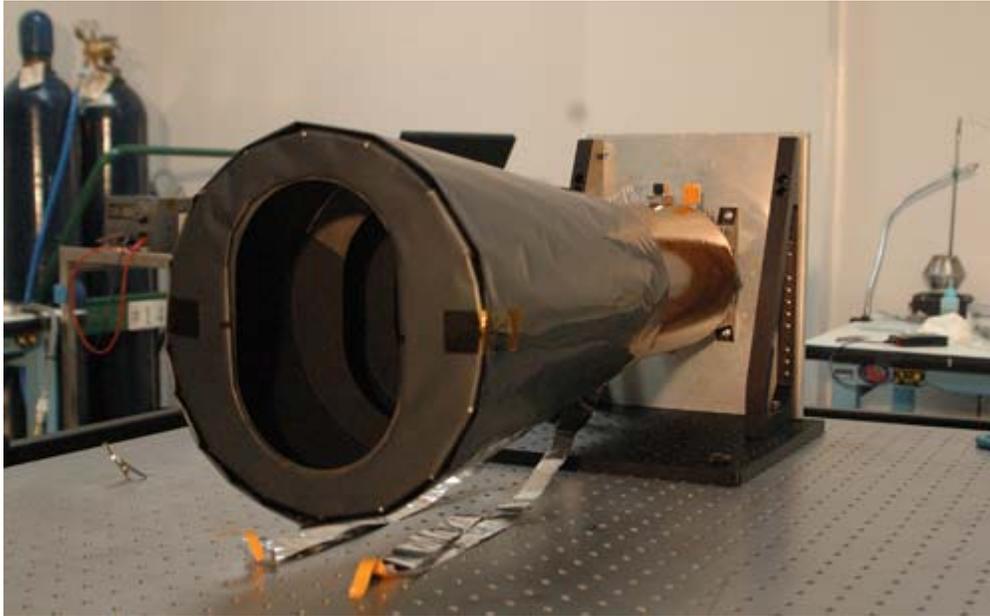
The High Resolution Imaging Science Experiment camera is a 0.5 m reflecting telescope, the largest ever carried on a deep space mission, and has a resolution of 1 microradian (μrad), or 0.3 m from an altitude of 300 km. In comparison, satellite images of Earth are generally available with a resolution 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 $20,000 \times 40,000$ pixels (800 megapixels) and $4,000 \times 40,000$ 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.

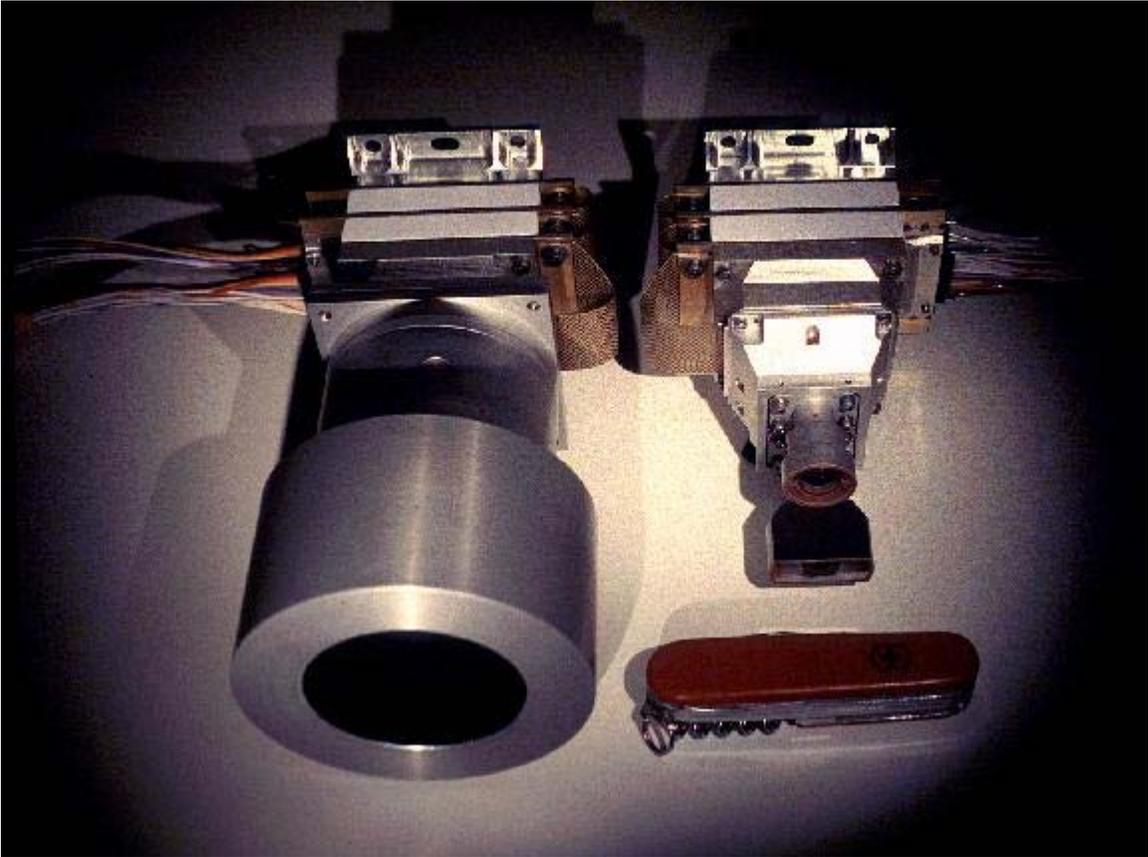
CTX (camera)



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.

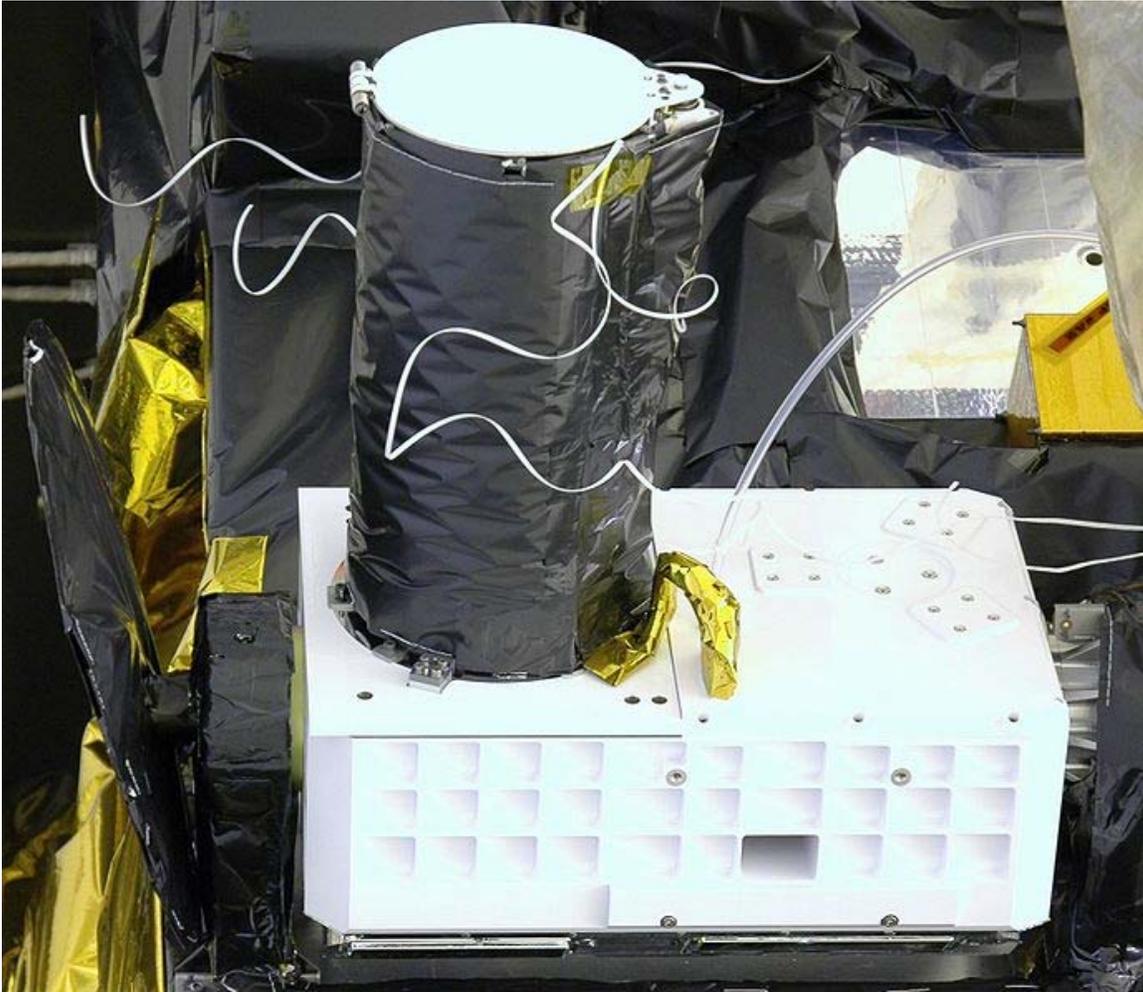
MARCI (camera)



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

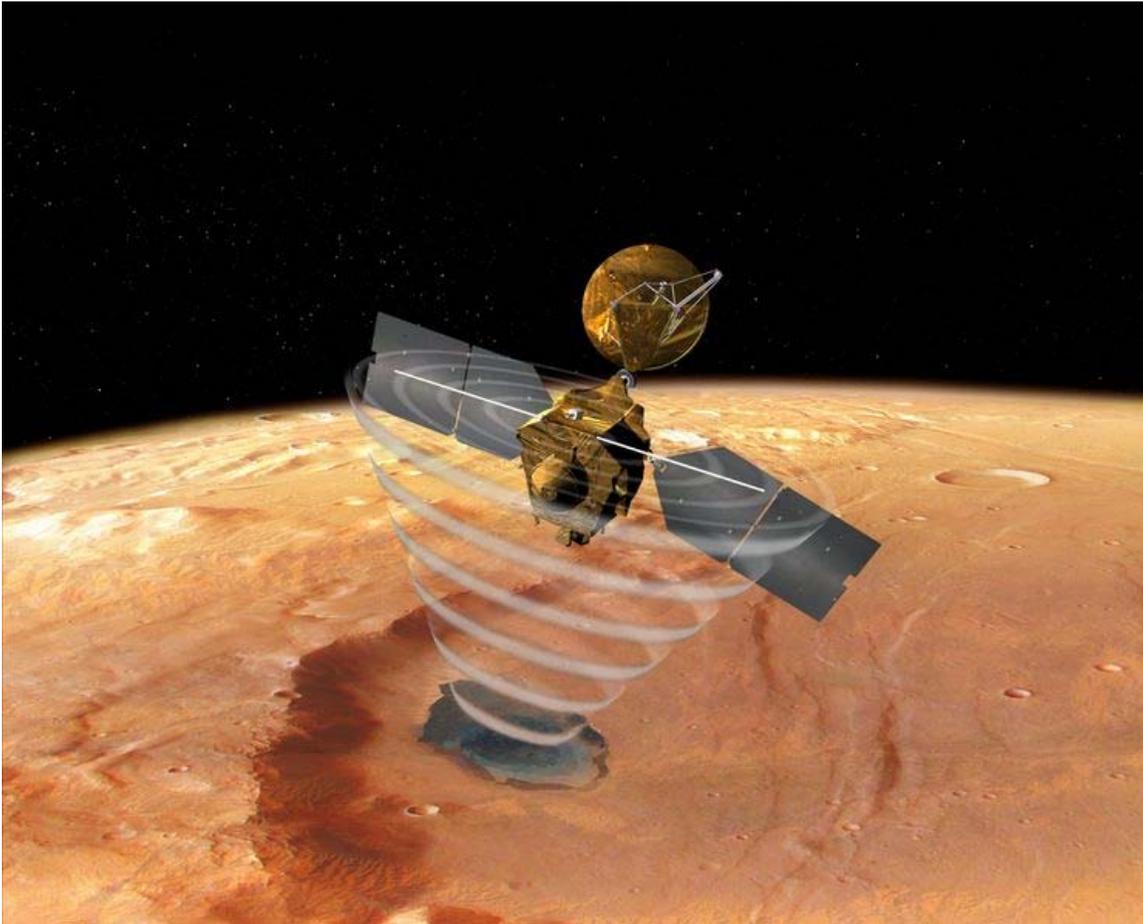
The Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) instrument is a visible and near infrared (VNIR) spectrometer that is used to produce detailed maps of the surface mineralogy of Mars. It operates from 370 to 3920 nm, measures the spectrum in 544 channels (each 6.55 nm wide), and has a 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.

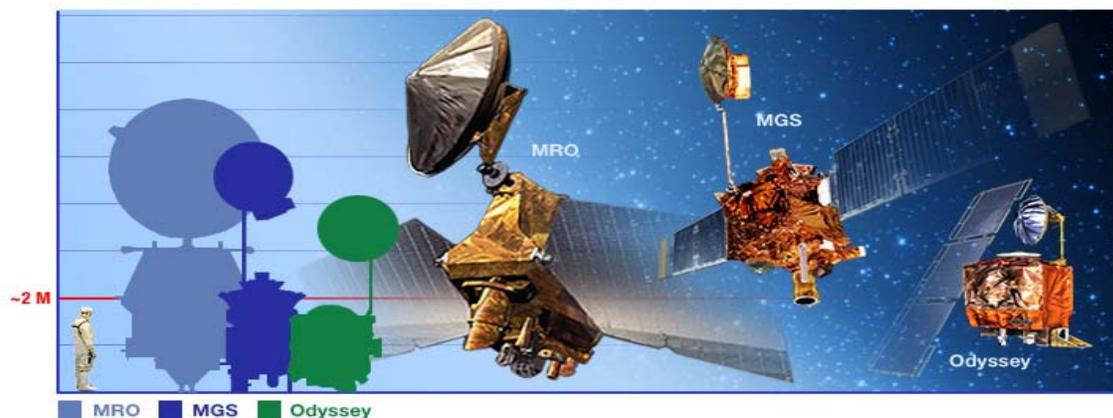
Engineering instruments

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



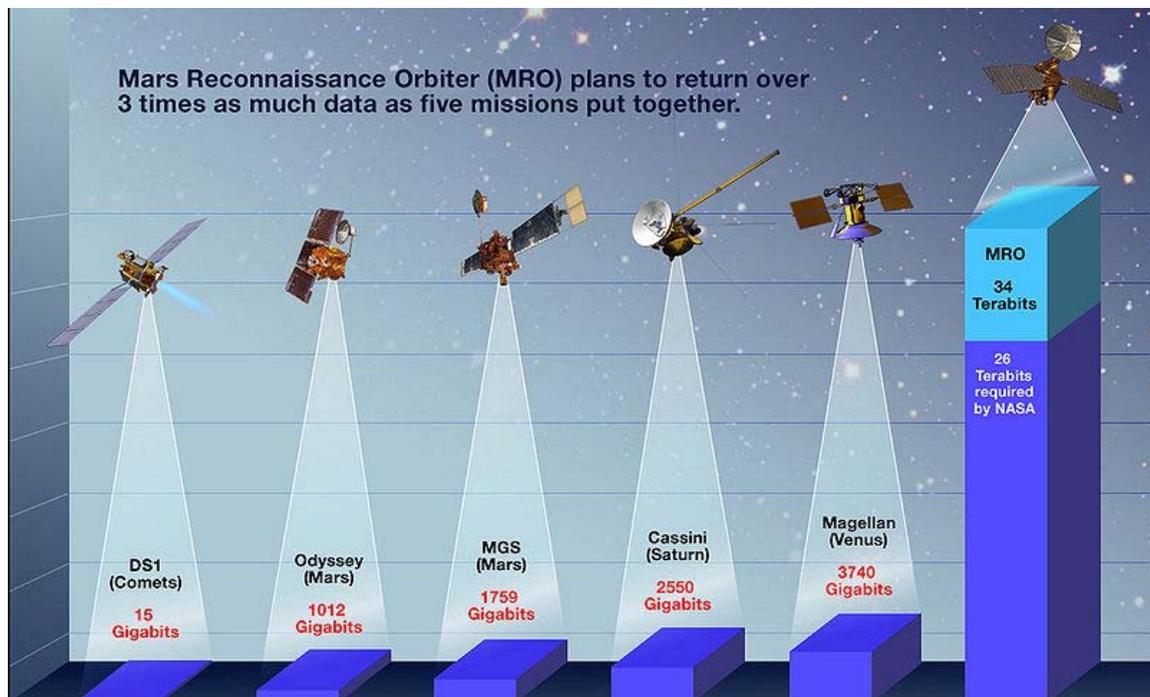
MRO High Gain Antenna installation

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

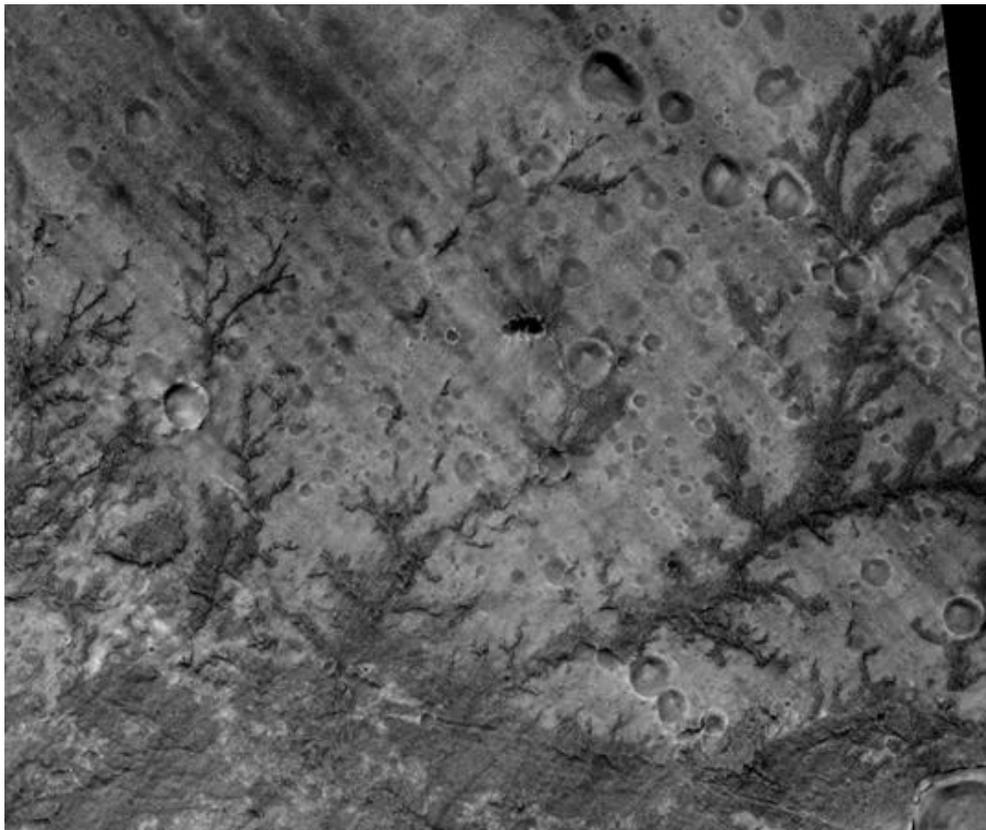


Lobate Debris Apron in Phlegra Montes, Cebrenia quadrangle. The debris apron is probably mostly ice with a thin covering of rock debris, so it could be a source of water for future Martian colonists. Scale bar is 500 meters long.

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 bulk 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.

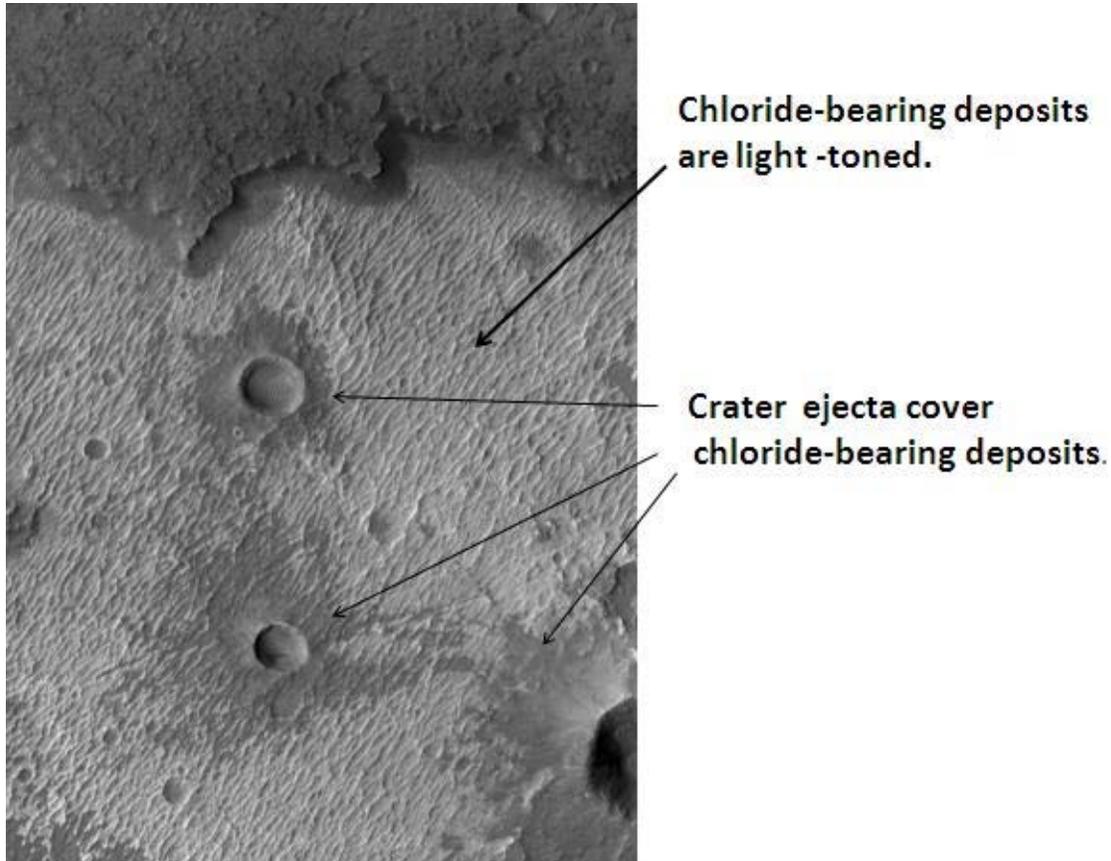
Inverted relief



Inverted Stream Channels in Antoniadi Crater, as seen by HiRISE

Some places on Mars show inverted relief. In these locations, a stream bed may be a raised feature, instead of a valley. The inverted former stream channels may be caused by the deposition of large rocks or due to cementation. In either case erosion would erode the surrounding land and leave the old channel as a raised ridge because the ridge will be more resistant to erosion. An image below, taken with HiRISE of Antoniadi Crater shows sinuous ridges that are old channels that have become inverted.

Chloride deposits



Evidence of water from chloride deposits in Phaethontis. Picture from HiRISE.

Using data from Mars Global surveyor, Mars Odyssey and the Mars Reconnaissance Orbiter, scientists have found widespread deposits of chloride minerals. A picture below shows some deposits within the Phaethontis quadrangle. Evidence suggests that the deposits were formed from the evaporation of mineral enriched waters. The research suggests that lakes may have been scattered over large areas of the Martian surface. Usually chlorides are the last minerals to come out of solution. Carbonates, sulfates, and silica should precipitate out ahead of them. Sulfates and silica have been found by the Mars Rovers on the surface. Places with chloride minerals may have once held various life forms. Furthermore, such areas should preserve traces of ancient life.

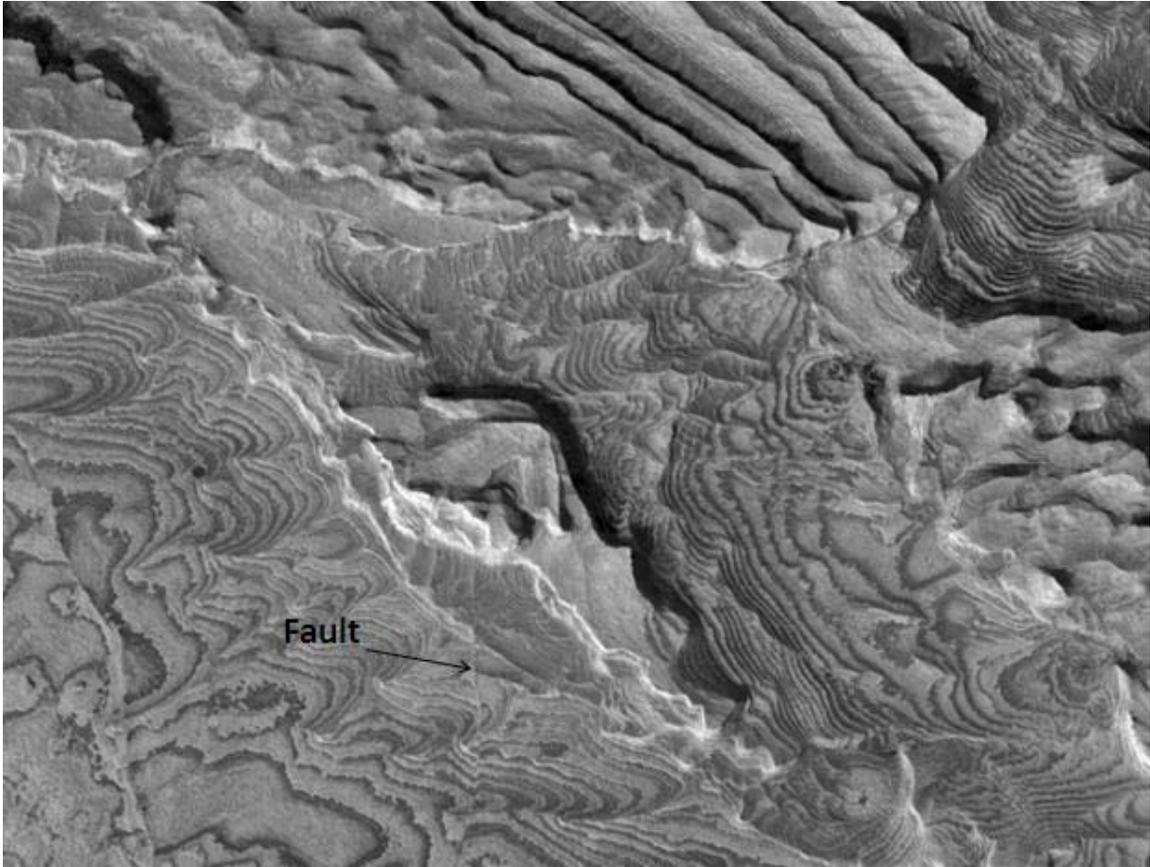
Other aqueous minerals

In a 2009 paper a large group of scientists reported on 9 to 10 different classes of minerals formed in the presence of water. Different types of clays (also called phyllosilicates) were found in many locations. The phyllosilicates identified included aluminum smectite, iron/magnesium smectite, kaolinite, prehnite, and chlorite. Rocks containing carbonate were found around the Isidis basin. Carbonates belong to one class in which life could have developed. Areas around Valles Marineris were found to contain hydrated silica and hydrated sulfates. The researchers identified hydrated sulfates and ferric minerals in Terra Meridiani and in Valles Marineris. Other minerals found on Mars were jarosite, alunite, hematite, opal, and gypsum. Two to five of the mineral classes were formed with the right pH and sufficient water to permit life to grow.

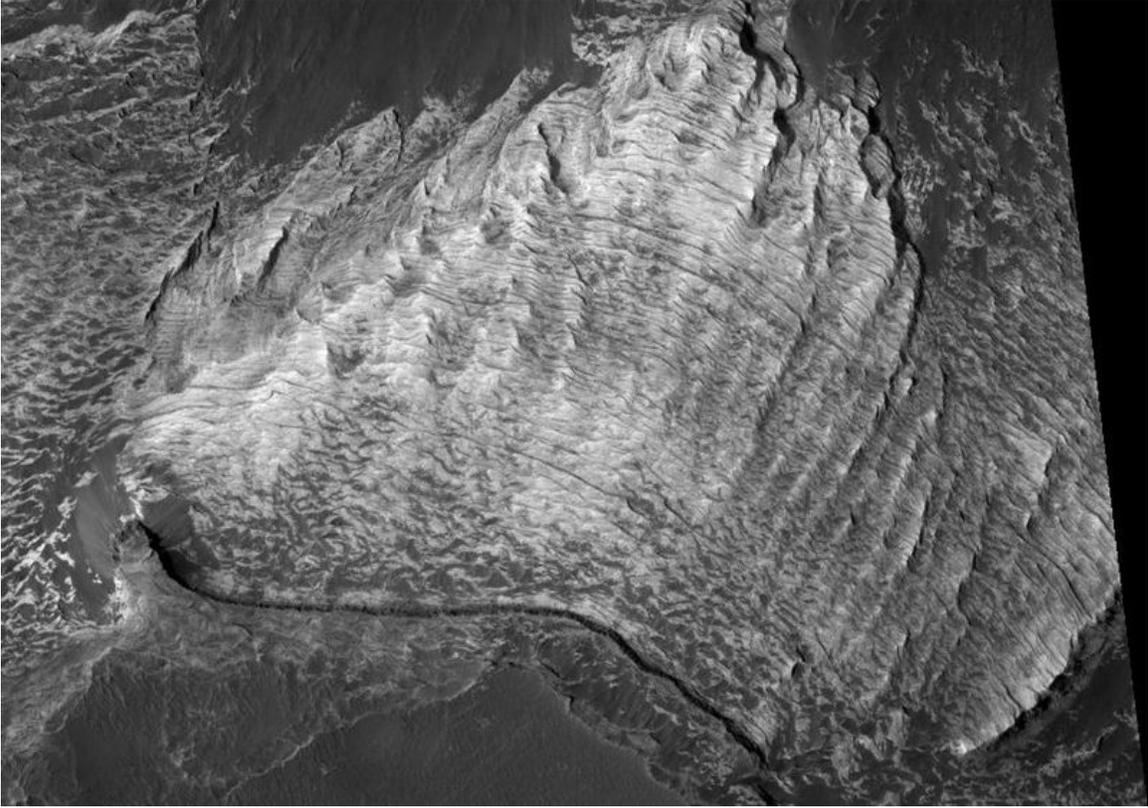
Layers

Columbus Crater contains layers, also called strata. Many places on Mars show rocks arranged in layers. Sometimes the layers are of different colors. Light-toned rocks on Mars have been associated with hydrated minerals like sulfates. The Mars Rover Opportunity examined such layers close-up with several instruments. Some layers are probably made up of fine particles because they seem to break up into fine dust. Other layers break up into large boulders so they are probably much harder. Basalt, a volcanic rock, is thought to be in the layers that form boulders. Basalt has been identified on Mars in many places. Instruments on orbiting spacecraft have detected clay (also called phyllosilicates) in some layers. Scientists are excited about finding hydrated minerals such as sulfates and clays on Mars because they are usually formed in the presence of water. Places that contain clays and/or other hydrated minerals would be good places to look for evidence of life.

Rock can form layers in a variety of ways. Volcanoes, wind, or water can produce layers.



Becquerel Crater layers, as seen by HiRISE.



Light colored layers in Eos Chaos, as seen by HiRISE



Columbus Crater Layers, as seen by HiRISE. This false-color image is about 800 feet across. Some of the layers contain hydrated minerals.

Avalanche

On February 19, 2008, Mars Reconnaissance Orbiter photographed an avalanche as it was occurring.



Martian avalanche and debris falls (HiRISE 2008)

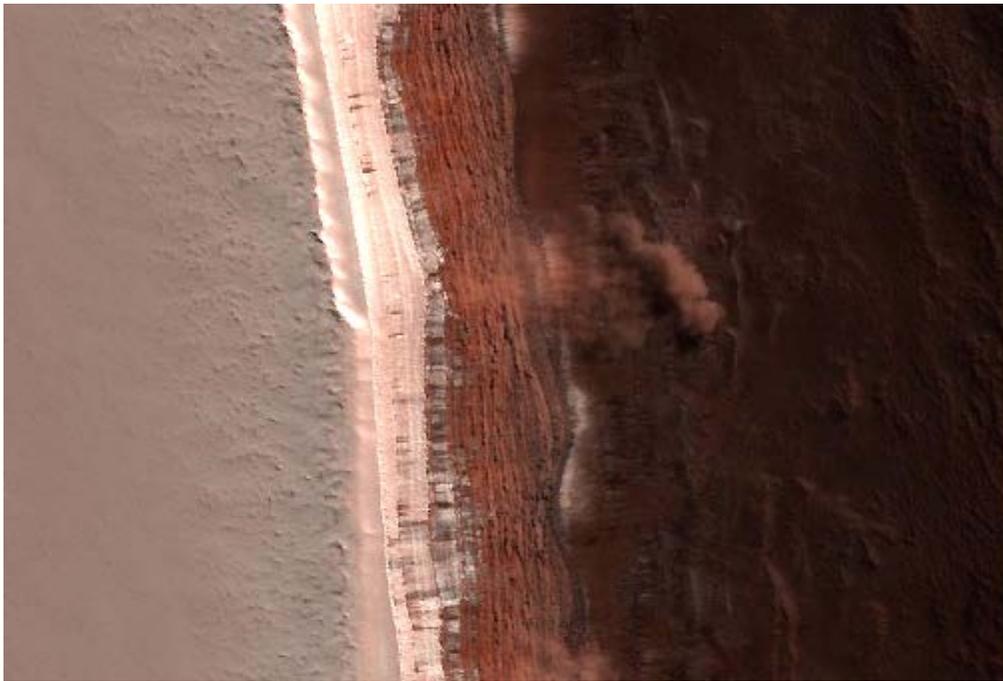


Image of the February 19, 2008 Mars avalanche captured by the Mars Reconnaissance Orbiter.



Closer shot of the avalanche



Dust clouds rise above the 2,300-foot (700 m) deep cliff

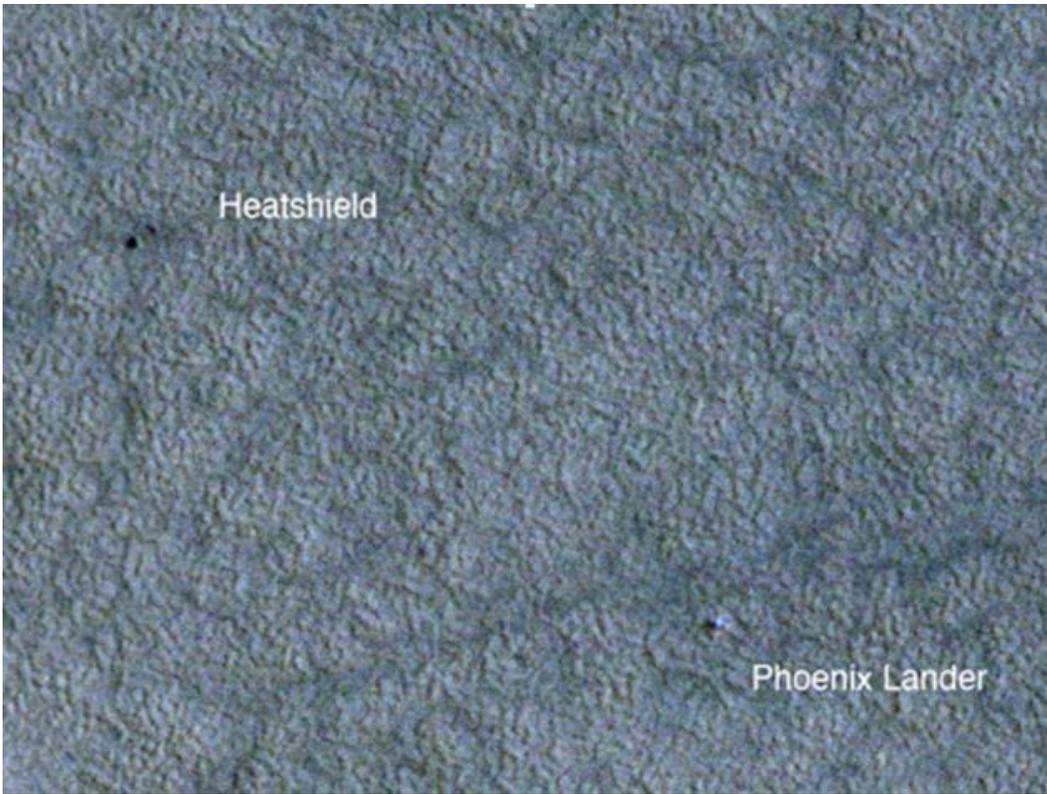


A photo with scale demonstrates the size of the avalanche

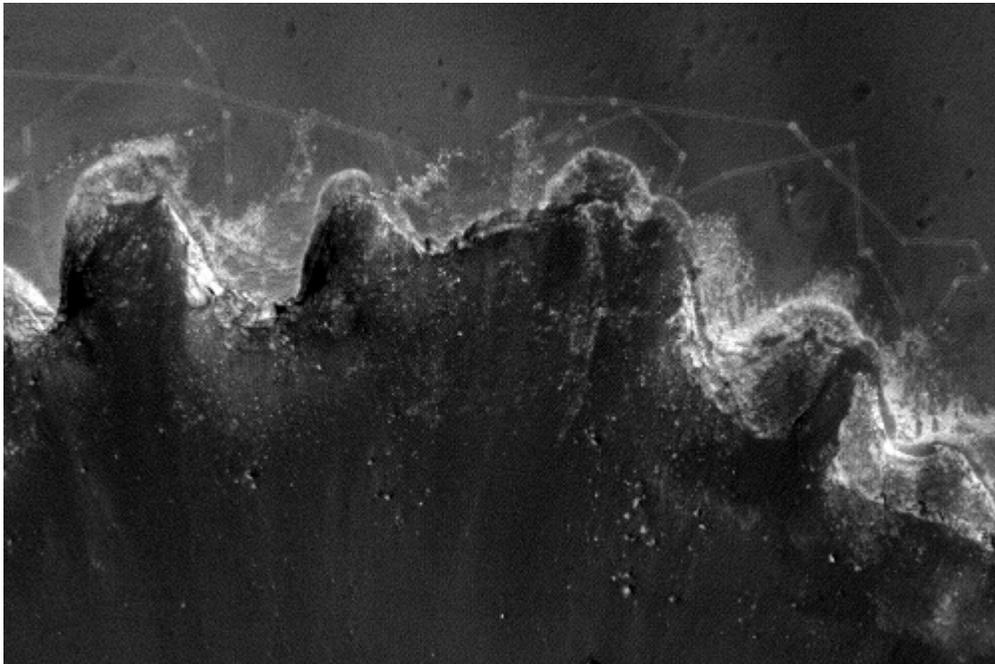
Other spacecraft



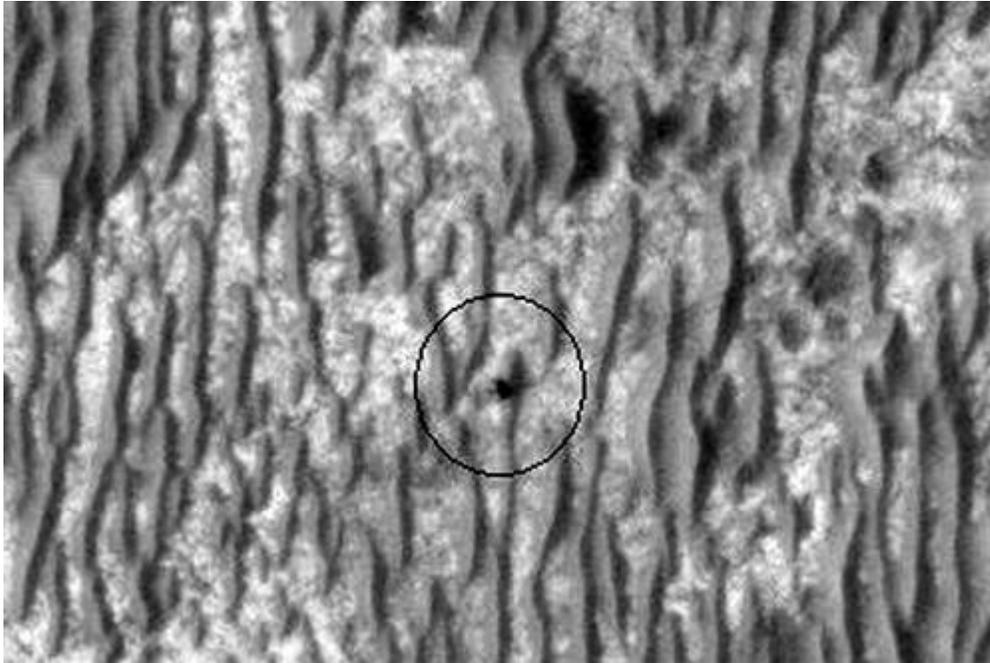
Image of Phoenix landing on Mars, as seen by HiRISE. Although in the image it appears to be descending into the crater, Phoenix actually landed 20 km away from it.



The Phoenix lander and its heatshield as seen by HiRISE



Tracks of the rover Opportunity, as seen by HiRISE. The white dots are places where the rover stopped to perform scientific observations or turned.



Opportunity as seen by HiRISE on January 29, 2009. Opportunity is on its way to Endeavour Crater, 17 km away at this point.

Chapter- 6

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, 163 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
Homepage	messenger.jhuapl.edu
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

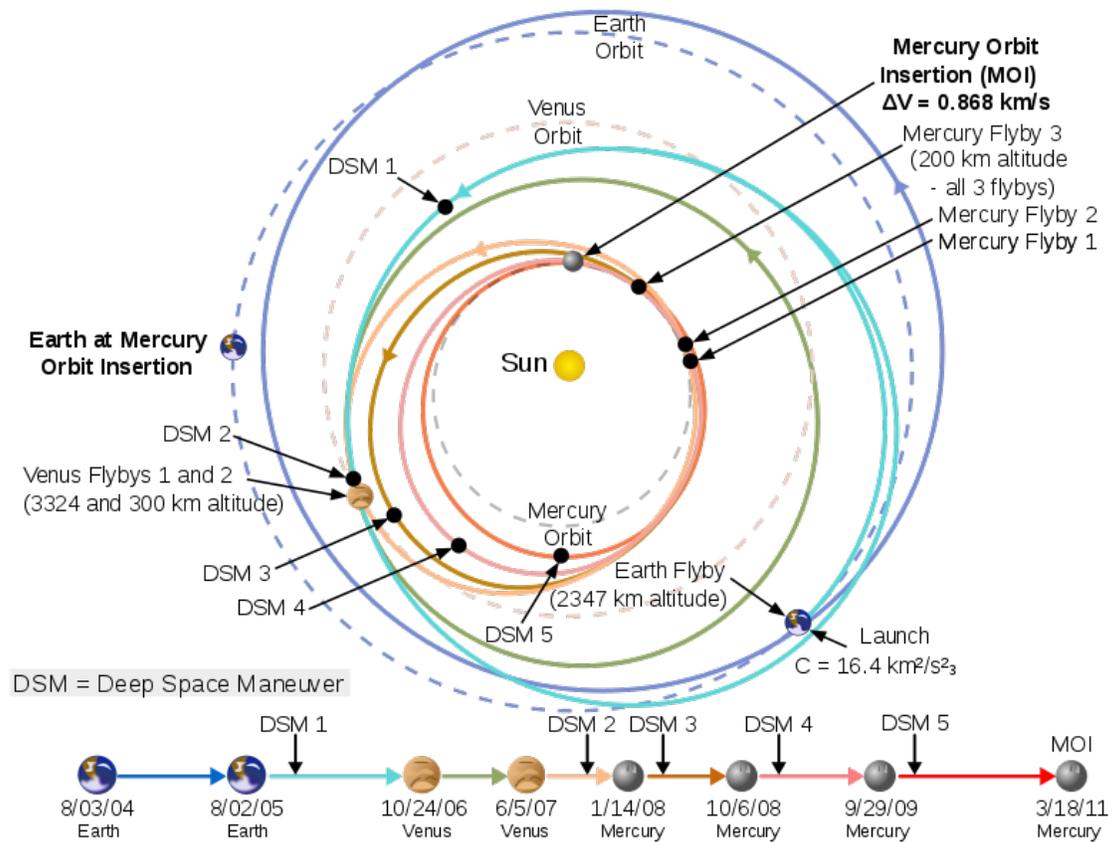


The launch of MESSENGER

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 December, 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.

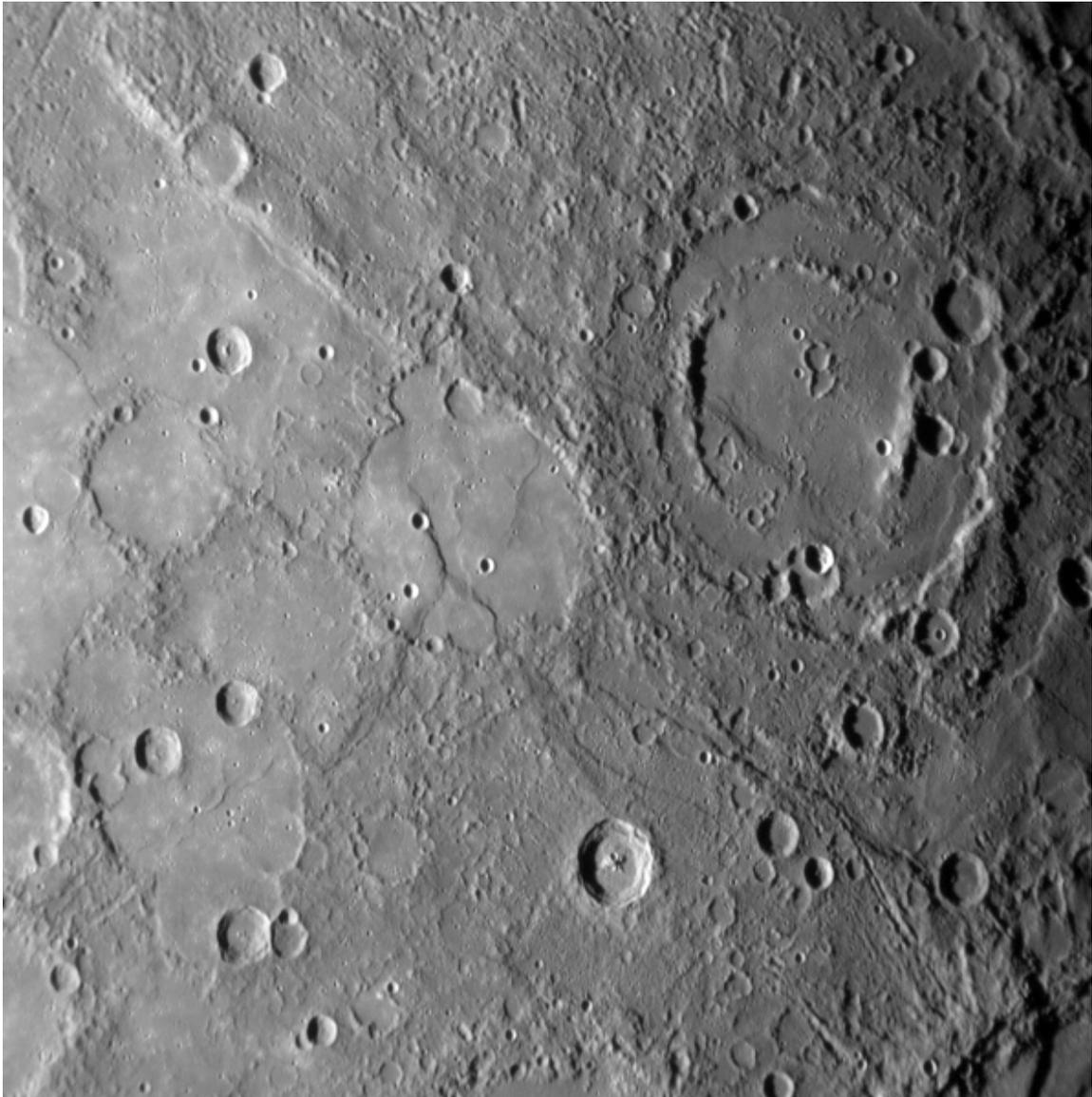
Main propulsion is via the 645 N (145 lbf), 317 s bipropellant LVA thruster. Four 22 N (4.9 lbf) monopropellant thrusters provide spacecraft steering during main thruster burns, and ten 4 N (0.9 lbf) monopropellant thrusters are used for attitude control. There is also a reaction wheel attitude control 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.

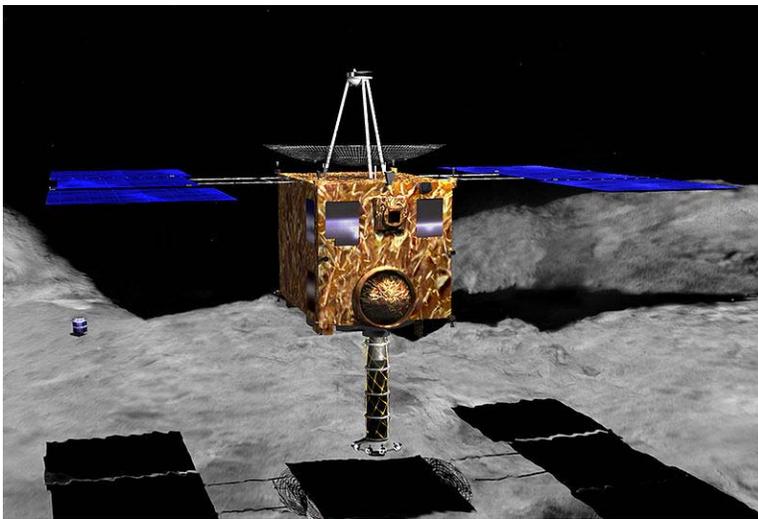
MESSENGER also provided visual evidence of volcanic activity on the surface of Mercury as well as evidence for a liquid planetary core.

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- 7

Hayabusa

Hayabusa



A computer rendering of Hayabusa above Itokawa's surface

Operator	● JAXA
Mission type	Asteroid sample return
Current destination	Returned to Earth on 13 June 2010
Launch date	9 May 2003
Launch vehicle	● M-V
Mission duration	7 years, 1 month and 4 days
COSPAR ID	2003-019A
Mass	510 kg (dry 380 kg)

Instruments

AMICA, LIDAR, NIRS, XRS

Hayabusa was an unmanned spacecraft developed by the Japan Aerospace Exploration Agency to return a sample of material from a small near-Earth asteroid named 25143 Itokawa to Earth for further analysis.

Hayabusa, formerly known as **MUSES-C** for Mu Space Engineering Spacecraft C, was launched on 9 May 2003 and rendezvoused with Itokawa in mid-September 2005. After arriving at Itokawa, Hayabusa studied the asteroid's shape, spin, topography, colour, composition, density, and history. In November 2005, it landed on the asteroid and collected samples in the form of tiny grains of asteroidal material, which were returned to Earth aboard the spacecraft on 13 June 2010.

The spacecraft also carried a detachable miniland, MINERVA, but this failed to reach the surface.

Mission firsts



Denis J. P. Moura (left) and Junichiro Kawaguchi (right) at the 2010 International Astronautical Congress (IAC)

Other spacecraft, notably Galileo and NEAR Shoemaker both sent by NASA, have visited asteroids before, but the Hayabusa mission was the first time that an attempt was made to return an asteroid sample to Earth for analysis.

In addition, Hayabusa was the first spacecraft designed to deliberately land on an asteroid and then take off again (*NEAR Shoemaker* made a controlled descent to the surface of 433 Eros in 2000, but it was not designed as a lander and was eventually deactivated after it arrived). Technically, Hayabusa was not designed to "land"; it simply touches the surface with its sample capturing device and then moves away. However, it was the first craft designed from the outset to make contact with the surface of an asteroid. Junichiro Kawaguchi of the Institute of Space and Astronautical Science was appointed to the leader of the mission.

Despite its designer's intention of a momentary contact, Hayabusa did land and sit on the asteroid surface for about 30 minutes.

Mission profile



The half-scale model of Hayabusa at the IAC in 2010

The Hayabusa spacecraft was launched on 9 May 2003 at 04:29:25 UTC on an M-V rocket from the Uchinoura Space Center (still called Kagoshima Space Center at that time). Following launch, the spacecraft's name was changed from the original MUSES-C

to Hayabusa, the Japanese word for falcon. The spacecraft's xenon ion engines (four separate units), operating near-continuously for two years, slowly moved Hayabusa toward a September 2005 rendezvous with Itokawa. As it arrived, the spacecraft did not go into orbit around the asteroid, but remained in a station-keeping heliocentric orbit close by.

Hayabusa surveyed the asteroid surface from a distance of about 20 km, the "gate position". After this the spacecraft moved closer to the surface (the "home position"), and then approached the asteroid for a series of soft landings and for the collection of samples at a safe site. Autonomous optical navigation was employed extensively during this period because the long communication delay prohibits Earth-based real-time commanding. At the second Hayabusa touchdown with its deployable collection horn, the spacecraft was programmed to fire tiny projectiles at the surface and then collect the resulting spray. Some tiny specks were collected by the spacecraft for analysis back on Earth.

After a few months in proximity to the asteroid, the spacecraft was scheduled to fire its engines to begin its cruise back to Earth. This maneuver was delayed due to problems with attitude control and the thrusters of the craft. Once it was on its return trajectory, the re-entry capsule was released from the main spacecraft three hours before reentry, and the capsule coasted on a ballistic trajectory, re-entering the Earth's atmosphere at 13:51, 13 June 2010 UTC. It is estimated that the capsule experienced peak deceleration of about 25 G and heating rates approximately 30 times those experienced by the Apollo spacecraft. It landed via parachute near Woomera, Australia.

In relation to the mission profile, JAXA defined the following success criteria and corresponding scores for major milestones in the mission prior to the launch of the Hayabusa spacecraft. As it shows, the Hayabusa spacecraft is a platform for testing new technology and the primary objective of the Hayabusa project is the world's first implementation of microwave discharge ion engines. Hence 'operation of ion engines for more than 1000 hours' is an achievement that gives a full score of 100 points, and the rest of the milestones are a series of world's first-time experiments built on it.

Success Criteria for HAYABUSA	Points	Status
Operation of Ion Engines	50 points	Success
Operation of Ion Engines for more than 1000 hours	100 points	Success
Earth Gravity Assist with Ion Engines	150 points	Success
Rendezvous with Itokawa with Autonomous Navigation	200 points	Success
Scientific Observation of Itokawa	250 points	Success
Touch-down and Sample Collection	275 points	Success
Capsule Recovered	400 points	Success
Sample obtained for Analysis	500 points	Success

MINERVA mini-lander

Hayabusa carried a tiny mini-lander (weighing only 591 g, and approximately 10 cm tall by 12 cm in diameter) named "MINERVA" (short for Micro/Nano Experimental Robot Vehicle for Asteroid). Unfortunately, an error during deployment resulted in the craft's failure.

This solar-powered vehicle was designed to take advantage of Itokawa's very low gravity by using an internal flywheel assembly to hop across the surface of the asteroid, relaying images from its cameras to Hayabusa whenever the two spacecraft were in sight of one another.

MINERVA was deployed on 12 November 2005. The lander release command was sent from Earth, but before the command could arrive, Hayabusa's altimeter measured its distance from Itokawa to be 44 m and thus started an automatic altitude keeping sequence. As a result, when the MINERVA release command arrived, MINERVA was released while the probe was ascending and at a higher altitude than intended, so that it escaped Itokawa's gravitational pull and tumbled into space.

Had it been successful, MINERVA would have been the first space hopper to see action. Instead it joins ranks with the hopper carried on the failed Phobos 2 mission, which also never saw use.

Scientific and engineering importance of the mission

Scientists' current understanding of asteroids depends greatly on meteorite samples, but it is very difficult to match up meteorite samples with the exact asteroids from which they came. Hayabusa would solve this problem by bringing back pristine samples from a specific, well-characterized asteroid. Accordingly, Hayabusa "will bridge the gap between ground observation data of asteroids and laboratory analysis of meteorite and cosmic dust collections," says mission scientist Hajime Yano. Also in comparing the data from the onboard instruments of the Hayabusa with the data from the NEAR Shoemaker mission will put the knowledge on a wider level.

The Hayabusa mission has a very deep engineering importance for JAXA, too. It allows JAXA to further test its technologies in the fields of ion engines, autonomous and optical navigation, deep space communication, and close movement on objects with low gravity among others. Second, since it was the first-ever preplanned soft contact with the surface of an asteroid (the NEAR Shoemaker landing on 433 Eros was not preplanned) it has enormous influence on further asteroid missions.

Changes in mission plan

The Hayabusa mission profile has been modified several times, both before and after launch.

- The spacecraft was originally intended to launch in July 2002 to the asteroid 4660 Nereus (the asteroid (10302) 1989 ML was considered as an alternative target). However, a July 2000 failure of Japan's M-5 rocket forced a delay in the launch, putting both Nereus and 1989 ML out of reach. As a result, the target asteroid was changed to 1998 SF₃₆, which was soon thereafter named for Japanese rocket pioneer Hideo Itokawa.
- Hayabusa was to deploy a small rover supplied by NASA and developed by JPL, called Muses-CN, onto the surface of the asteroid, but the rover was canceled by NASA in November 2000 due to budget constraints.
- In 2002, launch was postponed from December 2002 to May 2003 to recheck the O-rings of its reaction control system since one of them had been found to be using a different material than specified.
- In 2003, while Hayabusa was en-route to Itokawa, a large solar flare damaged the solar cells aboard the spacecraft. This reduction in electrical power reduced the efficiency of the ion engines, thus delaying the arrival at Itokawa from June to September 2005. Since orbital mechanics dictated that the spacecraft still had to leave the asteroid by November 2005, the amount of the time it was able to spend at Itokawa was greatly reduced and the number of landings on the asteroid was reduced from three to two.
- In 2005, two reaction wheels that govern the attitude movement of Hayabusa failed; the X-axis wheel failed on July 31, and the Y-axis on October 2. After the latter failure, the spacecraft was still able to turn on its X and Y axes with its thrusters. JAXA claimed that since global mapping of Itokawa had been completed, this was not a major problem, but the mission plan was altered. The failed reaction wheels were manufactured by Ithaco Space Systems, Inc, New York, which was later acquired by Goodrich Company.
- The 4 November 2005, 'rehearsal' landing on Itokawa failed, and was rescheduled.
- The original decision to sample two different sites on the asteroid was changed when one of the sites, Woomera Desert, was found to be too rocky for a safe landing.
- The 12 November 2005, release of the MINERVA miniprobe ended in failure.

Mission timeline

Up to the launch

The asteroid exploration mission by ISAS originates in 1986–1987 when the scientists investigated the feasibility of a sample return mission to Anteros and concluded that the technology was not yet developed. Between 1987 and 1994, joint ISAS / NASA group studied several missions: an asteroid rendezvous mission later became NEAR, and a comet sample return mission later became Stardust.

In 1995, ISAS selected the asteroid sampling as an engineering demonstration mission, MUSES-C, Nereus as the first choice of target, 1989 ML as the secondary choice, and MUSES-C project started in fiscal year 1996. In early development phase, Nereus was

considered out of reach and 1989 ML became the primary target. July 2000 failure of M-V forced a delay in the launch from July 2002 to November/December, putting both Nereus and 1989 ML out of reach. As a result, the target asteroid was changed to 1998 SF₃₆. In 2002, launch was postponed from December 2002 to May 2003 to recheck O-rings of reaction control system since one of it was found using different material than specification. On May 9, 2003 04:29:25 UTC, MUSES-C was launched by M-V rocket, and the probe was named "Hayabusa".

Cruising

Ion thruster checkout started on 27 May 2003. Full power operation started on 25 June.

Asteroids are named by their discoverer. ISAS asked LINEAR, the discoverer of 1998 SF₃₆, to offer the name after Hideo Itokawa, and on 6 August, Minor Planet Circular reported that the target asteroid 1998 SF₃₆ was named *Itokawa*.

On October 2003, ISAS and two other national aerospace agencies were merged to form JAXA.

On March 31, 2004, ion thruster operation was stopped to prepare for the Earth swing-by. Last manoeuvre operation before swing-by on May 12. On May 19, Hayabusa performed Earth swing-by. On 27 May, ion thruster operation was started again.

On February 18, 2005, Hayabusa passed aphelion at 1.7 AU. On 31 July, the X-axis reaction wheel failed. On 14 August, Hayabusa's first image of Itokawa was released. The picture was taken by the star tracker and shows a point of light, believed to be the asteroid, moving across the starfield. Other images were taken from 22 to 24 August. On August 28, Hayabusa was switched over from the ion engines to the bi-propellant thrusters for orbital maneuvering. From 4 September, Hayabusa's cameras were able to confirm Itokawa's elongated shape. From September 11, individual hills were discerned on the asteroid. On 12 September, Hayabusa was 20 km from Itokawa and JAXA scientists announced that Hayabusa had officially "arrived".

In proximity of Itokawa

On 15 September, a 'colour' image of the asteroid was released (which is, however, grey in colouring). On 4 October, JAXA announced that the spacecraft had successfully moved to its 'Home Position' 7 km from Itokawa. Closeup pictures were released. It was also announced that the spacecraft's second reaction wheel, governing the Y-axis, had failed, and that the craft was now being pointed by its rotation thrusters. On November 3, Hayabusa took station 3.0 km from Itokawa. It then began its descent, planned to include delivery of a target marker, and release of the Minerva minilanders. The descent went well initially, and navigation images with wide-angle cameras were obtained. However, at 1:50 am UTC (10:50 am JST) on 4 November, it was announced that due to a detection of an anomalous signal at the Go/NoGo decision, the descent, including release of Minerva and the target marker had been canceled. The project manager, Jun-ichiro

Kawaguchi, explained that the optical navigation system was not tracking the asteroid very well, probably caused by the complex shape of Itokawa. A few days delay was required to evaluate the situation and reschedule.

On 7 November, Hayabusa was 7.5 km from Itokawa. On November 9, Hayabusa performed a descent to 70 m to test the landing navigation and the laser altimeter. After that, Hayabusa backed off to a higher position, then descended again to 500 m and released one of the target markers into space to test the craft's ability to track it (this was confirmed). From analysis of the closeup images, the Woomera Desert site (Point B) was found to be too rocky to be suitable for landing. The Muses Sea site (Point A) was selected as the landing site, for both first and, if possible, second landings.

On 12 November, Hayabusa closed in to 55 m from the asteroid's surface. MINERVA was released but due to an error failed to reach the surface. On 19 November, Hayabusa landed on the asteroid. There was considerable confusion during and after the maneuver about precisely what had happened, because the high-gain antenna of the probe could not be used during final phase of touch-down, as well as the blackout during handover of ground station antenna from DSN to Usuda station. It was initially reported that Hayabusa had stopped at approximately 10 meters from the surface, hovering for 30 minutes for unknown reasons. Ground control sent a command to abort and ascend, and by the time the communication was regained, the probe had moved 100 km away from the asteroid. The probe had entered into a safe mode, slowly spinning to stabilize attitude. However, after regaining control and communication with the probe, the data from the landing attempt were downloaded and analyzed, and on 23 November, JAXA announced that the probe had indeed landed on the asteroid's surface. Unfortunately, the sampling sequence was not triggered since a sensor detected an obstacle during descent; the probe tried to abort the landing, but since its attitude was not appropriate for ascent, it chose instead a safe descent mode. This mode did not permit a sample to be taken, but there is a high probability that some dust may have whirled up into the sampling horn when it touched the asteroid, so the sample canister currently attached to the sampling horn was sealed. On November 25, a second touchdown attempt was performed. It was initially thought that this time, the sampling device was activated; however, later analysis decided that this was probably another failure and that no pellets were fired. Due to a leak in the thruster system, the probe was put in a "safe hold mode".

On 30 November, JAXA announced that control and communication with Hayabusa had been restored, but a problem remained with the craft's reaction control system, perhaps involving a frozen pipe. Mission control was working to resolve the problem before the craft's upcoming launch window for return to Earth. On December 6, Hayabusa was 550 km from Itokawa. JAXA held a press conference about the situation so far. On 27 November, the probe experienced a power outage when trying attitude correction, probably due to a fuel leakage. On 2 December, an attitude correction was tried, but the thruster did not generate enough force. On 3 December, the probe's Z-axis was found to be 20 to 30 degrees from the sun direction and increasing. On 4 December, as an emergency measure, xenon propellant from the ion engines was blown to correct the spin, and it was confirmed successful. Attitude control was commanded using the xenon gas.

On 5 December, attitude was corrected enough to regain communication through the medium gain antenna. Telemetry was obtained and analyzed. As the result of telemetry analysis, it was found that there was a strong possibility that the sampler projectile had not penetrated when it landed on 25 November. Due to the power outage, the telemetry log data was faulty. On 8 December, a sudden attitude change was observed, and communication with Hayabusa was lost. It was thought likely that the turbulence was caused by evaporation of 8 or 10cc of leaked fuel. This forced a wait of a month or two for Hayabusa to stabilize by conversion of precession to pure rotation, after which the rotation axis needed to be directed toward the Sun and Earth within a specific angular range. The probability of achieving this was estimated at 60% by December 2006, 70% by spring 2007.

Recovery and return to Earth

On 7 March 2006, JAXA announced that communication with Hayabusa had been recovered in the following stages: On 23 January, the beacon signal from the probe was detected. On 26 January, the probe responded to commands from ground control by changing beacon signal. On 6 February, an ejection of xenon propellant was commanded for attitude control to improve communication. The spin axis change rate was about two degrees per day. On 25 February, telemetry data was obtained through low-gain antenna. On 4 March, telemetry data was obtained through medium-gain antenna. On 6 March, Hayabusa's position was established at about 13,000 km ahead of Itokawa in its orbit with a relative speed of 3 m per second.

On 1 June, Hayabusa project manager Jun-ichiro Kawaguchi reported that they confirmed two out of four ion engines work normally, which would be sufficient for return journey. On 30 January 2007, Jaxa reported that 7 out of 11 batteries are working and the return capsule was sealed. On 25 April, JAXA reported that Hayabusa started the return journey. On 29 August, it was announced that Ion Engine C onboard Hayabusa, in addition to B and D, has been successfully re-ignited. On 29 October, JAXA reported that the first phase of trajectory maneuver operation has finished and the spacecraft is now put in spin-stabilized state. On 4 February 2009, JAXA reported success in reignition of ion engines and starting second phase of trajectory correction maneuver to return to the Earth. On 4 November 2009, the ion engine D automatically stopped working due to the anomaly from degradation.

On 19 November 2009, JAXA announced that they managed to combine the ion generator of ion engine B and the neutralizer of ion engine A. It is suboptimal but expected to be sufficient to generate the necessary delta-v. Out of 2,200 m/s delta-v necessary to return to the earth, about 2,000 m/s had been performed already, and about 200 m/s still necessary. On 5 March 2010, Hayabusa was on a trajectory that would have passed within the lunar orbit. Ion engine operation was suspended to measure the precise trajectory in preparation to perform Trajectory Correction Maneuver 1 to the Earth-rim trajectory. On 27 March, 06:17 UTC, Hayabusa was on a trajectory which would pass 20,000 km from Earth center, completing the orbit transfer operation from Itokawa to Earth. By 6 April, completed first stage of Trajectory Correction Maneuver (TCM-0)

which controlled coarsely to Earth rim trajectory. It was planned to be 60 days before reentry. By 4 May, completed TCM-1 maneuver to control precisely to Earth rim trajectory. On 22 May, TCM-2 started, continued for about 92.5 hours, and finished on 26 May. TCM-3 from 3 through 5 June to change the trajectory from the Earth rim to Woomera, South Australia, TCM-4 was performed on June 9 for about 2.5 hours for a precision control to Woomera Prohibited Area. The reentry capsule was released at 10:51 UTC of 13 June.

Reentry and capsule retrieval



Hayabusa re-entry filmed by a camera onboard NASA's DC-8 Airborne Laboratory. The glowing return capsule is seen forward of and below the main Hayabusa probe bus as the latter breaks up. The heat-shielded capsule continues leaving a wake after the main bus fragments have faded.



The glowing return capsule is seen forward of and below the parent Hayabusa probe bus as the latter breaks up.



The re-entry seen from the Woomera Test Range

The reentry capsule and the spacecraft reentered to the Earth atmosphere on 13 June 2010 at 13:51 UTC. The heat-shielded capsule made a parachute landing in the South Australian outback while the spacecraft broke up and incinerated in a large fireball.

An international team of scientists observed the 12.2 km/s entry of the capsule from 11.9 km (39,000 ft) on board NASA's DC-8 airborne laboratory, using a wide array of imaging and spectrographic cameras to measure the physical conditions during atmospheric reentry in a mission led by NASA's Ames Research Center, with Peter Jenniskens of the SETI Institute as the project scientist.

Since the reaction control system no longer functioned, the 510 kilograms (1,124 lb) space probe re-entered the Earth's atmosphere similar to the approach of an asteroid along with the sample re-entry capsule, and, as mission scientists expected, the majority of the spacecraft disintegrated upon entry.

The return capsule was predicted to land in a 20 km by 200 km area in the Woomera Prohibited Area, South Australia. Four ground teams surrounded this area and located the re-entry capsule by optical observation and a radio beacon. Then a team on board a helicopter was dispatched. They located the capsule and recorded its position with GPS. The capsule was successfully retrieved at 7:08 UTC of 14 June 2010. The two parts of the heat shield, which were jettisoned during the descent, were also found.

After confirming that the explosive devices used for parachute deployment were safe the capsule was packed inside a double layer of plastic bags filled with pure nitrogen gas to

reduce the risk of contamination. The soil at the landing site was also sampled for reference in case of contamination. Then the capsule was put inside a cargo container which had air suspension to keep the capsule below 1.5 G shock during transportation. The capsule and its heat shield parts were transported to Japan by a chartered plane and arrived at the curation facility at the JAXA/ISAS Sagami-hara campus on June 18.

Before the capsule was extracted from the protecting plastic bag, it was inspected using X-ray CT to determine its condition. Then the sample canister was extracted from the reentry capsule. The surface of the canister was cleaned using pure nitrogen gas and carbon dioxide; it was then placed in the canister opening device. The internal pressure of the canister was determined by a slight deformation of the canister as the pressure of the environment nitrogen gas in the clean chamber was varied. The nitrogen gas pressure was then adjusted to match the internal canister pressure to prevent the escape of any gas from the sample upon the opening of the canister.

On October 7, 2010, it was announced that approximately 100 particles were collected by the sample canister, and stated that some may be cosmic materials. The particles are smaller than 0.001 millimeters. Starting in November, JAXA plans the detailed analyses of the samples by splitting each particle and examining their crystal structure at SPring-8.

Confirmation of asteroid particles

On 16 November 2010, JAXA confirmed that most of the particles found in one of two compartments inside the Hayabusa sample return capsule came from Itokawa. Analysis with a scanning electron microscope identified about 1,500 grains as rocky particles, according to the JAXA press release. After further studying the analysis results and comparison of mineral compositions, most of them were judged to be of extraterrestrial origin, and definitely from the asteroid Itokawa.

According to Japanese scientists, the composition of Hayabusa's samples was more similar to primitive meteorites than known rocks from Earth. Their size is mostly less than 10 micrometers. The material matches chemical maps of Itokawa from Hayabusa's remote sensing instruments. The researchers found concentrations of olivine and pyroxene in the Hayabusa samples.

Further study of the samples will wait until 2011 because researchers are still developing special handling procedures to avoid contaminating the particles during the next phase of research.