Rosetta Rises to the Challenge

Few enterprises are more difficult or hazardous than space travel. Yet, even when compared with the achievements of its illustrious predecessors, ESA's Rosetta mission to orbit Comet Wirtanen and deploy a lander on its pristine surface must be regarded as one of the most challenging ventures ever undertaken in more than four decades of space exploration.

The first of the challenges faced by the Rosetta project team, the scientific collaborators and industrial partners was to design, build and test the complex comet chaser in time to meet the scheduled launch date in January 2003. With less than four years from the beginning of the development phase to launch, it was only possible to meet the series of tight deadlines through highly efficient and motivated team work, long shifts and remarkable dedication by all involved.

Having overcome the time constraints associated with the launch, the hundreds of engineers and scientists involved in Rosetta are now about to face the ultimate assessment of their endeavour – the ability of their creation to not only survive in deep space for more than a decade, but to successfully operate in the close vicinity of a comet and return a treasure trove of data that will revolutionise our knowledge of these mysterious worlds.

The Launch Window

As history has frequently shown, the first hours of a spacecraft's journey to the depths of the Solar System can be among the most critical. In the case of Rosetta, the odyssey will begin with launch from Kourou spaceport aboard an enhanced version (P1 Plus) of Ariane-5.

The first obstacle to be overcome is the limited launch window. In order to meet up with Comet Wirtanen, Rosetta must be launched within a period of 19 days, starting on 13 January 2003. On six of those days there will be a launch window of just 20-30 minutes. The remaining days account for a roll back of the rocket for replenishing of the cryogenic fuel. If this opportunity is missed, the mission will have to be postponed while another target is selected.

Fortunately, the Ariane-5 operator, Arianespace, has an excellent record in launching payloads within such a restricted time frame and has expressed its willingness to do everything possible to ensure that the launch will take place within the three-week window.

Meanwhile, the project team is also taking precautions to ensure that Rosetta launches on time:

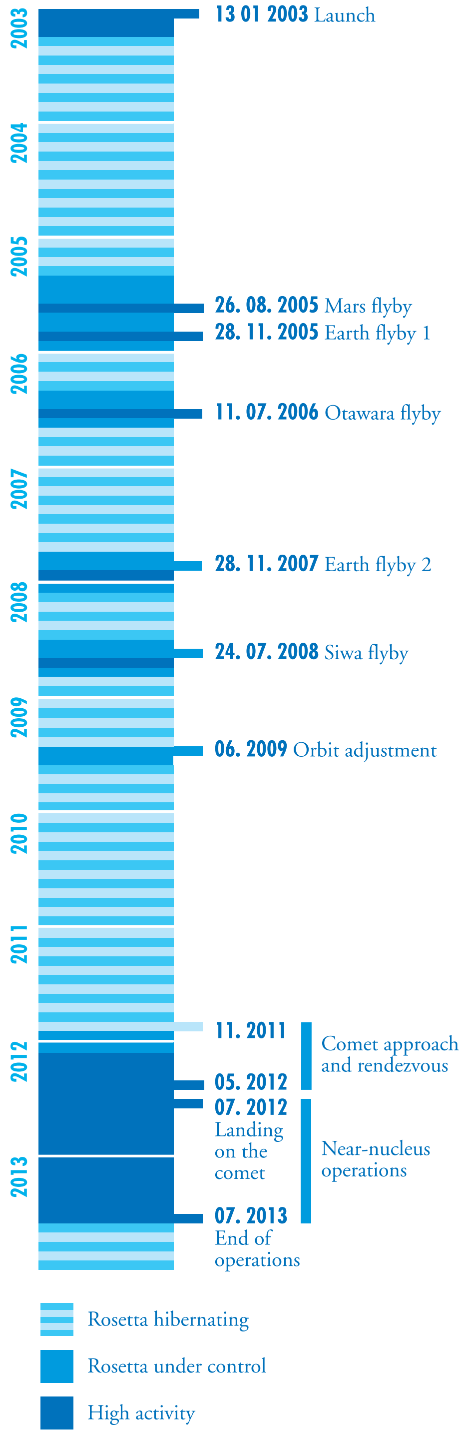
"We do not anticipate any drastic launch postponement," says John Ellwood, Rosetta project manager, "However, it is always prudent to have contingency plans. For example, we are able to work three shifts a day if the spacecraft testing or preparation fall behind schedule. There will be a spare upper stage at the Kourou launch centre if there are problems with Ariane-5 close to launch. A spare Ariane-5 main engine will also be on hand in France ready for shipment within 24 hours."

After the EPS upper stage and its Rosetta payload have been safely placed into a trajectory around the Earth, the next challenge will be to send the spacecraft on its way towards Comet Wirtanen, just two hours after lift-off from Kourou. Prior to reaching perigee (the closest point to the Earth), the upper stage will be re-ignited to inject Rosetta into the required Earth-escape trajectory towards Mars and the asteroid belt. This will be the first time that an Ariane-5 has boosted a spacecraft beyond Earth orbit.

Survival in Deep Space

Ensuring that the spacecraft survives the hazards of travelling through deep space for more than 10 years is one of the great challenges of the Rosetta mission. This prolonged journey will provide the ultimate test of the spacecraft's long-term reliability, robustness and ability to cope with unexpected problems.

Once the spacecraft is safely on its way,



its solar arrays and booms have been deployed and its systems checkout has been completed, Rosetta will have to survive lengthy periods of inactivity, punctuated by relatively short spells of intense action – the encounters with Mars, Earth and two asteroids.

Apart from the hazards posed by the hostile space environment – dust impacts, energetic solar particles, cosmic rays and extremes of temperature – the spacecraft will spend roughly two years in hibernation. To limit consumption of power and fuel, almost all of Rosetta's electrical systems will be switched off, with the exception of the radio receivers, command decoders and power supply. At such times, the spacecraft will spin once per minute while it faces the Sun, so that its solar panels can receive as much sunlight as possible.

Onboard Autonomy

Apart from the necessity to place Rosetta in hibernation for half of its interplanetary trek, the operational situation is further complicated by occasional communication blackouts (up to four weeks long) due to solar occultations, when the spacecraft passes behind the Sun. Even under optimum conditions, daily communication opportunities from the Australian ground station will last a maximum of about 12 hours.

So what happens if some unexpected malfunction or damage occurs during the prolonged interplanetary voyage? There were two options: (i) to provide Rosetta with enough 'artificial intelligence' to solve the problem without human intervention; or (ii) to analyse the problem on the ground and transmit remedial instructions to the spacecraft.

Unfortunately, although the second of these is usually preferable, the laws of physics and the vast distances involved mean that it is rarely feasible. For much of its trek to Comet Wirtanen, Rosetta will be beyond the orbit of Mars, eventually venturing all the way out to the orbit of Jupiter, 780 million kilometres from the Sun. Even travelling at the speed of light (300 000 km/s), radio signals will take up to 45 minutes to cross the vast gulf between the distant spacecraft and the Earth. By the time Rosetta receives a response, at least one and a half hours will have elapsed.

Since real time command and monitoring from the ground are out of the question, Rosetta has been designed with a considerable degree of autonomy. Although four onboard computers are programmed to deal with tasks such as data management and attitude and orbit control, only two are required to be operational at any one time. If the onboard monitoring system detects a problem that threatens the health of the spacecraft, the computers will take immediate corrective action, switching to a backup system if necessary.

"Rosetta has been designed to carry multiple computers that provide it with a sophisticated failure recognition and recovery capability," explains Jan van Casteren, Spacecraft System Manager. "It's a highly autonomous system based on two computers, each with two separate parts that can be interchanged. We always have the option to upload new, enhanced software over the 10-year mission. The software for each computer can also be interchanged. This means that both the Data Management System and the Attitude and Orbit Control subsystem can be run on all processors. If the spacecraft is in serious trouble, it automatically goes into safe mode – in other words, it goes into hibernation with its solar arrays pointing at the Sun. These backup systems should ensure that the spacecraft will remain operational during critical mission phases, including the highly complex scientific observations when Rosetta is orbiting close to the comet's nucleus."

Solar Power

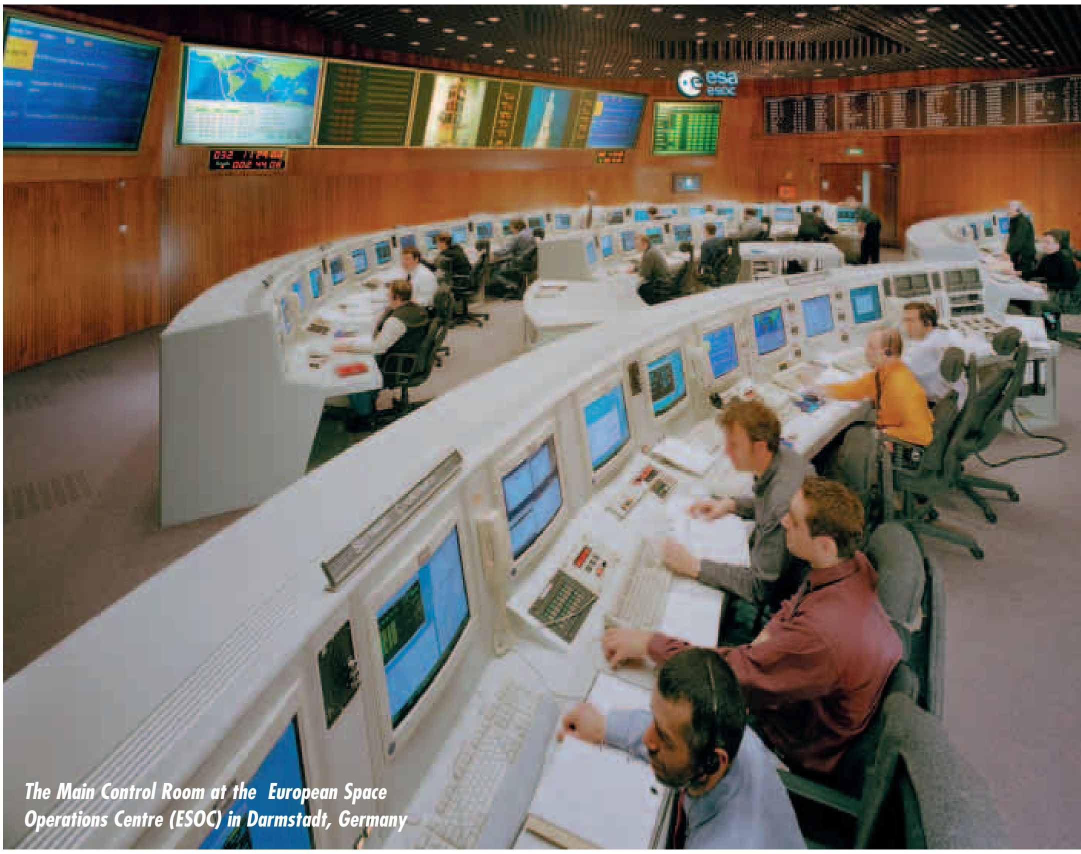
Venturing far from the Sun puts other serious constraints on Rosetta's design and performance, particularly its electricity supply and temperature.

Rosetta will set a record as the first space mission to journey far beyond the main asteroid belt while relying solely on solar cells for power generation. Unfortunately, there is a price to pay. When Rosetta reaches the orbit of Jupiter, where levels of sunlight are only 4% those on Earth, the spacecraft will be generating only 1/25th of the electricity that it can produce when in the inner Solar System.

In order to compensate for this drop in power, Rosetta is equipped with two enormous, steerable solar arrays that span 32 m tip-to-tip (longer than a tennis court) and cover an area of 62 square metres. Each of the 'wings' comprises 5 panels and

is fitted to the spacecraft body with a yoke and drive mechanism, allowing 180° rotation in order to capture the maximum amount of sunlight. Both sides of the arrays are electrically conductive, to avoid a buildup of electrostatic charge.

More than 22 000 non-reflective silicon cells have been specially developed for the Rosetta mission. The main challenge was to achieve maximum efficiency by designing a pyramid-shaped, non-reflective upper cell surface. Optimised for low-sunlight (40 W/m^2), low-temperature (-130°C) operation, these cells should provide an end-of-life conversion efficiency of 15%. They will generate up to 8700 W in the vicinity of the Earth and around 400 W (equivalent to the power consumed by four normal light bulbs) during the deep-space comet encounter.



The Main Control Room at the European Space Operations Centre (ESOC) in Darmstadt, Germany

Hot and Cold

Imagine leaving home for 11 years, to embark on a trek that will take you from the frozen wastes of Antarctica to the scorching deserts of Arabia. Working out how to survive such extremes of hot and cold would be a major headache.

In the same way, dramatic temperature variations were a major cause of concern for Rosetta's designers. When the spacecraft is cruising around the inner Solar System, bathed in the warmth of the Sun, its surface temperature may soar to 130°C, and even internal equipment may reach 50°C. However, in order to rendezvous with Comet Wirtanen, Rosetta will have to probe the frigid regions beyond the asteroid belt, where temperatures plummet to -150°C.

Since it is not feasible to wrap a spacecraft in multiple layers of warm clothing for periods of deep freeze, then strip these away when sunbathing is the order of the day, Rosetta has been provided with alternative ways of regulating its temperature.

Near the Sun, overheating will be prevented by using radiators to dissipate surplus heat into space. 14 louvers – high-tech Venetian blinds that control heat loss from the spacecraft – are fitted over the radiators on two sides of the spacecraft. Lovingly polished by hand, these assemblies of thin metal blades must be handled like precious antiques, since any scratching, contamination or fingerprints will degrade their heat-reflecting qualities.

The principle behind the louvers is quite simple. In the balmy regions between Earth and Mars, they are left fully open, allowing as much heat as possible to escape into space from Rosetta's radiators. During the prolonged periods of hibernation and comet rendezvous, however, heat conservation is the order of the day. Since the spacecraft's limited internal power supply – equivalent to the output from a few light bulbs – then becomes the main source of warmth, it is essential to retain as much heat as possible. This means completely closing the louvers to prevent any heat from escaping. Heaters located at strategic points (e.g. fuel tanks, pipework and thrusters) will also be turned on and the multi-layered blankets of insulating material come into their own.

Communications

Communications play an even more important role in space missions than they do in our everyday lives. Whereas it is reasonable to believe that a good friend is safe and sound after several weeks without speaking to them, the same cannot be assumed for a spacecraft millions of kilometres from home.

The task of keeping in touch with the far-roaming Rosetta falls on the operations team in the Mission Control Centre at the European Space Operations Centre (ESOC) in Darmstadt, Germany. They are responsible for mission planning, monitoring and controlling the spacecraft throughout its circuitous voyage to Comet Wirtanen. The flight-dynamics team at ESOC will calculate and predict its attitude and orbit, prepare orbit manoeuvres, and evaluate spacecraft dynamics and navigation. Ground controllers will also evaluate Rosetta's performance, preparing and validating modifications to onboard software when necessary.

Planning of the scientific mission and generation of commands to experiments will be conducted either from the Science

Operations Centre at ESOC or from ESTEC. During the climax of the mission, ESOC will be responsible for pre-processing, archiving and distributing the unique cometary data to the scientific community. Lander operations will be undertaken from the DLR Lander Control Centre in Cologne, Germany, with support from the CNES Lander Science Centre in Toulouse, France.

In order to keep in touch with their itinerant explorer, ground control will be able to use radio communications at both S-band (2 GHz) and X-band (8 GHz) frequencies. Rosetta itself has the capability to 'speak' and 'listen' to Earth via several antennas. Two low-gain antennas with wide-angle coverage will support emergency operations in S-band. There are also two medium-gain antennas, one for S-band and one for X-band. However, the primary communications link will be the 2.2 m-diameter high-gain antenna, which will be able to send and receive large amounts of data at both frequencies. This lightweight steerable dish is largely made of carbon fibre and tips the scales at just 45 kg, including the electronics.

The rate at which information can be transmitted from the spacecraft will vary considerably with its distance from Earth (up to 930 million km) and its level of activity, ranging between 8 bit/s and 64 kbit/s. However, during the comet-exploration phase, the minimum telemetry data rate will be 5 kbit/s. New computer software will be used to compress the data, so compensating for the limited downlink bandwidth and ensuring that as much information as possible will be returned. The unique results from Rosetta's experiments can be stored temporarily in the spacecraft's 25 Gbit mass memory for relay to Earth at a convenient time.

To ensure that optimal contact is maintained with the wandering spacecraft, ESA's network of ground stations has been augmented with a specially-built ground station at New Norcia (Western Australia). Equipped with a newly constructed 35 m dish and cryogenically cooled, low-noise amplifiers to receive Rosetta's weak radio signal, the state-of-the-art antenna will be remotely controlled from ESOC. NASA's Deep Space Network will offer back up for telemetry, telecommand and tracking operations during critical mission phases, while the Kourou station in French Guiana will provide additional support during the launch, early-orbit and near-Earth phases of the mission.


The New Norcia ground station in Western Australia

Longevity

One of the most significant but least-tangible challenges to Rosetta's success is the insidious passage of time. Not only must the hardware survive for more than 10 years in the hostile environment of space, but the mission teams must continue to function efficiently throughout the entire voyage.

At the time of the critical near-comet operations, it is very likely that many of the engineers who designed and tested the spacecraft 10 or 15 years earlier will no longer be available to offer support if unforeseen circumstances arise. In fact, a fair number of them may well have retired. In preparation for this inevitable turnover of personnel, a number of younger people are being drafted into the instrument teams, including several principal scientific investigators. In order to ensure that the replacements can slot into the programme as easily as possible, the Rosetta project is creating a database that contains complete information about the spacecraft and its complex mission.

The unusual duration of the mission means that considerable attention must be paid to proficiency and cross training of staff to guarantee backup support, while refreshing skills and motivation. Facilities available at ESOC to support tests and simulations will include a spacecraft simulator, an onboard-software maintenance facility, and the spacecraft electrical model. If spacecraft anomalies arise, these items at ESOC will be indispensable for reproducing the problems, developing and testing solutions prior to implementing corrective actions on the spacecraft itself.

"The first eight months of the mission will involve intensive activity that will enable everyone to become familiar with the spacecraft's behaviour," explains Manfred Warhaut, Rosetta Ground Segment Manager.

"There will then be periodic training and communication activities – once every 6-12 months – to keep the team on the ball, as well as for the operations during the Earth and Mars flybys. We will take care to have adequate training before each manoeuvre."

Navigation

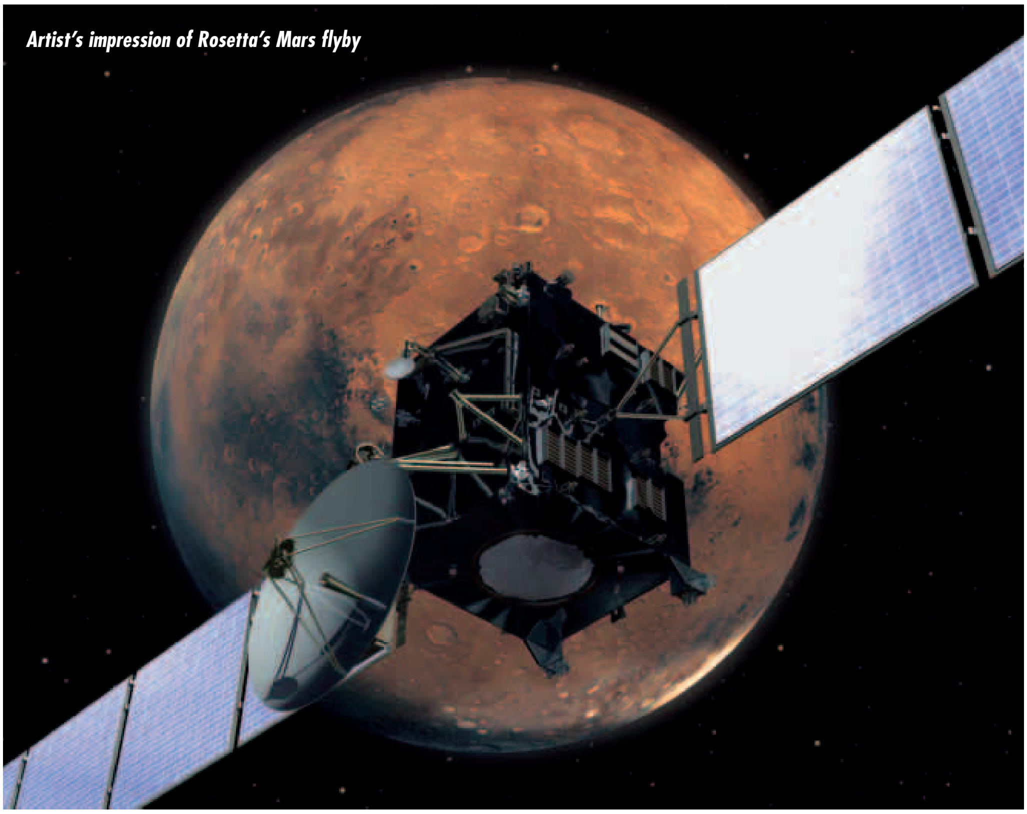
Rosetta's mission resembles a multi-million-kilometre, high-speed chase, hopefully culminating with the spacecraft and comet travelling alongside each other on parallel paths. Unfortunately, if Rosetta arrives too early or too late, the comet will not be there to meet it!

Achieving a long-distance rendezvous and matching orbits requires some highly complicated navigational calculations, particularly since not even the powerful Ariane-5 has the capability to send a three tonne spacecraft directly to Comet Wirtanen. To match the comet's velocity, Rosetta will have to be accelerated by 7.8 km/s after leaving Earth orbit. To achieve this, the spacecraft will bounce around the inner Solar System like a cosmic billiard ball, gaining speed from three planetary flybys. After an initial boost of 3.4 km/s from Ariane-5's upper stage, the spacecraft must take advantage of gravity assists from Mars (in 2005) and Earth (in 2005 and 2007).

In order to ensure that Rosetta stays on course throughout this circuitous passage, ground controllers will have to carefully monitor the spacecraft's velocity and position. This will be done by monitoring the telemetry and navigation images from the spacecraft, and by visual and radar tracking during the Earth encounters. Studies of the shift in frequency of the radio signals coming from Rosetta – the Doppler shift – will reveal how fast the robotic ambassador is travelling towards or away from us.

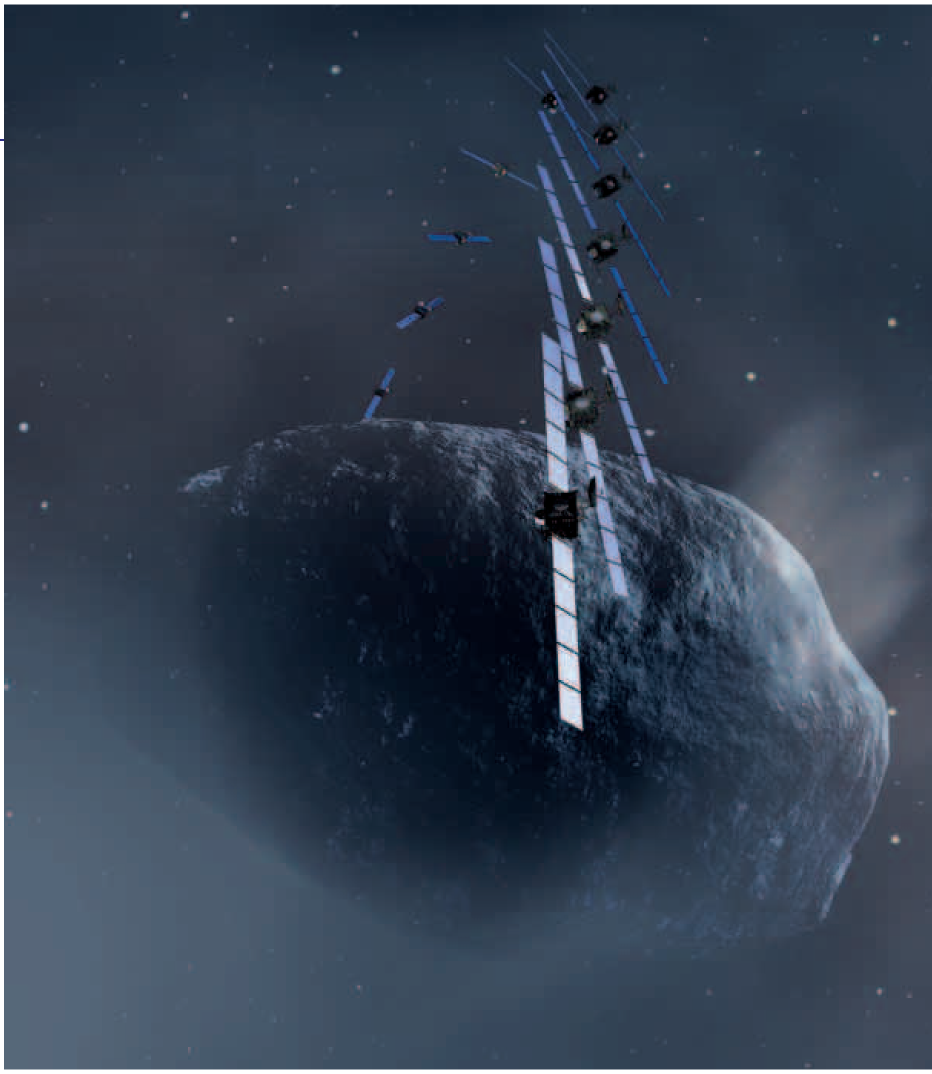
However, this is not sufficient to tie down Rosetta's motion. Like a Space Shuttle pilot trying to rendezvous with the fast-moving International Space Station, it is essential to know the quarry's position, speed and direction of movement. Unfortunately, comet orbits can be severely influenced by the gravitational pull of nearby planets. In the case of Comet Wirtanen, the orbit was significantly altered by close encounters with Jupiter in 1972 and 1984. As a result, the comet's orbital period was shortened from 6.7 years to 5.5 years. Outgassing from the nucleus may also modify a comet's trajectory, so a continuous observational programme using ground-based observatories has been put into place to accurately pin down Wirtanen's path.

Even if Rosetta follows the optimum route to its target, the final rendezvous is complicated by the fact that the comet's and the spacecraft's orbital planes do not coincide. Thus, about 8.5 years into the mission, the spacecraft's bi-propellant reaction-control system will have to be fired to make the largest manoeuvres of the mission in order to phase Rosetta's orbital plane with that of the comet. Once the onboard navigation cameras have detected the dark, inactive comet from a distance of some 300 000 km, the task of closing on the nucleus will become more straightforward.


Artist's impression of Rosetta's Mars flyby

Remote Science

Rosetta exists for one purpose – to complete humankind's first extended exploration of a comet. Although it has been equipped with a suite of state-of-the-art instruments, this alone is insufficient to ensure a successful outcome. Different experiments need different conditions to work properly and optimally. A particular environment, spacecraft orientation or orbit that is perfect for one instrument might fatally compromise the performance of another. For instance, Rosetta's dust-collecting instruments must pass through a dust jet from time to time to gather the ejected pristine material, but care must be taken to ensure that too much dust does not collect on optical instruments and other sensitive surfaces.



Rosetta orbiting Comet Wirtanen (artist's impression)

Clearly, proper coordination of the science operations is very important and every effort has to be made to coordinate these operations in order to maximize the outcome of the mission. This has been done by defining different 'mission scenarios' to meet the needs of the different instruments. In the above example, one mission scenario will be dedicated to the collection of dust (and gas) in a very active part of the coma (a jet), during which the cameras will be protected by leaving their covers on.

Each investigation also presents its own challenges. One of the most revolutionary experiments is CONSERT, which will send short pulses of radio waves through the cometary nucleus. By transmitting and receiving the pulses on the Orbiter and the Lander, the attenuation and the time delay of the radio signal propagating through the comet are determined. From this sounding data, information on the interior of the nucleus can be retrieved.

Since the time taken for wave propagation through different nucleus materials varies by tiny amounts, it is crucial to ensure that the clocks on the Orbiter and Lander are offset by no more than 5 to 100 nanoseconds (a nanosecond is a billionth of a second).

Imaging with instruments such as OSIRIS presents a different type of challenge. During the fast flybys at two asteroids, scientists want to take as many images as possible of the illuminated areas, as well as numerous high-resolution images when Rosetta is at its closest to the surfaces.

A number of constraints have to be considered here. Due to the rotation required to follow the asteroid, the spacecraft has times where it is not stable enough to take images. Between images, it may be necessary to turn the filter wheel very rapidly. Furthermore, the precise flyby time is uncertain until a few hours beforehand and the number of images has to be restricted because of the limited memory onboard the spacecraft.

Simultaneous imaging of very luminous and very dim objects is a particular headache close to the comet. One of Rosetta's main objectives is to image the faint dust jets emanating from the nucleus whilst the brightly illuminated nucleus is also in the field of view. Such requirements were a major design driver for OSIRIS and could only be achieved by a combination of extremely flat mirror optics, complex high-resolution readout electronics and considerable work by the developers to remove any 'noise' from the system.

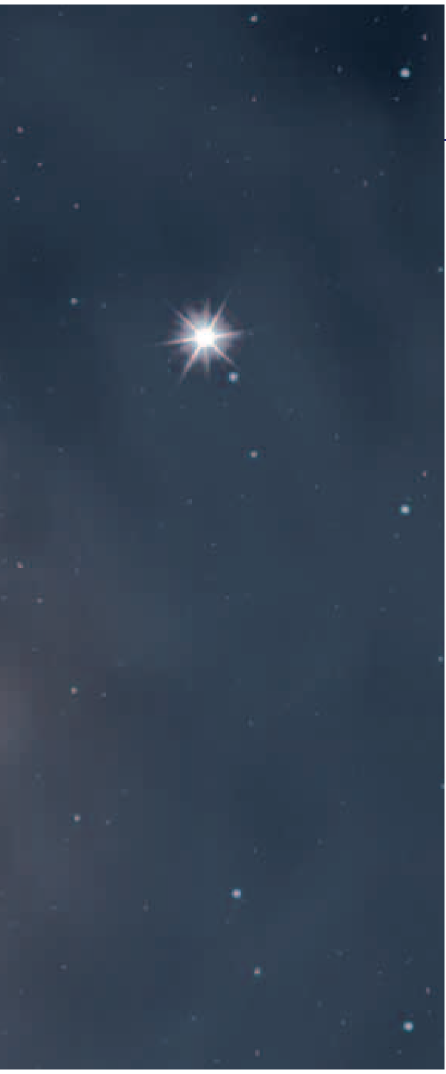
Landing on a Dirty Snowball

Landings on other worlds are remarkably difficult to achieve. During the last 40 years, the only objects in the Solar System on which robotic spacecraft have soft-landed have been the Moon, Venus, Mars and the near-Earth asteroid Eros. A decade from now, it will be the turn of Rosetta to make history with the first touch down on a comet.

By the summer of 2012, instruments on the Rosetta Orbiter will have mapped every square centimetre of the Comet Wirtanen's surface, enabling scientists to select a suitable landing site. The Orbiter's position and speed must by that stage have been precisely determined to within 10 cm and 1 mm/s, respectively, to ensure that Lander ejection takes place at the correct time for arrival at the selected site.

Following instructions uploaded from mission control, the 100 kg Lander will be released from the Rosetta Orbiter about one kilometre above the comet's nucleus. After a gentle push away from the 'mother ship', the box-shaped craft will deploy its landing gear and edge towards its target, prevented from tumbling by an internal flywheel that provides stability as its spins. A single cold-gas thruster will be able to provide a gradual upward push to improve the accuracy of the descent.

After a nail-biting 30 minute descent, sensors onboard the Lander will record the historic moment of touchdown for the helpless mission team back on Earth. Since the nucleus is so small, its gravitational pull will be extremely weak – 100 000 to 200 000 times lower than on the Earth's



surface – causing the Lander to touch down at no more than walking pace. Nevertheless, a damping system in the landing gear will be available to reduce the shock of impact and prevent a rebound.

The Lander also carries two harpoons. One of these will be fired at the moment of touchdown to anchor the spacecraft to the surface and prevent it from bouncing. Ice screws on each leg will also be rotated to bite into the nucleus and secure the Lander in place. The second harpoon will be held in reserve for use later in the mission if the first one becomes loose.

"Hopefully, gradient will not be a problem, since the spacecraft is designed to stay upright on a slope of up to about 30 degrees," says Philippe Kletzkine, Rosetta Lander Manager.

The operational lifetime of the Lander is highly uncertain. Its survival will depend on a number of factors such as power supply, temperature or surface activity on the comet. In order to ensure a significant science return, the most important images and measurements will be obtained within 60 hours of arrival. The remaining, more detailed investigations will be conducted as long as the Lander continues to function, relying on the remaining battery power and energy from the solar cells on the exterior of the Lander.

No one knows what this first soft landing on a cosmic iceberg will reveal. What we can be sure of is that the Orbiter and its little Lander will revolutionise our knowledge of comets, providing new insights into the nature and origins of these primordial objects.

The Rosetta Lander on Comet Wirtanen's surface (artist's impression)