8

Unveiling A Cosmic Iceberg

8.1 THE AWAKENING

Like the heroine of some fairy tale Rosetta awakened and called home on 20 January 2014, after a record 957 days in hibernation. At the speed of light, the signal took 44 minutes and 53 seconds to cross the 807 million km gulf to Earth.

During its long outward cruise toward the orbit of Jupiter, the intrepid explorer had traveled almost 800 million km from the Sun. Now, as Rosetta's orbit brought it back to a heliocentric distance of 'only' 673 million km, its giant solar wings began once again to receive sufficient energy to restore the spacecraft's systems to life.

Although it was still about 9 million km from its target, Comet 67P, Rosetta was awoken by its pre-programmed internal alarm clock at 10:00 UT. After warming up its star trackers, then activating its thrusters to cancel the slow spin that had stabilized it while inert, the spacecraft entered a planned safe mode. Over a period of about 6 hours, this resulted in Rosetta aiming its high-gain radio antenna at Earth. After switching on its transmitter, it sent the long-awaited signal which informed mission operators that it had survived what was perhaps the most hazardous part of its long trek.

The signal was received at 18:18 UT by the 70 meter diameter antenna (DSS-14) at NASA's Goldstone ground station in California, during the spacecraft's first window of opportunity to communicate with Earth.[1] As soon as the renewal of

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[1] NASA's DSN network continued to provide routine tracking and telecommand support for several weeks after Rosetta's awakening on 20 January, until the Earth distance had decreased to enable ESA's 35 meter stations at New Norcia, Cebreros and Malargüe to take over. Tracking passes lasting 7 hours were scheduled every day for the first week, then daily 5 hour passes over DSN and ESA stations.

P. Bond, *Rosetta: The Remarkable Story of Europe's Comet Explorer*,
Springer Praxis Books, https://doi.org/10.1007/978-3-030-60720-3_8

contact was confirmed by ESA's Space Operations Center (ESOC) in Darmstadt, Germany, the message "Hello, world!" was posted on the @ESA_Rosetta twitter account.

Acquisition of signal (AOS) came 18 minutes later than hoped, but well within expectations. This delay was due to the onboard computer automatically rebooting itself at the beginning of the sequence to exit hibernation, but this was not considered to be an issue.[2] In safe mode, it transmitted a simple radio tone using the S-band transmitter and waited for instructions from Earth.

Within several hours, the Flight Control Team had established full control, and switched on the more powerful X-band transmitter to facilitate a faster download rate of about 9 kbps. The incoming stream of high-rate housekeeping data (telemetry) gave a detailed look at the health and status of crucial propulsion, attitude-keeping and power systems, among others.

The propellant tank temperatures were now running at 7-9°C, slightly colder than the 10-15°C expected but well within predictions. The solar arrays appeared to have suffered little, if any, degradation during the 31 months of spacecraft silence, and their power levels were similar to those prior to hibernation.

As Andrea Accomazzo, the ESA spacecraft operations manager, explained, "We were most concerned about power, and seeing if the solar arrays were generating sufficient electricity to support the planned recommissioning activities. But even though we were still 673 million km from the Sun, we were getting enough power and the arrays appear to have come through hibernation with no degradation."

"We have our comet chaser back," said Alvaro Giménez, the ESA Director of Science and Robotic Exploration.

"This was one alarm clock *not* to hit snooze on," said Fred Jansen, the ESA Rosetta mission manager, "and after a tense day we are absolutely delighted to have our spacecraft awake and back online."

Over the next several days, detailed health checks verified that the rest of the systems were as expected, and Rosetta was declared fully functional.

"We're now recording tracking station data, and in a few days will be able to conduct the first full orbit determination since wake up," announced Frank Dreger, the head of flight dynamics at ESOC.

Three of the four reaction wheels – gyroscopes used to control the spacecraft's orientation – were reactivated flawlessly, although they were initially operated at low speed (around 250 rpm). The fourth, wheel B, which had caused concern earlier (see Chapter 7), was activated on 3 February, and, once controllers were happy with its behavior, they established four-wheel control by the attitude and orbit

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[2] A similar computer reboot had occurred midway through the long hibernation, due to a 'memory leak' caused by background software processes that continued to run, filling up the buffers.

control system (AOCS) on 7 February. The next few weeks were spent testing and configuring onboard systems, including the solid-state mass memory that would store science and operations data until it could be downloaded.

The next phase, from mid-March to late April, saw the gradual recommissioning of Rosetta's 11 science instruments. The Rosetta Mission Operations Center at ESOC coordinated these tests to ensure that each instrument would be ready to perform on arrival at Comet 67P. The first instrument to be switched on was the OSIRIS imaging system. Brief initial checkouts for ALICE and RPC were also conducted.

Rosetta got its first sighting of the tiny, distant comet since awakening when two 'first light' images were taken by OSIRIS on 20-21 March. However, at a range of some 5 million km, the comet covered less than one pixel. OSIRIS was then tasked to take navigation images that could be used for fine-tuning a series of comet rendezvous maneuvers, scheduled for May. In addition, it started taking light curve measurements to enable the rotation period of the comet to be determined. By 4 May, the distance to 67P had closed to 2 million km and the imagery showed the comet developing a coma that soon extended some 1,300 km into space.

Box 8.1: Mars Express Helps to Arouse Rosetta

Capturing Rosetta's wake-up signal was not without its challenges, although ESOC was able to predict the spacecraft's location in the sky to within 2,000 km at a distance of 807 million km, equivalent to a tiny fraction the diameter of a full Moon.

In order to ensure that the communications procedures to be carried out were correct, a test campaign was carried out using ESA's Mars Express, which carried a similar radio system to that of Rosetta. The spacecraft, in orbit around the Red Planet, 'pretended' to be Rosetta transmitting to the NASA ground stations that were to be used to listen for the signal, DSS-14 in Canberra and DSS-63 in Goldstone, to reduce the possibility of any problems in receiving the comet chaser's wake up call.

The test called for ESOC to command Mars Express to use its S-band transponders (normally only used for radio science or during emergency communications) to transmit at a very low bit rate, just as Rosetta was programmed to do.

This involved a lot of behind-the-scenes work from both ESA's Mars Express team and their colleagues at NASA's DSN (including having them come in to work on weekends and on the U.S. Thanksgiving holiday). But it paid off: a series of five test passes demonstrated that the 70 meter antennas and the teams manning them were ready for Rosetta's wake up.

By the end of March, eight instruments were undergoing reactivation: ALICE, CONSERT, COSIMA, GIADA, MIDAS, ROSINA, RPC and RSI. Some, such as MIDAS and COSIMA, were given software uploads to improve their performance. In the case of the COSIMA dust analyzer, the update was uploaded in early April and, after being switched off and on again, it was up and running with a fresh memory.

Meanwhile, the Philae lander was also switched on for the first time since hibernation. This wake-up command from Earth (via Rosetta) had been uploaded the previous week and it was executed at 06:00 UT on 28 March. A confirmation signal was received when the spacecraft next communicated with Earth, at 11:35 UT. The first image from ÇIVA on the lander, taken on 15 April, showed both of Rosetta's solar arrays.

8.2 COMMISSIONING PROBLEMS

Not all of the instrument reawakening and commissioning procedures went to plan, however. For example, the Ion Composition Analyzer (ICA) suffered some problems during its initial commissioning, and six weeks were to pass before it was finally given a clean bill of health. In order to avoid another 'latch up', in which a circuit in the instrument would start to draw excessive current and become too hot, it was decided to limit the operations of the ICA until Rosetta was close to the comet.

Similarly, all three of the ROSINA spectrometers were affected either by low temperature or software issues, producing error event messages when they were first turned on in April. One issue was due to the temperature of the detector in the Double Focusing Mass Spectrometer (DFMS) being 0.8°C below its operating limit of –30°C. Also, one of the Reflectron Time-of-Flight parameters was wrongly set and the Comet Pressure Sensor was too cold, producing erroneous offset values. These issues were solved three weeks later by a software patch and a spacecraft turn to warm the DFMS. However, it was not until May that the instrument team expressed their satisfaction with its performance.

In the case of the VIRTIS instrument, principal investigator Fabrizio Capaccioni recalled:

> We were quite tense and also a bit rusty in the instrument handling; in fact, we ended up uploading the wrong telecommand sequences!
>
> The onboard software returned a flurry of unpleasant comments directed to us and to some of our relatives – including deceased ones! We did not expect to have made mistakes, so we got really scared when the instrument responded as it did. The worst thoughts came to our minds. Was it a broken sensor? A faulty component? All those years of expectations and planning, for what?
>
> We had to quickly verify the received housekeeping data and the uploaded sequences as we didn't have much time: we had an interactive session of only few hours and we had many checks to do.

> An accurate verification of the parts in small print of the user manual got us back on our feet. We indeed had reversed the order of some telecommanding calls, and we had to go back to the sequences we uploaded in the cruise phase and redesign the initialization procedure in a few minutes, hoping not to have made any further mistakes. Thanks to all the people involved, it all went well and the onboard software was finally satisfied. We remained on good terms with it ever since.

The post-hibernation checkout of the MIRO microwave instrument also gave an unpleasant surprise, even though the instrument team was very cautious, turning on one component at a time and monitoring its performance carefully.

Early in the turn-on sequence, and near the end of a tracking pass, one of MIRO's sensors reported that the spectrometer's temperature shot up from around 20°C to 45°C for several seconds. Was that an indication of a short circuit? But everything else appeared normal, and staff in the control facility in Darmstadt said they saw nothing unusual.

MIRO's original principal investigator, Sam Gulkis, had just a few minutes to decide what to do, before radio contact with the spacecraft was lost for several hours. Should he shut down MIRO to prevent further damage in case something was short-circuiting, or keep it on to avoid the risk of something having broken that would prevent it being turned back on in the future?

Based in Darmstadt, Gulkis decided to leave MIRO on while Rosetta was out of contact. It was after midnight in Darmstadt when this happened, and it had been a long day, so he went to sleep while team members at JPL (where it was still daytime) continued investigating. Sam later told them he fell asleep thinking the instrument was lost before Rosetta had even arrived at the comet.

At JPL, someone asked, "Why didn't the control center in Darmstadt, who monitor all of the instruments, warn us that they'd seen a temperature spike?" Instead, Darmstadt had reported everything was normal. He was surprise to find that Darmstadt had not been asked to monitor the particular spectrometer temperature that spiked.

At the same time, a second person contacted the lead engineer for MIRO and described the situation to her, saying one of the temperature sensors was known to be unreliable – even on the ground prior to launch, it would sometimes give crazy readings.

Looking back through the instrument's documents, the team confirmed that the temperature sensor that spiked was the unreliable one.

"Because we knew it was unreliable when we launched it in 2004, we'd told ESOC *not* to monitor it," recalled *Mark Hofstadter*, who succeeded Gulkis. "But by 2014 we had forgotten the problem, and at JPL we were looking at all of our temperature sensors and saw the (false) spike. When Sam woke up, we were able to tell him that he made the right choice in leaving MIRO turned on, and when Rosetta came back in contact with the Earth, we saw that MIRO was operating normally with all temperatures and currents as expected."

There were also nerve-wracking moments during the post-hibernation commissioning of the Rosetta Plasma Consortium (RPC), which comprised five sensors tasked with investigating the magnetic, electric and plasma environment of Comet 67P.

"A critical moment for RPC was the loss of the main power supply of our plasma unit," said team member *Ingo Richter.* "A capacitor died and got a short circuit, causing the complete failure of our main power supply. Fortunately, the plasma unit is equipped with a completely redundant power supply, which was immediately started in order to provide the power. The back-up system was working fine after ten years in space!"

Meanwhile, the RPC's ICA sensor suffered overheating, and was automatically switched off. This was a problem that had occurred several times during the cruise phase, but the team had hoped to see less of it when the instrument temperature was lower.

Another team member, *Hans Nilsson,* recalled, "We discovered that a loss of data that we had sometimes seen was due to a systematic problem in the instrument. It was causing the loss of up to half our data. We ran the instrument for only brief periods of time, fearing that the next overheating event might kill the instrument. The overheating appeared to get more common, and when we had two within a few days, we feared that the end was near for our instrument. But the opposite happened. Suddenly the overheating events became very rare, and we could start to operate the instrument continuously. After some more time, we discovered that, using an alternative mode, we also got rid of the data loss. Seldom has an instrument improved so much during a mission!"

After all the alarms and tension, the payload was finally ready to scrutinize Comet 67P. On 13 May, the Rosetta team held a commissioning 'close out' review, with each of the orbiter and lander instruments being given a formal 'Go' for routine science operations.

8.3 NAVIGATING TOWARDS A COMET

At the time of coming out of hibernation, Rosetta was still about 9 million km from the comet, and traveling at 800 m/s relative to 67P. In order to rendezvous with the comet, and fly alongside, it would be necessary to close to within 100 km and then slow their relative speed almost to zero.

The first major milestone occurred on 7 May, when Rosetta made the first of 10 planned orbit correction maneuvers (OCM) designed to put it onto the proper trajectory to arrive at 67P on 6 August. The first thruster burn, which was a test to check that all the systems were working properly, began at 17:30 UT. This reduced the vehicle's speed relative to the comet from about 775 m/s to 755 m/s.

Fig. 8.1: Paolo Ferri, ESA's head of operations (left), Rosetta mission manager Fred Jansen (right) and Rosetta spacecraft operations manager Sylvain Lodiot (seated) monitoring the 21 May orbit correction maneuver. (ESA)

The first of three large OCMs in the Near Comet Drift (NCD) set, took place on 21 May. The thrusters fired for 7 hours 16 minutes and reduced Rosetta's relative speed by 289.9 m/s. This was one of the longest burns in ESA spaceflight history. The burn started at 15:23 UT (spacecraft time) and was carried out autonomously, using commands that had been uploaded two days earlier. The burn consumed about 218 kg of fuel.

The second major OCM, on 4 June, consumed another 190 kg of propellant and delivered a delta-V of 269.5 m/s. This burn began at 14:21:58 UT and ran for 6 hours 39 minutes, which was about two minutes less than expected, but the outcome was well within margins. The third major OCM followed at 13:17 UT on 18 June, lasted for 136 minutes 41 seconds, and yielded a delta-V of 88.7 m/s.

These four burns had provided 667.8 m/s of the roughly 775 m/s needed to reduce the relative velocity to less than 1 m/s when Rosetta completed its rendezvous. The specification for each OCM was based on the performance of the previous burn and refinement of 67P's position from OSIRIS and the navigation camera images. The commands were uploaded several days in advance, and timed for when the spacecraft would be visible to a ground station, so that the mission control team at ESOC could receive telemetry and monitor the maneuver in near-real time.

The next phase involved four Far Approach Trajectory (FAT) burns at weekly intervals in the period 2-23 July. The first began at 12:05:57 UT on 2 July and was scheduled to continue for 1 hour 33 minutes 13 seconds. It ended about a minute earlier than expected, but achieved the desired change in velocity of 58.7 m/s.

The next three FAT burns were made on 9, 16 and 23 July. Each was shorter in duration and designed to generate a smaller delta-V than the previous burn. All were successful. The burn on 9 July lasted 46 minutes 2 seconds and achieved a delta-V of 25.7 m/s. The third burn was started at 11:36 UT on 16 July. It lasted about 26 minutes and reduced Rosetta's speed by 11 m/s relative to the comet.

The final FAT burn was made when Rosetta had closed in to about 4,500 km of its target. It began at 10:38 UT on 23 July (spacecraft time), lasted 16 minutes 35 seconds, and was designed to reduce the speed by about 4.82 m/s, after which the spacecraft's relative speed would be a modest 3.5 m/s.

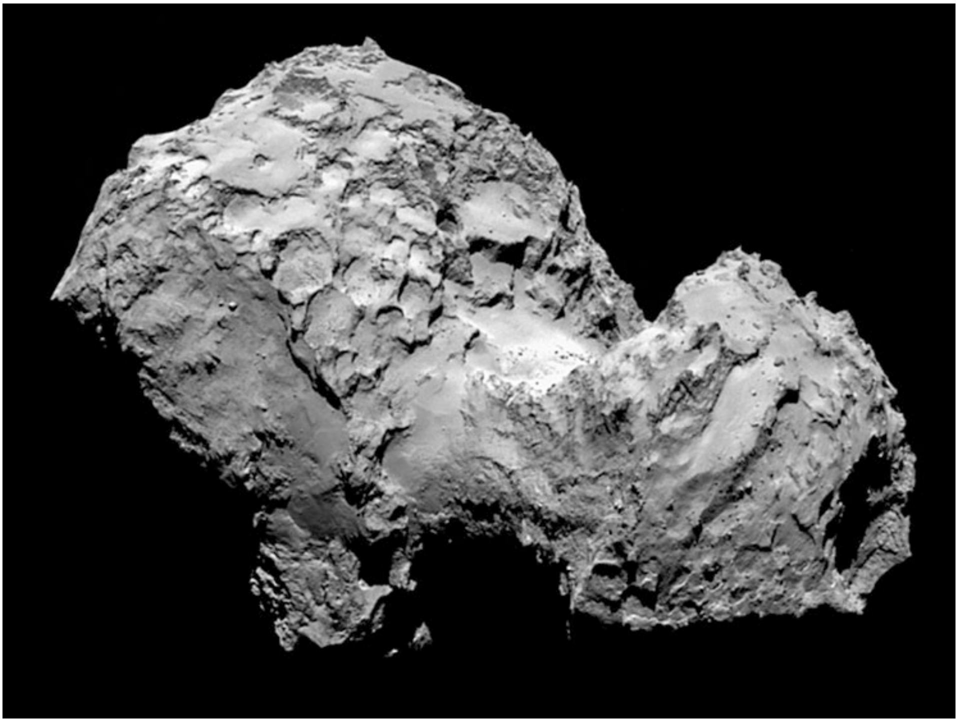

Fig. 8.2: The rugged, bi-lobed configuration of Comet 67P is clearly visible in this OSIRIS image taken on 3 August 2014, three days prior to Rosetta's arrival. (ESA/Rosetta/MPS for OSIRIS Team MPS/UPD/LAM/IAA/SSO/INTA/UPM/DASP/IDA)

The CATP (Close Approach Trajectory, Pre-Insertion) burn started at 09:00 UT on 3 August and continued for about 13 minutes 12 seconds. It bent the spacecraft's trajectory towards the comet to trim the 'miss distance' from 200 km to 70 km. It also trimmed some 3.2 m/s off the relative rate, so that the final approach would occur at a walking pace of about 1 m/s.

8.4 ARRIVAL!

The moment that everyone involved in the Rosetta mission had been awaiting since launch a decade ago, arrived on 6 August, with the CATI (Close Approach Trajectory, Insertion) burn sending the spacecraft looping around its final target.

Table 8.1: Planned Timetable for Rosetta's Arrival at Comet 67P on 6 August 2014. (Times are UT)

08:00 – BoT New Norcia tracking station. AoS telemetry data flow. Rosetta slews into position for thruster burn.
09:00:01 – Start of CATI thruster burn. Start of orbit entry maneuver. One-way light time delay for signal confirmation on ground.
09:06:27 – End of CATI thruster burn. Rosetta now on first leg of comet orbit. Rosetta slews back to comet-pointing mode.
09:22:30 – Start of thruster burn confirmed on ground.
09:28:56 – End of thruster burn confirmed on ground.
19:43 – EoT New Norcia.
19:48 – BoT Malargüe tracking station.

Key: BoT: Beginning of track. EoT: End of track. AoS: Acquisition of signal. LoS: Loss of signal. One-way signal time was 22 minutes 29 seconds. The planned duration of the CATI thruster burn was 6 minutes 26 seconds.

Although the thruster firing of only 6 minutes 26 seconds was termed the final insertion burn, CATI did not actually put Rosetta into orbit around the comet – the spacecraft was still too far away to be captured by its feeble gravity. Instead, the delta-V of about 1 m/s achieved a speed that was approximately equal to that of the comet at a stand-off distance of about 100 km.

ESA Director General Jean-Jacques Dordain reported, "After ten years, five months and four days traveling towards our destination, looping around the Sun five times and clocking up 6.4 billion kilometers, we are delighted to announce finally – 'We are here.' Europe's Rosetta is now the first spacecraft in history to rendezvous with a comet, a major highlight in exploring our origins."

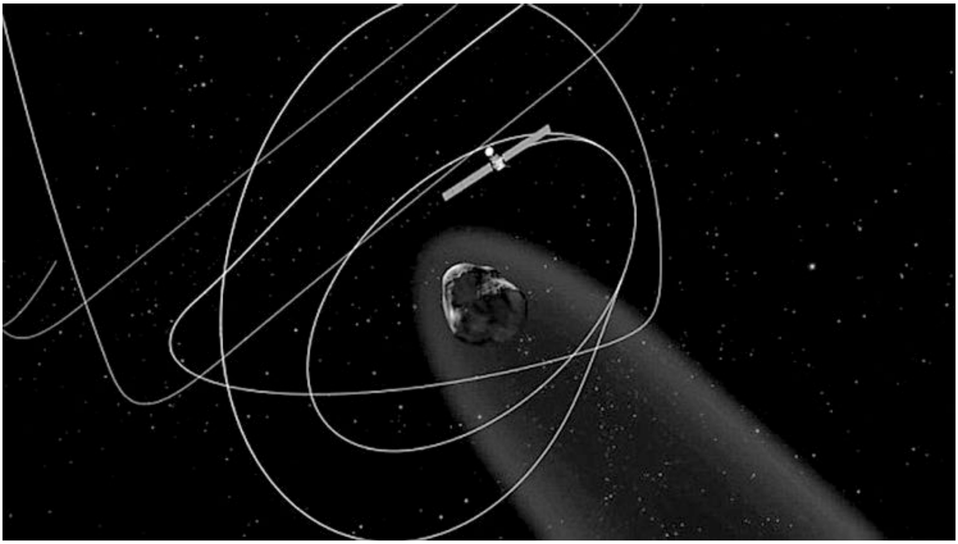

Fig. 8.3: After chasing Comet 67P, Rosetta slightly overtook it and 'entered orbit' from the 'front' of the comet, as the spacecraft and the comet traveled through space. The first three orbits were actually triangular arcs on the sunward side. Over the following weeks, Rosetta executed a complex series of maneuvers that reduced the separation from around 100 km to 25-30 km, in the process circularizing its orbit. This image is not to scale: Rosetta's solar arrays spanned 32 meters and the nucleus of the comet was approximately 4 km wide. (ESA – C. Carreau)

With its speed and direction of flight now matching those of the comet, the spacecraft began to follow a series of triangular (tetrahedral) arcs, each about 100 km long, around the nucleus. A small CAT thruster firing was performed at the apex of each triangle – which was initially every Wednesday and Sunday – to move Rosetta onto the next arc and enable it to remain near the comet. Each burn also lowered the fly-by distance (altitude). As time went by, these arcs above the surface were to be progressively lowered until 67P's gravity finally captured the spacecraft. As the altitude dropped below 30 km, the orbit would become circular.

The burns took place as follows:

- 10 August: CAT Change 1 lasted 6 minutes 25 seconds and the delta-V of 0.88 m/s put Rosetta onto the next arc at approximately 100 km fly-by altitude.
- 13 August: CAT Change 2 lasted 6 minutes 22 seconds and the delta-V of 0.87 m/s put Rosetta onto the next arc, which was also at about 100 km fly-by altitude.
- 17 August: CAT Change 3 lasted 6 minutes 19 seconds and the delta-V of 0.85 m/s started the descent toward the next triangular orbit ('Little CAT') which reached an altitude of about 80 km on 19 August.

- 20 August: CAT Change 4 lowered orbit to about 60 km on 22 August.
- 24 August: CAT Change 5 started the first arc of the ‘Little CAT’ triangle, when the altitude was about 72 km. Closest approach between 24 and 25 August was about 50 km.
- 27 August: CAT Change 6 burn.
- 31 August: Rosetta initiated the third and final arc of ‘Little CAT’, followed by the transition to the two maneuvers of the Transfer to Global Mapping (TGM).

An example of the incredible precision of the flight dynamics calculations in support of these intricate maneuvers, was the one made after the 13 August burn. It showed that the thrusters had over-performed by about 0.2%, which equated to approximately +2 mm/s.

8.5 GLOBAL MAPPING

The Global Mapping Phase (GMP) started on 10 September, and was scheduled to last until 7 October. Its aim was to gather high-resolution imagery and other science data to characterize the potential landing sites for the Philae lander, while also continuing to monitor how Rosetta responded to the environment of an active comet, prior to moving closer in. Five candidate landing sites for Philae had already been identified on 23-24 August 2014 (see Chapter 9).

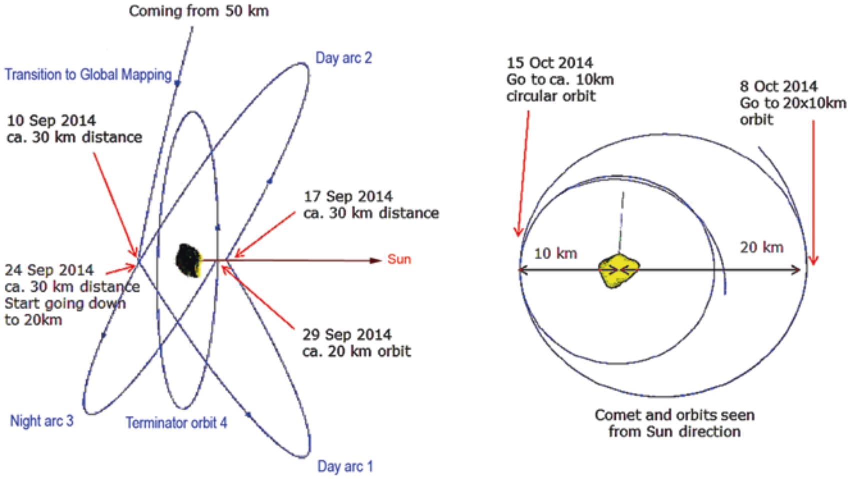

Fig. 8.4: Rosetta’s Global Mapping Phase Orbital Changes. (ESA)

Rather than flying one complete orbit around the nucleus, Rosetta conducted two, seven-day-long, half orbits at about 30 km, in different planes. The transition to the GMP began at 09:00 UT on 10 September, when the spacecraft was traveling above the terminator – the boundary between night and day on the comet's surface. It performed a 19 cm/s burn to adopt a roughly 30 km circular orbit. At the same time, the plane of the orbit was orientated 60 degrees to the Sun direction, so that it would orbit over areas of the nucleus in their 'morning hours'.

Table 8.2: Global Mapping Phase Burns During September 2014

Burn	Date	Delta-V (m/s)	Duration (min: sec)
TGM1	03/09	0.56	04:55
TGM2	07/09	0.45	04:18
GMP1	10/09	0.193	02:19
GMP slot 1	14/09	0.025	00:32
GMP2A	17/09	0.085	01:23
GMP2B	17/09	0.087	01:25
GMP slot 2	21/09	0.018	00:25
GMP3	24/09	0.016	00:24
GMP4	29/09	0.106	01:37

Key: TGM: Transfer to Global Mapping. GMP: Global Mapping Phase.

Seven days later, when the spacecraft was again above the terminator, it performed a burn to change the plane of its orbit in order to fly over 'afternoon' areas. From 18 September, it was in a 28 × 29 km orbit with a period of 13 days 14 hours 59 minutes.

When Rosetta's minimum altitude dropped to just 29 km, it was low enough to be captured by the comet's feeble gravity, and for its orbit to become circular.

On 24 September, at the end of the second 30 km arc, the orbit was shifted above the comet's night side, just before dawn. Flying 30 degrees ahead of the terminator plane, the instruments could determine the thermal characteristics of the night side of the nucleus.

Shortly prior to entering the night arc, Rosetta completed a small maneuver to lower its orbit, so that when it crossed the terminator plane five days later, it would be at an altitude of about 20 km.

On 29 September, another maneuver circularized the orbit at 20 km in the terminator plane. After a week there, the mission team decided that it was safe to go closer.

A series of maneuvers reduced Rosetta's distance from an 18.6 km orbit with a period of 7 days to an intermediate orbit of approximately 18.6 × 9.8 km with a period of about 5 days.

The orbit was circularized at 9.8 km, with a period of approximately 66 hours, on 15 October, and the mission began its Close Observation Phase (COP). This remarkably low altitude was designed to provide higher resolution images of the

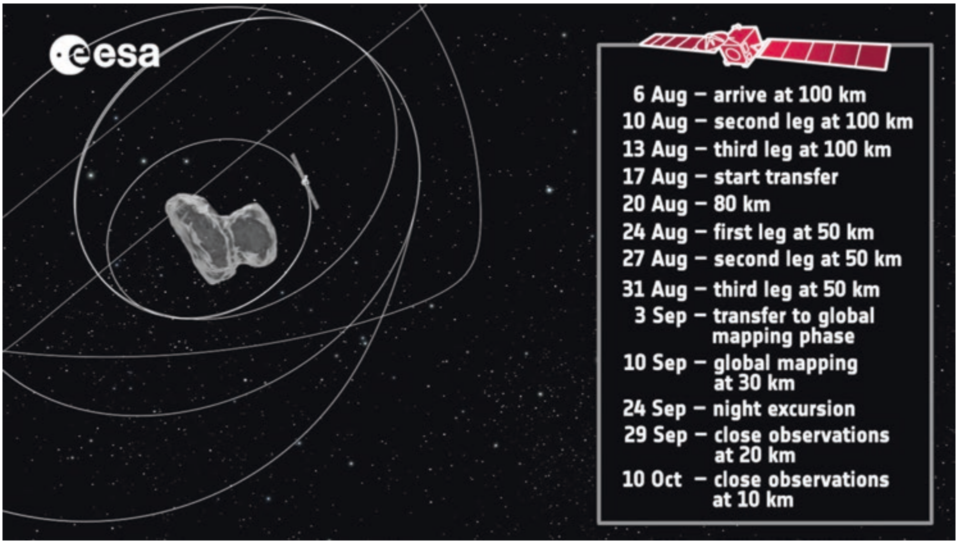

Fig. 8.5: The landmark events in Rosetta's move to a 10 km orbit above the comet. (ESA)

primary landing site, in the region named Agilkia. The new orbit also enabled Rosetta's instruments to collect dust and measure the composition of gases close to the nucleus.

8.6 LANDER RELEASE

Rosetta stayed in the 10 km COP orbit until 28 October, when a brief thruster burn placed it on a very elliptical trajectory that rapidly moved the spacecraft out of the 10 km circular orbit in the terminator plane. The thruster burn lasted 82 seconds and the delta-V of 0.081 m/s began the transfer into a slightly elliptical 'lander pre-delivery' orbit approximately 30 km from the center of the comet. (See Chapter 9 for more details on Philae's landing and outcome)

Three days later, on 31 October, a 90 second thruster burn provided a delta-V of 9.3 cm/s that moved Rosetta into the planned lander delivery orbit, at a height of about 30 km. This orbit was to be maintained until the pre-delivery maneuver planned to occur 2 hours prior to the release of the lander on the morning of 12 November. Some minor 'touch up' burns were added in order to maintain Rosetta on this orbit.

Despite several hiccups in preparing the lander for release and descent, the first 'Go/No Go' decision was made at 19:00 UT on 11 November. This confirmed Rosetta was in the correct orbit for delivering Philae to the surface at the required time. At midnight, the commands to control the separation and delivery were ready for uploading. The orbiter was also verified to be ready for the upcoming descent operations.

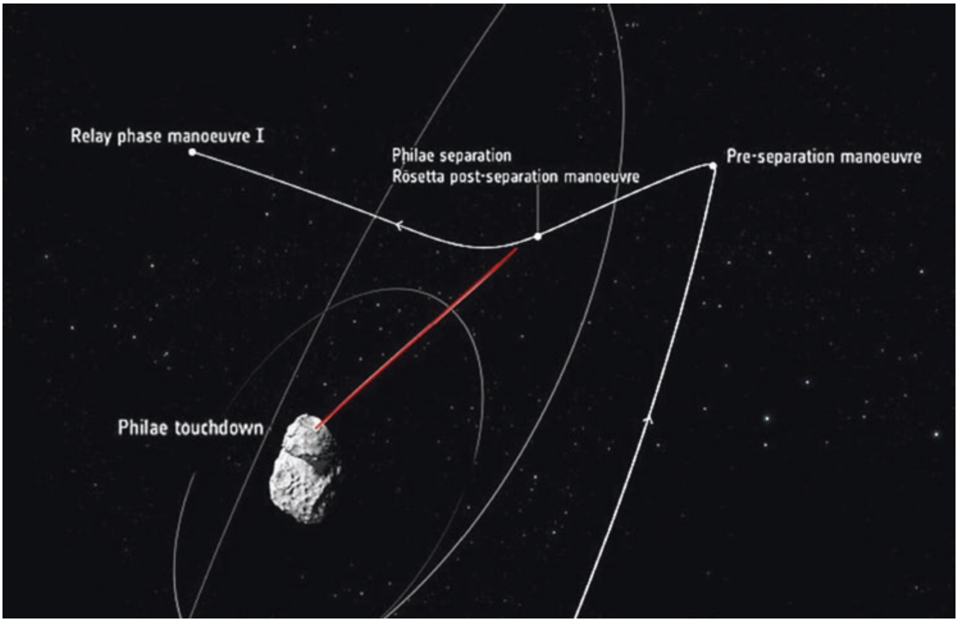

Fig. 8.6: Rosetta's maneuvers on 12 November, the day that the Philae lander was released. The descent trajectory is shown in red. (ESA, modified by Peter Bond)

The final pre-delivery maneuver by Rosetta was conducted at 07:35 UT on 12 November, enabling the orbiter to achieve the planned release point about 22.5 km from the comet's center. Next, was the final 'Go/No Go' decision which verified that the two spacecraft, the orbit, the ground stations, the ground systems and the flight teams were all ready for landing. The release of Philae occurred at 08:35 UT (spacecraft time).

Forty minutes later, Rosetta fired its thrusters to depart the elliptical delivery orbit. This shifted Rosetta to a safe distance from the comet, whilst helping to guarantee visibility of Philae at touchdown.

At 10:23 UT (spacecraft time), OSIRIS-NAC took a sequence of images that showed details of the lander, confirming the deployment of its three legs and antennas.

After a descent lasting seven hours, Philae touched down at 15:34 UT. The teams at ESOC in Darmstadt and the DLR Lander Control Center in Cologne had to wait 28 minutes 20 seconds until the signal, relayed via the orbiter, was picked up by both the ESA station in Malargüe, Argentina, and the NASA DSN station in Madrid, Spain (see Chapter 9).

A clear strong signal was received, with some breaks, but the lander's telemetry stabilized at about 17:32 UT and communication was maintained until Rosetta dropped below the lander's horizon at 17:59 UT, breaking its line-of-sight link. The fact that this occurred about an hour earlier than expected for the target landing site at Agilkia was explained away as being due to local horizon interference.

However, it soon became clear that although the descent had gone well, something had gone seriously wrong with the landing.

Later on 12 November, having analyzed the lander's telemetry, the Lander Control Center in Cologne and the Philae Science, Operations and Navigation Center in Toulouse reported that there were touchdowns at 15:34, 17:25 and 17:32 UT. Philae had bounced twice. Its precise whereabouts were unknown, but at least it was on the surface.

Fortunately, Philae's instruments were operating and delivering images and data (see Chapter 9). All went well during the second lander-orbiter communication slot between 06:01 UT and 09:58 UT on 13 November.

"We had a perfect pass," said Andrea Accomazzo, the Rosetta flight director. "The radio link was extremely stable and we could download everything according to the nominal plan."

Further communications sessions occurred over the next two days. The last time that Rosetta achieved contact was at 22:19 UT on 14 November. The signal was initially intermittent, but quickly stabilized and remained good until 00:36 UT on 15 November. But Philae's power was rapidly depleting. It completed its primary science mission after nearly 57 hours on the comet's surface.

From now on, no contact with Philae would be possible unless sufficient sunlight reached its solar panels to generate the power needed to awaken it. To increase the odds of this occurring when the comet was nearer the Sun, controllers sent the lander commands to raise its body by about 4 cm and rotate it through 35 degrees.

Meanwhile, whenever the opportunity arose, the orbiter's OSIRIS instrument would take high-resolution images to enable scientists to search for the tiny lander in the rugged region on the small lobe of 67P, where it was thought to have come to rest.

8.7 ESCORTING A COMET

With Philae in hibernation, a new phase of operations began for the Rosetta team.

"With lander delivery complete, Rosetta will resume routine science observations and we will transition to the Comet Escort Phase," said flight director Andrea Accomazzo. "This science-gathering phase will take us into next year as we go with the comet towards the Sun, passing perihelion, or closest approach, on 13 August, at 186 million kilometers from our star."

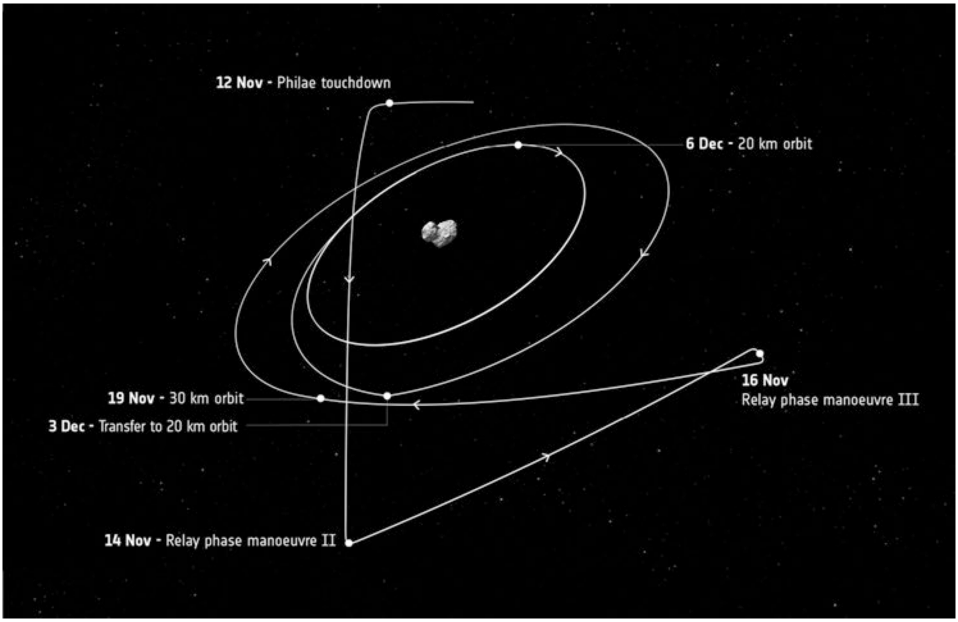

Fig. 8.7: Rosetta's main maneuvers after Philae's release on 12 November 2014. (ESA)

On 16 November, the flight control team moved from the large main control room at ESA's Space Operations Center in Darmstadt, where key operations during landing were performed, to the smaller dedicated control room that was usually employed to fly the spacecraft.

Rosetta carried out thruster burns on 14, 16, 19, 22 and 26 November to temporarily reinstate its circular orbit at about 30 km. All future trajectories would be designed purely to optimize the use of the scientific instruments.

Two thruster burns on 3 and 6 December caused Rosetta to drop down to a 20 × 20 km circular orbit again. The spacecraft was then orbiting above the terminator, the day-night boundary on the comet's surface. This orbit would be used to map large parts of the nucleus at high resolution and to conduct gas, dust and plasma measurements as surface outgassing and jet activity continued to increase.

Rosetta remained in this orbit until 20 December, when the first of two burns began its climb back to a 30 km circular orbit. After the second burn on 24 December, the spacecraft stayed in this orbit for about 6 weeks before initiating a new phase involving a series of close fly-bys of the nucleus.

8.8 FLY-BY OPERATIONS

Near-comet operations during 2014 had involved frequent maneuvers that required rapid adjustments and intense activity by mission planners and the flight control team.

After Philae had been delivered onto the nucleus, the mission entered its main science phase, a very different type of operation with its own unpredictable challenges. With little time to take a breath and relax, the off-duty ESOC flight control team remained on call around the clock.

During the main science phase, the orbiter's trajectory was set by the Rosetta Science Ground Segment (RSGS) at ESAC in Spain, where 16-week planning calendars were drawn up by the long term planning (LTP) process. Sixteen weeks prior to the start of an LTP cycle, the RSGS proposed a trajectory for that cycle, and the flight dynamics team at ESOC checked it against current spacecraft and mission constraints. Pursuing the main science phase, the flight control team adopted a regular weekly planning cycle that had two very short term plans (VSTPs), one drawn up on Monday for Wednesday to Saturday, and the other on Thursday for Saturday to Wednesday.

The procedure was as follows:

- On planning days, the most recent navigation inputs, i.e. NAVCAM images and radiometric data from the ground stations, arrived early in the morning. The flight dynamics team at ESOC took optical images with the navigation camera five times per day. These images were then used to reconstruct the position and trajectory of Rosetta with respect to 67P.
- Production of all flight dynamics commands needed for the upcoming VSTP and covering (among others) trajectory and pointing strategy for that period.
- Merging of flight dynamics products with instrument commands and spacecraft platform commands.
- Ensuring that this merger was conflict free by reconciling instrument, spacecraft and mission constraints.
- Generating commands to be uploaded to the spacecraft, as well all data files needed on the ground. These included, for example, the ground tracking station instructions for the ESTRACK and NASA DSN stations for that VSTP, and the instructions for the automation tool in the ground control system.

Mission planners maintained two parallel trajectory plans, described as 'preferred' and 'high activity'. The desire was always to fly the preferred path, operating as close to the nucleus as conditions would permit, based upon specific assumptions about the level of comet activity. The second plan was a fallback in case the preferred orbit became unsafe. The flight control team always had to be ready to respond to an increase in the level of activity by moving the spacecraft farther from the nucleus.

As Laurence O'Rourke of the Rosetta Science Operations Center in Spain, emphasized, "The desire is to place the spacecraft as close as feasible to the comet before the activity becomes too high to maintain closed orbits."

Also, if the optical navigation process were to fail, the operations teams, with the approval of the mission manager, could command Rosetta to move clear.

8.9 THE COMET COMES ALIVE

Starting on 26 January 2015, Rosetta entered conjunction season – a four-week period when it was more or less on the opposite side of the Sun from Earth, when the Sun interfered with line-of-sight radio transmission. The consequent reduction in data rates restricted the amount of data that could be downloaded during a given ground station pass.

"Now, using ESA's 35 meter ESTRACK stations we get 14 kilobits per second (kbps), and this goes up to 45 kilobits per second when we use NASA's 70 meter stations," said Sylvain Lodiot, the spacecraft operations manager.

By June, when the orbital geometry had improved and the spacecraft was closer to Earth, data rates via the ESTRACK stations recovered to the maximum rate of 91 kbps.

The first opportunity for in-depth study of the comet's evolving nucleus and coma began with a thruster burn on 4 February that placed Rosetta on an elliptical orbit that took it more than 140 km from the comet on 7 February, and then headed inward again.

Table 8.3: Thruster Burns Associated With The 6 km Fly-by

4 Feb: Depart from 26 km terminator orbit.
7 Feb: Reach 142 km from comet, then turn back.
11 Feb: Arc back down to 101 km.
14 Feb: Reach 50 km stand-off distance; turn and burn for the closest fly-by arc.
14 Feb: 6 km flyby at 12:40:50 UT

At about 12:41 UT on 14 February, Rosetta made its closest ever fly-by of 67P by swooping over the Imhotep region on the larger lobe at an altitude of only 6 km.

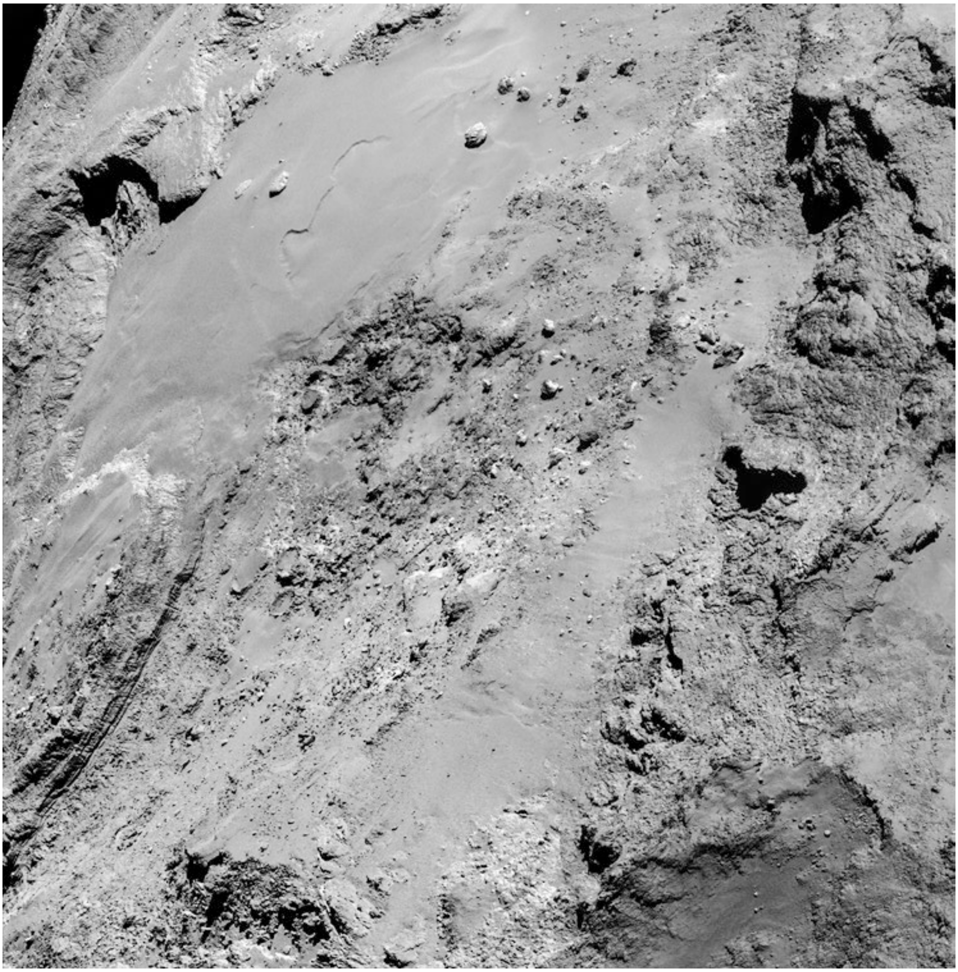

Fig. 8.8: A mosaic of four images taken on 14 February 2015 during Rosetta's first dedicated close fly-by. It features the Imhotep region on the larger lobe of the comet. The images were taken at 14:15 UT from a distance of 8.9 km. The scale is 0.76 meters per pixel, and the area measures 1.35 × 1.37 km. The closest point of approach, at about 6 km from the surface, was at 12:41 UT. (ESA/Rosetta/NAVCAM – CC BY-SA IGO 3.0)

This fly-by took Rosetta over the most active regions of the comet, allowing its instruments to obtain images and spectra of the surface with unprecedented resolution and over a range of wavelengths.

It also provided a unique opportunity to directly sample the innermost regions of the coma, where material escaping from the nucleus is fed into the coma and the tail. In particular, the instruments were looking for zones where the outflowing gas and dust were accelerated away from the surface, to determine how these constituents evolved as a function of distance from the comet.

Fig. 8.9: A close-up view of the steep slopes and smoother terrain in the Imhotep region by the OSIRIS-NAC at an altitude of 6 km during Rosetta's fly-by on 14 February 2015. The area covers 228 × 228 meters and the spatial resolution is 11 cm per pixel. The penumbral shadow of the spacecraft can be seen at the bottom. (ESA/Rosetta/MPS for OSIRIS Team MPS/UPD/LAM/IAA/SSO/INTA/UPM/DASP/IDA)

The Sun was directly behind the spacecraft during the fly-by, enabling shadow-free images to be taken. The one exception was Rosetta's shadow on the surface, which appeared in OSIRIS images as a dark, roughly rectangular, penumbra (see Fig. 8.9). The geometry meant that, in a departure from the norm, the flat face of the solar panels was oriented more or less parallel to the comet's surface.

By studying the reflectivity of the surface as it varied with the angle at which the sunlight fell on it, scientists hoped to gain a more insight into the dust grains on the nucleus. The surface was already known to be very dark, reflecting a mere 6% of the sunlight that it receives.

Box 8.2: The OSIRIS Controversy

In November 2014, scientists attending a conference in Tucson, Arizona, presented some "staggering images" of Comet 67P, including the first color pictures of the nucleus, that had been taken by the OSIRIS high-resolution camera. However, none of these images had been released to the public by Rosetta's operator, the European Space Agency (ESA), in contrast to the regular flow of less detailed images from the orbiter's navigation cameras.

The journal Science reported that Project Scientist Matt Taylor was "reduced to learning about the new results at the Arizona conference by thumbing through Twitter feeds on his phone." So what was going on?

Writing in Science, journalist Eric Hand wrote: "For the Rosetta mission, there is an explicit tension between satisfying the public with new discoveries and allowing scientists first crack at publishing papers based on their own hard-won data." He continued: "In particular, the camera team, led by principal investigator Holger Sierks, has come under special criticism for what some say is a stingy release policy."

Mark McCaughrean, an ESA senior science adviser at ESTEC in the Netherlands, was quoted as saying: "It's a family that's fighting, and Holger is in the middle of it, because he holds the crown jewels."

Media and others used to rapid dissemination of images and other data from NASA missions argued that a similar policy should be followed by ESA for the flagship Rosetta mission. However, as James Green, the director of NASA's planetary science division in Washington, D.C., pointed out, ESA relies much more on contributions from Member States, whereas NASA pays for most instrument development directly.

"It's easier for [NASA] to negotiate [data release] because we're paying the bills," said Green, whereas ESA has to do it "by influence".

On Rosetta, for example, ESA contributed very little toward the cost of developing the €100 million OSIRIS camera, and the agency therefore had less control over how its images were disseminated.

Furthermore, prior to Rosetta's launch in 2004, a data embargo of 6 months was set for all the instrument teams. However, McCaughrean pointed out that mission documents also stipulated that instrument teams must provide "adequate support" to ESA management in its communication efforts.

"I believe that [the OSIRIS camera team's support] has by no means been adequate, and they believe it has," McCaughrean was quoted as saying. "But they hold the images, and it's a completely asymmetric relationship."

Sierks, based at the Max-Planck-Institute for Solar System Research in Göttingen, Germany, argued that the OSIRIS team had already been providing a fair amount of data to the public – about one image every week. He also said that the priority should go to researchers who wanted to use the images in their papers for scientific journals, some of which enforced strict embargoes.

The OSIRIS data releases during the mission typically lagged far behind the actual date they were taken. It was not until December 2015 that ESA announced a new website on which the OSIRIS team would be releasing images on a regular basis – at least one per week. In May 2016, ESA released a large quantity of science data to the public which covered the mission through to 19 December 2014. However, it was not until April 2019 that the entire catalogue of more than 70,000 OSIRIS images of Comet 67P was published on a new website called the OSIRIS Image Viewer.

In a recent personal communication, Holger Sierks revisited the OSIRIS image release policy:

> *I think we were all overwhelmed by the public interest, ESA and us. The public interest was stimulated by ESA, and pushed all of us to increase the efforts on PR, focusing primarily on imagery, understandably, and so the tension on releases came up.*
>
> *We were in good agreement with ESA on the release of images in approach to the comet, as we were for the fly-bys at Earth, Mars, Steins, and Lutetia. We had a plan for the comet. With the increased demand on images, and the first papers hitting editors from outside the team based on released public images, tension increased. There is no agreement with the outside world not using the data other than for following the mission.*
>
> *We were providing ESA with images required for all operational aspects, including regular navigation and the landing of Philae and the orbiter, in real time. We reported to the ESA project appropriately, and showed all detail of our imagery at the Science Working Team meetings.*
>
> *A full access of ESA to our image archive, as ESA may have liked, was not possible, as the images had to get calibrated, and interpreted by the team to a level. With the huge investments by a number of key European research institutes, and space agencies, we also had to find a balance in return.*
>
> *The signed agreement on the proprietary period reads 12 months; we had discussions shortening it to 6 months as due for NASA missions and our NASA Rosetta partners, but shortening could not be agreed on with the groups that delivered their hardware 10 years ago on the basis of the agreed 12 months. And it is a true statement, the instruments are not*

owned by ESA, ESA is providing and flying the bus, as ESA'S director of science once stated.

All OSIRIS images were delivered to the PSA (Planetary Science Archive) of ESA in due time, raw and calibrated, following the 12 months proprietary phase, and the ESA archiving time line. They are publicly available ever since ESA put them on the archive.

For the fun of sharing the images, and enjoying them browsing for specific topics, we ran a student's project and published the full archive [on website] https://rosetta-osiris.eu/ . It is far more handsome than the science archives by the space agencies. We see more than 500 unique visitors per day still accessing the server.

8.10 SWAMPED BY FALSE STARS

Apart from an increase in drag on the spacecraft and its giant solar wings as a result of flying through denser regions of outflowing gas and dust, Rosetta almost lost its way.

Some two hours prior to closest approach, the star tracker began to lose the ability to identify enough stars to navigate correctly, and occasionally locked onto 'false stars'. This was due to the reflective particles in the coma. The spacecraft switched to some back-up units, including the back-up star tracker, but this also experienced tracking problems owing to the number of dust particles in the field-of-view during the fly-by.

"With a lot of luck, the spacecraft did not end up in safe mode," pointed out Sylvain Lodiot, the operations manager. "Although in this case we could have recovered the spacecraft and resumed operations as planned, the science instruments would have automatically switched off in the meantime. By the time they were switched back on, we would have been relatively far away from the comet again."

After this close fly-by, the mission entered its next phase, in which Rosetta was to execute a series of fly-bys at distances that varied from about 15 km to 100 km. This shift from 'bound orbits' to fly-bys had always been planned for this phase of the mission, based on predictions of increasing cometary activity and the safety of the spacecraft.

The range of fly-by distances also balanced the needs of the instruments, to optimize their respective scientific returns. For example, during some of the close fly-bys, Rosetta would move over the comet almost in step with its rotation to allow the instruments to monitor a single point on the surface. In contrast, the more distant fly-bys provided a broader context with wide-angle views of the nucleus and its growing coma.

Immediately after Rosetta's extremely close fly-by on 14 February, it traveled away from the comet, reaching a distance of 253 km from its center three days later.

The next pass by the nucleus involved a new trajectory arc which took the spacecraft within about 55 km of the surface on 23 February, as part of the effort to sample the material which was flowing away from the comet at various distances.

During 12-20 March, the orbiter transmitted continuously to the Philae lander in the hope of a response, but to no avail. The most likely time to establish contact occurred during the 11 fly-bys in which the orbiter's path placed it in a particularly favorable position with respect to the lander in local daytime, when Philae's solar panels would be receiving sunlight and charging its battery.

The smooth progress of the near-nucleus operations was interrupted on 28 March, during a fly-by that passed within about 14 km of the large lobe. Navigational issues similar to those of 14 February recurred. Again, the primary star tracker experienced difficulties in locking on to its guide stars while approaching the active comet. Attempts to regain tracking capabilities were hindered by the amount of background noise, which produced hundreds of 'false stars', and it was almost 24 hours before tracking was properly re-established.

In the meantime, a spacecraft attitude error had built up, resulting in the high-gain antenna pointing away from Earth. As a result, a significant drop in the strength of the radio signal received by ground stations was registered.

After recovery of the star tracking system, the high-gain's error was corrected automatically, returning the received signal from the spacecraft to full strength.

But the 'false stars' continued. When comparisons with other navigation mechanisms showed inconsistencies with the star trackers, some onboard reconfigurations were begun. While this was underway, the same error occurred again, this time resulting in an automatic safe mode that turned off many key systems, including the science instruments. Nevertheless, some data were returned, and the NAVCAMs took images during the inward leg and shortly after closest approach.

Although the operations team toiled successfully to recover the spacecraft from safe mode to normal status over the next 24 hours, it took much longer to reactivate all of the science instruments.

Meanwhile, Rosetta moved onto a pre-planned escape trajectory which took it some 400 km from 67P. An orbital correction maneuver was performed on 1 April to start to bring it back. After a second maneuver on 4 April, the desired distance of 140 km was achieved on 8 April.

Nevertheless, the continuing navigational difficulties associated with 'false stars' necessitated a new strategy for near-comet operations. The desire to keep Rosetta safe whilst maximizing its scientific return required mission planners to modify the existing flight plans as the comet spewed out increasingly large amounts of dust.

"This has ultimately meant a complete replanning of the upcoming fly-by trajectories," said Sylvain Lodiot. "We're first moving to a terminator orbit at a distance of 140 km and then we are targeting 100 km. Then we will adopt a similar strategy to when we first approached the comet, in August last year. That is, we'll fly 'pyramid' trajectories, starting at about 100 km on 11 April, and we'll monitor how the spacecraft reacts before moving closer."

During May and June, the operations team flew Rosetta at the safer distance of roughly 200 km from the comet in order to avoid further navigation issues. It was also maneuvered into a terminator trajectory, in the hope this would reduce the degree to which the dust confused the star trackers.

As the weeks went by, the plan was to slowly edge Rosetta nearer to the comet whilst closely monitoring the performance of the star trackers in 'continuous tracking mode'. By late June, its closest approach was down to 165 km.

Meanwhile, from March 2015 onward, Philae's environmental conditions were expected to improve, with higher surface temperatures and better illumination. When the orbital geometry was suitable, Rosetta periodically switched on its receiver to listen for signals from the dormant lander.

These efforts paid off on the evening of 13 June, when communications with Philae were re-established after 211 days of silence. The orbiter maintained a weak, but steady, radio link for some 85 seconds. The relayed signals were received by ESOC in Darmstadt at 20:28 UT (see Chapter 9).

A second burst of lander data was received at about 21:26 UT on 14 June, lasting just a few seconds. These data were confirmed to be giving the lander's current status, indicating that its internal temperature had already risen to –5°C.

Philae issued short bursts of housekeeping telemetry over the following days, including data from its thermal, power, and computer subsystems.

On 15 June, teams at ESA, DLR and CNES agreed to a new trajectory that would optimize the opportunities for lander-to-orbiter communication. This planning required a great deal of coordination between the flight dynamics experts at ESOC in Darmstadt, the Rosetta Science Ground Segment (RSGS/ESAC), the Philae Lander Control Center team (DLR Cologne), and the Science Operations Navigation Center (SONC) at CNES/Toulouse.

Their efforts resulted in Rosetta making two 'dog-leg' burns, beginning on 16 June, to put it into a modified orbit designed to establish more frequent and longer contacts with Philae. The new orbit included an already planned lowering from 200 km to 180 km, and 'nadir pointing' (continuously pointing Rosetta's communications unit at the comet) in the latitudes where the lander was believed to be located.

These modifications enabled the lander to make a further six intermittent contacts on 19, 20, 21, 23 and 24 June, and 9 July. Housekeeping data were transferred from Philae to Rosetta on all of these dates, apart from 23 June, but the communications links were too short and unstable to enable any scientific measurements to be commanded.

During the first weeks of July, Rosetta flew along the terminator plane at distances between 180 km and 153 km, and at latitudes between 0 and 54 degrees, seeking the best location for communicating with Philae. However, by this time the increased levels of outflowing gas and dust meant the star trackers were partially swamped over the weekend of 10-11 July, and the spacecraft had to retreat to safer distances of 170-190 km.

Despite Philae's temperature rising above 0°C as the comet approached perihelion in August, no further contacts were made with the lander. Perhaps it was transmitting, but the orbiter, at its safe altitude, was too far away to pick up the weak signal.

With activity subsiding after perihelion, Rosetta was able to safely approach the nucleus once again. However, despite repeated passes, no signals were detected, and attempts to send commands 'in the blind' to trigger a response from it also failed to produce a result.

8.11 PERIHELION AND BEYOND

On 23 June 2015, ESA confirmed that the Rosetta mission would be extended to the end of September 2016. The nominal mission was funded to the end of December 2015, but ESA's Science Program Committee issued formal approval to continue it for a further nine months.

This extension meant that the orbiter would continue to accompany Comet 67P after it made its perihelion passage on 13 August 2015 and headed back into deep space.[3] By continuing its study of the comet as it receded from the Sun, Rosetta would provide scientists with a more complete picture of how the activity of a comet increases and decreases along its orbit.

The additional observations by Rosetta would also provide improved in-situ data to compare with complementary Earth-based observations. (Professional and amateur astronomers across the globe had observed the comet as it neared perihelion, and observations using professional telescopes were planned every night around closest approach.)

As expected, the amount of material being ejected by the comet's jets increased dramatically up to, and after, the closest approach to the Sun. Scientists estimated that, at peak activity, the nucleus was shedding 1,000 kg of dust per second, producing perilous conditions for Rosetta.

In the days leading up to perihelion, the orbiter had to retreat to altitudes of between 325 km and 340 km to prevent its star trackers being confused by 'false stars'.

The first year of exploration at 67P had been largely focused on near-comet studies, but this changed on 23 September, when Rosetta was inserted into a new trajectory that carried it up to 1,500 km from the nucleus in the direction of the Sun.

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[3] Perihelion occurred at 02:03 UT on 13 August, 186 million km (1.24 AU) from the Sun, between the orbits of Earth and Mars. At that time, the one-way travel time for a signal was 14 minutes 44 seconds.

During this three-week excursion, the orbiter retreated much farther from the nucleus than at any time since its arrival in August 2014 (see Appendix 3). The maximum distance was achieved by the end of September, with the spacecraft heading back toward the nucleus by mid-October.

The main science goal driving this course of action was to make a broader study of the coma while the comet's activity remained high, post-perihelion. Almost all of the instruments were operating, but this phase was of particular interest to the Rosetta Plasma Consortium, who were keen to investigate the bow shock, the boundary between the comet's magnetosphere and the ambient solar wind environment.

"Previous measurements performed during fly-bys [by other missions] only provided limited data points about the bow shocks of a handful of comets," explained Claire Vallat, a Rosetta scientist at the European Space Astronomy Center (ESAC). "Rosetta, instead, will take data over several days, monitoring the evolution of the plasma environment of 67P shortly after its perihelion."

Meanwhile, another significant scientific opportunity opened in May 2015, as the southern hemisphere of the nucleus started to be bathed in sunlight after more than five years of darkness. Previously, only the MIRO microwave instrument had been able to study this frigid region. Now Rosetta was able to undertake the first multi-instrument observations of the comet's south polar regions.

A number of passes over the southern hemisphere were achieved before the brief southern summer ended in early 2016 – significantly, both before and after perihelion. In late October, after the three-week trip into the coma, the mission team scheduled a number of orbits that would compare the northern and southern hemispheres, making slower passes in the south in order to maximize the observational opportunities.

In March-April 2016, Rosetta went on another far excursion, this time on the night side, to study the wider coma, tail, and plasma environment. It reached a distance of about 1,000 km on 30 March and then headed back in, flying past the nucleus at an altitude of 30 km about a fortnight later.

The operations plan for the following weeks included a close fly-by and orbits dedicated to a range of science observations. Unfortunately, despite a decline in activity after perihelion, the environment was still dusty enough to cause navigational errors.

8.12 ANOTHER DRAMATIC SAFE MODE

The continuing false detections by the star trackers led to Rosetta entering safe mode on the weekend of 28-29 May, when it was just 5 km above the nucleus. After the star trackers were confused by dust, they locked on to a 'false star' which led to spacecraft pointing errors that would trigger an automatic shift to safe mode. Unknown to controllers on Earth, the lack of star tracker data prevented the spacecraft's computer from entering Safe Hold Mode. Instead, it became locked in an intermediate Sun-keeping Mode. As a result, contact with Rosetta was lost for nearly 24 hours.

"We had no signal from the spacecraft, so we were 'in the blind', which is the worst situation possible," said Sylvain Lodiot, the spacecraft operations manager. "Also we had not received the telemetry telling us the spacecraft was going to safe mode. So we were not sure what had happened."

In an effort to recover the spacecraft, Lodiot persuaded the flight dynamics team and the mission manager to send commands in the blind to power cycle (i.e. switch on and off) the star trackers.

As Lodiot says:

> Once I convinced them and got the 'Go', my team sent the command via the low-gain antenna. And it worked! The hung star tracker began to acquire stars, which allowed the transition from Sun-keeping Mode to Safe Hold Mode, and then we got the signal back from the spacecraft.
>
> It was an extremely dramatic weekend. After we sent commands 'in the blind', which successfully tackled the hung star tracker issue, an additional false star detection almost sent the spacecraft back into safe mode again.
>
> I remember that weekend very well. 29th May is the birthday of my daughter, so I was in France, but I spent the previous night and most of the 29th on the phone before driving back and going straight to work on Sunday afternoon. I was not very popular that day at home ... I even missed the (birthday) cake.

In accordance with normal practice during such an event, extra ground tracking station time was sought in order to provide additional support for recovering the spacecraft. The already scheduled Rosetta tracking slot with ESA's New Norcia station in Australia was extended by claiming time from Mars Express operations. The 'blind' command was sent by New Norcia and, later, ESA's Cebreros station in Spain assisted with the recovery.

Eventually, the spacecraft was returned to three-axis stabilized safe mode. However, it took some time for the ground team to receive the NAVCAM images needed to confirm its exact position relative to the comet. Despite the safe mode, controllers were able to resume science operations by 2 June, and to continue with the plan to maneuver Rosetta into a 30 km orbit.

Less than a month prior to the end of the mission, imagery from OSIRIS-NAC revealed the long-lost Philae lander, wedged in a deep crack in the Abydos region of the nucleus – as had been inferred. Taken on 2 September when the orbiter came within 2.7 km of the surface, the images clearly showed the 1 meter wide body of the lander, along with two of its three legs, lying on its side (see Chapter 9).

"With only a month left of the Rosetta mission, we are so happy to have finally imaged Philae, and to see it in such amazing detail," said OSIRIS team member Cecilia Tubiana, who was the first person to see the images when they were downlinked.

8.13 THE GRAND FINALE

As comet activity diminished post-perihelion, the operations team could move Rosetta much closer in order to undertake a detailed survey of the changes that had occurred on its surface and in its environment. There was also the opportunity to use the experience gained in operating Rosetta close to the nucleus in order to carry out new and slightly riskier investigations, including flights over the night side to observe plasma, dust, and gas interactions, and collection of samples of dust ejected close to the nucleus.

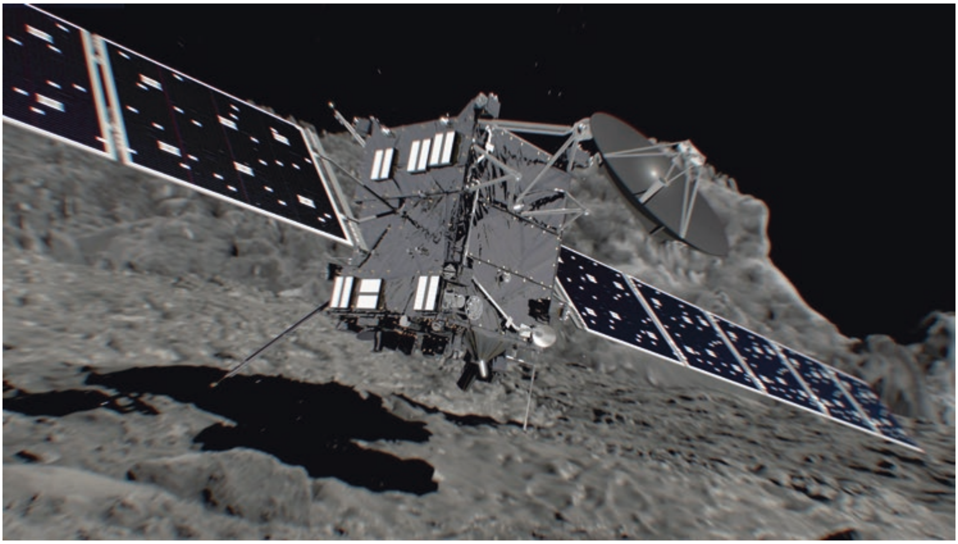

Fig. 8.10: An artist's impression of the Rosetta spacecraft shortly prior to its landing on 67P on 30 September 2016. (ESA)

When discussing the eventual termination of the mission, the mission team favoured setting the huge orbiter down on the surface of the nucleus. This would provide a new science bonanza as the instruments would return data right up until the end of the mission, gathering unique data at unprecedentedly close distances.

By the end of September 2016, Rosetta and 67P would have retreated to a distance at which there was not enough sunlight to power the scientific instruments and operate the spacecraft efficiently and safely. Also, communication would be restricted for several weeks because the comet would be behind the Sun from the vantage point of Earth, making it difficult to relay both scientific data and operational commands.

"This time, as we're riding along next to the comet, the most logical way to end the mission is to set Rosetta down on the surface," said Patrick Martin, Rosetta's mission manager. "But there is still a lot to do to confirm that this end-of-mission scenario is possible. We will first have to see what the status of the spacecraft is after perihelion and how well it is performing close to the comet, and later we will have to try and determine where on the surface we can have a touchdown."

On 21 July, ESA reported that the controlled impact on 67P would be made on 30 September 2016, in the Ma'at region of the small lobe. This target was chosen for its scientific potential, and for being consistent with key operational constraints imposed on the descent.

Starting on 9 August, Rosetta began to fly elliptical orbits that brought it progressively closer to 67P. Every three days, it made another fly-by, facilitating unprecedented close-up studies. At its closest, it was within 1.76 km of the rugged surface.

As Sylvain Lodiot said:

> Although we've been flying Rosetta around the comet for two years now, our biggest challenge yet will be keeping it operating safely for the final weeks of the mission in the unpredictable environment of this comet and so far from the Sun and Earth.
>
> We are already feeling the difference in gravitational pull of the comet as we fly closer and closer. It is increasing the spacecraft's orbital period, which has to be corrected by small maneuvers. But this is why we have these fly-overs, stepping down in small increments to be robust against these issues when we make the final approach.

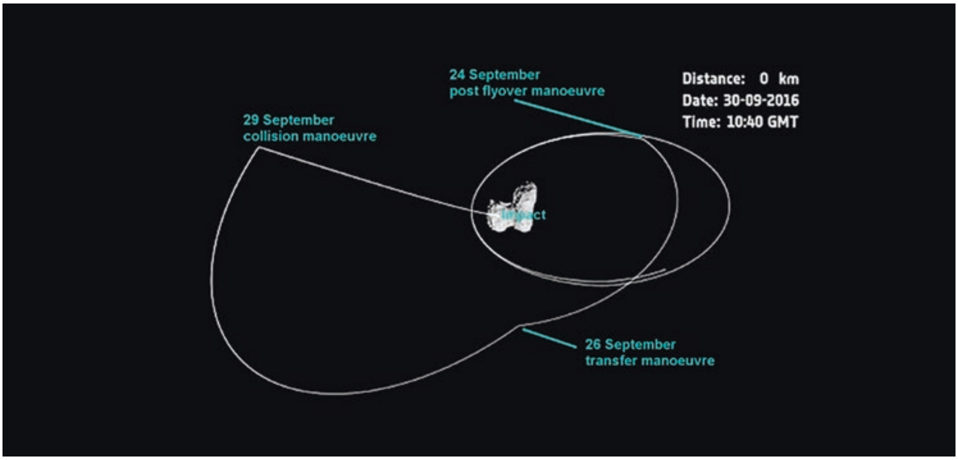

Fig. 8.11: A simplified overview of Rosetta's last week of maneuvers at 67P. After the final fly-over on 24 September, it transferred towards the 'initial point' of a 16 × 23 km orbit. A short series of maneuvers over the following days lined up Rosetta with the desired impact site. The collision course maneuver took place on 29 September, initiating the descent from an altitude of about 20 km on 30 September. (ESA)

On 24 September, after the final fly-over, flight controllers initiated a series of maneuvers to line up the spacecraft for its final descent. Two days later, Rosetta completed a short burn to put it on the 16 × 23 km trajectory around the comet from which it would eventually descend to the surface.

To prevent the spacecraft from entering a safe mode and losing contact prior to impact, its operators reprogrammed some of its tolerance to errors, and some star tracker checks were disabled for several weeks prior to the terminal descent.

Rosetta's final maneuver was a thruster firing which began at 20:48:11 UT on 29 September and lasted for 208 seconds. This nudged the spacecraft onto a collision course with the nucleus, initiating a leisurely 14 hour descent from an altitude of 19 km.

Shortly thereafter, its navigation cameras took a set of five images to confirm that it was following the planned trajectory and to refine the predicted impact time. After they were downloaded in the early hours of 30 September, the flight team used them to calculate the time of impact within a 4 minute window.

Initially the velocity was only 30 cm/s (about 1 km/h), but this gradually increased due to the gravity of the comet. At about 55 minutes prior to touchdown, some 2 km above the surface, Rosetta was closing in at 60 cm/s. The speed at impact was expected to be 90 cm/s, similar to that of Philae when it made its first touchdown.

During what was essentially a slow free-fall, six of the spacecraft's science instruments were providing unprecedented high-resolution images and data on the gas, dust and plasma in close to the comet. It was hoped they would continue to provide data until the vehicle was between 20 meters and 5 meters from the surface.[4]

The planned touchdown site was a flat area on the small lobe of the nucleus, close to a cluster of active pits in the Ma'at region. The intriguing pits were more than 100 meters in diameter and 50-60 meters deep. The specific target was a site adjacent to a 130 meter wide pit that the team had nicknamed Deir el-Medina, after a man-made pit in an ancient Egyptian town of the same name. Of particular interest were the walls of the pits, which exhibited intriguing lumpy structures referred to as 'goose bumps'. The speculation was that these structures, which were about a meter across, were related to the 'cometesimals' that accreted to produce the nucleus.

Early in the descent, OSIRIS imaged the regions of the large lobe the spacecraft was passing over, and then, as the small lobe loomed, it provided close-ups of the walls of the Ma'at pits and the intended landing site, nicknamed Sais.

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[4] Rosetta was now so far from the Sun that it could not generate enough power from its solar panels to operate all of the instruments simultaneously. MIDAS, COSIMA and VIRTIS were shut down because their potential science return was considered to be lower.

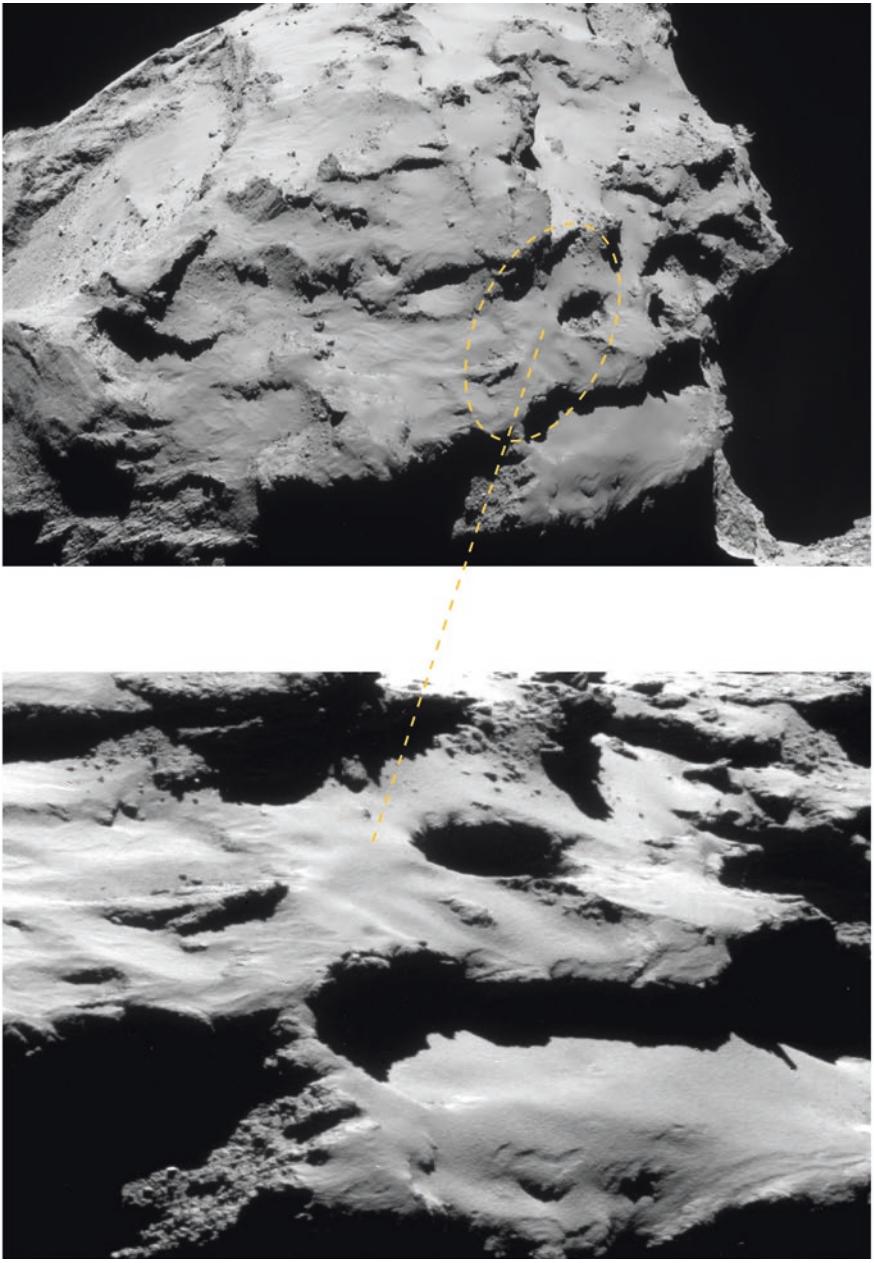


Fig. 8.12: The site selected for Rosetta's final touchdown was in the 500 × 700 meter yellow ellipse. The target was a flat area in the Ma'at region, close to some active pits on the small lobe of the nucleus. The image was taken with Rosetta's NAVCAM. (ESA)

In order to downlink the maximum number of images in the limited time available, especially in the final phase of the descent, the images were compressed by a factor of up to 20 times. In addition, instead of returning a small number with 2,048 × 2,048 pixels, a larger number of smaller ones were to be returned, with sizes from 1,000 × 1,000 down to 480 × 480 pixels.

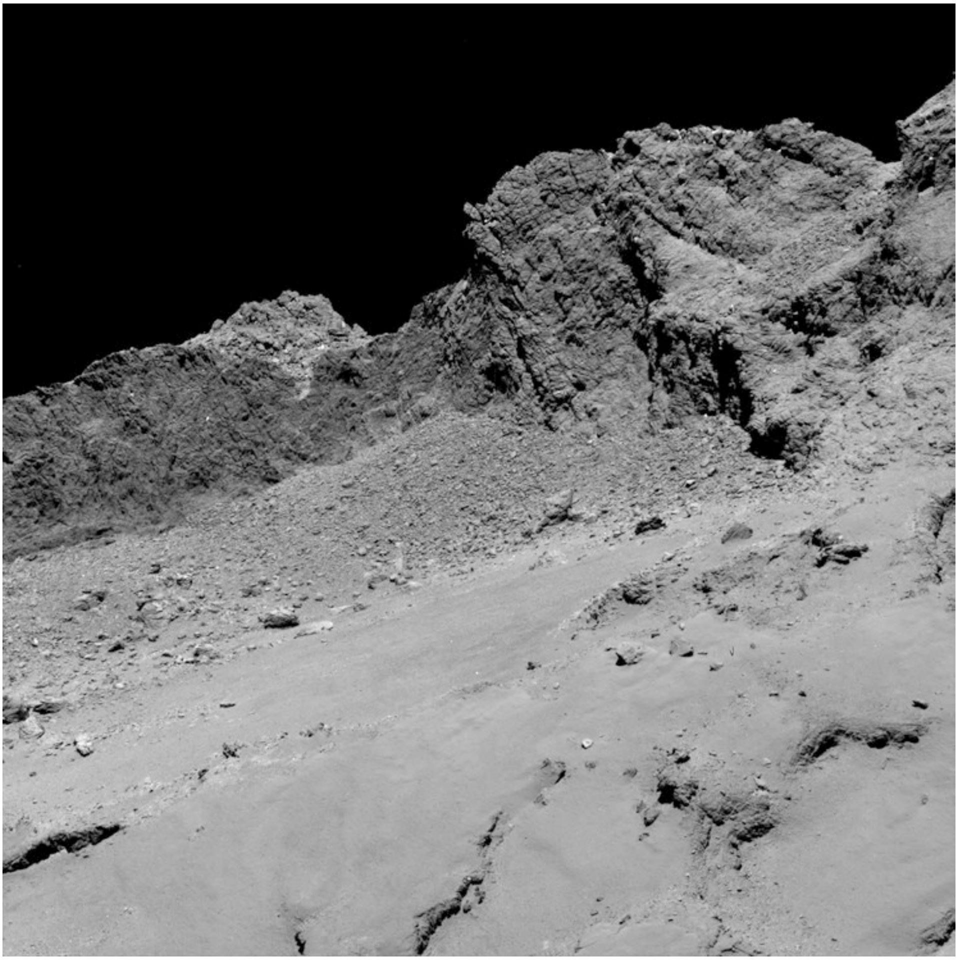
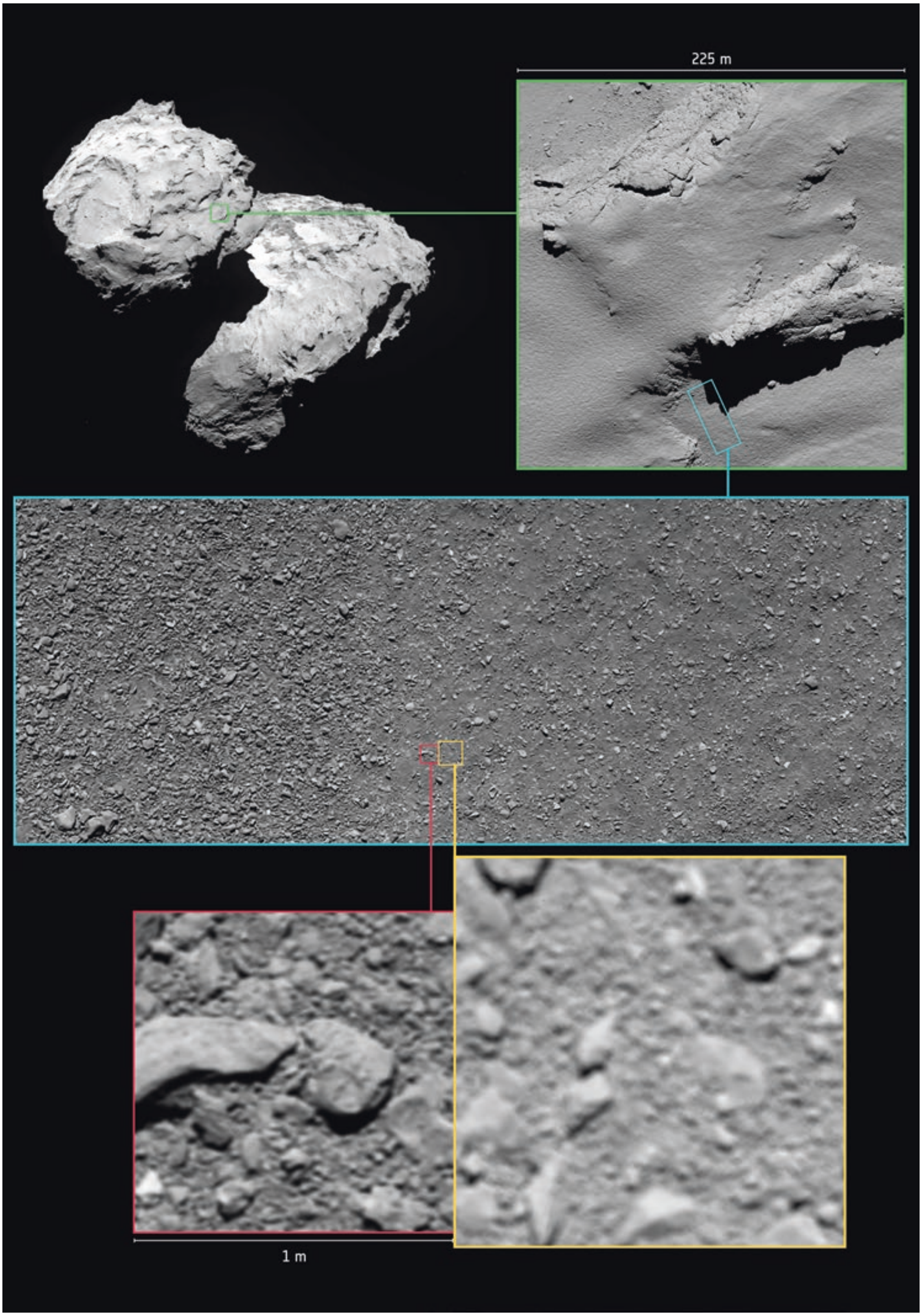


Fig. 8.13: OSIRIS-NAC captured this image of Comet 67P on 30 September 2016 from an altitude of about 16 km above the surface, as the spacecraft made its controlled descent. It spans about 614 meters with a resolution of about 30 cm per pixel. (ESA/Rosetta/MPS for OSIRIS Team MPS/UPD/LAM/IAA/SSO/INTA/UPM/DASP/IDA)


225 m
1 m

Below an altitude of 200-300 meters, the images were blurred because the cameras were not designed to image the comet from such close proximity: the NAC lost its focus below an altitude of around 1 km, and the WAC when the range fell below 200-300 meters.

What ESA and the OSIRIS team believed to be the final image from the spacecraft showed a slightly blurred view of a patch of stony ground, taken from an estimated altitude of 51 meters and thought to span an area about 2.4 meters across. Subsequent analysis revised the altitude to 24.7±1.5 meters. The uncertainty arose from the precise method of altitude calculation and the model used for the shape of the nucleus.

After the excitement of the historic landing had died down, the camera team found several unprocessed telemetry packets on their server and set out to investigate. As OSIRIS principal investigator Holger Sierks reflected, ""We thought, wow, that could be another image."

The transmission had been interrupted when Rosetta hit the ground, but three full packets of data had been received: 12,228 bytes in total, or just over half of a complete image. This was not recognized as an image by the automatic processing software, but engineers in Göttingen were able to make sense of these data fragments and process them into an image.

Released in May 2017, the reconstructed image was taken from a height of 19.5±1.5 meters and showed a patch of ground equivalent to a 1 × 1 meter square at a scale of 2 mm per pixel (see Fig. 8.14).

Meanwhile, ROSINA collected unique data on the density and composition of gas close to the comet. It was able to detect a tiny increase in the gas pressure around the nucleus as the spacecraft descended. MIRO complemented OSIRIS and ROSINA by measuring the surface temperature. GIADA measured the dust density

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Fig. 8.14: An annotated image indicating the approximate locations of some of Rosetta's final images. Top left: a global view shows the area in which Rosetta touched down in the Ma'at region of the smaller lobe. This image was taken by the OSIRIS Narrow Angle Camera on 5 August 2014 from a distance of 123 km. Top right: an image taken by the same camera from an altitude of 5.7 km, during Rosetta's descent on 30 September 2016. The scale is about 11 cm per pixel, and the image measures about 225 meters across. The final touchdown point, named Sais, is seen in the bottom right of the image, within a shallow, ancient pit. Exposed, dust-free terrain is evident in the pit walls and cliff edges. The image is rotated 180 degrees with respect to the global context image at top left. Middle: an OSIRIS Wide Angle Camera image taken from an altitude of about 331 meters. The scale is about 33 mm per pixel and the image measures about 55 meters across. A mix of coarse and fine-grained material is visible. Bottom right: the last complete image returned by Rosetta, taken from a height of 24.7±1.5 meters. Bottom left: the final image (reconstructed after Rosetta's landing) was taken at an altitude of 19.5±1.5 meters. The scale is 2 mm per pixel and it measures about 1 meter wide. (ESA/Rosetta/MPS for OSIRIS Team MPS/UPD/LAM/IAA/SSO/INTA/UPM/DASP/IDA)

and the acceleration of grains away from the nucleus. The RPC suite took a unique close-up look at the interaction between the solar wind and the surface of the comet and sampled levitating charged dust grains. ALICE obtained its highest resolution ultraviolet spectra of the surface, plus measurements which complemented some of the RPC data. RSI made the most accurate measurements of the gravity field.

During the 14 hour descent, the spacecraft sent an uninterrupted stream of data, until its final signal arrived at ESOC in Darmstadt at 11:19 UT (after the 40 minute time delay due to the spacecraft's distance from Earth), then there was silence as the spacecraft ceased transmitting upon impact.

Thousands of engineers and scientists who had worked on the mission, along with members of the international press, watched a live broadcast of the Rosetta Finale, which was streamed to venues in different countries.

The curtain had come down on Rosetta's remarkable comet chase.

The ROSINA principal investigator, Kathrin Altwegg, who had been involved in the project since 1994, spoke for everyone when she said, "I feel a little melancholic. But it's a colossal end!"

Rosetta operations manager Sylvain Lodiot said, "We've operated in the harsh environment of the comet for 786 days, made a number of dramatic fly-bys close to its surface, survived several unexpected outbursts from the comet, and recovered from multiple spacecraft safe modes. The operations in this final phase have challenged us more than ever before, but it's a fitting end to Rosetta's incredible adventure to follow its lander down to the comet."

Box 8.2: Shutting Down Rosetta

The International Telecommunication Union (ITU) regulations required that Rosetta's radio transmitter be switched off permanently at the end of its mission. Since the spacecraft wasn't designed to have its transmitter permanently off, the operations team had to upload a patch to modify the software.

The basic idea was to trigger a safe mode when the spacecraft touched the surface. Rosetta would experience a sudden shift in its attitude or motion that its software would register as being beyond the permitted limits. Specifically, the software patch would trigger an FDIR (Failure Detection, Isolation and Recovery) response which would result in a safe mode. On completion of the safe mode sequence, the spacecraft would be entered into a passive, non-reactive mode that was initially designed only for ground testing prior to launch. This would mean that all of the attitude and orbit control units were turned off, as well as the transmitter.

Three hours prior to the expected impact on 30 September, the so-called 'point of no return', the ground team fully activated the passivation instructions. The first safe mode to occur after that would permanently shut down the spacecraft.

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