SMART-1
Impact on the Moon

Moon Science, Orbit Reboosts and Impact Observations

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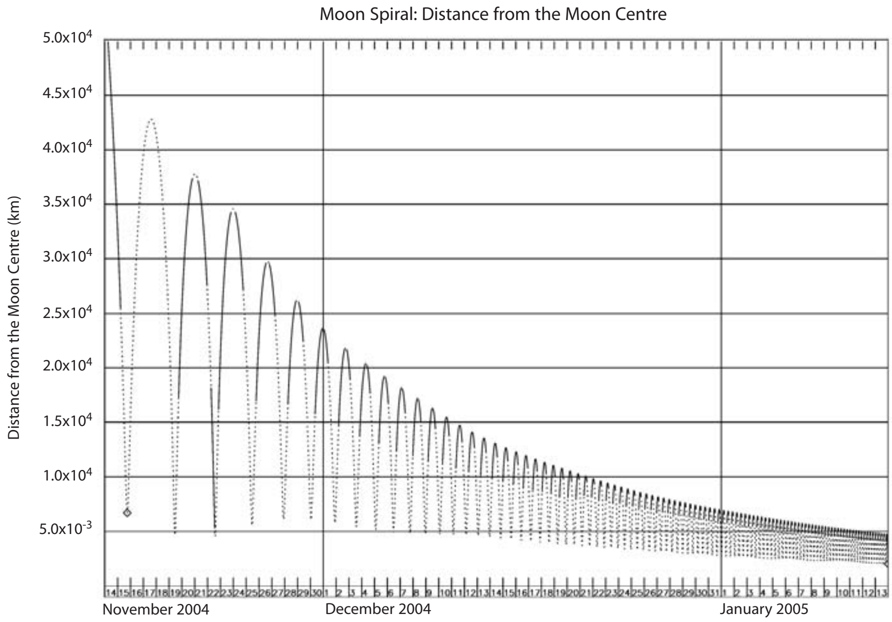
SMART-1 was launched in September 2003 and impacted the Moon 3 years later. It was the first of ESA's Small Missions for Advanced Research in Technology, with the main goal of testing electric propulsion. Following a spectacular navigation strategy, the craft reached the Moon, where its orbit was optimised for scientific observations. The instruments provided data throughout the mission, interrupted only by manoeuvres. The last of these had to be done with the attitude thrusters after exhausting the ion thruster's xenon fuel. The impact was observed from Earth by radio and infrared telescopes worldwide in an international campaign.

At the Moon

Immediately after the Moon's gravity captured SMART-1 on 15 November 2004, the ion engine was used to begin the spiral down into the final orbit. The operational lunar orbit was reached at the end of February 2005, requiring 13.5 kg of xenon and 236 thrust periods totalling 953 hours by the ion engine. The favourable launch date and the good performance of the electric propulsion system and the solar panels



SMART-1 spiralled down into its final orbit using its xenon thruster. The dotted parts of the curve show the thrust periods

during the cruise from Earth saved 5.5 kg of xenon, which could then be used to lower the highest point of the orbit ('apolune') from the planned 10 000 km to 4600 km, improving the resolution of the science observations.

After achieving the primary goal of testing and validating SMART-1's new technologies – especially the electric propulsion system – the mission was handed over to the Solar Systems Science Operations Division, who converted it into a scientific lunar mission. The main instruments were:

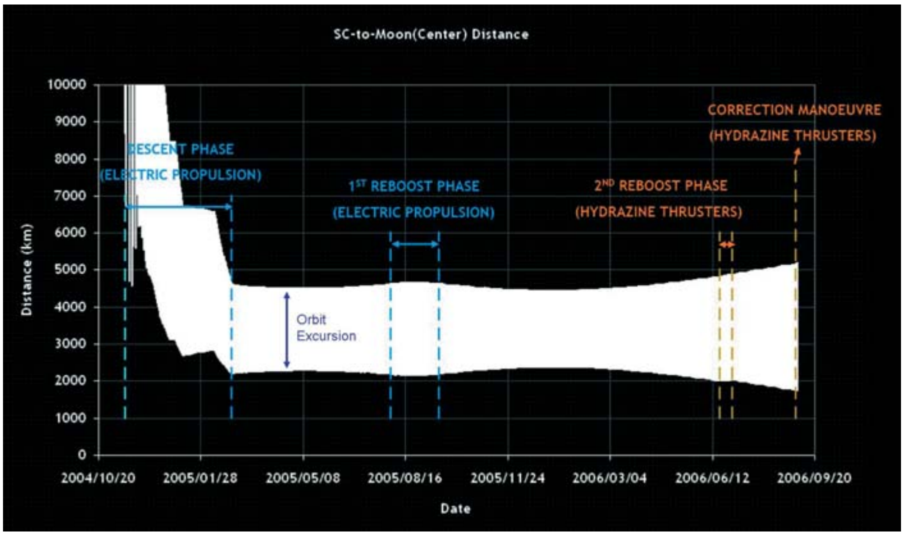
- D-CIXS (Demonstration of a Compact X-ray Spectrometer): an X-ray spectrometer to investigate the composition of the Moon;
- AMIE: Advanced Moon Micro-Imager. A miniaturised camera with a 4-band filter;
- SIR: an infrared spectrometer to search for ice and make a mineralogical map.

The science phase began in March 2005. The new orbit period, reduced to 5 hours from around the 12 hours originally planned, had major consequences for some of the ground systems and the spacecraft. With more orbit revolutions available, more scientific observations could be made, so the mission planning system had to be upgraded to cope with the increased number of commands (>2000/day on average) and data dumps. SMART's memory stores, logic and distribution had to be redesigned to cope with the increased data load. All the payloads were put together in a single memory store, permitting the full automation of all science data dumps. This ultimately led to a high degree of automation of all ground and onboard operations: 70% of the ground station contact periods were unmanned towards the end of the mission.

Consideration of extending the mission started soon after SMART-1 was captured by the Moon. Several strategies and cases were evaluated, aiming at improving the scientific observations during the extension. The best option could only be achieved by increasing the 'argument of perilune' (the position of the closest approach to the Moon) to improve the illumination conditions, coincidentally avoiding early impact. This required using up the remaining xenon and giving up any further control over the orbit for the rest of the mission.

The manoeuvres began on 2 August 2005 and continued through 207 revolutions around the Moon, until 17 September 2005. The ion thrusting required new procedures to use the xenon beyond the minimum residual of 1.8 kg originally specified by the manufacturer. The last few days of operations consisted mainly of letting the almost empty high-pressure tank fill

SMART-1 at the Moon. The left scale shows the distance from the Moon's centre. The bottom of the white band shows the closest approach each orbit (perilune); the top marks the highest (apolune)



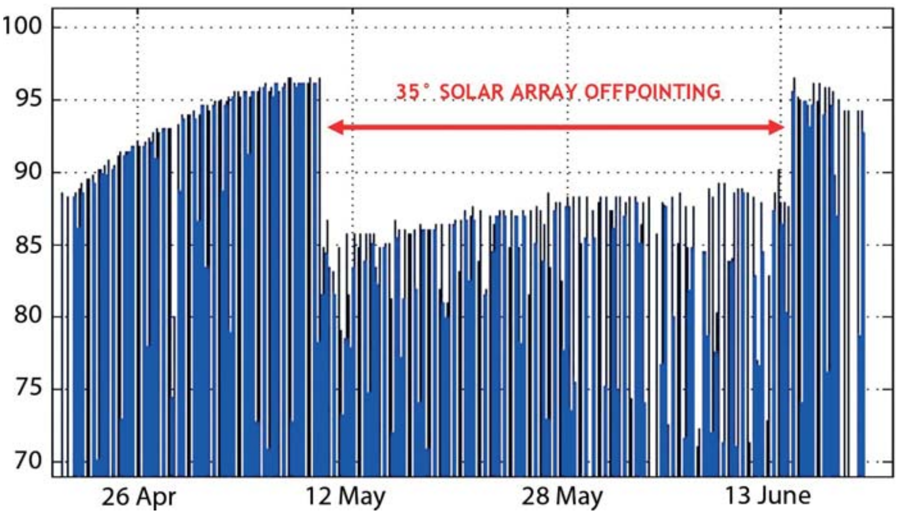
up the downstream low-pressure tank to about 2 bars, the bare minimum that was needed to fire the ion engine before it flamed out. The last pulse lasted just 10 minutes before the engine flamed out for the last time.

Science at the Moon

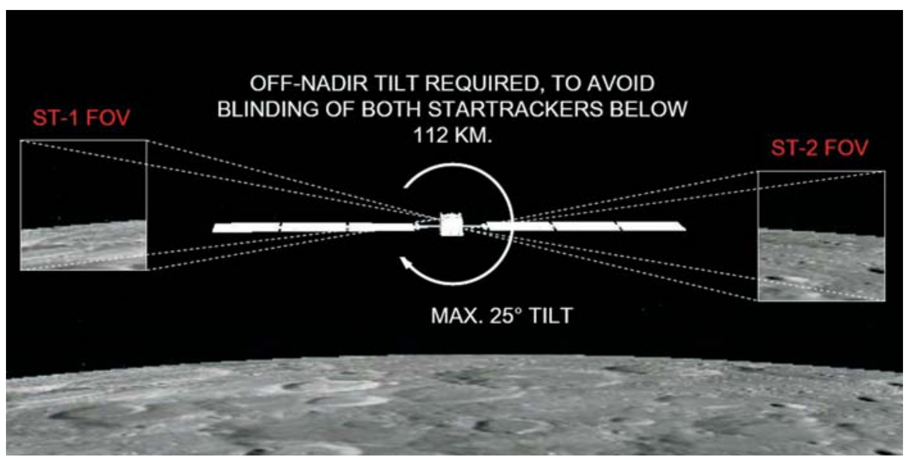
All of the scientific instruments were called upon during the observation phase. The team at the Science and Technology Operations Centre at ESTEC developed special tools to get the most out of these observations. Most observations were done with the instruments pointing towards the Moon's centre, with the solar array square-on to the Sun ('nadir pointing'). Two special pointing modes could also be used for short periods: push-broom and target tracking.

In the push-broom mode, AMIE took a sequence of images along the ground-track. Colour images were created by combining the same scenes shot through different filters.

Occasionally, SMART-1 used target-tracking: as the craft travelled around the Moon at several hundred metres per second, AMIE was kept pointing at the same target.



Angling the solar wings 35° from the Sun solved the overheating problem. The vertical axis shows the array temperature in °C



Nadir-pointing was not possible below 112 km

Solar array off-pointing

Analysis of the expected Moon impact by the Thermal & Structures Division at ESTEC concluded that the solar array temperature could rise too high in May 2006. For some time during each orbit, SMART-1 was in full sunlight and close to the lunar surface. In that situation, the front sides of the solar wings were heated by the Sun as the backsides were exposed to a fully illuminated Moon. This caused the array temperature to rise to potentially dangerous levels, to around 97ºC – up to 10ºC higher than predicted.

Between 9 May and 13 June 2006, the Flight Control Team angled the solar wings 35º from the Sun, immediately cooling the panels by 13ºC and eliminating the risk of damage, at the expense of an 18% drop in power generation.

The Moon was everywhere!

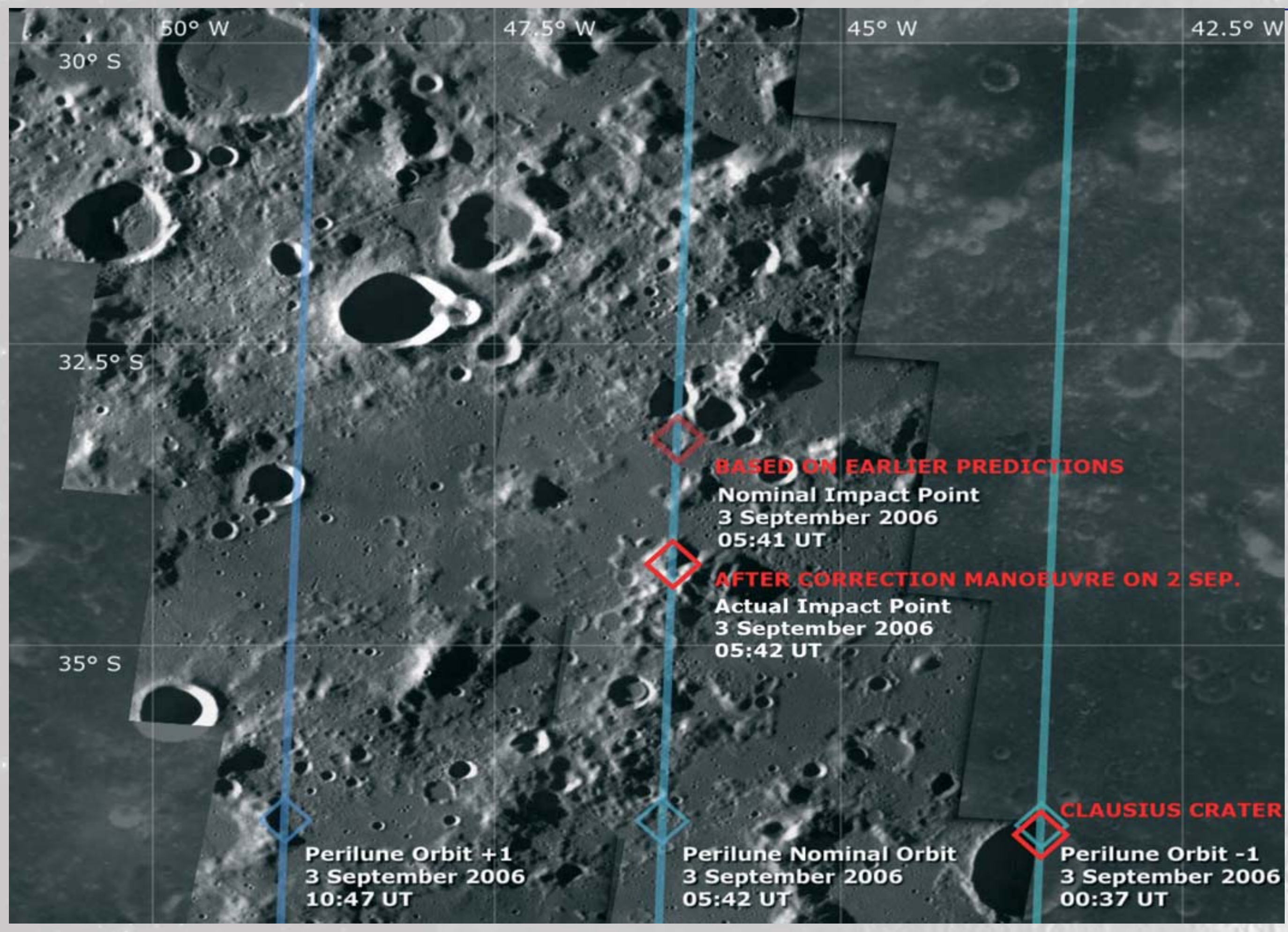
Getting closer to impact, it became increasingly difficult to avoid violating spacecraft rules. At low altitude, as SMART's sky was filled by the Moon, pointing was a problem, as both startrackers were threatened with blinding.

Pointing at a fixed spot was no longer feasible at altitudes below 240 km because SMART could not turn fast enough. Nadir-pointing was no longer possible below 112 km, because both startrackers had the surface in their fields of view. This was finally solved by tilting SMART by 25º from nadir during perilune passages.

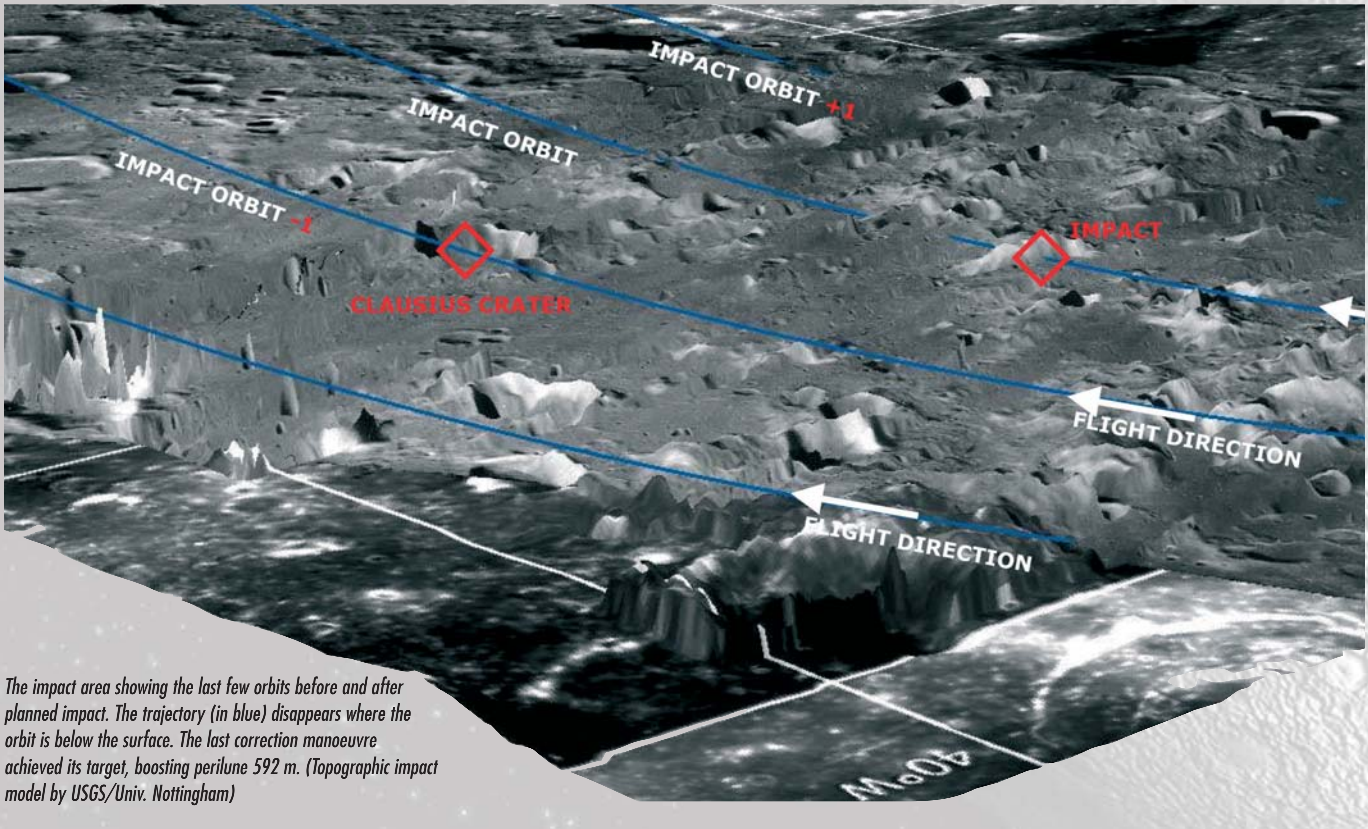
Moon Impact

From the end of the reboost phase in September 2005, SMART-1 was flying around the Moon without orbit control. The height of its closest approaches () 'perilune' was gradually falling as perturbations from Earth's gravity took their inevitable toll.

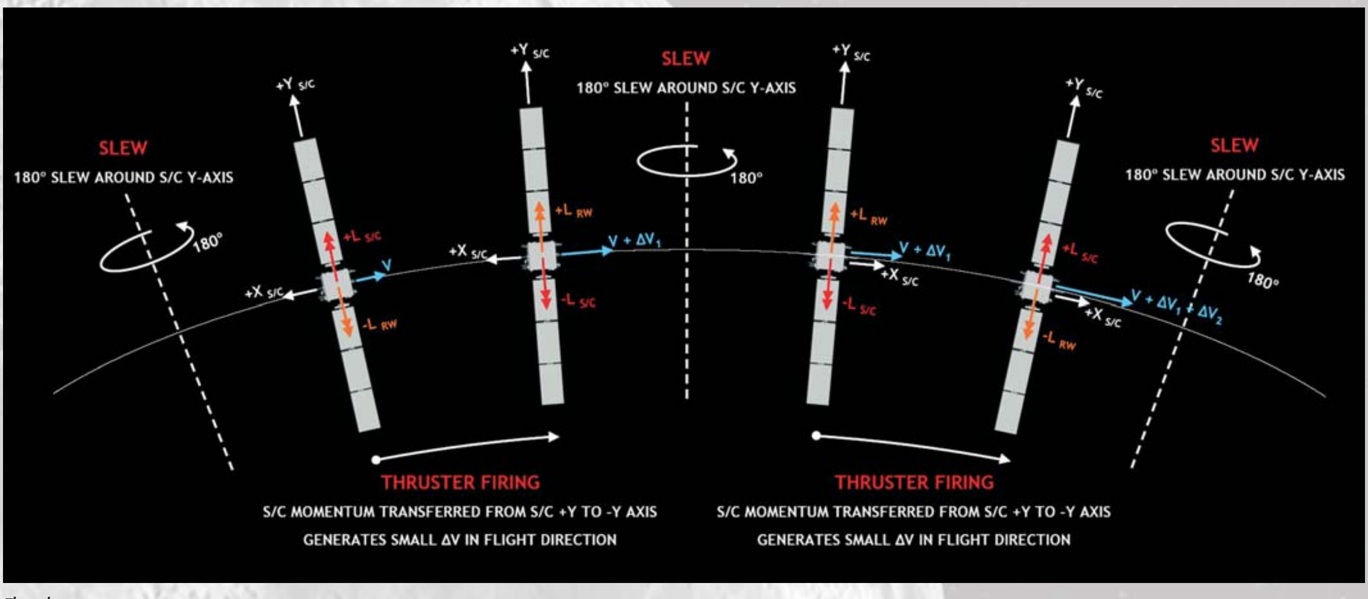
The orbit predictions carried out in early 2006 indicated that impact would occur on the far side by mid-August 2006. The scientific community, interested in organising a campaign to observe the impact, requested that ESOC and the Swedish Space Corp should investigate ways to shift the impact to the near side. This happened at



SMART-1 might have hit crater Clausius



The impact area showing the last few orbits before and after planned impact. The trajectory (in blue) disappears where the orbit is below the surface. The last correction manoeuvre achieved its target, boosting perilune 592 m. (Topographic impact model by USGS/Univ. Nottingham)



The reboost strategy

a stage when the ion engine had already exhausted its fuel.

The question was how to obtain the ~11.8 m/s change in velocity ('delta-V') to raise the orbit by just 90 km. The only option was to use the attitude thrusters. Since SMART-1 was designed to be propelled only by electric propulsion, the chemical thrusters were optimised for attitude control (by offloading the angular momentum built up in the reaction wheels).

The Flight Dynamics Team analysed the possibility of harnessing the small delta-V incidentally produced by firing the attitude thrusters as they offloaded the reaction wheels. They finally came up with a complex scheme involving a series of offloadings around apolune, transferring SMART's angular momentum from one side to the other, and vice versa. In between reaction wheel offloadings, the craft would then be slewed such that the delta-V was aligned with the flight direction. The overall effect was the desired orbital change.

The attitude-thruster reboost phase started on 19 June 2006 and finished on 2 July 2006. During 65 revolutions around the Moon, SMART-1 performed seven wheel offloadings per orbit in the ~3 hours centred around apolune, accumulating 520 offloadings. For comparison, a similar delta-V would require only a few minutes' thrust by a satellite like Mars Express.

Approaching impact

A week before impact, the Mission Control Team together with Industry decided to take advantage of the frequent startracker blindings by the Moon. The startrackers gathered some 150 images between 12:15 and 13:06 UT on 1 September while going through perilune (altitude ~12 km). The images were compiled into a movie that can be viewed at:

http://www.esa.int/SPECIALS/SMART-1/SEMZ16BVLRE_0.html
http://esamultimedia.esa.int/multimedia/smart-1/060901_Startracker_Auto_Imaging_v4.wmv

The rim of Clausius Crater

For months, the best information the Mission Control Team could obtain about the surface in the impact area was derived from the US Clementine lunar orbiter. This was initially used to select the impact date and time. Four days before impact, the Flight Dynamics Team contacted Anthony Cook of the University of Nottingham (UK). Dr Cook, a specialist in 3-D digital image interpretation and stereo image analysis, applied the SMART-1 orbit to his 3-D topographic model of the Moon – and obtained a surprising result. His analysis in cooperation with Mark Rosiek of the US Geological Survey indicated a high probability of hitting the rim of Clausius, a medium-sized crater at 43.5ºW/36.5ºS during the perilune passage on the penultimate orbit.

There was no time to confirm this result independently, so the Mission Control Team organised an internal meeting to decide what to do. If Cook and Rosiek were right, then the impact would occur an orbit earlier, jeopardising the observation campaign, unless a last-minute manoeuvre was done just 2 days before expected impact. The risk was that the orbit might be raised too much, causing the impact to occur an orbit later. It was a difficult dilemma, with a short time for a decision.

The Team gathered all the images already taken by SMART-1 of the potential impact area in order to correlate them with the 3-D topography model provided by Cook and Rosiek. This exercise confirmed the topography of the model. The Team accepted that the orbit could intersect the rim of Clausius, as the rim proved to be ~1500 m higher than expected from Clementine.

The impact site as viewed from Earth

The decision was to maximise the probability of impacting as planned during the morning of 3 September. As a result, during the night of 1–2 September, the controllers had to make a last correction manoeuvre to boost the penultimate perilune by a mere 600 m; 592 m was achieved.

Impact observations

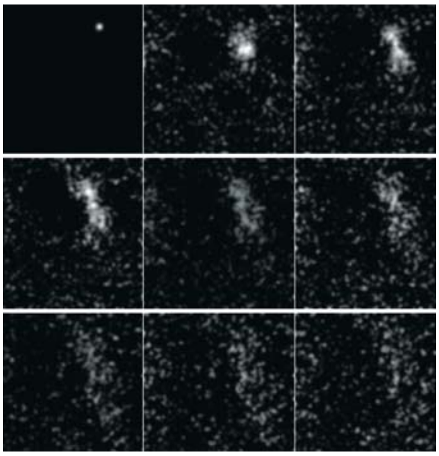
Impact was now expected on the Moon's near side, in a dark area close to the terminator (the line separating day from night), at a grazing angle of 5–10º and a speed of ~2 km/s. The time and location were planned to favour observations of the event from telescopes on Earth.

The predicted effects included a thermal flash and possible fireball from the leftover hydrazine fuel aboard SMART-1, a crater perhaps 5–10 m across, and dust and other ejected material travelling some distance across the surface.

The observation campaign counted on professional and amateur observers worldwide, including South Africa, the Canary Islands, South America and the USA. It involved a core of participating telescopes, including: the South African Large Telescope (SALT), the Calar Alto observatory in Andalucía (E), the ESA Optical Ground Station on Tenerife (E), the CEA Cariri observatory in Brazil, the Argentina National Telescope, the Canada-France-Hawaii Telescope (CFHT), the Japanese Subaru Auxiliary telescopes on Hawaii, and Sweden's Odin satellite.

Five radio telescopes were coordinated by the Joint Institute for VLBI (Very Long Baseline Interferometry) in Europe (JIVE): the Medicina 32 m antenna in Italy, the Fortaleza 14 m antenna in Brazil, the German-Chilean TIGO 6 m antenna in Chile, the Mount Pleasant Observatory of the University of Tasmania (Australia) and the Australia Telescope Compact Array.

With the impact calculated to be at 05:42 UT, observers from North and South America and the East Pacific would be able to see it at night. The best view would be from the US west coast, Hawaii and the East Pacific.



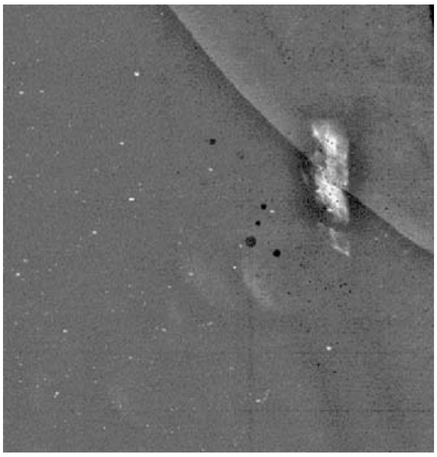
The flash and dust cloud following impact (CFHT)

The impact

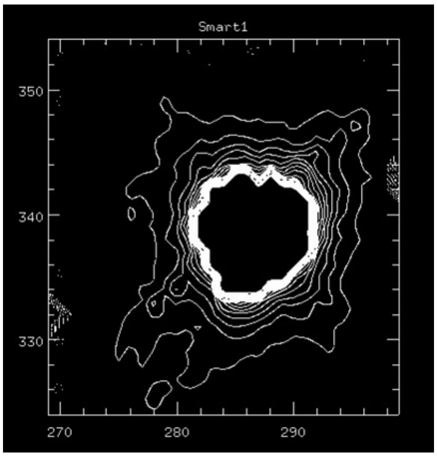
On 3 September, early in the morning, the SMART-1 team had to face another last-minute contingency: the servo-drivers of ESA's antenna in New Norcia, Australia, signalled a problem and there was nothing that could be done remotely to resolve it. While an engineer was telephoned to drive from Perth to New Norcia as fast as possible, the Flight Control Team started developing a contingency procedure using the Perth antenna with the New Norcia antenna in fixed pointing. Fortunately, by the time journalists started gathering behind the glass wall of the ESOC's Main Control Room, the problem had been resolved at the station.

A wall screen displayed the last events programmed on board for execution

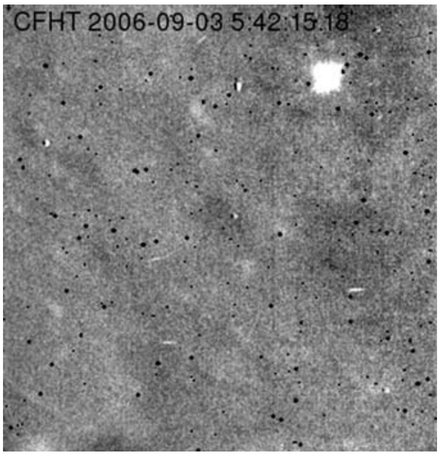
The lunar impact of SMART-1. (CFHT)



Brightness contours of the impact flash. (CFHT)



SMART-1 strikes the Moon. (CFHT)



before the impact. The team set up another big screen showing the telemetry scrolling down in real time. On both sides of the room, two large clocks displayed the count down.

A growing buzz of excitement took over the room as impact time approached. Starting at 17 s, everyone in the room found themselves chorusing the countdown – just as was done for the birth of the mission some 3 years before.

The freeze of the scrolling telemetry just a second after zero left everyone in the room in static silence for a few seconds until somebody broke the silence with applause that was joined in by all.

The mission team and the journalists had a few seconds to relax before all eyes went back to the main wall screen, now showing the images being received from the Canada-France-Hawaii Telescope. The telescope, equipped with a new infrared mosaic camera, suddenly offered a stunning image of the SMART-1 impact, a very bright flash on the dim landscape lit by earthshine. The image was made available to ESA and the world via the internet just moments after SMART-1 radio silence had made clear that the mission had ended.

From a detailed analysis of the CFHT infrared movie, a cloud of ejecta travelling some 80 km in about 130 s was reported by Christian Veillet.

The last signal, from SMART-1's KaTE/Ka-band experiment, was received on Earth at 05:42:25 UT, through the NASA Deep Space Network radio station DSS13 in the California desert.

CSIRO, TIGO and the Mount Pleasant Observatory all heard the final signal. The radio observations were done with very high accuracy; SMART-1 sent its last signals to Earth at 05:42:21:759 UT. These times were in close agreement with the last flight dynamics prediction of 05:42:20 UT, and with the last telemetry frame received at ESOC through New Norcia.

Conclusions

SMART-1 not only achieved its primary objective of validating the use of electric propulsion for interplanetary missions, but also fulfilled all of its secondary objectives in technology demonstration and science.

ESA gained valuable expertise in navigation techniques using low-thrust propulsion. The procedures used to exhaust the xenon fuel and the use of attitude thrusters to generate delta-V were a first for ESA. Similarly, ground operations experimented with innovative cost-effective operational concepts, such as reduced-staff spacecraft controlling, distribution of spacecraft housekeeping telemetry via the internet and a high level of automated operations.

In addition, SMART-1 sparked unexpected interest in international and cross-agency cooperation in areas such as ground station support (with Germany); tracking co-targeting and Moon exploration cooperation (with China and India); and VLBI science and Ka-band experiments (with NASA). In view of the recent plans for future scientific and human missions to the Moon by several agencies, SMART-1 can be seen as a pathfinder for renewed lunar exploration.

For the Mission Control Team, the end brought mixed feelings: the satisfaction of having accomplished a complex mission, but sadness in seeing the end of an adventure. All of those involved are looking forward to new adventures at the Moon and elsewhere in the Solar System.