Europe at the Moon: SMART-1 Highlights

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SMART-1 is Europe's first lunar mission, the current step in developing an international program of lunar exploration. The spacecraft was launched on 23 September 2003 as an Ariane 5 Auxiliary passenger to Geostationary Transfer Orbit (GTO), performed a 14 month long cruise using the tiny thrust of electric propulsion alone, reached lunar capture in Nov 2004, and lunar science orbit in March 2005. SMART-1 carries seven hardware experiments (performing 10 investigations, including three remote sensing instruments, used during the cruise, the mission's nominal six months and one year extension in lunar science orbit.

The remote sensing instruments contribute to key planetary scientific questions, related to theories of lunar origin and evolution, the global and local crustal composition, the search for cold traps at the lunar poles and the mapping of potential lunar resources.

Solar Electric Propulsion to the Moon

SMART (Small Missions for Advanced Research in Technology) are technology demonstration missions offering an early opportunity for science as well as a new management approach. ESA's SMART-1 mission is specifically designed to test technologies to be used on future ESA "cornerstone" missions (Figure 1). Its main rationale is to demonstrate Deep Space Electric Propulsion and other technologies for future interplanetary and deep space missions. SMART-1 has been launched from Kourou on 27 September 2003 on an Ariane 5 as an auxiliary passenger into Geostationary Transfer Orbit (GTO). The SMART-1 spacecraft involved industrial contributions and instrument contributions from 15 ESA members states, and scientific associates from Europe, US, Russia, Ukraine, Japan, India and China.

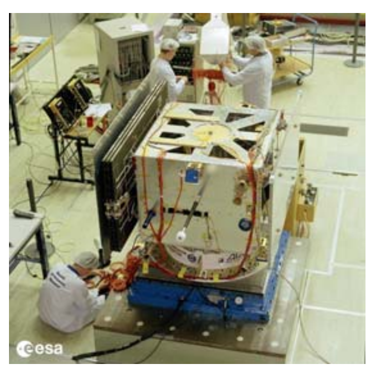


Fig.1a: SMART-1 spacecraft during integration and functional tests (http://sci.esa.int/smart-1/)

After nominal Low Earth Operations, and spiraling out of the inner radiation belts, the spacecraft and the payload have been commissioned successfully. The use of solar electric propulsion to carry the craft from within the Earth's gravity-well during the 15-18 month cruise phase allowed cruise science and in-flight calibration to be completed prior to arrival at the Moon, after which a nominal six month lunar mapping phase has been performed before a 1 year extension approved until August 2006. The baseline lunar orbit is highly elliptical, with a perilune between 300 and 700 km close to the lunar south pole. The apolune lowered from 10000 to 3000 km as fuel could be saved during the early cruise phase, so as the science return of the mission can be optimised during the lunar mapping phase, thanks to the increased resolution and sensitivity.

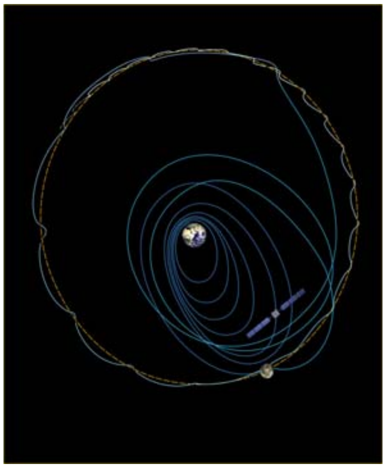


Fig.1b: SMART-1 spacecraft trajectory spiralling out from Earth

SMART-1 instruments

Seven instruments are operating in all mission phases (cruise/lunar), performing 10 distinct science and technology investigations (Table 1). Science instruments, led by Principal Investigators (PIs) were mostly funded from PIs and co-Is national sources. Technology Experiments, led by Technology Investigators (TIs) were partly funded by ESA. Three instruments are used for spacecraft and planetary environment studies: Electric Propulsion Diagnostic Package (EPDP), Spacecraft Potential, Electron and Dust Experiment (SPEDE) and Radio Science Investigation with SMART-1 (RSIS). Lunar exosphere studies are planned for EPDP and SPEDE. Three instruments are used for lunar remote sensing: the global X-ray mapping spectrometer (D-CIXS) with X-ray Solar Monitor (XSM), near infrared mapping spectrometer (SIR), and the localised high spatial resolution colour imaging camera (AMIE). Overall science objectives for the mission are shown in Table 2.

Table 1. SMART-1 Hardware Instruments and *Additional Investigations*

		Mass (kg)	Power (W)
EPDP	(Electric Propulsion Diagnostic Package)	2.4	18
SPEDE	(Spacecraft Potential Electron and Dust Exp.)	0.8	1.8
KATE	(Ka-Band TT&C Experiment)	6.2	26
RSIS	(Radio-Science Investigations for SMART-1)		*(using KATE & AMIE)*
D-CIXS	(Demo Compact Imaging X-ray Spectrometer)	5.2	18
XSM	(X-ray Solar Monitoring)		(with D-CIXS)
SIR	(SMART-1 InfraRed spectrometer)	2.3	4.1
AMIE	(Advanced Moon micro-Imager Experiment)	2.1	9
Laserlink	(Experimental Deep-space Laser link)		*(using AMIE)*
OBAN	(On-Board Autonomous Navigation Exp.)		*(using AMIE)*

Table 2. Overall Science Measurements Objectives for SMART-1

SMART-1 CRUISE TECHNOLOGY AND SCIENCE DEMONSTRATION:
- Technology demonstration of instruments
- Earth imaging and magnetospheric studies
- X-ray monitoring of Sun & cosmic sources

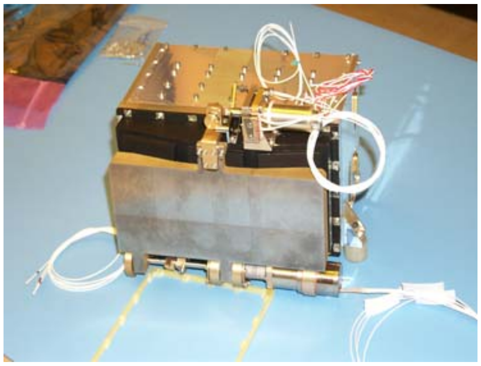
SMART-1 LUNAR SCIENCE AND EXPLORATION THEMES
How do rocky planets form and evolve: Origin of the Moon, early magma ocean, evolution
What processes shape rocky planets: Impacts, tectonics, volcanism, erosion, volatiles
Preparation to future lunar science and exploration from orbit and surface

SMART-1 MEASUREMENTS METHODS
- First global X-ray mapping of Mg, Al, Si (50 km resolution)
- First infrared spectral mineralogy mapping 0.9-2.5µm
- Colour imaging via 0.75, 0.9, 0.95 µm + clear white channels at high resolution (up to 40 m/pxl)
- Polar areas illumination and resource mapping

The X-ray Moon

The D-CIXS **(Demonstration of a Compact X-ray Spectrometer)** experiment deploys a new X-ray spectrometer as well as a solar X-ray monitor (XSM). D-CIXS' collimator and advanced Swept Charge Device (SCD, 0.5 - 10 keV) permit high sensitivity X-ray measurements compared to previous sensors, critical to detect the very weak lunar source. D-CIXS science aims at providing a 50 km resolution map of absolute abundances of Magnesium, Silicon, Aluminium.

D-CIXS lunar studies will be applied to the refinement of bulk crustal composition estimates, bearing on theories of the origin and evolution of the Moon, the characterisation of the lunar crusts, the study of South Pole-Aitken Basin (SPA) and other lunar basins, and the mapping of potential lunar resources (Fig 3).



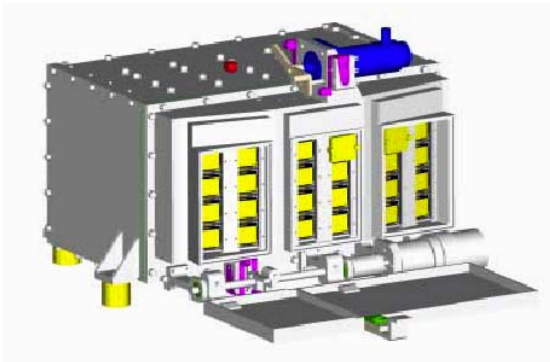


Fig.2: D-CIXS flight unit (left) vs mid-term design (right). D-CIXS was built in Rutherford Appleton Labs, with support from UK, ESA, Finland, France, Spain, Sweden, Japan, India, US. It has a 12 x 32 deg Field of View, for Global mapping of the lunar surface (elemental composition) via X-ray fluorescence. It uses a parallel X-ray Solar Monitor, built in Finland, to monitor Solar X-ray flares and coronal monitoring (calibration).

Bulk crustal composition has bearing on theories of origin and evolution of the Moon. D-CIXS will produce the first global view of the lunar surface in X-ray fluorescence (XRF), elemental abundances of Mg, Al and Si (and Fe plus others such as Ca, Ti if solar activity permits) across the whole Moon. The South Pole-Aitken Basin (SPA) and large lunar impact basins will be also mapped with D-CIXS. These will be the first XRF measurements of the lunar surface since the Apollo 15 and 16 missions, which covered just 9% of the Moon and were restricted to equatorial regions. More importantly, rather than the elemental ratios derived from the Apollo measurements, D-CIXS will derive absolute elemental abundances, by measuring (with X-ray Solar Monitor XSM) the incident solar spectrum that causes the lunar surface to fluoresce in X-rays. First D-CIXS Moon measurements are shown in Fig. 3.
D-CIXS will provide a global distribution of Mg and permit the production of global magnesium numbers (Mg# = Mg/Mg+Fe). The mapping of Mg# is a key to study the evidence of a primitive source, the relations of Mg-suite rocks vs ferroan anorthosites or KREEP, and the constraints on the magma ocean model/evolution. D-CIXS' more comprehensive characterisation of Mg# will aid estimates of bulk crustal composition and theories for the evolution of the lunar crust, which in turn will help to address the thermal and physical evolution of the Moon.

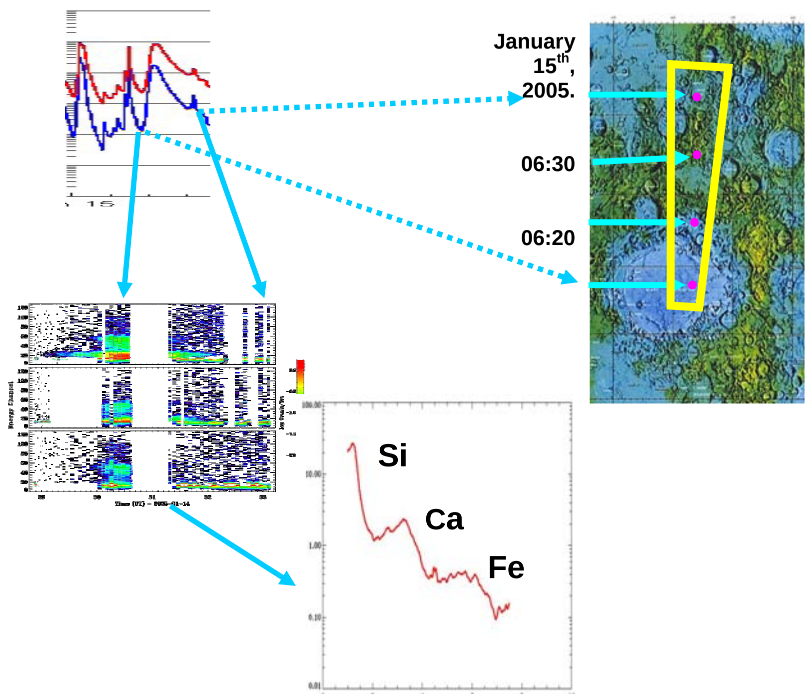
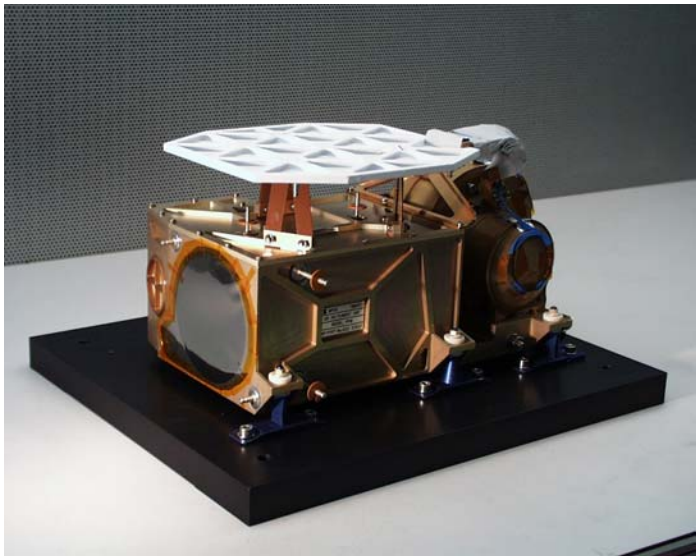


Fig.3: First SMART-1/ D-CIXS lunar measurements obtained during solar flare on 15 January 2005, when orbiting over Mare Crisium and near highlands. The spectra obtained from the three D-CIXS facets were summed over the duration of the flare, giving the spectrum showing chemical elements such as Silicon, Iron and Calcium for the first time from orbit. The elemental abundances were derived along the track, and compared in particular with samples from Mare Crisium returned by Luna 24.

The Infrared Moon

The SIR **(SMART-1 Infrared Spectrometer)** (Fig. 4), with 256 spectral channels over the range 0.93 to 2.4 μm, has been mapping the mineral composition across the lunar surface with a maximum spatial resolution of 300 m from perilune.



Built by Max Planck Society, Lindau with support from Germany, UK, Ireland, Poland, SIR is the space-qualified version of a miniature monolithic grating spectrometer (0.93 - 2.4 μm, 256 channels, resolution 6 nm/ pixel.) Its science objectives include: Mapping of the lunar surface in near infrared (up to 300 m spatial resolution); discrimination of the major rock forming minerals ; Search for signature of possible South Pole Aitken Basin exposed materials from lower crust/mantle; Investigation of Space Weathering and illumination geometry effects; central peaks, walls, rims and ejecta blankets of large impact craters, giving the stratigraphy of the lunar crust in specific areas.

Fig. 4: Optical Unit of the SIR infrared spectrometer (protoflight model)

SIR has high enough spectral resolution to separate the pyroxene and olivine signatures in lunar soils (Figure 5). This is a key in our understanding of the evolution of crustal materials, as the distribution of olivine is poorly constrained in current models. Olivine is considered by many to be a common mineral in the lunar mantle, so its distribution throughout the lunar crust and across the lunar surface is of critical importance to models of crustal differentiation and evolution. A key target for observations using the SIR instrument will be the 2,500 km diameter South Pole-Aitken Basin (SPA), which may have dug through to expose materials from the lunar mantle (Lucey et al., 1998). This is strongly debated, however, and many consider the anomalously mafic units in the region to represent lower crustal materials rather than lunar mantle units (e.g. Pieters et al., 1997). If measurements of the olivine and pyroxene distribution throughout the SPA can be made, the results would have a strong bearing on this contentious issue and would allow for improved models of crustal differentiation and thermal evolutionary models. SIR will help to further this study. First SIR lunar spectra are shown in Fig. 5b.

SIR data will help to refine compositional analyses from Clementine/ Lunar Prospector data. IR spectrometry, with spatial resolution as good as 300 m will permit to distinguish units on central peaks, walls, rims and ejecta blankets of large impact craters, allowing for stratigraphic studies of the lunar crust (Basilevsky et al, 2004). Observations of small diameter craters showing a wide age range help studies of the influence of space weathering on reflectance spectra. Furthermore, the SMART-1 target pointing has allowed SIR to take nearly continuously spectra while the phase angle is changing.

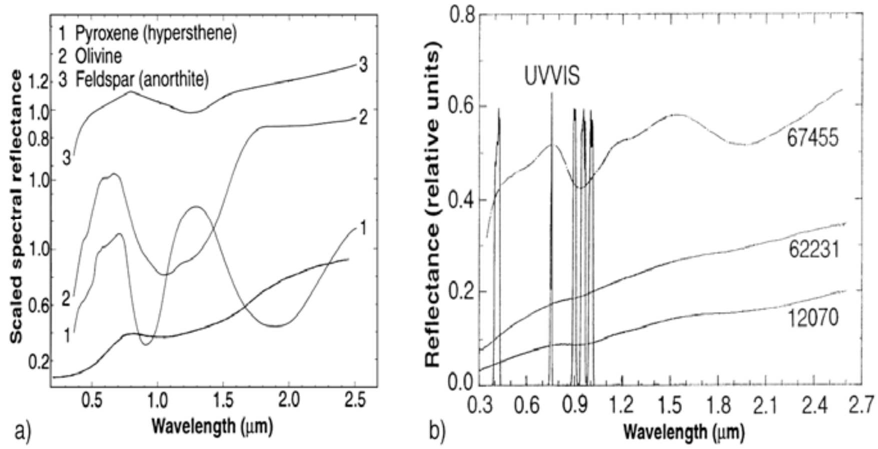


Fig. 5a: Reflectance spectra of key lunar minerals at UVVIS and NIR wavelengths (Courtesy of C. Pieters). The left hand plot shows the spectra of pyroxenes (1), olivines (2) and feldspar (3) while the middle plot shows reflectance spectra of lunar samples. The NIR measurements up to 2.4 µm provided by SIR allow for the separation of the mineralogical signatures. AMIE filters correspond to 0.75, 0.9, and 0.96 µm.

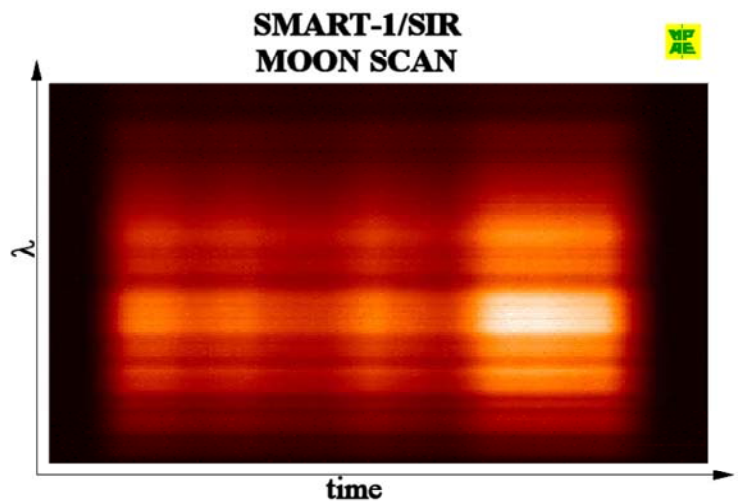


Fig. 5b: First SMART-1 spectra of the Moon obtained by scanning the SIR infrared spectrometer from limb to limb, showing lunar regions of different albedo.

A Micro-Camera for Great Looks

The micro camera AMIE (**Advanced Moon Imaging Experiment**) (see Fig. 6) provides high-resolution CCD images of selected lunar areas (Table 5 lists the broad objectives of the camera). Demonstration images of the Earth and Moon were obtained during the cruise and final approach before lunar capture (Figs. 7 and 8). AMIE includes filters deposited on the CCD in white light + three filters for colour analyses, with bands at 750 nm, 900 nm and 950 nm. These provide data on the 1 μm absorption of pyroxene and olivine. The camera has an average resolution of 80 m/pixel, and 30 m/pixel near a 300 km perilune. AMIE images provides a geological context (Figure 10) for SIR and D-CIXS data, and colour or multi-phase angle complement. Repeated and long exposures high resolution images of the lunar south pole will be obtained. This could allow the identification of shadowed or double-shadowed areas, the search for potential 'water ice traps' or 'cold traps'. Also, SMART-1 has been mapping potential sites of 'eternal light' and 'eternal shadow' (see Fig. 9), landing sites (see Fig. 12) or other sites relevant for future lunar exploration (lunar bases, power supplies).

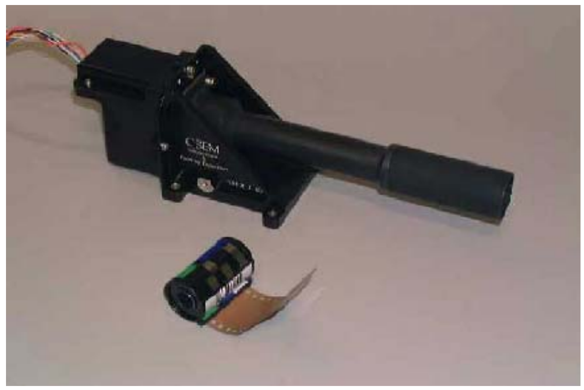


Fig.6: AMIE camera optical and detector unit. Built in Switzerland, with support from ESA and Co-Investigators from France, Italy, Finland, The Netherlands, ESA RSSD. Within 1.8 kg (Optical Head 400 g), 9W, its technology includes a Packaged 3-D interconnect technology camera, 5.3° FOV, 1024 x 1024 Si-CCD, 5 colours: panchromatic + laser-link + 3 medium-band filters (0.75, 0.9, and 0.96 μm), High-density CCD electronics & Micro-DPU Digital Processing Unit.
It provides high-resolution multi-colour imaging with up to 40 m pixel at 400 km perilune, and complements SIR and D-CIXS and Apollo/Clementine. It supports the laser-link experiment, OBAN On Board Autonomous Navigation Experiment, RSIS Radio Science Libration Experiment.

A precursor to the international lunar fleet

SMART-1 is Europe's first lunar mission and is contributing to developing an international program of lunar exploration. Its instruments are returning data that will be relevant to a broad range of lunar studies. The mission will provide the first global X-ray map of the Moon, global high spectral resolution NIR spectrometry, high spatial resolution colour imaging of selected regions with a perilune near the lunar south pole. Combined, these will aid a large number of science studies, from bulk crustal composition and theories of lunar origin/evolution to the search for cold traps at the lunar poles and the mapping of potential lunar resources.

The SMART-1 spacecraft is operated from ESOC in Darmstadt. The Mission Operations Centre (MOC) includes the Main Control Room (MCR) augmented by a Flight Dynamics Room, Dedicated Control Rooms, and Project Support Rooms. During the Launch and Early Orbit Phase (LEOP) and during the Moon Capture Phase, the MCR was used for SMART-1 mission control. During the routine operations phases, a Dedicated Control Room has been used. The SMART-1 Science and Technology Operations Coordination (STOC) is located at ESTEC. STOC interfaces to the MOC to which it provides inputs to the Flight Operation Plan for the payload commanding at spacecraft level. The STOC implements joint payload operations (see Fig. 10), following overarching priorities defined by science themes. The Experiment Operation Facilities are located at each Principle Investigator site. They are connected to the STOC and MOC via the network and remotely operate the experiments. The coordination of the scientific activities is carried within the Science and Technology Working Team (STWT) chaired by the Project Scientist, and via the STOC. Experiment requests for operations, commands and data delivery are routed via the STOC.

SMART-1 data are archived following the PDS Planetary Data Systems Standards. There will be an inter-calibration and integration of the SMART-1 data both between the instruments and with existing data from previous missions such as Apollo (see Fig. 12), Luna, Clementine and Lunar Prospector. The SMART-1 team has also cooperated with the teams from upcoming missions (Japanese SELENE and Lunar-A, Indian Chandrayaan-1, Chinese Chang'E1, US Lunar Reconnaissance Orbiter) and will look at studying sites for future landers and rovers.

SMART-1 is due to impact the Moon on September 3rd 2006, in the nearside, in an area called Lacus Excellentiae, south of Mare Humorum.

Further information and updates on the SMART-1 mission status can be found on the ESA Science Web pages, at: http://sci.esa.int/smart-1/.

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REFERENCES

Foing, B.H., Perry, M., Exploration and Utilisation of the Moon, Proceedings of the Fourth ILEWG Conference held at ESTEC, in July 2000, ESA SP-462 , 2000

Foing, B.H. et al, SMART-1 mission to the moon: Status, first results and goals, *Adv. Space Research* 37, 6, 2006

Foing, B. H., Racca, G. D., Marini, A. et al, SMART-1 mission to the moon: Technology and science goals, *Adv. Space Research* 31, 2323, 2003

Foing, B.H., D. Heather, M. Almeida and SMART-1 STWT, The Science Goals of SMART-1, *Earth, Moon & Planets*, **85-86**, pp. 523-531, 2001.

Foing, B.H., Lunar Exploration, *Planetary & Space Science*, **50**, 14-15, pp. v-vi, 2002.

Racca, G.D., A. Marini,, L. Stagnaro et al., SMART-1 Mission Description and Development Status, *Planetary & Space Science*, **50**, pp.1323-1337, 2002.

Racca, G.D., B.H.Foing, M., Coradini, SMART-1: the first time of Europe to the Moon, *Earth Moon and Planets*, **85-86**, pp.379-395, 2001.

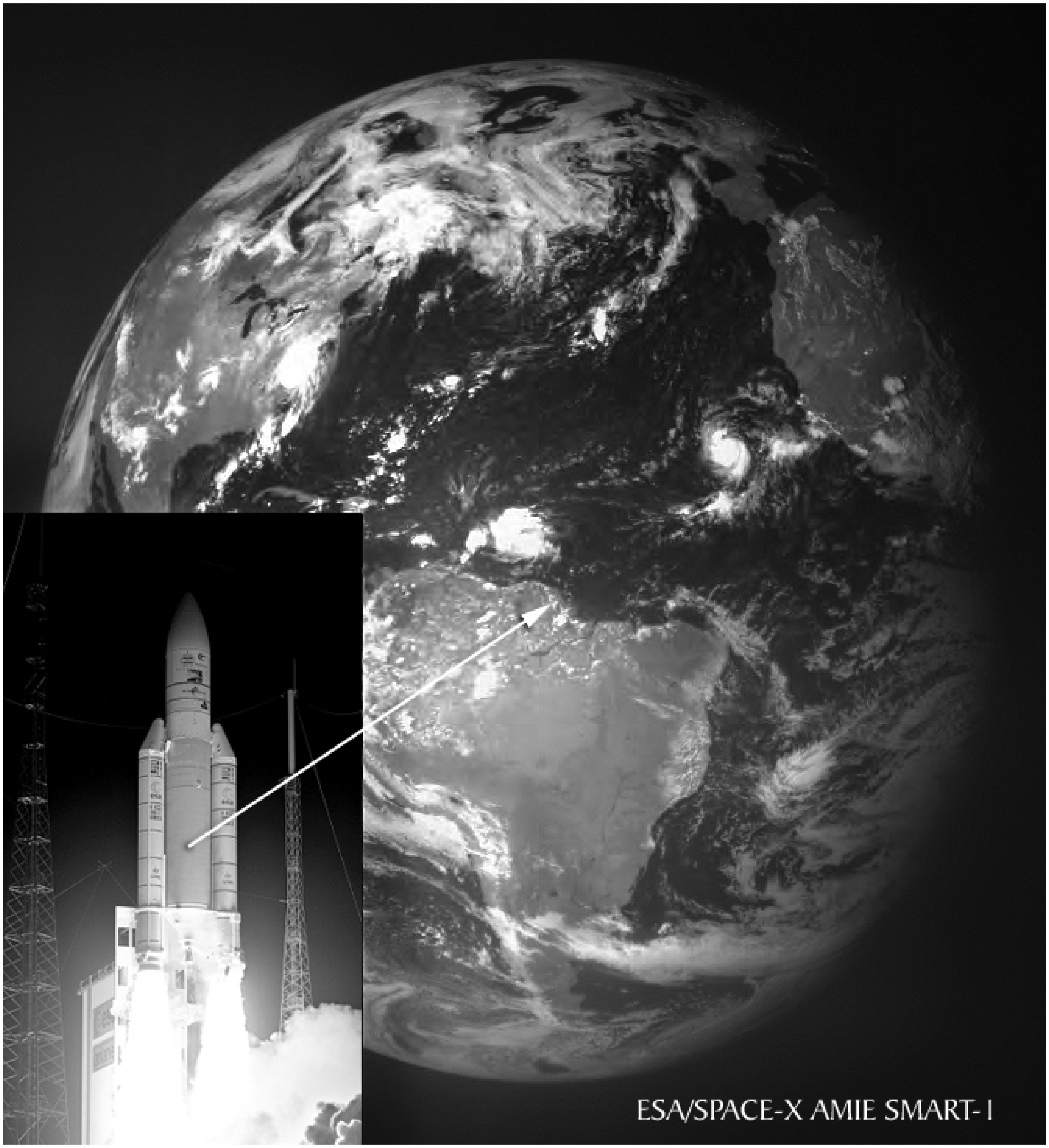

Fig.7 SMART-1 AMIE view of the Atlantic Ocean, the Americas, West Africa and Europe obtained during the cruise one year after launch (the insert shows the Ariane 5 rocket that launched SMART-1 from Kourou spaceport in French Guyana on 27 September 2003)

Fig. 8: Images of the Moon taken on 12 November 2004 from 60,000 km. This is the first European view of the lunar North pole and the farside. (Credit: ESA/SMART-1/AMIE).

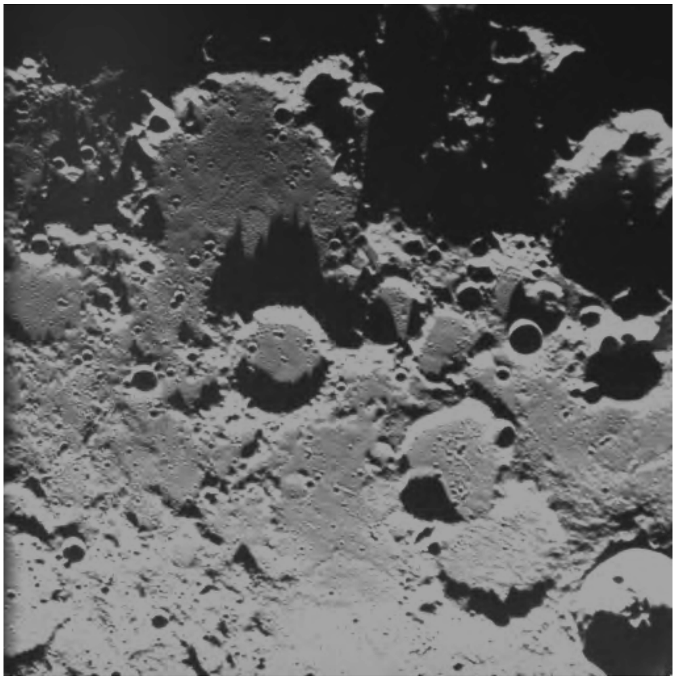

Fig. 9: AMIE view of polar light and long cast shadows over polar regions. The field of view here is 250 km, and the North pole is at the upper left. SMART-1 monitored the illumination during Northern winter and identified potential areas of eternal light on the rim a crater near the North pole. (Credit: ESA/SMART-1/AMIE)

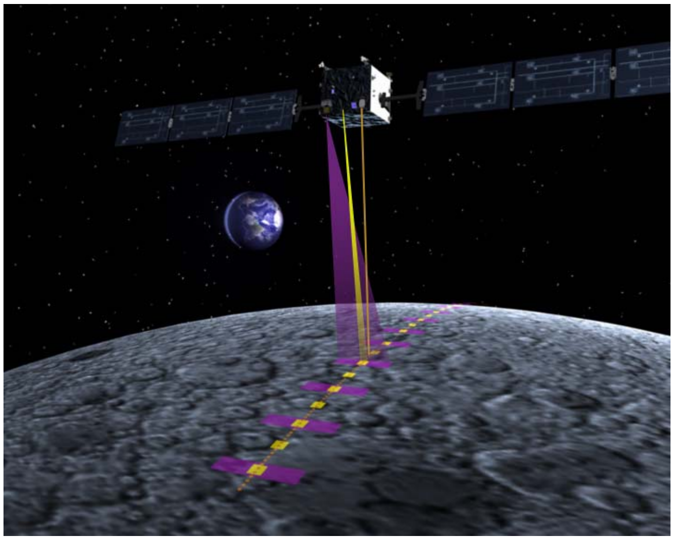

Fig. 10: Comparison between the swaths of the SMART-1 remote sensing instruments in lunar orbit: D-CIXS (32 x 12 deg), AMIE (5x5 deg or 2.5x1.25 deg colour frames) and SIR (4 arcmin point spectral continuous mapping)

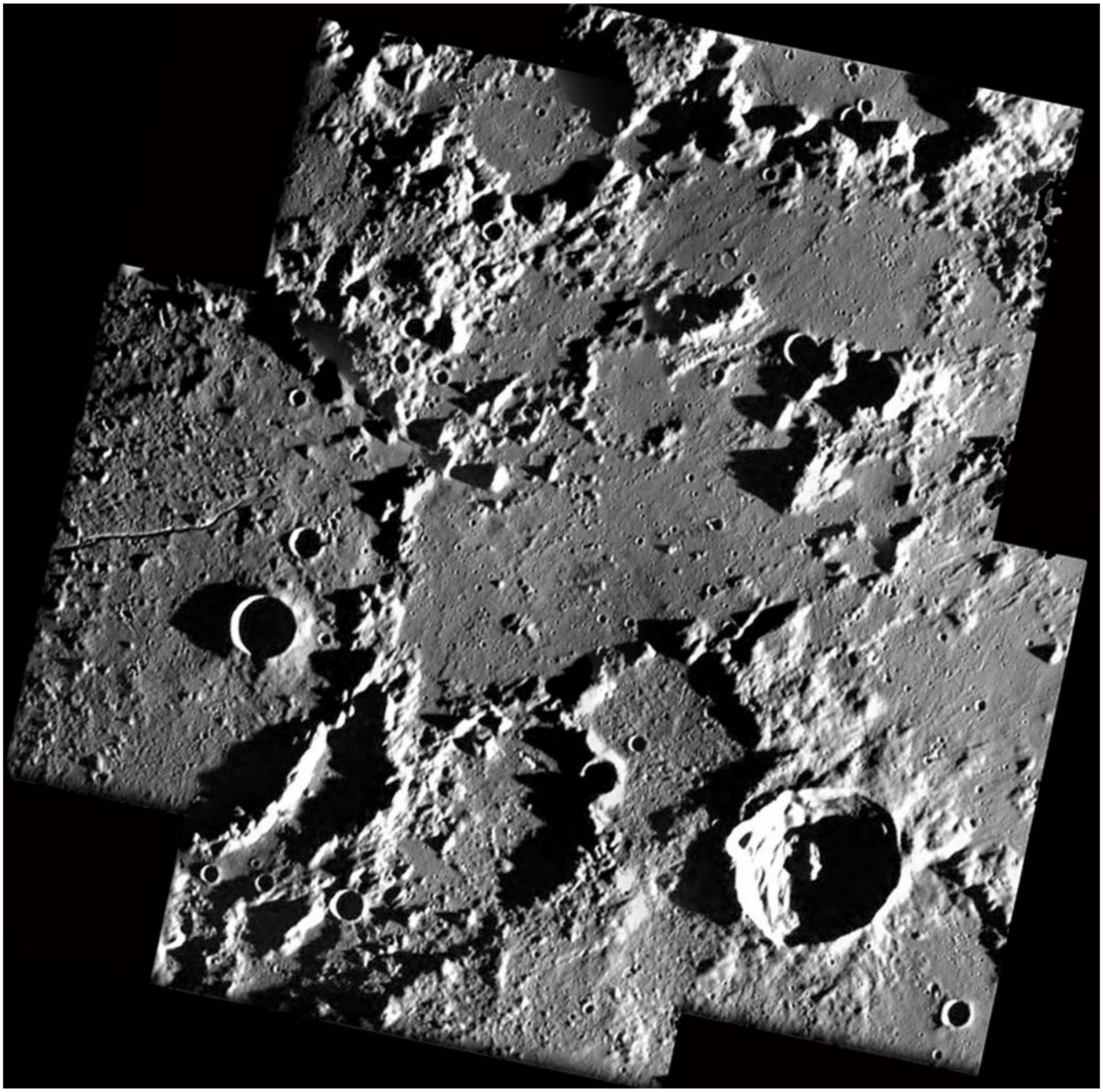

Fig. 11 : SMART-1 mosaic of area at the northern edge of Mare Frigoris (63 N, 17 E) between craters Mayer and Bond from images obtained on 5 and 6 February 2006 from 2700 km altitude. The field of view is about 260 km on the Moon. On the lower right, the fresh crater Mayer with a 38 km diameter shows a sharp-edged rim and a rough central peak. On the left part, the crater Bond is littered with scattered blocks, likely originating from the impact that created the Imbrium basin.

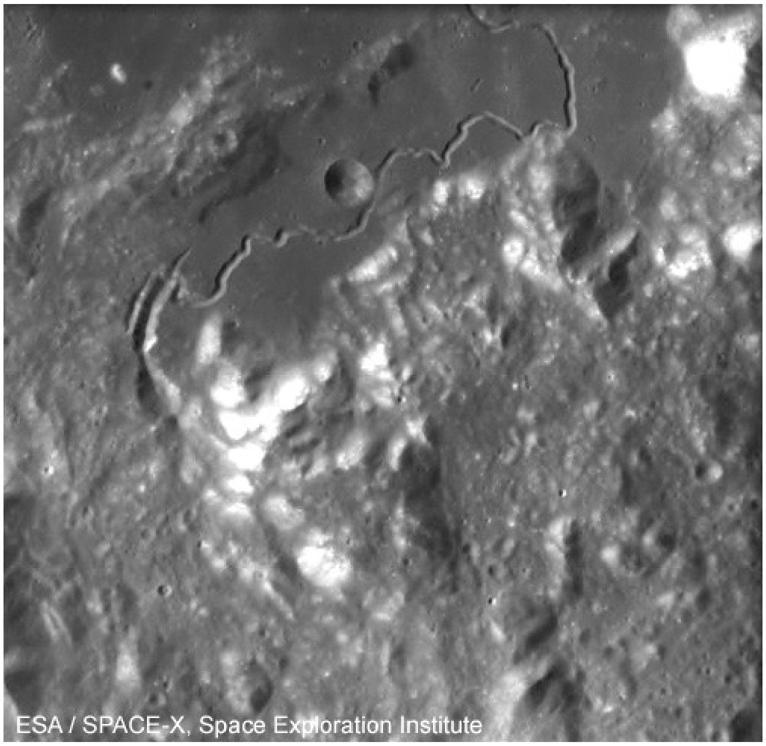

Fig. 12: SMART-1 view of the Hadley rille near Apollo 15 landing site (at the top right of the image). This view from 2000 km distance is covering a field of 100 km on the south East edge of Mare Imbrium. The rille is a giant lava tube over 120 km long and up to 1500 m across, that was investigated from the edge by astronauts David R. Scott and James B. Irwin during the Apollo 15 mission in 1971.