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SMART-1 Technology, Scientific Results and Heritage for Future Space Missions

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Abstract

ESA's SMART-1 mission to the Moon achieved record firsts such as: 1) first Small Mission for Advanced Research and Technology; with spacecraft built and integrated in 2.5 years and launched 3.5 years after mission approval; 2) first mission leaving the Earth orbit using solar power alone; 3) most fuel effective mission (60 liters of Xenon) and longest travel (13 month) to the Moon!; 4) first ESA mission reaching the Moon and first European views of lunar poles; 5) first European demonstration of a wide range of new technologies: Li-Ion modular battery, deep-space communications in X- and Ka-bands, and autonomous positioning for navigation; 6) first lunar demonstration of an infrared spectrometer and of a Swept Charge Detector Lunar X-ray fluorescence spectrometer ; 7) first ESA mission with opportunity for lunar science, elemental geochemistry, surface mineralogy mapping, surface geology and precursor studies for exploration; 8) first controlled impact landing on the Moon with real time observations campaign; 9) first mission supporting goals of the International Lunar Exploration Working Group (ILEWG) in technical and scientific exchange, international collaboration, public and youth engagement; 10) first mission preparing the ground for ESA collaboration in Chandrayaan-1, Chang' E1 and future international lunar exploration.

We review SMART-1 highlights and new results that are relevant to the preparation for future lunar exploration. The technology and methods had impact on space research and applications. Recent SMART-1 results are relevant to topics on: 1) the study of properties of the lunar dust, 2) impact craters and ejecta, 3) the study of illumination, 4) radio observations and science from the Moon, 5) support to future missions, 6) identifying and characterising sites for exploration and exploitation. On these respective topics, we discuss recent SMART-1 results and challenges. We also discuss the use of SMART-1 publications library. The SMART-1 archive observations have been used to support the goals of ILEWG. SMART-1 has been useful to prepare for Kaguya, Chandrayaan-1, Chang'E 1, the US Lunar

Reconnaissance Orbiter, the LCROSS impact, future lunar landers and upcoming missions, and to contribute towards objectives of the Moon Village and future exploration.

1. Europe to the Moon with ion engines and miniaturised technologies

SMART-1 stands for ESA's 1st Small Mission for Advanced Research and Technology [1,2,3]. Its main objective has been achieved to demonstrate Solar Electric Primary Propulsion (SEP) for future Cornerstones (such as BepiColombo) and to test new technologies for spacecraft and instruments. The SMART-1 365 kg spacecraft (Fig.1) was launched on 27 Sept. 2003, as an Ariane-5 auxiliary passenger and injected in GTO Geostationary Transfer Orbit, then spiraled out using ion propulsion until lunar capture in November 2004. The SMART-1 spacecraft reached on 15 March 2005 a lunar orbit of 400-3000 km for a nominal science period of six months, with 1 year extension until impact on 3 September 2006. SMART-1 science payload, with a total mass of 19 kg, featured many innovative instruments and advanced technologies [1], with a miniaturized high-resolution camera (AMIE) for lunar surface imaging, a near-infrared point-spectrometer (SIR) for lunar mineralogy investigation, and a very compact X-ray spectrometer (D-CIXS) [4-6] for fluorescence spectroscopy and imagery of the Moon's surface elemental composition. The payload also included two plasma experiments: SPEDE (Spacecraft Potential, Electron and Dust Experiment,) and EPDP (Electric propulsion diagnostic Package), an experiment (KaTE) that demonstrated deep-space telemetry and tele-command communications in the X and Ka-bands, a radio-science experiment (RSIS), a deep space optical link (Laser-Link Experiment), using the ESA Optical Ground station in Tenerife, and the validation of a system of autonomous navigation (OBAN) based on image processing.

Fig. 1 View of SMART-1 spacecraft during integration of instruments and tests at ESTEC

SMART-1 demonstrated these instruments new technologies, and provided an opportunity for science [1-12]. The SMART-1 spacecraft operated on a lunar science orbit for 18 months until impact on 3 September 2006.

2. SMART-1 instruments and lunar science

Earth and Moon have shared a common history for 4500 million years. Knowing the Moon more thoroughly can help scientists to understand our home in space. SMART-1 science investigations included studies of geophysical processes (volcanism, tectonics, cratering, erosion, space weathering, polar processes) for comparative planetology, of the chemical composition of the Moon, and high resolution studies in preparation for future steps of lunar exploration. The mission addressed several topics such as the accretional processes that led to the formation of rocky planets, and the origin and evolution of the Earth-Moon system [8, 12]. A package of three spectroscopy and imaging instruments has performed science at the Moon.

AMIE (Advanced-Moon micro-Imager Experiment) is a miniature high resolution (35 m pixel at 350 km perilune height) camera, equipped with a fixed panchromatic and 3-colour filter, for Moon topography and imaging support to other experiments [7, 10, 11]. The micro camera AMIE has provided high-resolution CCD images of selected lunar areas, and coverage of lunar surface as given in Fig.2 . It included filters deposited on the CCD in white light + three filters for colour analyses, with bands at 750 nm, 900 nm and 950 nm (measuring the 1μm absorption of pyroxene and olivine). AMIE images provided a geological context for SIR and D-CIXS data, and colour or multi-phase angle complement. Photometric anomalies associated to the regolith roughness, ejecta blankets, and lunar swirls were mapped and modelled [14] (Kaydash et al 2009) and opposition phase effect [15] (Muinonen et al 2011). AMIE data were used as part of an international effort to observe calibration targets over several lunar mission [16] (Pieters et al 2008). AMIE has been used to map sites of interest at south Pole Shackleton crater [17] (Bussey et al 2011) , and specific areas inside the huge South Pole–Aitken impact basin [22] (Borst et al 2012) that are relevant to the study of cataclysm bombardment, and to preview future sites for sampling return. Lunar North polar maps and South pole (Fig 6) repeated high resolution images have been obtained, giving a monitoring of illumination to map potential sites relevant for future exploration [23, 24] (Foing et al 2008, Grieger 2010).

Fig. 2 Coverage of the lunar surface at given resolution obtained by SMART-1 AMIE imaging camera in Mercator projection (top) and for the South polar area

SIR (SMART-1 Infra-Red Spectrometer) has been operating in the 0.9-2.6 μm wavelength range and carrying out mineralogical survey of the lunar crust [25, 26] (Keller et al 2001, Basilevsky et al 2004, Foing et al 2008). SIR had high enough spectral resolution to separate the pyroxene and olivine signatures in lunar soils. SIR data with spatial resolution as good as 400 m permitted to distinguish units on central peaks, walls, rims and ejecta blankets of large impact craters, allowing for stratigraphic studies of the lunar crust. We learned from experience from SIR for the SIR-2 improved instrument [27, 28, 29] (Bugiolacchi et al 2011,

Bhatt et al 2012, Bhattacharya et al 2011) that was launched on the 22nd October 2008 on India's Chandrayaan-1 mission to the Moon.

Fig. 3 SMART-1 D-CIXS measurements from a near-side flare event overlain with model predictions of Apollo 11 (green), Apollo 12 (blue) and Apollo 16 (red) average soil compositions (a) Full spectrum from 0 to 8 keV. (b) Linear scaled close up of measured X-ray flux and models from 3 to 8 keV, illustrating the fit to the Ca Kα peak (3.7 keV) and a Ti Kα peak (4.5 keV). Note that the Ti concentration is intermediate between the Apollo 11 and Apollo 12 compositions; a least-variance fit to the data yields a Ti abundance of 3±2 wt% (Swinyard et al 2009).

D-CIXS (Demonstration of a Compact Imaging X-ray Spectrometer) is based on novel detector and filter/collimator technologies, and has performed the first lunar X-ray fluorescence global mapping in the 0.5–10 keV range [4,5,9], in order to map the lunar elemental composition. It was supported in its operation by XSM (X-ray Solar Monitor) which also monitored coronal X-ray emission and solar flares [6]. Bulk crustal composition has bearing on theories of origin and evolution of the Moon. D-CIXS produced the first global measurements of the lunar surface in X-ray fluorescence (XRF), in order to estimate elemental abundances of Mg, Al and Si (and Fe when solar activity permitted) across the whole Moon, including the South Pole-Aitken Basin (SPA) and large lunar impact basins. For instance, D-CIXS measurements of Si, Mg, Al, Ca and Fe lines were made over North of Mare Crisium during the 15 Jan 2005 solar flare, permitting the first detection of Calcium from lunar orbit [9]. Scientific observations made during two solar flare events show the first detection of Titanium from the lunar surface [21] (see Fig. 3) . The X-ray Solar Monitor XSM has been used to calibrate D-CIXS measurements, and to monitor solar X-ray variations during flares in conjunction with other space solar observatories [19, 20a, 20b](Vaananen et al 2009, Alha et al 2008, 2012)

We learned from the experience of D-CIXS to aid the design of Chandrayaan-1 X-ray spectrometer (C1XS) [30-33] (Grande et al 2009, Crawford et al 2009, Narendranath et al 2011, Howe et al 2009)

The SMART-1 experiments have been operated according to illumination and altitude conditions during the nominal science phase of 6-months and 1 year extension, in elliptical Moon orbit [12, 34, 35] (Foing et al 2007 Camino et al 2007) . Both the planning and co-ordination of the Technology and science experiments operations were carried out at ESA/ESTEC (SMART-1 STOC) [36] (Koschny et al 2007). More than 32,000 AMIE images were acquired during 18 Months of lunar science operations [37] (Grieger et al 2008). The SMART-1 data are available at ESA Planetary Science Archive PSA [13] (and in PSA new version, see [38] (Besse et al 2016) , based on the PDS (Planetary Data System) Standard. Even if SMART-1 was primarily a technology demonstration mission, it has provided opportunities for science and exploration studies.

To date, 86 refereed papers and more than 370 conference or technical papers have been published based on SMART-1 . An ADS library of refereed SMART-1 related papers

published after launch can be found on ESA Cosmos website). SMART-1 related papers received more than 900 citations (on ADS). The SMART-1 publications library can be used to access, review and analyse the technical, scientific results of the mission, and as feed forward the preparation of future missions. SMART-1 data are accessible at ESA Planetary Science Archive PSA [38, 39]. SMART-1 highlights and results have also been shared with the public and youth giving visibility to European space activities. A selection of SMART-1 images and webstories released regularly during the mission on ESA SciTech website, have been also posted on new ESA Open Access platform [40] http://open.esa.int/the-moon-by-smart-1/.

3. SMART-1 hard landing and impact observation campaign

Due to the Earth-Sun-Moon perturbations, the SMART-1 spacecraft without Xenon fuel left, was doomed naturally to impact the Moon farside. With the help of the SMART-1 operations team, using the residuals from hydrazine attitude control thrusters, we planned a spacecraft orbital strategy to fine tune the exact time and place of impact of the Moon to enable observing conditions from Earth. The impact took place on 3 September 2006 . See [41] (Foing et al 2006) , [42] (Racca et al 2009) for further details and references concerning the SMART-1 mission operations and in particular the hard landing phase. The project scientist coordinated a SMART-1 impact observing campaign team involving observatories from South and North America, Hawaii and Canaries (in case the probe would impact on previous lunar orbit, 5 hours earlier than nominal) [43] (Foing et al 2006) . The probe impacted within 1 second of planning. Some theoreticians had predicted that nothing could be seen. We had real-time detection of a clear impact flash and debris clouds observed from Canada France Hawaii [44] (Veillet & Foing 2007) and transmitted to ESA operations centre, and from some amateur telescopes, but the North American continent was overcast. From this we could derive the flash energetics and dynamics of debris clouds. We also confirmed laboratory simulation predictions of a ricochet for the SMART-1 very low grazing incidence [12, 43, 44] and [45] (Burchell et al 2007). A new analysis of SMART-1 impact has incorporated new laboratory experiments and modelling of the predicted crater [46, 47] (Burchell et al 2010, 2015). The SMART-1 impact experience and observations have been helpful to prepare for the Kaguya impact campaign and for LCROSS mission and future spacecraft impacts observations.

The SMART-1 impact observed from Earth was modelled using laboratory experiments predicting the size of asymmetric crater and ejecta [45-47]]. Views of SMART-1 landing site in the 'Lake of Excellence' were taken by SMART-1/AMIE images on 19 August 2006 (2 weeks before impact!) . We offer a bottle of special SMART-1 launch champagne bottle to the first space or ground team that will detect a possible elongated crater (about 4 x 8 m) formed by SMART-1 impact as predicted with models and laboratory simulations [46] (Burchell et al 2010) .

4. Recent specific SMART-1 lunar new results for science and exploration

We highlight here some new SMART-1 lunar results for science and exploration. Recent SMART-1 published results are relevant to topics on: 1) analysis of properties of the lunar dust, 2) investigation of volcanic processes, impact craters and the related ejecta, 3) study of illumination, 4) radio observations and science from the Moon, 5) support to future missions, 6) identifying and characterising sites for exploration and exploitation.

4.1) Study of properties of the lunar dust and multi-angular photometry

Fig. 5 Photometric anomalies of lunar surface around crater Lavoisier with SMART-1 AMIE showing top image from 45 degree illumination, and steepness ratios of images from different illumination phase angle. (Courtesy [14] Kaydash et al 2009).

Anomalies of reflectance function in the vicinity of Lavoisier floor fractured crater seem associated with pyroclastic deposits. Low albedo patches have also anomalous reflectance steepness function. The crater floor appears blanketed by various pyroclastic debris coming from several local venting sources.

A study of multi-angular imaging observations of the lunar crater Lavoisier (Fig.5) made by the AMIE camera onboard SMART-1 has been undertaken, with phase angles ranging from 26° to 83°. Despite this limited phase coverage, a first-order photometric survey has been carried out. Dark patches believed to be pyroclastic deposits [48] (Gaddis et al 2003) show similar photometric behaviour (backward scattering, high surface roughness); another dark region within Lavoisier F crater appears to display an even higher surface roughness, associated with a less pronounced backward scattering. [49,50] (Souchon et al 2009, 2013). Multi-angular photometry of Mare and specific regions was performed to diagnose the regolith roughness and to constrain models of light reflection and scattering [15] that can be extended to understand the surface of other moons and asteroids. That is relevant to the study of lunar dust.

4.2. Study of volcanic processes

Sinuous rilles are probably the most recognisable of small volcanic features on the Moon. Many partially resemble river valleys on Earth. However, the lunar rilles usually flow away from small pit structures. The rilles mark lava channels or collapsed lava tubes that formed during mare volcanism. Indeed, the lunar samples indicate that the Moon has always been dry, thus confirming the volcanic origin of the rilles.

Fig. 4 SMART-1 views Hadley Rille near Apollo 15 landing site. SMART-1/AMIE obtained this image from an altitude of about 2000 km. It covers an area of about 100 km and shows the region

around Hadley Rille centred at approximately 25° North and 3° East. A zoom of SMART-1 image of the Hadley rille is compared to the sketch of Apollo 15 traverses [23] (Foing et al 2008).

The Hadley rille (Fig. 4) begins at the curved gash on the left side of this image, and is seen clearest in the rectangular, mare-floored valley in the centre of the image. It is over 120 km long, and up to 1500 m across and over 300 m deep in places. The rille formed nearly 3.3 Gyr ago. In contrast, lava channels on Hawaii are usually under 10 km long and are only 50-100 m wide. The Hadley C crater next to the rille is about 5 km in diameter. The Hadley Rille and the St George peak are fairly well known because NASA astronauts David R. Scott and James B. Irwin landed there during the Apollo 15 mission in 1971 [51] . The landing site is near the upper right part of the rille (26.1° North and 3.9° East) on a dark mare plain called Palus Putredinis (Marsh of Decay).

4.3. Polar illumination mapped and monitored

The lunar North [52, 53] and South polar illumination [54] was mapped and monitored over the entire year. This permitted to identify "SMART-1 peaks of quasi-eternal light" and to assess their topography [17, 24, 52, 53, 54]. The south pole is located on the rim of Shackleton crater. SMART-1 took images around the crater, which is a strong contender for a future robotic and human exploration site and for a permanent human base. The polar mosaics (Fig. 6) show geological features of interest within reach from the south pole. Monitoring of the illumination of selected polar sites has allowed scientists to confirm that a ridge located 10 km from the Shackleton rim is prominently illuminated, and could be a strong contender for a potential future lunar outpost. The large number of impact craters in the area indicates that the terrain is ancient. An example is crater Amundsen, 105 km in diameter, lying 100 km from the pole. It shows central peaks and asymmetric terraces that deserve geological and geochemistry studies, and it includes a permanently shaded area that contains ices.

Using SMART-1 images, SMART-1 AMIE investigators and collaborators have also counted small impact craters on Shackleton ejecta blanket to estimate the age of the crater [17]. They have found that the number of craters is twice that of Apollo 15 landing site, which would make the Shackleton crater between 3.6 to 4.3 Gyr old.

Fig.6: SMART-1 /AMIE mosaic of the lunar South Pole (Credit: ESA/SMART-1/AMIE, mosaic by Ellouzi & Foing) [54] . The pictures were taken between May 2005 and February 2006, during different phases of the mission. at a distance of about 400 km, allowing medium-field (about 40 km across) and high-resolution views (40 m/pixel). Each individual image includes areas imaged with colour filters and a more exposed area. The differences have been corrected accordingly to obtain this mosaic. The mosaic, composed of about 40 images obtained over more than 30 orbits, covers an area of about 500 by 150 km. The lunar near-side facing Earth is at the top of the map, while the far-side is at the bottom.

Fig. 7 (left) *One* **of** *109 of 113 SMART-1 images of Shackleton area taken over the season*, *where we identified a best illuminated peak [76] (Grieger et al 2009, 2010)*. This "SMART-1 peak of quasi eternal sunlight" is at 7 km from Shackleton rim and could be used as a site to supply electricity for the future international lunar base.*

Fig. 8 (right, on same scale as Fig . 7) . *A topography for this SMART-1 peak derived from shape from shading modelling [76]* *(Grieger et al 2010)*, in complement to then available altimetry that has now been strongly improved thanks to the subsequent lunar missions.*

* See [76]   link on http://m.esa.int/var/esa/storage/images/media/videos/peak_of_light/29487-4-eng-GB/Peak_of_Light_highlight_mob.jpg

4.4. Using SMART-1 archives to support other missions

The Kaguya mission provided high resolution multiband imaging and spectrometry [55] (Haruyama et al 2008), [56] (Ohtake et al 2008) , with application to polar regions. The Laser altimeter experiment [57] (Noda et al 2008) derived elevation models from which they established most continuously lit surfaces of 89 % for north and 86 % for south .

The Chang'E1 & Chang'E2 missions [58] (Zheng et al 2008) derived images [59] (Wu et al 2014) , altimetry [60] (Ping J. et al 2009) and temperature variation maps [61] (Zheng Y.C. et al 2012) over the lunar surface and in particular polar regions.

The Lunar Prospector mission [62] Binder et al had previously indicated evidence of enhanced hydrogen [63] Feldman et al 1998 in the permanent shadowed floors of polar craters, possible sign of water ice – a relevant element when choosing a human outpost. Later measurements by Onboard Chandrayaan-1 spacecraft [64], the M3 spectrometer team has confirmed the presence of OH-bearing minerals [65] Pieters et al 2009. The LCROSS satellite [66, 67] performed an impact showed the presence of water ice at its impact site [68]. The LRO Lunar Reconnaissance Orbiter [69] obtained detailed images [70], as well as altimeter topography [71] of polar regions. The LRO neutron spectrometer [72] have also further mapped the locations of enhanced subsurface ice.

SMART-1 SIR data were combined with HySI data from Chandrayaan-1 to study the composition of the central peak of craters [22]. The SMART-1 archive observations have been used to support Kaguya, Chandrayaan-1, Chang'E 1, the US Lunar Reconnaissance Orbiter, the LCROSS impact, and upcoming missions. SMART-1 data were used for studies of potential sites relevant to future exploration [12, 17, 52]. The SMART-1 team had the opportunity to collaborate with international scientists from subsequent missions and to compare the data , in particular from multiple missions. [73, 74] (Foing et al 2008, 2009) . A Moon Atlas has been developed from the fusion of individual SMART-1 AMIE pictures [75] (Fonseca J. et al 2012). The SMART-1 images of lunar poles and peaks of light were also used for virtual simulations of polar illumination and lunar journey [76] (Grieger et al 2009).

4.5. Science from the Moon, radio observations and tracking

The SMART-1 X-Ray Solar Monitor data were used for activity and flare studies of the Sun as a star in conjunction with GOES and RHESSI [19] or to design future coronal X-ray instruments [20]. Taking into account calibrations for all instruments, XSM and GOES total emission measures (TEM) and temperatures (T) were derived. The model-independent flux comparison with XSM and GOES

data at the 1 - 8 Å band shows that the fluxes agree with a ratio of 0.94 +/- 0.09 for the data up to April 2005 [20a & 20b].

SMART-1 was also used for radio occultation experiments [18] (Pluchino et al 2011). In fact, in the spring of 2006 it provided an opportunity to investigate the lunar ionosphere. A set of occultations of the Moon ionosphere was obtained between Aug 29th and Sep 1st of 2006. The events occurred when the Moon phase was about 40-60%, thus with significant differences of physical conditions between individual immersion and emersion. They gathered radio occultation data in S, X and Ka-band by virtue of the two 32-meter in diameter radiotelescopes of IRA-INAF (the Radioastronomy section of the Italian National Institute for Astrophysics) located both in Italy, and more precisely in Medicina (Bologna) and in Noto (Siracusa).

SMART-1 orbit tracking and autonomous operation technologies [3] (Racca et al 2002), [4] (Marini et 2002) were validated. VLBI (Very Long Baseline Interferometry) test observations were performed with SMART-1 in May, June, August 2006 in preparation for the impact campaign ([43] Foing et al 2006, [77] Gurvits et al 2006,) and for Selene VLBI gravimetry experiments [78] (Hanada et al 2008). VLBI for better gravimetry in SELENE. Tracking data from various lunar missions including SMART-1 have been analysed [79] (Goossens et al 2008)

4.6 SMART-1 and ILEWG recommendations

Since its creation in 1994, the International Lunar Exploration Working Group (ILEWG) organised a forum for the scientific, engineering, public community and the space agencies involved in lunar exploration [80-86].

ILEWG several task groups have advanced work in the areas of lunar science explo

ration, living and working on the Moon, key technologies, utilization of lunar resources, infrastructure of lunar bases, surface operations, society, law, policy and commerce, public outreach, education and also supports the Young Lunar Explorers. Regular declarations of ILEWG summarize findings and give recommendations that are summarized by a large community [80-86]. ILEWG logical and progressive roadmap was defined in 1995 and is de facto implemented with the recent fleet of orbiter precursors for science, technology and reconnaissance. The second phase with number of coordinated surface elements supported its orbital assets will constitute the "Global Robotic Village". The third phase will see the deployment of large systems in preparation for astronauts. The fourth phase will see the transition from short missions to permanent human presence at international bases.

The SMART-1 experience and data have been used to support working areas of ILEWG : Science of, on, and from the Moon; Living and working on the Moon; Key technologies; Utilization of lunar resources; Infrastructures for lunar bases; Surface operations; Society, law, policy, and commerce; Public outreach, education, multicultural aspects; and Young Lunar and Planetary Explorers. SMART-1 results contributed to the implementation of recommendations established by the community at large [80-86] during International Conferences on Exploration and Utilisation of the Moon (ICEUM), and by the COSPAR Planetary Exploration Panel [87].

4.7 SMART-1 lessons for future exploration:

The SMART-1 preparation, operations and exploitation have been coordinated with follow-up international lunar missions. SMART-1 has participated to efforts coordinated by the International Lunar Exploration Working Group (ILEWG) in support of Selene Kaguya, the Indian lunar mission Chandrayaan-1, the Chinese probes Chang'E 1 and Chang'E2, the USA Lunar Reconnaissance Orbiter, LCROSS impactor and subsequent lunar landers. SMART-1 has been contributing to prepare the next steps for exploration: demonstrating technologies and new methods for mission development, lunar science, survey of resources, monitoring polar illumination, and mapping of sites for potential landings, robotic villages and for future human activities towards International Lunar Bases. The SMART-1 teams (project, industry, science and technology, data users, international collaborators) have worked with the other international lunar missions teams to exchange information, collaborations, opportunities, future projects in the spirit of a Moon Village on Earth and in space [88].

With the new ESA policy on Open Access more than 100 images and webstories were released on new platform : http://open.esa.int/the-moon-by-smart-1/

"SMART1 ESA small technology mission has been an inspiring European journey to the Moon, where we invited many international collaborations. SMART1 open data and images can now be used further by world scientists , explorers, engineers as well as the community of students and citizens to prepare the next MoonVillage steps".

Links: http://sci.esa.int/smart-1/, http://sci.esa.int/ilewg/

https://www.cosmos.esa.int/web/guest/mission-publications

https://www.cosmos.esa.int/web/smart-1

http://www.esa.int/Our_Activities/Space_Science/SMART-1

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SMART-1 refereed publications library : http://adsabs.harvard.edu/cgi-bin/nph-abs_connect?library&libname=Latest+SMART-1+library&libid=563226ec7f

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Figures
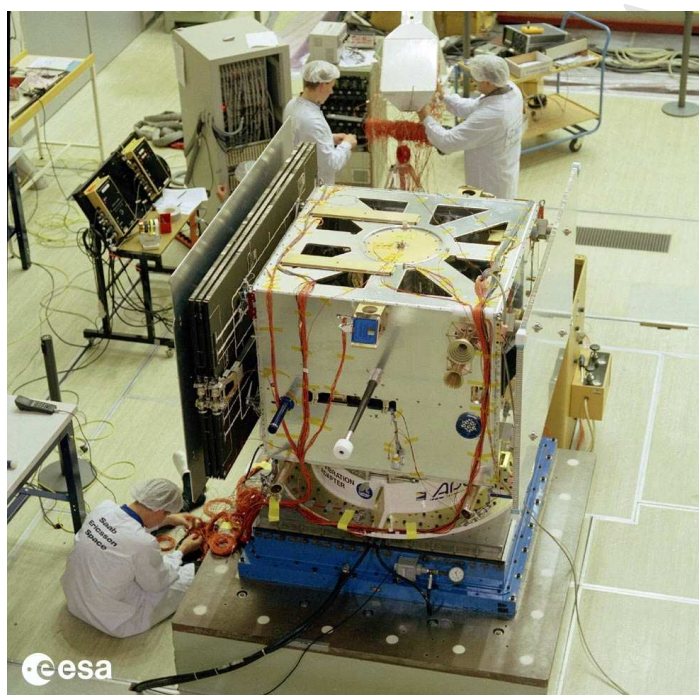
Fig. 1 View of SMART-1 spacecraft during integration of instruments and tests at ESTEC
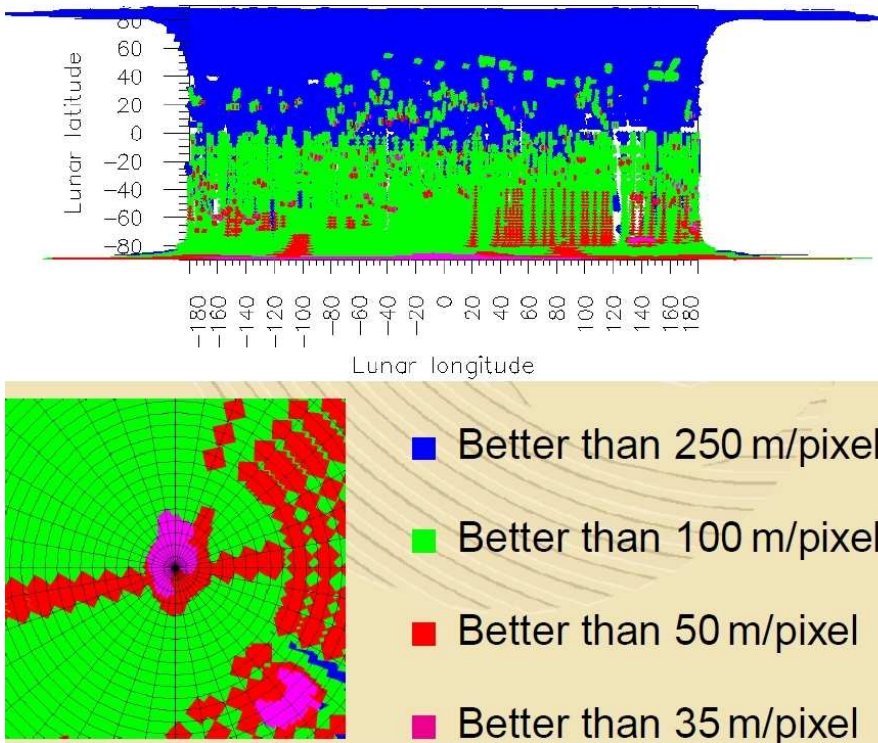
Fig. 2 Coverage of the lunar surface at given resolution obtained by SMART-1 AMIE *imaging camera in Mercator projection (top) and for the South polar area (bottom) (Grieger et al 2010)*
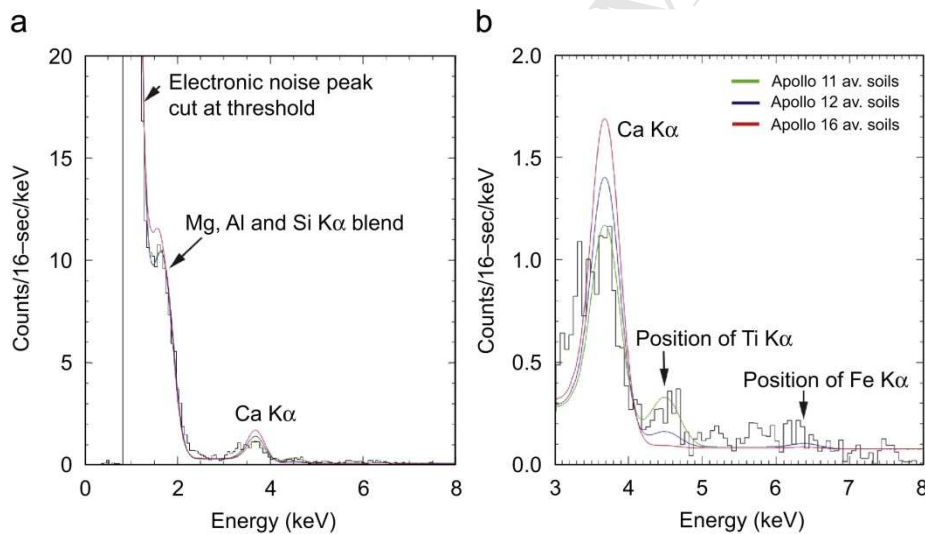

Fig. 3 SMART-1 D-CIXS measurements *from a near-side flare event overlain with model predictions of Apollo 11 (green), Apollo 12 (blue) and Apollo 16 (red) average soil compositions (a) Full spectrum from 0 to 8 keV. (b) Linear scaled close up of measured X-ray flux and models from 3 to 8 keV, illustrating the fit to the Ca Kα peak (3.7 keV) and a Ti Kα peak (4.5 keV). Note that the Ti concentration is intermediate between the Apollo 11 and Apollo 12 compositions; a least-variance fit to the data yields a Ti abundance of 3±2 wt% (Swinyard et al 2009).*
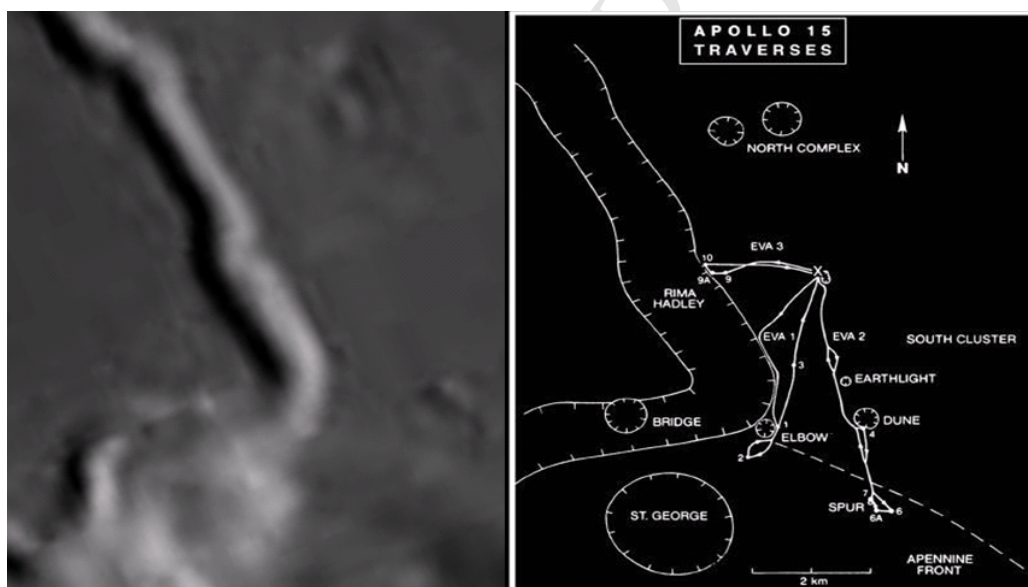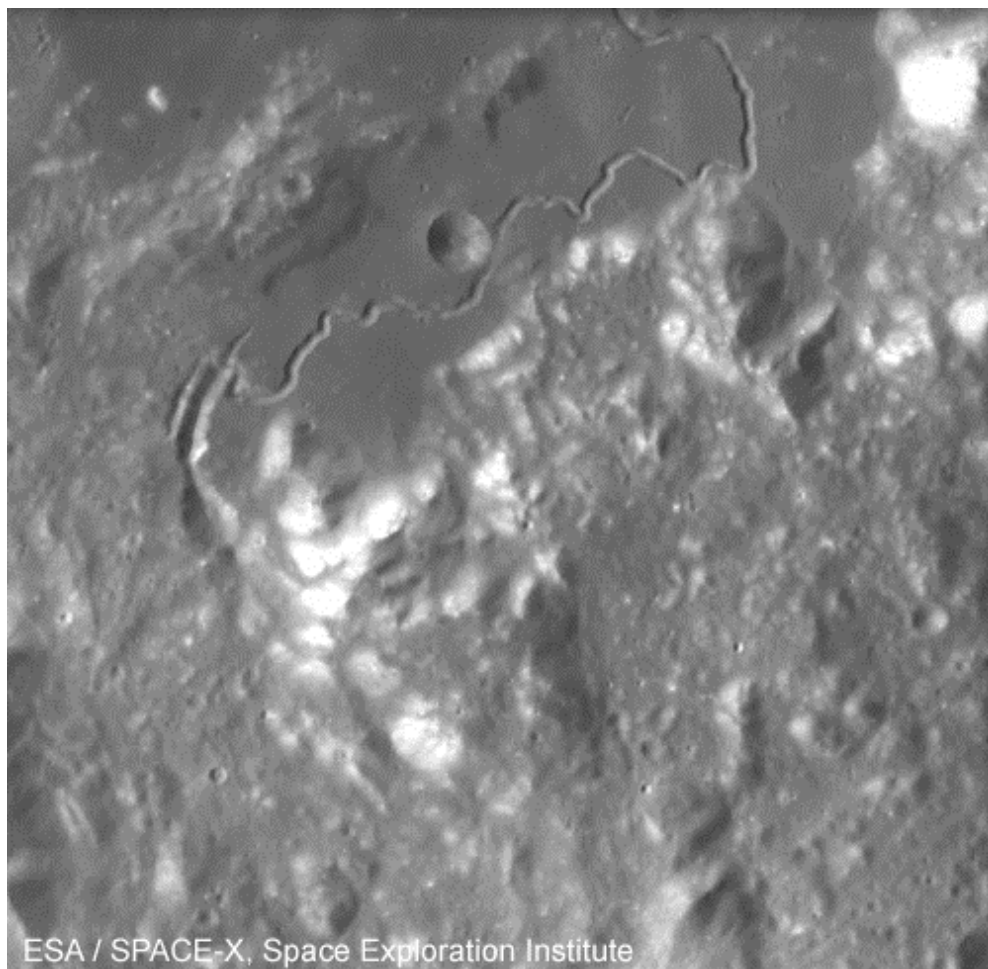
Fig. 4 SMART-1 views Hadley Rille near Apollo 15 landing site. *A zoom of SMART-1 image of the Hadley rille is compared to the sketch of Apollo 15 traverses (Foing et al 2012).*
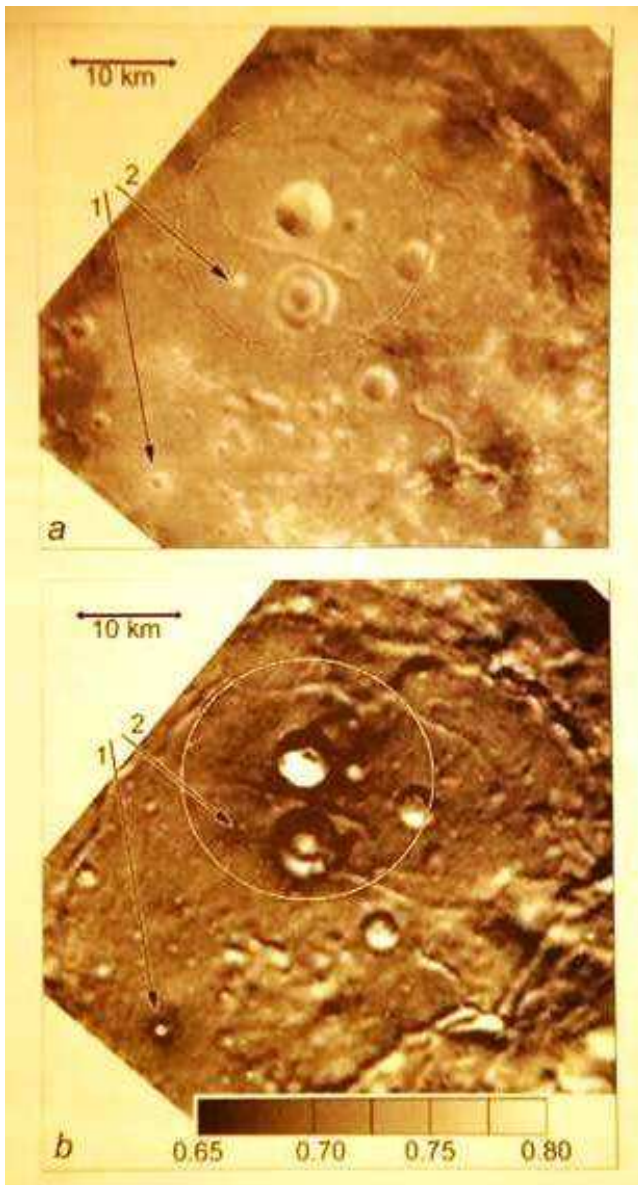
16

Fig. 5 Photometric anomalies of lunar surface around crater Lavoisier *with SMART-1 AMIE showing top image from 45 degree illumination, and steepness ratios of images from different illumination phase angle. (Courtesy Kaydash et al 2009)*
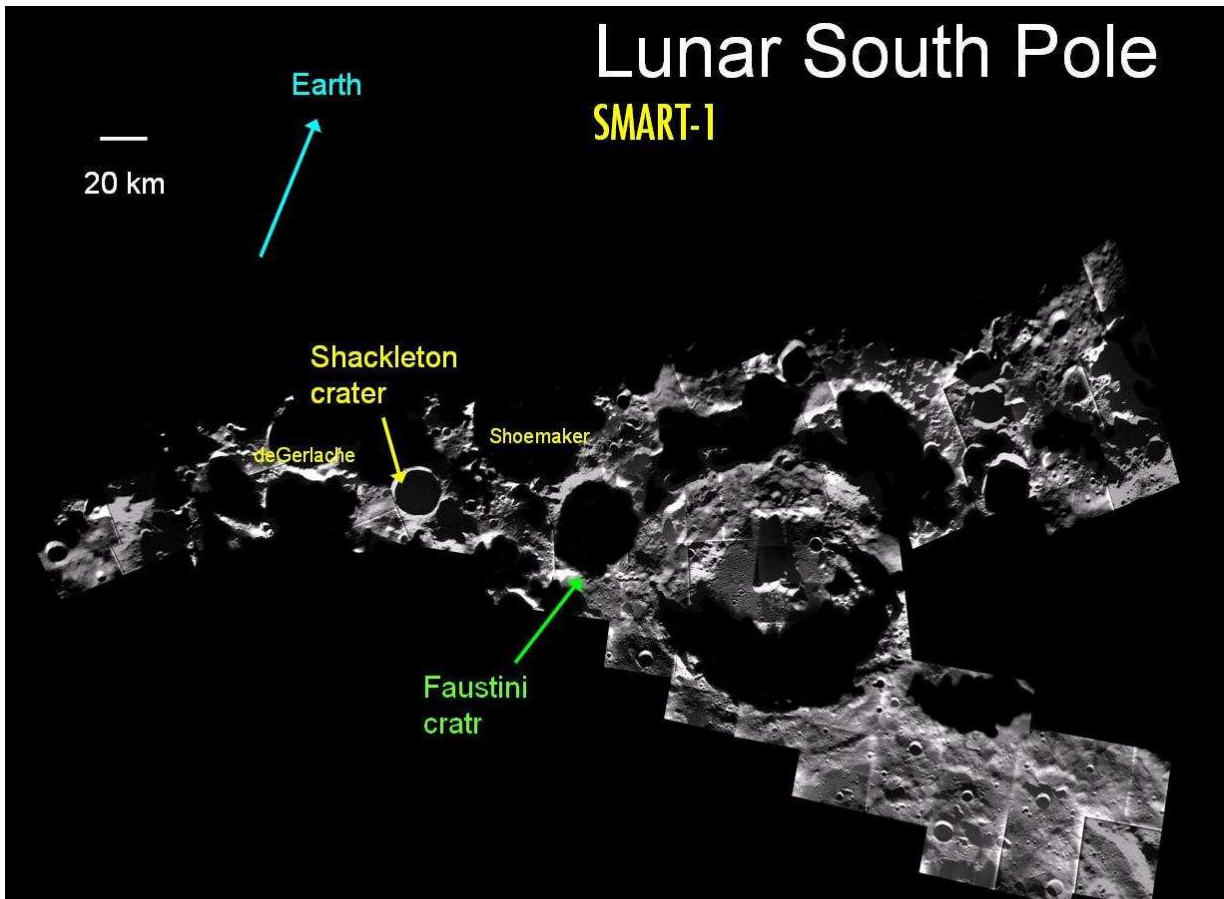
Fig.6: SMART-1 /AMIE mosaic of the lunar South Pole (Credit: ESA/SMART-1/AMIE, Mosaic by Ellouzi & Foing). The pictures were taken between May 2005 and February 2006, during different phases of the mission. at a distance of about 400 km, allowing medium-field (about 40 km across) and high-resolution views (40 m/pixel).
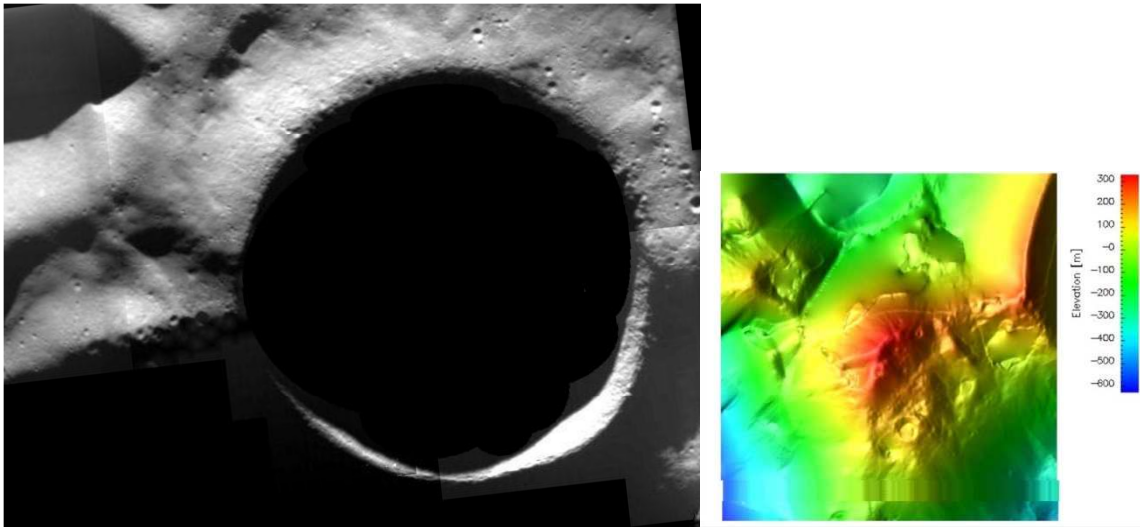
Fig. 7. (left), Fig. 8 (right)

Fig. 7 (left) One of *109 of 113* **SMART-1 images of Shackleton area taken over the season**, *where we identified a best illuminated peak [76] (Grieger et al 2009, 2010)*. This "SMART-1 peak of quasi eternal sunlight" is at 7 km from Shackleton rim and could be used as a site to supply electricity for the future international lunar base.*

Fig. 8 (right, on same scale as Fig . 7.) A **topography for SMART-1 peak of light** *was derived from shape from shading modelling [76](Grieger et al 2010)*, in complement to then available altimetry that has now been strongly improved thanks to the subsequent lunar missions. This was used for virtual simulations [76].*

* See [76] link on http://m.esa.int/var/esa/storage/images/media/videos/peak_of_light/29487-4-eng-GB/Peak_of_Light_highlight_mob.jpg