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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 L of Xenon) and longest travel (13 months) 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 (Foing et al., 2001; Racca et al., 2002a, 2002b). 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 400–3 000 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 (Foing et al., 2001), with a miniaturised

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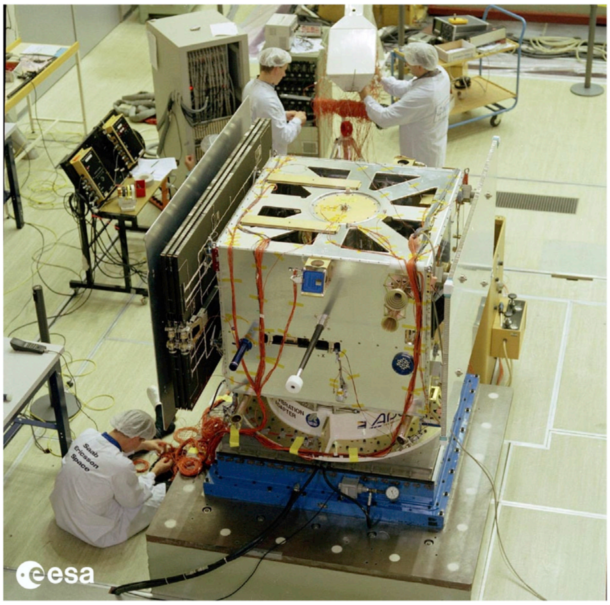

**Fig. 1.** View of SMART-1 spacecraft during integration of instruments and tests at ESTEC.

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) (Marini et al., 2002; Dunkin et al., 2003; Grande et al., 2003; Huovelin et al., 2002) 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.

SMART-1 demonstrated these instruments new technologies, and provided an opportunity for science (Foing et al., 2001; Racca et al., 2002a, 2002b; Marini et al., 2002; Dunkin et al., 2003; Grande et al., 2003; Huovelin et al., 2002; Shkuratov et al., 2003; Foing et al., 2003, 2006a; Grande et al., 2007; Pinet et al., 2005; Josset et al., 2006). 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 4 500 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 (Foing et al., 2003, 2006a). 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 (Shkuratov et al., 2003; Pinet et al., 2005; Josset et al., 2006). 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 1 μm 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 (Kaydash et al., 2009) and the opposition phase effect was measured and compared to theory (Muinonen et al., 2011). AMIE data were used as part of an international effort to observe calibration targets over several lunar mission (Pieters et al., 2008). AMIE has been used to map sites of interest at south Pole Shackleton crater (Bussey et al., 2011), and specific areas inside the huge South Pole–Aitken impact basin (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 (Foing et al.; Grieger et al., 2010).

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 (Keller et al., 2001; Basilevsky et al., 2004; Foing et al.). 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 (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.

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 (Marini et al., 2002; Dunkin et al., 2003; Grande et al., 2003; Grande et al., 2007), 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 (Huovelin et al., 2002). 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

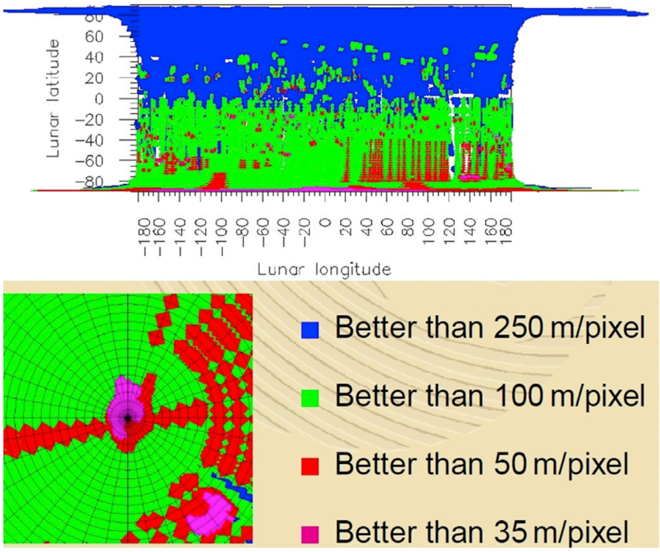

**Fig. 2.** Coverage of the lunar surface at given resolution obtained by SMART-1 AMIE imaging camera in Mercator projection (top) and for the South polar area.