Technology and Science from Earth to Moon: SMART-1 Experiments and their operations

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ABSTRACT
SMART-1, the first European mission to the Moon aimed at demonstrating the Solar Electric propulsion hosts 10 Technology and Science experiments. The monitoring of the spacecraft plasma environment and the thruster contamination produced by thruster is carried out by SPEDE (Spacecraft Potential, Electron and Dust Experiment) and EPDP (Electric Propulsion Diagnostic Package).

The miniaturised remote sensing instruments on-board SMART-1 are: AMIE (Advanced Moon micro-Imager Experiment), D-CIXS (Demonstration of a Compact Imaging X-ray Spectrometer), supported in its operation by XSM (X-ray Solar Monitor), and SIR (SMART-1 Infrared Spectrometer).

Technology experiments for deep-space communications and navigation are: KATE (Ka-Band TT&C Experiment), based on X/Ka-band transponder which also supports RSI (Radio-Science Investigations for SMART-1), Laser-link, demonstrating a deep-space laser communication link and OBAN (On-Board Autonomous Navigation experiment).

The Experiments will be performed during two distinct phases of the SMART-1 mission, including 17-month Earth escape phase and a nominal 6-month operational phase in elliptical Moon orbit.

The SMART-1 STOC (Science and Technology Operations Co-ordination) carries out the planning and co-ordination of the Technology and science experiments.

1. INTRODUCTION AND BACKGROUND
SMART-1 is the first of the Small Missions for Advanced Research in Technology of the ESA Horizon 2000 Science Plan. These missions have been introduced by ESA as one of the strategic elements into the Horizon 2000 Science Plan. The scientific importance of the SMART-1 mission resides mainly in its preparatory nature for upcoming truly scientific missions and in particular for those missions which will benefit of Solar Electric Primary Propulsion (SEPP) and deep space communications. Among these the Mercury Cornerstone study had clearly identified the SEPP as a key element to enable a low circular orbit. SMART-1 shall demonstrate the use of SEPP on a small mission, but representative of a future deep-space science mission. Therefore the emphasis is placed on the common system aspects and on the peculiar flight dynamics and control techniques needed for implementing the mission profile, rather than on the choice of a particular engine, which is more mission-specific.

The requirement for science output of SMART-1 is secondary to the technology demonstration objective. Nevertheless, in order to demonstrate practical utilisation of SEPP, the spacecraft should travel beyond an Earth orbit and reach some relevant solar system object. The Moon was chosen as a target for its scientific importance and relative ease of access from a commercial Geo-stationary Transfer Orbit (GTO). There is consequently an initial system allocation of 15 kg and 50 W for accommodation of science instruments.

SMART-1 is also a "first-ever" low-budget small mission for Science at ESA and in this sense it explores and tests new ways of implementing cost-effective procurement and efficient management. The budget constraints of SMART-1 also require a cost-effective approach to spacecraft development and verification, not only considering AIT cost, but also associated or induced effort during the design and analysis stages of the development programme.

The very peculiar mission profile – providing a spiral escape from Earth gravitational field in about 17 months and followed by weak capture of the Moon orbit and 6 months of lunar orbit operations – is described in [1]. At the time of writing (August 2002), SMART-1 spacecraft is undergoing the final AIV/AIT phase (see Fig. 1) with System and environmental testing. The launch is foreseen after 1st March 2003.

2. SMART-1 SCIENCE AND TECHNOLOGY EXPERIMENTS

2.1 Scientific Objectives

Although the main objective of the mission is essentially technological, a great deal of effort was spent to improve its scientific return. Scientific observations can indeed be carried out during both the lunar operational phase and the cruise phase.

The lunar observation phase will be performed from a polar orbit with the peri-lune on the South hemisphere at about 30° from the South Pole and at an altitude varying between 1,900 km and 300 km. The baseline apo-lune will have an altitude varying between 8,400 and 10,000 km.

SMART-1 Lunar scientific studies will concentrate on mineralogical mapping and elemental geochemistry and will include:

- Elemental geochemistry (X-ray imaging spectrometer, with a spatial resolution of 30 km at peri-lune)
- Mineralogy (Near-IR spectrometer combined with camera mapping)
- Geology, morphology (High resolution camera)
- Exospheric environment (Camera, plasma and dust experiment)

During the long cruise phase the following scientific investigations will be performed:

- Monitoring of X-ray variability of several cosmic sources and the Sun (X-ray spectrometer)
- Cometary detection and auroral X-ray monitoring on both hemispheres of the Earth (X-ray spectrometer)
- Monitoring optical micro-variability of stars
- Space-time variations of the plasma and electron environment in the Earth-Moon space

Finally, as mentioned, the ultimate scientific return of the SMART-1 mission resides in its objective to qualify the use of novel technologies for more ambitious future planetary missions.

2.2 Technology Objectives

As stated previously, the main design drive of the SMART-1 mission is to test in a deep-space representative mission the primary electric propulsion. The mission will qualify the system and its use as primary propulsion. The system aspects such as electrical power supply as well as thrust direction control and mechanical and thermal accommodation are main design drivers. In addition the characterisation of the electromagnetic, plasma and dust environment created by the functioning of the EP is addressed by two instruments: EPDP and SPEDE (see description later).

Other technologically advanced items are addressed by the SMART-1 payload. A new Deep Space X-Ka band transponder will be own as a technology payload. This transponder, essential to BepiColombo will allow also to perform a radio science investigation to monitor the dynamical performances of the electric propulsion system and to measure the rotational state of the Moon, as explained later in this paper. It also aims at assessing capabilities of an advanced X/Ka link for precise Doppler and ranging measurements in preparing future high-precision geodesy and relativity experiments.

Furthermore the possibility of employing laser communication for future Deep Space links will be investigated. The on-board camera (AMIE) will acquire and image the laser beam transmitted by the ESA Optical Ground Station (OGS) in Tenerife (Spain) see fig.2

Fig.2: The ESA OGS at the Observatorio del Teide, Tenerife

Two of the science instruments have also been selected due to their technological advances. The D-CIXS X-ray spectrometer has novel features, such as the micro-structure collimator and the Swept Charge Detector. The SIR near-IR spectrometer is of high relevance for planetary research as it is a very compact, miniaturised version derived from a quasi-
monolithic commercial quartz grating spectrometer.

2.3 Science and Technology Payload description

The payload is composed of technology and scientific experiments and its total mass is about 19 kg. The seven SMART-1 instruments support ten investigations.

EPDP Electric Propulsion Diagnostic Package (2.3 kg, 18 W). A suite of sensors for thruster diagnostics with ion energy up to 400 eV and spacecraft contamination monitoring. The PPA (Plasma Probe Assembly) is composed of a Retarding Potential Analyser and of a Langmuir Probe), see fig. 3.

The other sensors are meant to detect contamination of neutral Xe ions on the spacecraft surface and are a Quartz Crystal Micro-balance (QCM, fig.4) and a Solar cell.

SPEDE Spacecraft Potential, Electron and Dust Experiment (0.8 kg 1.8 W). Langmuir probes are made of tiny TiN sensor foils attached on two short (60 cm) booms (see fig.5) for measuring energy range of a few tens' of eV, with plasma density from 1/10 to 1000 particles/cm³.

KaTE X/Ka-band Telemetry and Telecommand (TT&C) Experiment (6.2 kg, 28 W). A X-up/X-down and Ka-down Deep-Space Transponder running turbo-codes, allowing up to 500 Kbps data rate from lunar orbit.

D-CIXS/XSM (see Fig. 7) Demonstration of a Compact Imaging X-ray Spectrometer (5.2 kg, 20 W, including XSM). A 12° x 32° FOV spectral imager in 0.5-10 keV range based on Swept Charge Device detectors and micro-collimators, measuring x-ray fluorescence from the lunar surface discriminating the solar background by means of the X-ray solar monitor (XSM, see afterwards).
LASER-LINK demonstration of a deep-space optical link acquisition (with AMIE), where a laser beam is sent in direction of SMART-1 S/C by the ESA Optical Ground Station situated in Tenerife (see Fig.10). The aim of the experiment is to prepare for deep-space laser communication link, by demonstrating acquisition of the laser-link up to lunar distance and to validate a novel beam arrangement in four sub-apertures for mitigating the effect of atmospheric turbulence on the laser beam. The AMIE camera will be used on-board SMART-1 to image the beam profile and detect the link acquisition.

OBAN (On Board Autonomous Navigation) concept verification (with AMIE), by means of discriminating the motion of a non-stellar target (planet, asteroid) against the starry background in a long exposure image. The camera information will be completed by the on-board star—tracker data and elaborated offline by the navigation software which generates the navigation data (on-ground simulation).

RSIS (Radio-Science investigations for SMART-1) uses KaTE to perform the characterisation of the X- and Ka-band communication channels and performance, Electric propulsion monitoring and the demonstration of a novel method for measuring the libration properties of a celestial body (the Moon for SMART-1, in preparation of BepiColombo) from the lunar orbit (with KATE and AMIE). The Electric propulsion monitoring is performed by tracking the Ka-band signal while the thruster is on, allowing measurements of the thrust force with a resolution in the order of $10^4$ N and of the acceleration of the S/C with a resolution of about 0.1 mm/s$^2$.

XSM (Fig.11) will monitor the solar X-ray emission in the 1-20 keV range for studying the solar corona activity, both in short and long
time scales. Observing “the Sun as a star” will contribute to test stellar X-ray emission models and study the solar-stellar connections.

Fig. 11: XSM flight unit

For further reading, reference paper [2] describes the science potential and goals of the scientific instruments, while [3] shows how the technology experiments prepare for future ESA Cornerstone missions.

3. SMART-1 EXPERIMENTS OPERATIONS

SMART-1 Experiments are carried out during the whole mission, after spacecraft commissioning.

3.1 Earth Escape Phase

Most of technology experiments are carried out during the cruise phase, together with calibration of science instruments.

In the early cruise phase just after launch, EPDP and SPEDE are commissioned, to be ready monitoring the Electric propulsion Commissioning and first Operations. All the other instruments are then commissioned in the following weeks when passes and orbital environment allow it.

During the first 75 days after Thruster switch-on, the electric propulsion is operating almost continuously, to rapidly raise the perigee to a safe height above the Van Allen radiation belts. During this period only SPEDE and EPDP will be operational, while XSM will start solar monitoring only close to the apogee. After this phase, the thrusting periods are optimised in a sequence of thrusting and coasting arcs, aimed at raising the orbit apogee and at consuming the least possible fuel.

During thrusting SPEDE is operating almost continuously, supported by EPDP for the electric propulsion monitor or at the same time XSM takes solar spectra.

During the coast arcs, the remote sensing instruments – AMIE, SIR and D-CIXS – will start performing their in-flight calibration and – in visibility of the Ground stations – either KAE or Laser-link will be operated.

During longer coast arcs (towards the end of the Escape Phase, where also the low-energy proton density is much lower) D-CIXS will perform X-ray observations of celestial objects, the Earth aurora and opportunity targets such as comets. AMIE will take images of the Earth and the Moon (for Public outreach) and target planets for carrying out the OBAN experiments.

During the longest thrust arcs at the end of the escape phase it will be possible to have KATE pointing at a Ground Station for a long time (~1-2 hours) while the thruster operates: in this situation it will be possible to perform the RSIS accurate measurements of the Electric Propulsion performance by tracking in Ka-band.

3.2 Lunar Phase

After the very delicate phase of the weak capture (see [1]), SMART-1 enters a Moon-centred orbit profile and thruster is switched on to reduce the apo-lune to the nominal observation orbit of 10000 km with a 300 km perilune and an argument of the peri-centre of 270°. During this phase only thruster monitoring will be performed.

The Moon observation phase will mostly run science experiments and KATE will be also for supporting science data telemetry throughput.

The core science observations for the lunar phase are the following:

- Global X-ray spectral imaging survey (D-CIXS/XSM).
- Near-Infrared spectroscopy and broadband spectral imaging (SIR+AMIE with colour filters).
- High-resolution imaging (AMIE).
- Exospheric & lunar plasma environment monitoring (SPEDE).
- RSIS: Demonstration of measurement method of (lunar) libration from Orbit (KAE/AMIE).

The orbit will evolve during the 6 months Moon phase with varying height and argument of the perilune [1], offering a variety of illumination and viewing conditions. The spacecraft will be mostly kept in a nadir pointed attitude, with some yaw manoeuvre to be performed for avoiding the spacecraft radiators to be excessively illuminated by the sun. Nevertheless off-pointing will be performed to aim at imaging and spectral target required by AMIE and SIR.

4. THE SMART-1 STOC

The SMART-1 Science and Technology Operation Co-ordination (STOC) is a service within the SMART-1 Project fully integrated within the Operations mission element. The purpose of the STOC is to co-ordinate the Science and Technology Operations and to
support the collection and the exploitation of the mission data.

SMART-1 being a low-cost mission, the STOC does not assume the characteristics of an usual Science Operation Centre of a scientific satellite mission, but - making use of available modern information technologies - it rather provides some vital tasks in a flexible and economic way, by being remotely accessed and interacting with the Mission Operations centre and with the Experiment Operations Facilities.

Due to the nature of SMART-1 Mission, science and technology data are collected together and throughout the whole mission, with a prevalence of Science data during the Moon orbiting Phase. The STOC will therefore act as a Science Operations Centre during this part of the mission, without however changing the organisation of the activities or the personnel.

The responsibilities of the STOC are in the terms of reference of co-ordination in the preparation and the conduct of SMART-1 Experiment Operations, for the whole duration of the mission till the spacecraft de-commissioning. In particular the STOC:

- Supports the Science and Technology Working team in the activities of Science Operation Planning
- Co-ordinates the preparation and conduct of the Experiment operations towards the PI's/IT's.
- Takes an active part in the experiment timelining process by generating the Experiment Science Master Plan from the inputs of all Experiments and provides it to ESOC (with no requirement of timeline optimisation).
- Monitors the Data Delivery to the Experiment teams.
- Maintains an archive of Raw data throughout the duration of the mission and supports the post-processing and Science archival activities at ESA.
- Analyses the results and prepares the "lessons learnt" for use on later projects

The STOC facility is located at ESTEC within the within the joint Science Operations for Planetary Missions (SOPM) facility of the ESA Research and Scientific Support Department (RSSD), which has been established to support all upcoming planetary missions, including Rosetta, Mars Express and BepiColombo. The potential synergy developing the mission operations tools, the re-use of the facilities and the expertise and the advantage of operating in a "specialised" environment, makes this solution the most attractive for the SMART-1 STOC, which is by definition meant to be low-cost and flexible.

A Workspace with the communication means towards the Mission Operation Centre (MOC) and the Experiment facilities and dedicated workstations linked to the generic planning, simulation and archiving facilities of the SOPM completes the SMART-1 STOC infrastructure.

The development of the software tools to be used for mission planning and scheduling has been also taken benefit form the synergy with other mission. SMART-1 uses EPS (Experiment planning system) linked to PTB (Project test-bed) as core tools, as thoroughly described in paper [4] in these same proceedings.

5. REFERENCES