# PAYLOADS ON-BOARD THE SMART-1 SPACECRAFT

**S/C interface, integration, test and early operations**

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**Abstract**

This paper focuses on the integration and test of the payloads onboard the SMART-1 spacecraft. Swedish Space Corporation is prime contractor for ESA's SMART-1, Europe's first Lunar mission The spacecraft was successfully launched on 27 September from Kourou.

The LEOP test phase has now been completed and all systems are performing nominally. The primary mission objective is to test the efficiency of electric propulsion and its impact on instruments and support systems, acting as a precursor for future interplanetary missions. Some of the scientific payloads play a key role in this concept by characterising the motor performance and its side effects. Others will look at the Moon, performing in particular a mineralogical survey of the still much unexplored lunar South Pole region. Observations of the Sun and other astronomical objects, as well as tests of a deep space transponder, are also planned.

Although the constraints in terms of mass, power and size have been very strict it has been possible to house all the planned payloads on-board this small spacecraft by using state-of-the-art concepts and methods of miniaturisation. Seven payloads with a total mass of less than 19 kg and a typical combined operational power of 15 W will perform a very ambitious agenda of observations.

The philosophy of interfacing the various payloads to the spacecraft support systems as well as the integration and test of the payloads on the spacecraft is discussed. A description of each payload and planned observations then follows. Finally early results are discussed.

## Introduction

To successfully accommodate seven payloads from different institutions, universities and private companies, each with its own mechanical, thermal, electrical and data handling interface, is a challenging task. In order to provide interface guidelines to the payload groups an Experiment Interface Document was launched at an early project stage. This document outlined all the constraints and requirements imposed on the payloads from the spacecraft support systems. Furthermore the document detailed test requirements on payload unit level, requirements on payload documentation, on reporting and interface documentation, delivery schedule of Engineering and Flight models and PA requirements. In order to support the payloads in the on-site testing, simulators for the spacecraft data handling and power systems were provided to each payload team. This approach resulted in delivery of payload models that were well adapted to the spacecraft interfaces and consequently could be integrated and tested on spacecraft level without creating major schedule problems.

Once onboard and tested the payloads participated in the spacecraft level system test programme. Specific mission scenarios were designed to simulate the payload combined operations during EP motor monitoring and moon observations. In the late test stages control was handed over to ESOC who tested all functions using the actual flight control procedures.

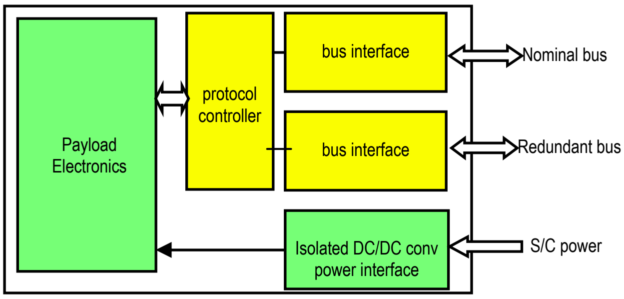
The seven payloads onboard the SMART-1 spacecraft are designed for a variety of scientific observations. Two payloads, EPDP and SPEDE, monitor the performance and possible side effects of the electric propulsion such as surface erosion, dust contamination, and S/C charging. The KaTE X/Ka band transponder provides very accurate ranging/doppler measurements. These data are used to determine the EP motor thrust performance by measuring the change in spacecraft speed and also to perform investigations on the moon libration. SIR and D-CIXS, spectrometers in the near-infrared and X-ray respectively, take part in a mineralogical mapping of the moon. The AMIE CCD camera provides images throughout the mission and is used in conjunction with SIR and D-CIXS for moon surface mapping. XSM monitors the solar activity and assists in calibrating the data from D-CIXS.

All instruments except KATE and XSM are mounted on a spacecraft panel which will be kept in shadow during the moon observations.

## Interfacing payloads to the spacecraft

Payloads interface the spacecraft support systems in mechanical, electrical, thermal, and data handling areas. In order to minimize problems during spacecraft integration and test, a sure schedule threat, a number of decisions and actions were taken during the early project phase. The Experiment Interface Document, issued soon after the project start, provided guidelines to the experimenter groups in terms of detailed description of the support system's interfaces, test requirements, spacecraft constraints, PA and documentation requirements and delivery schedule. In addition, an early requirement was put on all payload groups to issue separate interface documents on the electrical, data handling, mechanical and thermal interfaces. These actions helped all parties involved in a common understanding of the concept and misunderstandings could be clarified and corrected at an early stage of the project.

The electrical interfaces, in particular the data bus interface was regarded as a particularly critical part. The SMART-1 spacecraft uses a CAN-type data bus for all communication to and from units. In order to ensure the functionality of this payload interface, Swedish Space Corporation provided the detailed CAN-interface schematic to each team as well as all the components including a programmed FPGA chip containing the data transfer protocol. A bus interface simulator providing both correct electrical interface and possibility of simulating combined bus traffic was also developed and handed over to the teams. Thus all payloads were equipped with identical bus interfaces and could be tested on-site in an environment simulating the spacecraft data traffic. In order to further simplify system testing, a dedicated payload bus, separated from the system bus, was included in the spacecraft design. A similar approach was also used for the power system. The spacecraft uses separate solid state power converters (SSPC) with current level sensors allowing limited in-rush and steady state currents to provide power to each unit. Spacecraft identical SSPC's were delivered to all teams to ensure compatibility with the spacecraft power system. All these precautions proved very successful. Upon delivery payload units could be connected to the bus and power interfaces without major problems.




The data handling interface specified the telemetry and telecommand protocols, format of bus service messages, bus rate and spacecraft memory allocation. ESA's Telemetry/Telecommand Packet Standard and Packet Utilisation Standard (PUS) are being used for the spacecraft-ground communication. Some PUS simplifications were applied for the payload packets. The telemetry PUS packets are formatted in the payload controllers. Before bus transfer to the spacecraft memory, the protocol controller subdivides each packet into a number of 8 byte messages that are being sent with a fixed interval time. The receiving end restores the message before storage in the spacecraft memory. Since the payloads produce different amount of data per observation session, the message interval time is individually set to cope with the required data rate. Telecommands are handled in a similar way. The bus simulator provided a useful tool for testing all modes of the bus traffic. Mass memory space was allocated to each payload corresponding to the calculated amount of data being produced during the 4 days period in-between data downloads. Since the payload data volumes vary during the mission, the memory allocation will be reprogrammed during the flight. The table shows bus rate and the dynamic memory allocation during two of the mission phases. 375 Mbytes of spacecraft memory is used for storage of payload data. The EP motor monitoring payloads are prioritised in the early mission phases whereas moon observation payloads are given more memory during the lunar phase.

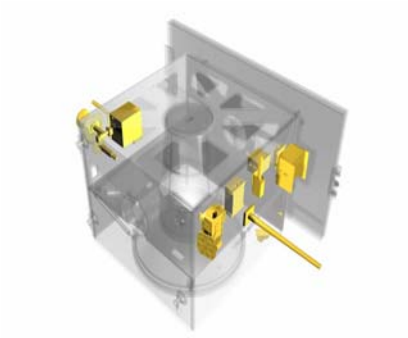
**Bus rate and memory budget**

| | Rate [kbit/s] | Mem [%] LEOP | Mem [%] Lunar |
|---|---|---|---|
| AMIE | 70 | 10 | 50 |
| SIR | 45 | 10 | 20 |
| D-CIXS | 7.5 | 15 | 18 |
| KATE | 4 | 5 | 2 |
| EPDP | 1 | 30 | 0 |
| SPEDE | 0.24 | 30 | 10 |

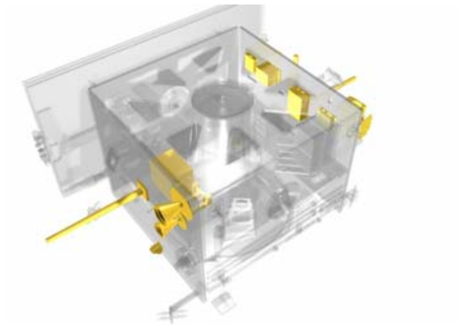
The thermal analysis specified expected interface temperatures in all modes of operation based on the thermal models delivered from the payloads. Most payloads are thermally coupled to the spacecraft panels but specific requirements on low operational temperatures for D-CIXS, SIR and XSM forced these units to decouple from the panels. A number of iterations with modifications in the payload's thermal design, in particular for the payloads being thermally decoupled from the spacecraft, were necessary to obtain satisfactory results.

Each payload unit is equipped with redundant spacecraft thermistors, SIR and D-CIXS also with spacecraft heaters to prevent off-limit low temperatures during eclipses. Payload temperatures are constantly monitored by the spacecraft software, switching off payloads being too hot and activating heaters in the cold cases.

Mechanical interfaces defined the physical properties of the payload units i.e. mass, size, CoG, alignment requirements etc. Accurate alignment of SIR and AMIE payloads were performed in order to facilitate common lunar observations allowing correlation of SIR spectra with optical images of the spotted area. Payload locations had to be carefully selected in order to avoid blocking of the field of view between payload and support system units. Thermal constraints forced all payloads but XSM and KaTE to be located on a panel that is kept in shadow during the moon observations.



| MASS BUDGET | |
|---|---|
| Payload | Mass [kg] |
| AMIE | 1.9 |
| SIR | 2.1 |
| D-CIXS | 5.2 |
| XSM | 0.2 |
| SPEDE | 0.7 |
| KATE | 6.1 |
| EPDP | 2.4 |
| **TOTAL** | **18.6** |



SIR, EPDP, AMIE, SPEDE and D-CIXS

XSM and KATE

**Test phase**

Prior to start of the system tests on spacecraft level, all payloads delivered engineering models of the controller electronics that were bench-tested at Swedish Space Corporation. These early tests focused on the electrical and data handling interfaces and used a mix of simulators and breadboard units on the spacecraft side. Test results went into the design of the flight models. Similar tests were conducted on the flight models, now using more mature spacecraft units, before delivery to the spacecraft. After checkout of mass and footprint, the payloads were integrated on the spacecraft and the power/data interfaces were tested first time in the spacecraft environment. Again the precautions taken earlier in terms of thorough interface control and testing paid off and no major obstacles were encountered. Note on the picture below how the payload panels are mounted on hinges providing easy access to the panel backsides and to the spacecraft interior.

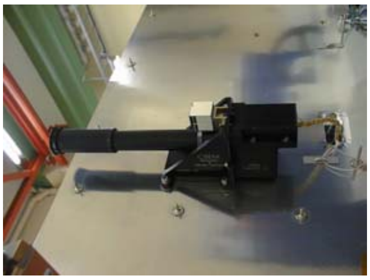
After this initial phase the payloads participated in all major spacecraft system tests. Special test scenarios were developed to allow realistic combined runs during the electrical performance tests, thermal tests and EP motor test. The payloads dedicated to moon observations were operated in a joint session simulating a lunar south-pole pass-by. EP motor monitoring payloads performed combined operations while the spacecraft was in simulated EP-mode and in particular during the EP-motor vacuum test. In order to provide relevant science data during the main system tests most payload detectors were attached to stimulators. After each major test phase an abbreviated functional test was run on the payloads to verify maintained correct function. Verification of the test data was performed both in real-time and by sending data to the payload groups. Expected house-keeping data results were defined in the test procedures and could be assessed by the test operators while instrument data from cameras and spectrographs were put on a payload team accessible ftp server immediately after test completion. This allowed the teams to evaluate the test data within short time, thus providing fast feed-back to the test site. Test data were complemented by log records as needed to allow for trouble-shooting. Team presence at the test site was requested only to handle exceptional debugging sessions.

During the final test stages, flight control procedures on all observation sequences were generated based on inputs from the payload teams. Control was handed over to the ESOC spacecraft control centre who tested all procedures running the spacecraft remote, generating commands and reading back telemetry. A final functional test prior to launch site delivery, also repeated before integration on the launcher, completed the test phase.

| ELECTRICAL TESTS SUMMARY | | | | |
|---|---|---|---|---|
| TEST | DATE | LEVEL | SETUP | COMMENT |
| Benchtest 1 | Q2 - 01 | Unit EM | BB Spacecraft Controller<br>Power simulators<br>Test S/W | Initial checkout of electrical and data handling interfaces. Only payloads controllers participated.<br>Commands from bus simulator. |
| Benchtest 2 | Q1 - 02 | Unit FM | EM System Unit<br>EM Power Unit<br>Test S/W | Complete checkout of electrical, data handling and mechanical interfaces. First issue of Command data base. Command scripts were used |
| S/C integration | Q3 - 02 | Spacecraft | QM System Unit<br>QM Power Unit<br>Early version of OBSW | Integration to spacecraft Checkout of electrical and mechanical interfaces. Functional test including detector assemblies. |
| System test 1 | Q3 - 02 | Spacecraft | Complete spacecraft | Operational scenarios for combined payload operations. Detectors connected to stimulators |
| EMC | Q4 - 02 | Spacecraft | Complete spacecraft | Test on radiated and conducted emission/susceptibility. |
| Solar sim test | Q4 - 02 | Spacecraft | Complete spacecraft | Thermal balance, thermal hot/cold cases. |
| EP motor test | Q4 - 02 | Spacecraft | Complete spacecraft | EP-monitoring and interference test of EP monitoring payloads. |
| System test 2 | Q1 - 03 | Spacecraft | Complete spacecraft<br>Flight S/W | Operational scenarios for combined payload operations. Detectors connected to stimulators. |
| ESOC test | Q2 - 03 | Spacecraft | Complete spacecraft<br>Flight S/W | Test of all payload flight procedures and operational scenarios. |
| Final tests | Q2 - 03 | Spacecraft | Complete spacecraft<br>Flight S/W | Abbreviated functional tests performed prior to shipment and at the launch site. |

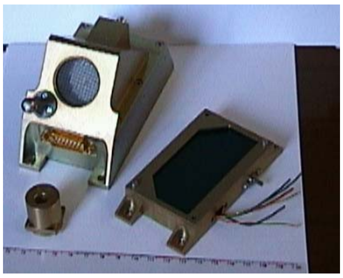
**The payloads**

**AMIE** Asteroid-Moon Imager is a miniaturized CCD camera developed by CSEM / Switzerland. The AMIE camera head uses a CCD-chip with image size 1024 by 1024 pixels. A composite filter in the 450-950 nm range for mineralogical observations covers part of the CCD area. Another area, intended for a laser-link experiment, is covered by a pass band filter centred at the laser wavelength. The optics constitutes a telephoto lens with a 5.3 deg field of view corresponding to 30 m / pixel at the planned perilune distance of 300 km. The camera head is supported by an electronic unit housing image processor, power and interface to the spacecraft data bus. AMIE will study moon's morphology, topography and surface texture, support the moon mineralogical survey performed by the spectrometers SIR and D-CIXS and provide pictures for public outreach.



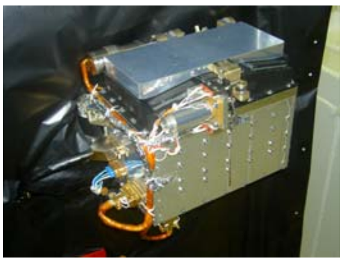
The laser-link experiment will test optical communication from ground to the spacecraft. ESA's optical ground station, located on the Canary Island, will be used to point a laser beam to AMIE's optics. Study of the atmospherical effects on the beam with the spacecraft at various Earth distance will be tested.

**EPDP**, The Electric Propulsion Diagnostic Package from Laben, Italy is designed to monitor the possible side-effect that the electric propulsion plasma may have on the spacecraft in terms of erosion/dust deposits and spacecraft charging. Ground measurements of such effects in vacuum chambers can not fully represent space conditions. Actual spaceflight data are therefore of prime importance for the design of future EP-powered missions.



The payload constitutes an electronic unit and a number of sensors positioned on the outer surfaces of the spacecraft. The Plasma probe assembly, located close to the EP motor will monitor the backflow of electrons. A Langmuir probe measures the plasma potential and a Retarding Potential Analyser will measure the ion energy and current density distribution. A solar cell and a Quartz-Crystal Micro-balance will both measure the amount of spurious material deposition.

**D-CIXS**, Demonstration of a Compact X-ray Spectrometer, from Rutherford Appleton Laboratory, United Kingdom. This payload will observe the Earth X-ray aurora and magnetotail during the Earth escape phase, perform astronomical observations, mainly focused on galactic sources, during the cruise phase and in moon orbit map the lunar surface composition by measuring secondary X-ray emissions thus supplementing AMIE and SIR observations.

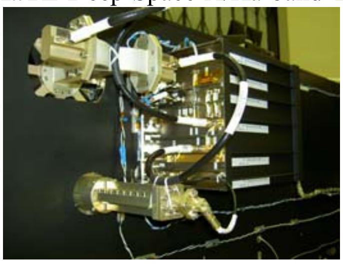


The detector head comprises a matrix of 24 X-ray sensitive Swept Charge Devices, collimators defining field of view and filters blocking background

UV and solar wind radiation. The 12 by 8 degrees field of view yields 50 km spatial resolution at 300 km perilune. A shield protects the instrument from the radiation belts during the early mission phase. The control electronics handle both D-CIXS and XSM instruments.

**XSM**, the X-ray Solar Monitor, developed by Metorex, Finland in conjunction with Helsinki University, Finland uses a –ray sensitive diode sensor mounted on a Peltier cooler. This instrument will monitor solar flares and serves also as a calibration tool for D-CIXS in measuring the solar X-rays. Spectral range is 1-20 keV. A shutter protects the sensor while passing through the radiation belts.

**KaTE** Deep Space X/Ka-band Telemetry and Telecommand Experiment, The experiment is being managed by ESTEC in conjunction with Astrium, Germany.



The KaTE experiment will validate new digital communications technology with very sensitive receivers onboard the spacecraft acting as a precursor for future deep space missions. New data encoding techniques enhancing the link performance will also be tested.

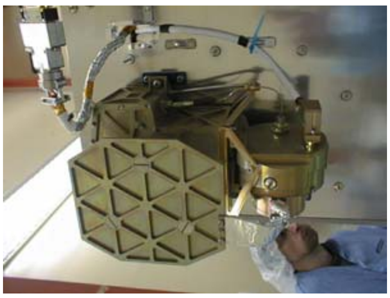
In addition, KaTE will also support RSIS, Radio Science Investigation with SMART-1. This experiment uses the very high resolution Doppler shift capabilities of the Ka/X-band transceiver to accurately track the spacecraft and thus determine the performance of the electric propulsion. The same system will also be used together with information from AMIE and the spacecraft star tracker to study the changes in the Moon's rotational state, commonly known as libration.

Ground facilities will use ESA's 35 m antenna in Perth as well as a small mobile X/Ka antenna asembly located at ESTEC.

The RF hardware constitutes Ka and X band horn antennas, a X-band transponder and a Ka band transmitter. Two data bus interfaces are used, one for command and housekeeping telemetry, the other for downlink of data from the spacecraft mass memory via the Ka-band transmitter.

**SPEDE** Spacecraft Potential, Electron and Dust Experiment from Finnish Meteorological Institute (FMI), Finland. This payload consists of two electric sensors mounted at the ends of 60 cm booms located on the opposite sides of the spacecraft. The sensors, controlled from an electronic unit, can be configured either as Langmuir or Electric Field probes. SPEDE will be used in conjunction with EPDP to monitor the EP motor plasma effects on the spacecraft. In addition the experiment will perform mapping of Earth and Moon plasma density and solar winds coupling to the Moon.

**SIR** SMART-1 Infrared Spectrometer from Max Planck Institute für Aeronomie, Germany. SIR is a miniaturised near-infrared spectrometer for lunar surface mineralogy studies. The instrument uses a 256 diode array detector operating in the 0.9-2.5 nm wavelength range. The detector is passively cooled by a radiator. Front-end optics constitutes a mirror assembly with 300 m spatial resolution at 300 km perilune distance. An electronic unit provides power, signal processing and interface to the spacecraft data bus. SIR will operate in conjunction with AMIE and D-CIXS to perform a mineralogical survey of the lunar surface. Since the spectral range also covers some spectral features of ices and frosts, SIR may be able to detect the presence of water, carbon dioxide and carbon monoxide on the lunar surface.



## Early results

Pre-commissioning of all payloads were successfully performed within a week after the launch. These early results constituted mainly housekeeping checkouts and test spectra of payloads SIR, D-CIXS and XSM. KaTE has performed an initial checkout focusing on housekeeping parameters, first communication test is scheduled in a couple of weeks. AMIE has performed diagnostic test including some test pictures. The EP monitoring payloads EPDP and SPEDE have performed final tests and calibrations and are now monitoring the EP-motor on a routine basis. D-CIXS and XSM have currently the detectors covered with radiation protective shields which will not open until the spacecraft has left the radiation belts in about 2 months time.

## Conclusion

In spite of the strict constraints on mass, power and size, it has been possible to house seven payloads on board the small SMART-1 spacecraft by utilising state-of-the-art concepts and methods of miniaturisation designed by devoted payload teams. Close interface control, use of simulators and early test start resulted in a smooth integration onto the spacecraft. With less than 19 kg and a typical combined operational power consumption of 15W, a wide variety of experiments will be performed. The scientific results obtained will undoubtedly increase the knowledge of Moon mineralogy, possibly giving more insights in the origin of our nearest neighbour in space. In addition valuable information will be obtained on the impact of electric propulsion on spacecrafts for the benefit of future missions.