SMART-1: EUROPE'S LUNAR MISSION PAVING THE WAY FOR NEW COST EFFECTIVE GROUND OPERATIONS (RCSGSO)

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ABSTRACT/RESUME

Smart-1 is the first of a series of ESA Small Missions for Advance Research and Technology where elements of the platform and the payload technology have been conceived as a demonstration for future cornerstone missions and an early opportunity for science.
It was launched on 27th of September 2003 and spiraled out over a 14-month period until being captured by the Moon on 15/11/2004, thus successfully achieving the primary objective set to demonstrate Solar Electric Propulsion.

The paper will show the pros and contras in some of the choices made for Smart-1 together with the developments and the solutions implemented to mitigate the problems found during the mission:

- Impact of on-board problems on operations
- Ground Segment automation
- Keeping the mission control team reduced
- The increased importance of the Mission Planning System
- Fast distribution of spacecraft data through internet for anomaly identification and analysis
- Summary of lessons learnt

1. SMART-1 MISSION

The target orbit after reaching the moon was polar with the pericentre close to the south pole between 300 and 450 km, while about 3000 km for the Apocentre. During the transfer phase, before reaching the moon, the spacecraft thrusting profile allowed extended periods for cruise science via the Low Gain Antennas in high rate.
The ion thruster was used to spiral out of the GTO and for all orbit maneuvers including lunar capture and descent.

SMART-1 is a 3-axes stabilised spacecraft consisting of a central cubic box, of approximate 1m dimensions, and two Solar Array (SA) wings. The complete spacecraft weighs 370 Kg at launch. The central structure is designed around a Xenon fuel tank, of capacity 49l, containing 82.5kg Xenon at launch. The power system uses high-efficiency TEC1 ***triple-junction*** cells solar cells of type ***GaInP2/GaAs/Ge***, which are sized to deliver 1850 W Beginning of Life (BOL). Split into two wings, of three panels each, the SAs span 14 meters tip to tip. The SAs are positioned on the spacecraft $^{+}$/-Y panels, and have been designed to be able to rotate. Power is routed over a fully regulated bus, controlled in three domains, by battery discharge regulators, battery charge regulators and Solar Array Shunt Regulators. ***Lithium Ion*** batteries provide power through eclipse phases of the mission, which are sized to support a maximum eclipse length of 2.1 hours (no thrusting). Primary propulsion is performed by the PPS®-1350-G ***Hall Effect Thruster***, which can be gimballed by the EPMEC (Electric Propulsion Mechanism), both to point through the changing spacecraft centre of mass, and to help conserve Hydrazine, in reducing disturbance torques. Attitude control is performed by the Reaction Wheels, with Hydrazine thrusters being used in lower spacecraft modes (e.g. rate reduction at launcher separation), and to de-saturate the Reaction Wheels. Attitude information is obtained through a combination of sun sensors, gyros and star trackers. The data handling subsystem contains cold redundancy, with autonomous Failure Detection Isolation and Recovery (FDIR) software handling any single failures. The main controller runs on ***a 32 bit CPU ERC32 Single Chip***. The Remote Terminal Units (RTUs) are connected to a ***COTS bus*** (CAN) to interface all units. Normal operation can continue in an absence of ground contact for ten days, and the spacecraft can survive in Safe mode for a period of two months or more.

Payload details are detailed in ref 1 G.Racca et al 2002.

Smart-1 is not only a mission for advance research and technology from the perspective of the satellite design, but an opportunity to experiment new ways of conducting ground operations taking advantage of both increased satellite autonomy and ground tools for automation.
The main purpose of Smart-1 was not to be cheap, but to be able to do advance research and space technology demonstrations at lower costs. The concept of lower costs is then relative to the type of mission, the objectives of the mission and the resources required for their achievement it comparison with other missions.

The price of an ESA middle size scientific mission can oscillate between 400-600 M€. The Smart-1 target cost was set to below 100M€.
James R.Wertz (1996) has been taking as a reference to illustrate the cost savings implemented in Smart-1 considering the organisational constraints and the modus operandi in the European Space Agency (ESA).

The main two ESA centers involved in operations are ESTEC and ESOC. The European Space Research and Technology Centre (ESTEC) is located in the Netherlands. This centre is the design hub for most ESA spacecraft and technology developments. The European Space Operations Centre (ESOC) in Germany is a multi-mission facility in charge of most ESA spacecraft operations.
ESOC holds the development responsibilities for all ESA ground stations, the associated communications networks, mission analysis and all flight dynamics operational services. ESOC develops mission control systems based on its Spacecraft Operations Control System known as "SCOS 2000", used to monitor and control spacecraft in several control centres around the world.

The approach followed by ESA for operations is ***a service oriented relation***, The Project management located at ESTEC acts as a customer with a contract signed with ESOC for operations. ESOC is seen then as another sub-contractor in the Project development process and has to report in a similar way as such in terms of cost and resources transparency.

2. METHODS TO SAVE COSTS

2.1. Short Development

The development of the platform was targeted as 3 years from start of development to launch. The Payload was composed of two groups, the first considered as part of the technology demonstration and the second scientific (1 G.Racca et al 2002). All were selected with announcements of opportunities during 1998. The selection criteria were based on technology novelty, the wish to bring maturity to some studies and offer flight opportunity. None of them had been flown before or were fully ready at the time of the kick off.

The initial schedule was as follows:

- Phase C/D kick-off October 1999
- Critical Design Review August 2001
- System Integration Ready February 2002
- Environmental Test campaign October –December 2002
- Flight Acceptance Review January 2003
- Launch readiness mid-March 2003
- Cruise phase (Earth –Moon) 14 –18 months
- Moon operations 6 months

The advantage of a short schedule is that the engineering team could concentrate their effort in ***focused objectives,*** addressing the real issues and their solutions on the spot. The design of the Smart-1 system units took full advantage of the experiences gained in the previous programmes with ***rapid prototyping*** of individual circuit boards, ***high modularity*** and strong focus on ***testability.***

2.2. Spacecraft Development Team

The ESA approach followed for Smart-1 was to deploy a reduced core team of experts at ESTEC controlling and supervising industry, holding periodic meetings at prime contractor premises, the Swedish Space Corporation (SSC) and arranging overall reviews at ESTEC with participation of other ESA experts.

The team co-location concept was not possible due to the intrinsic international and intercultural nature of ESA. Instead, it is seeing advantageous to exploit the new intercommunications techniques as the ones currently used at ESA for concurrent engineering (5 M. Bandecchi 2000). It permits specific and/or periodic communication sessions among the different located teams requiring high level of interaction and time synchronization. As a complement, the ESA Human Resources department is increasingly doing use of "expert communicators or facilitators" that acts as ***catalysers*** gathering the teams, facilitating the dialogue and removing frictions. This kind of approach contributes to get an effective true project atmosphere getting rid of the "us against them" mentality and helping all different team members to feel that they are part of a single team working together for success.

2.3. Mission System Engineering

The core team of the prime contractor the Swedish Space Corporation was composed of about 15 persons most Swedish citizens collocated in the main plant in Solna near Stockholm. The sub-contractors came from many different countries around Europe.

There was a direct interface between the operations team and the engineering industry team to solve issues, get information and share data.

The ***data sharing*** was as for all ESA missions using a central repository accessible via Internet at ESTEC (Data Management System -DMS).

Smart-1 managed ***to exchange anomalies information***. The ESOC anomaly report database was weekly incorporated in the general SSC Non Conformance Repository (NCR) database. The responses were weekly reported back to ESOC and fed back into the ESOC anomaly database. This permitted all parts to know what kinds of problems were happening in the other development areas and their progress.

Call for ***short reviews and workshops*** were arranged by any of the teams helping to efficiently resolve problems and motivate the engineers involved.

2.4. Navigation

This mission analysis effort was comparable to a cornerstone mission. The main reasons being:

- The long exposure to radiation, its effect in the efficiency of the Solar panels and its impact in the Electric Propulsion.
- The effect of the gravity field and perturbations.
- The different transfer orbit strategy required for any launch date.
- Continues re-calculation and production of products.

The assumption done for the mission analysis was to have a continuous thrust after 10 revolutions on GTO. This was required to reduce the time the spacecraft was exposed to the radiation belts and its detrimental effect in the efficiency of the solar panels and ultimately in the available power for the Electric Propulsion.

The transfer strategy for Smart-1 turned out to be extremely complex. The strategy implemented combined multi-revolution in low thrusts optimisation including coast arcs, with “resonance hoping” and gravity assists of different types (e.g. singular arcs).

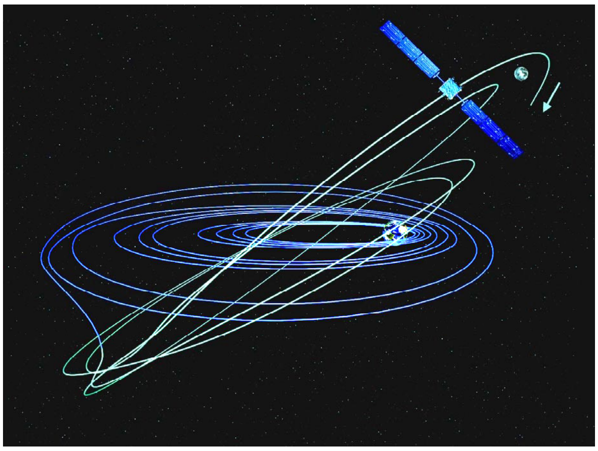


Figure 1 Simplified view of the Lunar transfer

The Lunar capture trajectory and subsequent transfer to the operational orbit around the Moon was computed in backward integration. The original target was an operational orbit with 300 Km periselenium and 10000 Km of aposelenium height, being the right ascension of the ascending node, the arrival epoch and the Moon equator free parameters.

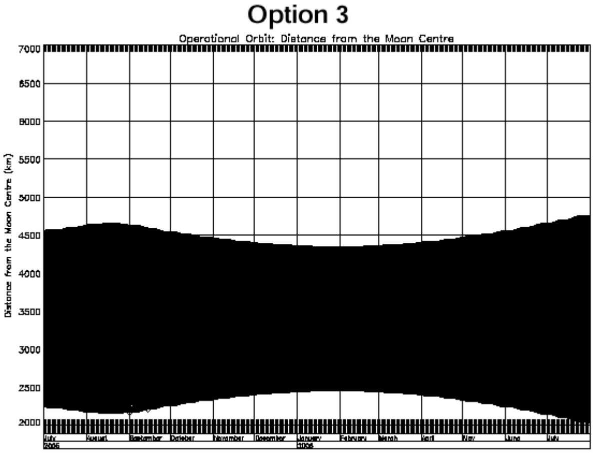


Figure 2 Moon distance in the mission extension

The good performance of the EP permitted a re-design of the orbit reducing the apolune to give an orbit of 300x3000 Km. This had to be further tuned later when the Xenon become marginal for a new mission extension of one year. The final option is depending on the use of gauging techniques with the last Xenon left in the tank. The theoretical target is indicated in *Figure 2* planned to be implemented in August September 2005.

3. SYSTEM DESIGN FEATURES

3.1. Spacecraft Design

What is not done on-board needs to be done on the ground. The goal is not only to get a good spacecraft design, but ***designed for operability***.
Problems overcome by ground procedures are normally translated in more work.

Two important aspects of the Smart-1design were its ***robustness*** and ***safe mode*** design.
The experience so far indicates that the hardware units are very robust. The occasions were the redundant units have been used were caused in most cases by software failures.

The second aspect of Smart-1 robustness is based on redundancy:
All basic units related to spacecraft safety are provided with cold redundancy

- TMTC units and receivers are hot redundant
- Buses are redundant for the Platform and Payload
- Two main controllers including memory are provided in ***cold*** redundancy.
- Electric Propulsion and related units with limited redundancy
- Payload units have no redundancy.

The spacecraft is only designed to be single-point failure tolerant against mission loss.

The main controller patches are however not persistent at power down. ***This concept can only work if no basic failure is in the original software before launch***. This happened in Smart-1 with the Error Detection And Correction (EDAC) algorithm and caused continues controller reset at every pass through the radiation belts during the first revolutions after launch. Operations were possible but required operations stress to avoid at any cost a cold reset or switch-over of controllers.

Operation stress means highly demanding additional support (extended shifts outside normal working hours, work under time pressure, etc) for the mission control team and ground stations facilities.

The ***Safe Mode*** is the base mode for all other modes and the recovery mode for emergency situations. Its purpose is to ensure power generation and ground communication using a minimum of on-board resources. The omni-directional antenna (LGA, 100 ° × 360 ° beam width) is used for communications. The Bapta Home function maximizes solar array power whenever in sunlight while the spacecraft rotates slowly (0.1 °/sec or 1 revolution per hour) around the sun vector. Autonomous momentum management unloads the reaction wheels. During eclipse body rate control is automatically performed

This mode was very well designed and tested on ground before the launch. It permitted a fast recovery during operations. and helped to reduce the operations stress when it later occurred in the transfer phase.

3.1.1. The On-board Software

The OBSW for SMART-1 is derived from the software developed by Spacebel for the Proba mission. The design is based on a layering concept with mission dependent application software. The application-specific software was developed by SSC: AOC Core, Thermal Core, FDIR Core and Power Core.

The on-board software was implemented using the ObjecTime development environment that supports automatic code generation as well as entry of hand-written source code. The platform controller is based on the real time the operating system VxWorks.

The concept permitted that ESOC Flight Dynamics integrated all these routines in the ground validation software thus permitting an optimum modelisation of the flying software during the mission (10 Livio Tucci et al 2004).

Most commands activities in Smart-1 (>98%) are implemented through the on-board Time Tag Queue (TTQ). This provides the capability to command on-board applications using up to 10.000 telecommands pre-loaded on board and released at their due time.

3.1.2. Flight Dynamics software

For Smart-1 the S/C manufacturer (Swedish Space Corporation, SSC) initially provided FD with their AOCMS and S/C dynamics emulator, which had the following characteristics: a) coded in Matlab/Simulink on a PC machine under Windows Operating System (OS), b)contains the AOCMS core of the real flying onboard s/w and c) developed by the manufacturer to internally test S/C AOCMS algorithms.

The SSC s/w was enhanced (10 Livio Tucci et al 2004), modified and ported (PC/Windows -> Solaris/Unix) in order to finally obtain a stand-alone C-executable program, fully integrated as an operational tool into the FD system on Solaris/Unix environment.

This new approach has allowed ESOC Flight Dynamics to ***drastically shorten s/w development time*** and to achieve a very high representative model of the flight system since the emulator incorporates the real AOCMS s/w of the S/C.

3.1.3. Autonomy

The key design elements of the Smart-1 were:

- Due to the long intervals between ground contacts (up to 10 days), the spacecraft was required to have the functionality to autonomously identify and recover from both hardware and software anomalies without affecting the ongoing mission activities. For certain anomalies the spacecraft will configure itself into survival configuration and await further instructions from ground.
- The overall SMART-1 spacecraft is designed for autonomy such that it can loose ground contact at any time and still survive for at least 2 months in a survival configuration.

The Failure Detection, Isolation and Recovery (FDIR) function is implemented on a strictly hierarchical basis, aiming at restoring a function with as local means and as little operational impact as practically possible. Failures related to units having redundancy or considered critical for survival are handled by local redundancy reconfiguration. Failures observable at subsystem and system level are either handled by means of multi-unit reconfigurations or operational mode changes respecting the control hierarchy (2 Elfving,A et al 2000).

3.2. Ground Segment Design

The main drivers of the Smart-1 ground segment development were:

- All facilities established for SMART-1 support will be based on extensions of existing ground segment infrastructure, tailored to meet the requirements of the SMART-1 mission. To minimise cost, maximum use of existing facilities and infrastructure shall be made with a minimum of modifications.

- The number of ground stations, the duration of the station passes, the choice of specific antennae shall be chosen for the SMART-1 mission to minimise the overall cost of investment and operations.
- All monitoring and control activities shall be optimised to cope with non-real time operations (nominally 1 pass every three/four days, engineering support only during working days

3.2.1. Re-using Facilities

Smart-1 has benefited from ESA general infrastructure and other projects developments:

- Generic NCTRS (Telemetry, Telecommand and Ranging gateway with the ground stations) validated by Integral and Rosetta.
- Generic Data Distribution System (DDS) derived from Rosetta.
- Space Link Extended Service function (SLE) validated by Integral and Rosetta.
- Ground Stations upgrades validated by Integral.
- Ground Segment Interface Unit (GSIU) Smart-1 specific based on generic Network Data Interface Unit (NDIU)
- FD systems and interfaces developed by Rosetta and Mars Express and partially re-used by Smart-1.
- S1- Mission Control Systems (MCS) based on ESOC SCOS 2000
- S1 Mission Planning System was Smart-1 mission specific.
- The Smart-1 simulator developed and procured by SSC.

The ground station utilisation was planned on the basis of 1 pass lasting 8 hours every 4 days.

The Dedicated control Room at ESOC is composed of 5 workstations connected to a redundant server configuration via 2 redundant gateways called “NCTRS” that permit the connection to the ESA ground network.

3.2.2. Adhering to Standards

The spacecraft to ground segment interface is based on the CCSDS packet telemetry and telecommand standard with two different bit rates for the downlink, 65 $Kbps^{-1}$ over a Medium Gain Antenna (MGA) and 2 $Kbps^{-1}$ through the Low Gain Antenna (LGA). Telecommand uplink is executed at 2 $Kbps^{-1}$. The on board data handling uses the ESA Packet Utilisation Standard (PUS) for the different services.

Originally Smart-1 was planning to use three stations during the LEOP: Kourou (French Guyana) Villafranca (Spain) and Perth (Western) Australia. Maspalomas (Canary Islands) was planned to be the primary station for the transfer and moon phases. ***The use of standards permitted a very cost effective increase of the ground stations*** by adding the Transportable (5.5 m dish) and Vil-1 (15 m dish) in Villafranca-Spain and the New Norcia station (35 m dish) in Western Australia.

The standards should not be violated unless fully justified. The only occasions the CCSDS were not followed: removal of command and telemetry data field headers from the Payload data and Frame Error Control Field not implemented, had consequences in the time stamp data of the payload and in bad telemetry rejections due to the Reed Solomon problem explained later.

3.2.3. System Validation Tests and Flight Control Procedures.

System Validation Test (SVT) is the main mechanism to validate the interfaces and functions of the Mission Operations Centre (MOC) and the spacecraft. This includes the verification of the satellite behaviour and associated control procedures, in particular Contingency Recovery Procedures (CRP) in a realistic flight configuration and the validation of the TM/TC database.

The tight schedule and the cost pressure of Smart-1 forced the ***interleaving of spacecraft tests with system validation tests with the MOC*** at ESOC. This concept saved costs of the spacecraft engineering team but caused a waste of time to the operations team trying to perform an SVT when the corresponding spacecraft tests had not been finished with success. The debugging of the spacecraft software problems had continuous changes in the planning and deviated the attention of the operations team.

The production of the Flight Operation Plan (FOP) was linked to the delivery of industry procedures and the Spacecraft User Manual (SUM). Their late availability was compensated by additional effort in the operations team that needed to help in the re-iterations and fine-tuning of the procedures.

Seven engineers developed the Smart-1 FOP in approximately one year. The first official issue 1.0 was released 0n 19/12/02, less than a year for launch (March 2003). The failure of the Ariane 5 in December 2002 delayed the launch and permitted two additional SVT in February and April/May and a few updates to the FOP before the final launch on 27th September 2003 following the simulations campaign. The organisation of a FOP review just before launch was a good decision in spite of the extra effort.

It is not an easy task to meet the right number of procedures before launch, and even more difficult to find the right balance between nominal and contingency procedures.

Table 1 Flight Operation Procedures

Mission	Nominal	Contingency	Payload
Smart-1	**452**	**129**	**289**
Rosetta	**879**	**155**	**422**
Mars Express	**742**	**289**	**344**
Envisat	**1093**	**905**	**654**

The development of procedures is not only a function of the on-board autonomy, but also the size of the team and the preparation time.

The number of contingency procedures that have been actually used during the Smart-1mission is **30%**.

3.2.4. Operations Concept Design

The original operations concept was as follows:

- Continuous thrust during the first three months of the mission to get as soon as possible out of the radiation belts (perilune height >20000 km). No Payload operations apart from Electric Propulsion related instruments (EPDP and SPEDE).
- First month of transfer phase dedicated to Payload commissioning.
- Sporadic Science activities until Moon capture.
- Moon phase lasting 6 months with 12 hours orbit. Two passes a week during normal working hours lasting 8 hours to uplink commands and download housekeeping and payload data.

As part of the ESA strategy to save costs on the spacecraft and on ground operations, several of the last missions have been ***sharing the platform design***. This has been the case of XMM and Integral and also the last ESA interplanetary missions: Rosetta, Mars Express and Venus Express (11 Elsa Montagnon 2005).
This approach has many advantages for operations; in particular it allows a very efficient ***re-use of the operations expertise and the ground facilities***. A new platform like Smart-1 requires new expertise that cannot be shared in the critical phases (launch, anomalies, support peaks) and specific ground segment development. This should always be taken into account in the early operations cost estimations.

3.3. Spacecraft Performance

The spacecraft performance is the main asset for success and cost savings. The methods for cost saving and the system design features determine how expensive and efficient the mission will be.

The anomalies can be due to ***operational errors, design failures*** or ***a negative impact of the environment***. They impede cost savings in operations and often lead to the opposite. Frequent anomalies require availability of ***expertise that cannot be released***.

The ***trade-off between on board autonomy and software reliability*** was a real issue in Smart-1.

3.4. Actual Operations and Anomalies

During the first 3 months of the mission by the end of 2003, the team was confronted with operational challenges of varying degrees, further aggravated by the strongest solar flares occurred in 40 years while the spacecraft was in continues thrust spiraling out of the radiations belts.

The first and most critical problem was detailed in section 3.1 above after the first revolution. The failure in the EDAC algorithm in the original software (non persistent patch) originated operations stress. This lasted until the spacecraft was out of the effect of the radiation belts in January 2004.
The anomalies later were a combination of ***environmental problems*** (high radiation doses, especially in the start trackers) and ***software bugs*** that required fine-tuning of several subsystems.

The Reed Solomon encoding occasionally becomes corrupted after switching data rates; this on-board problem cannot be repaired from ground and is being overcome by procedures and changes on ground.

The Danish Technical University (DTU) developed the second-generation of star trackers being first flown in the Proba mission. They are lightweight, robust and very sensitive while able to handle blinding at Earth transitions with high degree of autonomy (7 J. de Bruin 2005). During the first months of operation they required software tuning and adjustments for the space environment (8 M.Alonso 2005).

During the initial operation of the ion thrusters the ***Electric Propulsion Optocoupler Single Event Transient*** (OSET) were regularly observed and caused undesired shutdowns of the EP system (6 Milligan etal 2005).

The engine behaviour was characterised in such cases, a patch to the on-board software that allows identification of such false indications and automatically restarts the ion engine was made and implemented on board in the first quarter of 2004.

Control loop fluctuations in the engine were caused by the oscillation between two stable points of operation within the engine. This phenomena also observed during ground testing was avoided by tuning the parameters set of the engine.

It was later observed that the ***thrust performance*** was changing within thrust arcs. They were correlated to anode RMS current discontinuities and this permitted FD the time identification and the optimisation of the orbit determination.

Simultaneous uplink of command stacks and downlink turn out to be complicated. The command verification messages were designed with low priority level causing that some command verifications could not reach the ground system making the on-board queue model unreliable. This forced the split of uplink and downlink activities thus enlarging the requirements on ground contacts.

Later in the transfer phase, the change of the EP thrusting strategy and the elongation of the orbit had impact in the ***thermal behavior of some units that got too hot*** in parts of the orbit, in particular the batteries, the Star Trackers Camera Heads, some components of the Hydrazine subsystem and some Payload units.
The solution adopted was based on Flight Dynamics implementations: changing the spacecraft attitude, compensating the average effect of the Electric Propulsion gimbals on the Sun incidence on the +-Y panels and controlling from ground the reaction wheel off-loading to reduce the internal heat generation.

On 26th September 2004 an unexpected behaviour of the ***Xenon Flow Control A*** (XFC-A) was observed. This was temporary overcome by using XFC-B, with a return later to the A unit.

After the Moon capture on 15th of November 2004, the EP was re-started spiraling down to lower the orbit. The high temperatures working conditions of the Star Trackers were a major concern during the descend phase and required unexpected work during the descend phase.
After a pause in January, the Electric Propulsion was resumed on the 10th of February until Sunday the 27th, when it was definitely switched off at 09:40:16z. A one-hour correction manoeuvre was performed on 12/03/05.

Table 2 Smart-1 EP Bookkeeping

Smart-1 EP bookkeeping	**24/04/2005**
Number of Pulses	526
Date of the last Pulse	12-Mar-05
Accumulated Cathode A time	3511.59
Accumulated Cathode B time	1115.86
EP Hours firing	4627.456
Xenon Mass left (PVT method) kg*	>=6.05
Number of OSETs	33
Number of BB valve activations	361238

A double EDAC error in page 0 on 04/04/05 invalidated the housekeeping stores, part of the Payload stores and the on-board time-tag queue. The sudden appearance of double EDAC errors has not been explained at the moment.
Some of these problems had major operational impact in operations. They required increased shifts and additional ground network support throughout the mission.
Smart-1 did not enjoy the the PUS service 8. This impeded the development of ***On-Board Control Procedures (OBCP)*** as implemented in other ESA missions like Rosetta. The budget and the schedule did not permit their implementation; this would have permitted considerable manning and stress reduction during the first 3 months of the mission.

3.5. Mission Control Team

Smart-1 started sharing the Huygens team at a time when that mission was expected to be low demanding. This approach had to be abandoned once Huygens discovered the doppler problem in the receiver that caused a re-design of the mission. This caused the loss of a key engineer six months before launch.

The first fully dedicated Smart-1 member came in September 1999. The core team was then slowly growing until a few months prior to launch. 6 months before launch, Smart-1 got the temporal support from engineers working for other missions to complement the Launch and Early Operations (LEOP) Team and thus be able to provide support around the clock. This is reflected in the Figure 3 below where it is shown the distribution of the manpower allocated during the mission.
The team was gradually reduced a few weeks after the launch until conforming the routine phase mission control teams: Flight Dynamics Team, Software Support Team and Flight Control Team.

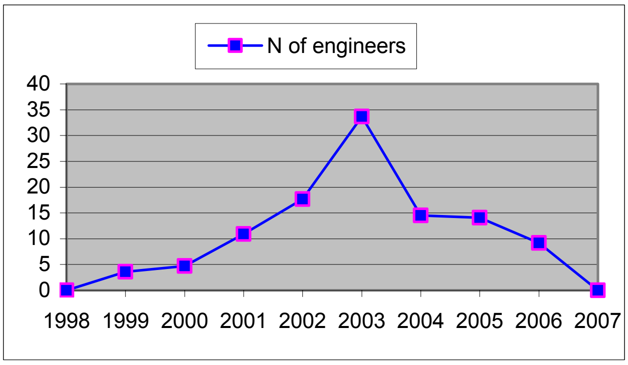


Figure 3 Smart-1 Manpower Evolution

The Flight Dynamics Team is shared with other missions at ESOC. The initial assumption was to use an average of 3 full time people during the cruise and scientific phase. This figure had to be corrected up by about 2 full time people due to the anomalies and the continuous science activities during the transfer phase. The Software Support Team is composed of 2 full time people plus one part time.
The composition of the FCT during the cruise and Moon phase is 7 full time people: 1 Spacecraft Operations Manager, 2 AOCS engineers, 2 EP + Power + Thermal engineers, 1 Data-Handling engineer doing also analyst work, and 1 TT& engineer doing also Payload and Mission planning.
They are in total 14 people fully dedicated to operations. The Science operation team of the STOC at ESTEC was originally planned to be 3 people and was increased to 5 due to the amount of science data being provided by Smart-1 in the lunar orbit.

The following should be noted in comparison with other classical missions:

- Smart-1 has no spacecraft controllers.
- High degree of ground operations automation at the expense of possible data loss.
- The Mission Control team does most trouble-shooting work since the Project and Industry Support are reduced.

The concept of removing spacecraft controllers was originated by the low level of operations planned for the initial and transfer phase until moon arrival. Routine operations are not very stimulating for engineers and this emphasizes the need to find ***a good balance between spacecraft controllers and engineers.***

In the case of Smart-1, operations never got routine. The availability of engineers allowed a rapid reaction against the anomalies, high degree of flexibility and innovation. ***A cross training program*** allowed them to share the subsystem knowledge and run nominal operations.

Smart-1 would have not been possible without a ***high motivation in the Mission Control Team.*** There was room for innovation in spite of being a "small mission" and they have been keen using it through the mission preparation and operations.

Further reduction of the operations teams can only be achieved by ***on-board autonomy and spacecraft performance***.

3.6. Risks

Smart-1 risks have been continuously evolving through the mission. They have been related to anomalies, resources and facilities.
The risks are higher and more numerous than for the classical missions. They require a continuous watch, pragmatic and fast decisions and acceptance. This last has required a new attitude with regard to the high standards at ESOC.
Unmanned operations could lead to slow reaction to anomalies and loss of data. In Smart-1, the first was improved with an automatic alarm system (see 4.1.2), the second was reduced with a software change done on board in Feb 2005.

3.7. Documentation

Considering the budget and manning available, the level of documentation produced in Smart-1 has been at a level of a bigger mission; a similar documentation set during the development phase and a similar number of operations reports during operations.

4. INNOVATIVE APPROACHES TO SAVE COSTS

Saving criteria cannot be applied in all areas with the same degree. The development of on-board autonomy or ground automation requires advancing funding to be compensated later with the reduction in manpower and/or other resources during the operations.

Once the spacecraft is launched, the on-board changes are mostly done by software or redundancy. The modifications on the ground are normally more cost-effective but are often accompanied by on-board changes. This re-enforces the need to be able to modify any software on-board and the possibility to implement new On Board Procedures (OBCP) from ground.

There have been in Smart-1 up to date 9 OBSW versions, 8 STSW patches, 28 versions of the OBSW Tunable and 26 star tracker software changes.

The concept of low cost and re-usage of facilities (see 3.2.1) did not permit Smart-1 to enjoy a budget for any extra development. The actual operations demand and the number of unexpected events strained the team in doing an additional effort in order to reduce the workload. The initiatives taken were compiled in two developments:

- The Smart-1 Mission Planning System (MPS)
- The Mission Utility Support Tool (MUST)

Both were developed in an ***iterative spiral prototyping model making the user part of the development team***. This concept permitted a fast development and delivery, an early user feedback and a product focus on real needs.

The first was developed by RHEA expanding the MOIS system used for the procedures development at ESOC

(12 O.Camino et al 2005). Its maintenance contract was slightly increased in order to cover the additional development.

The second was done with budget from the ESA general studies (GSTP) and close cooperation with OPS-OSC.

4.1.1. SMART-1 Mission Planning

The principle mode of operation is that all routine platform and payload operations are pre-planned and executed according to the Flight Operations Plan (FOP), driven by on-board time tagged commands (max 10.000) that are up-loaded during each ground station pass by the FCT.

The purpose of the Smart-1 MPS is to ensure the overall consistency of these operations request against a variety of operational and spacecraft resource constraints, such as power, storage, downlink capacity, prior to generating the required telecommand stack for uplink via the Mission Control System (MCS).

The MPS had to be developed with a maximum reuse of existing developments and ***off-the-shelf components*** without loosing flexibility and reusability (Figure 4).

The functionality of the MPS goes beyond payload scheduling by integrating operations defined by Flight Dynamics, the Station Scheduling Office and the Flight Control Team into a single, consistent mission plan.

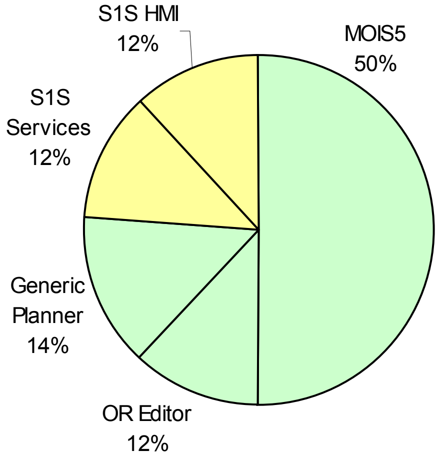


Figure 4 Smart-1 MPS Generic versus specific (yellow)

Today, the MPS together with the Operations Request Editor allows the Flight Control Team to automate routine activities by attaching command sequences to events from various sources. For Smart-1, these consist of: antenna selection, telemetry rate selection, platform telemetry configuration and routing, attitude profile segment execution, sun vectors execution, electric propulsion control, AOCS mode selection, reaction wheel off-loading, EP-OSETmonitoring, eclipse handling, reconfigurations driven by slant range, payload downloads, occultation handling, intelligent re-scheduling of MGA and telemetry routing during ground station handover.

In practical terms the Smart-1 ***MPS generates more than 98% of the commands sent to the spacecraft***.

Aside from the essential task of integrating payload requests with platform operations, the Mission Planning System increases the efficiency of the Flight Control Teams activities in the several important areas:

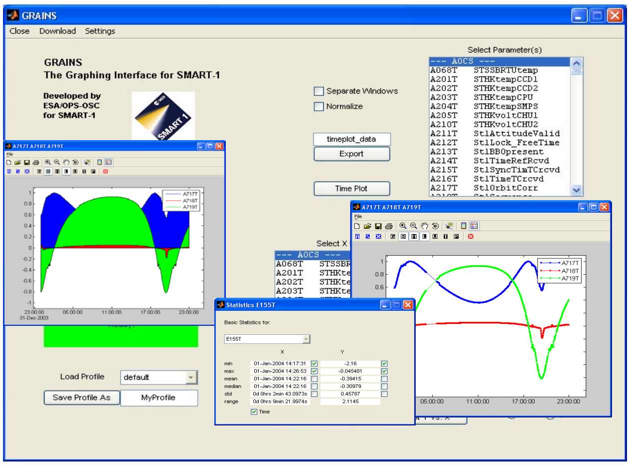
- An electronic interface with the database generated by the ESOC Station Scheduling Office means that all scheduled Smart-1 passes are automatically available to the Mission Planning System.
- A spacecraft database synchronisation through a direct link to the Mission Control System SCOS 2000 database permits any command changes to be automatically picked up by the Mission Planning System.
- Additional operation requests are easily constructed and added to the mission planning system to automate any operations which need to be scheduled relative to an event e.g. perilune/apolune passage, eclipse handling, enabling/disabling monitoring of the Electric Propulsion or performing reaction wheel offloading.

4.1.2. Spacecraft Data Analysis, the Mission Utility Support Tool (MUST)

The amount of anomalies at the early stages of the mission and the need to quickly pass the information to experts disperse around Europe put in evidence that the available tools were not appropriate.

This accelerated the development of an experimental tool co-funded by the General Studies Programme of ESA.

MUST is a collection of tools that supports the exportation, analysis and visualisation of spacecraft telemetry and ancillary mission data via Internet.



```
--- AOCS ---
A068T    STSSBRTUtemp
A201T    STHKtempCCD1
A202T    STHKtempCCD2
A203T    STHKtempCPU
A204T    STHKtempSMPS
A205T    STHKvoltCHU1
A210T    STHKvoltCHU2
A211T    StlAttitudeValid
A212T    StlLock_FreeTime
A213T    StlBBOpresent
A214T    StlTimeRefRcvd
A215T    StlSyncTimTCrcvd
A216T    StlTimeTCrcvd
A217T    StlOrbitCorr
```

	X		Y	
min	01-Jan-2004 14:17:31	☑	-2.16	☑
max	01-Jan-2004 14:26:53	☑	-0.045481	☑
mean	01-Jan-2004 14:22:16	☐	-0.39415	☐
median	01-Jan-2004 14:22:16	☐	-0.30979	☐
std	0d 0hrs 2min 43.0973s	☐	0.45787	☐
range	0d 0hrs 9min 21.9974s		2.1145	

Figure 5 MUST tool visualisation example

The prototype developed for Smart-1 has demonstrated during 2004 the validity of the design and its versatility to be used by other missions. It combines spacecraft telemetry and other ancillary data with web interfaces and alarming system (subset also available to mobile phones). Its implementation has been done securing the integrity of the source data without affecting the performance of the Mission Control Systems at ESOC (MCS).

Any engineer inside and outside ESA can access pseudo-real time all historical spacecraft data from any PC connected to the Internet. The client concept is based on freeware software and permits its distribution without license costs.

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The effort involved ***was 7 man months*** plus the contribution of the Smart-1 Flight Control Team.

5. COST SAVING QUANTIFICATION

The total cost of the Smart-1 mission including the mission extension is 120M€.

Smart-1 cost should not be evaluated just looking to the actual costs but as a function of the ***data return and services provided versus original requirements and spacecraft performance***.

The operations team has been kept in a level of ***14 people during the transfer phase to the moon***. The anomaly handling, additional passes and additional payload operations were not compensated by increasing the team size but by doing ***overtime first and automation later***. Reduction of the overtime was only possible thanks to an improvement in the spacecraft performance and the development of tools (see sec. 8 e)

The MPS has permitted to increase the maximum theoretical daily commanding (including margins) from 1000 to the ***current average of 1903*** (status June 2005) with peaks reaching ***4033*** in February 2005.

The MUST tool ***permits retrieval and analysis of data within 5-10 minutes***. The equivalent extracting the data from SCOS 2000 TDRS would have taken 2-3 hour for the data extraction plus a similar amount for its visualization and analysis. In addition there is no need to transfer this data to the external experts because they can retrieve it themselves (see *Figure* 5).

During the cruise phase, the ***payload operations were decoupled from the ground station coverage***. Science could be done disregarding ground station coverage by scheduling more passes than actually needed.

Operations later in the moon obliged to do short term planning (5 weeks in advance) and synchronize the dumps with the ground station passes.

The actual coverage provided has been ***8 times*** the originally planned. An estimation of the support required to cover the additional passes indicates that from 1 shift/day Smart-1 should have gone to 3 shift/day (*see Table 3).*

Table 3 smart-1 actual support against planned

	Original Plan	**Supported passes**
Passes/month (avg)	**7.5**	**60**
Total hours	**120**	**960**
Shift/day (estim.)	**1**	**3**

All ***payload dumps are currently automated***. Science activities are running around the clock 7 days a week. No operators are needed during the weekend and outside normal working hours.

The overall data return has been higher than planned because payload operations continued throughout the transfer phase instead of sporadic observations.

For the moon phase, it is expected a daily ***data return between 200 and 300% above the original requirements***.

All software developments and improvements done in the Mission Control Systems after launch were covered by the maintenance contract.

5.1. Launch delays

The flight operations team is at the end of the development chain. The core team is augmented for the simulations campaign just a few months before launch. This leaves reduced margin for cost reductions in case of launch delays. They can only be achieved if the preparation and ***deliveries run timely as planned and the people "on loan" can be re-allocated in a very short time***. This requires a combination of factors that cannot be anticipated.

Smart-1 launch was delayed in 2 occasions. Costs savings during the delays could be done but were constrained by the impossibility to re-allocate the teams any further.

5.2. Operations Service Quality

Smart-1 is fully compliance with all quality requirements according to the ESOC certification BS EN ISO 9001:2000 regarding the provision of services related to the operation of spacecraft, including design implementation and operation of ground segments, provision of ground segments and communications systems and flight dynamics.

6. CONCLUSIONS

From the ground operations perspective, Smart-1 has been the test lab to experience cost effective future trends in operations:

1. Spacecraft autonomy with continuous operations
2. Reduced support from Industry and Project after launch
3. Reduced Mission Control Teams (No Spacons)
4. Use of network spare capacity
5. Automation of ground operations

The first could be considered as partially successful. In spite of the high degree of on-board autonomy, the impact of the anomalies and the continuous changing orbit nature of this mission did not permit to reduce the ground station contacts and the ground intervention as planned.

The reduced support from industry and Project will impose a challenge for the future operations, the operations teams will have to be ***smaller with increased skills,*** they will have to able to dominate different subsystems and state of the arts tools to quickly react against anomalies.

The reduction of operations teams was limited due to the high demanding operations and anomalies. They have been compensated on one side by a small increase in team size and overtime. On the other side, increasing the ***services***, the spacecraft ***safety*** and the ***data return.***

Sharing teams of different missions with different operations concepts is very risky. It did not work with Smart-1/Huygens. The early know how of the mission design could not be retained.

The use of ground station spare capacity has been problematic due to the high level of upgrades and maintenance planned at ESOC during 2004 and 2005. The cost savings have been evident for the Project, but there have been ***hidden costs*** in the Network Team. Scheduling Officers and Flight Control Teams.

The ***allocation of a budget for innovative developments of the ground operations is*** highly recommended for future low cost missions. It contributes to motivation saving money and time.

The ***Mission Planning System is a key element*** for ground operations automation. It deserves the right attention and resources from the beginning.

Spacecraft data analysis and visualisation tools accessible via Internet are a MUST for future missions. The experts should be able to get the data quickly, anytime and anywhere in the world.

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