SMART-1, A PRECURSOR TO FUTURE DEEP SPACE AND SOLAR/HELIOSPHERIC MISSIONS

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ABSTRACT

SMART-1 is planned to be the first Small Mission for Advanced Research in Technology of the ESA Scientific Programme Horizons 2000 and will be launched in 2001. The mission is dedicated to the testing of new technologies for preparing future cornerstone missions, using Solar Electrical Propulsion in Deep Space. The mission operational lifetime contains periods for cruise phase until fly-by or rendezvous with planetary objects. The SMART-1 spacecraft will be launched in 2001 either on Ariane AS-AP5 or on Eurockot. The expected launch mass is 300-350 kg. Two launch opportunities were studied: i) Ariane 5 Piggyback in a standard Geostationary Transfer Orbit; ii) Dedicated launcher (e.g. EUROCKOT) into escape trajectory. Two Solar Electric Propulsion types are considered: 1) Stationary Plasma Thrusters (e.g. PPS-1350), provide high thrust (70 mN) and medium specific impulse (1600 s); 2) Ion thrusters (e.g. RIT-10, UK-10), provide low thrust (20 mN) and high specific impulse (3000 s). SMART-1 can be a precursor to future deep space solar/heliospheric missions, both by qualifying the Solar Electric Propulsion System Technology, or by demonstrating new spacecraft and instrument technologies.

Key words: Solar Electrical Propulsion, Moon, Sun, Near-earth objects, Instrumentation, Technologies

1. ESA FUTURE SOLAR MISSIONS STUDIES

Two solar and heliospheric missions were studied by ESA in support to the Horizon 2000 Plus Survey Committee activities. One called STEREO aims at 3D observation from the Sun, from 1 AU solar orbit. A second mission was a Stereoscopic Solar Corona Probe, a mission into a region near the Sun. This includes the use of an electric propulsion system, during the whole mission to approach the Sun in a quasi-spiralling orbit (Raccà 1997). Considering state-of-the-art electric propulsion and subsystems, and a launch mass of 1400 kg with Ariane 5, Racca and Fleck (1995) found that 400 kg could be available to subsystems and instruments for an approach of 14 solar radii. In the Tenerife conference, the recommended mission where ESA could focus was a high latitude orbiting mission at 0.5 AU distance (SPORT), or a near-solar mission, co-rotating at 30 solar radii, making use of Mercury gravity assist (Inter-Helios type). For both missions as well, solar electric prime propulsion would represent a decisive enabling factor. For the ESA Mercury cornerstone mission, the electric propulsion (possibly combined with Venus and Mercury multiple gravity assists) would permit a significant gain. Therefore, SMART-1 can be used as a precursor mission in deep space using Electric Propulsion as Primary Propulsion.

2. SMART-1 SCIENCE OBJECTIVES

The SMART-1 mission, whose principal purpose is to test the electrical propulsion, shall have the ability to carry a scientific payload. The bodies that could be explored in the course of this mission are Near Earth Object(s) (NEO) and/or the Moon. The total mass of the payload lies between 15 and 25 kg, depending on the mission scenario. Important science can also be carried out during the cruise phase of the mission, e.g. dealing with astrophysical observations. We summarise here some science goals (and the type of instruments which could address them) on SMART-1.

Planetary Science could include:

- Gravitometry and NEO mass (Flyby tracking),
- NEO Coarse volume and density (Microcameras),
- NEO Rotational properties (Cameras),
- Planetary coarse imaging and albedo (Narrow FOV visible and UV imager),
- Geology, morphology, stereo mapping and topography (High resolution camera),
- Mineralogy (Visible and IR mapper),
- Geochemistry (X-ray spectro imager),
- Planetary environment (Wide FOV and UV imager)

Cruise Science could include:

- Earth magnetospheric auroral imaging and geocoronal emission (cameras),
- Monitoring of Sun (X-rays) and CMEs (Wide FOV imager)
Sky large field imaging (Visible and UV cameras),
Variability monitoring of active galactic nuclei, cataclysmic and active binaries (X-ray spectro-imager),
Molecular line observations (Sub-mm receiver).

3. SCENARIOS FOR THE SMART-1 MISSION

Considering technical constraints from launcher, and electric propulsion engines, three SMART-1 mission options were identified:

- A mission whose trajectory is bound to the Earth-Moon system. This includes missions to the Moon, with weak capture in elliptical lunar orbit. Alternatively Earth-Moon system tours can be conceived (flyby or rendezvous to the Moon or to the L4/L5 Lagrangian points). A mission in this category can be flown with both SPT and ion engines, with payload mass from 10 kg to 20 kg and minimum mission lifetime from 250 to 450 days.

- A flyby to a NEO, either an asteroid or a comet. This mission can be performed compatibly with a launch with Ariane 5 as a piggyback passenger in GTO, but only by using an ion engine. The payload mass is limited to maximum 10 kg and the minimum mission lifetime exceeds 2.5 years.

- A NEO rendez-vous mission is feasible with a dedicated launcher like Eurockot. The expected payload mass, depending on the chosen asteroids and launch date, is approximately 20 kg with some limited growth possibility. The minimum mission lifetime is about 1.5 years and varies greatly according to the target.

A cruise phase is present in all above mission categories. The cruise phase duration, spanning from 100 days to one year, is strongly depending on the mission option and selected target.

4. SELECTED SMART-1 SCIENCE PAYLOAD

After the issue of Announcement of Opportunity for Scientific Payload on 6 March, more than 15 letters of intent were received. An AO clarification meeting was held on 20 March 1998. Responses to the Science AO were due on 13 April 1998, and the activities for proposal screening and evaluation meetings, and SSWG - AWG - SSAC recommendations were completed before the SPC endorsement of the payload selection on 29 May 1998.

The selection criteria for individual Science payload instrument proposals reflected the specific nature of the SMART-1 mission as a flight test of Solar Electric Propulsion for future deep-space Cornerstone Missions. The evaluation criteria included:

- Scientific, technical and programmatic compatibility with the SMART-1 mission concept and schedule.
- Enhancement of the flight testing of Solar Electric Propulsion for future deep-space missions.
- Value of the scientific investigation and the technology employed for future cornerstone missions, e.g., mission to Mercury, deep space astronomy missions.
- Contribution of the proposed investigation towards the characterisation of the spacecraft environment in the presence/operation of Solar Electric Propulsion thrusters (e.g., possible interference, electromagnetic environment, surface contamination).
- Originality, merit, innovation
- Demonstrated technological feasibility, readiness and development status of the proposed instrumentation.
- Innovation of method or technology used for the investigation
- Reliability and state of space qualification
- Technical compatibility with available spacecraft resources and mission constraints.
- Competence and experience of the team in all relevant areas (e.g. science, management, space technology, proposed techniques, software development and technology etc.).
- Adequacy of proposed management scheme (including organigramme and planning) to ensure a timely execution of instrument development within the SMART-1 schedule.
- Adequacy of funding, manpower and institutional support for the proposed investigation.
- Communication, public outreach and education

The Peer review committee selected a Core Science Payload, including the following instruments:

- GEMINI, a High Resolution Imaging System, using a detector development ongoing for Rosetta. A light weight 1m focal length telescope will allow a resolution of 14 m at 1000km, and will provide superb images from the Moon or in the event of asteroid rendez-vous. A specific technique of TDI (Time Delayed Integration) for the CCD allows to drift the CCD charges during the exposure in order to gain sensitivity without smearing by orbital drift.

- AMIE is a Micro-imager experiment based on a development from the ESA Technology Research Programme (TRP) to be applied on the Rosetta/CIVA experiment. It includes a CCD, optical head and control electronics in a mass of 35 g. The experiment also includes a low-power micro-DPU of major interest for future missions.

- SI is a visible/near infrared Spectral Imager for the determination of the spatial distribution of minerals of the SMART-1 targets (Moon or Near Earth objects).

- SAGA is an Integrated Imaging Electronics Package, combining micro-DPUs, buffer memory, power converter of the three previous experiments. This allows a significant mass reduction, and to limit mechanical and thermal interfaces. It also forces the integration and miniaturisation of the electronics which is technologically required for future deep space missions.
- RSI is a Radio Science Investigation aiming at a very precise tracking of the SMART-1 spacecraft, using a planned technology X-Ka radio link payload. It allows to determine the mass, and moments of inertia of the asteroid targets. It would measure the space curvature parameter due to general relativity with an accuracy of $10^{-9}$. Also solar coronal sounding radio science will be conducted.

- IXS is an Imaging X-ray Spectrometer building on developments made for the XMM X-ray CCD cameras. It uses bended MCP as a new technique for X-ray collimation (based on lobster eye principle) providing a spatial resolution of 3-10 arcmin. It allows to map the elemental distribution of SMART-1 targets (Si, Mg, Fe, Mg, Na, O and C in the energy range from 0.5 to 10 keV). It also includes a solar X-ray monitor for absolute calibration, which can provide useful data for solar activity and flare monitoring, and stereo science. In addition, IXS can be operated during the cruise phase to monitor the X-ray variability of cosmic sources (solar-like stars, active binaries, active galactic nuclei).

- SPEDE (Spacecraft Potential, Electron and Dust Experiment) will characterise the plasma environment around the SMART-1 spacecraft.

- SMOG (Survey of Molecular Oxygen in the Galaxy) will focus on the technological demonstration in view of FIRST (Digital Auto-Correlator) and Planck (LFI amplifier) missions.

A set of additional science payload was identified depending on resources available and of technology payload allocation.

- UVMAP is an experiment for Lyman Alpha and Ultra Violet Mapping. This concerns imaging of Earth auroral, geocoronal and magnetospheric emission. It has a high sensitivity to detect very faint outgassing around the Moon or Near Earth objects such as Comet - Asteroid Transition Objects. It follows up developments for SOHO/SWAN.

- MAIDS is an experiment to measure the solar wind magnetic field during the cruise.

- TESTS is a proposed Thruster Environment Package to monitor the plasma effects due to the Solar Electric Propulsion, and the spacecraft interaction with the solar wind.

This recommended payload is subject to confirmation considering technical, funding and programmatic constraints.

5. MISSION SCENARIOS

The recommended science payload is compatible with both the asteroid and the lunar mission scenarios, the final choice depending on the choice of launcher and on the resources from the spacecraft. In both cases there can be extended periods of time that can be used for cruise science astronomy observations. The Peer Review Committee gave the following priorities for the mission:

1. NEO Rendez-vous after Lunar Gravity Assist Flyby.

The Near Earth Object recommended in order of interest are Comet Asteroid Transition Object and C-type asteroids. Besides their interest for cometary and early solar system understanding, they represent a class of objects that pose specific hazards to Earth.

Objects targets for rendez-vous have been identified for a launch in 2001-2002 and a decision will be taken after an exhaustive search and optimisation.

The lunar gravity assist would allow enhanced payload and shorter cruise time, as well as an opportunity for lunar polar science flyby. Also the high resolution mapping of rims of almost eternal light areas is of interest for future lunar landing and outpost.

2. Lunar near-polar orbit

This option would allow an orbit with 1000 km perigee and 10000 km apogee. This would allow further contribution on lunar science than the previously mentioned flyby. The lowering of the orbit would cost significant fuel mass, but the high resolution instruments would provide advances even from 1000 km perigee.

6. CHEMICAL VS ELECTRIC PROPULSION

A typical figure of merit for a space propulsion system is the ratio between the impulse and the amount (measured by its weight on Earth) of fuel necessary to provide it, i.e the specific impulse. The specific impulse $N_s/(kg/g)$ is measured simply in seconds [s]. The specific impulse is a figure of merit characterised by the fuel employed, the type of thruster and the operating conditions. For large velocity changes it is very important to use a propulsion system with high specific impulse in order to reduce the amount of on board fuel, which can become a considerable part of the overall spacecraft mass. The specific impulse is also indirectly measuring the efficiency of energy conversion. In a chemical propulsion system, the energy is stored in the fuel and is delivered and transformed into spacecraft kinetic energy, by exploiting the fuel chemical reaction with an oxidiser (e.g. Hydrazine and Nitrogen Tetroxide) or decomposition (Hydrazine into Ammonia, Hydrogen and Nitrogen). In other words the chemical energy contained in the fuel is the energy source. In order to achieve a considerable improvement in specific impulse another source of energy must be used. The solar electric propulsion engines use solar energy converted into electrical energy by solar cells to ionise and accelerate the fuel. The mechanism and working principles depend upon the type of electric propulsion engine.

The most important technology to be flown on SMART-1 is the solar electric primary propulsion. Europe has today a large inventory of electric thrusters, currently under development or already at qualification level for application on Telecom spacecraft, which can be used as primary propulsion thrusters for deep-space missions of the size of SMART-1. For a technology flight demonstration such as SMART-1, which is power and mass constrained, the selection of candidate thrusters is restricted to the following technologies:

- Stationary Plasma Thrusters

They are a family of electric propulsion engines belonging to the category of Hall-effect Thrusters. In
this class, the PPS1350 provides a nominal thrust of 70 mN at 1640 s specific impulse (Isp) and 1350 W of nominal input power. The thruster can also work at reduced power. This type of thruster has been already qualified for 7000 hours of operations in cycles.

- Radiofrequency Ionisation Thrusters
  In this class of ion engine, the RIT-10 provides a maximum thrust of 23 mN at 3060 s Isp for an input power of 700 W. Thrust can be modulated. The thruster is being qualified for 15000 hours of operations in cycles at 15 mN level.

- Electron Bombardment Ionisation Thrusters
  They also belong to the category of ion engines. In this class, the UK-10 current version provides a maximum thrust of 23 mN at 3400 s Isp for an input power of 700 W. Thrust can be modulated.

7. SMART-1 TECHNOLOGY PAYLOAD

The SMART-1 payload is indeed made of two categories: bus and instrument technology and scientifically relevant payloads. In both cases the selection of the items to be flown is made during the design phase, through an AO process. The AO for technology items has been issued in April 1998. The proposals have been received on June 5th. The electric propulsion system will be procured via a competitive ITT. In the scope of the present Announcement of Opportunity for Technology items, the following categories of Technology Experiments (TE) were considered:

- Key spacecraft technologies
  They will be prime constituent of the spacecraft or of one of its sub-systems. An example of such technology item could be the Lithium-carbon battery used as sole power source during eclipse and not backed-up by any conventional type of battery. Moreover, an example of a complete spacecraft unit realised as a technology experiment could be a deep-space T-T&C package, including an X/Ka-band transponder and antennas, if fully supporting all telemetry of the scientific data.

- Instrument technology
  This includes micro-cameras, micro-DPUs or miniaturised instruments, or the advanced technology for the SMOG instrument

- Technology experiments in support of SEPP
  This includes a plasma diagnostics package to measure the spacecraft environment in presence of Solar Electric Propulsion.

- Technology experiments for spacecraft units
  These are complements of on-board technology items to be operated as experiments, i.e. in parallel to a spacecraft unit/part realised with a conventional technology. An example of such an item could be a novel type of gyro, operated in parallel to the nominal Attitude Control device, to characterise and compare its performance in-flight.

8. SPACECRAFT DESIGN

The spacecraft has been preliminarily designed for accommodation on both Ariane 5 CYCLADE configuration and within the Eurockot fairing. This requirement strongly constrains the geometric envelope to a cylinder of 2.4 m diameter and 1.0 m height. The size of the solar panels is a critical parameter in the spacecraft design. Depending on the available solar cells the maximum power ranges form 1300 W with GaAs/Ge cells to 1500 W with GaInP/GaAs/Ge cells. The power system will make use of Li-C batteries. The spacecraft is stabilised on three-axis with zero momentum. Two solar panel wings are rotating to provide continuous tracking of the Sun during the mission, while allowing a rotation perpendicular to the solar vector to cover all thrust directions. A data handling and attitude control system based on the Odin spacecraft is foreseen. Star sensors will provide attitude information. Fibre-optic gyro or accelerometer packages are also foreseen for safe modes and rate damping. The actuators will be reaction wheels and mono-propellant hydrazine thrusters in addition to the two axis gimbals of the SEPP. The communication system is based on an S-band transponder supporting packetised command and telemetry. A X/Ka band transponder is also foreseen as technology experiment, together with a TWT high power amplifier. In case of the NEO mission the communication subsystem should be based on a S/S-X or X/X-band deep space transponder and high gain antennas. The platform dry mass ranges between 250 kg and 290 kg, depending from the type of engine and their redundancy. The Xe fuel and by consequence the payload mass available is strongly linked to the chosen mission. However the maximum fuel expected is 70 kg Xe and an upper limit of 20 kg for payload has been set.

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10. REFERENCES

      http://www.estec.esa.nl/spdwww/smarti1/html