SMART-1: THE FIRST TIME OF EUROPE TO THE MOON

Wandering in the Earth–Moon Space

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Abstract. After 40 years from the first lunar missions, Europe has started for the first time the development of a mission which has the Moon as a target. SMART-1 will be the first Western-European mission to the Earth's satellite. The primary objective of the mission is to flight test technology innovation for the future scientific deep-space missions. This paper describes the mission concept, the technology and the scientific aspects.

Keywords: Flight dynamics, Moon, space missions, technology

Abbreviations: ESA – European Space Agency; ESTEC – European Space Technology and Research Centre; FOV – Field Of View

1. The First European Lunar project

It may look rather surprising that ESA initiate the development of a lunar mission after 40 years from the first exploration mission (Luna 1) and with a prospective to launch a spacecraft which will orbit the Moon about 35 years after Armstrong and Aldrin had walked on it. There are however good reasons for it!

After the Apollo and Luna series, the Moon was let in peace by the space explorers for nearly two decades.* At the end of the seventies and during the eighties, however, new missions were studied which aimed at completing the scientific investigations started with the previous missions. Also ESA performed some mission studies, e.g., POLO (Polar Orbiting Lunar Observatory, 1979), the Lunar European Demonstration Approach, **LEDA** (Kassing and Novara, 1995), the Moon Orbiting Observatory **MORO** (Coradini et al., 1996) and set up priorities for a scientific exploration and utilisation of the Moon (ESA SP-1150, 1992). Especially the MORO study showed that a large community of European planetary scientists were strongly advocating the initiative of a scientific lunar orbiter.

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* From Luna 24 in 1976 until Clementine in 1994, no lunar missions took place with the exception of the lunar flyby of the Japanese probe Hiten in 1990.

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In the frame of a more recent initiative, the Small Missions for Advanced Research in Technology of the ESA Scientific Programme Horizons 2000, a lunar mission was reconsidered. The first of these small missions, SMART-1, is devoted to the testing of new technologies for preparing future cornerstone missions, using Solar Electric Propulsion in Deep Space. The mission study begun in 1997: several configurations (Racca et al., 1998a), electric propulsion options (Racca et al., 1998b) and planetary targets were considered. The mission was finally approved by the Science Programme Committee of the European Space Agency in November 1999, on the basis of a lunar mission described in this paper. The Moon was initially chosen as mission planetary target mainly because it is the easiest reachable planetary body. A secondary reason was the lunar scientific investigation that could be performed by means of the instrument technologies which were selected to be on board. During the development and optimisation of the required flight trajectories, it became also quite clear that the development necessary in this area was of great value for future missions, like the planned mission to Mercury, BepiColombo.

2. Mission Overview

The spacecraft will be launched in 2002 as an Ariane 5 Cyclade-like auxiliary payload. The spacecraft will be delivered in a Standard Geostationary Transfer Orbit (GTO).[*] After a cruise phase which may last from 14 up to 18 months, the spacecraft will be placed in orbit around the Moon, using solar-electric propulsion. The cruise phase to the Moon contains periods for cruise science and the science operations phase around the Moon will last 6 months.

The overall spacecraft mass shall remain within about 350 kg at launch. This is mainly due to the need to provide the spacecraft with an initial acceleration of about 2×10^{-4} m s^{-2}. This acceleration is necessary in order to maintain a reasonable time of flight and to ensure proper lunar injection capability. In addition an increase of mass is reflected into a greater launch cost.

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 perilune 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 apolune will have an altitude varying between 8,400 and 10,000 km. SMART-1 Lunar scientific studies

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[*] An Ariane 5 Standard GTO has a perigee radius of 6,628 km, an apogee radius of 42,164 km, an inclination of 7° and an argument of perigee of 178°.

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 perilune).
- 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 hemisphere 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 chosen electric propulsion (EP) engine is an existing and well-proven one. The mission will qualify the system and its use as *primary propulsion*. Indeed the main objective is to prepare the way for the future use of it in more complex missions such as the planned Mercury mission BepiColombo. 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 will be used. A new type of LiC battery cells with modular charge/discharge management will be flight qualified as a novel energy storage system. A new Deep Space X-Ka band transponder will be flown 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).

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. PAYLOAD

The payload is composed of technology and scientific experiments and its total mass has been capped at 15 kg. The six SMART-1 instruments support ten investigations. The six instruments are:

- **EPDP** Electric Propulsion Diagnostic Package (2.3 kg, 18 W). A suite of sensor for thruster diagnostics with ion energy up to 400 eV and spacecraft contamination monitoring.
- **SPEDE** Spacecraft Potential, Electron and Dust Experiment (0.7 kg 1.2 W). Langmuir probes on short booms for energy range of a few tens of eV, with plasma density from 1/10 to 1000 particles cm^{-3}.
- **KaTE** X/Ka-band Telemetry and Telecommand (TT&C) Experiment (5.2 kg, 18 W). A X-up/X-down and Ka-down Deep-Space Transponder running turbo-codes, allowing up to 500 Kbs^{-1} data rate from lunar orbit.
- **D-CIXS/XSM** Demonstration of a Compact Imaging X-ray Spectrometer (3.3 kg, 13 W). A $8^\circ \times 24^\circ$ FOV spectral imager in 0.5–10 keV range based on Swept Charge Device detectors and micro-collimators, including also a X-ray solar monitor.
- **AMIE** Asteroid-Moon Imaging Experiment (1.8 kg, 9 W). A 5.3° FOV miniaturised camera with a 4-band fixed filter. The camera is based on high-density 3-D Multi-Chip Module electronics.
- **SIR** SMART-1 Infrared Spectrometer (1.7 kg, 2.5 W). A 1 mrad FOV point spectrometer with 256 channels operating in the 0.9-2.4 μm wavelength range (NIR) for lunar mineralogy.

The four supported guest investigations are:

- Laser-link demonstration of a deep-space optical link acquisition (with AMIE).
- OBAN (On Board Autonomous Navigation) concept verification (with AMIE).
- RSIS (Radio-Science investigations for SMART-1) Electric propulsion monitoring and demonstration of in-orbit libration measurement method (with KATE and AMIE).
- XSM 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.

For further reading, Foing et al. (2000) describe the science potential and goals of the scientific instruments, while Marini et al. (2000) show how the technology experiments prepare for future ESA Cornerstone missions.

3. Electric Propulsion

The most important technology to be flown on SMART-1 is the Solar Electric Primary Propulsion (SEPP). Indeed, SMART-1 shall demonstrate the system aspects of the SEPP and no development for a new electric propulsion engine was envisaged. The benefits of electric propulsion for planetary missions are well-known (Racca, 2000) and basically reside in the high specific impulse that this type of engines possess in comparison to conventional chemical rockets. The requirements for a specific engine are strongly depending upon the size of the spacecraft, its available power and the mission total ΔV. 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.

The selected EP system is based on a Stationary Plasma Thrusters (SPT), which constitute a family of electric propulsion engines belonging to the category of "Hall-effect Thrusters". In this type of thrusters, electrons from an external cathode enter a ceramic discharge chamber, attracted by an anode piece. On their way to the anode, the electrons encounter a radial magnetic field created between inner and outer coils, causing cyclotron motion around the magnetic field lines. Collisions between drifting electrons and Xenon gas create the plasma. The ions created are accelerated by the negative potential existing in the area near the exit of the chamber due to the Hall-effect. The external cathode acts also as a neutraliser, injecting electrons into the beam, in order to maintain zero-charge equilibrium in the thrust beam and on the spacecraft. The PPS1350, shown in Figure 1, has an exit diameter of 100 mm and 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 (corresponding to a total impulse of 2×10^6 Ns).

4. Low Thrust Trajectory Design

The optimisation of low-thrust trajectories has been studied by ESA extensively in the early eighties. More recently, with the advent of real missions based on Electric Propulsion, the problem has been tackled again in a more operational fashion. Jehn et al. (2000) describe and provides references for the optimisation methods

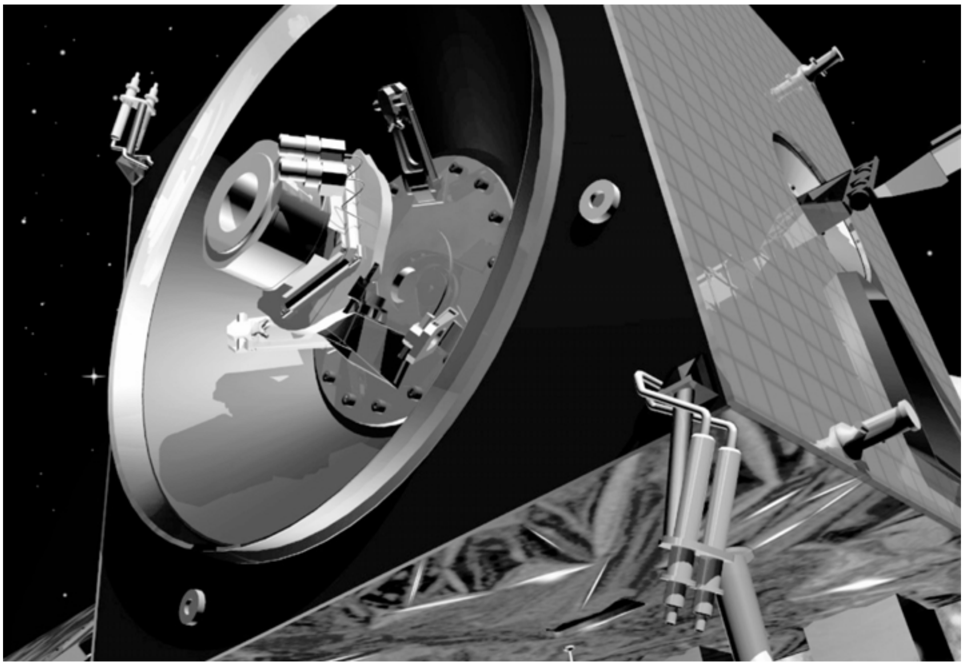

Figure 1. Close-up view of the SMART-1 Spacecraft -Z panel. The Electric Propulsion thruster PPS-1350 is visible mounted on a Thruster Orientation Mechanism shown with hold down points in their released position. The ring represents the launcher interface. Four of the eight hydrazine thrusters are also visible, canted to provide pure torques in all directions. The solar array extension arm mounted on its drive mechanism is shown on the +Y face.

used by ESA/ESOC. For SMART-1, the trajectory to be optimised starts from the Earth GTO and ends into the lunar operational orbit. For optimisation purposes the trajectory is divided in 4 phases:

1. From GTO to an orbit with perigee altitude 20,000 km and apogee altitude about 68,000 km and inclination 7°;
2. from the phase 1 final orbit to a 135,000 km × 338,000 km, about 30° inclination orbit;
3. from the phase 2 final orbit to a complete lunar capture;
4. from the lunar capture to the lunar operational orbit.

During the phase 1 trajectory, a continuous tangential thrusting is applied, to leave the radiation belt zone as soon as possible. The phase 2 trajectory is optimised by applying a method based on the Pontryagin maximum principle (Jehn and Cano, 1999). The same method is used for the optimisation of the phase 4 trajectory. The solution to the problem is a trajectory which combines coast and thrust arcs. During the thrust arcs, the engine is fired in a direction which has a out-of-plane and in-plane component with respect to the velocity vector.

The optimisation during the third phase and the matching of the three phases is calculated using a gradient projection method for a set of parameters defining the

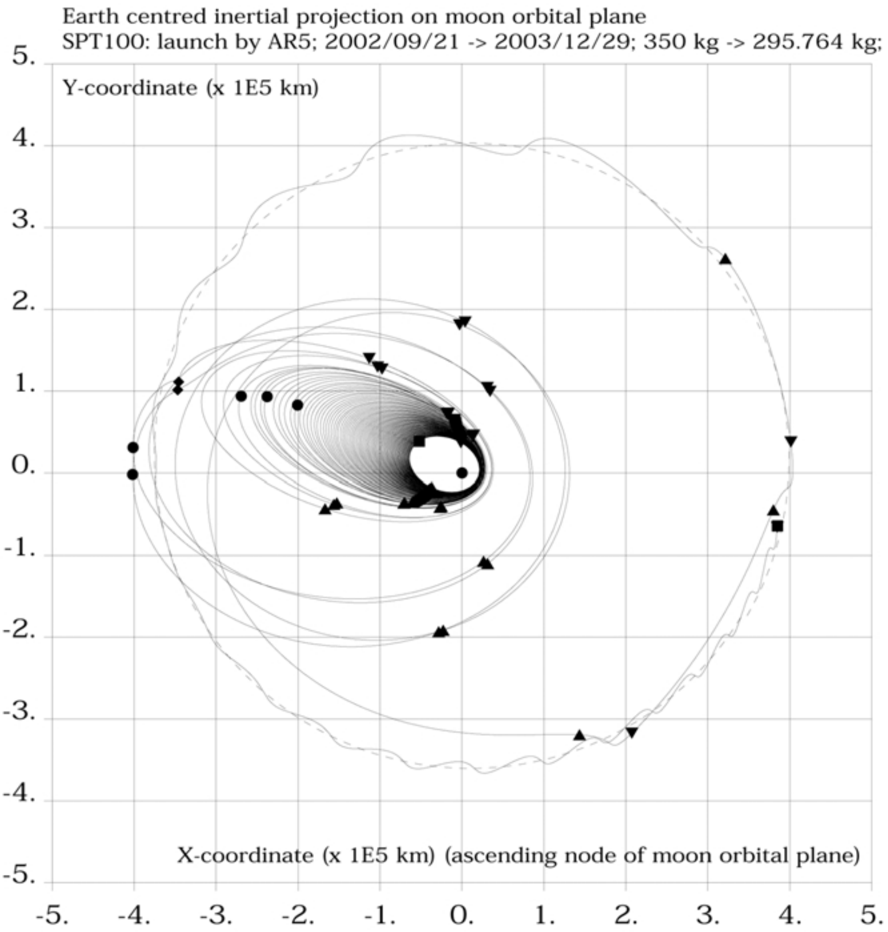

Figure 2. Transfer trajectory from GTO to Moon orbit (Box = trajectory start, triangle up = thrust start, triangle down = thrust end, circle = apogee, diamond = swing-by).

thrust law directly. The building blocks of these trajectories are thrust arcs, Moon resonances, Moon swing-by's and the lunar capture (Schoenmaekers et al., 1999).

During the ascent spiral, the apogee radius gradually increases. From 200,000 km onwards, the Moon starts to significantly perturb the orbit once every lunar revolution, i.e., every 27.4 days. These perturbations are called *Moon resonances* and occur near apogee when the Earth-spacecraft direction is close to the Earth-Moon direction. The Moon perturbation is only significant over a rather small part of the orbit near the point of closest approach which is near to apogee. The magnitude of the perturbation increases with decreasing distance to the Moon. The only parameter of a Moon resonance which can be easily controlled is the phasing with the Moon when reaching the apogee. It is controlled by tuning the orbital periods prior to the resonance via the length of the thrust arcs.

Moon resonances are encounters with the Moon outside its sphere of influence. Once the distance of closest approach to the Moon gets within the sphere of influence, i.e., lower than 60,000 km, we can call these gravitational interactions about *Moon swing-by's*. The obtained trajectory is shown in Figure 2. Lunar capture starts from when the spacecraft is gravitationally bound to the Moon, though still very perturbed by the Earth. For this reason, it is necessary to lower the capture orbit towards the operational orbit by means of thrusting. The capture occurs at a semi-major axis of about 28,000 km which is then decreased to an operational orbit of about 7,200 km semi-major axis. The time employed is in the order of 32 days.

The trajectory described here is certainly not the quickest way to reach the Moon. As a matter of fact, for this mission and with this spacecraft a chemical engine would be more suitable. However SMART-1 serves also as a test of the flight dynamics techniques to be used for future missions. In particular BepiColombo will have to exercise low-thrust trajectories combined with gravity assists (Venus and Mercury in that case) which are indeed tested for the first with SMART-1.

5. Science Instrument Technology

A set of miniaturised instruments for imaging and spectrometry has been selected for testing novel technologies and for supporting original lunar science investigations, in the field of the Moon surface chemistry (Foing et al., 2000). These instruments (see also Marini et al. (2000)) feature compactness, resistance to the environment and technological characteristics which make them ideal precursors for the instruments which will be selected for future planetary missions like BepiColombo.

5.1. X-RAY FLUORESCENCE SPECTROMETER

D-CIXS (Demonstration of a Compact Imaging X-ray Spectrometer) is an X-ray imaging spectrometer based on novel Swept Charge Device (SCD) detectors and a micro-structure collimator/filter assembly. The SCD's are single pixel detectors based on CCD technology but they have an electrode and clocking arrangement that *sweeps* the charge to one capacitance collector in a corner of the chip. Reading noise is anticipated to be as low as 3 electrons rms at 100 kHz Correlated Double Sampling frequency. The operating temperature is also significantly higher than for conventional CCD (the SCD operates with good SNR already at -10 °C) and the robustness against radiation is improved. The micro-collimator (microscope photo in Figure 3) is an assembly of a few tiny meshes realised with micro-lithographic techniques, stacked and sandwiched between 0.4 μm thick aluminium foil-filters, employed to block the visible light and to reduce the background electron flux. The collimator/filter is assembled in a block with the ceramic housing of a set of detectors including also Tantalum radiation shields. 4 blocks of 6 detectors are arranged

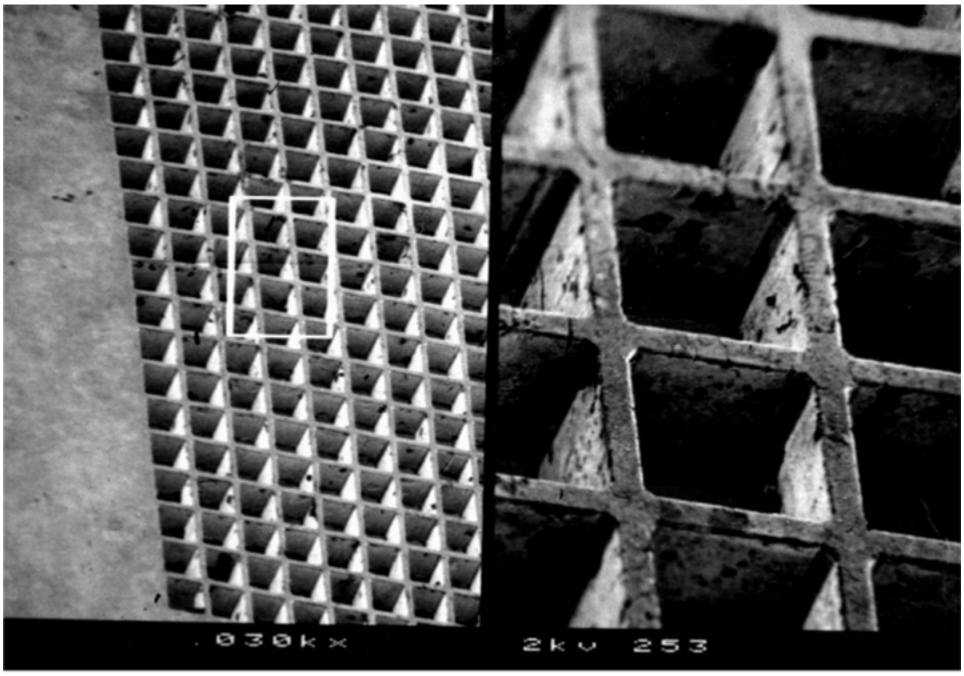

Figure 3. Microscope view (two zoom views) of the microstructure collimator of D-CIXS (Grande et al., 2000).

in a housing, which provides an overall of 32° by 12° Field-Of-View (FOV). The housing is covered by a radiation-shield door operated by a rotary mechanism, to protect the assembly from the low-energy protons. With its large FOV, D-CIXS aims at observing both diffused celestial X-ray sources and at measuring secondary X-ray emissions for lunar crust global elemental mapping in the 0.5–10 keV spectral range, with 140 eV resolution. D-CIXS is supported by two wide-field-of-view (104°) X-ray Solar Monitors (XSM), realised with Silicon diodes cooled by Peltier elements, which are used to calibrate the D-CIXS spectra with respect to the background flux and to map solar X-emissions in the 0.8 −20 keV spectral range. The overall D-CIXS/XSM assembly weighs about 3.5 kg and has a peak power consumption lower than 20 W.

5.2. NEAR-IR REFLECTANCE SPECTROMETER

SIR (SMART-1 Infrared Spectrometer) is a miniaturised quasi-monolithic reflectance-spectrometer, operating in the Near-Infrared, resolving 256 spectral channels in the 0.9–2.4 μm wavelength range, with a resolution per channel of 6 nm/pixel. The quartz spectrometer core is derived from a commercial device and it is coupled by a single optical fibre to a folded lightweight off-axis telescope with an aperture of 70 mm and a field-of-view of 1.1 mrad. The Infrared detector is a

Figure 4. CAD view of the AMIE micro-imager head. The long tele-objective tube with the sun-baffle is fixed to the mounting frame. The cube of the proximity electronic is within the radiation shield shown at the left hand side.

novel InGaAs array, which provides good SNR performance already at −70 °C. The instrument is passively cooled by a dedicated radiator which keeps the optics and the spectrometer assembly in the range of the optimum detection temperature, during the observation phases.

SIR is able to take both single spectra and bursts of spectra, for high-resolution mapping and angular spectroscopy. SIR weighs less than 2 kg and consumes a maximum of 3 W. It will be tested in lunar orbit to survey the Moon surface and measure selected mineralogical features in previously uncovered near-infrared regions.

5.3. MICRO-IMAGER

The micro-imager **AMIE** (Asteroid and Moon micro-Imager Experiment) is a miniature camera based on a 1024 × 1024 pixel Silicon CCD, imaging in 4 different spectral bands (450, 750, 847 and 950 nm) by means of a thin film filter deposited on a sapphire plate stacked to the CCD surface. With a 16.5 mm aperture and 154 mm focal length Tele-objective, AMIE has a square field-of-view of 5.3° and resolves about 30 m on the surface at the lowest perilune height. AMIE has an autonomous signal processing and image storage capabilities and the CCD proximity electronics is realised with 3-D interconnect mini-boards folded and potted in epoxy resin matrix. AMIE has two units: the external miniaturised optical head where the proximity conditioning electronics is hosted within a 4 mm Aluminum radiation shield and the signal processing and interface unit inside the spacecraft: all together AMIE weighs 1.8 kg and consumes a maximum of 9W. High-resolution images will be taken at the lunar South Pole region and throughout the whole mission. The AMIE camera will be pointed to a feature on the lunar surface to enhance the SNR by longer exposure. Earth and Moon images for public relations and public outreach and education will be made available at large via internet. A view of the AMIE head is given in Figure 4.

5.4. LIBRATION MEASUREMENT

The Moon libration measurement is a part of the **RSIS** experiment (Radio Science Investigation for SMART-1) and it is an absolute measurement from orbit of the libration properties of Moon, by means of imaging the Moon surface and tracking with high accuracy the spacecraft orbit at the same time. The AMIE micro-imager and the KATE Ka-band channel are used for the purpose. A delicate calibration in two successive orbits is needed to reach the desired accuracy (about 3% is anticipated on the oscillations in latitude, the largest) and the measurement shall be performed as close as possible to the poles, where the effect is maximum. If successfully validated, the method tested with the Moon (whose libration properties are well-known from ground-based laser interferometry) will be directly applied in BepiColombo mission to investigate the rotational properties of Mercury.

6. Conclusion

Although several missions have flown to the Moon, still many open questions remain about our natural satellite. Its formation and global elemental and mineralogical composition are still key issues to be investigated. Our understanding of the evolution of the Solar System, terrestrial planets, Earth-Moon system and the Moon itself will be greatly improved by an orbiting lunar mission. In addition, mapping of resources for future lunar bases is essential.

SMART-1 will contribute to these, while performing its primary task to flight-prove new technologies, propulsion means and space flight techniques for future exploration of the solar system.

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