SMILE: A joint ESA/CAS mission to investigate the interaction between the solar wind and Earth's magnetosphere

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ABSTRACT

The Solar wind Magnetosphere Ionosphere Link Explorer (SMILE) is a collaborative science mission between ESA and the Chinese Academy of Sciences (CAS). SMILE is a novel self-standing mission to observe the coupling of the solar wind and Earth's magnetosphere via X-Ray imaging of the solar wind — magnetosphere interaction zones, UV imaging of global auroral distributions and simultaneous in-situ solar wind, magnetosheath plasma and magnetic field measurements. The SMILE mission proposal was submitted by a consortium of European, Chinese and Canadian scientists following a joint call for mission by ESA and CAS. It was formally selected by ESA's Science Programme Committee (SPC) as an element of the ESA Science Program in November 2015, with the goal of a launch at the end of 2021.

In order to achieve its scientific objectives, the SMILE payload will comprise four instruments: the Soft X-ray Imager (SXI), which will spectrally map the Earth's magnetopause, magnetosheath and magnetospheric cusps; the UltraViolet Imager (UVI), dedicated to imaging the auroral regions; the Light Ion Analyser (LIA) and the MAGnetometer (MAG), which will establish the solar wind properties simultaneously with the imaging instruments. We report on the status of the mission and payload developments and the findings of a design study carried out in parallel at the concurrent design facilities (CDF) of ESA and CAS in October/November 2015.

Keywords: SMILE, ESA, CAS, magnetosphere, solar wind, SXI, UVI, LIA, MAG

1. INTRODUCTION

Despite the impressive progress made in the characterization of many of the key regions of Earth's geospace environment, a significant number of key science questions (see section 2) still remain unanswered today as they require a global perspective of the solar wind — magnetospheric interaction zones. Until now, global knowledge of the shape, position, size and morphology of the dayside magnetospheric boundaries could only have been achieved with a forbiddingly large flotilla of satellites in Earth orbit. SMILE is a space mission which aims to fill this niche by measuring Earth's global system responses to solar wind and geomagnetic variations. SMILE will investigate these dynamic responses in a unique manner, never attempted before, by combining soft X-ray imaging of the Earth's magnetopause and magnetospheric cusps with simultaneous UV imaging of the northern aurora. SMILE is designed as a self-standing mission and will carry in-situ instrumentation to monitor the solar wind conditions. With its unique capabilities, SMILE will complement all solar, solar wind and in-situ magnetospheric observations, including both space- and ground-based observatories, thus enabling the first-ever observations of the full chain of events that drive space weather.

SMILE was proposed as a collaborative mission between the European Space Agency (ESA) and the Chinese Academy of Sciences (CAS). Discussions between ESA and CAS have led to the following sharing of responsibilities: the two imaging instruments are provided by PI institutes in Europe and Canada, and the two in-situ instruments by institutes in China. The satellite service module and a propulsion module required for orbit injection fall under the responsibility of CAS, while the payload module carrying the science instruments, the assembly and verification activities and the spacecraft launch will be under the responsibility of ESA. The launch of the spacecraft is planned at the end of 2021.

2. SCIENCE OBJECTIVES

Due to its inherent complexity and cross-system coupling over a large range of spatial and temporal scales, the coupled magnetosphere-ionosphere system exhibits strikingly non-linear dynamic behavior in response to the constantly changing solar wind. Our understanding of the physical processes that drive these complex systems has significantly developed as a result of increasingly capable satellite missions and through global auroral imaging, which provides the global context for multipoint in situ spacecraft measurements. Despite these extremely powerful experimental tools, a large number of key science questions still remain unresolved such as:

- What are the fundamental modes of the dayside solar wind/magnetosphere interaction and in particular, what is the manner in which energy and plasma enters the magnetosphere?
- What defines the substorm cycle, which is thought to be the elemental phenomenon controlling the circulation of energy and plasma internally in the magnetosphere?
- How do CME-driven storms arise and what is their relationship to substorms?

Answering these questions requires knowledge of the global nature and information on the location and shape of the outer magnetospheric boundaries i.e. the magnetopause and the cusps. Large scale imaging of these boundaries from space can provide the global view that is needed.

Recent discoveries have shown, that the outer magnetospheric boundaries can be imaged via the process of solar wind charge exchange (SWCX) X-ray emission.[1–3] The interaction of solar wind ions with neutral atoms in the Earth's exosphere produces characteristic soft X-ray lines, with intensities that peak in the cusps and dayside magnetosheath. SWCX emission can thus be used to image the boundaries that control/regulate the flow of solar wind mass and energy into the magnetosphere, and also provides information about the composition of the solar wind through the emission of X-ray spectral lines.[4,5] The Soft X-ray Imager (SXI) will observe the location, shape, and motion of the dayside magnetospheric boundaries, including the bow shock, magnetopause, and cusps through direct imaging and spectroscopy of these SWCX emissions. An example of the imaging data expected from SXI is shown in figure 1.

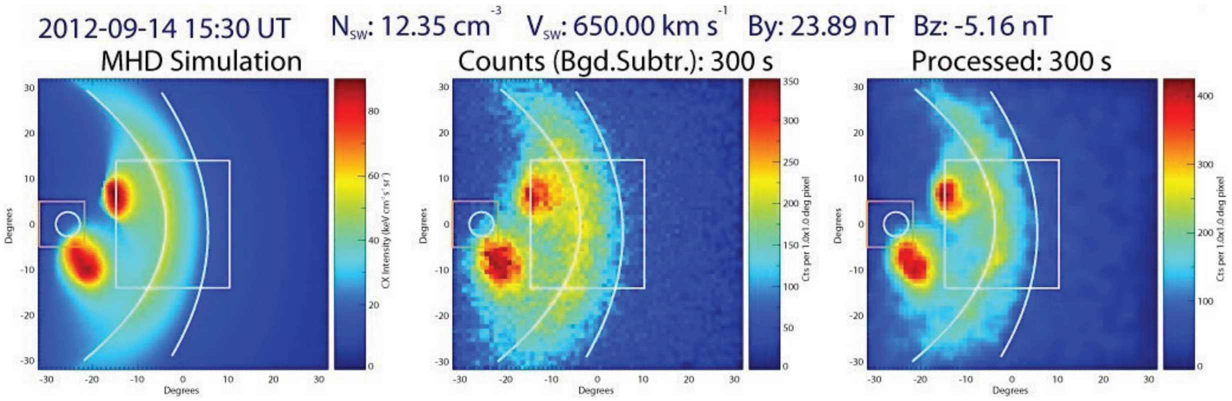

Figure 1. Simulated dayside magnetosphere after the arrival of an interplanetary shock. The figure shows original MHD simulation data (left), the predicted counts (centre) and the processed image (right).

In parallel, the Ultraviolet Imager (UVI) will observe the location and width of the auroral oval, and the transient and localized brightenings that occur within and on the edges of the auroral oval. This information will be used to quantify the internal configuration of the magnetotail and lobes. UVI will help to elucidate the consequences of the dayside interactions observed by SXI. SMILE is designed as a stand-alone mission that performs independent solar wind plasma and magnetic field measurements from its near-Earth vantage point, thereby obviating past concerns regarding the arrival times and spatial extent of solar wind features that arose in studies employing distant solar wind monitors. The key parameters to be measured include the solar wind magnetic field strength and orientation, both provided by the onboard, dual fluxgate Magnetometer (MAG). The in-situ Light Ion Analyzer (LIA) will determine the basic moments of the solar wind distributions, such as density, velocity, temperature tensor, and heat flux vector of the solar wind plasma under all solar wind conditions encountered.

3. SMILE MISSION CONCEPT

The primary scientific goal of SMILE is to provide remote sensing measurements of the magnetospheric cusps, the magnetopause and the bow shock, with the associated goals of providing simultaneous auroral imaging of the Earth and coordinated in-situ plasma and magnetic field measurements. Several considerations must be made to establish the optimum orbit for the needs of the mission. The orbit must be at large enough altitudes to obtain X-ray views of the outside edge of the magnetopause, but on the other hand must not have too large an altitude such that the angles between objects of interest (e.g. the cusps) and objects that have to be kept out of the SXI field of view (e.g. the Earth) become prohibitively small. Vantage points from far above the ecliptic plane generally offer better simultaneous views of the Northern and Southern cusps together, and better views of the polar regions of the Earth. The times of high radiation flux within the Earth's equatorial belts are kept to a minimum at such highly inclined orbits. Finally, communication constraints also have to be taken into account, as the available data rate decreases significantly with increasing distance to ground stations. Orbits of high ellipticity and high inclination offer a good compromise between these partly conflicting requirements. Consequently, a science orbit of 5000 km×121000 km ($\sim$19 Earth radii) altitude with a high inclination of $\geq 63°$ and an argument of perigee of 270° was chosen, offering a short, low altitude phase near perigee for efficient communication, while the spacecraft will spend the majority of time at high altitudes near apogee, thus providing long times at the optimum vantage point over Earth's north polar region.

The baseline launch scenario will be a shared launch into a sun synchronous orbit (SSO), likely with a mid-sized launch vehicle such as Soyuz-Fregat. The initial orbit depends on the primary passenger, but is currently assumed to be at 700 km altitude with an inclination of 98.2°. The back-up option is a dedicated launch with a Vega-C launcher, which would deliver the spacecraft to a orbit with a perigee altitude of 200 km and an apogee altitude of 700 km with an inclination of $67 - 70°$. Upon completion of the launch and early operations phase, science orbit acquisition will involve raising of the apogee from the launch orbit to 19 Earth radii followed by raising of the perigee to 5000 km. A dedicated propulsion stage will provide the delta-v required for these maneuvers. The propulsion stage is jettisoned after the perigee raising and remains in the science orbit. The spacecraft will then enter its 3 years nominal science operation phase in which ground communication will preferably be carried out during the perigee passes, with Troll (Antarctica), Kourou (French Guiana) and Sanya (China) being the baselined primary communication ground stations. The science orbit is unstable and will end with an uncontrolled descent into Earth's atmosphere in significantly less than 25 years after launch, in compliance with space debris requirements.

4. THE SMILE PAYLOAD

In order to achieve the scientific objectives (section 2) the SMILE payload comprises: a Soft X-ray Imager (SXI) which will spectrally map the Earth's magnetopause, magnetosheath and magnetospheric cusps, an Ultraviolet Imager (UVI) dedicated to imaging the auroral regions, a Light Ion Analyser (LIA) and a MAGnetometer (MAG), which will establish the solar wind properties simultaneously with the imaging instruments.

4.1 The Soft X-ray Imager: SXI

The soft X-ray imager (SXI) is developed by the University of Leicester with contributions from other institutes in the UK, Austria, Hungary, Spain, the Czech Republic, Norway, Ireland and China. SXI will observe the location, shape, and motion of dayside magnetospheric boundaries, including the bow shock, magnetopause, and cusp regions in the soft X-ray band ranging from 0.2 to 5 keV. SXI will also measure the time-dependent solar wind composition from the brightness of the various SWCX X-ray emission lines. The energy resolution of the detector has to be sufficient to resolve isolated SWCX lines, such as the OVII and OVIII lines or the emission lines of heavier ions.

The SXI instrument is a wide field lobster-eye telescope equipped with X-ray optimized CCD detectors. The focusing optics is formed by an 4×8 array of square pore micro channel plates (MCPs) manufactured by PHOTONIS (France), slumped to a common radius of curvature of 60 cm. The individual 40×40 mm^2 MCPs are 1 mm thick, with a pore cross section of 20×20 μm^2 and a wall thickness of 6 μm. The baseline coating for the reflecting surfaces is iridium. The MCPs are mounted on a spherical frame with a radius of curvature of 60 cm which, by the basic geometrical principles of the lobster-eye telescope, results in a focal length of 30 cm. The lobster-eye telescope provides a field of view of 15.6°×27.3° in this configuration.

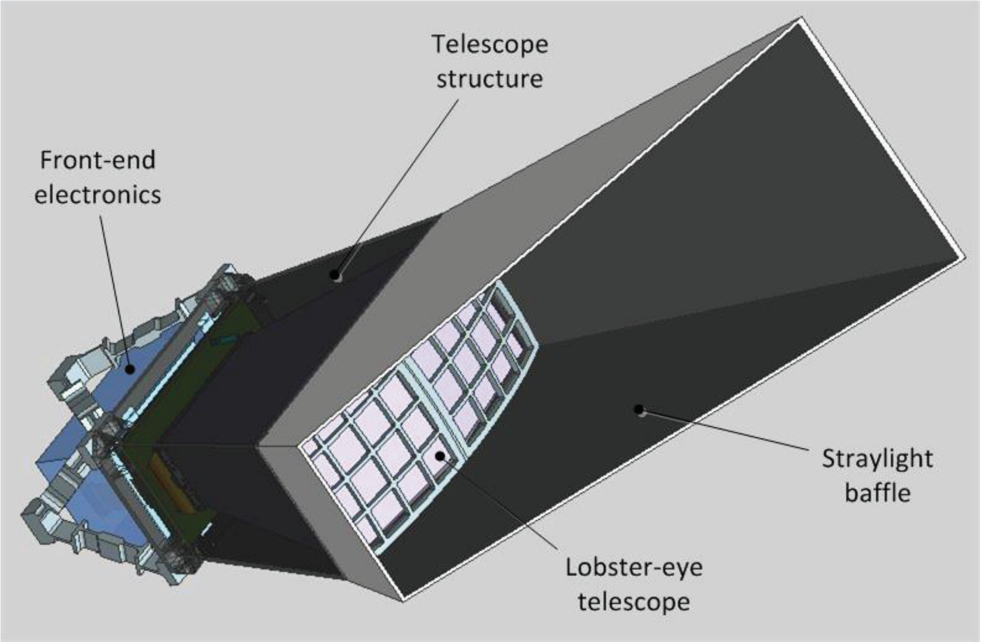

Figure 2. 3D-model of the SXI instrument.

The SXI focal plane consist of 2 large format, back-illuminated CCDs. Each CCD, supplied by e2v (UK) contains 4510×4510 native pixels with a pixel size of 18 μm. A fraction (about 1/6) of the active area near the read-out end of each CCD array will be used as framestore area by which "asymmetric" frame transfer read-out with a factor of 6 on-chip pixel binning in the read-out direction is realized. The predicted read noise is about 3 e^- rms, resulting in an estimated X-ray energy resolution of ~42 eV FWHM at 0.5 keV.

Because of the wide field of view of SXI and the requirement for a pointing direction relatively close to Earth, the instrument requires an optical baffle extending beyond the actual telescope to minimize the straylight reaching the focal plane. The instrument design also foresees optical/UV filters – currently 310 Å aluminum on 2180 Å polyimide placed on top of the individual MCP arrays of the telescope optics – to block astrophysical and local plasmaspheric emission. The sensitivity of the CCD arrays to radiation damage also necessitates the integration of a shielding door in front of the sensors to protect the CCDs during passage of the radiation belts. The associated door mechanism will be operated before and after each passing of the radiation belt. The magnitude and impact of the radiation environment is currently under study.

4.2 The Ultraviolet Imager: UVI

Simultaneously with the SXI observations the UVI instrument will monitor Earth's Northern aurora (Aurora Borealis), to link the processes of solar wind injection into the magnetosphere with those acting on the charged particles precipitating into the cusps and eventually the aurora. The focus on dayside interactions and the need to identify the polar cap boundary at all local times means that the images must capture the aurora even in sunlight. For this, the UVI will employ new filter technologies and an innovative telescope design to obtain state-of-the-art UV images. UVI is developed by the University of Calgary and Honeywell Aerospace (Formally ComDEV International), with contributions from Belgium and China.

The UV camera will consist of a single imaging system targeted at a fraction of the Lyman-Birge-Hopfield (LBH) N_2 wavelength band (160-180 nm). UVI utilizes a four mirror on-axis system with an intensified CMOS detector system, providing a field of view of $10^\circ \times 10^\circ$. The image-forming section of the camera comprises a fast, on-axis, all-reflecting telescope. This type of reflecting telescope is very compact and has excellent light gathering power. Moreover, it has excellent resolution over most of its field of view and has a high throughput in the far-ultraviolet part of the spectrum. Thin film filter coatings will be deposited on each of the imaging mirrors to provide signal filtering and definition of the science wavelength band. Further filtering is accomplished via the individual components of the detector.

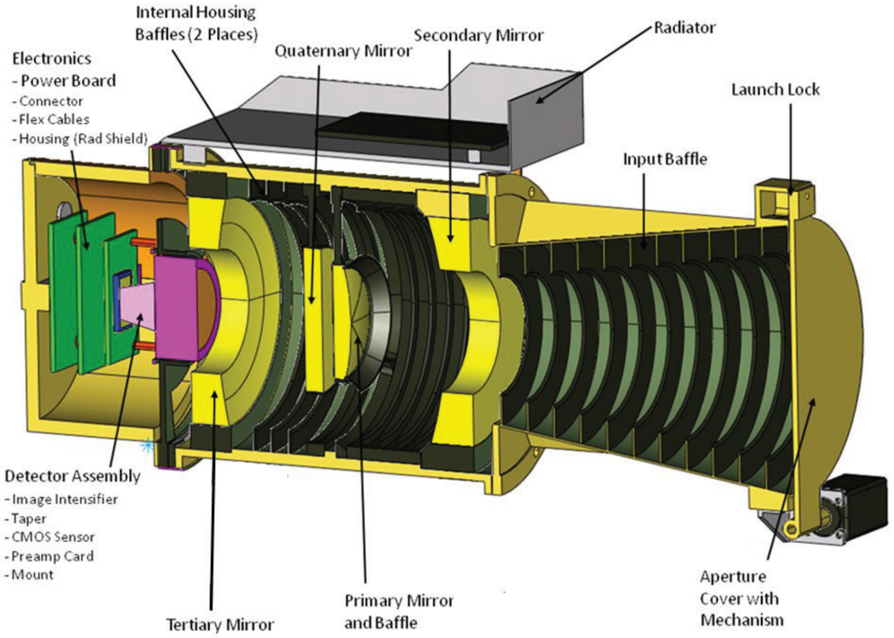

Figure 3. 3D-model of the UVI instrument.

The detector system comprises a micro-channel plate (MCP) based image intensifier, optically coupled to a CMOS detector. The telescope optics images the light onto a MCP which is coated with a suitable photocathode material. The photoelectrons are amplified by the MCP and converted back to light again with an aluminum coated phosphor. These photons are then coupled through a short fiber optic relay (fiber taper) onto the CMOS sensor. The baseline detector is a 512×512 pixels STAR250 CMOS sensor, which, in this configuration yields a spatial resolution of $\sim$100 km from apogee over the entire $10^\circ \times 10^\circ$ field of view even with the baseline binning to 256×256 spatial elements. The CMOS system will not require any mechanical shutter and provides greatly improved radiation hardness compared to a CCD sensor. Preliminary system modeling shows that the combination of the four filtering surfaces, image intensifier and the CMOS sensor can accomplish the out-of-band rejection required to image the aurora in fully sunlit conditions and provide the required sensitivity of $\sim$20 Rayleighs in a 60 s exposure.

4.3 The Light Ion Analyzer: LIA

The in-situ plasma analyzer LIA is developed by the National Space Science Center in China with contributions from the UK and France. LIA will determine the basic moments of the solar wind distributions, such as density, velocity, temperature tensor, and heat flux vector under different solar wind conditions.

The baseline LIA design is a top-hat type electrostatic analyzer, in which the hemispherical charged particle optics section only permits particles of a selected energy and charge to reach the MCP detector subsystem. The selection of the particle energy is realized by applying a negative high-voltage to the inner hemisphere of the analyzer. By design, the ion analyzer will provide an instantaneous field of view of $360° \times 3°$ but is also equipped with a field of view deflector system (FDS): by application of high voltage to either the upper or lower deflector electrodes of the FDS, the incoming plasma ions can be steered from a selected arrival direction into the analyzer section. The native instantaneous field of view can in this way be scanned in the elevation direction by sweeping the high voltage applied on the deflector electrodes. An acceptance angle of up to ±45° can be realized for ion energies below 10 keV and up to ±22° for energies above 10 keV respectively.

Besides the field of view deflection system, the LIA design will also include a “top-cap” electrode to provide a variable geometric factor system (VGFS). The VGFS allows the variation of the instrument sensitivity and increases the dynamic range of the sensor by up to two orders of magnitude and therefore allows the optimisation of its response to the ions in the different plasma populations encountered in the SMILE orbit. The LIA electronics will be able to change the system geometric factor with sufficient speed to be capable of sampling different parts of the solar wind energy range with different sensitivity. The analyzer will be mounted on the spacecraft such that the angle between the Sun and the center plane of the sensor are within ±20°, particularly during parts of the orbit when the SXI and UVI are acquiring images. This will ensure that both the solar wind and average plasma sheet flow directions remain within the FOV.

4.4 The Magnetometer: MAG

The magnetometer experiment MAG is also developed by the National Space Science Center in China with contributions from the UK. The scientific goal of MAG is to establish the orientation and magnitude of the solar wind magnetic field. This information is of critical importance for understanding and interpreting the X-ray imaging data. The magnetometer will be used in combination with the in-situ plasma measurements to detect interplanetary shocks and solar wind discontinuities passing over the spacecraft. The interfaces that MAG will measure are typically moving at hundreds of km/s in the solar wind and consequently only take a few seconds to pass over the spacecraft. To fully characterize the properties of these boundaries, it is necessary to examine their substructure. The magnetometer is therefore designed to measure the magnetic field at a sampling rate of up to 40 Hz and with an accuracy of 0.1 nT.

In its baseline design, MAG consist of two individual sensor heads, each of which comprises three tri-axial ring-core fluxgate sensors oriented along three orthogonal axes, thus sampling the three spatial components of the local magnetic field. The fluxgate sensor design is known to exhibit good stability and has extensive space heritage. Both sensor heads are mounted on a 2.5 m, three segment deployable boom, heritage of the Chinese FengYun-4 mission. The material of the boom has to be of non-magnetic or low magnetic material respectively in order to minimize stray magnetic fields. The sensor heads are connected to a spacecraft mounted electronics box via an electrical harness. The electronics unit consists of an FPGA based digital processing unit with a DC/DC converter and dedicated front-end electronics for each of the two sensors heads.

5. ESA/CAS DESIGN STUDY

During the course of October to December 2015, a parallel study in the concurrent design facilities (CDF) of ESA and CAS was held, with the scope of:

- sketching a suitable preliminary design for the SMILE service module (SVM), propulsion module (PM) and payload module (PLM) including the possible accommodation of the instruments and a detailed interface analysis,

- analyzing the spacecraft accommodation on possible launchers, including a dual launch configuration on Soyuz,
- optimization of the mission profile and defining the required ground operations,
- conducting mutual reviews of the proposed designs for consistency,
- performing a cost and risk analysis of the mission.

The result of the study is a consistent preliminary baseline design which allows to understand the technical and programmatic implications of the SMILE mission.

5.1 Spacecraft system design

The left panel of figure 4 shows the physical layout of the SMILE spacecraft composite in launch configuration, comprising the Payload Module (PLM), the Service Module (SVM), and the Propulsion Module (PM). The main characteristics of the SMILE spacecraft, which, in this configuration is compatible with the Vega and both position of the Soyuz launchers, are summarized in Table 1.

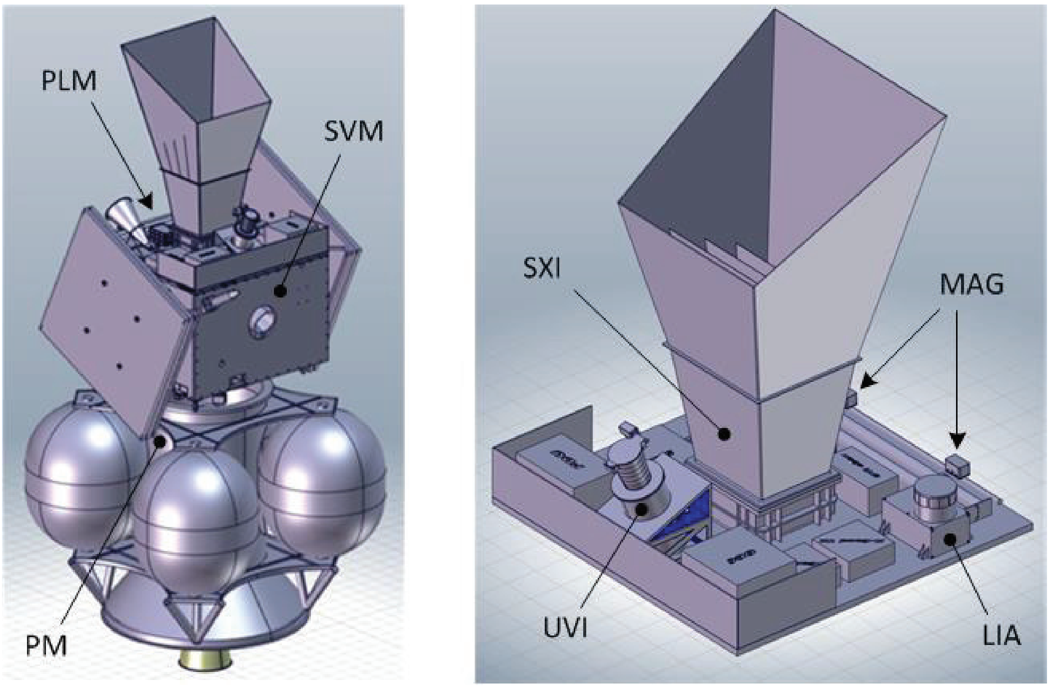

Figure 4. Left: preliminary design concept of the SMILE spacecraft composite in launch configuration. Right: CDF configuration of the SMILE payload module with preliminary accommodation of the science instruments.

The CDF configuration of the payload module (PLM) carrying the four SMILE science instruments is shown in the right panel of figure 4. The PLM is a single 20 mm aluminum honeycomb sandwich plate which also constitutes the top cover plate of the service module (SVM). This setup was chosen in order to minimize the total system mass, which - keeping the compatibility with the envisaged launcher options in mind - was one of the mayor design drivers for the spacecraft. The final configuration of the PLM and the accommodation of the science instruments is subject to an independent study carried out competitively by European industries.

5.2 Radiation environment

A first analysis of the planned science orbit predicts a relatively large accumulated radiation dose resulting from the crossing of Earth's radiation belts twice every orbit. The total ionizing dose (TID) is dominated by trapped

Table 1. Main characteristics of the SMILE spacecraft.

Spacecraft mass (incl. margin)	652 kg, dry mass 1960 kg, wet mass (incl. propellants) 351 kg, spacecraft wet mass w/o PM
Spacecraft height	3242 mm, total stack incl. adapters 1762 mm, spacecraft w/o propulsion module (PM)
Spacecraft dimensions	1000×1000×1762 mm, w/o PM
Attitude control	3-axis stabilized; 4 reaction wheels, eight 1 N thrusters
Propulsion module (PM)	4 propellant tanks, one 490 N thruster; jettisoned after orbit injection
Power system	5.4 m^2 fixed solar panels, 60 Ah battery
Communication	X-band for science data download on PLM S-band for telemetry and telecommand on SVM
Thermal system	aluminum and flexible SSM sheet radiators and heat pipes; no active thermal control

electrons for low shielding thicknesses (below 5 mm), while the total non-ionizing dose (TNID) mainly results from solar protons. At least 4 mm of aluminum equivalent shielding thickness is required to reduce the TID to acceptable target levels of about 10 krad (Si) with a radiation design margin of 100%. With this shielding thickness, the expected TNID is 1×10^{10} (10 MeV protons)/cm^2. The additional shielding mass must be taken into account at system level.

5.3 Power and communication

The primary power for the SMILE satellite is generated by two fixed GaAs solar arrays with a total area of 5.4 m^2 mounted on each side of the SVM. The spacecraft powers system also comprises a set of lithium ion batteries with a total capacity of 60 Ah, sized to provide sufficient power during the eclipse phases of the orbit. Power to the PLM power distribution unit, which in turn supplies the individual science instrument, is provided by the SVM in the form of a regulated power bus.

The communication subsystems of the spacecraft comprise two omni-directional S-band antennas mounted on the SVM and one medium gain X-band antenna located on the PLM. The S-band system is mainly used for transmitting telecommands and spacecraft housekeeping data, while all science data will be transmitted via the X-band system. The estimated total data volume generated by the four science instruments will be in the order of 30 Gbit/orbit. Several ground stations were considered for communications with the spacecraft with Troll located in Antarctica, Kourou in French Guiana and Sanya in China being the baselined primary communication ground stations. Assuming contact to one ground station close to perigee passage for each orbit, the estimated science data volume can be downloaded in less than 10 min.

5.4 Mission operation

The X-band medium gain antenna selected for SMILE has to be directed to the ground station for any X-Band data transfer. This requires a slew of the spacecraft to support such pointing for the duration of the passes. The impact on the AOCS subsystem and power subsystems during these pointing periods will need to be considered in the spacecraft design. To cope with the various pointing constraints and to ensure a safe and efficient operation of the spacecraft along the orbit and through the whole mission lifetime, several pointing modes are required. The pointing mode which will be used most of the mission time is driven by the observational constraints placed by the scientific targets. In this “Earth pointing mode”, the UVI boresight is pointing at the Earth with nadir close to the center of the field of view, while the SXI boresight is kept in the spacecraft-Earth-Sun plane, pointing towards the Earth-Sun direction. To avoid Sun or Earth illumination of the imaging instruments respectively and to maximize the ground station communication slots, an additional "Illumination Avoidance mode" in which the instruments are pointed away from Sun and Earth while the solar panels keep pointing towards the Sun, and a "Communications pointing mode" where the medium gain antenna is pointing towards a selected ground station and the instruments are pointed away from the Sun and Earth at the same time, are required.

6. SMILE DEVELOPMENT SCHEDULE

The SMILE mission concept was proposed following a joint call for a mission from ESA and CAS, which was issued in January 2015. The mission was formally selected by ESA's Science Programme Committee in November 2015 as an element of ESA's Science Program. SMILE is currently under study by ESA and CAS with instrument design studies carried out independently by instrument teams in Europe, Canada and China. A number of development milestones including reviews on payload and spacecraft level are planned, leading up to a proposed launch in 2021.

The first phase of the development will be dedicated to the definition of the system requirements and interfaces, followed by the preparation of a preliminary design concept. Preliminary design reviews on instrument and spacecraft module level are foreseen in Spring 2018. Critical design reviews in Spring 2019 will mark the start of the implementation phase with a delivery of the instrument flight hardware and start of the PLM integration activities expected in Summer 2020. Spacecraft AIT activities are planned in the period between January and September 2021, which will get the system ready for launch in November 2021.

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