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Abstract:
The main goal of the SWIPE project is to bring the terrestrial concept of Wireless Sensor Networks to the benefit of space exploration, particularly to planetary surface exploration. Dozens and up to hundreds or thousands of small wireless sensors (also called smart dust) could be deployed from a satellite orbiting the planet or by a rover exploring the planet surface. These autonomous sensors then create their own network, while some of them establish a link with an orbiting satellite. Data processing algorithms are applied to reduce the amount of data sent to the satellite and later to Earth. In order to drive the SWIPE project, a mission based on a Moon exploration scenario was designed in a precursor task. Despite the fact that this project will be carried out in a way that its results may be later used in other exploration missions, specific mission details are required to drive the hardware design and give a realistic feel for the variables involved in such a design process. This mission report is used as input on this document, providing mission constraints and early decisions regarding mission location, scientific relevance, satellite orbits and even network topologies that are here used to derive the SWIPE project requirements. This system requirements document starts precisely by summarising the outcome of the mission design report and listing the main conclusions and decisions taken that will serve as baseline for deriving the requirements. It then presents initial configuration and feasibility studies that were carried out by the Consortium. Some of the constraints that come out of these studies will be used to narrow down the vast design space for SWIPE, especially in terms of hardware. Afterwards, the requirement definition process is explained in detail and split into general, payload, node bus and network requirements. The last section in the document provides a summary table, for quick reference.

[1] Nature of deliverable: **R** = Report; **P** = Prototype; **D** = Demonstrator; **O** = Other
[2] Dissemination level: **PU** = Public; **PP** = Restricted to other programme participants (including the Commission Services); **RE** = Restricted to a group specified by the consortium (including the Commission Services); **CO** = Confidential, only for members of the consortium (including the Commission Services).

Document History

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Executive Summary

This system requirements document starts by summarising the outcome of the mission design report and listing the main conclusions and decisions taken that will serve as baseline for deriving the requirements. It then presents initial configuration and feasibility studies that were carried out by the Consortium. Some of the constraints that come out of these studies will be used to narrow down the vast design space for SWIPE, especially in terms of hardware. Afterwards, the requirement definition process is explained in detail and split into general, payload, node bus and network requirements. The last section in the document provides a summary table, for quick reference.

The requirements for the SWIPE project have been set taking into account two essential aspects: have a simple and short list of requirements that can be easily verified and handled throughout the entire project and have design requirements that contemplate real mission scenarios beyond the SWIPE FP7 scope and timeline. The first is extremely important to ensure the success of any research project. It avoids conflicting requirements and having an overly constrained design pool. The latter ensures the representativeness of the SWIPE results. The envisaged SWIPE validation prototypes will be built without space environment concerns, such as redundancy, radiation hardening or space-qualified manufacturing processes, since this is out of the scope of the project. Nevertheless, the requirements will ensure to as much extent as possible that the design takes a real mission into account, using sensors with adequate measurement range or fault tolerance techniques embedded into the design. With this set of requirements the Consortium believes that the work performed and the results obtained during this project will be applicable to future manned or unmanned planetary exploration missions based on Wireless Sensor Networks.

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List of Acronyms

Acronym	Meaning
A/D	Analog-to-Digital
ASIC	Application-Specific Integrated Circuit
CAD	Computer-Aided Design
COMM	Communications module
DDS	Dust Deposition Sensor
EEE	Electrical, Electronic and Electromechanical
EM	Electromagnetic
ESA	European Space Agency
ESTRACK	European Space Tracking network
IR	Infrared
LoS	Line-of-Sight
MMPP	Materials, Mechanical Parts and Processes
NLoS	Non-Line-of-Sight
SEE	Single Event Effects
SEU	Single Event Upsets
SWIPE	Space WIreless sensor networks for Planetary Exploration
TID	Total Ionising Dose
UV	Ultraviolet
VIS	Visible
WSN	Wireless Sensor Network

Table 1 – List of acronyms.

1 Introduction

The main goal of the SWIPE project is to bring the terrestrial concept of Wireless Sensor Networks to the benefit of space exploration, particularly to planetary surface exploration. The SWIPE concept is depicted in Figure 1. Dozens and up to hundreds or thousands of small wireless sensors (also called smart dust) could be deployed from a satellite orbiting the planet or by a rover exploring the planet surface. These autonomous sensors then create their own network, while some of them establish a link with an orbiting satellite. Data processing algorithms are applied to reduce the amount of data sent to the satellite and later to Earth.

This concept can be applied to any sort of planetary exploration mission, though the sensors, hardware design, node topology (including number of nodes) and deployment method varies, depending on the mission requirements. The SWIPE network however is going to be designed for scalability and to be flexible enough to cope with different operational scenarios. The SWIPE node includes the sensor set and a support bus that provides power, communication and management capabilities. Apart from this regular SWIPE node, the network foresees two other node types: data sinks, which are in charge of collecting and processing the data generated by the SWIPE nodes, and exit points, nodes that have satellite communication capability and are responsible for transmitting the data collected by the data sinks to the satellite. The best combination of these entities will ultimately depend on the mission requirements.

In order to drive the SWIPE project, a mission based on a Moon exploration scenario was designed in a precursor task. Despite the fact that this project will be carried out in a way that its results may be later used in other exploration missions, specific mission details are required to drive the hardware design and give a realistic feel for the variables involved in such a design process. This mission report [Crosnier et al, 2013] is used as input on this document, providing mission constraints and early decisions regarding mission location, scientific relevance, satellite orbits and even network topologies that are here used to derive the SWIPE project requirements.

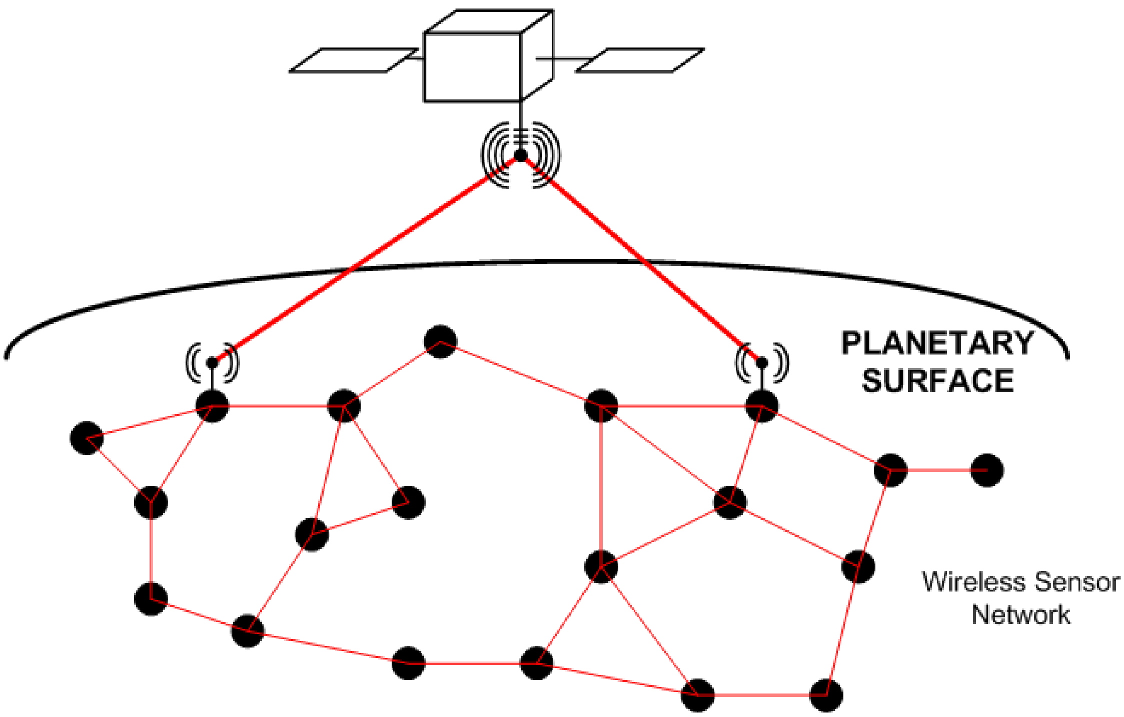

Figure 1 – SWIPE concept.

This system requirements document starts precisely by summarising the outcome of the mission design report and listing the main conclusions and decisions taken that will serve as baseline for deriving the requirements. It then presents initial configuration and feasibility studies that were carried out by the Consortium. Some of the constraints that come out of these studies will be used to narrow down the vast design space for SWIPE, especially in terms of hardware. Afterwards, the requirement definition process is explained in detail and split into general, payload, node bus and network requirements. The last section in the document provides a summary table, for quick reference.

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2 Mission Summary

SWIPE's baseline mission scenario is the Moon. This has been defined in [Crosnier et al, 2013], together with the main reasons that make it currently the best solar system body to be targeted by a Wireless Sensor Network mission such as SWIPE. [Crosnier et al, 2013] also designed the SWIPE mission in detail and the main purpose of this section is to reproduce the main outcomes of the mission design process, especially those that will drive the scientific and technological requirements of the SWIPE nodes and network.

2.1 Objectives and Location

One of the most interesting local features on the Moon's surface are swirls. Swirls have a high albedo such as the Reiner Gamma swirl [Hood et al, 2001] and tend to be associated with magnetic anomalies [Halekas et al, 2001]. Therefore, some scientists speculate that they are consequences of different space weathering conditions. The fact is that these anomalies have not been studied in detail yet and there is not much information available about them. SWIPE will thus focus on studying one of these anomalies.

The SWIPE mission design report [Crosnier et al, 2013] analysed several different swirl locations on the Moon surface, divided between nearside and farside. The nearside swirls have been extensively studied with remote observations whereas farside swirls are more enigmatic. Actually, the entire farside is less known and understood, which from a scientific point of view makes it more interesting to choose such a location. By analysing different locations against several features of interest of the Moon, Mare Ingenii is the site that gathers the highest number of interesting elements, from a scientific perspective. **Mare Ingenii was the selected landing site for the SWIPE mission**.

2.2 Sensor Packages

One of the most important results of the mission design report is a list of possible sensors to be used in the SWIPE Moon scenario and their relevance for the mission. Relevance was assessed both for human exploration and planetary science objectives, while keeping in mind that the most interesting objective of SWIPE is to support or prepare for a manned mission to the Moon. The main outcome of this analysis is summarised in Table 2.

Package	Sensor	(M)andatory/ (O)ptional	Relevance	
			Human exploration	Planetary science
Radiation	TID	M	High	Low
	SEE	M	High	High
	Magnetometer	O	Low	High
Illumination and Thermal	Illumination	M	High	Medium
	Thermal	M	High	None
Dust	Deposition	M	Medium	High
	Trajectory and speed	O	Medium	High
	Electrical fields	O	High	High
Geophysical	Seismometer	O	Low	High
	Heat flow	O	None	High
	EM sounding	O	None	High
	Laser retroreflector	O	None	High

Table 2 – Sensor packages recommended for SWIPE.

2.3 Timeline

The multiple sensors listed in Table 2 impose different constraints in the mission timeline, regarding not only measurement times, but also total mission duration for a maximum scientific return. For instance, the radiation environment changes according to the magnetic field variations. Major changes in the field occur during one synodic period (1 Moon day and around 1 Earth month); however the magnetic field is also affected by the solar activity, which reaches a maximum every 11 years approximately. On the other hand, geophysical events are rare and hard to predict, so several years would be required to have representative data. Table 3 summarises these requirements. In the end, **a minimum mission duration of 8 synodic cycles (approximately 8 months) was chosen, with possible extension up to a few years.**

Sensor Package	Mission length		
	Minimum	Preferable	Optimal
Radiation	1 synodic cycle	8 synodic cycles	5-6 years
Illumination and thermal	1 synodic cycle	6 synodic cycles	1 year
Dust	1 synodic cycle	8 synodic cycles	5-6 years
Geophysical	1 year	2 years	6 years

Table 3 – Overall timescale requirements imposed by each sensor package.

In terms of the measurement timeline, this also varies between sensors and will impose operational requirements for the SWIPE nodes, with impact on power and data budgets. Table 4 lists the measurement period for each sensor.

Sensor	Measurement Period		Notes
	Lunar day	Terminator[1]	
Radiation	5 min	5 min	Can be extended to 1 hour if necessary.
Illumination and thermal	10 min	10 min	May be switched off during lunar nights.
Deposition	-	2 measures	Before and after terminator
Trajectory and speed	-	Continuous	
Electrical field	15 min	Continuous	Can be extended to 1 hour if necessary.
Seismometer	Continuous	Continuous	
EM sounding	Continuous	Continuous	Stops operation after 1 year.
Heat flow	6 hours	6 hours	May be extended to 12 hour if necessary. Stops operation after 1 synodic period.

Table 4 – Measurement period for each sensor.

2.4 Network Topology

This mission design proposes three network sizes, which will depend on the deployment scenario: minimal, normal and extended. **The minimal network size is 5 km long**, in order to cover for the darkest and brightest area. **Normal coverage is achieved with a square with a side of 5 km** in order to encompass several albedo variations whereas **the extended coverage will be about 7 km large and 10 km long**, in order to include the curling shape of the swirl.

Another important piece of information that can be taken from the mission design report [Crosnier et al, 2013] is the maximum distance between nodes which still allows them to

[1] Terminator is defined as the period between 3 hours before and 3 hours after the sunset or the sunrise.

communicate. Unlike Earth, the radio line-of-sight on the Moon is not superior to the visual line-of-sight, for the radio waves are not reflected by the atmospheric layers. Besides, the Moon curvature is superior to Earth because its diameter is smaller. A realistic analysis estimates that **nodes are not expected to be able to communicate beyond 1000 m**.

The spacing between nodes is based on two factors: the swirl pattern and the line-of-sight constraints. In a scientific perspective, the requirement is set up to spacing inferior to 500 m considering the variation of albedo on the swirl pattern. Considering the radio constraint, the minimal distance between each node must be less than about 1000 m without local relief and roughness consideration. With boulders less than 18 cm the node range is reduced to 500 m. Taking all this into account, **the distance between nodes should be approximately 500 m**. To further determine the required number of nodes for the mission, it is important to consider two aspects: the network resiliency and the deployment accuracy. The analysis is done in [Crosnier et al, 2013] and a summary is presented in Table 5.

	Minimal coverage		**Preferable coverage**		**Extended coverage**	
	Low resiliency	**High resiliency**	**Low resiliency**	**High resiliency**	**Low resiliency**	**High resiliency**
Surface (km^2)	2.5 (5 x 0.5)		25 (5 x 5)		70 (10 x 7)	
Number of nodes (accurate positioning)	20	40	100	200	280	560
Number of nodes (erratic positioning)	-[1]	80	-	400	-	1200

Table 5 – Required nodes to fulfil the mission goals depending on the coverage and resiliency.

2.5 *Environmental Considerations*

2.5.1 Energy Resources

Resource energy available on the Moon is limited. The only one that is currently used is solar energy however the slow rotation period implies long period of night and day which is equal to about 14.25 earth-days on equator. **The maximum solar flux is equal to 1426 W/m^2 whereas the minimum reaches 1315 W/m^2** depending on the Earth and Moon positions.

2.5.2 Temperature

The temperature limits are extreme because of the absence of atmosphere. **The maximum temperature may reach about 110°C (383 K) during the lunar day and down to -180°C (93 K) during the lunar night**. The average temperature on mid-latitude is between 220K and 255 K with high variation of about 110K. The lunar farside receives 1% more solar energy because that side of the Moon is closer to the sun during the lunar day.

2.5.3 Radiation

The radiation environment is very harsh because the Moon is not protected by a magnetosphere. Although the WSN is located on a magnetic anomaly, the radiation protection and resilience must not be minimised since one of the mission objectives is to determine the protection level that magnetic anomalies can provide for future manned missions. Besides, the magnitude of the magnetic field is low and gamma cosmic rays seem to not be affected by the feeble magnetic field. As a consequence, **the sensor nodes need to be resilient to every spatial radiation from cosmic rays to solar wind and also to the solar event radiations**.

[1] Erratic deployment is always based on a high resiliency of nodes to prevent topologic failure.

2.5.4 Illumination

The maximum solar flux is equal to 1426 W/m^2 whereas the minimum reaches 1315 W/m^2 depending on the Earth and Moon positions. The solar irradiance depends on the solar incidence and illumination duration. This is of major importance to design the node power modules, such as the solar cells. Figure 2 shows the solar elevation and azimuth during one lunar day (lunar days and nights are considered to have the same reference duration of half the synodic period, i.e. 14 Earth-days, 18 hours, 22 minutes).

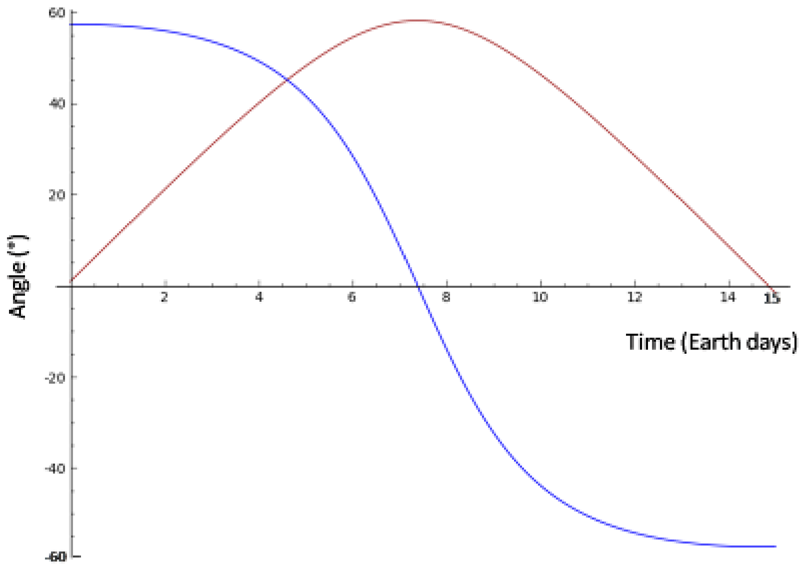

Figure 2 – Solar elevation (red) and azimuth (blue) during the lunar day.

2.6 Satellite Orbit Configuration

To design the communication links between the WSN and the orbiting satellite and from the satellite to Earth, information about the selected orbit is required. [Crosnier et al, 2013] considered three orbits with different elevations: quasi-polar orbit (86º), low inclination orbit (27º) and an equatorial orbit (0ºC). To limit the mission costs, the number of satellite to be deployed is limited to one, which means that there are no possibilities to provide continuous connectivity. Moreover, a small distance between the satellite and the WSN is a requirement to minimize the node power consumption.

Quasi polar orbit (86°) and low inclined orbit (27°) are not viable because the interruption of connection may last too long, which would jeopardize the SWIPE mission. Therefore, an equatorial orbit of 500 km altitude (Figure 3) is the selected orbit in order to maximize the line-of-sight duration but also to avoid too long non-connectivity between the orbiter and the WSN. Reference orbit information is provided in Table 6.

Inclination	0°
Altitude	500km
Period	9532s (2h38m52s)
Line of sight duration	1083s (18m03s)
Non-line-of-sight duration	8449s (2h20m49s)
Line of sight per Earth-day	~2h51m
Line of sight elevation (max)	6.637°
Line of sight azimuth (min / max)	-35.34 °/ 35.34°

Table 6 – Reference orbit information for the selected orbit.

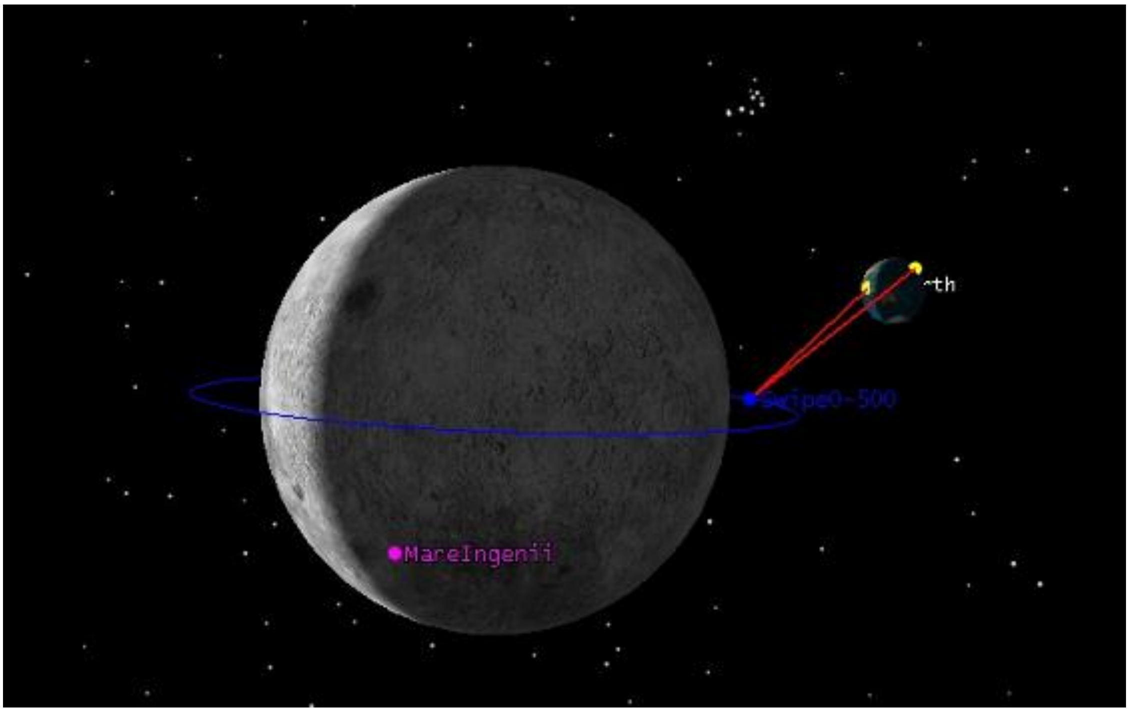

Figure 3 – Moon orbit with 0° inclination and 500km altitude.

3 General Node Description

The last section summarised the mission design results from [Crosnier et al, 2013], which includes a complete and detailed assessment of the most promising scenarios for a planetary exploration mission based on a wireless sensor network, which is the concept of SWIPE. This assessment was made focusing on two potential mission goals, human exploration and planetary science, and essentially from a mission perspective, i.e. based on desirable scientific objectives. Even though the mission design already made some technical considerations, and before deriving requirements for SWIPE, some initial decisions need to be made in order to bridge the scientific goals with the technological capability. The early considerations that will be presented in this section will thus set initial constraints that narrow down the multiplicity of possibilities and help to focus the research in one particular direction.

The key idea to keep in mind throughout the SWIPE project is scalability. WSNs are made of spatially distributed autonomous sensors, which in SWIPE will cooperate to take measurements of the lunar surface and pass their data through a network to a central processing location. Looking back at Table 5, it is possible to see that for one single planetary feature, the number of sensors in the network may rise from some tenths to thousands, with just a slight increase in the covered area. Since the interesting feature of WSNs is to provide accurate measurements over a certain area, the more sensors the network has, the “tighter” the mesh is and the better the results are. Moreover, the SWIPE concept is meant to be used in multiple mission types and scenarios, which have different requirements in terms of coverage, accuracy and generated data. All this needs to be taken into account at this stage. In other words, the SWIPE WSN needs to be scalable, both at node and network level.

From a space mission perspective, the SWIPE concept is viable if it ensures not only that the mission objectives are accomplishable, but also that the mission itself is feasible from an economical and technological point of view. In order to deploy a thousand sensors in the Moon surface, these need to have three key characteristics: low mass, small size and low manufacturing cost. Mass and size are bounded together and can be reduced by sacrificing payload functionality on each node, i.e. the amount of sensors. Low manufacturing cost can be ensured by defining simple processes and taking advantage of the “mass production” factor. However, the design is still challenging taking into account that the nodes need to take and process measurements, collect and store power, communicate within the network and to a satellite and have a robust structure, capable of withstanding the deployment phase and the operating environment. SWIPE will take these three design drivers into account when designing its node for the envisaged Moon mission.

3.1 Payload Selection

The first step is to choose the SWIPE payload, i.e. the sensor or set of sensors that will drive the rest of the node design. [Crosnier et al, 2013] identified the ideal set of sensor packages for a Moon exploration mission, which is summarised in Table 5. The mission design proposes radiation, illumination/thermal, dust and geophysical sensors, which are evaluated in terms of mandatory or optional for the mission and their relevance is assessed for both human exploration and planetary science scenarios.

Keeping in mind the low mass and small size criteria mentioned before, only a subset of these sensors is going to be used in SWIPE. In order to maximise the mission return, all the mandatory sensors will be selected and the remaining will not be considered. This option is also coherent with the initial main motivation of SWIPE, i.e. to support future manned missions to other planets, since the highest relevance for the human exploration comes from the mandatory sensors. Therefore, the selected sensors for the SWIPE node are:

- **Radiation sensor:** situated on the top part of the node, capable of monitoring the radiation environment of the moon surface. The radiation sensor will measure the Total Ionizing Dose (TID) and Single Event Upsets (SEUs) at various energy threshold levels.
- **Surface thermal sensor:** three thermal sensors will be situated outside the node structure and in such a way that, once the node is activated, they stay in contact with the lunar ground for thermal measurements.
- **Multispectral irradiance sensors**, sensitive to the visible (VIS), infra-red (IR) and ultraviolet (UV) spectral bands, will measure the lunar illumination environment. Three multispectral sensors will be placed on the node for a total field of view of 360º.
- **Dust Deposition sensor**, which will measure the dust deposited over a horizontal surface during a certain exposition time to estimate the dust deposition rate as a function of solar incidence.

3.2 Node Preliminary Configuration

Considering this set of sensors and their configuration constraints, it is possible to derive a preliminary node concept to match those requirements, always keeping in mind the key design drivers: low mass and volume and simplicity in processes to reduce manufacturing costs. It is important to note that the concept presented herein is not final and is a starting point, both for requirements and the architectural design that will follow in the WP3 tasks.

3.2.1 Block Diagram

The overall division at node level can be done using two main blocks: the payload, i.e. the sensors, and the node bus, which will provide support functionality for the sensor operation and the WSN formation. Apart from the sensors selected in the previous section, the payload module includes an acquisition electronics module for adequate sensor signal conditioning and A/D conversion. This module will then be linked to the node bus, which will have a system control module, acting as the node command centre. This system control is the data interface of the payload module. It commands the sensors operation and receives their processed data.

An electrical power module will also be required for the node operation. Based on the mission design, this power module needs to account for generation, storage and eventually control. Power generation will be done by solar cells and a deployable solution will be considered to maximise the solar cell area and power generation. Batteries for power storage are necessary to ensure that enough energy for node operation is available during the long lunar nights. A power distribution and control unit may also be included, though this will be considered at a later stage, during the architectural design, in order to understand if it is necessary or a simpler design can be achieved.

Finally, the node needs a communications module, which will be in charge of the Wireless Sensor Network and the satellite link data exchange and management. The technology used will be Software-Defined Radio, which is flexible and modular to the point that it enables the implementation of the ad hoc network algorithms that will generate the Wireless Sensor Network on the ground. This module will be connected to the system control module to exchange data to/from the network and will handle alone the network management. The system will have omnidirectional coverage, with WSN and satellite gateway communications.

A general SWIPE node block diagram is presented in Figure 4. This block diagram will be used as a starting point for the node architecture definition in WP3 activities.

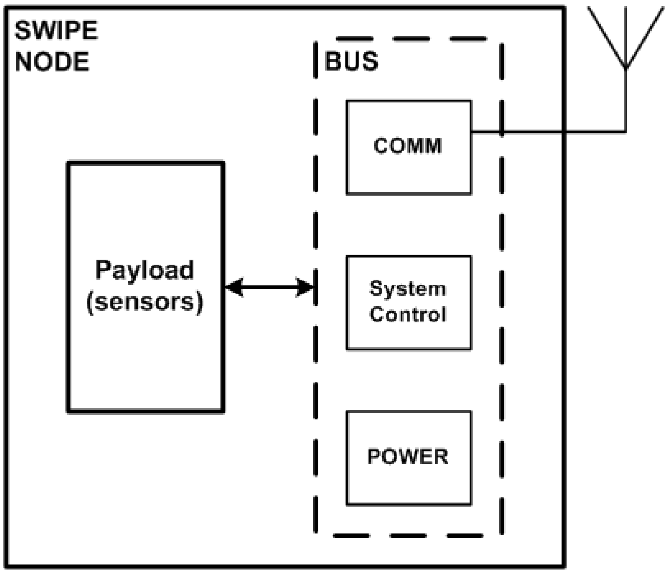

Figure 4 – Preliminary SWIPE node block diagram.

3.2.2 Node Housing

The node structure, as already mentioned, needs to be robust enough to protect the node systems, especially during deployment. It also needs to cope with the different sensor configurations. For instance, there will be three illumination sensors to ensure 360º sensing coverage, and the thermal sensors need to be in contact with the lunar soil, to measure the ground temperature. The antennas also need to be positioned in order to achieve an omnidirectional radiation pattern.

The most adequate geometry to select for the node is a tetrahedron. Its three inclined lateral faces are appropriate for both illumination sensors and antennas. The top vertex can be cut to place the radiation sensor and the dust deposition sensor can be placed at the bottom. The inside of the node can host the batteries and the electronics, which will be less exposed to the external radiation. A picture of the envisaged node CAD model is in Figure 5 for a more intuitive understanding of the concept.

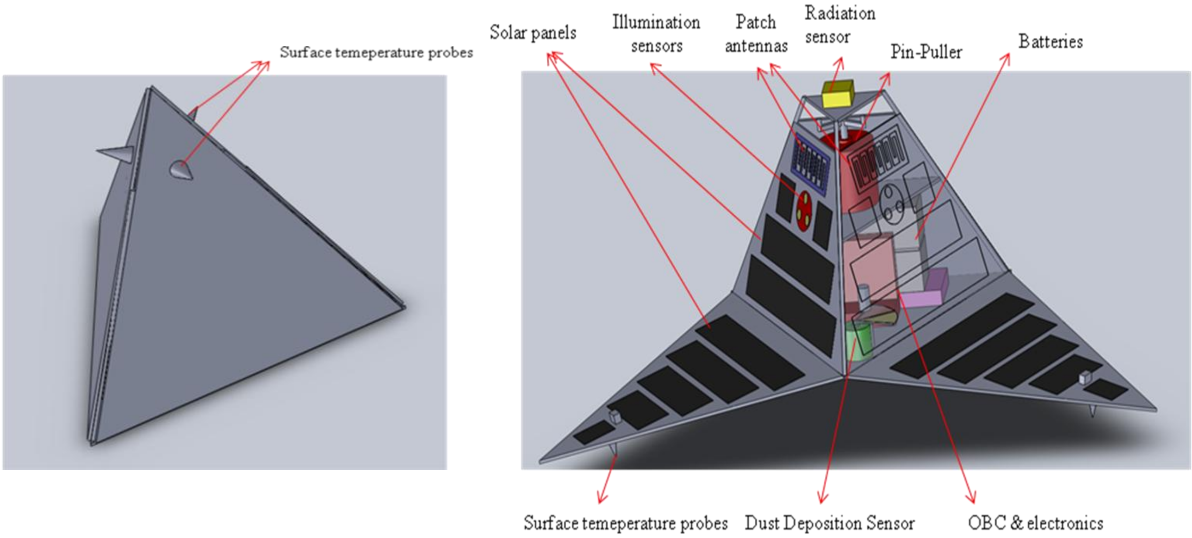

Figure 5 – Preliminary node configuration, based on a small size tetrahedral structure. The walls of the tetrahedron are deployable, once over the lunar surface they become solar panels.

It can also be seen that the current configuration foresees deployable solar panels. This option has interesting advantages. When closed, it offers full protection to the sensors and panels, from the environment during transportation and from dust that can levitate during the node deployment. This configuration also automatically puts the thermal sensors in contact with the soil, without the need for further complex mechanisms. Finally, the available area for solar panels is greatly increased, which provides higher autonomy to the nodes and enables higher performance, either for sensing or communicating.

Early estimates of mass and volume determined that the proposed configuration should fit in a tetrahedron envelope of 200 mm for the base triangle side and 200 mm of height. The total mass should also not exceed 2 kg. These figures are compatible with the scalability principle of SWIPE and would make it feasible to launch a large amount of nodes and an orbiter satellite with the current existing launcher capability.

As a final note, it is important to stress that both configuration and mass and volume figures are estimates at this stage. The design process may prove that this configuration is not optimal or it may come to the conclusion that the mass and volume of the node can still be further reduced. For this reason, this section will be seen as a guideline on the requirement definition process of the next chapters.

4 General Node Requirements

Based on the reference mission scenario and on the node configuration, described in the last two sections, this section kicks off the requirement definition for the SWIPE project. It presents general considerations for design, development and test and defines requirements that apply to the SWIPE node as a system. Specific payload, bus and network requirements will be derived later in this document.

Also relevant to note is the Consortium criteria to derive the SWIPE requirements, in order to achieve a wise balance between a real space mission and the project validation objectives. It is important to understand that the scope of the SWIPE project is not to develop a space-qualified solution or to perform exhaustive environmental tests. However, if the design process does not take the aspects of a real space mission into account, the results obtained in SWIPE may not be representative enough in order to be used by the partners in future exploitation scenarios.

Therefore, the general design concept will take into account real space mission conditions and will give recommendations and solutions for the proposed system to be compatible with a real mission scenario. However, the detailed design for the SWIPE node prototype development will just consider environmental conditions on Earth and will use commercial or industrial grade hardware. This approach will be explained in detail in the next subsections, for each particular case.

4.1 Configuration requirements

It was already mentioned in the previous sections that mass and volume are two design drivers for the SWIPE node, since they are the enablers for the concept scalability. The preliminary configuration analysis in Section 3.2 has allowed the Consortium to gain some sensitivity to reasonable values for dimensions and mass that ensure the feasibility of the nodes, while ensuring its desired functionality.

When thinking about scalability in a real mission, the main driving factor is mass. Ultimately, the limiting factor of a space launch campaign is the amount of mass to put into orbit. Geometry and dimensions may have an impact of other environmental aspects during launch, such as vibration loads or the centre of gravity, but mass is the critical figure, the one that sets also the mission costs or the capability of the current existing launcher technology. Therefore, a requirement will be set on maximum node mass, but not on dimensions and geometry, since these may be optimised at a later stage in the project.

A preliminary analysis has shown that a total mass of 2 kg is challenging, but feasible. Taking into account the baseline mission for SWIPE, 2 kg per node will be extremely challenging for the deployment strategies studied in WP2.3, this target seems at the moment the best trade-off between mass reduction and design constraints.

[GEN01] The SWIPE node total mass shall not exceed 2 kg.

Looking from a broader perspective, it is important to understand that a reasonable node mass is highly dependent on the mission (and therefore the sensor payload). Other missions may require a different topology or a different sensing capability, which has an impact on the node mass. Therefore, even though the requirement is set based on the reference mission to the Moon, the SWIPE design will always try to minimise mass as a key design driver, to ensure as much as possible its applicability to other mission scenarios.

Finally, and despite the fact that no requirement will be set on dimensions or geometry of the node, there is one fundamental, but extremely important requirement to be set in terms of configuration: the node housing must accommodate all the node modules, either on the surface or inside the structure. The detailed configuration will then be later defined in the node architecture, but such a requirement already constrains the housing design.

[GEN02] The SWIPE node housing shall accommodate all physical node modules.

4.2 Environmental requirements

Environmental requirements usually cover both the operational environment and the launch environment. Launch requirements however are not particularly interesting for the SWIPE project objectives, mainly for two reasons: on the one hand, no launcher has been selected for a future SWIPE mission, as this is out of the scope of the project and is highly dependent on many factors, such as launcher availability and capability. On the other hand, since no qualification tests are foreseen within the project, there would be no way of validating the requirements. For this reason, it was decided not to derive launch environment requirements for SWIPE.

The operational environment however can and must be taken into account in the design, as it has a large impact on the architecture definition and the modes of operation. The node design must take into account the extreme temperatures on the Moon surface and the dust layers that can jeopardise the node operation with harmful effects, such as material abrasion, mechanism movement hindrance, optical obscuration or electrical/electronic problems.

[GEN03] The SWIPE node shall be designed to survive temperatures between -180ºC and 110ºC.

[GEN04] The SWIPE nodes shall be designed in order to avoid potential dust harmful effects.

Another critical environmental hazard is radiation. The Moon offers no protection against it, since it does not have an atmosphere or a magnetosphere. The node design should therefore be tolerant to Single Event Effects (SEEs) to avoid data corruption and system malfunctioning. Many techniques are used to avoid these effects, such as cold redundancy, radiation hardening or data processing algorithms. However, for the SWIPE node, mass is a critical issue and any fault tolerance techniques shall not have a strong impact on the node mass. This will narrow down the scope of possible methodologies used during the design stages of the project.

[GEN05] The SWIPE nodes shall be designed with fault tolerance techniques, as long as they do not have an impact on the node mass.

Finally, it is important to stress that these requirements are applicable for the design only. The node prototypes that will be developed for the test and validation activities will not take all of these requirements into account, as explained in the next subsection.

4.3 Prototype requirements

Despite the fact that the SWIPE nodes are meant to be used in space, it is out of the scope of this project to space qualify the prototypes that will be developed for testing purposes. This is mainly due to two reasons: on the one hand, the main SWIPE goal is to develop prototypes in order to validate the concept of using WSNs for planetary exploration. Testing will be done in an Earth-analogue scenario, as similar as possible to a planetary environment, but without concerns about launch loads, radiation protection or any other harsh environmental condition. On the other hand, space-qualified materials, parts, processes and testing are extremely costly and time consuming and could not fit in the project budget and schedule. Furthermore, space qualification only makes sense at higher maturity levels, after the basic concepts and technologies are validated.

Therefore, the SWIPE node platform and payload will be developed using commercial or industrial grade Electronic, Electrical and Electromechanical (EEE) components. Correspondingly, no space qualified Materials, Mechanical Parts and Processes (MMPP) will be required for node platform and payload manufacturing. Following this philosophy it will be possible to reduce the development costs of the prototypes, while the functionality and performance results are still comparable to those potentially obtained by a space-qualified node envisaged by the design.

To guide the node prototype development, some environmental requirements will be set as a baseline, basically to ensure survival during transportation and operation during the tests. The SWIPE nodes must operate not only in a controlled laboratory environment, but also at the Earth-analogue that will be selected during the project execution. Therefore:

[GEN06] The SWIPE prototypes shall cope with the following temperature ranges:

- **Operational temperature range: -10ºC to 70ºC**
- **Survival temperature range: -20ºC to 90ºC**

Since no launch is foreseen during the scope of the project, no launcher loads or vibration requirements are needed and no dedicated structural or vibration tests are foreseen during this project. However, and since the prototype nodes need to be transported to the analogue site for the field trials, they need to survive low levels of shock or vibration during transportation.

[GEN07] The SWIPE nodes shall withstand the following vibration loads:

- **at 48 Hz: 1.5 g**
- **at 96 Hz: 2.0 g**
- **at 144 Hz: 1.5 g**

[GEN08] The SWIPE nodes shall withstand the following static loads (along the 3 axes):

- **n_x = +1.3 g**
- **n_y = +4.0 g**
- **n_z = +1.0 g**

4.4 Test requirements

Tests are foreseen in SWIPE as part of the concept validation. The SWIPE Consortium defined two types of tests to be performed: controlled laboratory testing to prove mainly the functionality and test the system behaviour, including the network, and an Earth-analogue campaign, in a similar environment as the one of the Moon. The location of this site will be defined during the project, together with the test procedures.

[GEN09] The SWIPE nodes and network shall be tested in a controlled laboratory environment and in a representative Earth-analogue environment.

The tests must be defined in order to achieve two main goals: enable the SWIPE functional and performance requirements and specifications to be verified and evaluated and validate the SWIPE concept as a distributed sensing solution for planetary exploration.

[GEN10] The SWIPE tests shall evaluate the node and network functionality and performance against the SWIPE requirements.

[GEN11] The SWIPE tests shall enable the validation of the SWIPE concept and the assessment of its viability.

Finally, it is important to stress out that space qualification of the hardware is out of the scope of the SWIPE project and therefore testing does not foresee any thermal-vacuum, shock, vibration and radiation tests on these prototypes.

5 Payload Requirements

The SWIPE node concept foresees the development of a small meteorological station that will monitor basic data of the lunar surface intended to better understand lunar environment for future human exploration. The selected sensors are, as mentioned in Section 3.1:

- Radiation sensor.
- Surface thermal sensor.
- Multispectral irradiance sensor.
- Dust deposition sensor.

These four sensors are considered to be the node payload. The next subsections go through the requirements for the design and development of each of these sensors.

5.1 Radiation sensor

There are several different types of radiation sensors intended to measure different radiation sources, levels or even effects on electronics. According to the recommendations in [Crosnier et al, 2013], the most valuable radiation effects to be measured depending on cost, accuracy, energy consumption and mass criteria are:

- Single Event Upsets (SEUs). The sensor shall be capable of measuring SEUs and differentiate its related energy. At least three threshold levels defining different levels of energy will be selected and each SEU will be related with one of these levels.
- Total Ionizing Dose (TID). It will be possible to estimate the TID to which the component has been subjected by measuring the degradation of different components with the radiation. The main parameters of these components will be measured and the data obtained will be used to estimate the TID.

[PAY01] The radiation sensor shall be able to detect Single Event Upsets and differentiate them at least at three different energy levels.

[PAY02] The radiation sensor shall be able to measure the Total Ionizing Dose.

From preliminary studies, the implementation of this sensor will be done in a rad-hard mixed signal ASIC. The performance of this type of sensors is completely dependent of the technology used for the ASIC implementation. For this reason it will be not possible to accurately define the sensor specifications until the technology is selected. Technology selection will be done in the design phase and only after architecture definition, when it will be known which blocks are to be integrated in the ASIC and therefore which technology shall be used.

Since radiation campaigns are extremely expensive, they have not been considered within the scope of this project (SWIPE foresees the development of prototypes using commercial components). For this reason the sensor cannot be physically calibrated under radiation (future opportunities for radiation campaigns will be identified, though they are out of the scope of this project).

Mechanical and power requirements for the radiation node are not going to be derived independently for each sensor. The global mass requirement in [GEN01] applies to the node as a system and the system architecture shall prepare and maintain accurate system budgets to monitor the individual mass and power budgets. However, the sensor will be designed based on two factors: the low mass/volume key driver already discussed before, which also has the consequence of minimising the power consumption (and reducing the amount of necessary solar panels and/or battery cells), and the feasibility limits of sensor design and manufacturing coming from the previous experience of Arquimea.

5.2 Surface thermal sensor

As the name indicates, the thermal sensor shall measure the temperature at the planetary surface (in this case, the Moon). The mission design also recommended that the thermal sensor has at least three measuring points. Given the environmental scenario, the most appropriate way of measuring the temperature is by conduction. The thermal sensor will be attached to a high thermal conductivity and low thermal inertia material that will be used as a probe. Each probe must then be in contact with the surface.

[PAY03] The thermal sensor shall measure the surface temperature in at least three different points.

[PAY04] The thermal sensor shall measure the temperature by conduction.

According to the mission definition, the nodes would be subjected to temperatures ranging from -180ºC to 110ºC throughout an entire synodic period. The sensors therefore shall be able to measure temperatures at least in this range to avoid saturation. On the performance side, a resolution of 0.5ºC and an accuracy of 1ºC are reasonable values from a mission point of view.

[PAY05] The thermal sensor shall be able to measure surface temperatures at least between -180ºC and 110ºC.

[PAY06] The thermal sensor shall measure temperatures at least with an accuracy of ±1ºC and a resolution of ±0.5ºC.

It is important to note that the thermal sensor performance will not be tested and validated over the entire measuring range specified in [PAY05], since extensive environmental testing is out of the scope of the project. However, this range will be taken into account during the design process and eventually during manufacturing.

The same concerns to keep mass, dimensions and power budgets as low as possible, while still feasible, apply to the thermal sensor.

5.3 Multispectral Irradiance sensor

According to the mission design, the illumination sensor must be able to measure the incident irradiance at three different spectral intervals, one in the infrared (IR) side of the spectrum, a second one in the ultraviolet (UV) range and a third one in the visible (VIS) range. The illumination sensor shall also be able to measure the irradiance in all directions, in order to achieve full 360º planar coverage. The preliminary configuration considers that each group of sensors (IR, VIS and UV) will be mounted within a mechanical support (optical head) and a total of three will be placed in the node to achieve the full coverage.

[PAY07] The illumination sensor shall measure the irradiance in the ultraviolet, infrared and visible spectral ranges.

[PAY08] The illumination sensor shall measure the irradiance with a 360º planar coverage.

On the other hand, since the solar flux on the Moon can reach 1426 W/m^2, the illumination sensor must be able to measure irradiance values at least up to this maximum solar flux level without saturation.

[PAY09] The illumination sensor shall be able to measure irradiance levels up to at least 1426 W/m^2.

The mission design does not specify any requirements on resolution and accuracy for the irradiance measurements and these are highly dependent on the technology used. The final selection of the technology is only made during the design tasks at a later stage in the project. Therefore, no specific requirements will be set on the illumination sensor performance. Nevertheless, the sensor design will be made in order to achieve the best accuracy and resolution possible, keeping in mind the mass constraints imposed by the design drivers.

5.4 Dust deposition sensor

Dust is an important parameter to be measured over the Moon surface for better understanding of levitation phenomena (electric charge of the dust, trajectory, velocity…). For the SWIPE project, a Dust Deposition Sensor (DDS) is proposed, intended to measure the dust deposited over a horizontal surface during a certain exposition time. This type of sensor can be designed to be integrated in the node with low power/volume/mass overhead.

[PAY10] The Dust Deposition Sensor shall be able to measure the amount of levitated dust from the Moon surface.

The DDS principle of operation is based on measuring the percentage of opacity caused by the deposition of lunar dust and debris in the surface of a test solar cell. The Dust Deposition Sensor will be based in the use of two solar cells or photodiodes of identical dimensions and characteristics. Both of them will be exposed to the same environmental conditions in terms of temperature and radiation, although one of them will be protected from dust deposition and the other not. A mechanical device will permit to move the reference cell/photodiode to obtain the measure required in few seconds.

Performance requirements are also difficult to derive for the DDS, especially since there isn't sufficient scientific information available about the dust levitation phenomena on the Moon surface. The mission will focus on taking measurements only before and after a terminator (sunset or sunrise) to assess if terminators have any impact on the magnetic field that could cause charged dust particles to levitate.

Since no desired performance is specified from the mission side, no accuracy and resolution requirements will be derived here. Just like with the illumination sensor, the design will be made for the best possible performance. The same concerns to keep mass, dimensions and power budgets as low as possible, while still feasible, apply to the dust deposition sensor.

5.5 Payload acquisition electronics

The payload acquisition electronics will be responsible for activating and commanding the different sensors, conditioning the measures, digitising them and sending the data to the system control module (Figure 4). In short, this module must provide the sensor measurements in digital form and with a resolution that is acceptable in terms of the mission scientific goals and relevant from a sensor output point of view. Therefore, it was defined that the analog-to-digital conversion process shall have a resolution of at least 12 bits and 10 effective bits.

[PAY11] The payload acquisition electronics shall provide the sensor measurements in digital form to the system control module.

[PAY12] The sensor digital measurements shall have a resolution of at least 12 bits and 10 effective bits.

Since the measurements must be transmitted to the system control module, the payload acquisition electronics must have a data communications interface. The protocol used will be defined later during the architecture design.

[PAY13] The payload acquisition module shall have a data communication interface.

6 Node Bus Requirements

The node bus includes three modules, as shown in Figure 4: the system control module, the power module and the communications module. After the general node and payload requirements definition, this section sets and justifies the specific requirements that will drive the design of these three hardware modules.

6.1 System Control Module

The system control module is the central managing unit in the SWIPE node. It has the global responsibility of supervising and managing the operation of the remaining modules and act as a data processing interface of the payload measurements. This module can be physical or logical depending on the architecture adopted. Nevertheless, the node management role must be ensured.

[BUS01] The SWIPE node system control module shall supervise and manage the operation of the payload, communications and power modules.

Apart from the sensor measurements generated by the payload module, the SWIPE node must also generate internal housekeeping data, which will be used to monitor the health of the different system modules. Typically, housekeeping data is generated by all modules and includes functional parameters and variables that ultimately dictate the module correct or incorrect behaviour. This data is then collected by the system control module and can be used in two ways: to make local node control decisions or to be transmitted for further monitoring, operations or debugging.

This has a considerable impact on the node and network design (particularly in the storage capacity and the network data rates) and cannot be neglected. Based on the measurement periods in Table 4, it is reasonable to set the housekeeping data generation period not higher than 1 minute. On the one hand, node health monitoring shall be made more frequently than the science operation. On the other, it does not flood the network and the local processing capabilities with irrelevant amounts of housekeeping data.

[BUS02] The SWIPE node shall generate housekeeping data with a period not higher than 1 minute.

Please note that the requirement is not set in terms of transmitted housekeeping data, since this depends essentially on the control architecture established for the SWIPE node, as well as on the data processing mechanisms considered. The same applies to the frequency of housekeeping data sent to Earth, which depends on the data processing defined at data sink level. These data collecting nodes may filter housekeeping information from different nodes and send it to Earth in a different format. All these issues will be defined during the architecture studies, but they demand for a requirement on node data processing capability.

[BUS03] The SWIPE node shall support the implementation of data processing and/or fusion algorithms.

Another concern at node level is the data storage capacity. Each SWIPE node shall be capable of storing the measurements and the housekeeping data before transmitting it. Since it is extremely difficult at this stage to calculate the required storage capacity for all possible operation scenarios, some assumptions were made to achieve a minimum capacity value to include in the requirements.

The main criterion to determine the minimum required storage capacity is that each node is able to store its generated data, before sending it to the network. Based on the principle of operation of the WSN, the first assumption is that each node sends its data as soon as it is generated and processed at node level. The worst-case scenario is having one set of data from all sensors and one set of housekeeping data stored in memory at the same time. Based on the sensor description and payload requirements, it is possible to determine the size of the generated data by each sensor in a single measurement. The housekeeping data is more difficult to estimate since the parameters haven't been defined yet. For simplicity, it is assumed that it has the same size of the payload data. The date and time of the measurements also has to be stored and, finally, a 20% safety margin is added to account for any network overheads. Table 7 summarises the size and period of the generated data on each node.

Data type	Quantity	Data (bit)	Total (bit)	Period (s)
Sensors			***264***	
Radiation	1	84	84	300
Thermal	3	12	36	600
Illumination	3	36	108	600
Dust Deposition	1	36	36	(4 measurements in one synodic period)
Housekeeping			***264***	60
Date/Time Header			***48***	-
Safety Margin			20%	-
TOTAL generated data per node			***692***	

Table 7 – Payload and housekeeping data generated at node level.

Apart from the generated data at node level, each node needs to have capacity to store the network routing table, which at least contains the addresses of all nodes in the network (including the satellite), and, since the network shall support multihop communications (see Section 7), the addresses of the next-hops in order to reach those nodes. Moreover, each node needs to be able to store data coming from other nodes. This is extremely hard to estimate at this stage, since it depends on the network topology, the position and number of the data sinks in the network, and on eventual failures that reduce the routing paths. Therefore, this will not be taken into account for the minimum storage requirement calculations. Table 8 calculates the required storage, taking all this into account.

Data type	Quantity	Data (bit)	Total (bit)
Generated by the node	1	692	692
Routing table	1201 x 2	32	76864
TOTAL storage required by the node			***77556 bit***
			9695 bytes

Table 8 – Storage requirements at node level.

It is possible to see that the routing table is the element that requires the highest amount of storage space. The size of this table is proportional to the number of nodes. In total, each node needs to have at least 9695 bytes of storage capability, which is not a standard value for memories. The requirement will therefore be set to 16 kB of memory, which already provides flexibility, in case more housekeeping data needs to be stored. It is important to stress that the requirement sets this as a minimum value, since the definition of the architecture and, in particular, of the routing/data fusion algorithms may reach the conclusion that more space is required.

[BUS04] Each SWIPE node shall have at least 8 kB of storage capacity.

In order to ensure the correct operation of the nodes as a sensing network, the system control module of every SWIPE node shall be provided with a time reference that is common across the entire network. This does not necessarily require precise synchronisation between all nodes when taking measurements for instance, but the time reference shall be the same in order to simplify the time-tagging of the measurements. This reference may be determined at node level or eventually provided by the orbiting satellite.

[BUS05] All SWIPE nodes shall have the same time reference.

Finally, an important interface requirement concerns data communications with the payload module, to match [PAY13]. Since at this stage the node bus architecture is not defined, the system control module shall have at least one data communication interface.

[BUS06] The SWIPE node system control module shall have at least one data communication interface.

6.2 Power Module

Energy for the SWIPE nodes operation may be made available from different sources, such as the Sun or a small nuclear reactor. However, an important conclusion taken from the mission design report [Crosnier et al, 2013] is that the most adequate energy source to power the SWIPE nodes is solar energy. Therefore, in order to use this energy, the nodes must be able to generate power from it.

[BUS07] The SWIPE node power module shall be able to generate power from solar energy.

The mission analysis also showed that the Sun will not be visible during the entire mission lifetime, subjecting the nodes to light and dark periods during one synodic day. Therefore, to ensure operation capabilities during the dark periods, the nodes must have a power storage mechanism.

[BUS08] The SWIPE node power module shall be able to store the generated power.

The stored energy must be sufficient to ensure the node operation. This dimensioning depends greatly on the node power budget, which will be calculated in detail as part of the node architecture task. Based on this power budget, the required power storage capacity and the number of solar cells needed can be determined.

[BUS09] The SWIPE node power module shall store enough power to ensure the SWIPE node operation.

Finally, the power module is responsible for distributing this energy stored by all the SWIPE node modules. The power management scheme will be defined as part of the architecture.

[BUS10] The SWIPE node power module shall be able to distribute power to all SWIPE node modules.

6.3 Communications Module

The communications module is responsible for all communications between the nodes and the outside. This module must support the creation of the Wireless Sensor Network and, when placed in an exit point, the establishment of the satellite link. Since the nodes may need to relay data from other nodes and receive commands from Earth or the orbiting satellite, nodes must have the capability to transmit and receive data.

[BUS11] The SWIPE node communications module shall be able to transmit and receive data.

The network topology information coming from the mission design and summarised in Section 2.4 provides valuable information to define communication requirements. The maximum distance between nodes in the proposed topologies is 500 m. This shall be the minimum distance at which two nodes must be able to communicate. Furthermore, the mission design mentions that a line-of-sight of the nodes may not be possible beyond 1000 m. This gives valuable information for the design. Since communications are only physically possible up to 1000 m, this may prevent that the communications module is unnecessarily overdimensioned.

[BUS12] The SWIPE node communications module shall be able to communicate with another node at a distance of at least 500 m.

The topology also shows that a node may need to communicate in any direction, with any neighbour within range. Therefore, the communications module must ensure an omnidirectional coverage.

[BUS13] The SWIPE node communications module shall be able to communicate with another node in all directions.

As already mentioned, the exit points (i.e. the SWIPE nodes that send the WSN data to the satellite) must be able to communicate with the orbiting satellite, apart from the regular WSN communications. The communications module of these exit nodes must therefore be capable of providing a satellite link as well. Requirements for this link are specified in Section 7.

[BUS14] The communications module of the SWIPE exit points shall be capable of communicating with the WSN and the satellite.

In order to be part of the WSN, the communications module must be able to support the implementation of networking functions. The requirements for the network are defined in detail in Section 7, but the communications module must ensure that this capability is present.

[BUS15] The SWIPE node communications module shall support the implementation of networking functions.

In terms of interfaces, the data that the communications module must transmit or the data it receives are processed at the system control module. Therefore, an internal data interface must exist between these modules.

[BUS16] The SWIPE node communications module shall have an internal data interface.

Finally, it is important for the network setup that the node positions are known, especially considering deployment scenarios that are nor accurate or deterministic. One easy way of achieving this is by using ranging techniques implemented in the communications to determine the relative distance between nodes. This allows each node to know the nodes that are within communication range and, at a higher level (e.g. satellite), to have the global picture of the WSN topology. For this reason, the nodes are required to have such capability.

[BUS17] Each SWIPE node shall be able to determine its distance to all nodes within communication range.

7 Network Requirements

So far, all requirements defined in the previous sections concerned the SWIPE physical node, i.e. essentially hardware. This section will address the network requirements, those that will drive the design of the Wireless Sensor Network and the other two segments to be designed in SWIPE: the satellite gateway (satellite-WSN, at the exit points) and the Earth link (between the satellite and Earth).

As mentioned in Section 3, one of the main drivers of the SWIPE project is scalability. This challenge can be tackled at hardware level, by developing a node that can be quickly and cheaply manufactured in large quantities, but needs to be backed up by a network design that can accommodate a highly-variable number of nodes, in order to be used in as much missions as possible. Since the network scalability concept applies to a number of network nodes that can range from tens to millions, a requirement must be formulated based on the largest number of nodes devised by the reference mission scenario, including the orbiting satellite.

[NET01] The SWIPE network shall support at least 1201 nodes.

In order to properly apply routing algorithms and performance metrics, each network node needs to be uniquely identifiable. The addresses of every network node and how to access them are compiled in a routing table that is stored locally at each SWIPE node.

[NET02] Each SWIPE network node shall have a unique identifier.

Just like the node hardware should be as much as possible tolerant to any transient faults originated by radiation, the SWIPE network must also be tolerant to node permanent failures. This is already an important specification of Wireless Sensor Networks for terrestrial applications, which in Space has an even higher relevance. When talking about thousands of nodes in a planetary exploration endeavour, together with an orbiting satellite and eventually a rover, it is not admissible that one single failure in one node can jeopardise the entire mission and render the rest of the nodes completely useless.

In fact, thinking about large quantities of nodes that may be deployed using rather violent approaches such as deployed from a certain altitude, it is a real possibility that some of the nodes actually don’t survive the deployment phase. This may happen for several reasons. For instance, it may not survive the impact or it may end up in a location that is obstructed by a boulder and is not able to collect energy for operation or ends up being so far away from the rest of the SWIPE nodes that it can’t establish a link with any other node in the network.

Since the deployment strategies may vary depending on the mission and keeping in mind that the network should be as flexible as possible to be used in different scenarios, the SWIPE network shall be designed to prevent this situation and, if one or more nodes in the network is temporarily or permanently disabled, to find another communication route for those that were relaying on the faulty nodes to disseminate their data. The number of node failures that the network can handle depends strictly on the network topology ((n-1)-resiliency property).

The fault tolerance requirement entails i) that the network must be capable of autonomously reconfiguring (see requirement [NET04]) ii) that all the network functions are available even in case of a permanent node failure; therefore, at least two nodes must be capable of playing the exit point role (see requirement [NET06]) and at least two nodes must be capable of playing the data sink role (see requirement [NET07]).

[NET03] The SWIPE network shall be tolerant to node failures.

One basic function that is required for node failure tolerance in the network is the ability to reconfigure itself. When something changes in the network, such as a non-responding node, the surrounding nodes that were relaying their data on the failing node must update their routing tables to find new possible relays within communications range.

On a different note, in order to make the network operation more efficient, it is common to consider multiple criteria to define the routes. This can be made based on the position of the nodes, which in the SWIPE baseline scenario does not change, or can use additional information such as the available power at each node and the power consumption rate. This means that the shortest path may not be the most efficient from a network point of view. To provide this capability to the network architectural design, the network will need to adapt constantly to the varying conditions of the SWIPE nodes and reconfigure itself whenever needed.

[NET04] The SWIPE network shall be reconfigurable.

However, the reconfiguration process needs time to execute. The network reconfiguration algorithm must ensure a certain performance at this level, in order to cope with the mission objectives. The performance driver should be the lowest measurement period of the SWIPE nodes. This way, the network ensures that it can perform its maintenance in time before the next generated data packages are ready to be sent at node level. The minimum measurement period in the SWIPE reference mission is 5 minutes.

[NET05] The SWIPE network reconfiguration time shall not be higher than 5 minutes.

The previous requirements apply to the network as a whole. In the next subsections, more requirements will be derived for the specific SWIPE network segments.

7.1 Wireless Sensor Network (WSN)

The Wireless Sensor Network (WSN) is the most challenging segment of the SWIPE network. It is created by the SWIPE nodes on the planetary surface and has to handle unpredictable node failures, take into account a scalable and usually large number of network nodes and include data processing capabilities to optimise the amount of data that will be handed over to the other network segments.

As mentioned previously, the WSN foresees the existence of three types of network nodes: regular sensing nodes, data sinks and exit points. In terms of hardware they may or may not be different as will be later defined in the architecture, but in the network they are seen as different roles, which may or may not be aggregated at the same physical SWIPE node. The data sinks are super-nodes that collect the generated data from the entire network, process this data and send it to the exit points. The exit points are nodes with satellite communication capability that will receive the WSN processed data and send it to the orbiting satellite, which will relay it later to Earth.

Determining the number of exit points and data sinks and their distribution in the network is part of the network design. This is highly dependent on the positioning of the nodes, which in SWIPE is static, on the amount of generated data and on the routing algorithms used. Depending on the physical node architecture and capability, the number of network nodes on each role may even be adaptive, with nodes taking up tasks as deemed necessary.

From the requirements perspective, it makes sense to define a minimum number of these entities for redundancy purposes. If only one exit point exists and it fails, the WSN is not capable of communicating with the satellite and the whole mission fails. The data sinks are not so critical, but if the network suddenly doesn't have any, the overall efficiency is greatly affected. The node raw data would probably be sent to the exit points directly, which could lead to an operational overload and, ultimately, failure in sending the data to the satellite. For this reason, the network must have at least two exit points and two data sinks.

[NET06] The SWIPE network WSN segment shall have at least two exit points.

[NET07] The SWIPE network WSN segment shall have at least two data sinks.

An important feature of the SWIPE network, which was already mentioned, is the capability of relaying data between network nodes. Without this ability, all nodes would need to be in range of a data sink for the WSN to operate properly and routing would not be necessary. With the selected topology and the maximum communications range defined for SWIPE, this scenario is impossible and therefore the network must support multi-hop communications between nodes out of range.

[NET08] The SWIPE network WSN segment shall support multi-hop communications.

Just like it was mentioned in Section 6.1 that the SWIPE node bus shall support the implementation of data processing and fusion algorithms, the network shall also have this capability. One of the main advantages of SWIPE is the capability of adding this type of data compression techniques to a WSN, in order to reduce the amount of data to be transmitted back to Earth.

At this stage, it is not yet defined how the overall data processing is made in SWIPE. It can be made in several steps, such as node level, after taking the measurements and at data sink level, after collecting the entire WSN data. However, some data fusion or processing techniques may also be applied at network level, during transportation of data from a node to a sink. The feasibility and the relevance of this approach are to be assessed during the data processing studies, but the network shall be capable of supporting such implementation.

[NET09] The SWIPE network WSN segment shall support the implementation of data processing and/or fusion algorithms.

Finally, a requirement should be set in terms of the data rate required in the WSN segment. At this stage it is possible to estimate the amount of data generated by the SWIPE nodes, based on Table 7 and the mission specifications summarised in Section 2. However, more data will be generated for the network operation, between management parameters and network headers that may be added to the messages generated by the SWIPE nodes. This amount of data depends on the network design that will be made later during the project and therefore, to have a baseline reference, a requirement on minimum data rate will be defined based only on generated data at node level.

The first step is to determine the total amount of data generated during two specific periods: during line-of-sight (LoS) with the orbiting satellite and during non-line-of-sight (NLoS), when no communication link with the orbiter can be established. The sum of both gives the total generated data during one satellite orbit period. Reference LoS and NLoS durations are available in Table 6. Information about the data generated by each SWIPE node, including sensor and housekeeping data, and the generation period was already defined in Table 7.

Table 9 uses both to derive total amounts of generated data for LoS and NLoS periods (1083s and 8449s, respectively).

Source	Data on each measurement (bit)	Measurement period (s)	Bulk Data LoS (bit)	Bulk Data NLoS (bit)
Radiation Sensor	132	300	477	3718
Thermal Sensor	84	600	152	1183
Illumination Sensor	156	600	282	2197
Dust Deposition Sensor	84	(4 measurements over one synodic period)	0	336
Housekeeping	312	60	5632	43935
TOTAL generated data at node level			**6543**	**51369**
Number of nodes			1200	
TOTAL generated data in the WSN			***7851600***	***61642800***

Table 9 – Generated data at node level during Line-of-Sight (LoS) and Non-Line-of-Sight (NLoS) periods.

Data on each measurement account for the respective type of data already with the locally generated time headers represented in Table 7. It is assumed as a worst-case that every individual source of data gets a time tag, which may not always be true.

The criterion for defining the minimum data rate is that all data generated during the period where no contact with the satellite is possible (NLoS) must be readily available at an exit point, as soon as the WSN has once again satellite coverage. This would be simply done dividing the total amount of data generated during the NLoS period by the NLoS period. However, the fact that nodes relay data from other nodes means that the same data may circulate in the network several times. This is difficult to estimate at this stage, since it depends on the routing algorithm used, and therefore, just like for the storage calculations, it is not taken into account for the minimum data rate requirement calculations. This is thus given by:

$$\text{Minimum data rate (WSN)} = \frac{61642800\,\text{bit}}{8449\,\text{s}} = 7296\,\text{bit/s} \quad (1)$$

It is important to stress that this doesn't take into account the additional overhead imposed by the network, including the average number of hops, and should be seen as the minimum data rate imposed by the mission. This value needs to (and most probably will) be increased later on the project based on the final network design.

[NET10] The SWIPE network WSN segment minimum data rate shall be 8 kbit/s.

7.2 Satellite Gateway

The satellite gateway segment of the SWIPE network links the exit points of the Wireless Sensor Network and the orbiting satellite. All data generated and processed by the SWIPE nodes will ultimately go through this link. At the same time, this link is the only path that commands coming from Earth are able to take in order to reach the nodes. This requires that the WSN-satellite link supports communications in both directions.

[NET11] The SWIPE network WSN-satellite segment shall be bidirectional.

However, most of the link traffic comes from the WSN and this will be the main driver for designing the satellite gateway segment: this link must be able to send all data generated by the WSN in one satellite orbit during the time that the satellite can communicate with the sensor network. This sets a requirement in terms of minimum data rate, just like [NET10] does for the WSN segment.

Table 9 already determined the size of the bulk data generated during the visibility (LoS) and non-visibility (NLoS) periods. Adding both, it is possible to determine the total amount of data generated during one satellite orbit. Dividing it by the visibility period (LoS period) in Table 6, it is possible to reach a minimum required data rate for the WSN-satellite segment.

$$\text{Minimum data rate (Satellite Gateway)} = \frac{(7851600 + 61642800)\,\text{bit}}{1083\,\text{s}} = 64169\,\text{bit/s} \qquad (2)$$

This data rate is significantly higher than the one required for the WSN, which makes sense, since the satellite gateway will have to handle the generated data from all nodes in less time than the WSN.

[NET12] The SWIPE network WSN-satellite segment minimum data rate shall be 65 kbit/s.

One particular characteristic of SWIPE is that this link will not be designed separately from the Wireless Sensor Network. Previous terrestrial experience of the Consortium has shown that there are advantages to integrate the satellite gateway in the network design and devise routing and optimisation algorithms that look at the network as a whole. During the architecture and design stages the applicability of this approach to the SWIPE scenario will be analysed in detail.

7.3 Earth Link

Finally, the last segment of the SWIPE mission that will be addressed in the project is the Earth-satellite link. Given the huge distances involved in this segment, when compared to the WSN and the satellite gateway, it doesn’t make sense to consider it part of the entire network design. The architecture of this link will be designed separately and its performance is constrained to the existing capability on Earth for long distance space communications.

The most suitable candidate is the European Space Tracking (ESTRACK) network, which consists of several ground-based space-tracking stations. This network is operated by the European Space Operations Centre for the ESA. It handles and facilitates communications from and to ESA spaces probes. This specific worldwide network is composed of ten stations owned by ESA and four cooperative stations. This topology is necessary to maximize the connection duration between space probes and the ground network. In addition, the maximum antenna size is 35 meters to counterbalance the huge free space loss and to allow communication from deep space.

In SWIPE, the Earth-satellite segment needs large receiving antennas to cope with the required performance of the SWIPE mission. As a consequence, the link between Earth and the orbiter must be compliant with the ESTRACK network. The performance evaluation and orbiter design must be then determined taking into account at least the two largest types of antenna of ESTRACK; 35m and 15m of diameter.

[NET13] The SWIPE network Earth-satellite segment shall be compatible with the ESTRACK Ground Station network.

Ideally, the Earth-satellite segment should be able to transmit to the ESTRACK ground station network during one Earth rotation, all the data collected during one Earth day. The Earth rotation period should allow the satellite to see at least once an ESTRACK ground station during this period. However, since this is difficult to assess, no specific requirement on performance will be set for this link.

8 Summary of Requirements

All SWIPE requirements are compiled in Table 10 to Table 13 for quick reference.

Reference	Description
[GEN01]	The SWIPE node total mass shall not exceed 2 kg.
[GEN02]	The SWIPE node housing shall accommodate all physical node modules.
[GEN03]	The SWIPE node shall be designed to survive temperatures between -180ºC and 110ºC.
[GEN04]	The SWIPE nodes shall be designed in order to avoid potential dust harmful effects.
[GEN05]	The SWIPE nodes shall be designed with fault tolerance techniques, as long as they do not have an impact on the node mass.
[GEN06]	The SWIPE prototypes shall cope with the following temperature ranges:
[GEN07]	The SWIPE nodes shall withstand the following vibration loads:
[GEN08]	The SWIPE nodes shall withstand the following static loads (along the 3 axes):
[GEN09]	The SWIPE nodes and network shall be tested in a controlled laboratory environment and in a representative Earth-analogue environment.
[GEN10]	The SWIPE tests shall evaluate the node and network functionality and performance against the SWIPE requirements.
[GEN11]	The SWIPE tests shall enable the validation of the SWIPE concept and the assessment of its viability.

Table 10 – SWIPE General node requirements.

Reference	Description
[PAY01]	The radiation sensor shall be able to detect Single Event Upsets and differentiate them at least at three different energy levels.
[PAY02]	The radiation sensor shall be able to measure the Total Ionizing Dose.
[PAY03]	The thermal sensor shall measure the surface temperature in at least three different points.
[PAY04]	The thermal sensor shall measure the temperature by conduction.
[PAY05]	The thermal sensor shall be able to measure surface temperatures at least between -180ºC and 110ºC.
[PAY06]	The thermal sensor shall measure temperatures at least with an accuracy of ±1ºC and a resolution of ±0.5ºC.
[PAY07]	The illumination sensor shall measure the irradiance in the ultraviolet, infrared and visible spectral ranges.
[PAY08]	The illumination sensor shall measure the irradiance with a 360º planar coverage.
[PAY09]	The illumination sensor shall be able to measure irradiance levels up to at least 1426 W/m2.
[PAY10]	The Dust Deposition Sensor shall be able to measure the amount of levitated dust from the Moon surface.
[PAY11]	The payload acquisition electronics shall provide the sensor measurements in digital form to the system control module.
[PAY12]	The sensor digital measurements shall have a resolution of at least 12 bits and 10 effective bits.
[PAY13]	The payload acquisition module shall have a data communication interface.

Table 11 – SWIPE payload requirements.

Reference	Description
[BUS01]	The SWIPE node system control module shall supervise and manage the operation of the payload, communications and power modules.
[BUS02]	The SWIPE node shall generate housekeeping data with a period not higher than 1 minute.
[BUS03]	The SWIPE node shall support the implementation of data processing and/or fusion algorithms.
[BUS04]	Each SWIPE node shall have at least 8 kB of storage capacity.
[BUS05]	All SWIPE nodes shall have the same time reference.
[BUS06]	The SWIPE node system control module shall have at least one data communication interface.
[BUS07]	The SWIPE node power module shall be able to generate power from solar energy.
[BUS08]	The SWIPE node power module shall be able to store the generated power.
[BUS09]	The SWIPE node power module shall store enough power to ensure the SWIPE node operation.
[BUS10]	The SWIPE node power module shall be able to distribute power to all SWIPE node modules.
[BUS11]	The SWIPE node communications module shall be able to transmit and receive data.
[BUS12]	The SWIPE node communications module shall be able to communicate with another node at a distance of at least 500 m.
[BUS13]	The SWIPE node communications module shall be able to communicate with another node in all directions.
[BUS14]	The communications module of the SWIPE exit points shall be capable of communicating with the WSN and the satellite.
[BUS15]	The SWIPE node communications module shall support the implementation of networking functions.
[BUS16]	The SWIPE node communications module shall have an internal data interface.
[BUS17]	Each SWIPE node shall be able to determine its distance to all nodes within communication range.

Table 12 – SWIPE node bus requirements.

Reference	Description
[NET01]	The SWIPE network shall support at least 1201 nodes.
[NET02]	Each SWIPE network node shall have a unique identifier.
[NET03]	The SWIPE network shall be tolerant to node failures.
[NET04]	The SWIPE network shall be reconfigurable.
[NET05]	The SWIPE network reconfiguration time shall not be higher than 5 minutes.
[NET06]	The SWIPE network WSN segment shall have at least two exit points.
[NET07]	The SWIPE network WSN segment shall have at least two data sinks.
[NET08]	The SWIPE network WSN segment shall support multi-hop communications.
[NET09]	The SWIPE network WSN segment shall support the implementation of data processing and/or fusion algorithms.
[NET10]	The SWIPE network WSN segment minimum data rate shall be 8 kbit/s.
[NET11]	The SWIPE network WSN-satellite segment shall be bidirectional.
[NET12]	The SWIPE network WSN-satellite segment minimum data rate shall be 65 kbit/s.
[NET13]	The SWIPE network Earth-satellite segment shall be compatible with the ESTRACK Ground Station network.

Table 13 – SWIPE network requirements.

References

[Crosnier et al, 2013] Crosnier, M. et al, SWIPE Mission Design Report, European Commission Seventh Framework Programme – Space Theme, Reference: 312826-SWIPE-D2.1-MissionDesignReport, Issue 1.0, September 2013.

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