PROJECT FINAL REPORT

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1 Executive Summary

The potential of Mobile wireless Ad hoc Networks (MANET) is significantly high. MANET applications often happen in infrastructure-less or remote regions where connectivity to the outside world has to be provided by some other means. Satellite is one of the solutions to provide this remote connectivity and sometimes the only solution. On the other hand, Wireless Sensor Networks (WSNs) are made of spatially distributed autonomous sensors, which cooperate to monitor a certain physical or environmental condition and pass their data through a network to a central processing location. In Space, these two concepts can be naturally combined together, as the sensor network can be a hybrid mobile ad hoc network (wireless sensor network with satellite link capabilities), giving the sensors the flexibility to be used in virtually any environment.

SWIPE intended to bring these two terrestrial technologies to space. In order to prepare for manned missions to other planets, it is necessary to monitor permanently the surface environment and have a clear notion of its conditions. Hundreds or thousands of small wireless sensors would be deployed to assure a uniform and sufficient coverage. These autonomous sensors would then create their own ad hoc network while some of them, equipped with satellite communication capabilities, would establish a link between the WSN and the satellite. Data gathered from the sensors would be processed and sent to the satellite and later to Earth.

The first year of the SWIPE project was spent around three main technical and scientific areas: mission design, requirement definition and architecture design. The first was dedicated to the analysis of potential scenarios and justification of the selected one (Moon), as well as to the detailed mission definition, using a SWIPE-based network for Moon exploration. Work also focused on studying potential deployment scenarios of the SWIPE nodes. The requirements definition based itself on the reference mission previously designed and derived node and network requirements that would be used later for architecture, subsystem and network design. Finally, the architecture definition focused on the high-level system decisions at node and network level, designed the satellite gateway and Earth links for the baseline mission and also presented an end-to-end architecture considering all network segments and ensuring consistency among them.

The second period of the SWIPE project included the design, manufacturing, integration and test of the SWIPE nodes and algorithms. Design was divided into hardware (communications module, OBC, power module, payload – which includes sensors and data acquisition – and node structure) and software (network algorithms and data fusion/processing techniques); manufacturing and integration of the hardware and software (implementation) into 1 prototype and 6 nodes; and finally testing, which foresaw laboratory tests, Earth-analogue field trials in Svalbard and an overall evaluation of the results, including some extended simulations/emulations of the software algorithms considering larger networks.

Apart from these activities, which were the core of the technical work for this period, particular care was taken to ensure proper dissemination activities and outreach for the SWIPE project. The project website was maintained, together with a Facebook page, with the major achievements during the project execution. Several scientific and technological papers have been published and major Space conferences have been attended (e.g. IAC, AHS). Consortium partners have also attended relevant events to present SWIPE to target audiences and results have been incorporated by academic partners in their lectures. Additionally, BSc and PhD theses have been carried out in the scope of SWIPE activities.

2 Project Context and Objectives

The potential of Mobile wireless Ad hoc Networks (MANET) is significantly high. The application of MANET to areas such as emergency rescue, scientific investigations or home and enterprise networking, together with the automatic adaptation of the network topology to the field context, make these a great asset in providing local connectivity. MANET applications often happen in infrastructure-less or remote regions where connectivity to the outside world has to be provided by some other means. Satellite is one of the solutions to provide this remote connectivity and sometimes the only solution. Current expectations dictate that satellite will be seen not only as a component of an alternative routing path but also as part of a unique (really integrated) system. On the other hand, Wireless Sensor Networks (WSNs) are made of spatially distributed autonomous sensors, which cooperate to monitor a certain physical or environmental condition and pass their data through a network to a central processing location. These networks, initially motivated by military applications, are used in industry for process and machine health monitoring and appear to be a promising tool in several areas like catastrophe evaluation, fire monitoring, environmental experiments and in other distributed sensing applications.

In Space, these two concepts can be naturally combined together, as the sensor network can be a hybrid mobile ad hoc network (wireless sensor network with satellite link capabilities), giving the sensors the flexibility to be used in virtually any environment. Challenges of merging these two technologies for space applications include developing efficient hybrid MANET communications, integration of these nodes with the sensor itself in a standard, low-cost and reliable manner, adapting the communications to the planet RF environment (attenuations, geography, etc.) and testing different measurement modes: data sink, data pole or by request.

SWIPE intended to bring these two terrestrial technologies to space. In order to prepare for manned missions to other planets, it is necessary to monitor permanently the surface environment and have a clear notion of its conditions. Dozens and up to hundreds or thousands of small wireless sensors could be deployed onto the surface to assure a uniform and sufficient coverage. These autonomous sensors would then create their own ad hoc network while some of them, equipped with satellite communication capabilities, would establish a link between the WSN and the satellite. Data gathered from the sensors would be processed and sent to the satellite and later to Earth. SWIPE aimed to define a mission scenario in detail based on Moon surface exploration, as well as mission and system requirements, and also to perform system level design of the three different communication segments involved: within the sensor network, between the sensor network and the relay satellite and between the satellite and Earth.

However, SWIPE’s main goal was to design and develop 7 node prototypes (1 breadboard model, 3 fully functional nodes comprising both communications and sensors and 3 network nodes, without the sensor payload). The whole system would finally be integrated and evaluated in laboratory and also in one Earth-analogue field test, chosen according to the mission scenario. Extensive research in novel multi-sensor data processing and data fusion techniques was also within the project scope.

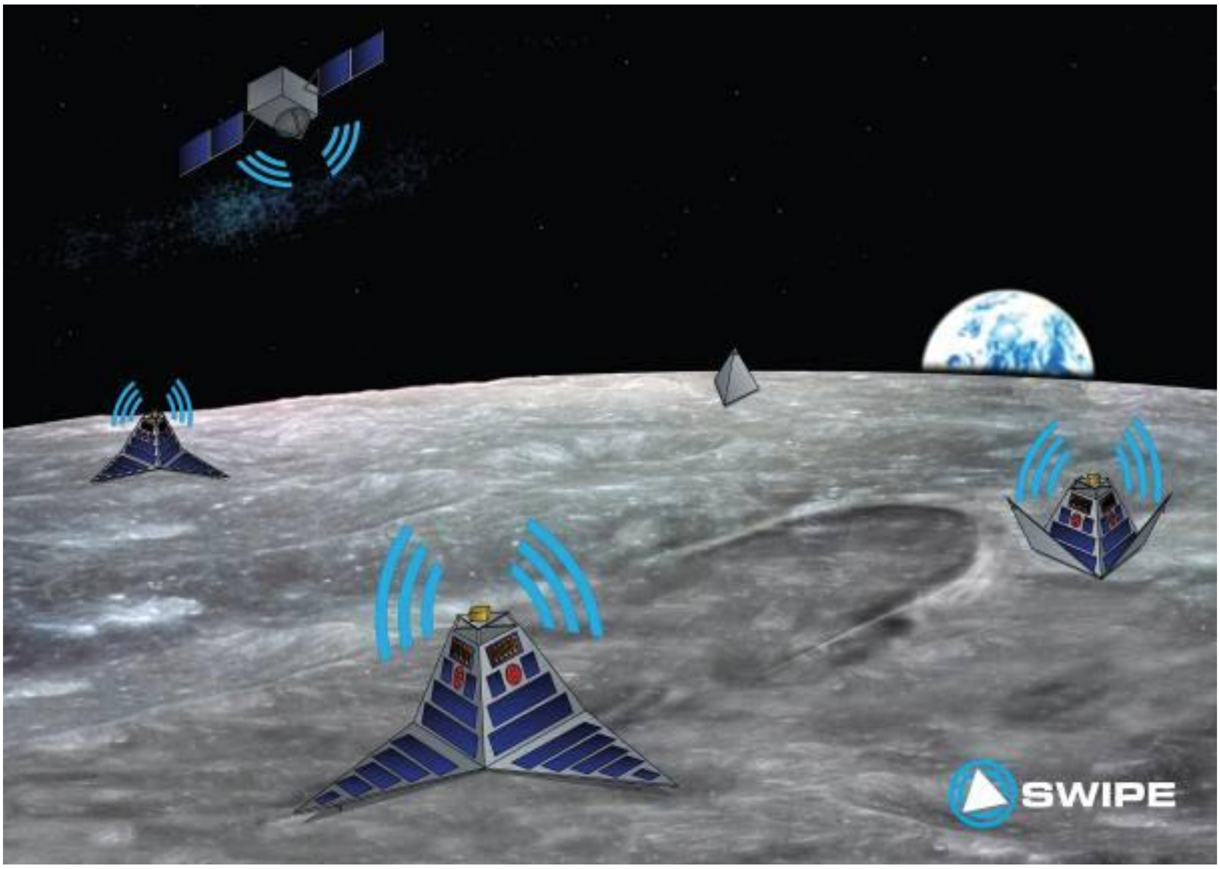

Figure 1 - Planetary surface environment monitoring scenario, using WSN with ad hoc networking and satellite communication capabilities.

2.1.1 Context and Background

Ad hoc networks and MANETs in particular have an enormous potential on terrestrial applications. Its application to areas such as emergency rescue, environmental observation, scientific research, commercial environments, home and enterprise networking, educational applications, military operations, entertainment and location-aware services holds great promises. In an ad hoc network, there are no masters to connect to. Each node may establish a connection with all other nodes in its neighbourhood, enabling those which are not in range to communicate through other nodes acting as relays. This sort of networks is ideal for highly dynamic environments, large quantities of nodes and/or large geographical coverage needs.

Bringing this technology to space enables several different advanced scenarios such as the use a Wireless Sensor Network (WSN) based on MANETs for planetary exploration, for instance. In fact, combining this technology with a network of sensors seems almost natural, since these networks have usually a larger number of nodes and need to cover large geographical areas. There are several possible application scenarios for WSNs referenced in the major agencies' roadmaps. For instance, NASA's programme had a topic in Environmental Monitoring Safety & Emergency Response, where real-time particle monitoring and sensors are included. The European Space Technology Platform (ESTP) roadmap on the other side clearly stated that one of Europe's top-level objectives was the spin-in of technologies and one of the needs is in the planetary exploration, namely in the remote sensing area.

2.1.2 Objectives and expected achievements

SWIPE's main goal is to prove the applicability of ad hoc networking in space and particularly on a planetary exploration scenario, based on a Wireless Sensor Network. Even though the main target of the project was the network and the associated communications, the project complemented this with the development of a set of sensors that will allowed to show the scientific benefit of the SWIPE concept.

After a preliminary assessment the consortium selected a mission scenario based on the Moon, though the network research and sensor development (with some adjustments) done in SWIPE can be applied to other potential surface environments, like Mars for instance. In order to provide a solid backdrop and playground for the research foreseen, the Consortium considered important to perform a detailed mission design and to derive meaningful requirements. The idea was to develop the work as if a true real mission was to be flown in the near future. Based on this, SWIPE performed technical system level architecture definitions, both for the hardware sensor node and the three link segments: ad hoc WSN, satellite- WSN and satellite-Earth. The purpose of such a thorough analysis was to give the WSN a proper communications scenario that could drive its detailed design.

SWIPE then focused on bringing the terrestrial ad hoc expertise to the WSN scenario. The protocol was implemented on a state of the art Software-Defined Radio (SDR) hardware platform, which gave each node the capability of communicating and networking. New and existing terrestrial ad hoc algorithms and routing techniques were further investigated and adjusted to a WSN application and finally implemented on top of the SDR platform. Efficient methods for multi-sensor data processing and data fusion were also addressed in SWIPE, since this is an extremely relevant subject, to remove redundant information and reduce the amount of data to transmit. Another very relevant issue in Wireless Sensor Networks is power and energy. This means that at node level, for example, very high capacity batteries or the capability to recharge is desirable. SWIPE addressed the important issue of power through the network perspective as well, by designing energy-aware algorithms that take into account the battery levels of the nodes to extend the network lifetime as much as possible.

To take the most advantage of the mission design and of this ad hoc technology, SWIPE's objectives included the design of the full node, including a suite of sensors and supporting modules. A meteorological station comprising a set of four sensors was designed taking into account a future deployment, according to the mission design. Power and control modules were developed, to support the interface between the measurements and the network and to provide energy to the node. Although all hardware developed was based on commercial components, space-qualified equivalents have been identified whenever possible.

Finally, all modules were manufactured and 7 node prototypes (1 breadboard model, 3 fully functional nodes comprising both communications and sensors and 3 network nodes, without the sensor payload) were integrated. Extensive testing has been carried out in a laboratory environment and afterwards in an Earth-analogue environment.

In short, the proposed project objectives were to:

- Understand the complexities and needs inherent to a planetary exploration mission, especially the environment variables which could affect and drive the WSN design.
    - Perform a planetary exploration mission design for the surface of the Moon.
    - Design the different communication link segments.
- Develop efficient hybrid satellite-MANET routing algorithms for a planetary WSN scenario.
    - Further develop and adapt existent terrestrial algorithms to space.
    - Choose adequate topologies and study energy-aware routing algorithms.

- Perform multi-sensor data processing and fusion.
  - Develop data processing/fusion/scheduling techniques power and size constrained.
  - Develop data processing and data fusion at both node and network level.
- Develop the 7 node prototypes.
  - Design an SDR platform to support hybrid MANET-satellite communications.
  - Design and develop an innovative meteorological station for space applications.
  - Develop control and power modules.
  - Achieve a compact integration design and configuration.
- Perform extensive tests in high-fidelity environments.
  - Perform preliminary laboratory tests.
  - Coordinate a field test campaign in high-fidelity environment.
  - Analyze and evaluate the WSN functionality and performance.

Table 1 compiles the scientific and technical objectives versus technical achievements.

Scientific and Technical Objectives	**Expected Achievements**	**From WP**
Analyze different exploration scenarios and indentify the variables affecting distributed sensing.	Choose a Moon based mission scenario and derive mission requirements.	WP2
Design a sensor node configuration adequate to the mission scenario.	Systems Design.	WP3
Design of a communications relay link, between the WSN on the planetary surface and a ground station on Earth	Analyse RF protocols (Proximity or Earth based) and establish design of Satellite relay communication to Earth	WP3
Develop an end-to-end architectural design of the communications in a WSN mission.	Design of a communications architecture, including the WSN, WSN-satellite and satellite-Earth segments.	WP3
Adapt efficient terrestrial hybrid-MANET algorithms for a planetary exploration WSN application.	Ad hoc network algorithms to address the WSN problem.	WP4
Apply multi-sensor data processing and data fusion.	Develop mechanisms for processing and fusion the information coming from several sensors.	WP4
Implement the hybrid MANET algorithms on top of the SDR platform.	Establish a MANET between at least three nodes.	WP5, WP6
Improve and adapt a set of sensors to be used as a meteorological station for planetary exploration.	Develop a compact set of four sensors (radiation sensor, illumination experiment, temperature sensor and dust deposition sensor).	WP5
Integrate the communication platform and the sensor in one autonomous node.	Integrate 7 node prototypes.	WP5
Validate the nodes and the concept in a high-fidelity environment.	Perform field tests in Moon-resembling terrestrial scenarios.	WP6

Table 1 – Scientific objectives vs. technical achievements.

3 Main S&T results/foregrounds

The main results of the SWIPE project can be grouped in the following categories, involving mission definition aspects, hardware modules and software development:

- Moon mission WSN design and deployment studies
- Node wireless sensor network algorithms.
- Node data processing and fusion algorithms.
- Node payload sensor modules
- Node communications module.
- Node system control module (OBC).
- Node power generation, storage and distribution module.
- Node housing mechanical design.
- Node petal deployment system.

3.1 Mission design and deployment studies

The first step in SWIPE was to select a planetary exploration scenario and derive a simplified mission design to help drive the SWIPE project requirements. It is extremely important to note that the objective was not to entirely design in detail a possible SWIPE mission, which is clearly beyond the scope of the project, but instead to trade-off and define key parameters that are required to define representative requirements for the project. Taking this into account, the Moon was selected as the baseline scenario, mainly based on the prospects of future targets for exploration and also for its proximity conditions with Earth.

Regarding the mission itself, it comprises SWIPE nodes and an orbiting satellite to be used as relay to Earth. The mission was then designed to define essentially three points: the location of the nodes, the satellite orbit and the sensor package. The node location was selected to be Mare Ingenii on the farside of the Moon. This location was selected based on its rather unexplored landscapes, including swirls, which are very interesting features, from a scientific point of view. Finally, the sensor package selected was based on the scientific relevance and feasibility to implement in small nodes. The selection included a radiation sensor, an UV, IR and visible illumination sensor, temperature probes and a dust deposition sensor.

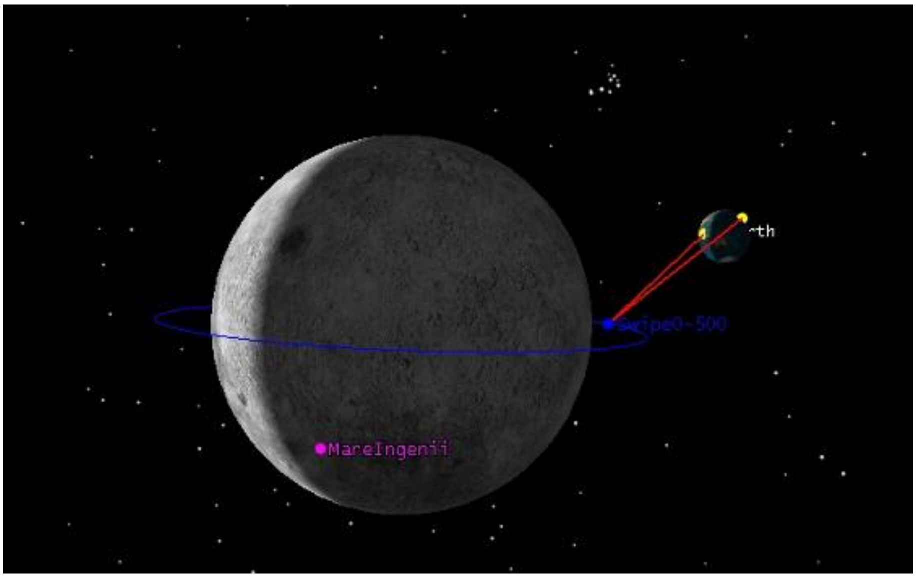

Figure 2 – Selected orbit and landing site for the mission.

An additional mission aspect covered in SWIPE, which certainly has an impact on the selected design drivers, was a deployment strategy study and a launcher assessment for such a mission.

	Minimal coverage	Normal coverage	Extended coverage
Launcher	Soyuz 2-1B	Ariane 5 ECA	Ariane 5 ECA
Option	Each sensor is precisely dropped by a rover	Each sensor is precisely dropped by several rovers	Each sensor is thrown thanks to a quasi-lander
Number of nodes	10-20	50-100	?(>100)
Comments	The rover must be precisely designed to limit the deployment duration	The rover must be designed to limit the deployment duration. Higher complexity for the rovers-to-earth communication	TRL very low and a development of a new technology is costly and time consuming

Table 2 – Deployment selection in function of the coverage of the mission

3.2 *Wireless sensor network algorithms*

The WSN design was based on the existing scenarios and the initially devised requirements and architecture. An extensive review of the current state of the art was done before starting the network design. The network topology issue was envisaged to be based on a clustered approach, to face with large scale networks, and then selected to be based on a Connected Dominating Set (CDS). Since power is a major concern in any space mission, energy-aware routing algorithms have been designed to ensure adequate balancing between nodes and to increase the network lifetime. Moreover, a mechanism to periodically elect the data sinks has been proposed, in order to distribute, in the WSN, the effort of collection, storage and fusion of housekeeping and scientific data generated by the SWIPE nodes. Finally, a specific sensor data aggregation algorithm was designed, with the aim of reducing the amount of data disseminated throughout the network. The topology, routing, data sinks election and sensor data aggregation algorithms have been simulated and evaluated using a MATLAB environment.

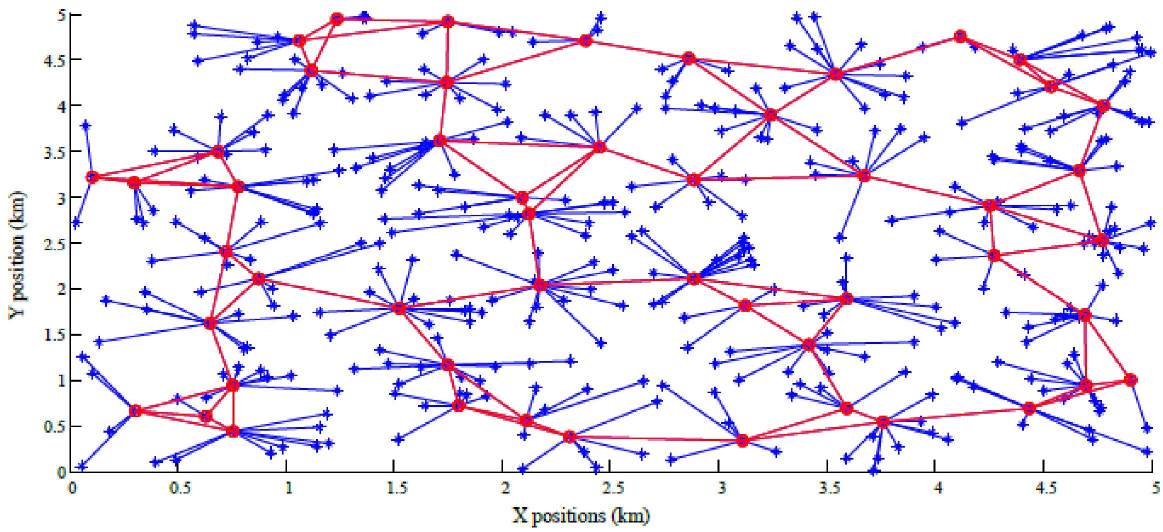

Figure 3 – Clustered network topology used in SWIPE.

3.3 Multi-sensor data processing

The data processing and fusion algorithms were designed to operate both at node and network/global levels and therefore were developed in tight collaboration with the WSN algorithms described above. The design process started with investigating the characteristics of the scientific data (i.e. Thermal, Irradiance, Radiation and Dust data) and the associated data processing/fusion algorithms, as well as of the housekeeping data (e.g. node internal temperature and residential battery level) and its data processing algorithms. Specific attention was given to the identification of data characteristics and corresponding processing strategies for optimising the operating life of the WSN and the accuracy of the sensor data. Both local node and network levels were addressed by applying various data processing algorithms such as Kalman filtering, statistical approaches and consensus algorithms. In addition, a sensor scheduling algorithm was also introduced to reduce the exchange of control/data information between the regular nodes and the cluster heads. A set of models and simulations of the data processing/fusion algorithms was also made, providing valuable inputs for the implementation of those algorithms on the node processor.

3.4 Payload sensor suite

The payload was the design driver of the rest of the node hardware. It includes two main modules: the sensors (radiation, temperature, illumination and dust deposition) and the acquisition and control electronics board that collects and processes the signals from the sensors.

3.4.1 Radiation Sensor

When thinking about the space environment the one element that is most hazardous both to human beings and technological devices is radiation. On Ground, we are shielded by the Earth atmosphere, which prevents most of the cosmic radiation to reach us, but in Space, especially beyond the Van Allen radiation belts, radiation is a major concern. When preparing a Moon mission, either manned or unmanned, having a clear picture of the radiation patterns is extremely important to ensure that systems can support the expected environment. Since the main envisaged goal of a future SWIPE-based mission is to prepare for or give support to both manned and robotic missions to the Moon, including a radiation sensor in the wireless sensor network nodes is extremely relevant. In the particular case of the mission driving the SWIPE project, measuring radiation has a scientific impact as well to understand the behaviour of radiation around the magnetic anomalies (swirls) which are the target of the mission.

The sensor was developed in an ASIC. The technology selected for the design and manufacturing of this ASIC is a European commercial high voltage technology with proven radiation heritage. The ASIC has been made tolerant to radiation using different radiation hardening techniques: Enclose Layout Transistors (ELTs), systematic guard rings to avoid latch-up between nMos and pMos transistors or Triple Modular Redundancy (TMR) among others. The ASIC also includes the auxiliary front-end electronics; a multiplexing and switching system to measure all the integrated sensors and a configurable charge amplifier to provide a normalized output signal. The sensor is capable of measuring two different radiation parameters: TID and SEUs.

3.4.2 Surface Thermal Sensor

Temperature monitoring is not so relevant for planetary science missions, since the Moon models are sufficiently accurate for this particular variable, but it has a mandatory importance for human exploration missions. For this reason, and since their overhead and complexity are extremely small, surface thermal sensors were chosen to be part of the sensor suite of the SWIPE node payload.

The surface thermal sensor is composed by three small probes at the edges of the node petals that will slightly penetrate the Moon surface, once the panels are deployed. This will allow the sensors to have better contact with the soil and will also improve the stability of the measurements. The fact that three probes are used contributes to redundancy but also to assessing a local spatial distribution of temperature, which may be relevant for some types of missions.

3.4.3 Multispectral Irradiance Sensor

The irradiance sensor is also part of the SWIPE node's sensor suite and is dedicated to the monitoring of the lunar illumination environment. The sensors cover the visible (VIS), infra-red (IR) and ultraviolet (UV) bands, which are relevant for both planetary science and human exploration missions. Even though the illumination environment is rather well known, monitoring variations induced by the solar activity or exploring less known areas (such as the swirls, which seem to have different illumination patterns) have led to the inclusion of this type of sensor in the SWIPE payload.

The SWIPE nodes have three multispectral irradiance sensors. Each of these sensors has three different photodiode detectors for the different spectral bands covered (UV, VIS and IR). The three sensors are strategically placed around the node structure, in a triangular configuration, in order to achieve omnidirectional coverage. This is important to monitor all the surrounding environment and identify any potential sources of illumination.

3.4.4 Dust Deposition Sensor

The dust deposition sensor (DDS) measures the dust deposited over a detector over the different stages of the Moon day. The dust behaviour on the Moon is scarcely known and the factors that influence its dynamics remain to be discovered. The thin layer of dust that covers the surface is also extremely harmful for robotic devices and human beings, since it can lead to the degradation of the astronaut suits or the mechanical parts on the landers or rovers. This fact was already identified during the early manned Apollo missions on the Moon. For these reasons, including dust monitoring capabilities in a SWIPE-enabled mission is relevant for both scientific and human exploration purposes.

Since the Moon has no atmosphere and therefore no wind, the dust levitation effects identified in the Apollo missions is still a mystery to be solved, for instance whether the suspension is caused by solar wind or by the lunar magnetic field or by neither of them at all. Since the SWIPE mission is focused on the swirls, these magnetic anomalies may give additional hints about this phenomenon. The measurements will be focused on the terminators (day/night transitions) to assess the thermal influence, but their operational profiles may be changed based on the results obtained.

The dust sensor selected was a dust deposition sensor mainly due to simplicity. Other dust sensors, involving more active measurement techniques, could have been selected instead, but these usually demand more resources (power, mass and volume) which would increase complexity and cost of a SWIPE node and have therefore been discarded. The DDS is placed on top of the node to avoid the interference of the node structure on the dust particle dynamics and therefore increase the representativeness of the results.

3.5 Communications Module

The communications module is the external interface of the SWIPE nodes and provides them with connectivity to the wireless sensor network. It interfaces directly with the OBC for operation and data sending/receiving. The module is composed by an electronics PCB and three patch antennas, disposed in the same fashion as the irradiance sensors, in order to achieve omnidirectional coverage. The communications module is present on every node, though for exit points, which need a separate gateway to connect with the orbiting satellite, the module requires a different RF and antenna design.

This subsystem was designed using Software-Defined Radio (SDR) technology, a state-of-the-art technology that enables most radio functions to be implemented in software instead of hardware. This gives the radio higher levels of flexibility, not only in terms of operating frequencies (allowing for instance to change frequency during the mission, without the need for direct intervention on the hardware) but also in terms of implementing other applications that can take advantage of RF capability.

This is for instance the case for networking in SWIPE. Ad hoc networking algorithms can be implemented on top of the SDR platform without any hardware overhead. This technology is the enabler for creating and maintaining the wireless sensor network. Another relevant application explored in SWIPE is ranging, the capability to determine the relative distance between nodes, valuable for the network topology discovery and routing algorithms operation.

3.6 System Control Module

The system control module is the decision and operations centre of the node. All activities are coordinated by this module, which has interfaces with all other modules: data interface with the payload for commanding measurements, requesting sensor data or changing operation mode; data interface with the communications module for sending data to the wireless sensor network or processing new received messages; and electrical interfaces with the power module to command the power supply to each individual module and monitor the available power resources.

This module is also in charge of the node housekeeping management, constantly monitoring the system health and status and acting accordingly. It processes data coming from housekeeping thermal sensors, for instance. It is also within the system control module that the data processing and data fusion algorithms operate.

Typically, such subsystem in designed as an On-Board Computer (OBC), a central processing entity implemented with a microprocessor. The module also includes memory for storage capability. The system control in SWIPE is based on a low-power MSP430 microcontroller.

3.7 Power Module

The power module is in charge of generating, storing, regulating and distributing power to the different node components. Apart from the power interfaces with all subsystems, this module is operated from the system control module, especially with regards to controlling which subsystems are switched on or off. This module shall also assure that housekeeping data concerning power status of the node is available for the system control.

Power generation uses solar energy and therefore solar cells are used on the outer and inner faces of the node structure, to ensure that power is available for the node initialisation stage (which includes opening solar petals) and then normal operations. Power storage is assured by using batteries placed inside the node for better thermal control. Battery levels are available as housekeeping data for the system control and the networking algorithms in the communications module.

3.8 Housing

The node housing includes the mechanical structure that hosts the SWIPE payload and bus modules and the node petals, deployable mechanical triangles that have embedded solar cells and part of the payload sensors placed as well. The main purpose of this component is to provide accommodation capability to the components, structural resistance to the electronics and environmental protection (especially radiation) to the SWIPE systems.

The structure was devised in a tetrahedral shape for better sensor and communications coverage and node mechanical stability. The inner structure core accommodates the electronic boards, while solar cells, sensors and antennas are placed on the outer faces. The structure was designed trading off structural stiffness, available space for the different node components and mass reduction to comply with mass requirements.

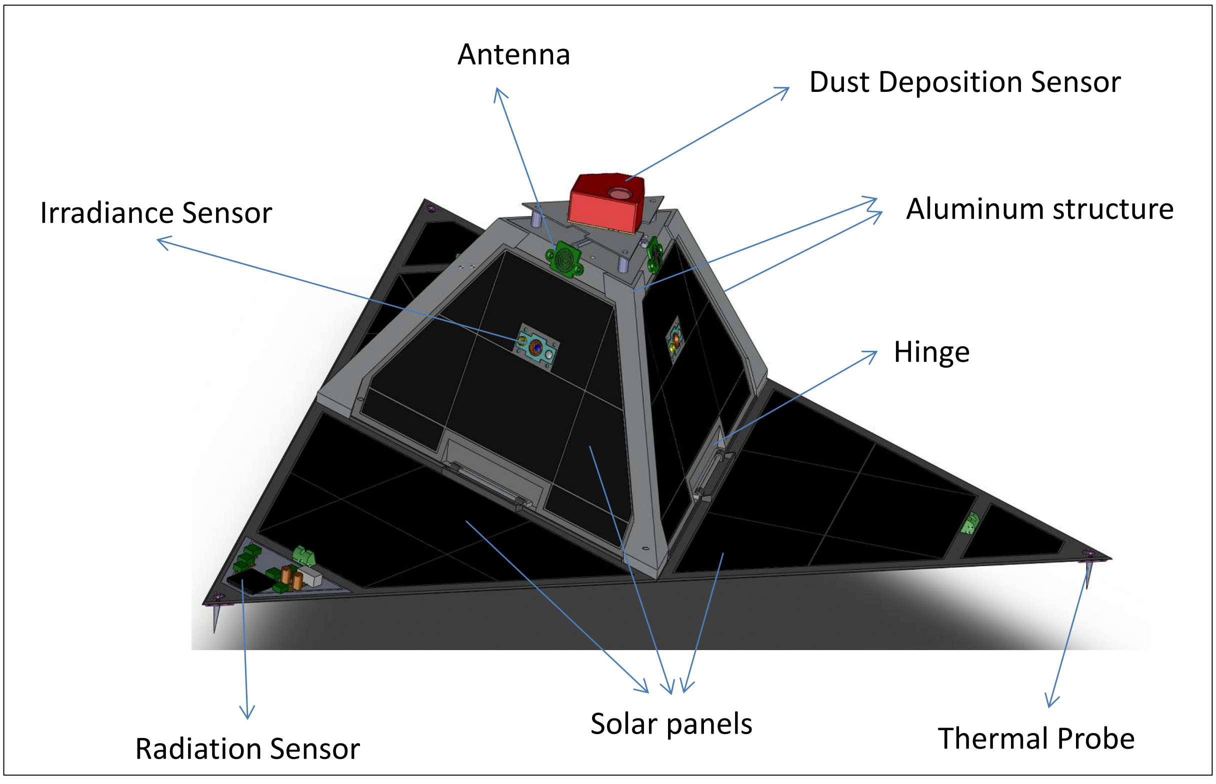

Figure 4 – SWIPE node configuration (open, after deploying panels).

3.9 Deployment Mechanism

The SWIPE nodes have two possible configurations: when closed, the node is a pure tetrahedron and all sensors and electronics are protected from the surrounding environment. This is the initial state of the sensors, during transport and deployment. When the node operations begin, one of the first stages is to deploy the petals, in order to expose the sensors and majority of solar cells to the outside. This is the open state of the nodes and is irreversible.

To ensure that the node petals are opened, a mechanical deployment system was designed for the SWIPE node. It had to be reliable and accurate, in order to avoid a hard collision of the petals with the lunar surface. Otherwise, the deployment generates huge amounts of dust levitated from the surface, which take several days to set back and will most probably contaminate the SWIPE node subsystems during the process. This device is used only once at the initial operations stage and, after deployed, the structure configuration does not change.

The release mechanism used for the deployment of the solar panels is a Pin Puller from the family of actuators based on Shape Memory Alloy (SMA) from Arquimea. Pin Puller non-explosive release actuators are mechanical devices whose function is to retract a pin, used to lock a system that has to be released or deployed for operation. This mechanism is low shock and non-explosive and incorporates a redundant SMA trigger capable of independently operating the actuator. It is reusable and can be reset by hand with the help of a tool, by simply retracting the pin. These release mechanisms are high reliability devices enhanced for space environment and commonly used in spacecraft for solar panels, antennas or payloads deployment.

4 Potential impact, dissemination and exploitation

A significant number of space exploration roadmaps, if not all, include robotic exploration as a necessary precursor to human space exploration. Furthermore, most visions for space exploration envisage the cooperation of humans with robotic explorers and the use of precursor autonomous systems or instruments that could cooperate and ultimately be used and supervised by human explorers (including NASA's roadmap for robotic and human exploration of Mars of 2005 or the ESTP SRA which mentions specifically sensor networks for planetary exploration. Moreover, ESA's wireless technology dossier also considers WSN for planetary exploitation). In order to prepare adequately human exploration of other celestial bodies, adequate knowledge of the target bodies (e.g. planets, moons or asteroids) is mandatory. Currently, the analysis and identification of areas of interest and possible landing locations has relied mostly on remote sensing by orbiters. However remote sensing has its limits and particular local phenomena (e.g. dust, wind, local terrain properties) and in particular knowledge about how these phenomena vary according to space and time (spatial and time gradients) is sometimes hard to acquire precisely with remote sensing. The capability to have "eyes on the ground" would be extremely interesting. Rovers have provided this capability so far very successfully. Still, rovers cannot achieve spatial and temporal diversity simultaneously (either they take measures over time in the same place or take measurements over a certain area but never at the same time). The possibility to deploy wireless sensor networks as a tool to collect spatial and temporal diverse data for a large area and to work as a support element to astronauts is interesting. Additionally, a sustainable human presence in other planets and moons will require that a number of systems, instruments and robotic explorers be networked to facilitate monitoring and maintenance, to exploit lower range communication links. Ultimately, these networked systems should mostly autonomous removing the need for the astronaut to manually configure them or re-configure them anytime a particular part of the network drops out because of malfunctions or lack of power.

SWIPE will have its larger impact precisely in this domain as the main objective of the project is to develop a new WSN architecture and new nodes comprising a sensor suite which the consortium believes is interesting in large variety of missions and environments. Furthermore, and completely in line with the programme's expected impact, SWIPE will take advanced technologies which have been developed for terrestrial applications (including specific research by SMEs) and apply them to research problems in the space domain. SWIPE will overcome technological issues of using such kind of hybrid networks resources to the most (optimising resource usage, enhancing monitoring data collection and fusion, minimizing energy, bandwidth and costs), especially considering the space context. Successful delivery of SWIPE concept and objectives requires significant synergy among research organisations, industrial companies, and broadcasters across Europe. In this context, SWIPE presents an excellent contribution with added value at the European level, which includes partners within the consortium who have strong track records of participating in several European projects, and majority of these projects are relevant to Space initiatives. There exists strong SME presence inside the SWIPE consortium, who illustrate excellent track records in participating and coordinating EU funded projects. The presence of two Universities and Research Institutes will ensure the development of innovative solutions that overcome concretely the actual state-of-art.

4.1 Dissemination activities

A SWIPE **public website** was created and published. The website was continuously updated and used to boost information flow between all entities with an interest in the project: the REA, space agencies, large industry, universities, technological centers, etc. It was also be used to disseminate relevant information to interested parties. The website was available from the first months of the project, to immediately generate awareness of the public audience about SWIPE. The website maintenance activities included the following ones:

- The website was updated as soon as new important information needs to be disseminated to the public audience. In particular, the project news should be dynamically uploaded on the website and delivered, when latest news are available, to the registered mail addresses, for rapid dissemination.
- All the public deliverables, the dissemination material, the published papers, the events attended by the SWIPE consortium and the internal meetings details are posted on the website, as soon as they are available.

In order to monitor the website traffic, a specific **website monitoring tool** was associated to the website (http://www.google.com/analytics/). Moreover, to increase the visits to the SWIPE website, a **Facebook page** linking to the website was setup and put on-line.

A set of **promotional literature** was created to support the marketing strategy, including leaflets and brochures. Such material was disseminated both in electronic-form on the website and in paper format during events organized or attended by the SWIPE consortium.

The results which will be produced during the evolution of the project were used to write **articles and papers** to be presented in international conferences as well as published to journals, magazines, etc. The SWIPE-related papers published include:

- G. Oddi, A. Pietrabissa, “A distributed multi-path algorithm for wireless ad-hoc networks based on Wardrop routing”, Proc. 21st Mediterranean Conference on Control and Automation (MED 2013), June 25-28, 2013, Platanias-Chania, Crete, Greece.
- P. Rodrigues, A. Oliveira, R. Mendes, F. Alvarez, M. Crosnier, T. Vladimirova, F. Delli Priscoli, G. Oddi, A. Pietrabissa, “Wireless sensor networks for moon exploration”, IAF 64th International Astronautical Congress (IAC 2013), Beijing, China, 23-27 September, 2013.
- G. Oddi, A. Pietrabissa, F.Liberati, "*Energy-balancing in multi-hop Wireless Sensor Networks (WSNs): an approach based on reinforcement learning*", 9th NASA/ESA Conference on Adaptive Hardware and Systems (AHS) Conference, Leicester, United Kingdom, July 2014.
- P. Rodrigues, A. Oliveira, F. Alvarez, R.Cabás, M. Crosnier, T. Vladimirova, X. Zhai, H. Jing, G. Oddi, A. Pietrabissa, F. Liberati, " *Space Wireless Sensor Networks (WSNs) for planetary exploration: node and network architectures*", 9th NASA/ESA Conference on Adaptive Hardware and Systems (AHS) Conference, Leicester, United Kingdom, July 2014.
- X. Zhai, H. Jing, T. Vladimirova, "*Multi-Sensor Data Fusion in Wireless Sensor Networks for Planetary Exploration*", 9th NASA/ESA Conference on Adaptive Hardware and Systems (AHS) Conference, Leicester, United Kingdom, July 2014.
- F. Alvarez, D. Millen, C. Rivera, C. Benito, J. Lopez, D. Fernandez, L. Moreno, *“New approaches in low power and mass payload for Wireless Sensor Networks (WSNs) for lunar surface exploration”*, IEEE SENSORS Conference, November 2014.
- G. Oddi, A. Pietrabissa, F. Liberati, A. Di Giorgio, R. Gambuti, A. Lanna, V. Suraci, F. Delli Priscoli, “*An any-sink energy-efficient routing protocol in multi-hop Wireless Sensor Networks for planetary exploration*”, submitted to the International Journal of Communication Systems, Special Issue - Energy Efficient Networking, Wiley Online Library, Online ISSN: 1099-1131.
- A. Pietrabissa, G. Oddi, F. Liberati “*A distributed algorithm for ad-hoc network partitioning based on Voronoi tassellation*”, submitted to the Control Engineering Practice (CEP) journal, Elsevier, ISSN: 0967-0661.

- F. Liberati, G. Oddi, and A. Pietrabissa, "*A Lightweight Sensor Scheduling Algorithm for Clustered Wireless Sensor Networks*", submitted to the 23rd Mediterranean Conference on Control and Automation (MED 2015), to be held in Torremolinos, Spain, on June 16th-19th, 2015.
- A paper, written by ULEIC, was presented by Prof. Tanya Vladimirova at the *Sixth International Conference on Emerging Security Technologies* Braunschweig, Germany, during 3-5 September 2015 and published in the conference proceedings. The website of the conference is available at the following link: http://www.est-conf.org/est2015/ Title and Authors: X. Zhai and T. Vladimirova, "Data Aggregation in Wireless Sensor Networks for Lunar Exploration using Data Aggregation Algorithms in Wireless Sensor Networks for Planetary Exploration".
- P. Rodrigues, A. Oliveira, F. Liberati, G. Oddi, A. Pietrabissa, F. Alvarez, R. Cabas, T. Vladimirova, X. Zhai, M. Crosnier, "*Moon exploration using Wireless Sensor Networks: from design to test*", 66th International Astronautical Congress 2015 (IAC 2015), Jerusalem, Israel,12th-16th October, 2015.
- F. Alvarez, P. Rodrigues, P. Sinogas, A. Oliveira, T. Vladimirova, X. Zhai, F. Liberati, G. Oddi, A. Pietrabissa, D. Milen, C. Rivera, M. Crosnier, L. Moreno, "*Low power lightweight micro-meteorological station for Wireless Sensor Network based space exploration*", 66th International Astronautical Congress 2015 (IAC 2015), Jerusalem, Israel,12th-16th October, 2015.
- A. Pietrabissa, G. Oddi, F. Liberati "*A distributed algorithm for ad-hoc network partitioning based on Voronoi tassellation*", submitted to Ad-hoc Networks journal, Elsevier, ISSN: 1570-8705. The paper has been preliminary accepted subject to revisions.
- F. Liberati, A. Pietrabissa, A. Di Giorgio, V. Suraci, F. Delli Priscoli, "*An Opinion Dynamics Model with Applications to Data Fusion in Wireless Sensor Networks*", in preparation.
- A paper, written by ULEIC, was accepted for publication by the AIAA Journal of Aerospace Information Systems, previously known as the *AIAA Journal of Aerospace Computing, Information and Communication*. The website of the journal is available at the following link: http://arc.aiaa.org/loi/jacic. Title and Authors: X. Zhai and T. Vladimirova, "Efficient Data Processing Algorithms for Wireless Sensor Networks based Planetary Exploration".

SWIPE presentations in relevant events, included:

- Presentation of the SWIPE project in the "Workshop: Innovative Satellite Technologies and Perspectives for Aerospace applications", held in Rome the 12th March 2015 and organized by the Engineers Association of Rome – Complex Systems Engineering Committee. The audience was composed by more than 20 people (engineers in various sectors such as electronics, systems, telecommunication, mechanics, etc.). Some successful projects from the FP7, in the field of space technologies, were presented, including the SWIPE project.
- Prof. Tanya Vladimirova gave a key-note address "Challenges of Embedded Systems for Mission Critical Applications", at the *5th International Conference on Emerging Security Technologies (EST)*, on the 12th September 2014 in Alcala de Henares, Spain. As part of the presentation she introduced the concept of the SWIPE project and outlined its main developments, in particular, she provided details about the data fusion work.
- Prof. Tanya Vladimirova gave several research talks and lectures to prospective students, their parents and visitors during *Open Days of the Department of Engineering* on a regular basis throughout the review period. In these talks and lectures she presented a description of the SWIPE concept and objectives as well as its main technical developments, spreading the word about the project.

- F. Alvarez (ARQ) was the co-chair of the "A4L-F: LOW POWER SOLUTIONS" session and presented the following paper: "*New approaches in low power and mass payload for wireless sensor networks (WSNs) for lunar surface exploration".*
- Corporate presentations in different events:
    - Space Industry Days in Paris (4-5 Feb 2015).
    - Spain at CERN, CERN (27- Oct-2014).
    - H2020 Space Infoday in Porto (25 Feb 2015).
- Participation in the call for Ideas "Space Exploration as a driver for Growth and Competitiveness: opportunities for the private sector" for ESA and participation in the CFI information Day organized on April 28 at ESTEC.
- Participation through a presentation on the Eurospace Exploration Workshop that took place at ESTEC on April 29-30th with the objective of promote SWIPE technology in future ESA road-map for space exploration.

SWIPE presentations in the context of academic lectures and courses, included:

- Set of seminars in the context of the course "Control of Communication and Energy Networks", within the Master in Control Engineering of the University ofRome Sapienza, related to the academic year 2015-2016 (the total audience was about 70 students).
- Presentation of the SWIPE project during the lessons of the courses on automatic control "Controlli Automatici" (Automatic Control) and "Fondamenti di Automatica" (Automatica Foundations) held at the University of Rome "La Sapienza", (the total audience was more than 100 students).
- Preparation of a set of presentations for the course "Controllo e Gestione delle Reti" (Network control and management), held within the on-line university "Università degli Studi eCampus". The students of the course were about 10. The fundamentals of WSN and MANET routing algorithms have been presented to the students, in both video lessons and physical seminars.

SWIPE-related theses and degrees include:

- PhD course of Mr. Francisco Álvarez (working in the Arquimea company) progresses appropriately. This PhD course, within the University Carlos III of Madrid is closely related with SWIPE project work and its results are additional inputs for the activities of the project including dissemination activities.
- CRAT supervision of a student of the Bachelor Degree course in Telecommunication Engineering of the University of Rome "La Sapienza" who terminated her thesis during the period covered by the project. Francesca Costanzo, "*Progetto di un algoritmo per l'elezione di nodi data sink in reti di sensori wireless*", December 2014. This thesis focused on data sink election in WSNs and was mainly related to the activities of WP4.1.
- CRAT supervision of a student of the PhD student Federico Lisi, of the doctorate school in "Automatica, bioingegneria e ricerca operativa" (ABRO) the University of Rome "La Sapienza"; his work in SWIPE was focused in the implementation of the virtual machines used in the tests described in Deliverable 6.3 and in the paper "*Testing of a routing algorithm for wireless sensor networks with applications to planetary exploration*", presented at the 2015 International Astronautical Congress (IAC-2015).

4.2 Exploitation plan

Space technology follows a standardised development and maturing process based on Technology Readiness Levels (TRL). The process starts with fundamental research and concept validation using prototypes in relevant environments, which are the stages covered in SWIPE. After the concept validation, the technology needs to undergo a space qualification campaign, involving environmental and robustness testing in space-equivalent conditions. Finally, the technology is considered to be flight-proven once it is validated successfully in space and from there on it gains space heritage.

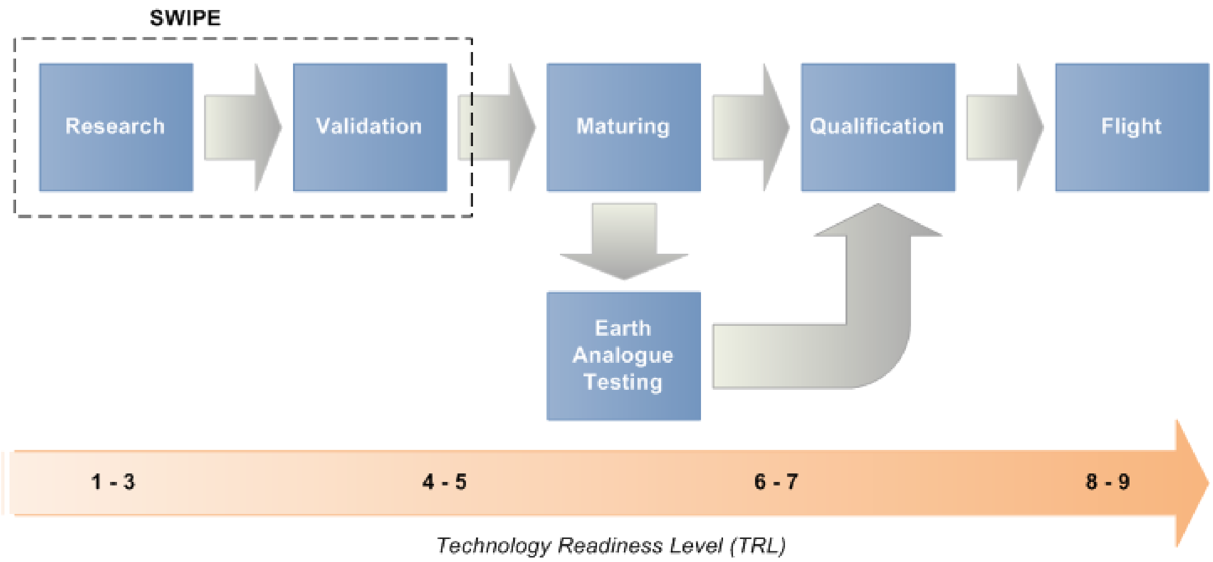

Figure 5 – Typical space technology evolution and development phases.

Undergoing this process is a required condition to bring new technology to the space market. It is a conservative, expensive and slow approach, being challenged nowadays by new mission types, especially those based on small satellites, which propose cheaper and faster access to Space. However, given the fact that the SWIPE concept requires a rather complex mission, the approach in Figure 5 is being considered as a baseline for the SWIPE exploitation strategy. However, during the exploitation task, other approaches were considered, including the latest trends in affordable space missions and eventually new models, and their applicability to SWIPE.

As mentioned above, by the end of the SWIPE project the two first steps shown in Figure 5 were already covered. The Consortium will have to mature the technologies, testing them in Earth analogue scenarios and pursue qualification of the design and look for flight opportunities to achieve a flight-proven readiness level (TRL9). Once achieved, the technology is qualified and a SWIPE mission could be devised and included in the space exploration roadmaps of the major Space Agencies around the world. As mentioned, the process is strenuous and long, requiring large investments and a long-term vision to be successful.

5 Website and contacts

More information about the project is available at http://space.tekever.com. The main contacts for SWIPE results on each partner are provided below:

TEKEVER (Coordinator)
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Mr. Philippe Boutry (philippe.boutry@astrium.eads.net)

University of Leicester
Prof. Tanya Vladimirova (tv29@leicester.ac.uk)

University of Rome, CRAT
Dr. Antonio Pietrabissa (pietrabissa@dis.uniroma1.it)

6 Ethics screening

At the request of the ethical screening that SWIPE was subject to, the consortium has prepared clarifications that were included in the Description of Work. The following subsections make a final update based on the project execution and results.

6.1 Issue 1 – Dissemination and exploitation of SWIPE with respect to terrestrial applications and dual use

SWIPE's dissemination and exploitation plans have primarily focused on the space domain and space players and stakeholders. This is where the bulk of the effort and investment from the Consortium partners was. Dissemination of project results targeting applications other than those in the space domain have been avoided. Concerning the exploitation of SWIPE, the Consortium plans to exploit the developed technologies in the space market (which is precisely the topic's and the coordinator's purpose – to bring terrestrial SME research into the space domain and to encourage the coordinator's involvement in the space market).

Particularly, no dissemination and exploitation of SWIPE results has targeted military applications or military users. Additionally, whereas the concept of a Wireless Sensor Network that connects to the outside world using a satellite link may be applied in defence environments, SWIPE's technology development is too specific and dedicated to the space conditions (various planets, different radiation environments, different radio propagation environments, different atmospheres and conditions of pressure, humidity, temperature) to be directly useful or applicable for military purposes. Therefore, the concept demonstrated by SWIPE would require substantial rework and a new research focus in order to be even considered, let alone used, in military applications.

It should be noted that the SWIPE concept was built upon previous work in sensors, sensor networks and hybrid ad-hoc satellite networks carried out by the partners in the civilian domain. The focus during the project has always been on the spin-in of terrestrial technology to space and not the inverse (spin-off of space technology to terrestrial applications).

6.2 Issue 2 – Use of sensitive or classified information, materials or techniques in SWIPE

The Consortium confirms that **NO** sensitive or classified information, materials or techniques has been applied or studied in SWIPE.

6.3 Issue 3 – Terrestrial applications in SWIPE, consideration of the European Data Protection Directive and Crypto concept

As previously mentioned, the main target and focus of SWIPE was the application of the hybrid Wireless Sensor and Satellite Network based on ad-hoc networking to the exploration of planetary surfaces, in line with European space exploration roadmaps. Hence, no terrestrial application of SWIPE was considered during the project and the environments where SWIPE will be applied (other planetary surfaces such as the Moon, Mars or asteroids) do not support human life.

Any potential application and implementation of the SWIPE concept to terrestrial applications has been completely outside the scope of this Project. Therefore, the Consortium firmly considered that, given the Project's focused target on space exploration applications, it was neither necessary nor suitable to develop a crypto concept.

In fact, no sensitive data has been generated throughout the project. Nonetheless, the Consortium has abided to the applicable data protection legislation.

6.4 Requirements

The consortium hereby confirms that no field tests have taken place in developing countries. The field trials were carried out in the Svalbard Archipelago, under sovereignty of Norway, which has an already existent infrastructure built for researchers. All required authorisations have been granted and no vulnerable or protected ecosystems have been threatened.