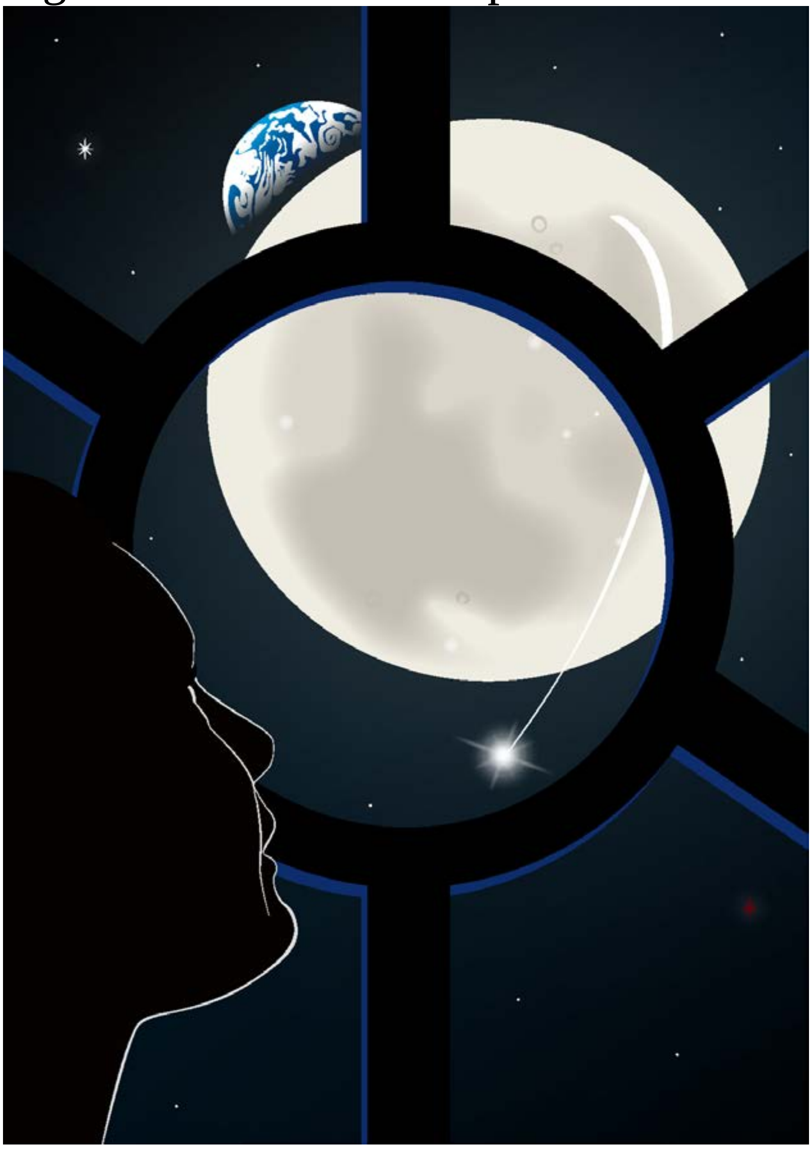
ESA UNCLASSIFIED - For Official Use

estec

European Space Research
and Technology Centre
Keplerlaan 1
2201 AZ Noordwijk
The Netherlands

Research Opportunities on the Deep Space Gateway: Findings from the Workshop and Call For Ideas



Prepared by	**James Carpenter and the DSG Science Advisory Team and workshop Session Chairs: Clive Speak, Alexander Chouker, Monica Talevi, Rumi Nakamura, Andrea Santangelo, Ian Crawford, David Cullen, Ben Bussey, Jessica Grenouilleau**
	HRE-S
Reference	**ESA-HSO-K-RP-0284**
Issue/Revision	**1.1**
Date of Issue	**07/02/2018**
Status	**Approved**

European Space Agency
Agence spatiale européenne

Approval

Title Research Opportunities on the Deep Space Gateway: Findings from the Workshop and Call For Ideas	
Issue Number 1	**Revision Number** 1
Author James Carpenter and the DSG Science Advisory Team and workshop Session Chairs: Clive Speak, Alexander Chouker, Monica Talevi, Rumi Nakamura, Andrea Santangelo, Ian Crawford, David Cullen, Ben Bussey, Jessica Grenouilleau	**Date** 07/02/2018
Approved By	**Date of Approval**
Bernhard Hufenbach	Bernhard Hufenbach Digitally signed by Bernhard Hufenbach Date: 2018.02.26 10:48:48 +01'00'

CHANGE LOG

Research Opportunities on the Deep Space Gateway: Findings from the Workshop and Call For Ideas	Issue Nr.	Revision Number	Date

CHANGE RECORD

Issue Number 1	Revision Number 1		
Reason for change	**Date**	**Pages**	**Paragraph(s)**

DISTRIBUTION

Name/Organisational Unit

Table of contents:

1 INTRODUCTION

Between August and October 2017 ESA held a call for research ideas [RD1] from the European research community to inform the development of the Deep Space Gateway (DSG); a spaceship in lunar vicinity, which will host crewed missions and operate without crew in between. The DSG is planned to be built and operated during the 2020's as humanity's next step beyond Low Earth Orbit and out into the Solar System.

The more than 100 inputs received on the scientific and other research which could be performed on this platform were discussed and consolidated at a workshop at ESA ESTEC, in the Netherlands, on 5th and 6th December, which was attended by more than 200 people.

The end product of this consultation is a compendium of ideas for utilisation [RD2] and a collection of findings and recommendations, contained within this document, which highlight the major research opportunities and the technical aspects upon which realisation of these opportunities depends.

2 INTRODUCING THE DEEP SPACE GATEWAY

The Deep Space Gateway is being established as a strategic platform, from which human exploration of the Solar System can set forth. Its location in the lunar vicinity, and outside of the Earth's deep gravity well allows it to be used as a staging post for exploration missions to the lunar surface and eventually to other deep space destinations including Mars. It is also a platform in a location where the human and technological challenges of long duration human missions in deep space can be investigated and addressed. The platform is being prepared through an international cooperation led by NASA and the partners agencies of the International Space Station (ESA, JAXA and CSA and Roscosmos).

The technical definition of the DSG is driven by the technical needs of preparing deep space human exploration. It could also support opportunistic scientific research. This research could relate to a wide range of scientific disciplines. Investigations related to these various research areas will carry with them specific technical implications for the DSG.

3 SUMMARY OF FINDINGS

This section presents a consolidated summary of the findings in the research areas of Life Sciences, Solar System, Lunar and Earth Sciences, Physical Sciences and Astronomy, and Technology. Common themes and overarching technical needs and dependencies are identified. These represent the aspects which need to be considered as the highest priority in order to enable research to be performed on the DSG.

3.1 Research areas of interest

An extensive collection of research ideas was submitted and presented in response to the Call for Ideas [RD1] and the following workshop. Of note are the diversity of research topics that could be addressed on the DSG, subject to the availability of sufficient resources and capabilities and noting that such availability will be limited, in particular during Phase 1 of the DSG as envisaged. A complete compendium of the ideas received is contained in RD2.

The research areas have been grouped according to research disciplines:

- Life Sciences
- Solar System, Lunar and Earth Sciences
- Physical Sciences and Astronomy
- Technology

This grouping seeks to combine the domains considered in the ESA Science Working Groups (Life Sciences, Physical Sciences, Solar System, Astronomy) with the distribution of research topics as submitted in response to the call.

The approaches proposed for implementing the research can be considered as cross cutting themes, which are common across research domains. These have been identified as:

- Lunar surface access and operations
- Sample return from the Moon (or other Solar System bodies)
- External passive exposure
- External pointed observation
- External small sat and CubeSat deployment
- Internal experiments within the habitable volume

A challenge is to define common capabilities and interfaces for each research approach that meet the needs of diverse investigation types for each research discipline. The identified technical needs are reported in Section 3.2. A potential approach to research platforms and interfaces is presented in Section 3.4.

3.2 Technical options and dependencies

This section describes general technical findings including the major technical dependencies for realisation of research on the DSG.

3.2.1 Crew time

For the research activities presented there was generally little need for extensive crew activity. For many experiments crew activity is limited to deployment of experiments or the retrieval of experiments and samples.

Exceptions may exist for some life sciences work although this requires more detailed analysis. Opportunities may exist for in-situ analysis of samples for which there may be a time dependency on the results, prohibiting analysis after return to Earth.

3.2.2 External access and facilities

Many possible experiments require access to the exterior of the DSG and external mounting points for these payloads are needed. Some of these external payloads require egress from the controlled environment of the pressurised volume before external exposure and ingress into the pressurised volume after exposure. These experiments may then be returned to Earth. For these experiments airlock access to the exterior is required. It is noted that the stated dimensions of the airlock place major constraints on the sizes of payloads that can be considered. A larger airlock than that notionally planned would be beneficial.

Other experiments may be transported without pressurisation and could be attached externally without passing through the pressurised volume and may not require later ingress.

External experiments may be passive, requiring exposure to the local environment with knowledge of the pointing (with varying quality) and local event history during exposure, or active pointing, requiring specific pointing directions during exposure.

The externality of the DSG could also be considered as a location for storage of equipment and facilities, avoiding unnecessary use of the limited internal volume.

3.2.3 Internal facilities

The approximately 1.5m^3 of interior volume expected to be available for science inside the DSG is considered to be very small but is useable for research. It is necessary to clarify how this volume is distributed inside the DSG. A preference would be for a single volume made available for science. If this volume were then made available in a modular way so that experiments of different sizes could be accommodated within it, with a standard interface and perhaps standard modular form factor (e.g. CubeSat unit model) then this could allow optimum use of the space and accommodate experiments of different sizes. In order to secure the longer term utility of the DSG for research its design should anticipate and enable future growth in research capacity and capability.

In addition, the use of the internal volume for science when not in use for astronaut habitation should also be considered.

Common interfaces should be defined for all internal payloads.

Research would benefit significantly from the availability of a centrifuge system to provide a 1G gravity control facility for comparison with microgravity experiments or to isolate effects that are not gravity dependant.

It is also important to establish a clear understanding of the microbial ecology of the interior.

3.2.4 Power and data handling

It was found that a centralised data handling, storage and TT&C subsystem is required for payloads to handle and distribute uploaded commands and downloaded data and telemetry. This subsystem will need to be able to process and store raw data from experiments and forward to Earth when communications links allow. The sizing and requirements for this subsystem will be driven by the data volumes and rates for the various payloads, the downlink bandwidth and availability for payloads and the need for real time or near real time interaction between ground and some payloads. These needs are not yet defined but expectations are that data volumes will be driven by imaging.

The nominal power bus of 120V DC is not considered appropriate for payloads. A dedicated power interface is required, which operates at a lower voltage. 28V is a typical operating voltage for payloads.

This data interface should be made available for payloads located both inside and outside of the DSG.

3.2.5 Robotics

In order to deploy, retrieve and service external payloads there is a need to have external robotics capabilities, perhaps in the form of an external robotic arm. A generic User Interface for robotics was identified as a high priority capability. This would provide a human-robot interface that would allow operation of a diverse set of robots, locally at the DSG or elsewhere, in particular on the lunar surface. The interface would need to be versatile and adaptable to fit the different operational and user requirements for the various different kinds of robotic systems that might be operated from within the DSG.

3.2.6 Communications

For research applications the communications with Earth need not be continuous but must be reliable, predictable and have sufficient bandwidth and data volume to meet the needs of the envisaged payloads. It is important to note that post ISS there is an expectation for high data rates from the research community. Moreover, there is an ever growing expectation amongst the public for high data volume products, in particular high resolution streamed video products and an increasing expectation of products that allow interaction and immersion. Effective public engagement in the mid 2020's will undoubtedly require that such products can be produced and communications systems should be established with this in mind.

Of particular note is the role that could be played in providing a telecommunications relay from the lunar surface to Earth. The existence of such a relay is an enabler for a number of surface mission types, in particular those to the unexplored lunar far side, and would be mission enhancing for missions to the lunar polar regions.

3.2.7 CubeSats and microsats

A number of research, commercial and operations supporting activities could be enabled by the ability to deploy small sats such as CubeSats. To enable this the DSG would need to have a means of receiving CubeSats and then deploying them. For some CubeSat and small sats an additional capability to support local communications would be needed along with the ability to support navigation around the DSG.

3.2.8 Lunar surface access

DSG enabled access to the lunar surface and the return of lunar samples would yield a tremendous and diverse scientific return and address multiple high priority scientific topics across multiple disciplines. Areas where the DSG could support such science include:

- providing communications relay to Earth,
- providing teleoperations for robotic systems with low latency from the DSG to the lunar surface,
- mission staging for surface access,
- lander fuelling or refuelling for reusable landers and ascenders, retrieving and returning samples from the lunar surface,
- screening of samples before return to Earth (if required) or performing time or environment critical analyses (e.g. on samples containing volatiles).

The Human-Enhanced Robotic Architecture and Capability for Lunar Exploration and Science (HERACLES) mission concept, currently under study by a number of agencies, was highlighted as a good example of what could be done. It was identified that several different and complementary approaches could be taken to lunar surface access including precursor-human missions such as HERACLES, recurrent missions, re-flying capabilities to multiple sites for different science and ultimately human missions.

3.2.9 Orbits

The suitabilities of the notional Near Rectilinear Halo Orbit (NRHO) and Halo orbit around the second Earth-Moon Lagrange point need to be analysed in detail for different science applications. For many scientific investigations, the orbits are acceptable. For remote sensing experiments and deployment of some of surface platforms these orbits may prove to be unsuitable.

3.2.10 Research funding and Announcements of Opportunity

In order to realise the opportunity to perform research the timely initiation of activities is critical and the release of an Announcement of Opportunity should be prepared soon. The short time scales will require that interfaces are well defined and that heritage and maturity will be key selection parameters. Any call will need to be supported with a clear scheme for financial support.

Also essential is a clear definition of the governance of the resources available on board and the way that this will be shared between the partner agencies.

A goal should be to have feasibility studies during 2019, allowing a selection in 2020 ready for implementation and utilisation during Phase 1, notionally ending in 2026.

3.3 General findings

3.3.1 Research as a beneficiary of the DSG

The DSG is an infrastructure which presents opportunities for research. Research and science do not in themselves justify the infrastructure but can contribute to an overall business case.

The nominal interfaces as described in the call are useable with some exceptions, but there should be a presumption of future expansion that is designed in and planned for. Detailed assessment of specific research areas and the needs will be required to identify the detailed needs of research interfaces.

There is a general need to understand and quantify the expected external environment in terms of its chemical and electromagnetic cleanliness.

3.3.2 Education as a beneficiary of the DSG

The DSG offers excellent opportunities for education and for the inspiration of a future generation of scientists and engineers. It should be noted however that outreach and education are not the same thing. Education needs to be targeted as a specific area. Outreach and public engagement are also important but need a dedicated approach, independent from but synergistic with that applied to education.

Education opportunities can begin during the development of DSG and need not wait until the platform is operational. It should be an objective to find ways of providing educational access to the development process. Provision should also be made for educational activities during flight. These need not be crew time intensive or dependant. An example is the use on the ISS of Raspberry Pi and similar approaches could be taken. These initiatives should be considered at both platform and payload levels and should include access to professional data sets and know-how.

3.3.3 The need for public engagement

The DSG should mark the beginning of a new era in space exploration and marks the furthest distance from Earth that humans have ever travelled. There is a tremendous opportunity to engage the public and to bring them along for the journey ahead. However, it is noted that public engagement will also need to focus on explaining the context for the DSG and its broader role for exploration and sustainability. Realising the benefits of the DSG will therefore require a high profile, coordinated and engaging public communications effort.

3.3.4 International cooperation and coordination

International coordination is an enabler and a benefit. In order to maximise the opportunity detailed international coordination will be needed. An objective should also be to use the opportunities for research as a means to increase participation and extend the international cooperation.

3.3.5 Integrating DSG research into deep space human exploration

Studies performed on the DSG that are intended to feed into and support deep space missions for humans (e.g. to Mars) may be undertaken. However, it is not clear that meaningful results could be available in a timeframe which is consistent with the apparent need dates indicated by current planning for prolonged human missions in deep space environments.

3.4 Possible research platforms on the DSG

Consolidating the various needs of different payloads and experiment types leads to the identification of a group of distinct platforms (interface types) which could be considered for the DSG, with different locations and interfaces.

These can be summarised as:

1. **External passive exposure platform** for samples, materials and technologies, accommodating samples of materials and exposing them to the external environment. The platform would have zero to low power and data requirements, but externally exposed samples would need to be retrievable and returnable to Earth.
2. **External environment and effects exposure platform**, accommodating monitoring instrumentation for environment and effects measurements, without strict pointing requirements and for which data and power volumes and rates are modest. Instrumentation would need to be attached externally but retrieval and return might not be a requirement. In this case however requirements for disposal muct also be considered.
3. **External remote sensing platform** accommodating optical instrumentation with pointing requirements for Moon, Earth or space pointing instruments. Data volume from this platform would likely be higher as they would consist largely of image data sets. The ability to provide dedicated pointing for instruments and the suitability of DSG orbits for such investigations would need to be confirmed.
4. **CubeSat / small sat deployment platform** and local communication and navigation infrastructure.
5. **Generic User Interface for tele robotics.**
6. **Common interface for internal payloads** (ICE Cubes as an example).

3.5 Follow up steps

The following steps have been identified:

- Inputs to NASA DSG science workshop in USA in February 2018;
- Discuss with international partners about coordinating an approach for research, next steps, access for research and calls and the establishment of a governance scheme for utilisation of the Gateway;
- Investigate feasibility and define consolidated requirements for internal and external research platforms;
- Prepare an approach to initial experiments down selection for Phase A studies in 2019;
- Prepare an Announcement of Opportunity for payloads with a goal of selecting experiments in early 2020 for flight during DSG Phase 1;
- Define a funding scheme for selected payloads in advance of an Announcement of Opportunity;
- Investigate opportunities for commercial partnerships linked to development and operation of research facilities and research activities.

4 LIFE SCIENCES OVERVIEW

The following section resulted from a combination of inputs:

- the co-chairs of the life sciences session of the ESA DSG Workshop and who authored this section of this report - David Cullen (Cranfield University, UK), Alexander Choukèr (University of Munich, Germany);
- the subset of community submitted abstracts that were identified as relevant to a life sciences remit within the context of the DSG as selected by ESA DSG Workshop Science Advisory Group (see RD2);
- the presentations of the 19 selected abstracts at the DSG workshop presented in a life sciences session over a 1 day period;
- a discussion session held after the presentations and with a group comprising the presenters and other members of the workshop who attended the session and aided by a discussion panel selected by the session co-chairs from the presenters and which comprised: Alexander Choukèr (co-chair), Hervé Cottin, David Cullen (co-chair), Christine Hellweg, Monica Monici and Ann Visscher and which aimed to have at least one panel member able to comment in detail on a sub-area of the life sciences session as identified in the next section.

4.1 Identified Research Topics

The 19 presentations were broadly clustered into 6 areas by the life sciences session co-chairs and these areas and the titles of the individual presentations are listed below:

- **Life sciences on internal platforms (2 presentations)**
  - DSG biology twin box (DeepCytoLab)
  - The Deep Space Petri-Pod (DSPP): A general purpose biological platform for the deep space environment

- **Life sciences on external platforms (2 presentations)**
  - Organic exposure facility for astrobiology and astrochemistry
  - LOGOS (lunar organisms, geomicrobiology and organic compound space experiment)

- **DSG radiation environment (4 presentations)**
  - DEEPRAD (deep space radiation measurements)
  - BIOMER-biological response to moon environment and radiation
  - Autonomous Monitoring Of Radiation Environment (AMORE)
  - Effects of cosmic radiation on human psychoemotional performance and neurological status

- **Astronauts as subjects of experimentation (6 presentations)**
  - Personal systems for crew enhanced SPE protection (PYSCHE)
  - Inflammation markers in subjects exposed to deep space environment
  - Development of a system for laser therapy in space
  - Sensing and monitoring of astronauts' bio-activities for big data generation and analysis

- Integrative countermeasure device for deep space human exploration
- Health effects and physico- chemical properties of lunar regolith

- **Microbiology (2 presentations)**
  - Microbial space biotechnology supporting future human and robotic space exploration
  - Electroactive biofilms in space

- **Higher plants (3 presentations)**
  - Chronic radiation on plants (CROP)
  - Manipulation and irrigation of self-sustained greenhouses
  - Lunar regolith for plant-based life support

The crucial aspects of the **DSG radiation environments** discussed that should be considered for DSG Phase 1 are Galactic Cosmic Rays (GCR), and Solar Proton Events (SPE), with monitoring both inside (distributed) and outside.

A number of science questions were addressed by microbiology in support of astrobiology, biotechnological applications including In Situ Resource Utilisation (ISRU). Absent was consideration of microbiology (microbial ecology) as an integrated part of DSG for areas such as humans/microbiome, life support including plant growth, habitat environment. This was however considered a key aspect to consider.

Limited resources in DSG Phase 1 limit opportunities for **higher plant experiments** requiring plant growth to be implemented.

No proposals were received which required animal research. Such approaches are used to get better mammalian experimental statistics in comparison to human subjects.

4.2 Technical needs

4.2.1 Internal Platforms for Life Sciences

Given the expected limited space for life sciences experiments in the DSG, to offer the greatest flexibility and maximise the potential science return, and learn from experiences on the ISS, there should be an internal platform that offers common multiple interfaces (mechanical, electrical and communications) to allow flexibility in experimental design and implementation. This would allow both a common set of experimental hardware features to be available as well as the flexibility to accept bespoke experimental hardware for a given experiment. This can be seen, using existing ESA examples, as hybrid of the KUBIK, Biolab and ICE Cubes approaches. Within this context a range of features would be required including: miniaturised and automated microbial, mammalian cell and micro-animals/ microfauna (e.g. nematodes) incubators/growth chambers/bioreactors, appropriate observational techniques such as microscopy and spectroscopy, ability to provide 1g and fractional g environments, and the ability to store experiments and samples pre- and post-experimentation in controlled conditions (i.e. at +4°C and -20°C). Additionally, it would be useful to have the capacity to perform small animal (mammal) studies.

4.2.2 CubeSat Deployment for Life Sciences

The ability to upload, store if necessary, and deploy CubeSats via the DSG would provide additional opportunities for life sciences. Therefore the ability would be required to upload, store and deploy CubeSat spacecraft (e.g. from 1U to 6U form factor) and for the DSG to provide a communications link to free-flying CubeSats where necessary. Where possible it would be advantageous for the deployment to be robotic and avoid a dependency on astronaut crew time.

4.2.3 External Platforms for Life Sciences

External platforms for life sciences experiments allowing the placement of a number of life sciences experiments would allow exposure to various DSG space environments. Such a platform should:

- have a number of common interface points to allow multiple experiments to be housed with common mechanical, power and communications interfaces (for example based upon CubeSat relevant considerations) to allow active experiments;
- have simplified placement and retrieval of the externally place experiments (for example robotic placement and retrieval avoiding the use of astronaut crew time);
- have appropriate pre and post exposure storage of experiments on the DSG, current exemplars being the ESA Expose and planned Exobiology Facility on the ISS;
- have the ability to both measure and control contaminants from the DSG in the external environment to minimise the impact of DSG contamination on external exposure experiments (a known problem on the ISS).

4.2.4 Radiation Monitoring for Life Sciences

It is important to have the ability to monitor external and distributed internal radiation environments relevant to the DSG (i.e. SPE, GCR and secondary radiations) and individual astronaut crew exposure.

4.2.5 Astronauts as Experimental Subjects

Research could be performed through the ability to perform studies relating to both science (although limited examples described in the workshop) and mitigation/counter measures using astronauts as test subjects. To optimise data collection and subsequent exploitation, there should be a single international campaign to instrument all astronaut crew members with a diverse suite of wearable physiological and biomedical sensors and to gather further pre and post flight biomedical data and inflight biomedical samples for post-flight analysis to generate a central large dataset that would be made available to the scientific community. This should maximise the science return to the scientific community given the expected limited access to astronaut crew time and test subjects for experimentation.

4.2.6 Habitable Environmental Microbiology

It would be beneficial to implement studies of the DSG habitat environmental microbiology in order to characterise it and to study its variability with time. Details of such studies would need to be investigated.

4.2.7 Higher Plant Growth

The ability to house internal life sciences facilities with an appropriate sub-set of higher plant growth experiments would be enabling for some life sciences investigations. In the initial phase of DSG implementation/deployment the most feasible approaches would probably be related to seed storage and seed germination only (i.e. key initial steps in higher plant growth).

4.2.8 Other technical needs

The baseline of a 120V DC power supply to experiments is viewed as limiting in that most experiments would expect to require other voltages. Therefore, if each experiment required its own power conversion, this would be an inappropriate use of experiment mass and volume.

4.3 General findings

The unique aspects the DSG offers the life sciences are access to the deep space radiation environment and, given the initial operation constraints for astronaut crews, aspects of isolation. There was no direct discussion or interest highlighted concerning the quality of microgravity and the local magnetic field.

The specific location of the DSG relative to the Moon from a life sciences perspective are only relevant when access to lunar surface or lunar samples become available during DSG timeline.

A discussion of how results from studies on the DSG of various aspects of human presence in deep space could be efficiently input into future interplanetary mission design (i.e. human Mars missions) resulted in the observation of a time mismatch between the future availability of results from the DSG and on-going/current design of human interplanetary missions.

Due to the limited resources and the inter-agency communities involved, there was discussion of the possible need to change the scopes of AOs and ways of implementation. For example: (i) should the AO's be specific question driven rather than PI/curiosity driven, (ii) should research consortia be international, across the partner countries in order to maximise access to and share the benefits of the limited flight opportunities.

A challenge for the life sciences community will be to adapt to the boundary conditions when compared to previous experiences with space platforms such as the ISS:

- limited facilities – internal & external experiment volume, mass, frequency of access
- limited astronaut availability
- Earth return capability (not discussed in detail)
- potential of robotic teleoperations capability in context of experimental flexibility

5 SOLAR SYSTEM, LUNAR AND EARTH SCIENCES

5.1 Identified Research Topics

A large variety of research topics in the area of lunar sciences, Earth-Moon system and Solar System science have been identified that could benefit from utilisation of the DSG as a deep space environment exposed platform, a lunar orbiter and its capabilities of supporting Moon surface access. The main research directions can be grouped to:

- Moon surface/subsurface investigation
- Radiation, dust, and micro-meteoroids
- Plasma processes

The primary advantage for science of using the DSG is its ability to make the Moon a stable platform for lunar and other deep space exploration as well as Earth-Moon System observation.

5.1.1 Moon surface/subsurface investigation

The DSG can enable a wide range of lunar surface studies, both as a platform for remote-sensing observations and to support surface operations. The DSG may support in situ surface measurements by deploying static landers, penetrators, robotic rovers, and sample return missions. The DSG will especially enable human-assisted sample return mission concepts, where tele-robotically controlled surface assets are used to collect samples which are then transported to the DSG for later return to Earth with the Orion capsule. Such an approach is expected to greatly enhance both the mass and diversity of lunar sample collection compared to what could be achieved only robotically.

The importance of combination of using global view or context information provided by multi-spectral remote sensing measurements from DSG and the returned sample or surface observations are stressed in a number of proposals. Such lunar science, including remote sensing of the surface and support for surface operations requires an infrastructure in lunar orbit, such as DSG, and cannot be done in LEO. This combination of remote-sensing, in situ measurements, and sample return will address high-priority scientific questions relating to the geological evolution of the Moon, the origin of the Earth-Moon system, the distribution and nature of lunar volatiles, and the study of space weathering processes.

5.1.2 Radiation, dust, and micro-meteoroids

The orbit of the DSG is identified to provide a unique viewing geometry to study both Moon and Earth's exosphere/atmosphere from multi-spectral observations with global coverage. The nearside of the Moon is also proposed as an attractive location of monitoring Earth's radiation budget by deploying multi-spectral radiometer from DSG. Such remote sensing of the Earth from the DSG and from the Moon is expected to provide new information for climate diagnostics of Earth.

Dust flux detectors onboard the DSG are proposed to determine the initial abundance of natural cosmic dust from comets, asteroids and the Moon as well as to determine the extent and propagation of anthropogenic space debris. Measurements of the dust flux on the way to the Moon and in the vicinity of the Moon can identify and analyse the contributions of dust from the Moon and other bodies. Characterising dust, micro-meteoroid, and radiation environments with the DSG is also important to support the calibration of environmental models and to test measurement techniques as a preparation for future lunar and Mars exploration.

5.1.3 Plasma processes

In-situ detection and analysis of plasmas and magnetic fields, and of the masses and energies of neutral and ion particles from the DSG can be used to study various plasma processes involving the Moon's surface and exosphere. The DSG is expected to enable characterization of the exospheres, outflows from the Moon and the Earth's exosphere and detection of variability in solar activity. These combined measurements would support our developing understanding of plasma interaction between the Moon surface/exosphere and plasma from Earth's magnetosphere and solar wind in an extensive way.

The DSG orbit provides a unique opportunity to study interaction between solar wind and Earth's magnetosphere plasmas, in particular processes related to the distant tail, where only limited observations exist so far. In-situ particles and electro-magnetic field measurements by DSG and by CubeSats deployed from DSG are proposed in order to study long-term variability in solar wind-Earth's magnetosphere interaction. Furthermore, different X-ray imaging techniques can be applied to obtain large-scale images of emission from the magnetosphere: magnetotail and magnetopause, as well as from Sun. These observations would deliver a global view of the Earth's magnetosphere and solar wind-magnetosphere interaction which is not possible from LEO.

Studies of plasma processes using DSG as an experiment platform are also proposed. These could include release of tracer ions from DSG in order to track transport and energization of plasma across boundaries; artificial release of volatiles under the absence of the residual atmosphere and gravity field; release of projectile to study impact process.

5.1.4 Areas with the highest potential science impact

Some high potential impacts from the above mentioned studies are:

- Surface exploration is important for understanding lunar geology, magnetic fields, space weathering on Moon. In addition, studies of solar wind particles and cosmogenic nuclei in lunar samples (especially buried palaeoregolith deposits) will enable studies of the history of solar activity and galactic processes such as nearby supernova explosions and spiral arm transits.
- Human assisted sample return will have the highest impact for lunar science, given the increased mass and diversity of sample collection.
- Combination of remote sensing and surface measurements will lead to significant science return.

- Remote-sensing of Earth from the vicinity of the Moon enables a new view angle and provides a new platform for Earth's climate observation.
- Monitoring dust abundances and micro-meteorites in lunar vicinity provides significant information that can be used for designing future spacecraft.
- In situ measurements of plasma/neutral escape from the Moon will enable studies of exospheres on other airless planetary bodies and Earth. This, combined with surface data, would enable the comparison of the state of the early Moon's atmosphere with that of the current Earth-Moon system and thereby help infer details of solar-system evolution.
- Long-term monitoring of the impact of solar wind-plasma on Earth's magnetospheric plasma is important to understand plasma processes applicable to many other objects in the universe.

5.2 Technical needs

Some key technical needs associated with the identified investigations are:

- External mounting facilities with data and power interfaces
- Ability to deploy sub-satellites/CubeSats/penetrators
- Ability to change orbit is desirable: different applications prefer different orbits
- Stable platform (consider external gimbal-mounted platform)
- Ability to transfer samples from a robotic lunar surface return vehicle to Orion vehicle
- Ability to perform tele-robotic operations on the surface
- Ability of astronauts on DSG to conduct spacewalks is important for some proposed experiments/operations
- External electromagnetic cleanliness is important for some experiments (consider long boom to facilitate this)

6 ASTRONOMY AND PHYSICAL SCIENCES

6.1 Identified Research Topics

6.1.1 Research that could benefit from the Deep Space Gateway that could not be performed in Low Earth Orbit

A number of aspects of the DSG were identified as relevant for astronomy and physical sciences research. The DSG will be outside the van Allen belts of the Earth and this provides some unique opportunities for science. As the van Allen belts prevent the low energy cosmic rays from reaching the Earth and LEO satellites, DSG provides an ideal way of monitoring the low energy spectrum of cosmic radiation for the first time. This may reveal, for example, decay products from dark matter candidates. The van Allen belts will shield DSG from the man-made radiation contamination from Earth and could provide an excellent environment to study the Universe at electromagnetic frequencies between kHz and MHz, thus reveal the Universe before the first stars were born.

The location of the DSG, being simply further from the Earth than LEO, will offer unique opportunities to science. Any detector of any type of emission from an astrophysical source could be used in coherent conjunction with a similar detector on Earth to provide triangulation, through precision timing, to a higher accuracy than is currently available. This idea was brought up in the context of locating Gamma Ray Burst sources more accurately, when triggered by a gravitational wave detection event, so that optical counterparts can be successfully found and observed. This is very topical. The remoteness of the Moon from the Earth also allows the Earth's atmosphere to be studied from a new vantage point. This research could further our knowledge of the physical processes in the Earth's atmosphere but would provide data on the 'Earth as an exoplanet'. This could help extract information on the atmospheres of real exoplanets from data collected from transits and occultations. Another idea that was motivated by the geometry of the Earth-Moon system with respect to the ecliptic was that the DSG could be an outpost for early warnings of Near Earth Objects, if it were equipped with a small infra-red telescope. (Note that this idea was suggested during the discussion session and has not been documented).

Also discussed were:
- Characterization of the Moon water;
- Early detection of NEOs;
- Space weather;
- Research on large facilities can take advantage of the infrastructure of DSG;
- Study of characteristics of radiation environment;
- Reliability of electronic systems.

High impact areas identified were:
- Identification of GRB's and counterparts of GW events is a fast growing field of research, this requires long baselines;
- Characterization of the Earth atmosphere properties from very far is relevant for exo-planets search (atmospheric studies of exo-planets);

- Observation of the radiation and particle environment (Dark Matter);
- Opening the kHz-MHz radio window after the dark ages;
- Interesting proposals for deployment of large telescopes;
- Not yet explored: interdisciplinary activities lunar paleocosmic history.

6.1.2 Technical issues

The issues that arose for exploiting the radiation environment were associated with possibility of pointing mass spectrometers with small acceptance solid angles. Exploitation of the long baseline between DSG instruments and terrestrial detectors would require accurate timing which suggests the presence of precise clocks in lunar orbit. Tracking of the DSG orbit could be improved by optical technology if a retroreflector were attached to the spacecraft, such as the one used for Lunar Laser Ranging. However, the interpretation of the tracking data in terms of the long term Earth-Moon distance, for example, would depend on the orbit being a geodesic one (i.e. defined by gravity) which is not the case for halo orbits.

One outcome of the discussions was that the experiments did not need the aid of the crew (with the possible exception of the adjustment of the pointing of directionally sensitive radiation detectors).

Some discussion was on the possibility of further space vehicles being launched from DSG such as CubeSats. These ideas included large constellations of coherent optical or radio telescopes. However, these ideas seemed difficult to implement within the DSG mission framework.

6.2 Technical needs

Technical needs that were identified included:

- CubeSats deployment, booms for radio interferometers (35 meter radio antennae long time scale);
- Precision timing (e.g. GPS);
- Need for pointing of external radiation detectors;
- CubeSat deployment (perhaps including the possibility of retrieval) containing booms for radio interferometers (35 meter radio antennae would be typical exposed on long time scales);
- Communication relays;
- Data Storage provided by the DSG would be beneficial;
- Mounting points with power and data interfaces;
- No major crew time appears to be needed requested; crew would primarily be requested to mount hardware but not to operate.

7 TECHNOLOGY

A diverse range of ideas related to research related to technology development were identified. This section summarises these topics, the opportunities for technology research and the dependencies that have been identified.

7.1 Identified Research Topics

A number of different technology related research topics were identified. These are summarised below.

Exposure to the deep space environment and observation of the effects on materials and technologies would support the development and assessment of new materials, in particular for space exploration applications. In addition, these exposures could be used to raise the Technology Readiness Levels (TRL) for new technologies to be applied in space exploration.

The use, analysis and development of robotics and telepresence were also highlighted as important areas. These robotics investigations and applications could be performed locally at the DSG or remotely at the lunar surface, offering significant synergies with scientific research objectives and needs.

The deployment of small satellites and related technologies could be used to facilitate technology research, often without further requirements or interaction needed with the DSG, or in an operational sense in support of DSG operations and maintenance (e.g. for DSG external observations).

On board 3D printing (additive manufacturing) was identified as an area where research could be performed to prepare for later applications in exploration and to provide functional support by providing needed equipment without the need for resupply. Manufacturing could be performed using materials supplied from Earth but could also trial the use of materials supplied from the lunar surface.

A number of technology activities related to on board sample analysis and handling were identified. These could use both engineering samples and planetary material samples (e.g. from the Moon).

Other research related to landing and system related technologies and their testing/application on the DSG.

7.2 Technical needs

It was considered that the space available for research is useful but very small and very limited. As DSG is developed, expansion and enhancement of the resources available for research generally should be considered and designed for.

One proposed solution to the space limitations is to consider using the living volume for payloads when no crew are present.

A centralised data handling and storage system for payloads would reduce the volume, power and cost requirements for payloads and would reduce the overall complexity of payload operations; maximising the use of the available resources. In preparing such a system attention needs to be payed to predicting the user needs and expectations as they will exist in the coming years and to establish requirements based on that.

The nominal power supply of 120V DC is challenging for payloads to handle and may be hazardous. It is important to investigate the possibility of a dedicated lower voltage payload power line.

External attachment points needed to enable external exposure payloads. These could be both passive or have data and power interfaces.

Ingress and egress are required to enable exposure payloads to be placed outside and retrieved after exposures. In this case, the airlock hatch size is a limiting factor for the experiments that could be considered.

External robotic manipulation of payloads is needed to mount and dismount payloads. A Canadarm or similar system might be considered for this.

The DSG can be a hub for tele robotics for both the Moon’s surface and local robots outside DSG. For this a Generic User Interface should be considered to allow versatility and simplicity of interface for any robots to be tele-operated from the DSG.

Untended/autonomous operations should be assumed as a baseline for all payloads, with minimal crew involvement needed.

CubeSat deployment, transportation and handling are needed and multiple CubeSat/small sat opportunities were identified. In some cases, this will require local communications, navigation and situational awareness.

Communications with Earth need not be continuous but must be reliable, predictable and have sufficient bandwidth/data volume. It is important to note that public and researchers expectations in the next decade will be for high bandwidth systems offering high data rates and a high degree of interaction with payloads.

8 EDUCATION

8.1 Introduction

This section presents a consolidated summary of the findings prepared in the area of Education. Fundamental principles, basic requirements and dependencies are identified, together with a preliminary set of ideas to be considered for future implementation. These represent the aspects which need to be considered as the highest priority in order to enable education to be effectively performed on the DSG.

Education is a process which aims at the development of know-how, competences & skills through structured paths and methodologies that take into account the abilities and development stadium of a learner. Formal education activities also have to take into account additional boundary conditions such as national education systems and curricula, both in schools and academia. In this sense, education differs from communication in that it has to go beyond the sole inspiration and awareness-creation aspect typical of communication, and it has to devise education-specific ‘languages,’ processes and contents.

In order to properly meet ESA and Europe’s education objectives, any education activity making use of, or benefitting from, the DSG platform and related technology and science investigation programmes has to take into account the need for:

- **Large scale reach** and a large scale access mechanism to the planned education activities, in order not to benefit only restricted educator and student communities or individuals;
- **Accessibility over long periods of time**, in order to allow participation and engagement of different ‘generations’ of students and educators over time;
- **Suitability** of proposed activities to meet national formal education needs, from school to university levels (also considering that school activities have to take place within the school year, i.e. Sept-Jun, and that multiple-year university activities have to be concluded within a typical university study cycle);
- **Complementarity** with existing educational efforts, and uniqueness of added value;
- **Affordability and sustainability** in the medium-long term in terms of supporting resources, considering that the beneficiary education communities usually have limited or no resources at their disposal.

The types of education activities discussed and hereby presented address in particular the STEM (Science, Technology, Engineering and Mathematics) field, but a potential opening to arts, history and social sciences may also be assessed in the future (STEAM). In addition:

- for primary and secondary school levels, space is used as a unique inspirational *context* for the teaching and learning of STEM subjects, competences and skills;
- for university level, space science and technology, and the related professional know-how and skills, are the *subject* of teaching and learning.

8.2 Education advantages of the Deep Space Gateway

Inspiration is a key part of successful educational projects, as it is able to trigger curiosity and successfully ignite the subsequent learning process. In this sense, the DSG, as the upcoming '*farthest human outpost in space*,' and as a means to enable future *human interplanetary exploration*, provides an incredibly powerful inspirational context and tool in support of STEM educational programmes. Curiosity and the need to explore are indeed deeply built in the human nature – especially in youngsters - and keep representing some of the strongest drivers in the history of mankind.

In addition, the access to the DSG for educational purposes allows the related educational initiatives to be aligned with contemporary, top-edge science and technology. This aspect is considered a key value in the modern pedagogy of STEM, as it enables to bridge the gap between the theory learnt at school/university and the **real practice of science.** Furthermore, it provides a direct, real-life introduction to the **jobs of today and tomorrow**.

8.3 Areas of greatest potential impact

A **basic scenario** for the educational use of the DSG would foresee a deployment *after* the mission is defined and designed. Curricular classroom resources, lessons, hands-on projects (science or technology based) could be drawn based on the most exciting examples among the DSG science and technology objectives, operations and investigations. These activities would be developed and implemented on ground with minimum support from the DSG (e.g. video messages from astronauts, selected imagery and data sets).

An **advanced scenario** for the educational use of the DSG would still include the basic scenario, but would add emphasis on *students playing an active role* in the DSG *exploitation* and, to the extent possible, *even design and development process*. Through the students' involvement in inquiry-based, project-based educational activities and real practice of science, the **highest possible inspirational and pedagogical impact** will be reached.

The identified elements of the advanced education scenario are outlined in the table below.

DSG project phase	**Activity**	**Target**	
Before the mission (design and development phases)	**Students' access to information on the real design process** (e.g. simulated data, design trade-offs information, etc.) for parallel students' system and subsystem engineering simulations, modelling, feasibility studies in Concurrent Design approach (CDF), orbital/mission analysis	University students	School students (TBC)

During the mission (operations and exploitation phases)	**Percentage of use of professional DSG platforms**:		
	- Student-built CubeSats launched from the DSG	University students	--
	- Percentage of observing/usage time of existing professional payload (in orbit and on the lunar surface) through dedicated Announcements of Opportunity (AO) with short turn-over time	University students	--
	- Percentage of usage time of 'plug & play' rack-style experiment facilities (similar to ISS' ICE Cubes), internal or external to the DSG, through dedicated Announcements of Opportunity (AO) with short turn-over time	University students	--
	Upload and use of dedicated educational hardware:		
	- Raspberry Pi computer (or similar device) with sensors, controllable from operators on ground (minimum or no crew time), for in-orbit student investigations	University students (TBC)	School students
	- Professional 2-ways audio-video equipment and amateur radio (HAM) station, for video and/or radio contacts with astronauts on board (role modelling, science demonstrations from orbit)	--	School students
	- Live HD web camera ('DSG live') for continuous imaging of the near space environment (DSG exterior, Moon surface, Earth), and classroom analysis	--	School students
	- 3D printer	University students	School students
	Use of the DSG itself as education tool:		

	- Use of DSG housekeeping & telemetry data, life-support systems data, astronaut data as basis for training and lessons (e.g. training on orbit dynamics, dV manoeuvres, etc.)	University students	School students
	Access to recent (quasi-real-time) and archived professional payload data for analysis and interpretation	University students	School students

8.4 Dependencies for Educational Impact

The needs identified in the Introduction, which have to be fulfilled for a successful and effective educational programme around the DSG require:

- the willingness and availability of the DSG partner Agencies to **invest** time and resources in order to allow a free-of-charge access to the DSG for educational purposes, in view of boosting the education of the space systems designers, operators and users of tomorrow;
- a proper **framework agreement** with the relevant user communities (e.g. PIs', industry), to: (i). allow access for students and educators to previously agreed data sets and information, formally addressing proprietary data issues, IPR and right of use from the very beginning; (ii). exploit ways to contribute to the transfer of know-how and expertise from the expert user communities to the educational targets; iii. involve students in the DSG professional research teams;
- an **early integration** of the DSG education planning in the overall DSG planning, from the earliest mission definition and hardware/payload selection phases.

9 REFRENCE DOCUMENTS

RD1. Call for Ideas: Research Opportunities on the Deep Space Gateway http://exploration.esa.int/science-e/www/object/doc.cfm?fobjectid=59392

RD2. Responses to the Call For Ideas: Research Opportunities on the Deep Space Gateway http://sci.esa.int/science-e/www/object/doc.cfm?fobjectid=59829