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# Acta Futura

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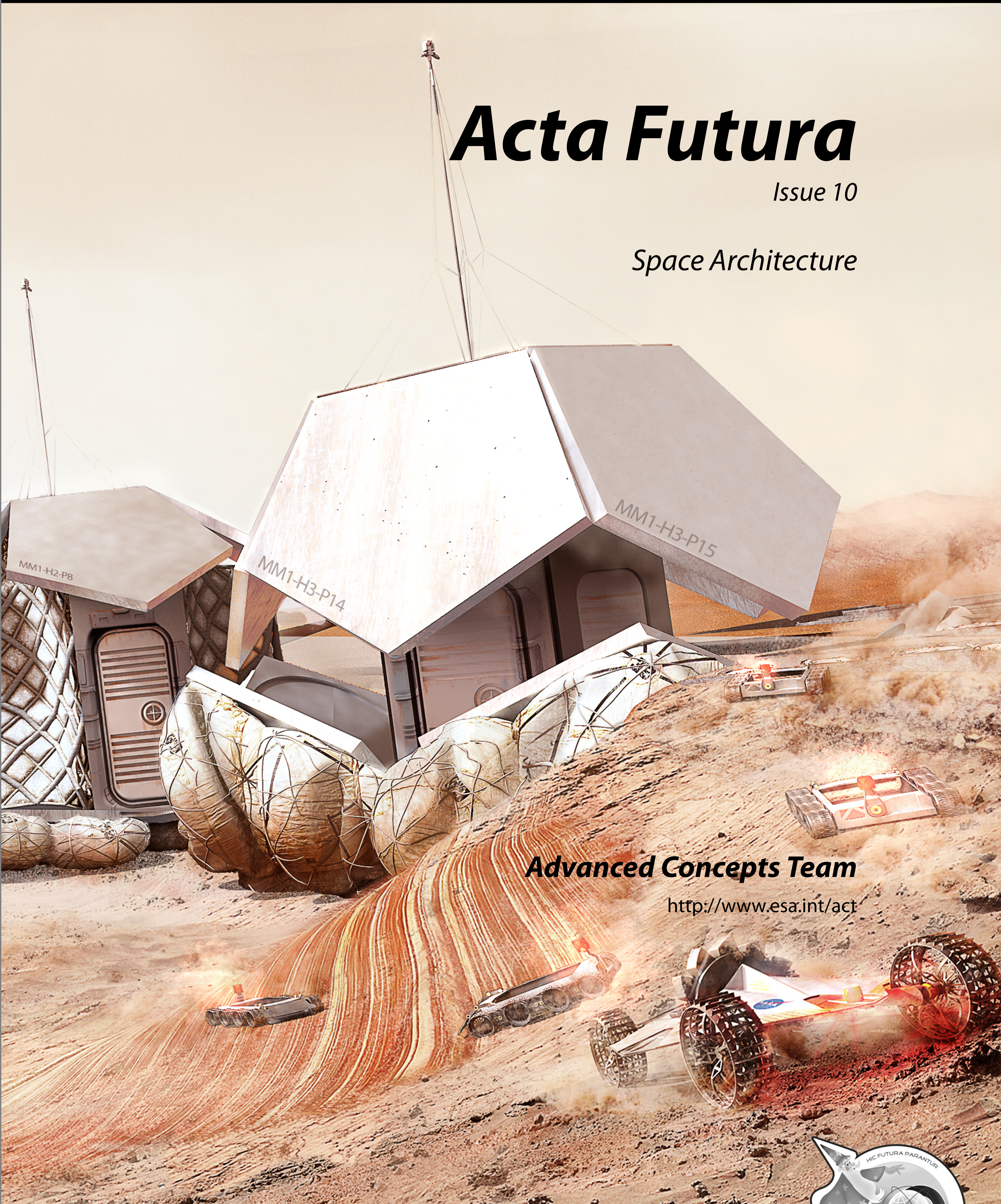
*Space Architecture*

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## Foreword

Space has the potential to unite mankind, inspire and push the boundaries of research and innovation all at once. To this end, the International Space Station has played an important role in fostering cooperation between the spacefaring nations since 1998, but what happens next? The debates about the future of human space exploration consider a cislunar station, the Moon and Mars as possible following moves. ESA's Director General, Johann-Dietrich Wörner, has turned his attention towards the Moon, considering it as a necessary intermediate step in reaching more distant destinations. His concept of a "Moon Village", as he explains in his interview to ESA on the 1st of March 2016, is not to be taken literally as "(...) single houses, a church, a town hall and so on. (The) idea only deals with the core of the concept of a village: people working and living together in the same place." It is more of a metaphor for an international collaboration, a global community, that brings together different actors from private as well as public sectors in our future endeavours for space exploration.

The vision involves human and robotic missions for science and exploration, made possible by a permanent lunar outpost. The outpost could function as a test bed for technology, new governance schemes and alliances, enabling various commercial activities, such as tourism and mining, and inspiring next generations through cultural and educational projects. But, whether the next step is the Moon or Mars, a common denominator for these missions would be the establishment of a long-term or permanent base for astronauts. Currently, concepts are being developed for analogue habitats and simulations, the first modules to be brought on to the surface, cislunar stations, and future planetary habitats and infrastructure built using local resources and robotic manufacturing techniques. In the process more and more attention is being given to the human factors and habitability principles as psychological and physiological issues will become more critical the longer the missions get.

This special issue of Acta Futura on Space Architecture presents a selection of advanced concepts related to establishing an extra-terrestrial outpost. In *Space Architecture and Habitability: An Asset in Aerospace Engineering and Architectural Curricula* Häuplik-Meusburger et al. discuss the issues related to the training of future space architects, an important topic not yet addressed in depth. Porter et al. list in *Architectural Design Principles for Extra-Terrestrial Habitats* a set of guidelines for psychologically and physiologically well designed space habitats. *Time Architecture* by Kolodziejczyk et al. presents a concept for a lighting system to influence the perception of time and the biological clock of astronauts. *Glance into the Future: Research Steps on a Path to a Continuous Human Presence on Moon, Mars and Beyond by DLR's System Analysis Space Segment Department* by Maiwald et al. and *Operational Lessons Learnt from the 2013 ILEWG EuroMoonMars-B Analogue Campaign for Future Habitat Operations on the Moon and Mars* by Cross et al. explore issues related to the preparation of such missions on Earth through analogue campaigns. Ideas about the overall mission design for the exploration of cis-lunar space and Mars are presented by Di Carlo et al. in *Human Exploration of Cis-lunar Space via Assets Tele-operated from EML2 (HECATE)* and Baldelli et al. *A Feasibility Study for A Short Duration Human Mission to the Martian Surface*. The journal ends with Cowley et al. and Wilkinson et al. presenting their concepts of 3D printed habitats on the Martian surface in *An ISRU-based Architecture for Human Habitats on Mars; the 'Lava Hive' Concept* and *Concept Design of an Outpost for Mars Using Autonomous Additive Swarm Construction*.

Hanna Läkk
*(Guest Editor)*

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Acta Futura

# Space Architecture and Habitability: An Asset in Aerospace Engineering and Architectural Curricula

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**Abstract.** Space Architecture is interdisciplinary; it connects diverse fields such as aerospace engineering, architecture and design, human factors design, space sciences, medicine, psychology, and art. Space Architecture combines the accuracy of technical systems, human needs for working and living, the interface design for the relationship between humans, and the built and natural environments. It is simultaneously technical, humanistic, and artistic and deals – most importantly - with the design process from a "big picture" perspective down to every detail of each component. In addition to traditional knowledge of planning and building processes, special knowledge is needed regarding how to design for humans in extreme environments and how to do so creatively. Many universities around the world offer aerospace engineering undergraduate and graduate programs, but only a few relate to the field of Space Architecture. This paper presents examples of educational practices illustrated with student projects from European and US academic institutions that offer space architecture as a mainstream or major component in their curriculum. It further explores the necessity of incorporating the discipline of Space Architecture and Habitability into aerospace engineering and architectural curricula [16].

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## 1 Introduction and Historical Precedents

Space Architecture, as a discipline, is not new. When NASA and the former Soviet Union turned their views towards long-term human missions in the 70s, space architects and designers were involved.

In 1967, architect Maynard Dalton was among eight people from the 'Advanced Spacecraft Technology Division' who received an award for "Preliminary Technical Data for Earth Orbit in Space Stations" [2]. In 1968, Dalton and Raymond Loewy, a world-renowned industrial designer, worked on the Saturn-Apollo and Skylab projects. Loewy is well known for his improvements to the existing layout, such as the implementation of a wardroom, where the crew could eat and work together, the wardroom window, the dining table, and the color design among other additions [8]. Dalton prepared the Skylab Experience Bulletins and became project engineer for the Space Station module (1971). At about the same time, from 1965 to the 1980's the Soviet Union's space systems 'Barmin Design Bureau' produced a complex research and planning project designing structures and mobile systems for a long-term lunar base. Architectural and structural design aspects were recognized as key elements of the project and thoroughly defined. The Lunar base 'Zvezda' was part of that work (1960-1980).

Galina Andrejewna Balaschowa can be considered the first female space architect. She started working at the Experimental Office OKB-1 as an architect in 1957 and moved a few years later to a space architecture department, where she worked closely with the founder of the Soviet space program Sergei Pavlovich Korolev. She contributed to the design of the Sojuz spacecraft, and Salyut and Mir stations.

Until today, many designs of space habitats have been created, but only a few were implemented in space programs around the world. Currently, only the International Space Station and Chinese Space Station are orbiting the Earth.

Both space stations are grand achievements, from an engineering and scientific point of view. However, important human factors and habitability design components seem to be sacrificed first, mainly because of budget cutoffs. As a result, the 'Habitation Module' for the ISS was suspended during the construction phase and only since 2008, all six crewmembers are provided with a personal sleep compartment.

In 2002 several members (including the authors) of the Technical Aerospace Architecture Committee of the American Institute of Aeronautics and Astronautics (AIAA) organized the first Space Architecture Symposium during the 'World Space Congress' in Houston in 2002. There, the following mission statement was developed: *"Space Architecture is the theory and practice of designing and building inhabited environments in outer space"* [3].

Following this quotation, Space Architecture as a discipline comprises the design of living and working environments in space and on planetary bodies, such as the Moon and Mars, and other celestial bodies. This includes space vehicles and space stations, planetary habitats, and associated infrastructure. Earth analogs for space applications, simulation and test facilities belong to the extended field of Space Architecture. Earth analogs include Antarctic, airborne, desert, high altitude, underground, and undersea environments;, as well as closed ecological systems.

## 2 Space Exploration Goals and Challenges

In contrast to early space missions, spacecraft design concepts for future space exploration cannot be based mainly upon engineering and structural requirements [6]. Humans in future long-duration spaceflight and exploration endeavors will play key roles within the mission. Consequently, human needs and requirements must be addressed in overall mission architecture and spacecraft design. Human factors need to be taken into account at every stage of the design process — considering people to be more than an 'element' of the system but its modifier and innovator.

Planning and building future long-term space missions will challenge both technology and human endurance. According to several space agencies including ESA, current road maps with planetary exploration missions' scenarios include short expeditions to the Moon, cis-lunar locations, asteroids, and long-term manned missions to Mars.

A human mission to Mars will include long travel times (6-9 months) each direction and a stay on the planet's surface between 3 months to 2 years [1, 22, 24]. It is obvious that all mission aspects influence each other and have to be addressed beforehand - at planning and design phases. Especially design considerations related to missions' lengths and destinations change significantly [16]:

- The longer and more isolated the mission, the more important will be the qualitative design of the habitat, including layout and integration of its structures, systems, and utilities.
- The longer and farther away from Earth, the more sustainable the habitat has to be and the more facilities will be needed for personalized activities, etc.

In order to meet challenges associated with space exploration, a new generation of professionals has to be educated [5]. Today's students and future spacecraft designers need to be prepared for the planning of human missions and designing appropriate artifacts. It is important that future mission planners, engineers and architects, as well as other professionals involved in the design for manned spaceflight are educated in order to [16]:

- Learn about space systems and human factors as equal elements of a spacecraft and mission design;
- Understanding connectivity and relationships between all design elements and overall mission planning;
- Operate at all scales from the 'overall picture' down to smallest details;
- Provide directed intention and judgment – not just analysis – towards design opportunities;

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- Address relationships between human behavior and built environment;
- Interact successfully with diverse fields and disciplines throughout the project's lifecycle.
- And last but not least: critical thinking.

Current problems of academic training for example include lack of understanding requirements derived from expertise in human factors that students and professionals trained in space engineering frequently demonstrate. On the other hand, students and professionals in the fields of architecture and design often are not adequately prepared with respect to engineering requirements and evaluation criteria. In addition, interdisciplinary interaction is challenged by dissimilar research and working methods, different glossary used for identification of design problems and requirements, and evaluation criteria that are often inconsistent. All those factors make teamwork and planning for future manned space missions even more difficult.

## 3 Habitability Principles

Knowledge of basic design requirements for a human mission is required already at an early stage of the design process. Several key requirements for human missions drive habitation design, examples include:

- Life Support (Atmosphere; Thermal Environment and Humidity; Food; Hygiene and Waste Collection; etc.)
- Hazards (Micrometeoroids; Microgravity; Radiation; Safety Hazards; etc.)
- Behavioral Implications (Personal Space and Privacy; Social Interaction versus Isolation; etc.)

Although various definitions for the term 'habitability' exist, it can be understood as *"a general term that connotes a level of environmental acceptability"* [10] as stated by Connors, Harrison, Akins and Faren in their book 'Living Aloft – Human Requirements for Extended spaceflight. Habitability can be used as a *"a general term to describe the suitability and value of a built habitat (house or spacecraft) for its inhabitants in a specific environment (Earth or Space) and over a certain period of time. Set into the space context, habitability can be understood as the measure of how well the (built) environment supports human health, safety and well-being to enable productive and reliable mission operation and success"* [15].

Historically it has been considered a low priority in the space mission planning process. Architects and engineers still discuss the degree of its importance, but when the effects of impaired habitability are understood as critical [7] and potentially life threatening, then understanding habitability and Human Factors *"will make mission success more likely"* [21].

Another definition refers to the Habitation Readiness Levels (HRLs) described by Conolly, Daues, Howard and Toups [9] in relation to well-known Technology Readiness Levels (TRLs). For them a (Lunar Surface) Habitation System is *"the integrated set of habitation assets to support a crewed mission and ensure a safe, productive, pressurized environment for human habitation."* Correlations between HRLs and TRLs are a good example how a human-centered design approach can be integrated into already established technical methodology.

All these definitions imply that the job of a space architect is to create an environment that is safe and comfortable for people to live and work, and return back home in a good physical and psychological state.

## 4 Current Educational Practices in Aerospace Design

Space-architecture and aerospace engineering practices have different approaches for identifying a problem and solution finding. Architecture and engineering disciplines also have different educational approaches with different tasks assigned. The same can be observed in other disciplines such as medicine, industrial design, physical sciences, etc. To achieve better integration of space architecture' objectives into engineering and architectural curricula both approaches need to be examined and assessed.

Interdisciplinary design processes add complexity when the goal is to create an optimized design that is compatible with mission goals, technological, scientific, design, and human factors requirements.. Designing a crew habitat for outer space, surface of Mars, or any other extra-terrestrial body is one of the biggest challenges for space architects and engineers. Interdisciplinary communication is vital for successful and efficient design and interactions between all parties involved in design and planning activities.

However, often disciplines and practices use different terminology and acronyms identifying entities, objects,

| Task | Engineering Approach | Architectural Approach |
|---|---|---|
| Problem Definition | Product-oriented | Process-oriented |
| Approach | Linear(analysis)<br>Start at the beginning of the process | Nonlinear and iterative (synthesis)<br>Start at critical points, then adjust |
| Workflow | Workflow from the start to the end<br>Done with numbers (quantitative methodology) | Workflow anywhere in the project<br>Done with models (qualitative methodology) |
| Solution | There is one ideal solution<br>Most decisions are quantifiable | There are many solutions<br>Some decisions are quantifiable |

Table 1. *Engineering and architectural approaches throughout processes. (Adapted from Brand N. Griffin)*

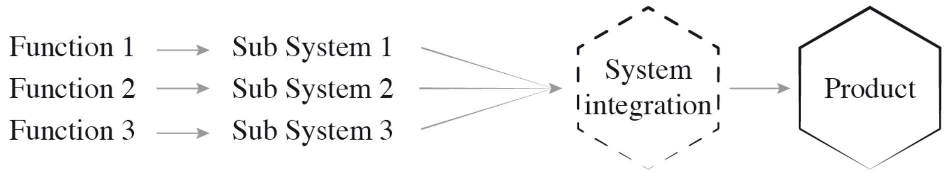


Figure 1. *Example of a common engineering design approach*

and functions. For example, even the meaning of a term 'design' differs between engineers and architects.

Misuse of terms and definitions can create confusion and misunderstanding, which may lead to significant design flaws and errors affecting overall planning and mission success. Table 1 shows examples of how different tasks can be understood by architects and engineers. In general: ways of identifying a problem, perceiving it, and finding design solutions can be quite different [11].

Engineering classes focus on learning about systems, subsystems, elements, and parts. Students understand connections between them in order design a system that performs a particular function for which those systems or units are designed. The engineering approach, illustrated in Fig. 1 uses system and sub-system requirements as constraints for the system. Each function is determined by a trade-off process. The organizational stage includes function determination and prerequisites. It is followed by generalized requirements, and the integration stage usually becomes a part of the process in professional system engineering practice. System engineering is dealing with a system as a whole and connects the traditional engineering disciplines. It also includes the evolutionary process of maturity levels [12, 20, 19].

A drawback of this approach may be the neglected human factor when it is not treated as an equal system element. The International Space Station is an example of an engineering design approach.Important human factors and habitability elements have been discarded in an early stage (eg. habitation module) or have been added very lately to the station (eg. personal crewquarters).

## 5 Space Architecture Educational Approach

*"Engineers think architects make things prettier, difficult to build, and more expensive. Some can, but space architects are different. They analyze like an engineer and synthesize like an architect"* [13].

The space architecture approach combines engineering thinking with criteria related to habitability and human factors, such as considered in architecture and industrial design, plus including other disciplines such as medicine and sciences.

When introducing architecture students to a design studio in Space Architecture, Marc M. Cohen states that: *"[...] it is always a challenge to orient them to the unique and peculiar characteristics of designing human habitation in vacuum and reduced gravity regimes.[...] The*

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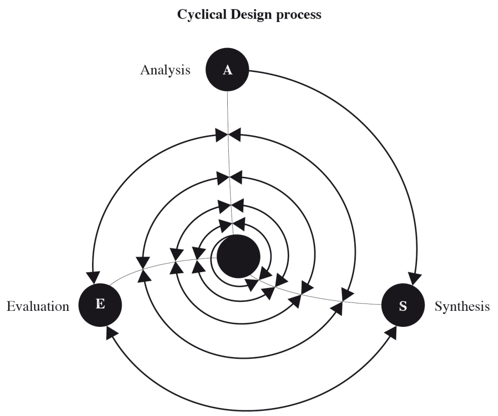


**Figure 2.** *Cyclical Design Process. (Original model by Donna P. Duerk, adapted by the authors)*

*challenge is a difficult one, given the shortness of time for a quarter or semester, and the variety of the students' backgrounds, with some stronger or weaker in engineering, human factors, materials science, and physics.[…] Also, the students often start from differing levels of professional preparation and training, so it is inevitable that each one interprets the information differently and takes an individual and often idiosyncratic approach*" [17].

Depending upon the overall topic (manned systems design, space structures and applications, lunar and planetary exploration, and terrestrial analogues) students usually start with extended research of relevant topics that include mission architecture, human factors, ergonomic influences, extreme environments, constraints and influences, and psycho-social factors. They will attain a good understanding of the system and associated structures through design, research, and analysis of specific projects.

Certain creativity and the development of 'out-of-the-box options' can be helpful at the beginning. The architectural approach to project development is basically non-linear and based on the synthesis of inputs from multiple disciplines. Design process cycles will evolve through time and levels of development. Fig. 2 shows an example diagram of a cyclical design process.

Furthermore, the design process is interdisciplinary (Fig. 3) and related to:

- Systems' and elements' Technology Readiness Levels (TRLs) and Habitability Readiness Levels (HRLs)
- Availability of resources (physical and intellectual
- Timeframe
- Societal and political support
- Economic and environmental impacts. (Testing and feedback)

Interrelationships between design stages and involvement of different disciplines should be established throughout the design and production development (Fig. 4). Other diagrams address similar reciprocal design processes but depict it from different perspectives: the spiral process reflects an architectural synthetically enhanced approach and is based on a system engineering process. The multi-linear diagram reflects engineering and architectural team efforts in pursuing integrated design solutions.

## 6 Educational Examples

There is still a need for an appropriate educational approach to enumerate space architectural objectives in related disciplines. This section of the paper shows examples of academic courses and workshops that demonstrate the importance of multidisciplinary work in order to expand the potential of design scenarios towards future space exploration mission planning and spacecraft and structures design.

### 6.1 ESA Habitat Design Workshop

In 2003, a number of students and young professionals formed an initiative to promote interdisciplinary design processes. The initiative was triggered by the lack of academic options and to follow up several personal meetings at different conferences. In 2004 this multidisciplinary highly motivated team of young architects, engineers, industrial designers and physicists from Austria, Italy, the Netherlands, England and Canada, known as the 'MoonMars Working Group' , began working on the idea of a habitat workshop. These efforts led to the Habitat Design Workshop, held on 2–9 April 2005 at ESA/ESTEC.

With the support of Piero Messina at ESA's Directorate for Human Spaceflight, Microgravity and Exploration and Bernard Foeing, ESA AURORA Program, the Moon- Mars Habitat Design Group put together an intense one-week programme based on lectures and

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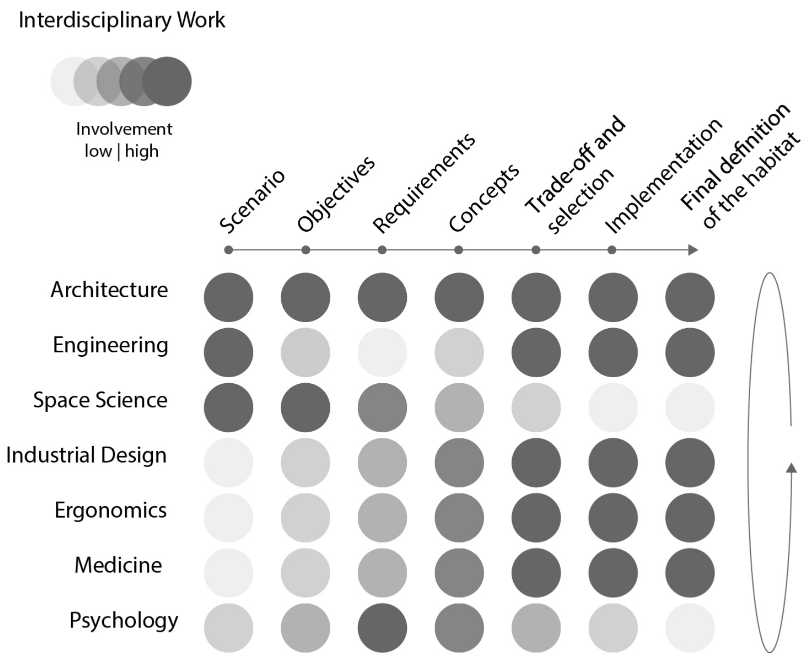


**Figure 3.** *Scheme of a disciplines relationships synthesized approach diagram*

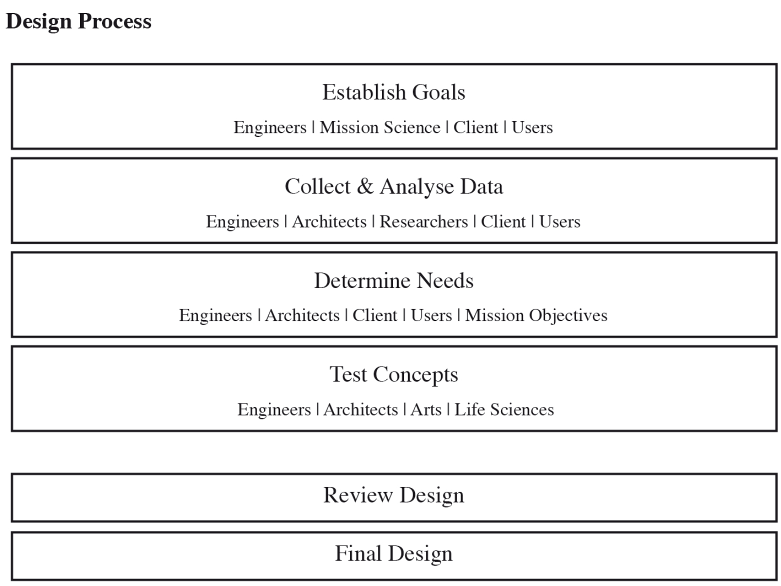


**Figure 4.** *Design process diagram. (Position paper on the role of space architecture [4])*


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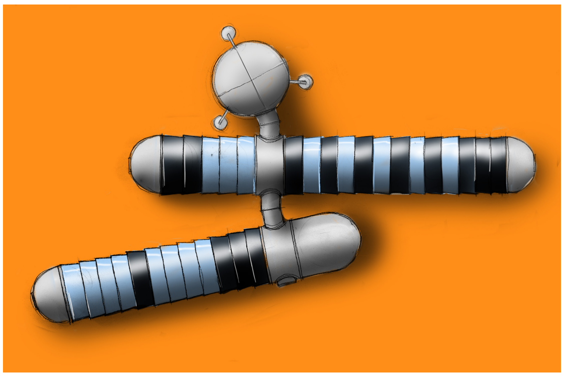

**Figure 5.** *The Elysium base presented a Mars outpost using soil and sand to make glass segments to be added to a pre-existing lander structure. (Team: B. Lansdorp, O. Clark, E. Sønneland, M. Gunter, G. Murph, K. von Bengtson)*

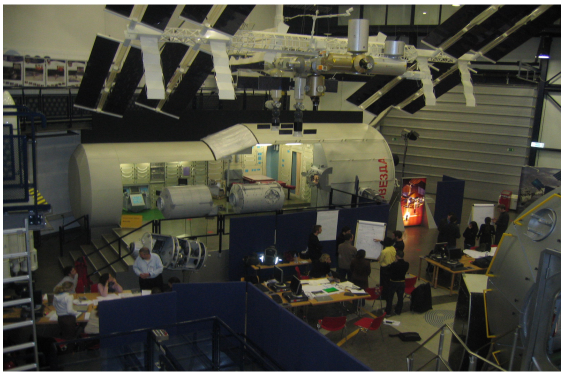

**Figure 6.** *The workshop and presentations of the ESA Habitat Design Workshop took place in ESTEC's ERASMUS facility*

group work, aimed not only at generating innovative designs but also at studying the group dynamics of a stressful, cross-disciplinary work environment.

The participants, 30 students and post-graduates were drawn from disciplines of engineering, medicine, physics, architecture and industrial design with the task to develop and design human habitation concepts. They could apply for one of the three scenarios: a base on Mars (an example is shown in Fig. 5), a base on the Moon, or an interplanetary transit vehicle that could land or "dock" on the Martian moon Phobos [23].

Following an extensive preparation of the participants via internet, the weeklong event was hosted in ESTEC's Erasmus Centre during the first week of April 2005 (Fig. 6).

The purpose of this work¬shop was to demonstrate the advantages of bringing together people from various disciplines at the very beginning of the design process. During that week, professionals from ESA and various space industries provided advisory for postgraduate students. The tight schedule foresaw an extensive lecture program in the mornings and working sessions in the afternoons and evenings.

At the end of the week, five final designs were presented to a final jury composed of ESA staff, industry representatives, and external experts and MoonMars organizers [23].

### 6.2 Space Architecture Design Studio

The TU Vienna is one of a few universities worldwide offering courses in Space Architecture that are integrated into the existing curricula of architecture. The design studio: 'Destination Moon' took part in the frame of the Master of Architecture program at the Vienna University of Technology (TU Vienna) in 2012. 25 students selected this one-semester program (March – June) and worked on their vision of a future research base on the Moon. All projects have been published and are available online for further information [17].

In the first phase of the studio a settlement strategy, based on a hypothetical scenario, had to be developed by the students. The emphasis of the second phase of the studio was on the actual design and implementation details of a lunar research station.

As most of the students had no previous knowledge in the field of Space Architecture, this course was accompanied by theme-specific lectures and workshops with space experts.

One of the biggest challenges for the students was that they could not rely on conventional architectural role models due to the total different physical and social environment. This mind shift and 'forced' critical thinking on basic questions like: *What is it for? What is happening there and why? can lead to real innovation – not only in the field of space architecture.*

In order to assess how well the students developed solutions, two kinds of reviews were provided: an internal one in the sense of a traditional studio review and an external one from the perspective of the larger world of human spaceflight. Space Architect Marc M. Cohen was invited to assess the feasibility of the projects in the professional practice of Space Architecture. The criteria encompassed three broad domains of evaluation: Concept, Representation, and Space Architecture Fea-

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| Evaluation Themes | Explanation |
|---|---|
| Analogy, including Backstory | The use of analogy is a time-honored and widespread practice in architecture. Some students use analogy, but that is not a requirement in any sense. However it can add a story line and a degree of richness to the narrative. |
| Formal Concept | Developing such a concept as a discrete physical and visual form is an essential step in architecture. |
| Imported Philosophy | It has become fashionable in recent decades to start an architecture project from a philosophical – instead of a formal – parti (Point of Departure). Although the use of imported and possibly irrelevant philosophy sometimes provokes controversy, the recording here addresses only whether it is present in the project. |
| Structural Concept | Because Space Architecture occurs in the extreme environment of vacuum and reduced or microgravity, the structure must not only support conventional live and dead loads, but also the pneumatic pressure of the atmosphere. |
| Geometric Construct | As part of the structural concept or the formal concept, a geometric concomitant often becomes a prominent organizing principle. |
| Science of Physics Concept | Some Space Architecture concepts invoke innovative applications of science, most often physics, in developing a habitat project. However, often as much peril can accrue to the project as benefit unless the architect brings a solid grasp of the science to the effort. |

Table 2. *Evaluation Themes for the Criteria CONCEPT for the Design Studio 'Destination Moon'. (Marc M. Cohen), as published in Destination Moon (TU Vienna, 2012) and Space Architecture Education for Engineers and Architects (Springer, 2016)*

tures, each divided into subthemes [17]. Table 2 gives an overview of the criteria definitions for the domain Concept.

Fig. 7 shows a visualization of the student project titled 'Twist'. The project 'Twist' creates a linear array of units that begins at the upper edge of a crater wall and follows the slope down towards the center. The form of these habitation units derives from the structure, which consist of a spiral spring. The crew will deploy this spiral inside the inflatable, giving it a form that provides volumes of varying shapes and sizes that can accommodate the living and working environment functions. The spiral will initially be flexible but its foam filling will harden into a rigid shape. This project got a good score in the domain Concept. Areas that needed further attention include the construction of the spiral to be further articulated, particularly the outer inflatable layer that would be filled with rigidized foam [17].

The domain Space Architecture Features encompassed a specific knowledge that students gained and applied in the studio. Evaluation themes for Space Architecture included multiple access, dual remote egress, multiple circulation loops, private quarters, work or lab area, plant growth area, life support, surface mobility, robotics and EVA access airlock [16, 17].

The 'Balloon in a bowl' habitat, featured in Fig. 8 consists of a deployable, hexagonal plan inflatable structure. It has an inner deployable / expandable framework. The functional modules include the Habitat, Greenhouses, and Regolith Processing. The Resistance / Residence pursues a philosophy of "environmental adaptation". The concept for an integrated inflatable and rigid structure that all deploys simultaneously is quite ingenious and the model explains it very well [17].

### 6.3 Prototyping, 1:1 Building and Field Simulation

In 2013, the design studio: 'Deployable Emergency Shelter on Mars' at the TU Vienna challenged the students to develop, build, and simulate an emergency shelter for Mars surface. The design brief requested an additional crew support element, with regards to potential EVA / science activities to be performed on Mars and related safety issues.

The primary feature had to be a portable and deployable shelter that can be employed in the event of an


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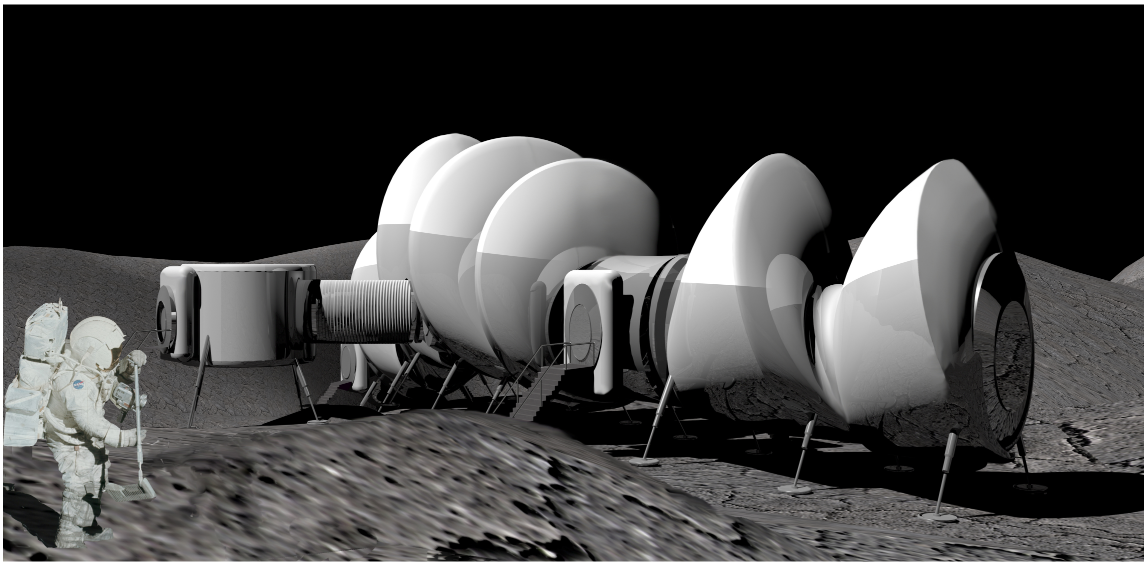

**Figure 7.** *Rendering of the project Twist by Daniela Siedler. Design Studio Destination Moon 2012 at the University of Technology, Institute for Architecture and Design, Department Hochbau 2. (TU Vienna, HB2, Siedler)*

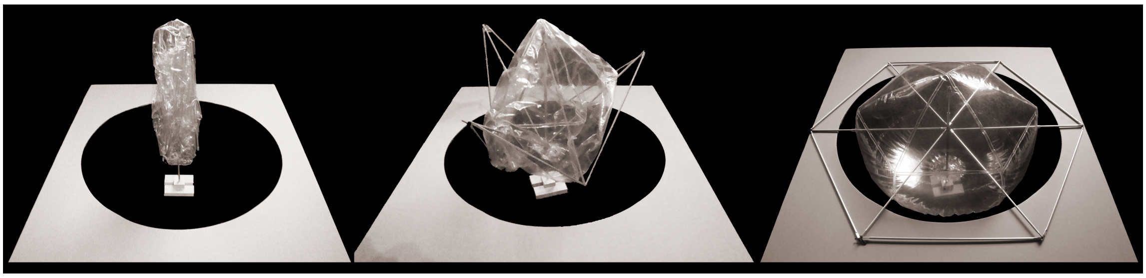

**Figure 8.** *Scale model showing the deployment process of the lunar base project Resistance / Residence undercover by Stefan Kristoffer. Design Studio Destination Moon 2012 at the University of Technology, Institute for Architecture and Design, Department Hochbau 2 (TU Vienna, HB2, Kristoffer)*

emergency requiring immediate action and where return to the base / rover is not possible in time.

Following the selection of prospective emergency scenarios and the definition of design criteria, a series of preliminary designs for an emergency shelter was developed within the HB2 academic design studio. In total three 1:1 prototypes were developed, built and revised (Fig. 9 and 10). The final prototype was tested during the Morocco Mars Analog Field Simulation in February 2013 as part of an operational evaluation of this deployable and portable multipurpose shelter. All design projects and the eventual prototypes have been published and are available online for further research [18].

The team at the TU Vienna chose a design-orientated approach along with a literature research of the state of the art and potential applications. Students were asked to work on emergency scenarios likely to happen on Mars and to develop the design criteria for the first models. Based on the most promising design, the first full scale prototype was developed and built. The second prototype was tested with the suit tester during a Dress Rehearsal Meeting in Innsbruck. The third mock-up was then tested during a field simulation in the Sahara, dealing with the three pre-defined contingency scenarios (Fig. 10).

Between the 1st and 28th of February 2013, the Austrian Space Forum (OEWF) conducted an integrated

Mars analogue field simulation in the northern Sahara near Erfoud, Morocco in the framework of the PolAres programme [18, 14]. The emergency deployable shelter was among the experiments preparing for future human Mars missions, conducted by a small field crew. The emergency scenarios were tested by a student team and the OEWF analogue astronauts during the analogue simulation mission (Fig. 12).A prototype was made to fit a number of human activities based on the most likely emergency scenarios during an EVA on Mars. Three selected emergency scenarios were tested during the simulation: One astronaut loses consciousness but is still breathing; Astronauts get exhausted and have to rest for a while; one astronaut falls down and suffers from a traumatic injury and/or space suit malfunction.

The evaluation was based upon a comparison between the shelter deployment behavior under controlled (laboratory) conditions versus the deployment in the field (to account for the influence of dust), as well as a subjective assessment of the developers, the on-site team including the analog astronauts and a post-mission inspection of the wear-and-tear patterns of the hardware. The evaluation demonstrated the expected good functionality of the mock-up. The deployment (pop up) worked as expected and took less than 1 minute. Opening (unzipping) the shelter was tested a number of times. Some difficulties were detected due to the small size of the zip pull tabs. Additional ribbons were then connected to the pull tabs allowing easier use with the space suit gloves. The deployment on a slope and rocky surface worked well.

The prototype was designed to allow functional adaptability including the adaption of the sitting and lying positions for the astronauts. The change between the two positions is achieved through air shifting between two supporting pneumatic cushions, one in front and one in the back of the shelter. The change between the two positions was tested with two astronauts inside the shelter. The mechanism worked well and efficiently. The analogue astronauts reported that sitting in the shelter was very comfortable and allowed them to fully relax. The sitting height was sufficient. The measurements of the astronauts $CO_2$ levels (carried out by the ÖWF) support this finding.

### 6.4 European – American Academic Collaboration

STAR Design is a cooperative program between NASA Johnson Space Center and the Lund Institute of Technology, Sweden that began in 1998. Each year is a different focus for the students. Architects and industrial designers from Lund have been participating in the NASA educational outreach program STAR Design since its beginning. Lund professors Per Liljeqvist (Industrial Design) and Tina-Henriette Kristiansen (Architecture) and their students worked on the development of innovative crew habitation systems and elements that could help in realizing ambitious plans of deep space exploration.

FIGURE 9. *Students simulate several procedures in order to adjust suitable body positions and to get a feeling for spatial and functional requirements. Design Studio Destination Moon 2012 at the University of Technology, Institute for Architecture and Design, Department Hochbau 2. (TU Vienna, HB2)*

As part of the program, the students spend two weeks during fall semester at NASA Johnson Space Center in Houston working with professionals from NASA, its Exploration Systems Engineering Office and the Advanced Extravehicular Activity Team. They also acquired space architecture design approaches by visiting SICSA (Sasakawa International Center for Space Architecture at the University of Houston). There, students learned about the human spaceflight program and developed their design concepts, with an emphasis on human needs, space environment, and its challenges for people and spacecraft design.
Larry Toups, from the Exploration Systems Engineering Office, oversees the program at JSC. According to him, the students' work could help NASA in agency's preparation for future missions to the Moon and Mars. Similar to the International Space Station and earlier US and Russian stations, the habitable volume of a structure on the Moon or Mars will be limited and much planning must take place in order to use that space as ef-


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**Figure 10.** *Last pre-test with the analog astronauts at the Austrian Space Forum. (OEWF, Zanella-Kux)*

**Figure 11.** *Last pre-test with the analog astronauts at the Austrian Space Forum. (OEWF, Zanella-Kux)*

ficiently as possible. (Fig. 12)

### 6.5 European – Russian Academic Collaboration

The annual International Youth Science School 'Space Development: Theory and Practice' has been running since 1997 at the Bauman Moscow State Technical University (BMSTU) with support from Ministry of Education and Science, and Russia's Federal Space Agency. Since then more than 2000 Russian and international students participated in the program. Many of them are already working on space projects in leading aerospace corporations and agencies of the world. Main educational element of the program is a group scientific project. Although participants of the school mostly come from engineering disciplines, it is open for all interested students.

Space architecture students from Houston and archi-

**Figure 12.** *Last pre-test with the analog astronauts at the Austrian Space Forum. (OEWF, Zanella-Kux)*

tecture students from Lund teamed up with aerospace, electrical, and robotic engineering students in several summer sessions developing creative design solutions for long-term manned space missions. Fig. 13 presents examples of their work. The students presented their results of the two-week team project to an external jury comprised of cosmonauts, MSTU professors, and industry professionals. Projects usually achieved a detailed schematic design stage.

## 7 Conclusion

The European-wide interdisciplinary approach has already proven its validity through the ESA Habitat Design Workshop in 2005 [23] and other academic programs in Europe and the US [17, 18]. The examples shown highlight how cross- fertilization among different disciplines can bring original solutions.

As a possible next step and with reference to current ESA plans of building a village on the Moon, the momentum can be used to continue and reinforce educational activities and networks with the goal to deliver innovative concepts for an international Moon village (and its associated technical, organizational, and social challenges).

For such a delicate international program, the inclusion of interdisciplinary educational activities is even more relevant as the same (old) difficulties and challenges of academic training still exist:

- Students and professionals are trained in space engineering but lack expertise in human factor derived requirements;
- Students and professionals in the fields of architecture and design are (often) not adequately prepared

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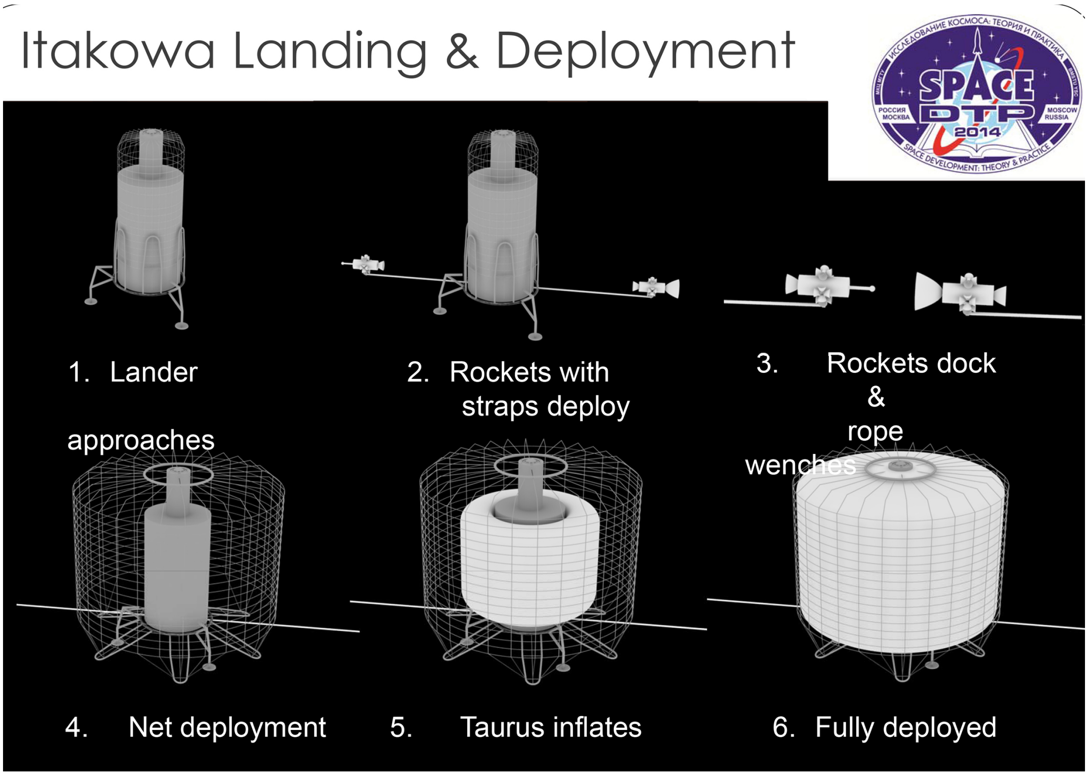


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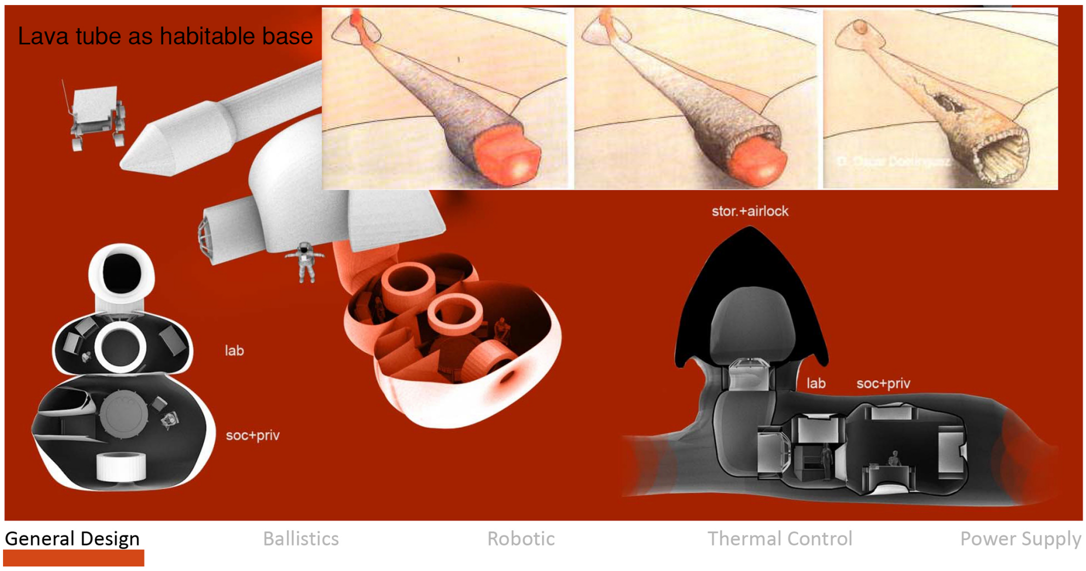


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Figure 13. *Mission to Mars: a – using an asteroid as a vehicle to Mars, habitat is docked to an asteroid; b – Mars surface habitat located in a lava tube*

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with respect to engineering requirements and evaluation criteria;

- Interdisciplinary interaction is challenged by different research and working methods;
- Different vocabulary is used for the identification of design problems and requirements, and evaluation criteria that are often inconsistent.

A multidisciplinary working approach within a workshop, design studio and alike can ignite to overcome many of these challenges that are so vital for every day work processes and results. In addition, the whole space community would benefit from new ideas derived in the workshop and through network building. The experience of such an interdisciplinary program – as part of the curricula - would help to train aerospace engineers with an understanding for the requirements related to human factors, as well as architects with the knowledge in aerospace engineering. Furthermore both professions will be introduced to the 'art of critical thinking and decision making'.

The authors have recently published a book to prepare students quickly to overcome first challenges in their learning experience. The book 'Space Architecture Education for Engineers and Architects' (Springer, 2016) takes on the mission of teaching students to design a space habitat and evaluate it at an HRL level 3. This means that the book should furnish lessons that will enable the student/reader to research, do task analysis, develop an operational concept and mission timeline, decide on areas, volumes, and adjacencies for activities and equipment, and to design lighting and other habitation systems using CAD, scale models, and drawings as appropriate.

As the former NASA astronaut Dr. Bonnie Dunbar put it, space exploration *"is no longer science fiction, but is science and engineering fact. We have also learned that space exploration is complex and very unforgiving of error. Designing spacecraft and space and planetary habitats for humans requires knowledge spanning a range of disciplines: engineering, medical sciences, psychology, human factors, life support systems, radiation protection/space weather, and other extreme space environments, at a minimum. These disciplines must result in an integrated human centered system, which should also be reliable, safe, and sustainable. This is space architecture"* (Foreword of the Book: Space Architecture Education for Engineers and Architects, 2016, by the authors).

## References

[1] Global Exploration Roadmap. https://goo.gl/UmpA3r. Accessed: January 2016.

[2] Space station planners. https://goo.gl/SRAzoc. Accessed: June 2015.

[3] The Millennium Charter. Space Architecture Mission Statement. https://goo.gl/H9j1bf, 2002. Accessed: December 2014.

[4] O. Alifanov, O. Bannova, I. Bekey, et al. Position paper on the role of space architecture. IAA, 2009.

[5] O. Bannova and L. Bell. Space architecture education as a part of aerospace engineering curriculum. *Acta Astronautica*, 69:1143–1147, 2011.

[6] C. Brown. *Elements of Spacecraft Design*. 2002.

[7] M. Cohen and S. Häuplik-Meusburger. What do we give up and leave behind? 45th International Conference on Environmental Systems, American Institute of Aeronautics and Astronautics, 12-16 July,2015.

[8] W. Compton and C. Benson. Living and Working in Space: A History of Skylab. https://goo.gl/QI5PGh, 1983. Accessed: January 2015.

[9] J. Connolly, K. Daues, J. R. Howard, et al. Definition and development of habitation readiness level (hrls) for planetary surface habitats. *Earth & Space 2006: Engineering, Construction, and Operations in Challenging Environment*, pages 1–8, 2006.

[10] M. Connors, A. Harrison, and F. Akins. *Living Aloft, Human Requirements for Extended Spaceflight*. 1999.

[11] N. Cross. Science and design methodology: a review. *Research in Engineering Design*, 5(2):63–69, 2006.

[12] M. David. Organising, valuing and improving the engineering design process. *Journal of Engineering Design*, 24(7):524–545, 2006.

[13] B. Griffin. Space Architecture. The Role, Work and Aptitude. AIAA, 4.-7. August, 2014.

DOI: 10.5281/zenodo.202149 

[14] G. Groemer, A. Soucek, N. Frischauf, et al. The mars2013 mars analog mission. *Astrobiology*, 14:360, 2014.

[15] S. Häuplik-Meusburger. *Architecture for Astronauts: An Activity-based Approach*. Springer, 2011.

[16] S. Häuplik-Meusburger and O. Bannova. *Space Architecture Education for Engineers and Architects: Designing and Planing beyond Earth*. Springer, 2016.

[17] S. Häuplik-Meusburger and S.-H. Lu. *Destination Moon - Future Living and Working Spaces*. Vienna University of Technology, 2012.

[18] S. Häuplik-Meusburger, S.-H. Lu, and P. Petrova. *Deployable Emergency Shelter MARS*. Vienna University of Technology, 2013.

[19] E. Kesseler and M. Guenov. *Advances in collaborative civil aeronautical multidisciplinary design optimization*. 2010.

[20] A. Kossiakoff, W. Sweet, S. Seymour, et al. *Systems Engineering Principles and Practice*. John Wiley & Sons Inc., 2011.

[21] W. Larson and L. Pranke. *Human Spaceflight: Mission Analysis and Design*. The McGraw-Hill Companies, 1999.

[22] NASA. NASA's Journey to Mars. Pioneering Next Steps in Space Exploration. https://goo.gl/9U7RLj. Accessed: January 2016.

[23] D. Robinson, G. Sterenborg, S. Häuplik-Meusburger, et al. Exploring the challenges of habitation design for extended human presence beyond low-earth orbit: Are new requirements and processes needed? *Acta Astronautica*, 62(12):721–732, 2008.

[24] J. Woerner. Moon village: Menschen und roboter gemeinsam auf dem mond. https://goo.gl/BaxG7e. Accessed: March 2016.



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# Architectural Design Principles for Extra-Terrestrial Habitats

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**Abstract.** Future space missions are expected to increase both in their duration and crew population, therefore further advancement in the design understanding of internal and external systems of space habitats is critical. To combat the detrimental effects of long-duration space flights and habitation within enclosed, isolated and confined environments, it is vital that space accommodation is designed to provide a high quality environment which supports the crew both physiologically and psychologically. This research project therefore studies the architectural principles which relate to habitability and their associated design parameters in relation to a proposed concept habitat design on the Moon and Mars. It proposes that there is a requirement for spatial planning guidance and regulations which will assist multi-disciplinary design teams in developing high quality living and working environments for astronauts [11]. It is also postulated that in order to assist with the application of these widely varying parameters into the initial conceptual design process, there would be a great benefit in the publication of an architectural design manual for extra-terrestrial habitats.

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## 1 Introduction

Mars exploration has gained a surge in popularity in the media in recent years due to recent robotic missions such as NASA's Curiosity Rover and concepts such as the Mars One project. The objective of sending humans to the surface of Mars and returning them safely to Earth will however be much more complex than any previous mission undertaken. Indeed the duration alone will significantly exceed that of any previous record of humans in space. To date, the longest period spent in space was undertaken by Russian cosmonaut Valeri Polyakov for a total of just over 437 days. He spent this time aboard the MIR space station from 1994 to 1995 and upon his return he was monitored to study the effects of prolonged exposure to a weightless environment. Due to his rigorous daily exercise regime in space it was found that there was less bone and muscle degradation than had been previously expected [14]. Due to the knowledge gained over many years from the study of astronauts, such as Polyakov, returning from space, it is known that there are a number of uncertainties and significant implications relating to the health of future astronauts selected for missions to Mars. Therefore the design of any accommodation needs to achieve very high levels of habitability and quality in order to minimise any detrimental psychological and physiological stresses. Architectural excellence can be achieved by adopting key architectural design principles such as space, light and comfort as well as addressing technical issues such as structural, mechanical and electronic engineering integrity. Architectural design issues can additionally be sub-divided into specific design parameters such as spatial design, spatial arrangement, lighting design, indirect external viewing methods, interior decor and furnishings. These important criteria have been incorporated into architectural design since antiquity and are still extremely relevant today, being almost universally applied and in many cases strictly employed.

A consequence of the severe limitation on a crew's ability to externally explore the landscape on the extra-terrestrial surface habitat of the Moon and Mars will be the confinement of the astronauts to an indoor environment for the vast majority of their mission. This confinement could lead to psychological stresses and so it is therefore essential that any future habitat design is very carefully considered with respect to a wide range of criteria and that any proposed design parameters are tested thoroughly in advance and optimised to ensure the well-being of all future inhabitants of Lunar and Martian colonies.

Although current proposals for future Lunar and Martian surface habitats remain at a conceptual stage, it has been possible over many years to study terrestrial analogues within extreme environments to gain an insight into potential future design requirements for extra-terrestrial habitats. Indeed, Moon and Mars analogues on Earth have been constructed for decades and are typically located in extreme locations. They all have rotating crews and attempt as rigorously as possible to simulate aspects of life on other worlds. Well known examples include the Halley VI Research Station in Antarctica, Hydrolab on a marine surface in the Bahamas and the Mars Desert Research Station in Utah, USA. All of these sites have been specifically chosen to support scientific research in an environment of relative similarity to an extra-terrestrial location, whilst at the same time providing opportunities for sample collection, dealing with extremes of temperature and facilitating the detailed study of the location's geographical, geological and geochemical environment and structure. Some have also been selected for their position relative to day lighting patterns [11]. The results of each scientific experiment to date have been carefully recorded and analysis of the data has informed contemporary strategic decision making with regards to the design of future habitats, as well as mission management plans. Simulations are of course a fraction of the cost of sending a crew into orbit and in addition to simulating isolation, they also provide opportunities to study a wide range of procedures with a high degree of safety during emergencies.

In this research project, as far as is possible, the architectural design methodology being proposed has been influenced by a thorough literature review of contemporary terrestrial analogues, analysis of the development of space architecture over the last fifty years and additionally the design principles that guide high quality architectural design on Earth. The architectural principles for designing for extra-terrestrial living proposed have also been influenced by the theoretical environmental and human factors expected to be present off-world. A number of these factors are very challenging to accommodate, but in order to facilitate high levels of habitability and comfort for future crews, an approach to design has to be developed which is holistic but at the same time detailed and technically excellent. Section 2 describes the key architectural design principles for habitability and sets out the main ideologies for designing an architecturally successful environment in space. Section 3 discusses these principles in much greater detail, breaking them down into specific design parameters.

## 2 Space Habitability Principles

### 2.1 Space Architecture and Habitability

Today in orbits around Earth, the modular tube-like architectural forms of the ISS and China's Tiangong 1 space station function as off world habitats constructed from components launched individually, in strict sequences and designed to fit within cylindrical rocket launch vehicles. These simple, geometric forms define the architectural language of today's space habitat design and in some sense express a language for space architecture in low Earth orbit (LEO).

Historically, architects have constructed buildings incorporating available local materials and knowledge of construction methods handed down over the generations. For example the Neolithic settlement Skara Brae in Scotland is a simple dry stone structure constructed over 5000 years ago, which blends into the contours of the landscape on Orkney (one of Scotland's northern most islands) and simply utilises the local readily available stone. The explorers and settlers of the New World during the 15th Century also used the resources they found on the new continents they had discovered and applied their previously acquired knowledge and skills as master builders. They did not transport their build-

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ings across the Atlantic Ocean. In the 21st Century the utilisation of available materials on Mars should be no different. Indeed, if we were to launch all the required modules to set up a settlement on Mars from Earth, it would be incredibly costly and inefficient in comparison to using local materials on the surface.

Since the early beginnings of human settlement, innumerable architectural languages and styles have formed unique structures all over the world and their architectural designs have responded to the context of the landscape, the existing architectural typology, the climatic conditions and the use of local materials - in today's metrics the latter activity substantially helps to reduce a building's carbon footprint. Good architecture adopts metrics designed to maximise spatial quality, light, thermal comfort and of course if possible provide aesthetic beauty. These attributes have been well known for centuries and were all summarised by Vitruvius in his book "De architectura" (written in the 1st Century BC) which stated that a structure must exhibit the three qualities of "firmitas, utilitas and venustas" [20]. Put simply, it must be strong, useful and beautiful.

Nowadays, with the development of innovative methods of off-site construction and fabrication, increasing numbers of similar buildings are being replicated across the globe with seemingly little regard to their cultural surroundings and historic context. For example, generic steel-framed structures clad in mass-produced panels can be found in most global cities and towns across the world despite the fact that they lack cultural context and a sense of individuality. In contrast however, there are still multiple examples of architecture exclusive to a specific location and a local material resource, such as the Japanese Shinden-sukuri style characteristic with its historic and cultural influence, the bamboo structures of Indonesia and the earthen structures of Mali and Yemen [19].

Despite the fact that today's space stations are in constant motion and therefore are more likely to be classed as vehicles rather than buildings, these orbiting assemblages are nonetheless still examples of architecture. The current, very topical issue of the possible next step in human exploration of the Solar System would be to initially establish a habitat on the surface of the Moon and Mars, with the intention of continually occupying them, either with a dedicated crew or rotating crews, in a similar manner to the ISS. For these proposals to be successful however, these future settlements must be of a high architectural quality.

A high quality habitat is key to providing a comfortable, efficient and highly flexible and adaptable environment for astronauts. In addition to the engineering design, construction and technical, operational challenges of building settlements on the Moon and Mars, another primary area of concern is the habitat interior. This environment functionally supports human living within the harsh landscapes of the Moon and Mars, but it should also promote a high quality existence for missions which may last for numerous years.

### 2.2 The Habitable Volume of Spacecraft

With regards to architectural design in space, the most obvious and fundamental factor relates to the specified dimensions and volumes of interior spaces. Habitable Volume (HV) is the free space that one can manoeuvre around within a spacecraft. This excludes any volume occupied by equipment. As a result the total spacecraft volume does not equal the HV (see Figure 1) [22]. Early space missions, since Yuri Gagarin's orbital flight in 1961 in the Vostok spacecraft, were designed to achieve the ultimate goal of putting man in space. The internal environment and human comfort level within Vostok was therefore not a primary design concern, and habitability was not the main priority. The HV fortunately has increased since then as mission duration and crew sizes have increased and comparative measurements are shown in the Table 1 below [13].

| **Mission** | **Habitable Volume ($m^3$)** |
|---|---:|
| Mercury | 1.56 |
| Vostok | 1.56 |
| Gemini | 1.13 |
| Apollo | 1.5 |
| Soyuz | 3.3 |
| Skylab | 120.3 |
| Space Shuttle | 9.25 |
| MIR | 50.0 |
| ISS | 64.7 |
| Tiangong 1 | 5.0 |

Table 1. *Habitable Volume per space habitat*

The earliest missions did not allow much free movement within a spacecraft as the crew were harnessed to their seats for the entire duration of the flight and as can be seen from the table above, habitability for these missions was therefore very low. This parameter has gradually increased over the succeeding decades to the current, more comfortable HV of the ISS. In any future Lunar and Martian habitat, the HV will depend on

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a number of factors such as the mission duration, the crew size, the requirement for increased privacy, opportunities to conduct personal hobbies, group activities, increased stowage etc. As a result, it is currently recommended that a HV value of 120 $m^3$ should be provided per crew member for any future Lunar or Martian mission [22]. Although it is recognised that this HV is a starting point for sizing interior spaces, subsequent design parameters within the HV must be applied to ensure this proposed habitable area is of sufficient size and as high a quality as possible.

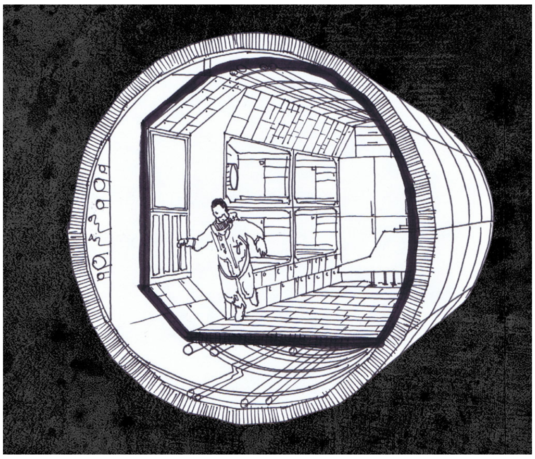

Figure 1. *Highlighted HV and systems volume combined.*

The structural and environmental systems designed within a space habitat are paramount in ensuring human survival. Without engineering excellence space travel would not be possible due to the extreme environments of interplanetary space and the conditions on the surface of other worlds. Proposed extra-terrestrial habitats will therefore require the highest levels of technical ingenuity in order to provide a safe internal environment for crews due to the challenging planetary surface conditions. These testing conditions include high levels of radiation, extreme temperature fluctuations, vacuums, abrasive and adhesive dust, potential meteorite impacts and reduced gravity (see Figure 2). Essentially, without the design of substantial artificial enclosures containing independent atmospheres and environments, life would simply not be possible [25].

The human body and mind is directly affected by its surrounding environment and therefore physical challenges related to anthropometric and biomechanical issues linked to human locomotion and the ergonomics of a space habitat will be major design considerations. For example, the simple action of opening a hatch can be very complex in a space environment; as can manoeuvring between modules. Careful consideration of day to day human activities will therefore be extremely important because the isolation and lack of additional medical care mean that it will be critical to minimise the risk of injury. Therefore the design of every space, workstation etc. will have to be carefully designed and scrutinised.

One of the biggest environmental factors which will affect the human body will be the reduced gravity on the Moon and Mars. This will cause a completely different locomotive (walking or turning around) experience compared to that experienced on Earth. As a result, all details such as furnishings, mechanical devices, supports and restraints will require careful consideration and redesign [4]. Of serious concern is the effect of reduced gravity on muscle and bone mass as well as its effect on other bodily functions such as the digestive system. There could also be detrimental effects on vision and colour perception as well as microscopic changes in the shape of body cells. Whilst architecture cannot directly combat these medical issues and effects, the provision of adequate space to exercise to try to maintain muscle and bone mass is essential, as well as the design of other spaces to perform a variety of other daily tasks. Any proposed HV must therefore be carefully considered at each stage in the design from the overall layout and arrangement of a space through to the arrangement of keypads, buttons and levers [21].

Aside from the physical effects on the human body in a space environment, there are a number of common and more specific psychological and sociological conditions that must be addressed from the outset of the design of a space habitat. Long duration missions will pose greater challenges to astronauts than any mission carried out to date. Long transit times between Earth and Mars, as well as the challenges of living on another world, with reduced gravity for up to three or four years, will be extremely demanding tests of the endurance of the astronauts. Indeed, they will be tested beyond any experience that has ever been encountered by humans to date.

Analysis of the research provided from previous space missions and earth analogues has led to better design solutions which have improved habitability. Although comfort levels are still considered to be low at present with regards to missions over one year in length, this issue is receiving increasing scrutiny in relation to seeking optimum design solutions for a potential permanent habitat on the Moon and Mars.

During the design of a terrestrial building there

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are various design parameters that architects, engineers and designers consider and implement. In the extra-terrestrial design process, environmental factors will have a much greater influence due to the vacuum of space and the thin atmosphere of Mars. In addition, radiation and thermal fluctuations will have significant influence on crew pursuits and will prohibit extra-vehicular activity (EVA) to short periods. The internal design of any habitat will therefore be crucial since astronauts will be confined to interior spaces for the majority of time in any mission and will live in a pressurised environment with a controlled atmosphere, monitored humidity and indoor air quality and regulated temperature and acoustics. Habitats will also need to also provide individual control measures, radiation shielding and sophisticated waste management systems and recycling facilities [3]. A wide range of architectural criteria will therefore have to be applied to the habitat design and these will be studied, adapted and improved over time, in order to achieve the optimum design parameters for high quality and comfortable living environments.

Ultimately a mission's success will depend on the performance of the crew. If any of them become physically or mentally incapable of carrying out their tasks, then the success of the mission will be jeopardised. As well as an individual's comfort and wellbeing the group dynamic will be incredibly important. The crew will have to collectively bond and the architecture should be designed to promote this by providing a relaxing, happy and fulfilling environment which reinforces social positivity amongst all members of the crew. It will be incredibly important to prevent, as far as is reasonably practical, negative interpersonal relations and social conflicts. Undoubtedly, if individuals are housed in a high quality and relaxing environment in which they are content, the mission will be more likely to succeed.

### 2.3 Psychological Factors

Depending on the particular mission, some astronauts may spend the rest of their careers or even their lives on Mars. These individuals will have particular tastes or styles they consider important and beautiful. Therefore, tailoring the decor, furniture, form and shape of a habitat, which will become their home, will be key to ensure human connections, happiness and a sense of wellbeing. For example, a personal preference of colour could make a difference to an individual's psychological wellbeing and so by implementing the architectural design parameters outlined in the following Section, it will be possible to fine-tune spaces to the requirements and personal taste of individual astronauts thus ensuring comfort and hopefully relaxation and contentment. Individual controls would also be desirable as individuals may prefer to vary daily room temperatures and/or levels of lighting [1].

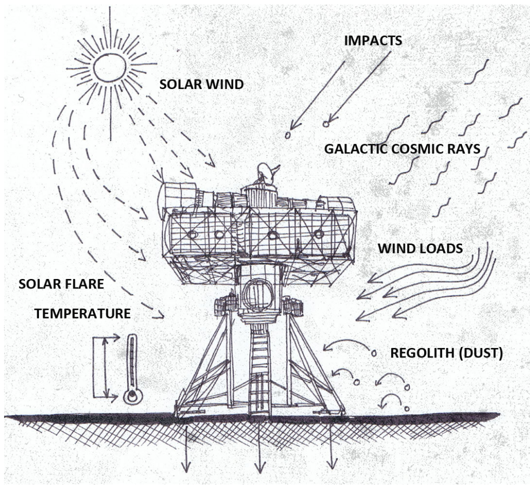


**Figure 2.** *Environmental threats to a surface habitat.*

It is reasonable to assume that a mission to Mars will consist of an international crew. Therefore architectural designs should be flexible to suit a variety of cultural customs, for example, specific religious practices require a space for prayer. Furthermore, to enhance the social cohesion of the crew, the inclusion of specific spaces in accordance with the cultural traditions of individuals and groups should be implemented where possible. As a result, a homogenous, fairly sterile design solution such as the ISS will most probably not be the most suitable design for a permanent surface habitat. Indeed, a combination of cultural elements and varying architectural styles and languages could provide a comforting environment for the entire crew and increase the level of habitability [18].

As has been discussed in this section, architectural quality, comfort and relaxation are all important general architectural principles that will be required of a HV. These broad principles are sub-divided into a number of important architectural design parameters that must be carefully considered. In order to test out the effect and consequences of these design challenges, a basic architectural concept for a Mars habitat has been proposed and developed and is described in the following section.

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## 3 Clarke Base: A Mars Habitat Concept Implementing Architectural Design Parameters

### 3.1 Overview of the Design

The Mars habitat concept design proposed in this paper, Clarke Base (named after science-fiction author Arthur C. Clarke) takes the form of a three stage construction process as described by Kennedy [15] (See Figure 3). Stage one consists of the delivery of rigid accommodation modules to the planetary surface with a fixed HV. These modules require no further assembly or construction on site and fulfil all requirements for living and working for a short term period of time. Stage two consists of the delivery and deployment of specially engineered inflatable structures. These membranes will require inflation, some frame and support assembly and will facilitate the rapid expansion of an accommodation structure with low volume and a reduced cost from Earth via transit vehicles. Additional radiation protection is required such as a 2-3.0 m layer of loose planetary soil (regolith) piled on top. Finally, stage three will consist of the completion of structures that are manufactured from locally sourced raw materials and constructed in-situ with minimal support from Earth. These structures will require all services and systems to be fully integrated into the fixed and inflatable modules in order to provide flexible habitable spaces.

This prototype Mars community design will therefore encompass a variety of architectural forms utilising structures manufactured on Earth in combination with structures constructed using local materials. It is proposed that these latter structures will employ in-situ resource utilisation (ISRU), which is essentially a construction technique with utilises regolith. In this case the soil is assumed to be the substrate construction material utilised within the structural forms created by large 3D printers. Mars regolith is understood to have similar properties to the aggregate components of high-strength concrete and therefore if printed into a single homogenous structure acting in compression it is hoped that it would have a very good strength credentials [22]. The site selected for Clarke Base, is in the equatorial region of Mars and has been chosen as a suitable location due to the availability of resources, proximity to areas of interest, shelter and available sunlight. From the outset, it is assumed that the habitat systems are technically viable and therefore the following sub-sections describing the design implications of the critical architectural design parameters.

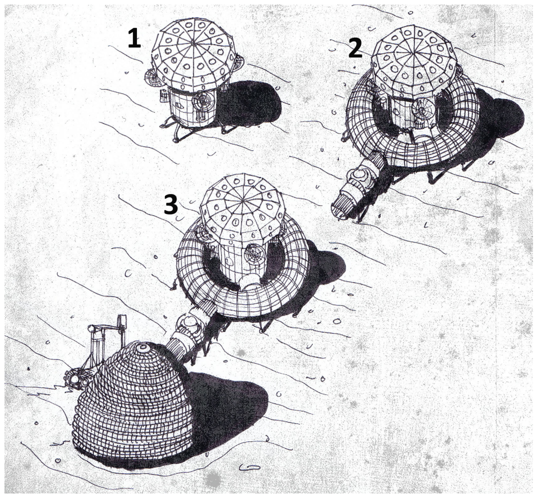


Figure 3. *Three stages illustrated.*

### 3.2 Arrangement and Layout

From the outset, the accommodation and the layout of technical systems is arranged with regards to an assigned hierarchy of spaces using a system of zoning. This enables the allocation of spaces to be ordered into appropriate arrangements. As with terrestrial architecture, this design strives to demonstrate unity, harmony, contrast, rhythm, balance, order, scale and proportion as well as generate an aesthetically pleasing environment. These design qualities require very different considerations from the functional and purely technical nature of some current space architecture.

All the required facilities within Clarke Base have been categorised into one of the following zones, namely: command and control; engineering; science; medical; transportation and civilian. In addition, the command and control is centrally configured in relation to the other zones to provide quick and easy access to systems from every part of the habitat [2]. Various planning arrangements have been considered in this research study such as a linear, grid and radial. Many of these standard arrangements have been previously tested in a generic form in analogues on Earth and each layout has its own particular advantages and disadvantages (See Figure 4). Some arrangements not regularly seen on Earth are the Contour and Rayed layout but they were proposed to widen the design options and improve the opportunities for quantitative and qualitative com-

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parison. The ISS follows a rigid, linear layout with some nodes and modules forming branches. These orbiting structures however can change with regards to their vertical orientation relative to one another and this makes this arrangement in space a totally different living environment compared to a similar arrangement of modules founded on Earth. When considering linear layouts in a Lunar and Martian context, the presence of gravity would provide a gravitational direction and therefore a uniform vertical alignment throughout the habitat as is experienced on Earth, such as recognisable floors, ceilings and walls.

In order to decide which layouts are the most successful in an extra-terrestrial context, it is important to study the proposed day to day activities of the crew. In long duration missions and permanent structures, there must be provision for adequate space to carry out a variety of activities and this inevitably leads to a high HV. The spaces required range from sleeping quarters and private workstations to kitchen or communal spaces where group activities occur. It is vital to ensure that work, rest and leisure are all conducted in separated spaces to allow for essential privacy and a change in an individual's environment throughout the day. Careful planning of spaces within the zones must also take into account factors such as noise and odour. For example, spaces such as sleeping quarters have not been placed in the vicinity of laboratories [17].

Clarke Base's conceptual layout is shown in Figure 5 and comprises a central rigid module with four surrounding modules. Encircling the central space is an inflatable torus for immediate expansion and this is connected to surrounding rigid modules by elongated inflatable tube-like structures which create additional space. In addition, several inflatable structures branch off these modules allowing for a rapid expansion of the habitat, facilitating the potential development of further nodes and inflatables. The final stage in constructing Clarke Base involves in-situ structures which are constructed once the necessary manufacturing and construction facilities have been established. These in-situ structures are more organic in form and therefore allow additional design freedom for the creation of new Martian architectural typologies, which depart from the industrial and currently monotonous modularity of space architecture. It is proposed here that in-situ structures are arranged in a manner similar to the design of existing villages, towns and communities on Earth. These separate buildings are interconnected through various tunnels and corridors. Each structure will tend to act as a singular dwelling, similar to a house within a village community. This allows a proposed habitat to develop an irregular, pattern which forms unique avenues and crescents; with larger structures forming communal and public spaces.

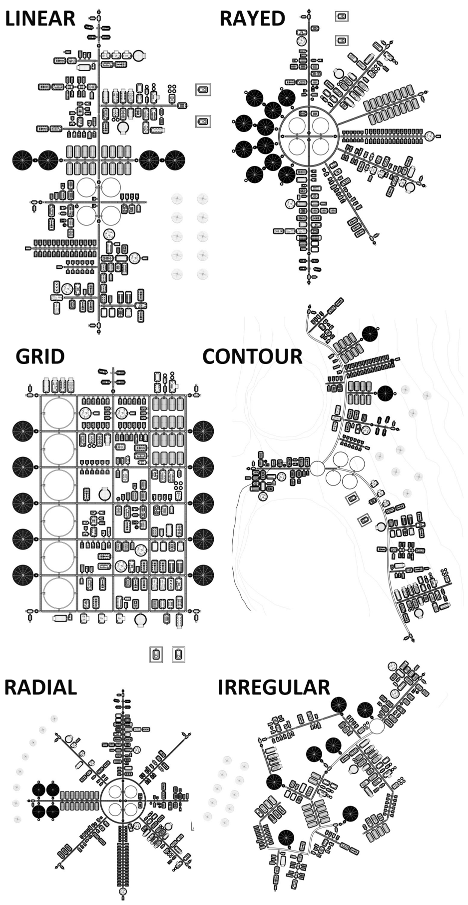


**Figure 4.** *Examples of proposed modular colony arrangements.*

### 3.3 Entrances, Thresholds and Circulation

In any building, an important factor is the design and implementation of effective and efficient circulation. This is imperative on space habitats to allow astronauts to ingress, egress and navigate through spaces easily and safely. A circulation network will of course be dependent on the layout of any habitat as a whole, but careful designs should ensure circulation efficiency, comfort and ease. Generally, circulation space is included in the HV of modules, and therefore in this

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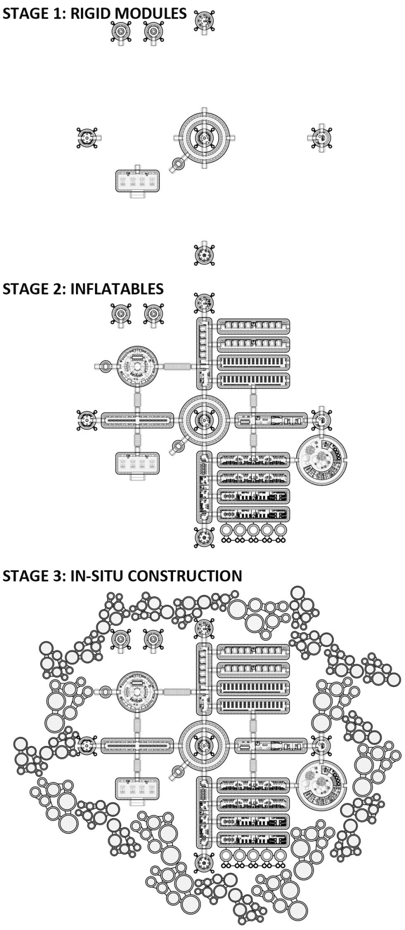


FIGURE 5. *Mars concept design three stage approach.*

radial layout scenario, circulation or access nodes feed the surrounding spaces from a central zone. These surrounding spaces are then connected to each other as the radial pattern suggests, through concentric ringed circulation. Compared to a completely linear arrangement, where access from one end to the other results in the corridors passing through each of the spaces between, radial layouts allow the inhabitants to utilise more direct paths that bypass other spaces. This enables efficient movement and ease of access for maintenance [8]. These considerations are also essential in providing privacy so that crew members bypass sleeping quarters and avoid disturbing their colleagues on different work schedules.

In Clarke Base, circulation is encouraged through connecting nodes and inflatable modules, giving various options to inhabitants to find quick routes through the space station. Entrances from the exterior comprise airlocks and dust-mitigating facilities to avoid internal contamination. Upon future expansion, all private living quarters are relocated to the surrounding stage three structures built from local regolith (see Figure 5), in order to avoid proximity of resting areas to research and experimental facilities, thus avoiding disturbance. With expansion to stage three, it can be seen that the linear arrangement shifts to a more organic form creating unique branches which digress from the main corridor artery. Although this results in a more complex and extended circulation network, the need to exercise, maintain health and avoid monotony are important considerations which benefit from additional translation paths.

### 3.4 Architectural Form

Space stations have typically consisted of modular cylindrical forms repeated across a linear arrangement [15]. Many future concepts propose similar rigid forms or alternative inflatable structures resembling domes, arches and vaults such as the Mars Homestead project [16]. The form will inevitably be dependent on a number of factors including the volume and internal capacity of the launch vehicle, although it is important to note that inflatable structures and membranes do not have this limitation and can generate various larger forms. The other architectural design proposal considered for Clarke Base includes the use of ISRU, whereby the material for construction is excavated, bound with a binding agent such as metal oxides, assembled and cured into its desired form. Substantial research into this construction option could be the potential solution to providing an efficient, relatively low-cost design that allows greater freedom of expression. This form of construction would most probably rely on some form of robotic machinery and it is conceivable that any form could be created by means of specially designed 3D printers or similar technologies. These could potentially manufacture complex geometrical forms including, domes, vaults and arches. These structural systems would then have the opportunity to include multiple levels, ramps, staircases, and natural, organic-shaped layouts. In addition, building elements such as bricks, columns and beams could be constructed and then erected on site by machinery or astronauts giving rise to multiple variations in architectural form and aesthetics [23].

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### 3.5 Ergonomic Design

In addition to the overall architectural planning and organisation, space habitats must consider detailed human dimensional design and ergonomic requirements. Investigation and development in these specialist fields has informed the minimum requirements for the dimensions of habitats in reduced gravity and their furnishings and common examples include dimensional specifications for workstations and dining tables. For example, an astronaut seated at a workstation in reduced gravity has a specific range that his/her hands can reach and interact with a control panel. This range will be different compared to their equivalent measurement on Earth. It is therefore important that in extra-terrestrial environments, detailed consideration is given to every detail to ensure that essential movements and interactions with controls are designed to be at comfortable positions. This will facilitate a comfortable and productive working environment [7]. As the arm range or reach vary depending on an astronaut's body dimensions, it is important to set up guidelines which define dimensions which are valid for the vast majority of astronauts, in the same way as guidelines on Earth for components such as handrails, stairs, ceilings and doors have specified minimum and sometimes maximum heights. For any future mission to the Moon or Mars, each individual piece of furniture or architectural element such as a staircase, bench etc., would have to be carefully considered and designed appropriately for the particular level of gravity as reduced gravity affects the locomotion of human limbs. These standard elements will therefore require further investigation and redesigning due to reduced gravity and this can be carried out by utilising anthropometric and ergonomic experiments. In summary, the dimensions of day to day interior furnishings which we use without thinking and are considered appropriate for Earth architecture will no longer be entirely relevant. They will instead act as a foundation for future research. Whilst the astronauts will eventually adapt to the level of gravity on their host planet, their maintenance of fitness levels will likely affect their locomotion. This may mean that in long term missions some architectural elements may require further redesign to accommodate changes in human physical capabilities.

In Clarke Base, illustrated previously, Martian gravity of 0.376 g has been taken into account for the design of all spaces within the modules and the ISRU structures. Ceiling heights have been set at a minimum level of 3.0 m and all reach envelopes and translation paths have been carefully analysed in order to provide enough space for inhabitants to navigate and work within the habitat with ease and an assurance of safety. Stairs for instance have been avoided where there are multiple levels and replaced instead with ladders in order to avoid an accident due to a change in human locomotion in reduced gravity.

### 3.6 Adaptability and Flexibility

For long duration missions it is important to avoid monotony in order to look after the psychological wellbeing of the crew. As on Earth, individuals will probably wish to change their interior decor or rearrange furniture as they would do in their homes. Whilst the main habitat structure shape will remain constant, the internal layout and the opportunity to add extensions is an important consideration to help facilitate flexible and adaptable design. Astronauts living on the Moon and Mars may desire change periodically. It is therefore essential that interiors can be altered to a certain degree to thereby increase the feeling of homeliness. This could mean the inclusion of sliding, rotating or collapsible walls to alter the internal layout of spaces, as well as the means to rearrange furniture, system racks and equipment [7].

The Clarke Base modules illustrated below have therefore been designed with folding and sliding components to allow a change of spacing and zoning as per the astronaut's desire. A simple grid system with a click-in mechanism also permits walls and furniture to be rearranged in various layouts. This would work in a similar manner to the rack system on the ISS, which provides adequate storage space and facilitates workstations etc [17]. The initial layout is of course optimised for space utilisation, however astronauts may desire change over time with respect to their requirement for a larger space or their need for additional privacy. The capacity to allow multiple arrangements for interiors has been considered from the outset to ensure that furniture, walls and other components can be rearranged with ease and assurance (see Figure 6).

### 3.7 Light

Natural light is the most desirable form of light on Earth to illuminate a space. It provides natural endorphins which lift the human spirit and is a natural source of Vitamin D. It also produces no sound unlike the noise intrusion sometimes caused by artificial

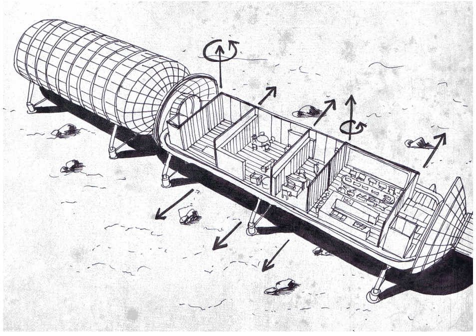

**Figure 6.** *Flexibility of internal wall configurations.*

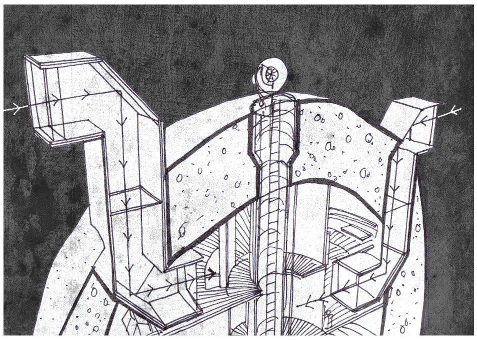

**Figure 7.** *Periscope with filters for natural light and views.*

lighting. Architects and designers strive to design buildings on Earth to maximise natural light. They employ mechanisms and techniques to flood interiors with light due to its well-known positive effects both physically and mentally. Indeed, entire architectural schemes have been built around the requirement to harness natural light and these have created distinctive and aesthetically pleasing forms. Whilst the intensity of sunlight experienced on Mars will be lower than on Earth, it is still advised that light be captured wherever possible to illuminate spaces naturally [24].

Unfortunately windows are considered to be a structural weakness in pressure vessels and are hazardous with regards to radiation exposure. They also pose an additional hazard as they would require EVAs to repair, clean and maintain them externally. For these reasons, it appears sensible to minimise the amount of windows in a space habitat in order to minimise risks. Unfortunately this reduces the level of habitability and therefore a compromise must be found which keeps the crew safe whilst allowing them to live in as exciting and stimulating an environment as possible.

Clarke Base incorporates natural light into the habitat through a system of angled mirrors, assembled within a structural framework similar to large periscopes (see Figure 7). In addition, special filters have been fitted to prevent radiation entering the space. Light is therefore gathered and channelled into multiple rooms through technologies designed to rotate and follow the sun's path. Additionally, to maximise light penetrations as much as possible, certain internal surfaces are coated in reflective materials to help distribute the light more effectively [6].

### 3.8 External Views

A connection to the outside world is vital, especially in a remote and distant region on the Martian surface, which will be new and exciting. There is a practical necessity for external vistas to facilitate docking procedures and provide direct views of external activities as well as possibly provide opportunities for space photography. Observing Earth from the ISS is a favourite pastime of many astronauts. This prompted the installation of the cupola window in 2010. Views towards the Earth, Moon and galaxy are a source of visual stimulation and a chance to escape the confinement of any space accommodation. These openings and vistas effectively expand the perception of the internal zone and psychologically provide a closer link to the exterior landscape [24].

On Earth we are surrounded by gardens, seasonal colours and changes, sunsets, wind, vegetation, buildings and art. On Mars these stimulants will not be present to the same degree. Whilst the Martian landscape appears interesting and captivating from afar, it does not contain life or the multitude of distractions that the Earth offers. Simulated windows and artificial or synthetic views can offer both visual stimulation and ensure maximum structural integrity of the module. These high resolution screens can cover large areas within the interior - larger than a window - and could display a sky, ocean, forest or mountain: instantly transforming the enclosed interior vessel to one with a view of nature and a connection with home.

Clarke Base contains large viewing areas with additional radiation filters and it is proposed that time limits would be included to reduce exposure to radiation [6]. Modules where astronauts will sleep for several hours, potentially absorbing radiation, have no natural lighting or views, again to minimise the exposure. Instead,

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sleeping quarters have been designed with large screens to simulate views of either the exterior or an environment on Earth as the crewmember desires.

### 3.9 Space Design and Perception

The perceived dimensions of a space can be altered without changing the volume. This can be achieved by the implementation of curved elements instead of angular ones with defined edges. In spaces of identical volumes, rooms with curved walls and surfaces appear larger than those with angled corners. Within the ISS the cylindrical form contains a cuboid volume internally, due to the position of workstations and storage racks. Despite being cylindrical in form, the internal space has defined edges and lines that connect to one another [12]. Replacing this with curved lines with no ends creates the illusion of a larger volume, as the perceived dimensions appear continuous or infinite within the space. These techniques could be used to make spaces within the habitat appear larger without increasing HV (see Figure 8). This may be beneficial when some zones are required to be a certain size due to constraints on materials or available space for construction. It is also beneficial to design spaces with irregularly shaped floor plans, such as an 'L' or 'S' shape so that an entire space cannot be observed as a whole from a certain vantage point. This is also true for any spaces with multiple levels or variations in ceiling heights [9].

Clarke Base's curved forms and floorplans, particularly in the stage three ISRU structures, give the spatial perception of larger spaces internally, which are further broken up by panel walls, dividers and specific curved furniture elements to create spaces within spaces. Due to the design freedom of 3D printing and microwave sintering, stage three spaces are designed as a variety of curved walls and ceilings, spaces which extend around corners using various dimensions in order to give the appearance of grander spaces (See Figure 8).

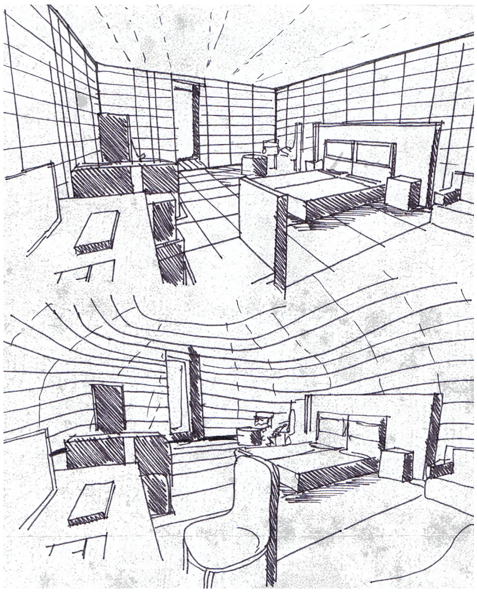

**Figure 8.** *Spatial perception: edges vs. curves.*

### 3.10 Decor

Simple factors such as the colour of the interior walls, floors and ceiling are important for psychological well-being as is the identification of colours in specific spaces for aiding the crew's perception of orientation in microgravity. A multi-sensory environment can affect the mood of the inhabitant, promote tranquillity, increase performance and boost morale [10]. Overall, colour and texture amongst other decor elements, can be incorporated in relation to living in space and it is hoped that this can have a profound impact to various degrees in reduced gravity scenarios. The saturation, hue, contrast, brightness, tone and distribution of the colours used are also important factors for the habitat's interior. The intensity and quantity in terms of the number of different colours used within one space is also an important factor, as too many variations of colours can be too intense, distracting and overstimulating, whilst more subtle changes are perceived to be more desirable. However some of these decisions again come down to individual preferences and it would be important to allow freedom of colour choice within individual, personalised areas of the habitat. As with the perceived dimensions of a space, the colour of the interior can also create the illusion of a smaller or larger space as well as create a distinct atmosphere. These techniques can be used in order to make a space seem much larger than it truly is [5].

The Russians, through Salyut and MIR, experimented with the use of colour to help give an orientation to their space stations, giving the ceiling a lighter colour than the floor [17]. On the Moon and Mars this will not be an issue, but it is still worth considering colour in setting the tone or mood of an environment and avoiding sterile white spaces. A variation of textures is also an important consideration to avoid monotony and stimulate the senses relating to touch. Subtle differences can indicate different zones and provide connotations of comfort in areas set aside for resting for example. [17].

In Clarke Base, the internal colours vary throughout the habitat depending on the zones. Warm tones of red and orange are used in rest areas; colder tones of blue and green in areas of work, and clinical whites in spaces that require high degrees of hygiene. Individual or group spaces are decorated according to personal preferences with no limitations, therefore these areas would require consultation with the crew. The spaces are, as far as possible, designed like any interior home or work space, employing patterns and designs as well as solid colours. A variety of colour palettes and textures are used either by way of the materials chosen or through artificial displays. These allow any desired image to be projected onto the walls, ceilings and floors, creating a dynamic multi-sensory environment. Coloured lighting is also incorporated to enhance the quality of a space as well as replicating natural colours – for instance that of a sunrise.

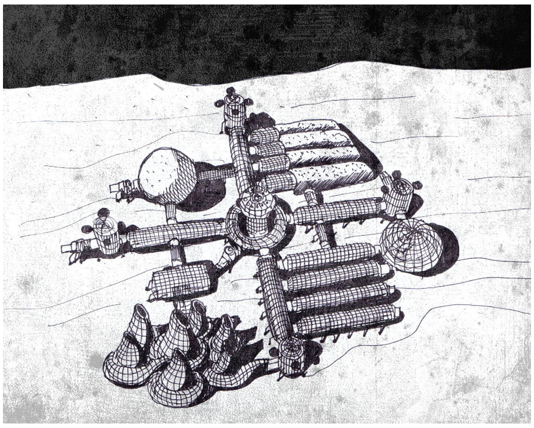

**Figure 9.** *Mars concept design with all three stages.*

## 4 Concluding Remarks

This paper has highlighted the key architectural design parameters essential to ensure the functional success of a space habitat and has also explored the less easily defined criteria which relate to psychological, physiological, cultural and emotional human characteristics. Generating holistic proposals which encompass all of these widely varying criteria is complex and challenging, but an essential part of space exploration planning. Specific civil engineering technologies such as ISRU constructed potentially using 3D printing, will allow the freedom to design structures of numerous architectural forms (see Figure 9) and permit future space architects to generate a novel and unique style based on the Martian or Lunar location and landscape. Indeed, in a sense, the architecture of a specific region on say Mars could become distinguishable and unique from another Martian region, just as Architecture is currently differentiated between different climatic zones, regions and cultures on Earth.

Aside from the generation of new architecture, the design parameters discussed in Section 3, which include ergonomic design challenges in response to lower gravity, could form part of a new extra-terrestrial architectural handbook. This document would require architects to design structures in accordance with extra-terrestrial planning and design data in a similar manner to the guidelines followed by Architects that are described within the UK Metric Handbook on Earth. This document describes architectural spatial planning rules based on ergonomics, good practice, construction techniques, health and safety and cultural norms and is fully integrated into the UK's building regulations and associated legislation [26]. Whilst a current guide exists for the interior design of habitats in orbit (NASA-STD-3001 and associated texts) [4], it is proposed by the authors that the above architectural manual or handbook is required for the design of structures on the Moon and Mars.

The literature review of previous spacecraft, space stations, terrestrial architecture and analogues, suggests that this holistic technical manual should contain minimum dimensions and ergonomic parameters developed to cover a variety of architectural design considerations. It must also contain important architectural parameters that generate designs, which can be implemented, tested and improved continually through experimentation and research. Throughout the lifespan of any structure on another celestial body, it is important to provide guidelines for delivering minimum requirements for achieving comfortable, stimulating and relaxing environments for future colonists. These "architectural instructions" would encompass aesthetic and spatial architectural design as well as HV and psychological factors. In particular the key design parameters of form, space, order, arrangement, layout, ergonomics, adaptability, natural lighting, views and interior decor.

To ensure these design parameters are optimised before surface habitation is implemented in reality, it is recommended that more analogue experiments are carried out within terrestrial analogues on Earth, such as a live build of Clarke Base or other concept designs.

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These experiments, which should utilise ISRU and be conducted in isolation, could carry out detailed social research into the way that large groups cope with isolated construction projects and prolonged periods of time in extreme climatic environments. It is hoped that through rigorous research and a detailed understanding of how highly trained individuals work and live together in artificial environments, this will allow scientists to carefully prepare potential future Martian pioneers for the journey and life ahead of them. It should also ensure that astronauts are psychologically and physically prepared to meet the challenges that they will encounter thereby ensuring the maximum possible opportunity for colonisation success.

## References


[1] C. Allen, R. Burnett, J. Charles, et al. Guidelines and capabilities for designing human missions.

[2] H. Benaroya. *Turning Dust to Gold: Building a Future on the Moon and Mars.* Praxis Publishing.

[3] H. Benaroya, L. Bernold., and K. Chua. Engineering, design and construction of lunar bases. 15(2):33–45.

[4] J. S. Centre. *NASA-STD-3000 Man-System Integration Standards.*

[5] Y. Clearwater. Space station habitability research. (17):217–222.

[6] B. Cooper, D. Schrunk, and B. Sharpe. *The Moon: Resources, Future Development and Settlement.* Praxis Publishing Ltd, second edition.

[7] W. Dempster. *The Anthropometry of Body Action.* Number 63 in Annals of the New York Academy of Sciences.

[8] O. Doule, V. Šálený, B. Hérin, et al. Omicron space habitat - research stage ii. (70):139–158.

[9] T. Dubbink. Designing for har decher: Ideas for martian habitats in the 20th century. https://goo.gl/ZUavSQ.

[10] A. Harrison. *Spacefaring: The Human Dimension.* University of California Press.

[11] A. Harrison. Humanizing outer space: architecture, habitability, and behavioral health. *Acta Astronautica*, (66):890–896, 2010.

[12] B. Imhof. Configuration options, habitability and architectural aspects of the transfer habitat module (thm) and the surface habitat on mars (shm)/esa's aurora human mission to mars (hmm) study. (60):571–587.

[13] R. Johnson and J. Stepanek. *Fundamentals of Aerospace Medicine.*

[14] A. Kalery, I. Sorokin, and M. Tyurin. Human space exploration beyond the international space station: Role of relations of human, machine and the "earth". (67):925–933.

[15] K. Kennedy. The vernacular of space architecture. https://goo.gl/93kkDt.

[16] B. Mackenzie, B. Leahy, G. Petrov, et al. The mars homestead: a mars base constructed from local materials. (7472):1–17.

[17] V. Martinez. Architectural design for space tourism. (64):382–390.

[18] V. Martinez. Architecture for space habitats. role of architectural design in planning artificial environment for long time manned space missions. (60):588–593.

[19] M. Moffet, M. W. F., and L. Wodehouse. *A World History of Architecture.* Laurence King Publishing.

[20] V. Pollio and M. Morgan. *Ten Books on Architecture.* Dover Publications.

[21] C. Rando, S. Baggerman, and L. Duvall. Habitability in space. In editor, editor, *Proceedings of the Human Factors and Ergonomics Society 49th Annual Meeting*, number 49, pages 5–9.

[22] J. Ruess, F. Schaenzlin. Structural design of a lunar habitat. (19).

[23] G. Sanders and W. Larson. Progress made in lunar in situ resource utilization under nasa's exploration technology and development program. (26):5–17.

[24] M. Seguin. Engaging space: Extraterrestrial architecture and the human psyche. (63):980–995.

[25] E. Steinberg and W. Bulleit. Considerations for design criteria for lunar structures. (7):188–198.

[26] R. Surveyors. Metric handbook. https://goo.gl/JkcTLV.


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# Time Architecture

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**Abstract.** Living in an artificial environment without access to the natural solar light, has a strong influence on the circadian clock of humans. Light is the most powerful synchroniser of human internal biological clock. The environmental conditions, however, are different in an extraterrestrial environment, such as in low Earth orbit, deep-space or on other planets. The exposure to the sunlight in space is influenced by the specific location of the habitat in relation to the Sun, as well as by specific habitat system, determining the amount of the crew's exposure to radiation. Therefore, disruptions in sleep-wake cycles have been common among astronauts. In addition, the lack of sunlight is known to induce Seasonal Affective Disorder (SAD), manifesting through fatigue, concentration and memory problems, decreased mood and obesity. In this paper we discuss the importance of considering time in architectural design as the crucial element to recover natural environment conditions in isolated interior spaces. We propose generic architectural tools for an artificial environment in order to influence an astronaut's perception of time. To regulate the biological clock of an astronaut, a specific lighting system for isolated environments is introduced. The projected simulation will be looped in a 24-h period, in order to regulate astronaut's circadian rhythm and create straightforward reference of the time of day. The light will be installed and tested in the M.A.R.S. analogue habitat in Poland.

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## 1 Introduction

In relativistic context, time cannot be separated from the three dimensions of space. In humans, timekeeping systems, called biological clocks, continuously synchronise sleep and activity cycles to rotation and revolution of the Earth. Biological clock consist of the central pacemaker neurons in the hypothalamus and autonomous or semi-autonomous peripheral pacemakers in other parts of the body, like the gut, heart or liver (Fig. 1). The biological clock is reset by environmental factors, mainly by light. Light signals represent the most important synchronization of timegiver (Zeitgeber). In addition, a variety of external stimuli such as temperature, nutrient availability or social interactions, may contribute to phase resetting of the circadian clock. The timing system is based on 9 major clock genes expressed by clock cells (period, frequency, timeless, clock, cycle, doubletime, shaggy, vrille, par domain protein 1$\epsilon$, casein kinase 2). Cyclic expression of these genes is based on interlocking transcriptional and translational feedback loops, which generate circadian oscillations that drive output pathways and rhythmic behavior such as locomotor activity, feeding, mating, etc. [25, 26]. Circadian rhythms control body temperature, heart activity, hormone secretion, blood pressure, oxygen consump-

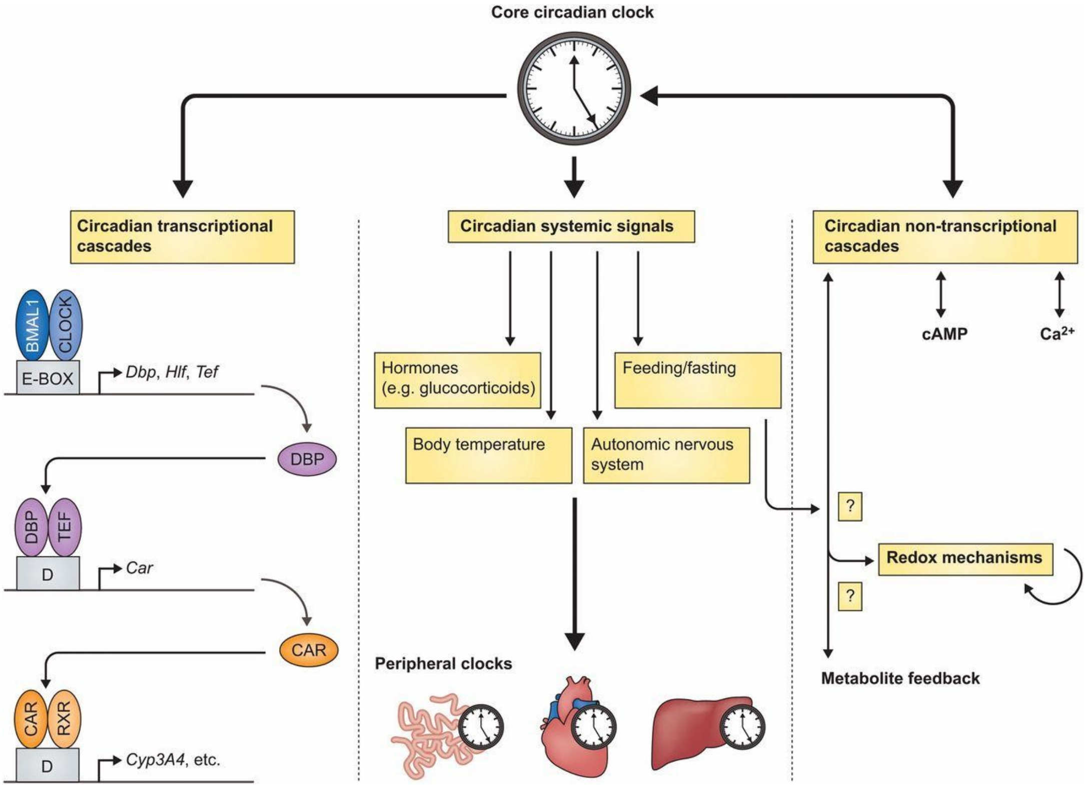


**FIGURE 1.** *The cellular regulation of clock-controlled processes can be achieved by direct clock gene expression via transcriptional cascades (left), systemic signals such as hormones, metabolic products and body temperature (center), and post-transcriptional cascades to propagate circadian signals to physiology, and vice versa (right). Credit: [18]*

tion and metabolism [14].

Perturbation of circadian rhythms, mainly caused by prolonged exposure to artificial light, has been well-documented to interfere with numerous aspects of health, and to provoke pathological conditions, including metabolic diseases such as obesity and type 2 diabetes (T2D), cardiovascular diseases, thrombosis, or cancer and neurodegenerative disorders [28]. Moreover, chronic sleep and circadian disruption cause extensive inflammation, modulated cortisol levels and significantly increased C-reactive protein (CRP), tumor necrosis factor $\alpha$ (TNF$\alpha$), and other inflammatory cytokine levels in plasma [15].

## 2 Existing Solutions to Simulate Sunlight

For greenhouses, aquaria and other bioreactors, lamps are developed to optimize conditions for efficient and healthy organism growth. Several MELiSSA (Micro-Ecological Life Support System Alternative managed by European Space Agency) studies have been performed to optimize light spectra for plant development. It is already clear that different climatic factors affect different biological processes. In the case of plants, temperature induces development (genetically programmed sequence of events during life cycle, formation of new organs, transitions from vegetative into flowering or fruiting phases), while light in combination with CO2 induces plant growth (morphology, elongation, leaf thickness, length and mass) [24]. The assembly based on the composition of several colors of LED lights obtains the best spectrum, for example Bridgelux LED's offer a coral grow lamp, where each light contains 112 x 1 Watt LEDs, red/blue/orange/white at 19:3:3:3 ratio. Such lamps are used not only to enhance growth, but also to stimulate flowering, seeding and fruiting (when blue and red light is provided simultaneously), increase vegetation periods (blue light), or to simulate sunlight during cloudy days [7]. An important advan-

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**Figure 2.** *CoeLux solutions. Examples of the window-shaped lamps imitating natural solar light source. Credit: [4]*

tage of LED technology over traditional light sources in sun simulators, such as xenon short-arc lamps and metal halide discharge lamps, is that it enables studying specific spectra and real time monitoring of light influence on molecular changes in living organisms. This control capability of precise spectral output and light uniformity will improve operating efficiency and research results. In addition, LED technology will decrease the operating and maintenance costs of the lighting system due to instant on/off and extended life of LEDs [30].

Sunlight simulants also meet increasing interest of architecture and lighting companies in order to increase human comfort, well-being and energy efficiency of buildings. Existing solutions come out from disruptive technologies, which change the way the space is designed and lit. It is possible to simulate daylight in interior spaces using lamps imitating dawn, dusk and even the movement of the sun. The exact biological effect of the simulator on human health, however, remains unclear and needs further investigation.

The solar simulators are characterized by specifications concerning spectral content, spatial uniformity and temporal stability. An output of a sun simulator is expressed in suns. 1 sun is typically defined as the nominal full sunlight intensity on a bright clear day on Earth, which measures 1000 W/m2. Examples of solar simulators are available from Abet Technologies [12], Eternal Sun [9], infinityPV [3], Newport Oriel [13], TS-Space Systems [5], Photo Emission Tech [19], Sciencetech [2], Spectrolab [6], ProPhotonix [30], WACOM [4]. One of the most developed and advanced technologies is provided by the CoeLux (Fig. 2). CoeLux technology is adjusted for all types of indoor architecture, where it can change the way spaces are experienced [1].

## 3 Lighting System for Spacecrafts

Guidelines for designing lighting system for a spacecraft could be found in a chapter about lighting from Human Integration Design Handbook published by NASA in 2014 [29]. The habitat lighting system design process must start with a clear statement of its function and task, the characterisation of its locations and orientation and architectural features which will meet all the requirements. On the International Space Station (ISS) fluorescent lighting panels are replaced with solid-state LED lighting modules that produce blue, white, or red light depending on the time. Fluorescent lamps with magnetic ballasts flicker at a normally unnoticeable frequency of 100 or 120 Hz. For some individuals suffering for example from vertigo [11], or chronic fatigue syndrome, such flickering can cause problems.

LED lighting, however, has no flickering, which makes it more similar to the sunlight. Shifting from blue to red light through an intermediate white stage could help to simulate the typical day/night cycle in the spacecraft. The blue lighting is meant to stimulate the retinal photopigment melanopsin, as well as the hor-

| Light | Protein | Function |
|---|---|---|
| 300-365 nm | Carotenoids, Vit. D, serotonin, cryptochromes | Synthesis |
| 198-380 nm | Interleukin IL-1, Prostaglandins D2, E2, F2⊠, Endothelin 1, Tumor necrosis factor (TNF⊠), Fibroblasts growth factor (bFGF), NO, beta-endorphines, trans-urocanic acid | Synthesis |
| 419-477 nm | Melatonin | Suppression |
| Intense light, about 10,000 lux | Cortisol | Suppression |

**Table 1.** *Examples of proteins sensitive to different types of light. Light can either induce or suppress the synthesis of these proteins in eye, skin or brain [17, 31, 22, 27, 16].*

mone melatonin, which helps a person to feel more alert and awake. The shift to red lighting reverses the process and helps to encourage feelings of sleepiness. This modification may help to sustain the body's circadian rhythms while in space and reduce insomnia, which can trigger deleterious effects.

Sleeping in space has long been a concern for NASA. A study showed that 50 percent of a Space Shuttle crews relied on medication to help sleep in orbit and nearly half of all medication used while in space was used to improve sleep. Unfortunately, the problem remains unsolved, since astronauts still lose their feeling about day and night on board of the ISS (private discussion with Andreas Mogensen and Jean-François Clervoy). Thus, the aim of this project is to look closer at biological adaptations to light, and based on this to propose and characterize generic tools for future lighting design.

## 4 Biological Requirements for Time Architecture

*"Light impacts on our circadian rhythms more powerfully than any drug." Charles Czeisler, Nature 2013* [21]

Lighting needs for human health have to be recharacterized and reevaluated, since the discovery of a novel non-rod, non-cone photoreceptor in the mammalian eye that mediates a range of 'non-visual' responses to light. Existing literature provides useful information about how to quantify non-visual spectral sensitivities to light but the optimal approach is far from decided. A flexible framework to describe the non-visual spectral effectiveness of light using a common language with a unified description of quantities and units is actually developed [33].

Dissecting specific light wavelengths and intensities corresponding to circadian proteins is the key to finding requirements for future designs of the optimal human health lighting conditions [10]. Light strongly affects brain areas such as the cortex, hypothalamus and emotion centers. The circadian and neurobehavioral effects of light are primarily mediated by photosensitive melanopsins and cryptochromes in retinal cells of the eye. A clear influence-response relationship between the visible short-wavelength 420 nm light and melatonin suppression with a half-saturation constant of 2.74 × 1011 photons/cm2/sec was shown. Another study revealed, that 460 nm light is significantly stronger than 420 nm light for melatonin suppression. Interestingly, 419 nm was the most efficient wavelength to induce melatonin suppression and inhibitory gamma-aminobutyric acid (GABA) neurons. Also monochromatic light 460 nm or blue light enriched 6500K lamps were sufficient [17]. UV light can alter cutaneous serotonergic system with subsequent effects on the central nervous system affecting the mood [23]. Solar energy absorbed by skin results in the transformation of a chromophore-like trans-urocanic acid to its cis-isomer form revealing agonistic activity on serotonin receptor 2A [31]. UV radiation increases the synthesis of vitamin D, beta-endorphines [22] and proteins involved in the DNA repairing processes. UV exposure can suppress the clinical symptoms of multiple sclerosis independently of vitamin D synthesis. Furthermore, UV generates nitric oxide (NO), which may reduce blood pressure and generally improve cardiovascular health. UVA-induced NO may also have antimicrobial effects and act as a neurotransmitter [27]. Research suggests that visible blue light in 450-480 nm range provides an altering function to the brain [16] and may aid in stabilizing circadian cycles. Table 1 represents spectral dependence of light to synthesis or suppression of specific proteins. Since certain amounts of blue LED light exposure may induce retinal damage (blue light exposure

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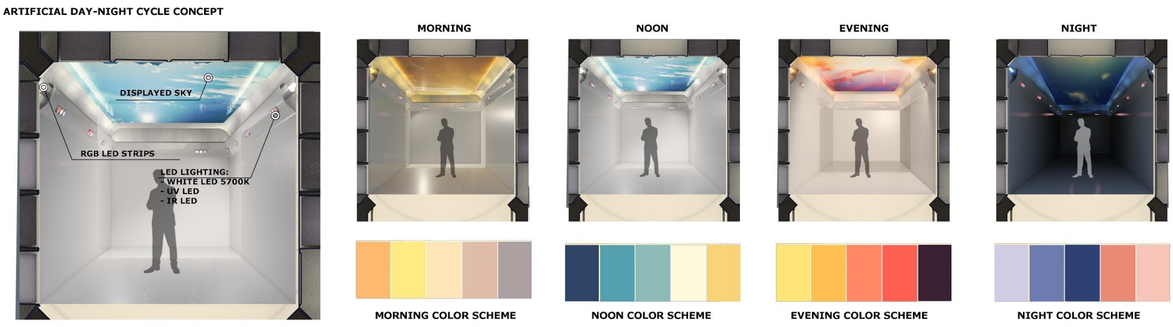


FIGURE 3. *Color palette used to simulate day, dawn and dusk lightning. RGB LED strips together with spotlights will simulate various times of a day.*

may cumulatively induce photoreceptor loss), the exact risks considering blue-light hazards for the pigmented human retina require further investigation [32, 8, 20].

## 5 Simulation of Day/Night Cycle by a Smart Lighting System

Our lighting system will mimic day and night cycles by creating an illusion of time passing. The sun's progression through the sky, along with sunrises and sunsets, is projected onto the ceiling using dedicated color pallets. Programmed RGB LED strips will simulate dawn, noon and dusk cycles by using morning, noon and evening color schemes. (Fig. 3) pursuing integrated design solutions.

In order to provide metabolic and homeostatic health of astronauts and reduce their problems with the melatonin cycle, the synthesis or suppression of specific proteins has to be induced by strengthening the light signals at specific wavelengths at specific times. Since the majority of clock proteins are activated by UV light, this high-energy radiation has to be used at low intensities to prevent DNA damage. The day/night cycle has to be framed within 24 h mode depending on the mission needs, which usually means 8h of night and 16h of day. The same lighting tools could simulate random weather systems, moon phases or seasons of the terrestrial year. The function of the system is not only to illuminate the base, but mostly to simulate day-night cycles by inducing clock protein cycles.

## 6 Experimental Design

An astronaut's circadian rhythm will be experimentally tested in the upcoming lunar analogue simulation campaign in August 2016 at the Polish Modular Analog Research Station (M.A.R.S.) (Fig. 4, up). Eight programmed types of LED lights (white LED 5700 K, UV 300 nm, violet 420 nm, blue 460 nm, green 500 nm, yellow 560 nm, red 700 nm and IR), and spectral spotlights will be installed in the facets just below the habitat's ceiling and evenly distributed on the contour of the room. A simulation of the sun's trajectory through the sky will be additionally assembled on the habitat's dome ceiling using high intensity bright light LED lamp combined with 8% of blue light (Fig. 4. bottom left). The simulation of solar movement will be provided by controlled mirror system located only in the central dome, while LED RGB strips with morning, noon and evening color schemes will be applied in all compartments of the habitat. Herewith, the possibility will be opened up to program different lengths of a day as well as various heights of simulated sun's trajectory. Directional heat, which will be used as an integral part of the habitat's thermal control system, will follow the artificial sun's movement, which might additionally contribute to the simulation of the solar effects. LED lights will be assembled in diverse modes depending on the number of specific LED lamps used (Fig. 4, bottom right): (A, B) spectral lamps with equal proportion of LED lights (14% of each sort of the wavelength type), (C, D) circadian lamps affecting clock protein synthesis by three or four reactive wavelengths (either 30% of 420 nm + 70% 460 nm and 500 nm, or 11% of 300 nm and 19% of 420 nm + 70% green).

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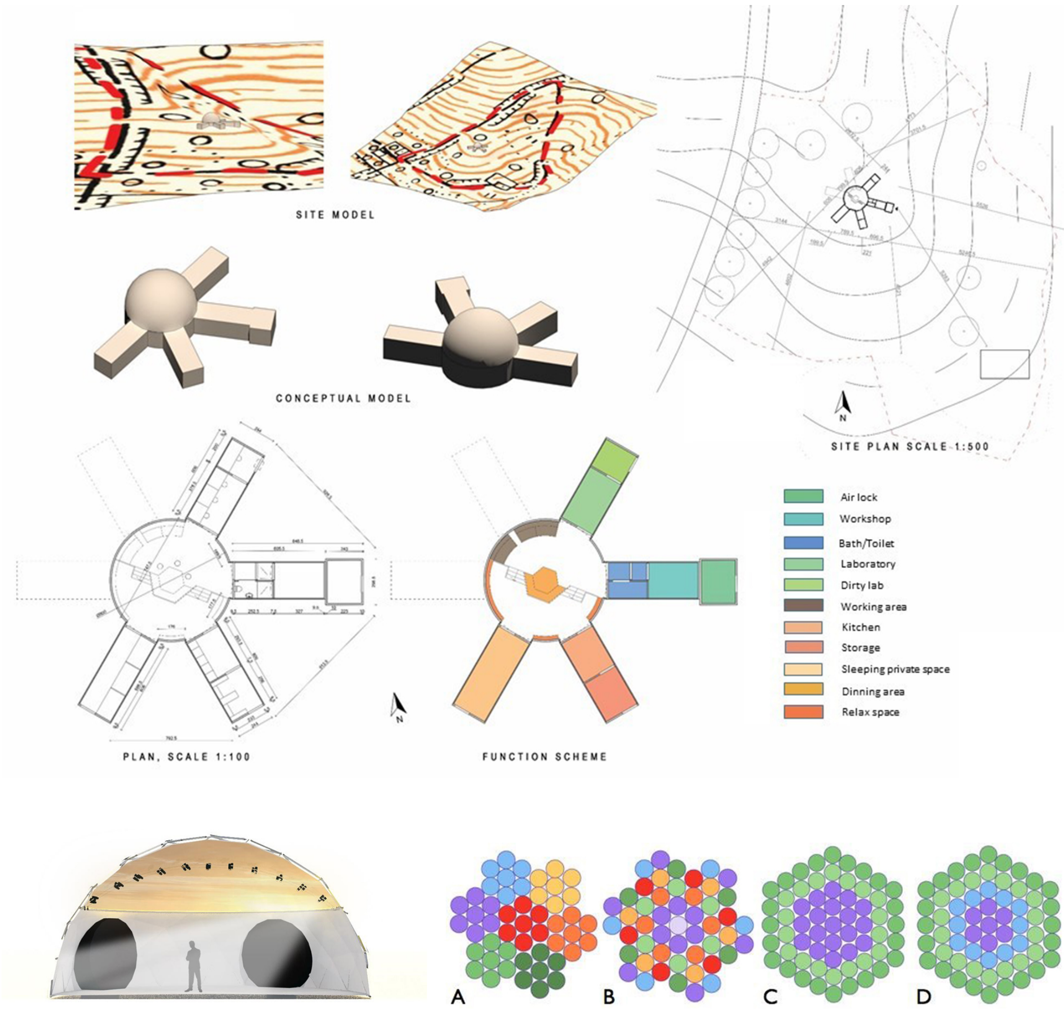


**Figure 4.** *The Modular Analog Research Station in Poland (ϕ=49°46'36".16 N, λ=21°05'22".27 E, h=351 m.n.p.m.). Conceptual model mounted in original site together with the plan and function scheme. Lighting setup in four elongated sections will be similar to the lighting in the dome using LED programmable lightning. Sun trajectory will be performed only in the central part of the base (up). Visualization of a sun trajectory across the sphere in the central part of the habitat using the mirror system (bottom, left). A various LED setups (bottom, right) will be tested to obtain different types of physiological lightning: spectral spotlights with seven various types of light wavelengths in clustered (A) and dispersed (B) configurations, circadian spotlights with UV, blue and green activation spectra (C, D).*

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## 7 Conclusion

Disruptive technologies in lighting and a better understanding of human physiology lead into a new era of healthy, smart, and economic way of building and living. The simulation of solar light in isolated spaces is a complex issue. The type of the light source, emission spectra and time duration have to be taken into account. LEDs are expected to become the primary light sources in the near future, including spacecrafts and space habitats. UV lighting is considered to be of a particular interest. UV light is also involved in the regulation of reproductive cycles in insects or in optimal plant and fish cultivation, which might be important in the future development of self-sustaining systems. It seems to be critical for activation and inhibition of specific photo-sensitive proteins, for example those, which synchronize the biological clocks of the astronaut crew and drives the physiological rhythms. In this paper we presented a concept design for a lighting system to improve metabolic and homeostatic health of astronauts and reduce their problems with the melatonin cycle. To achieve this, the synthesis or suppression of specific proteins has to be induced by strengthening the light signals at specific wavelengths at specific times. Since the majority of clock proteins are activated by UV light, the lighting system has an integrated UV lighting, which is used at low intensities to prevent DNA damage. In total our system has three components: a visualisation of a sky on the ceiling, spectral spotlights with seven various types of light wavelengths in clustered and dispersed configurations, and circadian spotlights with UV, blue and green activation spectra. The lighting system will be tested during the upcoming lunar analogue simulation campaign in August 2016 at the Polish Modular Analog Research Station (M.A.R.S.).

#### Author contributions

AK: concept proposal, writing manuscript, LO: lighting system design, graphic representations

## References


[1] Coelux. https://goo.gl/vW44hc.

[2] Fully reflective technology photovoltaic testing. https://goo.gl/k5gYRM.

[3] ISOSun simulator. https://goo.gl/9aDHmZ.

[4] Solar simulator. Wacom. https://goo.gl/m7Ax7L.

[5] Unisim solar simulator. TS-Space Systems. https://goo.gl/rQwncb.

[6] XT Series Continuous Wave Solar Simulator. https://goo.gl/tsMFDa.

[7] Home Hydroponic Led Grow light 120w LED Aquarium Coral Plant Grow Light Quad Band. https://goo.gl/1QRxKL, 2010.

[8] Health Effects of Artificial Light. EU Commission SCENIHR. https://goo.gl/hsNfCd, 2012.

[9] Solar simulation standard and AAA rating. Eternal sun. https://goo.gl/VqI1Sg, 2014.

[10] Interdisciplinary Laboratory of Performance-Integrated Design LIPID. https://goo.gl/Y6gDZE, 2015.

[11] Full spectrum or natural lighting products. http://askjan.org/cgi-win/OrgQuery.exe?Sol400, 2016.

[12] Solar simulators. https://goo.gl/zS4Xgz, 2016.

[13] Solar simulators. https://goo.gl/zoRNY1, 2016.

[14] R. Allada. Circadian clocks: A tale of two feedback loops. *Cell Press*, 112(3):284–286, 2003.

[15] K. Baron and K. Reid. Circadian misalignment and health. *International Review of Psychiatry*, 26(2):139–154, 2014.

[16] G. Brainard, J. Hanifin, J. Greeson, et al. Action spectrum for melatonin regulation in humans; evidence for a novel circadian photoreceptor. *Journal of Neuroscience*, 21(16), 2001.

[17] G. Brainard, D. Sliney, J. Hanifin, et al. Sensitivity of the human circadian system to short-wavelength (420nm) light. *Journal of Biological Rhytms*, 23(5), 2008.

[18] S. Brown. Circadian clock-mediated control of stem cell division and differentiation: beyond night and day. *Development*, 141(16):3105–3111, 2014.

[19] M. Chawla. A step by step guide to selecting the “right” solar simulator for your solar cell testing application. https://goo.gl/UIFSQt.


DOI: 10.5281/zenodo.202172 

[20] R. Collier, Y. Wang, S. Smith, et al. omplement deposition and microglial activation in the outer retina in light-induced retinopathy: inhibition by a 5-ht1a agonist. *Investigative Ophthalmology & Visual Science*, 52, 2011.

[21] C. Czeisler. Perspective: casting light on sleep deficiency. *Nature*, 497(7450), 2013.

[22] G. Fell, K. Robinson, C. Mao, et al. Skin beta-endorphin mediates addiction to uv light. *Cell Press*, 157(7), 2014.

[23] C. Harrington, T. Beswick, J. Leitenberger, et al. Addictive-like behaviours to ultraviolet light among frequent indoor tanners. *Clinical and Experimental Dermatology*, 36(1), 2011.

[24] E. Heuvenlink and C. Stanghellini. Crop and climate: microclimatic effect of the greenhouse environment. *Italus Hortus*, 14(1), 2007.

[25] W. Huang, K. Ramsey, B. Marcheva, et al. Circadian rhythms, sleep, and metabolism. *The Journal of Clinical Investigation*, 121(6):2133–2141, 2011.

[26] C. Johnson. *Chronobiology: Biological Timekeeping*. Sinauer Associates, Inc., 2004.

[27] A. Juzeniene and J. Moan. Beneficial effects of uv radiation other than via vitamin d production. *Dermatoendocrinol*, 4(2), 2012.

[28] E. Maury, H. Hong, and J. Bass. Circadian disruption in the pathogenesis of metabolic syndrome. *Diabetes & Metabolism*, 40(5):338–346, 2014.

[29] NASA. Human integration design handbook, 2014.

[30] K. Reynolds. ProPhotonix, LED-Based Sun-Simulator Design: Technical and Commercial Consideration. https://goo.gl/iYi3tW, 2015.

[31] J. Walterscheid, D. Nghiem, N. Kazimi, et al. Cis-urocanic acid, a sunlight-induced immunosuppressive factor activates immune suppression via the 5-ht2a receptor. *PNAS*, 103(46), 2006.

[32] A. Wunsch. Artificial lighting and health. https://goo.gl/dlmWBp, 2006.

[33] M. Ámundadóttir, S. Lockley, and M. Andersen. Unified framework to evaluate non-visual spectral effectiveness of light for human health. *Lighting Research and Technology*, 2016. ISSN: 1477-1535.

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**Acta Futura**

# Glance into the Future: Research Steps on a Path to a Continuous Human Presence on Moon, Mars and Beyond

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**Abstract.** Humans have been present in space for five decades and the dream of travelling and exploring space is even older. The next major step after a prolonged human presence on low Earth orbit is a prolonged human presence on other solar system bodies like Moon, Mars or even beyond. Since mid-2011 one research field of the System Analysis Space Segment (SARA) department of DLR has been the establishment of human outposts in the form of space habitats. This paper aims to showcase these activities and summarize their most important results in three primary branches. First, the design of a facility for the integrated testing and qualification of habitat technology on Earth. Second, one of the department's core competencies: Space greenhouse technology. This paper explains which steps, from concept over breadboard to laboratory work, eventually led to the current design, construction and operation of a space greenhouse analogue in Antarctica as well as the relevance for future space missions. The third branch, mainly intended to bolster the theoretical work with more practical insight into habitat design and operation are the analogue test site missions conducted by the department in 2013 and 2014. It is explained how these missions helped with the design and development of the current hardware projects and the future research facility.

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## 1 Introduction

For more than fifty years, humans have been present in space and the dream of travelling and exploring space is even older. The next major step after an extended human presence on low Earth orbit is an extended or even continuous human presence on other solar system bodies like Moon, Mars or even beyond.

Since mid-2011 one research field of the System Analysis Space Segment (SARA) department of DLR has been the establishment of human outposts in the form of space habitats. This paper aims to showcase these activities and summarize their most important results in three primary branches.

First, the design of a facility for the integrated testing and qualification of habitat technology on Earth. This proto-habitat's main purpose is not the analogous simulation of any kind of human mission to another celestial body, but to allow high-fidelity and continuous validation and integrated testing of habitat technology of various domains, e.g. life support, in-situ resource utilization and power. The current preliminary design is based on calculations of material fluxes (e.g. oxygen, hydrogen, carbon) within the habitat in various forms (water, CO2) to determine the rate of success regarding a closed loop of 100% .

The facility is based on a modular approach, where single modules exist and execute certain functions (e.g. acting as greenhouse) and are also modularly built themselves, i.e. parts of each subsystem can be exchanged for testing and further development. Depending largely on the amount of funding for such a research facility, further simulation oriented system parts can be included, e.g. a dome structure for EVA simulations and so on. Furthermore the design takes into account the needs of a human crew, including — as best as possible — comforts for the crew.

Besides the direct application for research on space capable technology, this facility is suitable for improving technology standards on Earth ensuring a reduction of environmental footprint and enabling more efficient urban habitation. Due to the high demand for efficient resource utilization in space, this facility can act as driver for the development for "greener" technologies on Earth at the same time.

The second branch of research presented in this paper focuses on one of the department's core competencies: Space greenhouse technology. Plant cultivation in large-scale closed environments is challenging and several key technologies necessary for space-based plant production are not yet space-qualified or remain in early stages of development. This paper explains which steps, from concept over breadboard to laboratory work eventually led to the current design, construction and operation of a space greenhouse analogue in Antarctica, as main part of the EDEN ISS project, as well as the relevance for future space missions. The EDEN ISS project is led by SARA and comprises 13 academic, scientific and industrial partners from Europe and Canada. The consortium will design and test essential plant cultivation technologies using an International Standard Payload Rack form factor cultivation system for potential testing on-board the International Space Station. Furthermore, a Future Exploration Greenhouse will be designed with respect to future planetary bio-regenerative life support system deployments.

The project aims to conduct an analogue test campaign at the highly-isolated German Antarctic Neumayer Station III beginning in December 2017 with a duration of 12 months. A small and mobile container-sized test facility will be built in order to provide realistic mass flow relationships. In addition to technology development and validation, food safety and plant handling procedures will be developed. These are integral aspects of the interaction between the crew and plants within closed environments.

The third branch, mainly intended to bolster the theoretical work with more practical insight into habitat design and operation is briefly presented in this paper: Analogue test site missions as conducted by the department in the Mars Desert Research Station in 2013 and 2014 as well as within NASA's HI-SEAS 2 campaign in 2014. It will be explained how these missions helped with the design and development of the current hardware projects and the future research facility.

Overall the paper provides a comprehensive view of SARA's activities within the field of future human spaceflight and exploration of the solar system, how these activities are interlinked, and their current outcome and results.

## 2 Incubator for Habitation

### 2.1 Background

Within DLR there is a long history of on-ground closed-loop habitation studies; for example the operation of the :envihab facility in Cologne [10] [22]. After the establishment of the DLR Institute of Space Systems in Bremen, the concept of a Facility of Laboratories for Sustainable Habitation (FLaSH) was initiated with preparatory work in cooperation with university student groups followed by a Concurrent Engineering (CE) feasibility study in 2011. The CE-process integrated the various disciplines — working collectively and in parallel — at the same site and facilitated the habitat design in the most efficient and consistent way. It was a guided process with access to a shared database and direct verbal and medial communication between all subsystem experts and therefore has been the perfect choice for the design of such a complex venture like FLaSH [5].

FLaSH's objectives, summarized in Tab. 1, were mainly the testing and qualification of different innovative technologies for systems and modules for space and terrestrial application. This was followed by testing the concept of a fully self-reliant artificial human habitat, public outreach for exploration and urban application, as well as the simulation of planetary exploration missions [23]. In subsequent years, the concept was further developed to a EU research proposal of a so-called Incubator for Habitation. The proposal regards a design

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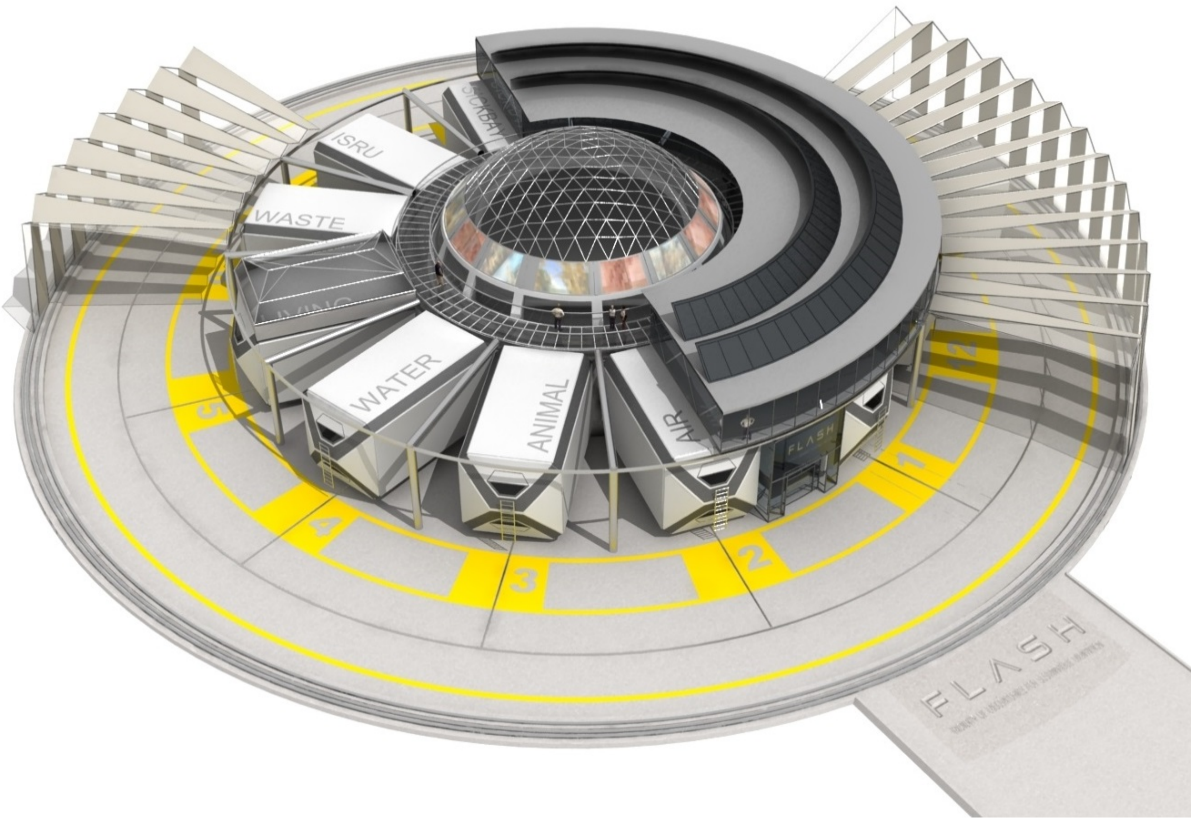


**Figure 1.** *The current design of the incubator central facility, image credit: Dr. Ondrej Doule (Space Innovations).*

study that would lead to a finished facility design beyond the current feasibility level of the study.

## 2.2 Design Overview

The general idea of the incubator for habitation is the design of a research facility, which offers the science community a common test environment to conduct cutting-edge research for sustainable human habitation. A preliminary layout of that incubator can be seen in Fig. 1. A dome structure is surrounded by a number of modules, housing the subsystems responsible for all necessary habitat functions. All modules are interconnected so that the flow of materials (e.g. air, water, waste, edible biomass) can be exchanged between the modules (sized 6 x 6 x 10 $m^3$). Furthermore there are office areas integrated into the design as well as public outreach constructions, e.g. a gallery for viewing the activities within the habitat (under observation of crew privacy).

In difference to the ordinary modules, the living module has three instead of two floors, with a glass cover allowing horizon view for the crew, to reduce the crew stress. There are movable protective covers for all modules, sheltering them against weather and other possible outer influences.

The modular approach allows the highest level of flexibility in subsystems and system research, especially considering the long-term strategy of this infrastructure. Research areas and further habitat additions (to allow tests and simulations for terrestrial and space applications) are foreseen to be connected to a control centre. The life support modules follow a twofold principle where physical/chemical systems form the backbone, guaranteeing a certain reliability and safety, as well as the function as a backup strategy. A primary bio-regenerative life support system (LSS) on top of the traditional LSS (including algae, higher plants, and animals) enables a further closure of the different loops.

By sealing off the test facility, the closed-loop situation is generated. Human crews can test (similar to e.g. MARS 500) the living and working situation

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| Objective-No. | Description |
|---|---|
| MI-OJ-0010 | Testing the concept of a fully self-reliant artificial human habitat |
| MI-OJ-0020 | Simulation of planetary exploration missions |
| MI-OJ-0030 | Testing and qualification of different innovative technologies for systems and modules for space and terrestrial application |
| MI-OJ-0040 | Public outreach for exploration and urban application |

Table 1. *Mission objectives of the Incubator for Habitation.*

in this environmentally-closed facility through several campaigns acting as the literally vital part of the habitation system. This infrastructure will offer a wide research spectrum for universities, research institutes and the industry in general where they can implement and test their own developed systems and technologies in relation to other habitat- and exploration technologies. Relevant areas are:

- Recycling and Conditioning (Air, Water, Waste),
- High-Tech farming (Agriculture, Animal Husbandry),
- Human Safety and Comfort (Living Module, Food Processing, Mobile Medical Care),
- Sustainable Resource Utilization and Advanced Manufacturing,
- Energy Redistribution and Storage,
- Automation and Control.

Acting as a focal point for this kind of research, the incubator's research infrastructure will also be capable of, and be tasked with, attracting and enabling research entities to participate within this field, even if they normally have no ties with the space sector.

The requirements for the design have been the accomodation of a 6 to 8 person crew for one year as well as a short term (2 weeks, simulating a resupply cargo vessel arriving ) crew extension to up to 12 persons. The design has to provide a 95% closed-loop cycle, the remaining 5% of resources have to be suppliable by (simulated) ISRU activities. Up to 90% of all consumer products and 30% of spare parts are to be produced within the habitat itself, to achieve a reduced amount of resupply. The facility has to have a modular layout, which allows exchange of technology and systems and has to be designed for a minimum life-time of 20 years. Each module consists of an inner and outer part. The latter is the shell that separates the facility from the outer environment, the inner part holds the actual systems and can be extended to be accessed (while not in a simulation).

In order to size the various subsystems for loop-closure, a matrix tool has been invented, which calculates and documents in- and outgoing material fluxes, e.g. oxygen, hydrogen and waste water, within the model habitat. How single subsystem outputs and demands fit together in the overall system is covered by the so called Material Trade Matrix, where the sum of the budgets of each module material flux is created. As soon as all material sums equal zero, the habitat loop is closed [21]. In Fig. 2 and Fig. 3 the Habitat Matrix is shown for the demands and the output of the individual modules. These figures would be summarized in the Trade Matrix to indicate any material with a lack or overproduction and thus perturbating the closed loop. The materials have been identified by the study team. For example, it becomes apparent that the Greenhouse Module has a demand of 46 kg of fertilizer, which can be produced by the Waste Module by recycling.

In addition to the technological topics, public participation and education are a central part of the idea behind the incubator for habitation: e.g. trainings and workshops on how the individual impact can be reduced now, which technologies are already helping with that and e.g. participating schools can contribute with small projects or experiments to the effort of the incubator. It is also envisioned to allow visitors the observation of the crew and experiments through the central glass-dome without disturbing them or altering the illusion of an off-Earth mission, see Fig. 1.

### 2.3 Terrestial Application

The intended facility design allows the coordinated research of various industry and science partners with the

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| Parameter Demand | Air Module | Animal Module | Food Processing Facility | Greenhouse Module | ISRU Module | Living Module | Sickbay | Waste Module | Water Module | Workshop Module |
|---|---|---|---|---|---|---|---|---|---|---|
| total anorganic solid waste demand in kg/day | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1,79 | 0 | 0 |
| total C6H12O6 demand in kg/day | 0 | 6,45 | 34,84 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| total CH4 demand in kg/day | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 3,45 | 0 |
| total CO2 demand in kg/day | 60,58 | 0 | 0 | 16,45 | 0 | 0 | 0 | 0 | 0 | 0,01 |
| total drinking water demand in kg/day | 24,78 | 960,48 | 50 | 0 | 0 | 153,6 | 0 | 23 | 0,5 | 10 |
| total Evaporated Water demand in kg/day | 28,10 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| total fertilizer demand in kg/day | 0 | 0 | 0 | 46 | 0 | 0 | 0 | 0 | 0 | 0 |
| total food demand in kg/day | 0 | 0 | 28,15 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| total green water demand in kg/day | 0 | 0 | 0 | 720 | 0 | 0 | 0 | 0 | 1 | 0 |
| total grey water demand in kg/day | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 554,48 | 0 |
| total H2 demand in kg/day | 0 | 0 | 0 | 0 | 1,13 | 0 | 0 | 0 | 0 | 0 |
| total liquid waste demand in kg/day | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 60 | 2405 | 0 |
| total Mars atmosphere output in kg/day | 0 | 0 | 0 | 0 | 20 | 0 | 0 | 0 | 0 | 0 |
| total Mars soil demand in kg/day | 0 | 0 | 0 | 0 | 105 | 0 | 0 | 0 | 0 | 0 |
| total O2 demand in kg/day | 0 | 34,4 | 0 | 0 | 0 | 6,56 | 0 | 2,58 | 15 | 0,70 |
| total organic solid waste demand in kg/day | 0 | 92,92 | 0 | 0 | 0 | 0 | 0 | 15 | 0 | 0 |
| total regolith demand in kg/day | 0 | 0 | 0 | 0 | 405 | 0 | 0 | 0 | 0 | 0 |
| total trace gas demand in kg/day | 0 | 5,0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| total yellow water demand in kg/day | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 12,92 | 0 | 0 |
| total ... demand in kg/day | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

**Figure 2.** *Demands within the Habitat Matrix as applied during the FLaSH study.*

| Parameter Output | Air Module | Animal Module | Food Processing Facility | Greenhouse Module | ISRU Module | Living Module | Sickbay | Waste Module | Water Module | Workshop Module |
|---|---|---|---|---|---|---|---|---|---|---|
| total anorganic solid waste output in kg/day | 0 | 0 | 0 | 0 | 454 | 0 | 0 | 0 | 0 | 1,79 |
| total Ar output in kg/day | 0 | 0 | 0 | 0 | 0,08 | 0 | 0 | 0 | 0 | 0 |
| total C6H12O6 output in kg/day | 41,30 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| total CH4 output in kg/day | 0 | 0 | 0 | 0 | 1,81 | 0 | 0 | 3,45 | 0 | 0 |
| total CH4 output in kg/day | 0 | 0 | 0 | 0 | 1,81 | 0 | 0 | 3,45 | 0 | 0 |
| total CO output in kg/day | 0 | 0 | 0 | 0 | 6,37 | 0 | 0 | 0 | 0 | 0 |
| total CO2 output in kg/day | 0 | 52,1 | 0,6 | 0 | 4,76 | 8 | 0 | 5,54 | 10,8 | 0 |
| total drinking water output in kg/day | 0 | 0 | 0 | 557,71 | 17,15 | 0 | 0 | 0 | 560,48 | 0 |
| total Evaporated Water output in kg/day | 0 | 8,5 | 6,8 | 0 | 0 | 14,45 | 0 | 0 | 0,4 | 0 |
| total fertilizer output in kg/day | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 46 | 0 | 0 |
| total food output in kg/day | 0 | 2,35 | 0 | 26,35 | 0 | 0 | 0 | 0 | 0 | 0 |
| total green water output in kg/day | 0 | 720 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| total grey water output in kg/day | 28,10 | 240 | 43,2 | 123,81 | 0 | 58,72 | 0 | 51,92 | 0 | 5 |
| total H2 output in kg/day | 0 | 0 | 0 | 0 | 0,01 | 0 | 0 | 0,014 | 0 | 0 |
| total liquid waste output in kg/day | 0 | 0 | 0 | 0 | 0 | 60 | 0 | 0 | 2400 | 5 |
| total N2 output in kg/day | 0 | 0 | 0 | 0 | 0,1 | 0 | 0 | 0 | 0 | 0 |
| total O2 output in kg/day | 44,06 | 0 | 0 | 11,96 | 36,82 | 0 | 0 | 0 | 0 | 0 |
| total oil/brine output in kg/day | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0,5 | 0 |
| total organic solid waste output in kg/day | 0 | 0 | 33,5 | 57,63 | 0 | 1,8 | 0 | 15 | 0 | 0 |
| total raw materials output in kg/day | 0 | 0 | 0 | 0 | 5 | 0 | 0 | 0 | 0 | 0 |
| total trace gas output in kg/day | 0 | 0 | 0 | 5 | 0 | 0 | 0 | 0 | 0 | 0 |
| total yellow water output in kg/day | 0 | 0 | 0 | 0 | 0 | 12,92 | 0 | 0 | 0 | 0 |
| total ... output in kg/day | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

**Figure 3.** *Outputs within the Habitat Matrix as applied during the FLaSH study.*

common goal of developing technology for more efficient and resource-saving living. While the 'living' is initially intended to be off-planet, the research milestones can and should be used to create similar effects for living on Earth. Using a centralized research installation for the maturation of such processes and technologies allows the creation of synergy effects and of awareness of potential cooperation within the relevant community and of options for contribution for entities which have previously not been aware of their relevance for this area of technology and science.

While in space resources are scarce whereas on Earth resources (e.g. water) can be found in more abundance, at least locally. For space missions critical resources need to be either transfered into orbit and to the mission destination or extracted at that destination; this has yet to be demonstrated. The larger the effort for this transfer (usually proportional to the distance from Earth), the larger the usefulness of an effective recycling of resources (e.g. turning used water into fresh water). Space based living and processes, e.g. food production, intended to be sustainable for a longer duration and less dependent on Earth resupply vehicles, consequently have to have a large efficiency or recycling rate. An extended human presence drives the demands of the corresponding technologies, systems and processes up. Applying these technologies, systems and processes on Earth can however eventually lead to improved efficiency of living on Earth. This means the incubator can lead to changes in processes, practices, and structures to moderate damages or to benefit from opportunities associated with climate change, urban development and environmentally difficult regions on Earth, e.g. deserts. Finally it can help to reduce the ecological footprint of the human population whilst maintaining and promoting the health and performance in today's society.

### 2.4 Further Development of the Concept

Currently the incubator's feasibility has been investigated and confirmed in the described study work by setting up basic layouts and budgets for its operation and construction. At the moment a proposal for a EU funded project is prepared within the Horizon 2020 programme, which after three years will culminate in a complete design of the facility. This includes a cost estimate, a legal framework for its operation and a network of research and industry partners for its utilization. The final step would encompass the actual construction and subsequent use of the facility, which is currently not estimated to happen before 2020.

## 3 Greenhouse for Antarctica and Space

### 3.1 Background

Recent achievements in growing plants on-board the International Space Station (ISS) have shown once again that plant cultivation in space is possible and beneficial to the living conditions of the crew. However, a review of plant production facilities flown in space shows such systems are limited in size and biomass production. The plant growth chambers operated on various spacecraft and stations so far have been built with the main purpose of doing science in space and not for being part of the life support system. [24]

Testing large plant cultivation systems as part of a bioregenerative life support system in space is mainly limited by the size of such systems, their energy consumption and the inexperience in operating them. Consequently, in the past different research groups and organizations relied on ground-based testing. Facilities such as, the Japanese Closed Ecology Experiment Facility (CEEF) [16], the Russian Bios facilities [9], NASA's Biomass Production Chamber (BPC) [11], the Chinese Lunar Palace 1 [7] and Biosphere 2 [14] have investigated the cultivation of plants in closed environments and even in closed ecology life support systems.

Those facilities were all part of larger research complexes which included laboratories, workshops and a large number of maintenance personnel. Testing life support systems and in particular plant cultivation technologies at analogue test sites with realistic mass flows has been suggested by researchers and organizational studies alike [12]. Some greenhouse systems have been deployed at analogue test sites such as the Arthur Clarke Mars Greenhouse in the Haughton crater in the Canadian Arctic [2], the Greenhab at the Mars Desert Research Station (MDRS) in Utah, USA [19] and the South Pole Food Growth Chamber (SPFGC) [18] at the US South Pole Station in Antarctica.

Within the wide range of analogue test sites (e.g. remote locations, deserts, polar regions) Antarctica has a number of conditions which make the continent predestined for life support testing and validation campaigns [6]. Those conditions are:

- Crew size,
- crew dynamics,
- inhospitable environment,
- technology dependency,
- extremely low biodiversity environment,
- similar habitat interfaces.

The long heritage of Antarctic greenhouses [3] substantiates that plant growth in Antarctic stations is possible and desired by the crew on-site. Consequently, Antarctica has been chosen as the primary target to test and validate plant cultivation technologies for future space missions by SARA.

In 2011 the EDEN (Evolution and Design of Environmentally-Closed Nutrition Sources) research group was created by SARA to focus on enhancing plant cultivation technologies for food production in space. From the beginning, one of the primary goals was the design, deployment and operation of a greenhouse module at an analogue test site, preferably in Antarctica, which eventually culminated in the EDEN ISS project.

### 3.2 EDEN ISS

EDEN ISS is a research project in the European Horizon 2020 framework. It consists of 13 research organizations, universities, SMEs and large industry partners from six countries in Europe and Canada. The project officially started in March 2015 and will last until the end of 2018. The main goal of EDEN ISS is:

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**The adaptation, integration, fine-tuning and demonstration of higher plant cultivation technologies and operation procedures for safe food production on-board ISS and for future human space exploration missions.**

It is further divided into three project phases regarding the creation of a greenhouse system:

1. Design phase (March 2015 - March 2016)
2. Hardware development phase (March 2016 - October 2017)
3. Antarctic campaign phase (October 2017 - December 2018)

A more detailed project overview and description can be found on the project website [1] and in [25].

*Design Overview*

The EDEN ISS greenhouse facility is designed to provide fresh produce for overwintering crews at the Neumayer III Antarctic station while at the same time advancing the readiness of a number of plant growth technologies (including a full ISPR, International Standard Payload Rack, plant cultivation system demonstrator) and operational procedures. The greenhouse will be located approximately 200 m south of the Neumayer Station III Antarctic research station.

The actual facility consists of two high cube shipping containers with a length of 6 m (20 ft), which will be placed on top of an external platform. The greenhouse is subdivided into three distinct sections, as shown in Figure 4:

- Cold porch: a small room providing storage and a small air buffer to limit the entry of cold air when the main entrance door of the facility is utilized.
- Service Section: houses the primary control, air management, thermal control and nutrient delivery systems of the greenhouse as well as the ISPR plant cultivation system.
- Future Exploration Greenhouse (FEG): the main plant growth area of the greenhouse facility, including multilevel plant growth racks operating in a precisely controlled environment.

Figure 5 shows a technical drawing of the complete facility. The image shows the preliminary design without outer side walls and roof.

The complete facility has a footprint of 29.5 $m^2$ (outer dimensions) and a usable inside area of roughly 25 $m^2$. The FEG makes up around half of the facility and contains the main plant production space. The plant growth area is arranged in a shelf configuration with up to four levels of cultivation area. In its current configuration the FEG has a total cultivation area of roughly 12.5 $m^2$.

EDEN ISS focuses on the cultivation of pick-and-eat vegetables which can only be stored for a few days. During the Antarctic campaign the following crops will be grown: various types of lettuce, dwarf tomatoes, cucumbers, bell peppers, radishes, strawberries, spinach, swiss chard, red mustard, chives, coriander, mint, parsley and basil. The objective is to have enough yield to provide a fresh mixed salad to the overwintering crew every week. Figure 6 shows the current allocation of crops within the shelf-like cultivation system of the FEG.

Crop selection was conducted via an evaluation developed by researchers from Wageningen University and Research in the Netherlands [8]. The method evaluates crops based on the categories yield, production and quality. The category yield has the subcriteria harvest index, space per time efficiency and light energy use efficiency. Commercially available seeds, maximum growth height, suitability for production system, required light intensity, first harvest time, disease resistance, reasonable shelf life, minimum handling time and spread harvest are the subcriteria in the category production. The category quality is divided into the subcriteria edible plant parts, ready-to-eat after harvest, texture, taste, pungency and appearance.

### 3.3 Mission in Antarctica and Beyond

The research and validation campaign in Antarctica will start in December 2017 when the greenhouse arrives at the Neumayer III research station. After setting up the greenhouse and performing an overall system test the plant cultivation will start in January 2018. For the initial two months of the expedition three members of the EDEN team will go to Antarctica. From February to December 2018 one EDEN team member will stay over winter together with a crew of engineers, scientists, a doctor and a cook (nine in total) at the Neumayer III station.

During the Antarctic campaign, the following datasets will be collected for research:

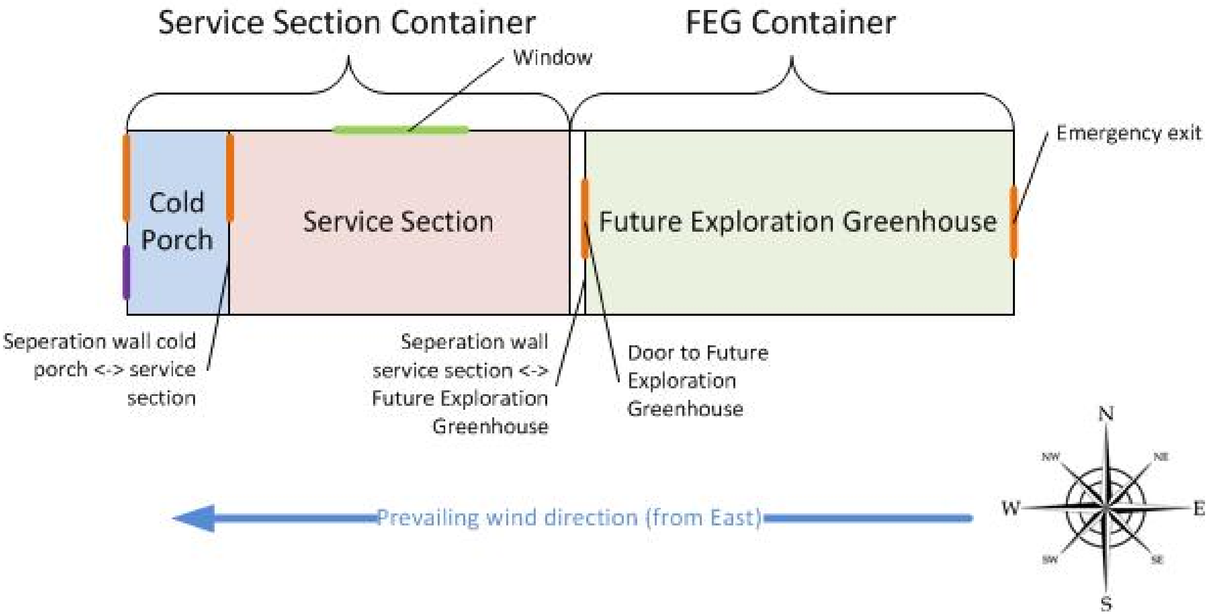


Figure 4. *Overview of the EDEN ISS greenhouse main elements*

**Plant Cultivation Data**
A large dataset associated with the growth of the selected crops destined for the EDEN ISS greenhouse will be generated during laboratory tests and the research campaign in Antarctica.

**Greenhouse Operations Data**
Datasets will be collected twice, once during test deployment, once during the operation phase. Data contains greenhouse environmental, system health and imaging data and can be used for comparison with other comparable plant production systems.

**ISPR Cultivation System Operations Data**
Collected three times, during testing, test deployment and operation. The data contains full-rack demonstrator environmental data, system health as well as imaging data.

**Food Quality and Safety Data**
Will be collected during assembly, testing and during operation in Antarctica. Determined by chemical composition (e.g. type of carbohydrates) and consumer perception.

**Microbial Investigations Data**
Sampling will occur on surfaces to gain an overview of the diversity and physiological capability of microorganisms under different growth conditions (e.g. different temperatures).

**Effects on Crew Data**
Analysis of crew mood, workability and cohesion.

The datasets will be evaluated by the EDEN ISS project team and according to the rules of the European Horizon 2020 research framework they will be openly accessible to the research community.

## 4 Analogue Testing

### 4.1 Background

Starting in early 2013 SARA began to conduct research campaigns at analogue test sites, namely the Mars Desert Research Station (MDRS) in Utah, USA [15], see Fig. 8, and the Hawaii Space Exploration Analog and Simulation (HI-SEAS) on Hawaii, USA [20]. Beginning with a precursor mission for preparation of plant experiments and for habitat design one member of the department was part of MDRS' Crew 125 in early 2013 and one year later a second scientist took part in Crew 135, and likewise in HI-SEAS Crew 2, for plant growth experiments. Furthermore, other members of SARA

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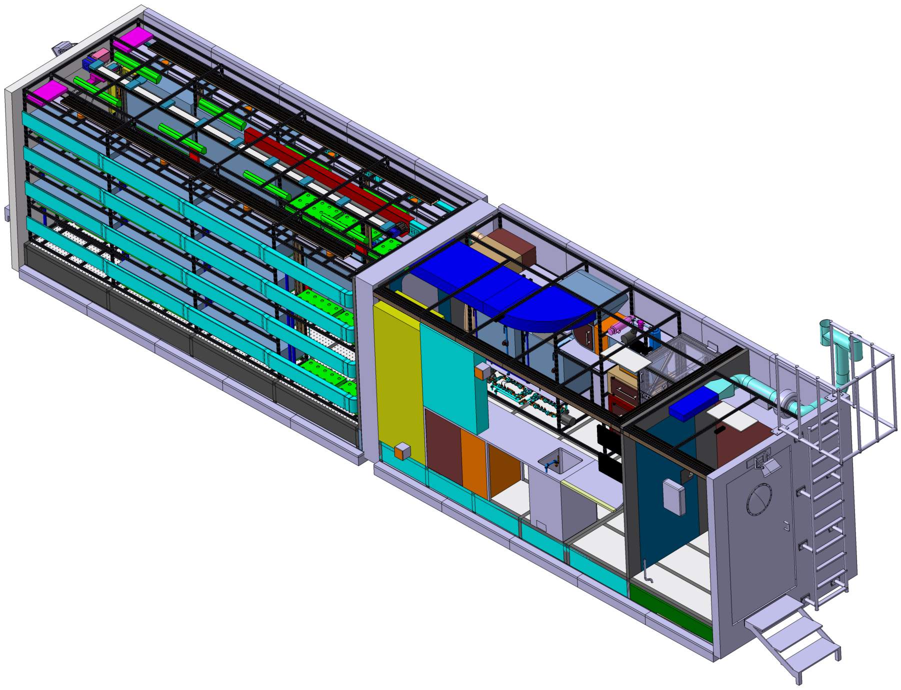

Figure 5. *CAD drawing of the EDEN ISS greenhouse with the cold porch and service section to the right and the FEG to the left.*

have taken part in analogue test site missions as well. The previously described Antarctica mission will further add to the general knowledge of living and working in an artificial habitation situation, adding insight for design and development of such systems.

### 4.2 Mission Objectives

*MDRS Crew 125*

MDRS Crew 125 was the second rotation of the EuroMoonMars campaign and lasted for two weeks. The general mission objectives ranged from several geological research experiments in the Utah desert, e.g. investigating life traces conservation [4, 17], to human factors research and technological experiments [4]. The latter was part of SARA's investigation. First of all the exact situation at MDRS was investigated to prepare interfaces, location and handling of a future plant growth experiment. The second objective for SARA's participation was the review on MDRS' design and layout to draw conclusion for the habitat design work of the department. This served to incorporate 'lessons learnt' into the design considerations before actually building an own habitat research station.

*MDRS Crew 135 and HI-SEAS 2*

The participation on Crew 135 was under the auspice of furthering the greenhouse equipment at MDRS. Overall Crew 135 was investigating the reliability of the mechanics, structure and power supply of the habitat as well as improving the illumination and automation of the station's greenhouse module. Besides that it was SARA's objective to install an artificial illumination system in MDRS' greenhouse and experiment with its contribution to plant growth by comparing growth with and without artificial illumination. Furthermore the greenhouse was reviewed regarding its properties, e.g. watering automation and thermal insulation, for recommendations on improvement.

During HI-SEAS Crew 2 mission the experiments were extensions of the plant experiments conducted during MDRS Crew 135 and focussed on the comparison of plant growth improvement of various illumination systems and their properties. The plants grown were let-

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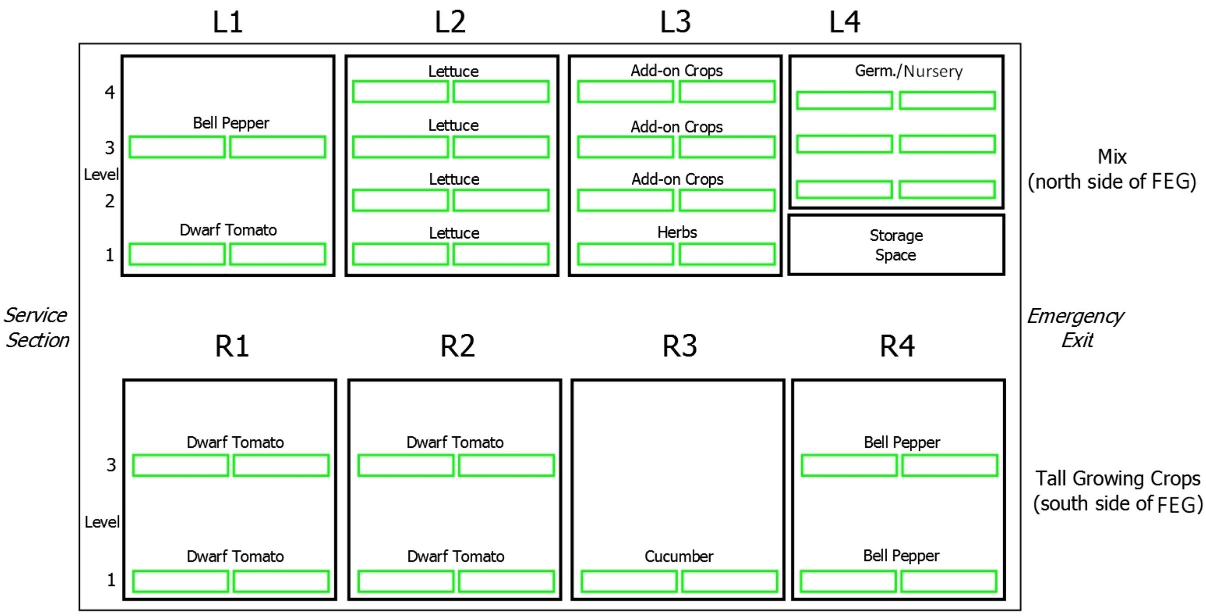


FIGURE 6. *Allocation of crops to the different cultivation units within the FEG. Green boxes indicate the growth trays. Add-on crops: Radish, strawberry, spinach, swiss chard, red mustard. Herbs: Chives, parsley, coriander, basil.*

tuce and radish.

### 4.3 Results and Impact

*MDRS Crew 125*

At the time of this crew rotation, MDRS had been in operation for more than 10 years. While wear-off of various components was detectable, it did not hinder the operation of the station. The most considerable wear-off was the condition of the outer airlock doors, as shown in Fig. 7. Both of them were significantly misaligned, which made closure and opening difficult. The hinges were under stress and had decayed to a point where they lost screws (likely due to rust and dynamic loads). During strong winds the door was pulled on very strongly and crashed into the hinges. Generally, the doors were the major wear-off element in the whole habitat. It is proposed to apply sliding doors (comparable to transport vehicles) and mount rails on the habitat walls on future facilities and also use sliding doors for I4H. Sliding doors would have three advantages:

- No dynamic loads on the door itself and its mounting,
- no area which can be attacked by wind forces,
- the door can be opened independently of the relative pressure from out- and inside.

FIGURE 7. *Left: The closed outer engineering airlock door with hinges on its right and no support on its left side. Right: One of the bottom hinges, strongly constructed, but decay and likely dynamic forces caused the loss of a screw.*

The large amount of utensils used in MDRS (especially for various experiments and also supply storage) suggest the need for more storage room. Certain elements could likely be stowed away in the ceilings of the rooms, as there is a strong steel beam structure, which

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is currently unused. Also an actual protocol for inventory and removing unusable elements from the inventory could help reduce the amount of required storage space and the time needed for locating the equipment.

There are two issues that regard the stateroom condition: extensive heat and lack of outside view.

There is enough room to have privacy and live relatively comfortably but the air flow within the rooms is minimal. Hot air is introduced via a venting system, creating a warm and dry atmosphere, which especially is disadvantageous for sleeping. As a result, crewmembers tend to sleep with open doors, which exposes them to the noise of the overall station venting system and water pump. Therefore effective and noise reduced venting measures need to be implemented in an actual habitat.

Windows in the staterooms would also add crew comfort. While these would introduce structural, radiation and heating problems in actual flight-hardware, these issues could be redeemed. Windows would also relax power demand as daylight removes the need for artificial illumination.

A more detailed description and analysis of the Mars Desert Research Station can be found in [13]. The proposed inprovements are intended for application in the incubator for habitation.

**Figure 8.** *MDRS with the main habitat (back) and greenhouse (front) during Crew 125's rotation.*

### *MDRS Crew 135*

The plant growth experiments conducted at MDRS showed the viability of using artificial light sources for improved plant growth properties. Within the 14 days rotation it was shown that depending on the plant age, lettuce could increase its fresh mass by between 11% and 34% when exposed to artificial illumination for 12 hours opposed to 10.5 hours of natural light for the control group. Similarly, the hypocotyl length was reduced by 20 to 28%, which is a sign for improved growth conditions. Consequently artificial illumination - without draining the power supply of MDRS significantly - has been recommended to MDRS management for improving the station's Greenhab efficiency, especially for crews in the early parts of the season, where natural illumination is scarce.

Furthermore Crew 135 made the recommendation to use plastic shelves, instead of wooden because of wear-off and risks of splinters. Also an automated watering system was proposed for reducing the time constraints of watering plants for the crew. Similarly a simple temperature control system would allow creating more suitable growth conditions for most plants, removing the large temperature variation from 0°C in the morning to 35°C during sunny days. More detail can be found in [13].

### *HI-SEAS Crew 2*

The artificial illumination experiments showed the dependence of fresh mass and hypocotyl length on illumination wavelength for radishes and lettuce. While red and blue light provided the best results in terms of hypocotyl length for radishes, it led to the least amount of fresh mass. Best results (improved by a factor of 1.5 to 1.8) were obtained with white light, suggesting that a combination of white and blue or red light would lead to optimal results concerning radishes. For lettuce the hypocotyl length did not show a significant variation based on illumination wavelength, but influenced the leaf mass, which was largest for red and blue lighting, i.e. about a factor 1.3 larger than for white light.

Secondary results of the mission have been that all crewmembers, even though previously not familiar with plant care, valued the inclusion of plants in the habitat and caring for them. The latter took about 15 minutes per average per day. A detailed description of these experiments and their results can be found in [20].

### *Lessons Learnt*

As mentioned before the major motivation for the analogue missions conducted by SARA have been possible impact the respective experience provides regarding the habitat and greenhouse design and their oper-

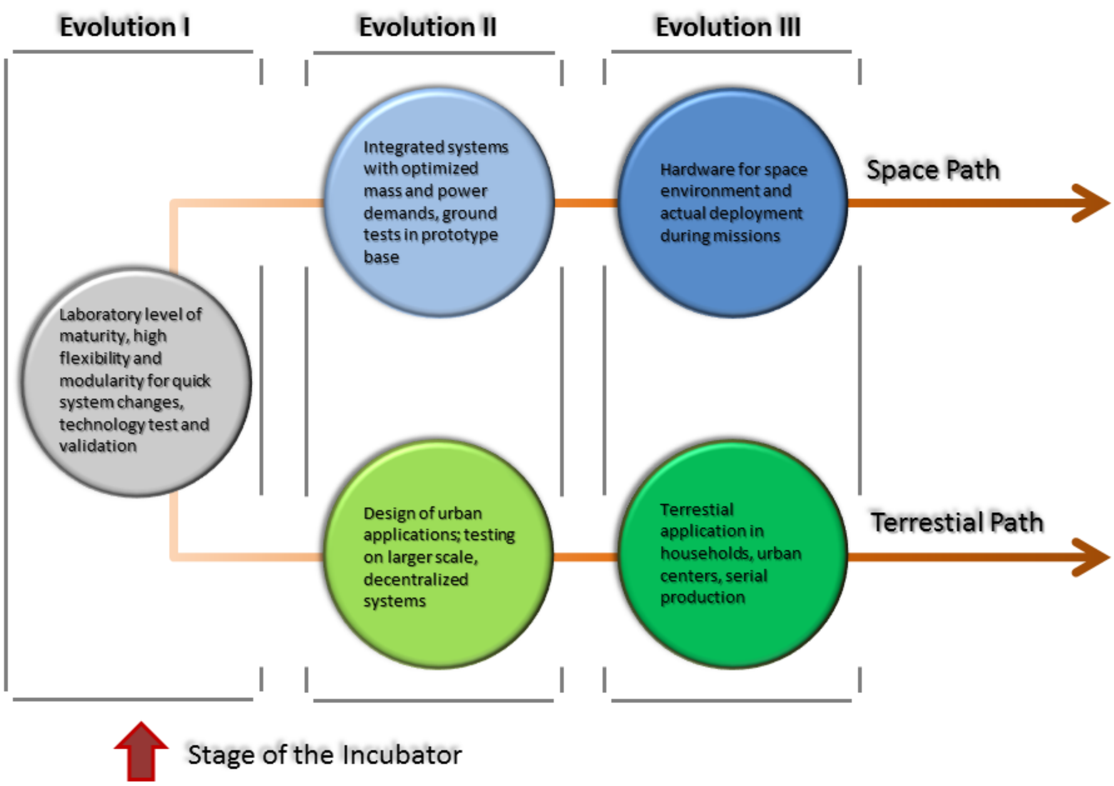


FIGURE 9. *Research path for terrestial and space habitation.*

ational processes. For instance, the door mechanisms and living quarter design as reviewed at MDRS will influence the design of the I4H's living quarters and outer doors. The procedures reviewed during greenhouse operation at MDRS and HI-SEAS will further procedures of EDEN ISS and its design.

## 5 Future Research

With the help of the incubator for habitation and the already maturing greenhouse technology, the research path is at a step where technology testing can occur in an integrated manner, as described in Section 2. However the idea is to eventually separate the research paths into their domains, namely space and terrestial application, as depicted in Fig. 9. While the first step is intended to allow the qualification and validation of the respective technologies (e.g. air management or plant cultivation), the second step will be directed at optimizing the designs to their specific purpose and with the validated technology approaches. For the space path this means reduction of mass and power demands, and integration into a real simulation environment to actually test such a planet-based habitat before applying it to a lunar or martian outpost. Likewise for the terrestial path, the next steps would be to incorporate and test these technologies into larger scale applications, e.g. the food production technology for vertical farming in urban areas, and decentralize them, e.g. water recycling in individual households of a city. The respective next step would be the actual application-ready design, i.e. an actual habitat on another planetary body or serial production and usage of technology that is capable of reducing the human ecological foot-print in everyday life. With the help of the incubator for habitation and the already maturing greenhouse technology, the research path is

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Concerning a timeframe, the building of the incubator is not foreseen to happen before 2020, whereas a dedicated space simluation habitat - requiring research results gained from the incubator's operation - is not expected before 2030. However its own operation will - because most systems will only be optimized and not specifically developed from scratch - likely produce the necessary results faster, i.e. the construction of an actual habitat for space could happen in the 2030s.

## 6 Conclusion and Outlook

The authors have shown the different paths taken by SARA to further the development of sophisticated habitation and greenhouse technology. It has been elaborated how habitation technology also has an impact on human ecological footprint on Earth and how design work can be enhanced and improved by analogue test site missions.

Currently SARA plans to improve the recent design for its habitation laboratory within a European Union funded project in the Research Infrastructure Call of 2016. Part of the proposed project is the complete technical design of the facility, but also of legal and operational processes behind the research.

The EDEN ISS project will advance the current state of plant cultivation in space through ground-based demonstration of key technologies. The demonstration of plant cultivation in a large-scale facility at the Neumayer III Station in Antarctica acts as a precursor for future experiments on ISS and strengthens the development of technologies for future missions to Moon and Mars. EDEN ISS will generate and provide scientific data to the whole bio-regenerative life support community.

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## References


[1] EDEN ISS. http://www.eden-iss.net, 2015.

[2] M. Bamsey, A. Berinstain, T. Graham, et al. Developing strategies for automated remote plant production systems: Environmental control and monitoring of the arthur clarke mars greenhouse in the canadian high arctic. *Advances in Space Research*, 44:1367–1381, 2009.

[3] M. Bamsey, P. Zabel, C. Zeidler, et al. Review of antarctic greenhouses and plant production facilities: A historical account of food plants on the ice. In *45th International Conference on Environmental Systems, 12-16 July 2015, Bellevue, Washington*, 2015.

[4] M. Battler, M. Cross, V. Maiwald, et al. Scientific studies, human-rover interactions, and technology demonstrations conducted by euromoonmars crew 125 at a gale crater analogue site. In *65th Inernational Astronautical Congress, 29 Sep - 3 Oct, Toronto, Canada*, 2014.

[5] A. Braukhane, D. Quantius, V. Maiwald, et al. Statistics and evaluation of 30+ concurrent engineering studies at DLR. In *International Workshop on System and Concurrent Engineering for Space Applications (SECESA), 17.-19. Oct., Lisbon, Portugal*, 2012.

[6] D. Bubenheim, M. Flynn, R. Lamparter, et al. Remote sites as analogs for lunar and mars habitat pilot studies. In *24th International Conference on Environmental Systems, 20-23 June 1994, Friedrichshafen, Germany*, 1994.

[7] C. Dong, L. Shao, Y. Fu, et al. Evaluation of wheat growth, morphological characteristics, biomass yield and quality in lunar palace-1, plant factory, green house and field systems. *Acta Astronautica*, 111:102–109, 2015.

[8] T. Dueck, F. Kempkes, E. Meinen, et al. Choosing crops for the cultivation in space. In *46th International Conference on Environmental Systems, 10-14 July 2016, Vienna, Austria*, 2016.

[9] I. Gitelson, G. Lisovsky, and R. MacElroy. *Man-made closed ecological systems*. Taylor & Francis, London, 2003.

[10] G. Horneck. Advanced life support systems and human exploratory missions. In *ALSS Workshop, April, ESTEC, Netherlands*, 2002.

[11] W. Knott. The breadboard project: A functioning celss plant growth system. *Advances in Space Research*, 12:45–52, 1992.

[12] N. Leys and F. Mastroleo. Towards human exploration of space: A european strategy - cluster 4: Habitat management - life support: Management and regeneration of air, water and food, 2012.

[13] V. Maiwald, L. Poulet, and D. Schubert. Advice from ares: Enhancing habitat and life support system design with martian and lunar analogue test site missions. In *65th Inernational Astronautical Congress, 29 Sep - 3 Oct, Toronto, Canada*, 2014.

[14] B. Marino, T. Mahato, J. Druitt, et al. The agricultural biome of biosphere 2. *Ecological Engineering*, 13:199–234, 1999.

[15] MDRS. Mars Desert Research Station. http://mdrs.marssociety.org/. Accessed 24th June 2014.

[16] K. Nitta. The mini-earth facility and present status of habitation experiment program. *Advances in Space Research*, 35:1531–1538, 2005.

[17] C. Orgel, M. Battler, B. H. Foing, et al. Fluvial sediments, concretions, evaporates at hansville, utah: An analogue field study for gale crater. In *European Planetary Science Congress 2013, 8-13 Sep., London, UK*, 2013.

[18] L. Patterson, G. Giacomelli, M. Kacira, et al. Description, operation and production of the south pole food growth chamber. *Acta Horticulturae*, 952:589–596, 2012.

[19] L. Poulet and O. Doule. Greenhouse automation, illumination and expansion study for mars desert research station. In *65th Inernational Astronautical Congress, 29 Sep - 3 Oct, Toronto, Canad*, 2014.

[20] L. Poulet, G. Massa, R. Wheeler, et al. Demonstration test of electrical lighting systems for plant growth in hi-seas analog mars habitat. In *65th*


 DOI: 10.5281/zenodo.202173

*Inernational Astronautical Congress, 29 Sep - 3 Oct, Toronto, Canada*, 2014.

[21] D. Quantius, F. Ruhhammer, and V. Maiwald. Balance of material fluxes within a closed-loop habitation system. In *63th International Astronautical Congress, 1 - 5 Oct., Naples, Italy*, 2012.

[22] D. Quantius, D. Schubert, V. Maiwald, et al. Habitat technology research at DLR. In *19th IAA Humans in Space, 07.-12. July, Cologne, Germany*, 2013.

[23] D. Quantius, D. Schubert, V. Maiwald, et al. Initial design of laboratories for sustainable habitation. *Acta Astronautica*, 94:541–562, 2013.

[24] P. Zabel, M. Bamsey, D. Schubert, et al. Review and analysis of plant growth chambers and greenhouse modules for space. In *44th International Conference on Environmental Systems, 13-17 July 2014, Tucson, Arizona*, 2014.

[25] P. Zabel, M. Bamsey, C. Zeidler, et al. Introducing eden iss - a european project on advancing plant cultivation technologies and operations. In *45th International Conference on Environmental Systems, 12-16 July 2015, Bellevue, Washington*, 2015.

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Acta Futura

# Operational Lessons Learnt from the 2013 ILEWG EuroMoonMars-B Analogue Campaign for Future Habitat Operations on the Moon and Mars

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**Abstract.** This paper discusses operational lessons learnt from the 2013 EuroMoonMars-B (MDRS crew 125) analogue campaign for future habitat operations on the Moon and Mars. The two-week campaign conducted a series of geologic, technological, operational, and human factors research toward the goals of the International Lunar Exploration Working Group (ILEWG). The results from those operations provide recommendations for future crewed expeditions for increasing the science return based on improved resource allocation and crew habitation.

## 1 Introduction

The four-week long International Lunar Exploration Working Group (ILEWG) EuroMoonMars 2013 campaign conducted a series of operations, human factors, and scientific exploration research primarily in the operations of conducting field geology to identify targets of astrobiological interest [1, 2]. This campaign followed a series of field campaigns organised by ILEWG and partners at the Mars Desert Research Station (MDRS) in order to validate technologies in the field [4, 5],to perform Moon-Mars geological and astrobiological research [3], to study human factors [16, 13, 10], to train students, and promote space science and exploration.

EuroMoonMars-B (MDRS Crew 125) was the second rotation of that campaign to take place at MDRS, shown in Figure 1 immediately following the EuroMoonMars-A group. The two-week campaign was a human Mars mission simulation focused on the area surrounding MDRS as a terrestrial analogue for Gale Crater on Mars. Gale Crater features evidence of several geological features that are commonly preserved and exposed in terrestrial desert environments: sedimentary rocks deposited by fluvial activity, inverted channels,

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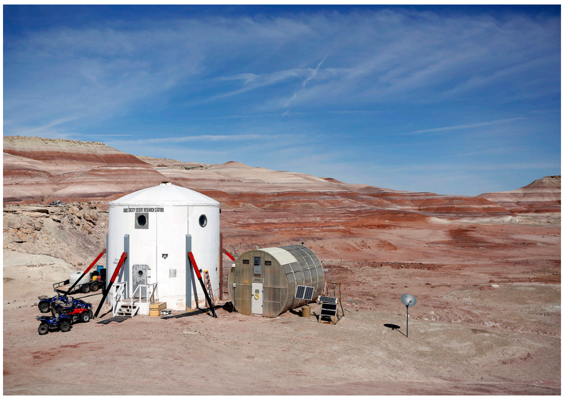

**Figure 1.** *The Mars Desert Research Station (MDRS) is located near Hanksville, Utah. It consists of the main habitat and work space called 'the Hab' (centre-left), a greenhouse called the 'GreenHab' (centre), and the Musk Observatory (not pictured). Electrical power is generated on site, and fresh water is supplied from Hanksville. Other equipment available for use is the 'Hab car' to drive to and from Hanksville, and five all terrain vehicles (ATVs) (left) for use on extra-vehicular activity (EVA). Picture courtesy of Jim Urquhart/Reuters.*


**Figure 2.** *Crew members were required to wear the EVA suits while in simulation at MDRS. Preparation for EVAs often required a significant amount of time to test radios, put on suits and pack sampling equipment. Picture courtesy of Jim Urquhart/Reuters.*

and concretions. All of these features are present in the desert region surrounding MDRS, and have been observed on Mars from either orbital imagery [7] or ground-level imagery from *Curiosity* [15]. These geological features are also potential indicators for past liquid water and may provide evidence for life.

The campaign included geologic studies of the region, and crew psychology studies. Additional studies in human-rover interaction, operational efficiency, technology demonstration, and human factors were also conducted. In all, EuroMoonMars-B completed more than 12 core objectives. The results of these studies provide insights into how future crewed campaigns can improve scientific outcomes, how simulation design can improve the realization of scientific objectives and the overall mission experience, and how habitat design influences such scientific campaigns.

This paper focuses on the operational aspects of this campaign; scientific objectives, where they influence the operations, are presented in brief. Scientific results are described in more detail in companion publications [8, 9, 1, 2].

## 2 Scientific and Supporting Activities for Gale Crater Analogue Mission

The operations of the analogue campaign were planned to what is believed to be similar to human exploration at Gale Crater. Scientific studies, technology demonstrations, and additional crew activities to support the operations of the campaign were conducted in parallel. These additional studies and activities are provided in the following sections. The overall scheduling of these activities is described in Section 3.

### 2.1 Geologic Studies for Gale Crater Analogue Mission

Orbital imagery was studied to identify macro-scale targets of interest and then extra vehicular activities (EVAs) were conducted at these location to identify micro-scale targets of interest. The summary of the geologic studies, which are further described in [9, 1, 2], are given in the following list and reference EVA numbers and locations provided in Table 1:

- **MDRS analogues of Gale Crater sites:** Specific areas were selected based on remote sensing data that looked similar to Gale Crater. Those areas were visited on EVAs to take panoramic context and up-close images of targets of interest. EVAs 3 and 5 at location B supported this study.

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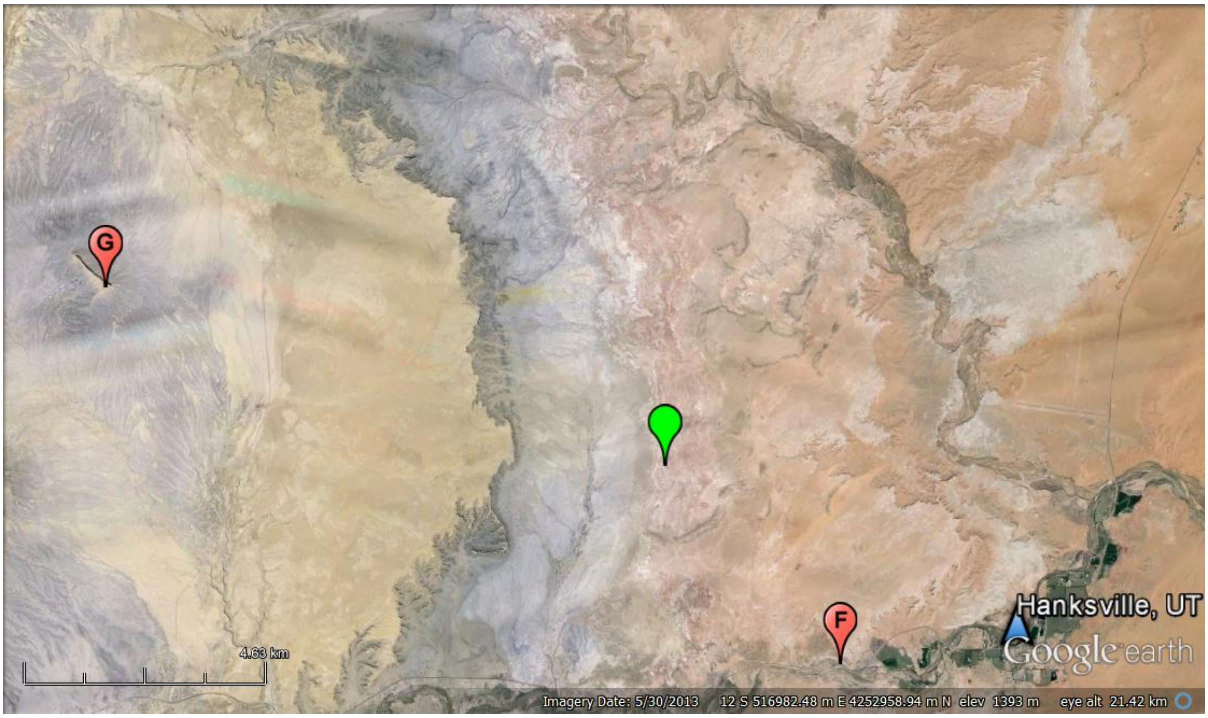


FIGURE 3. *Regional map view of MDRS (located at the unlabelled green flag) and EVA destinations. Also shown in the relative location of Hanksville, UT.*

- ***Curiosity* data comparison to MDRS:** Using ground data from *Curiosity* and images from the previous item, EVAs were planned to collect data to support additional geological experiments listed below. EVAs 3 and 5 at location B supported this study.

- **Sulphates from orbit / surface:** Sulphate-bearing mineral samples were collected at sites known to contain sulphate minerals from previous work. X-ray diffraction mineralogy data was compared to UV-Vis-nIR data as a proxy for orbital data to determine usefulness of orbital spectral data at Martian sites similar to those studied. EVAs 3 and 5 at location B, and EVA 11 at location F supported this study.

- **SediChem experiment:** The Morrison Formation Brushy Basin Member was examined to find terrestrial concretion analogues to those found in Gale Crater. EVAs 1,2, and 9 at location A; EVA 4 at location C; EVAs 6 and 7 at location D; and EVA 8 at location E all supported this study.

- **Vertical survey of hills and mesas:** Small hills near MDRS were surveyed for observable differences on the surface with imaging with resolution of 1-5 mm. The survey produced a series of images from the bottom of the hill to the top with context to up-close images to analyze the types of differences observable at these resolution scales regarding accumulation and erosional processes, dust coverage, characteristic particle sizes and shape, cementation signatures, aeolian or fluvial runoff and mass wasting erosional styles. EVAs 3 and 10 at location D supported this study.

- **Cryptobiotic crust experiment:** Similar to the above study, cryptobiotic crusts were examined at varying distances to identify visual differences from near to far. EVAs 1 and 2 at location A supported this study.

- **Sample analysis for astrobiology** Astrobiologically useful samples were collected from ash-bearing layers in Factory Butte for post-campaign analysis to test potential instruments to be flown on *Exo-*


**Figure 4.** *Regional map view of MDRS (located at the unlabelled green flag) and EVA destinations.*

*Mars*. EVA 12 at location G supported this study.

The EVAs for support of the Gale Crater analogues investigation were a central part of the operations at MDRS and dominated the daily schedule. Table 1 lists the EVAs in chronological order, and provides references to the destinations relative to MDRS in Figures 3 and 4.

### 2.2 Habitability and Sound Study

The habitability study of the 2013 ILEWG EuroMoonMars-B campaign was an ongoing research project since 2010 that is focused on psychological, physiological, environmental, socio-cultural, and operational human factors that may impact space missions [11, 13, 16, 10].

The research was aimed at finding a methodology for the improvement of safety, performance, and comfort by optimizing human factors. Different kinds of research were developed for analyzing human factors by means of habitability debriefings and by experimenting with sensory and creative stimulation, such as artistic performances or sound and music.

The habitability debriefing is a special instrument developed by Schlacht [10] to analyze problems and find solutions in order to optimize the interaction between the human and the system. The debriefing has two main innovative characteristics: it analyzes all the human factors, and it does this with the entire crew discussing them together.

As a result, the crew reported mainly operational problems connected with psychological factors (Table 2, from [8]). In particular, it validated the results of previous crew, which had reported 'communication' as the most relevant factor to be improved to increase mission safety, performance, and comfort (Table 3, from [8]).

The research during the EuroMoonMars-B campaign also investigated pleasant sounds as countermeasures to stress caused by living in isolated habitats and settlements in extreme environments, such as those encountered in crewed space missions. Reducing stress is one key factor in keeping the crew healthy and productive during the mission. Stress may impact immune systems and reduce crew performance [6]. Loss of productivity due to stress and related health problems, such as insomnia, depression and fatigue, will impact the ability to adhere to the detailed mission plan and meet the mission objectives. The result may be additional stress placed on other crew members as the schedule begins to

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| EVA # | Location | Flag |
|---|---|---|
| 1 | Kissing Camel Ridge | A |
| 2 | Kissing Camel Ridge | A |
| 3 | Lion's Den Canyon | B |
| 4 | Hab Ridge | C |
| 5 | Lion's Den Canyon | B |
| 6 | Stegosaurus Ridge | D |
| 7 | Stegosaurus Ridge | D |
| 8 | Dakota Sandstone | E |
| 9 | Kissing Camel Ridge | A |
| 10 | Stegosaurus Ridge | D |
| 11 | Coal Mine Wash | F |
| 12 | Factory Butte | G |
| 13 | Crowdsourcing EVA | 1-5 |

Table 1. *List of the EVAs during EuroMoonMars-B. The icon refers to the letter or number on the labelled flags on the maps shown in Figures 3 and 4. The locations listed are colloquial names and not an official geographical place name.*

Figure 5. *Active musical engagement was a form of creative outlet among the crew to help foster a positive working and living environment. © Ayako Ono 2013*

erode. It is therefore important to assess simple operational changes, such as designing a pleasant soundscape (sound design of the habitat) to help mitigate increasing stress. Additional multidisciplinary activities to reduce stress were also explored, such as active musical engagement shown in Figure 5, variation of pleasant sounds, and creative activity such as meal preparation and the creation of a 'Mars Zen Garden' shown in Figure 6.

The 2013 EuroMoonMars-B investigation on soundscape concluded on the basis of questionnaire analysis that passive music, active music and sounds of nature had positive effects on group dynamics, well-being, and in reducing stress from noise [17, 8]. However, different approaches are needed because music and sounds of nature may not always be effective in reducing stress especially related to communication issues. Considering that habitability within soundscape design may be even more important for long-duration space missions, the habitability study also increased the crew's awareness on the relevance of habitability factors providing some baseline data and a methodology for further investigation in long duration missions.

## 2.3 Lunar SimComm Demonstration

Bandwidth is limited when communicating to space, and also at MDRS. The satellite connection provided by the *Mars Society* at MDRS has daily data cap of 100 MB and at times suffers from small, variable delays and slow, variable speeds. One aspect of scheduling and operations planning was to consider internet as a limited resource that needs to be managed. Some days required greater amount of data, in the form of reports and photos, to be uploaded against the data cap. Accidental or intentional usage of high data-consuming computer applications, such as video conferencing or, large file downloads, needed to be accounted for in daily internet monitoring. The ability to communicate aurally and visually, in additional to textually, with mission and science support would be an improvement over the current text-only approach. However, type of communication should not impact the volume of science data to be delivered. With these communications limits in mind, the Lunar SimComm demonstration was performed to test a low-bandwidth communication platform.

VeaMea, from 2014 known as swyMe, is a participating company in the European Space Agency's technology transfer programme located in The Netherlands. They are developing software to broadcast and receive video and audio at high quality but at low bandwidths. This investigation in particular could be of benefit both technologically and is interesting for outreach purposes. This software was tested during EuroMoonMars-B between MDRS and the European Space Innovation Centre (ESIC) in The Netherlands. The objective was to demonstrate the possibility of low-bandwidth, delay-tolerate video communications over time-delays encountered between Earth and the Moon.

The first demonstration was to test the satellite Inter-

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| Field | Crew | Problem | Solutions |
|---|---|---|---|
| Operational (psychological) IVA | 5/6 | Mission support information flow (communication) | 1. Psychological screening<br>2. Education on support |
| Operational (physiological) | 4/6 | EVA suit design | 1. Use modified motorcycle helmet (safer)<br>2. Use small suits |
| Environmental, IVA | 4/6 | State-room temperature | 1. Individual thermal control<br>2. Isolate heating pipes |
| Operational (Psychological) IVA | 4/6 | Outdoor Toilets (safety, psychological discomfort, wasting time) | 1. Fix indoor toilet<br>2. Have real tunnel |

TABLE 2. *Habitability debriefing for Crew 125 [8], which includes identified problems and proposed solutions. The approached fields are operational, psychological, socio-cultural, physiological, and environmental. The crew ratio represents the number of crew members that find it relavent to the total number of crew members. IVA is Intra Vehicular Activity*

| Topics approached | Crew: | 91 | 100a | 113 | 124 | 125 | 143 |
|---|---|---|---|---|---|---|---|
| Communication | 5/6 | | x | x | x | x | x |
| Interior setting | 5/6 | x | | x | x | x | x |
| Toilet | 4/6 | x | x | | x | x | |
| Food (Nutella ®) | 3/5 | x | x | x | | | |
| Music | 2/6 | x | x | | | | |
| Gymnastics | 2/6 | x | x | | | | |
| Storage | 2/6 | x | | x | | | |

TABLE 3. *Debriefing summary for 2010 to 2013 habitability study [8, 12], which includes all approached fields (Operational, psychological, socio-cultural, physiological, environmental)*

net connection before conducting a live video conference. The initial demonstration showed that two-way communication was possible, and so an outreach event was organized at ESIC to demonstrate VeaMea's software. A 30 minute video conference was established between the EuroMoonMars-B crew at MDRS and an audience at ESIC. Also, three-way communication was established with remote support by Dr. Schlacht in Berlin, who was able to watch the visual communication and listen to the audio communication between ESIC and MDRS, and interact with ESIC. The crew introduced themselves and gave an explanation of the activities at MDRS. The audio and video quality was high and the technology self-corrected the occasional time-delay. A total of 5 MB, as measured by the satellite Internet monitor, was consumed for the 30 minute video conference, which was deemed a remarkable achievement by the crew.

The tested software proved to be an efficient form of communication without prohibitively increasing the Internet bandwidth consumption. Its current commercial use is in tele-medicine and tele-health, and enterprise video conferencing. This software, which is based on patented space technology, has been recommended to the Mars Society to be used at MDRS as it would enable improved communication between the MDRS crew and Mission Control.

### 2.4 Robotic Field Assistants

A key objective to sending humans to conduct field geology, or to explore another planet, is to increase the possible scientific return. A driver for that objective is to improve the efficiency of those humans such that they spend a greater portion of their time conducting their core science activities and reduce the burden of otherwise secondary activities. Much of the operations planning and scheduling centred on the execution and support of EVAs. Each EVA had a time allotment to conduct the EVA, and additional time allotments for supporting activities and preparation. A particular challenge for operations planning is scheduling sufficient EVAs to achieve the mission objectives. As each site

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**Figure 6.** *The tabletop 'Mars Zen Garden' was one example of creative outlets during EuroMoonMars-B. © Ayako Ono 2013*

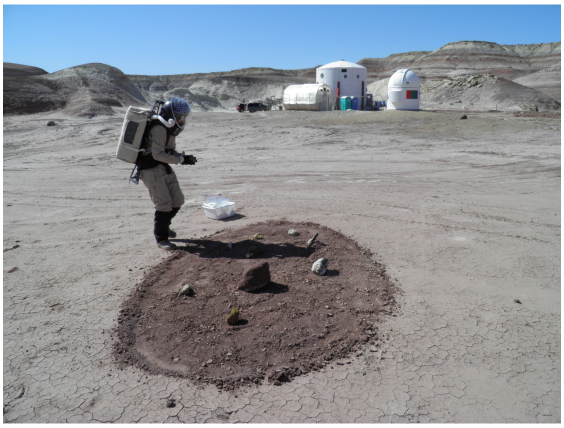

**Figure 7.** *A 'Mars Zen Garden' was created outside the Hab at MDRS. This Zen garden was a larger outdoor replica of an indoor tabletop Zen garden (shown in Figure 6) and one example of creative outlets performed during EuroMoonMars-B. © Ayako Ono 2013*

investigation has more available targets than time permits, it is essential that an investigation is performed efficiently so as to not impact the scheduling of other site investigations.

It is believed that robotic assistants and task automation would be valuable tools in order to meet the target of improved EVA efficiency in terms of time and personnel utilized to complete site investigation. During EuroMoonMars-B, the field geologists were observed and recorded conducting their site investigations and sample collections to assess common activities that could be off-loaded to robotic assistants or automation. The test cases investigated during EuroMoonMars-B indicate savings in crew time are achievable; the number of EVAs spent on a given science objective could be reduced allowing for additional science objectives [2].

## 3 Mission Scheduling

Planning for the operations to support the mission objectives began in advance of the EuroMoonMars campaign. EVA proposals and desired experiments to support the mission objectives were collected along with estimates of the time they required to complete. All of these proposals and time estimates were synthesized into a daily mission plan. The schedule needed to be sufficiently flexible to account for changes to the schedule due to new science targets, unforeseen maintenance, and additional demands on the crew. The schedule would be continually iterated throughout the mission duration, however the baseline served as an action item list for each day and incorporated the essential daily tasks such as meal preparation and maintenance. A secondary objective for the detailed schedule was to investigate post-mission how well the mission adhered to the initial schedule, and to what extent unforeseen issues required time to resolve. The mission schedule was discussed, prepared and iterated during the mission by the commander and executive officer days in advance and then discussed with the whole crew during briefings.

A table was set-up that included columns for each crew member in order to plan and record the daily schedule, and columns noting general crew tasks or allocations. These general crew tasks included meal preparation, engineering checks, reporting and communication with mission support; allocations included where

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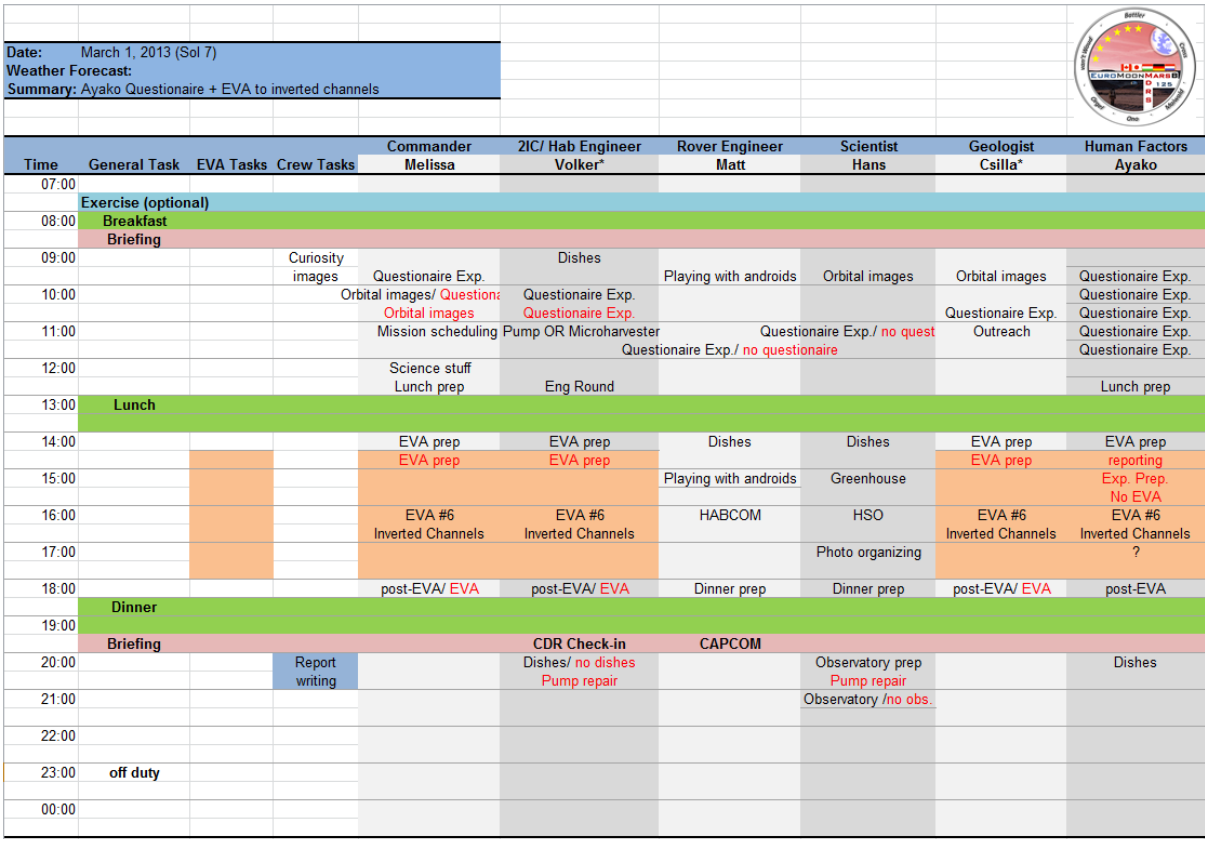

**Date:** March 1, 2013 (Sol 7)
**Weather Forecast:**
**Summary:** Ayako Questionaire + EVA to inverted channels

| Time | General Task | EVA Tasks | Crew Tasks | Commander Melissa | 2IC/ Hab Engineer Volker* | Rover Engineer Matt | Scientist Hans | Geologist Csilla* | Human Factors Ayako |
|---|---|---|---|---|---|---|---|---|---|
| 07:00 | | | | | | | | | |
| | Exercise (optional) | | | | | | | | |
| 08:00 | Breakfast | | | | | | | | |
| | Briefing | | | | | | | | |
| 09:00 | | | Curiosity images | | Dishes | | | | |
| | | | | Questionaire Exp. | | Playing with androids | Orbital images | Orbital images | Questionaire Exp. |
| 10:00 | | | | Orbital images/ Questiona | Questionaire Exp. | | | | Questionaire Exp. |
| | | | | Orbital images | Questionaire Exp. | | | Questionaire Exp. | Questionaire Exp. |
| 11:00 | | | | Mission scheduling | Pump OR Microharvester | | Questionaire Exp./ no quest | Outreach | Questionaire Exp. |
| | | | | | | Questionaire Exp./ no questionaire | | | Questionaire Exp. |
| 12:00 | | | | Science stuff | | | | | |
| | | | | Lunch prep | Eng Round | | | | Lunch prep |
| 13:00 | Lunch | | | | | | | | |
| | | | | | | | | | |
| 14:00 | | | | EVA prep | EVA prep | Dishes | Dishes | EVA prep | EVA prep |
| | | | | EVA prep | EVA prep | | | EVA prep | reporting |
| 15:00 | | | | | | Playing with androids | Greenhouse | | Exp. Prep. |
| | | | | | | | | | No EVA |
| 16:00 | | | | EVA #6 | EVA #6 | HABCOM | HSO | EVA #6 | EVA #6 |
| | | | | Inverted Channels | Inverted Channels | | | Inverted Channels | Inverted Channels |
| 17:00 | | | | | | | Photo organizing | | ? |
| | | | | | | | | | |
| 18:00 | | | | post-EVA/ EVA | post-EVA/ EVA | Dinner prep | Dinner prep | post-EVA/ EVA | post-EVA |
| | Dinner | | | | | | | | |
| 19:00 | | | | | | | | | |
| | Briefing | | | | CDR Check-in | CAPCOM | | | |
| 20:00 | | | Report writing | | Dishes/ no dishes | | Observatory prep | | Dishes |
| | | | | | Pump repair | | Pump repair | | |
| 21:00 | | | | | | | Observatory /no obs. | | |
| | | | | | | | | | |
| 22:00 | | | | | | | | | |
| | | | | | | | | | |
| 23:00 | off duty | | | | | | | | |
| | | | | | | | | | |
| 00:00 | | | | | | | | | |

FIGURE 8. *One example of a daily schedule for EuroMoonMars-B with colour codes marking important blocks of the schedule.*

the majority of the crew would be, EVA time allocations, and EVA tasks. Furthermore a colour code for certain blocks of actions was set-up to enable an easier identification in the schedule. The following colour-codes have been used:

- teal: Beginning of daily schedule (usually with exercise)
- light red: Briefings, i.e. mandatory for all crew
- orange: EVA time allotment
- blue: Report time (for reports to mission control)
- green: Meal times, usually taken as group

These blocks were marked to emphasize importance, e.g. the report time was mandatory for all crew members, depending on function, as reporting to mission control was time-sensitive and essential. Reports included summaries of the day from the Commander, Habitat Engineer and regarding the individual experiments and EVAs run during the day. Progress and condition of either experiments or the habitat were reported.

In the morning briefings a short summary of the day as planned was presented to the crew, where necessary adaptations were made. The evening briefings were used to plan the remaining day (e.g. review of geological samples) and the coming days and discuss issues with the crew. Adaptations to the schedule were made as necessary. On each morning the schedule of the day was placed at the wall of the habitat's crew area for display to the crew. An example daily schedule (here 7th mission day) is given in Figure 8. Activities were planned in time slots of 30 minutes, which was regarded as a useful compromise between detail and clarity.

During the day changes to the schedule were also noted to allow refinement of the scheduling process. These changes were noted in the schedule with red font colour, to distinguish them from the planned actions in


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black font colour. This is also visible in Figure 8. Essential roles, such as the capsule communicator (CapCom), who was the main contact person with Mission Control during communication windows, were marked as well for each rotation. For each day an asterisk behind two names denotes turns in showering allowance, which was one 2 minute shower every three days per crew member. Regarding individual tasks of the crew members, only transition to a new task is marked in the schedule, i.e. the previous action is assumed to last as long as no further action is marked in the schedule.

### 3.1 Meal Preparation

Meal preparation and clean-up for 6 individuals was a time consuming endeavour that required careful scheduling into the daily operations plan. Meals needed to be of sufficient quality to for both nutritional requirements as well as crew-well being, and as such required adequate time to prepare. The scheduling of preparation and clean-up tasks was such that those tasks did not interfere with EVAs. Crew members that had afternoon EVAs did not do clean-up after lunch nor dinner preparation as those tasks would interfere with EVA timing. Also, returning EVA team members would often be fatigued, and were required to complete EVA and science reports ahead of the mission support communication window, which itself would begin during the dinner period shortly after the EVA conclusion.

The crew was supplied with a fixed amount of food to last for the 2-week rotation. Left over food from previous crews was also available in the pantry. While there was more than enough available calories from food to sustain the crew for the 2 weeks, highly desirable food items needed to be rationed such that adequately enjoyable meals could be had until the end. An informal food allocation plan was established to meet this objective. Certain days that were projected to be particularly demanding were targeted for quick leftovers, and thus quick clean-up, from the previous day. Days that had EVAs that were projected to be particularly fatiguing were targeted for highly enjoyable food items. A mid-rotation 'feast' and a celebratory departure morning breakfast were allocated special food items.

The meal times served a dual purpose in that they were the only times that all six crew members were together, as shown in Figure 9; in addition to eating and socializing, the meal times were allocated for crew meetings. Breakfast served as the daily briefing and review of mission objectives. Lunch served as a review of the morning's progress and results from EVA, and also a pre-EVA briefing. Dinner, which coincided with the mission support communication window, served as the daily debrief and planning meeting for the following day. It was also the time to review the mission objectives in context with the preliminary schedule.

**Figure 9.** *Meal times were the few times during the day that all six crew members were together. Meal times were opportunities for both socializing and meetings. Picture courtesy of Jim Urquhart/Reuters.*

Generally, meal times allowed for some flexibility to be built into the schedule. As meal preparation was a secondary task, it allowed for scheduling conflicts to be relieved without significant impact to the overall mission. Crew members who had completed their required tasks could be reassigned to meal preparation and clean-up in place of another crew member who had incomplete (e.g. delayed EVA return, report writing) or unplanned (e.g. maintenance) tasks to complete.

### 3.2 GreenHab and Other Maintenance

The GreenHab is a greenhouse next to the Hab. It contains a variety of plants, as shown in Figure 10 requiring daily care, and the GreenHab itself requires daily maintenance and monitoring to ensure optimal growing conditions for the plants. Daily tending of the GreenHab included monitoring temperature and humidity, adjusting fans, watering and measuring amount of water needed, moving and re-potting plants as required, and occasionally harvested mature plants for food. The plants in the GreenHab during the EuroMoonMars-B rotation that required monitoring were avocado, Swiss chard, kale, radishes, watercress, sprouts, broccoli, mint, Viola, basil and Italian mix. The Swiss chard, kale, and

FIGURE 10. *Swiss chard was grown in the GreenHab, and eventually harvested along with radishes and kale for fresh vegetables that were consumed towards the end of the 2 week rotation. All plants in the GreenHab required daily monitoring for reporting to mission support. Picture courtesy of Jim Urquhart/Reuters.*

radishes were harvested for food, the Italian mix was used as seasoning, and an herbal tea was made. The GreenHab experienced unanticipated maintenance requirements with regards to temperature and ventilation, which required crew time diverted from planned tasks. Failure to attend to the GreenHab would have resulted in a loss of some or all of the plants which, on a real human mission, could lead to mission failure.

The main water pump, which is used to pump water from the outdoor reservoir to the indoor tank, failed and also required unanticipated maintenance. As with the GreenHab, this maintenance diverted crew time from planned activities. In these instances, crew members were pulled from participating in EVAs to assistance in the maintenance. While it is difficult to plan and schedule for unanticipated maintenance, the mission scheduling should be set up to allow for these unforeseen circumstances.

## 4 Scheduling Outcomes

Overall the mission schedule shows 68 deviations, shown in Figure 11, of the original planning, of which 12 only regard individual crew members. The remaining 56 were affecting the whole crew, e.g. by occurrence of unforeseen issues like a broken pump, which made repair works necessary and shifting of the repair crew's duties to other crew members.

In total 543 actions were planned in the schedule, with the minimum of 29 and the maximum of 60 at one day. For 12 mission days not including transfer days to and from the habitat, this makes an average of 45.25 planned actions per day and 5.7 deviations per day. Also relating the number of deviations to the number of planned actions, 475 actions were conducted as planned, i.e. a ratio of about 87.5 percent. Equipment breakdown, such as the water pump, resulted in 5 deviations that needed immediate attention and could not be implemented in the schedule at a later time as shown in Figure 8. For experiment changes 16 deviations occurred, i.e. experiments or preparation of them took longer than anticipated. For public outreach activities 12 deviations occurred.

Another contributor to the deviations was the time allotted for EVAs. Before the mission the time allotment for EVA preparation has been 30 minutes, assuming being suited up and gathering the equipment for each crew member would not last longer if always an extra crew person was assigned to help with the preparations. The same amount of time had been regarded for post-EVA activities, e.g. storing equipment.

But already with the first EVA it became clear that this time allotment was very optimistic. For 12 EVAs in 8 instances the preparation time has been 1 hour instead, which lead to the fact that during the course of the mission, the later EVAs were planned with 1 hour preparation time in advance. It should be noted that preparation did not involve planning of the EVA, i.e. route selection or scientific considerations, but only the immediate actions before the actual EVA, i.e. packing of equipment (e.g. tools, first aid kit, radio) and suiting up suits for exiting the habitat. Also during two EVAs the initially planned mission time was exceeded and the return to base delayed because sampling took longer than expected.

Other minor causes have been, e.g. deviations regarding data refinement or analysis or changes of daily chores like dinner preparation because other crew members had been finished with their tasks already. It shall be noted that only twice off-time has been scheduled, which was in the evening of the mid-day of the mission and at the last evening. In the former case the off-time was reduced because of repairs necessary.

It can be seen that experiments are the driving factor behind deviations, making up almost one quarter of all schedule deviations. Causes for this have been the collection of more samples than anticipated, more need for sample analysis. It is considered positive that science was the greater contributor to schedule devi-

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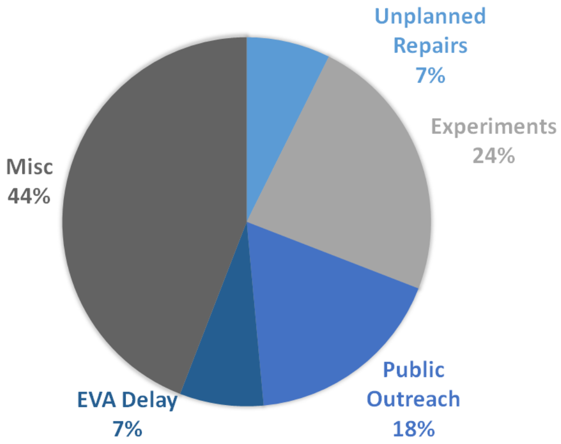


FIGURE 11. *Overview of the 68 deviations to the mission schedule.*

ations as the mission objective of EuroMoonMars-B, and any planetary exploration mission, was scientific return. Unforeseen maintenance issues resulted in some impact in daily planning, however they did not interfere with the overall science objectives. The initial preparation time of 30 minutes anticipated for EVAs has been to small and caused some deviations from schedule (it should be noted that some of these are only noted as one deviation for the EVA block, although several crew members have been affected). Correction of the preparation time allotment to 1 hour however, prevented further deviations from scheduling. Another significant factor has been public outreach. The large number of deviations shows that public outreach was important for EuroMoonMars-B, but not as important as the science for the mission. Especially due to the latter, outreach activities had been postponed a number of times and rescheduled, which explains the large number of deviations.

In general, 87.5% of the scheduled actions during EuroMoonMars-B went according to the time slot they had been given, which is to be considered a success. The planning of the schedule was supported by the need of reporting and discussion, for example the requirement of submitting EVA plans to mission control the day before for approval. Furthermore a conservative assumption on how much time would eventually be needed for a given task, that is incorporating enough time margins, facilitated in maintaining the schedule. At the same time EuroMoonMars-B adherence to the schedule and attempt to conduct the actions as planned in order to facilitate as much gain from the mission as possible was contributing to this high rate of schedule compliance. The fact that each crew member could contribute to the mission scheduling during briefings by giving feedback on the schedule prepared by the commander and executive officer proved to be an efficient method for setting up the daily schedule.

### 4.1 Operation Outcomes and Recommendations for Future Analogue Campaigns

A previously stated objective to sending humans to conduct field geology, or to explore another planet, is to increase the possible scientific return. However, that increase in return cannot be met by simply adding more tasks to a schedule. Similarly, insufficiently allocating time for each activity or crew rest can result in a degradation in performance or even crew refusal as seen in the 'strike in space' [14]. It is therefore recommended to carefully consider the amount of time allocated to each required task so as to avoid overloads. The schedule adherence during EuroMoonMars-B was considered successful, however the number of deviations did result in tasks requiring completion during previously-scheduled crew rest time.

Daily tasks were classified by function as noted in Section 3; however a priority, or time sensitivity, was not strictly given for each task. It is recommended that tasks be assigned a priority and time sensitivity so that deviations to high priority or time-sensitive tasks can be compensated by altering lower priority or time-insensitive tasks. It is also recommended to have a set of lower priority or time-insensitive tasks available should higher priority tasks conclude quicker than expected.

Future review of mission planning could incorporate several more detailed aspects. For example would it be reasonable to assume that crew morale has an influence on the ability to adhere to the mission schedule. While the subjective view of EuroMoonMars-B is that all crew members have been very motivated not only regarding their only work but also regarding overall mission success, and this may have contributed to the good schedule performance, this cannot be seen as a given fact. Review of other crews' schedule performance could include a parameter of crew moral (e.g. measured by conflicts within the group, or questionnaires) and see if there is a correlation with schedule performance. On the other hand it is likely reasonable to assume that a high rate of schedule deviations can increase the stress on the crew members and therefore actually influence the crew morale nega-

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| Problem | Solution | Cost |
|---|---|---|
| Insufficient time allocated to EVAs and preparation | Allocate addition time | Loss of time allocated to other duties |
| Unanticipated maintenance | Assign priority to tasks to account for unanticipated tasks | Potential loss of low-priority tasks |
| Inefficient text-base communication with Mission Control | Adopt low-bandwidth video messaging | Increased bandwidth consumption |
| Inefficient use of crew on EVAs | Adopt robotic or automated assistive technologies to off-load tasks | Increased technology development, increased potential for equipment failure |
| Rapid consumption of desirable food items | Maintain an accurate food inventory, and plan meals accordingly to ensure evenly paced desirable meals | Negligible, other than time spent on inventory |
| Crew stress | Maintain a pleasant soundscape of sounds of nature in the Hab | Negligible |
| Crew stress | Allow time for creative outlets, such as music | Negligible, if crew rest time is maintained |

Table 4. *Summary of lessons learnt: the encountered problems, the solution to the problem, and the associated cost of the solution*

tively.

One outcome of EuroMoonMars-B has been that the preparation time for EVAs has been about 1 hour. It would be interesting to see if there is a correlation between the preparation time and the purpose of the EVAs. The EVAs of EuroMoonMars-B had been mainly geological purposes and therefore certain parts of equipment needed to be prepared. It is possible that mission with different scientific foci, e.g. technology demonstration, have different experiences. Future investigations could review this further. A higher resolution of tracking the work time of each crew member might allow a thorough assessment on how much time is needed for which action type, i.e. daily routine, administration, maintenance and scientific work.

## 5 Conclusion

The authors presented the relevant aspects of an analogue test site mission, besides actual scientific activities and discussed their relation on crew well-being, performance and overall mission conduct.

- Sounds of nature and creative outlets can help reduce crew stress
- Effective video communication can replace text-based communication without significant impact on the allowable bandwidth
- Assessment of robotic assistants can lead to improved EVA efficiency
- Crew rest time is usually a buffer for schedule conflicts and is frequently reduced
- Concurrent plan development with daily briefing can help schedule adherence and adapt when necessary

It is recommended to further study these aspects in future missions as they have the potential to greatly influence mission outcome and crew efficiency.

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The authors would like to thank the numerous organizations that made this analogue campaign at MDRS possible: International Lunar Exploration Working Group (ILEWG), Centre for Planetary Science and Exploration, NSERC-CREATE: Technologies and Techniques for Earth and Space Exploration, University of Western Ontario Department of Electrical and Computer Engineering, Canadian Lunar Research Network, European Space Agency, Deutsches Zentrum für Luft- und Raumfahrt, NASA Ames, Blackshore Creative, The George Washington University (under grant from NASA Astrobiology Program), Vrije Universiteit Amsterdam, ESRI Hungary Kft. and Űrvilág and the mission support team of The Mars Society. We acknowledge the support teams that provided sample analysis and helped interpret the results. We are also grateful to the crew members of EuroMoonMars-A that invested energy to support the sample collection activities at MDRS.

## References

[1] M. Battler, M. Cross, V. Maiwald, et al. Scientific Studies, Human-Rover Interactions, and Technology Demonstrations Conducted by Euromoonmars Crew 125 at a Gale Crater Analogue Site. In *65th International Astronautical Congress*, 2014.

[2] M. D. Cross, M. Battler, V. Maiwald, et al. Operational Results of the EuroMoonMars-B Analogue Campaign at the Mars Desert Research Station. In *AIAA SPACE 2014 Conference and Exposition*, Reston, Virginia, aug 2014. American Institute of Aeronautics and Astronautics.

[3] P. Ehrenfreund, W. Röling, C. Thiel, et al. Astrobiology and habitability studies in preparation for future Mars missions: trends from investigating minerals, organics and biota. *International Journal of Astrobiology*, 10(03):239–253, may 2011.

[4] B. Foing, C. Stoker, and P. Ehrenfreund. Astrobiology field research in Moon/Mars analogue environments. *International Journal of Astrobiology*, 10(03):137–139, apr 2011.

[5] J. Hendrikse, B. Foing, E. Monaghan, et al. Highlights from remote controlled rover for EuroGeoMars MDRS campaign. In *Lunar and Planetary Science Conference*, 2010.

[6] N. Kanas and D. Manzey. *Space psychology and psychiatry*. Microcosm Press, New York, NY, 2nd editio edition, 2008.

[7] N. Mangold, V. Ansan, P. Masson, et al. Geomorphic study of fluvial landforms on the northern Valles Marineris plateau, Mars. *Journal of Geophysical Research*, 113(E8):E08009, aug 2008.

[8] A. Ono, I. L. Schlacht, J. Hendrikse, et al. Habitability in Mars Mission Simulation: Sounds as Stress Countermeasures. In *Lunar and Planetary Institute Science Conference Abstracts*, pages 1807–1808, 2013.

[9] C. Orgel, M. Battler, B. Foing, et al. Fluvial sediments and concretions at Hanksville, Utah: Preliminary results of An analogue field study for Gale crater, Mars. In *European Planetary Science Congress*, London, UK, 2013.

[10] I. L. Schlacht. *Space Habitability: Integrating Human Factors into the Design Process to Enhance Habitability in Long Duration Missions*. PhD thesis, Technischen Universität Berlin, 2012.

[11] I. L. Schlacht, J. Hendrikse, et al. MDRS 2012 ILEWG campaign: Testing habitability and performance at an analogue moon base infrastructure outpost on earth. In *63rd International Astronautical Congress*, 2012.

[12] I. L. Schlacht, S. Nazir, and D. Manca. Space vs. Chemical Domains: Virtual and Real Simulation to Increase Safety in Extreme Contexts. *Procedia Manufacturing*, 3:1817–1824, 2015.

[13] I. L. Schlacht, S. Voute, S. Irwin, et al. MoonMars Analogue Mission: EuroMoonMars 1 at the Mars Desert Research Station. In *38th COSPAR Scientific Assembly*, Bremen, Germany, 2010.

[14] C. B. Schoonhoven. Sociotechnical Considerations for the Development of the Space Station: Autonomy and the Human Element in Space. *Journal of Applied Behavioral Science*, 22(3):271–286, 1986.

[15] K. M. Stack, J. P. Grotzinger, L. C. Kah, et al. Diagenetic origin of nodules in the Sheepbed member, Yellowknife Bay formation, Gale Crater, Mars. *Journal of Geophysical Research: Planets*, pages n/a–n/a, jun 2014.

[16] C. S. Thiel, V. Pletser, and B. Foing. Human crew-related aspects for astrobiology research. *International Journal of Astrobiology*, 10(03):255–267, may 2011.

[17] R. S. Ulrich, R. F. Simons, B. D. Losito, et al. Stress recovery during exposure to natural and urban environments. *Journal of Environmental Psychology*, 11(3):201–230, sep 1991.

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**Acta Futura**

# Human Exploration of Cis-Lunar Space via Assets Tele-Operated from EML-2 (HECATE)

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**Abstract.** This paper presents the preliminary design of the international space mission HECATE (Human Exploration of Cis-lunar space via Assets Tele-operated from EML-2), aimed at exploring the far side of the Moon via tele-robotic activities during the 2020s. The exploration is realized by astronauts from HOPE (Human Orbiting Protected Environment), a space habitat in a halo orbit around the Earth-Moon Lagrange Point 2, a critical staging location for future robotic and human deep space missions. Inside the habitat, astronauts have access to tele-robotic hardware and instruments, used to tele-operate rovers and scientific equipment on the surface of the Moon. Plans to resupply and maintain HOPE for future missions, using a solar electric tug, are given. Ultimately, HOPE represents an energetically favorable intermediate locations for missions to Mars, Near-Earth Asteroids, and beyond.

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## 1 Introduction

The next giant leap for mankind is a long-duration mission to the Moon. This mission does not only address priority lunar science objectives but it also represents a milestone towards the exploration to farther planets. A key element of this future mission is the partnership of human and robotic components as well as tele-presence, the tele-operation of robotic assets on the lunar surface by astronauts in orbit in cis-lunar space. Tele-presence could significantly enhance the ability of humans and robots to explore together, allowing in the future the exploration of the most challenging locations in the Solar System and preparing sustainable exploration using local resources, as outlined in the Global Exploration Roadmap [29].

In the context of a future human-robot partnership for future space missions, the European Space Agency has defined the Human-Enhanced Robotic Architecture and Capability for Lunar Exploration and Science (HERACLES) as a frame for multiple international space agencies to study and define an architecture for lunar exploration [34].

Of primary importance for a long-duration mission to the Moon based on human-robotic interaction, is the design of a stable and safe habitat where astronauts can operate instruments and equipment for the tele-operations of the assets on the ground.

This paper presents a human mission for the tele-robotic exploration of the far side of the Moon, HECATE (Human Exploration of Cis-lunar Space via Assets Tele-operated from EML-2), focusing in particular on the design of the space habitat.

## 2 Mission Overview

Mission HECATE delivers a habitat (HOPE, Human Orbiting Protected Environment) in a halo orbit around the second Earth-Moon Lagrangian point (EML-2) during the years 2022-2024 to help a crew of three astronauts:

- perform tele-robotic exploration on the lunar surface;
- conduct human-assisted scientific experiment and sample return of lunar surface material;
- realize 3D printing;
- deploy and test components of a low frequency telescope;
- execute site reconnaissance for future human exploration of the Moon.

HOPE can also be utilized as a platform for future deep space exploration. The mission timeline is summarized in Table 1.

In January 2022 the first space station module, Brave, is launched from Kennedy Space Center using a Falcon Heavy launcher [13]. The upper stage of the Falcon Heavy performs the necessary maneuver to inject the module into a Weak Stability Boundary (WSB) trajectory [18]. After 4 months from launch, Brave is scheduled to arrive in EML-2.

In January 2023, a Space Launch System (SLS) Block 1 (cargo), [11], is adopted to deliver an interconnection/expansion module, Companion, to HOPE. It takes Companion 4 months to arrive at destination using a WSB transfer. Brave and Companion are expected to perform the necessary rendezvous and docking procedures autonomously. Until the crew arrives, HOPE remains dormant, except for standard operational checks.

In February 2024, an SLS Block 1B (cargo) carries a Bigelow B330 inflatable module [2], Tortuga, following a similar trajectory to those of Brave and Companion.

In March 2024, a Falcon Heavy is used to deliver a set of lunar robotic assets to the surface of the Moon via a direct transfer. The payload of Falcon Heavy consists of three landers, La Niña, La Pinta and La Santa Maria (Section 5), carrying a total of four rovers to three different locations on the far side of the Moon. The rovers are Messaggero (a humanoid rover), Oktagon 1 and Oktagon 2 (two 8-wheeled rovers) and Nozomi (a rover with 3D printing capabilities), or "MOON" for short (Section 6).

In April 2024 a crew of 3 astronauts departs from Kennedy Space Center on board of the Orion Multi-Purpose Crew Vehicle (MPCV), [10], launched into a Low Earth Orbit (LEO) by the NASA SLS Block 1 B. This launch vehicle is assumed flight proven at the proposed launch date. The upper stage of the Block 1 B performs the Trans-lunar Injection (TLI) such that the crew vehicle is placed in a prograde lunar flyby trajectory. Upon arrival at a lunar altitude of approximately 100 km, a propulsive maneuver is performed and the crew vehicle is placed on a trajectory to reach the station. Upon arrival at HOPE, approximately 10 days after launch, an orbit injection maneuver is performed. Successively, Orion docks to HOPE and the astronauts assist with the rendezvous, docking and inflation of Tortuga.

The astronauts arrive at HOPE 2 days before the beginning of the 14-days long lunar day and a total of 40 days are available to perform the necessary operations on the Moon and the scientific experiments on the space station. The crew performs tele-operated activities on the surface of the Moon utilizing the "MOON" rovers and the hardware described in Section 7. All the activities accomplish unique goals thanks to the exploitation of the human-robotic partnership between astronauts and assets on the lunar surface. Pre-planned activities,

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| Departure date | Arrival date | Launch vehicle | Payload | Transfer type |
|---|---|---|---|---|
| January 2022 | April 2022 | Falcon Heavy | Brave | WSB |
| January 2023 | April 2023 | SLS Block 1 (cargo) | Companion | WSB |
| February 2024 | May 2024 | SLS Block 1B (cargo) | Tortuga | WSB |
| March 2024 | March 2024 | Falcon Heavy | "MOON" Rovers | Direct |
| 18 April 2024 | 28 April 2024 | SLS Block 1 (crew) | Orion (crew) | Lunar Flyby |
| 8 June 2024 | June 2024 | N/A (return to Earth) | Orion (crew) | Lunar Flyby |

**Table 1.** *Summary of HECATE's launch sequence.*

like traverse route for the rovers, are available. However, based on the observations and results obtained during the operations, and in coordination with the Mission Control Center, the crew has the possibility to modify those plan in order to accomplish the scientific objectives (Section 8).

After the crew has spent 40 days on board of HOPE, Orion undocks from the space station beginning its journey back to Earth. In June 2024, Orion arrives at Earth, reenters the atmosphere and splashes down in the Pacific Ocean.

HOPE is left operational in EML-2 and kept available for use for future exploration and technology demonstration missions. As described in Section 3, sustainable plans to resupply HOPE have been laid out. HOPE's capabilities to be modular and expandable combined with its highly Earth-Moon energetic orbital location give the station the potential to become a "refueling depot" for missions heading beyond the Earth's sphere of influence. Furthermore, HOPE represents a safe haven between LEO and deep space; it represents an orbiting infrastructure accessible to humans to perform experiments on sample returns from various celestial bodies (such as Mars and Europa) to ensure that planetary protection procedures are respected.

## 3 Mission Analysis

The $\Delta V$ and time of flight required for each transfer of Table 1 are summarized in Table 2.

The departure dates are chosen so as to minimize the $\Delta V$ required to realize each transfer and taking into account eclipse condition in EML-2 and illumination conditions of the far side of the Moon [44].

The chosen orbit for HOPE is a halo orbit around EML-2 with $A_z$ amplitude of 8000 km [21]. This orbit has an orbital period of approximately 14 days and provides a permanent communication link with Earth. Moreover, the orbit of choice allows continuous coverage of the lunar far side surface which greatly facilitates the tele-robotic operations performed by the crew when on HOPE. In order to maintain HOPE in EML-2, a station keeping control is required throughout the entire mission duration. The $\Delta V$ needed for station keeping is approximately 50 m/s per year [23], resulting in 1900 kg of propellant required for the Attitude and Orbit Control System (AOCS) per year for the considered mass of HOPE (Section 4), [44].

HOPE is planned to be resupplied with propellant and cargo using a reusable tug equipped with Solar Electric Propulsion (SEP). The tug performs a transfer between a Geostationary Equatorial Orbit (GEO) and EML-2 [44]. A module is required to deliver the cargo to GEO, where the tug docks with it and transfers to the station. The initial launch of the tug with the cargo is going to be done as an auxiliary payload of an Ariane 5 launch in Geostationary Transfer Orbit (GTO), [39]. The electric engine is then used to move the cargo to EML-2. The thrust considered for the electric engine is $T = 0.6$ N and the specific impulse is $I_{sp} = 2800$ s. Table 3 describes $\Delta V$, mass and time of flight for each phase of the transfer considering an initial mass in GTO of 5500 kg and 2500 kg of cargo delivered to HOPE. The total resupply mission from GEO to EML-2 and back to GEO takes 300 days.

## 4 Space Station

A space station in cis-lunar space is fundamental not only to realize tele-robotic exploration of the Moon but also to support many additional activities: gathering of resources, in-orbit servicing for deep space destinations such as Mars and study and development of new technologies for future space exploration.

For mission HECATE, the habitat HOPE have a modular, expandable and versatile design capable of satisfying two major scientific requests: Enhancement of Moon Exploration (EME) and Fundamental Deep

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| Transfer type | ΔV [m/s] (one way) | ToF [days] |
|---|---|---|
| Direct transfer | 4435 | 6 |
| Lunar Flyby (LFB) transfer | 3480 | 10 |
| Weak Stability Boundary (WSB) | 3200 | 80-120 |
| Lunar surface to EML-2 | 2530 | 5-7 |
| Return from EML-2 to Earth via LFB | 390 | 10 |

**Table 2.** *Earth to EML-2 halo transfers.*

| Transfer | $m_0$ [kg] | $\Delta v$ [km/s] | ToF [days] | $m_{fuel}$ [kg] | $m_f$ [kg] |
|---|---|---|---|---|---|
| GTO - GEO | 5500 | 2.11 | 330 | 410 | 5090 |
| GEO - EML2 | 5090 | 2.13 | 210 | 380 | 4710 |
| EML2 - GEO | 2210 | 2.13 | 90 | 165 | 2015 |

**Table 3.** *Data for HOPE's resupply using SEP. $m_0$ is the initial mass, $m_{fuel}$ is the propellant mass and $m_f$ is the final mass.*

Space Research (FDSR).

In terms of EME the space station has been designed to fulfill the following tasks:

- Provide a stable and reliable platform for low-latency tele-robotic control of the lunar rovers and surface equipment. The short distance between the space station and the lunar surface permits a close to real time operation, with control latencies of around 400 ms [35]. The low latency time allows to conduct sample examination and soil operation in an accurate, robust and time efficient way, maximizing the effectiveness of the mission.
- Simplify and increase the reliability of multiple sample returns to the space station. Scientific experiments on the samples collected on the surface of the Moon are performed directly on the station, rather than sending the samples back to Earth. This aspect is crucial for an extensive scientific research of important compounds in the lunar soil. Moreover the sample return to the space station is remarkably less expensive than a direct return to the Earth, which introduces limitations and difficulties due to the re-entry phase [19].

As regards the FDSR, the most important aspects are:

- HOPE represents a deep space radiation laboratory, where space medicine experiments such as ALTEA [38] can be performed. Moreover, HOPE allows to develop, qualify and improve new materials and strategies for deep space radiation protection.
- HOPE allows to investigate and test new solutions for multi-functional materials for space environment design. This class of new materials provides efficient structural, thermal and radiation protection capabilities [24].

HOPE is composed of three modules: Brave, Companion and Tortuga (Figure 1).

Brave and Companion provide an initial combined free volume of 152 $m^3$, that is a volume per astronaut of 50 $m^3$. This is double the minimum value imposed by the NASA Standard 3000 [20]. The final configuration (Brave, Companion and Tortruga) provides an internal volume of 356 $m^3$ thanks to the use of the Bigelow Aerospace inflatable module, B330 (Tortuga).

### 4.1 Command Module (Brave)

A representation of Brave is given in Figure 2 . Brave is based on an adapted cryogenic composite fuel tank developed by NASA and Boeing. This strategy has been adopted in the past for the Skylab mission, that used a converted Saturn V propellant tank as a habitable space station, [25]. Using this structure has different advantages: it is already launch qualified, it provides a considerable amount of habitable volume, it is capable of withstanding the internal pressure necessary for manned missions and it has a relatively low cost [25]. Brave is based on the most recent advancement in Composite Cryotank Technology, which allows a structural mass of 1445 kg and a Technology Readiness Level (TRL) of 6 [22, 30]. Brave has a total length of 10 meters and a diameter of 5 meters, with an internal

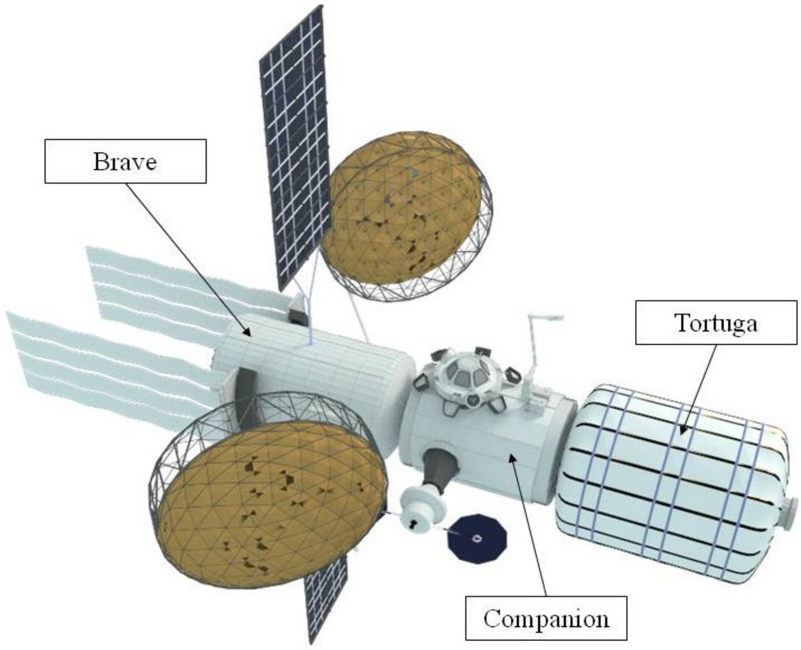


**Figure 1.** *HOPE space station.*

volume capable of housing many crucial subsystems. The total launch mass is of 14200 kg [44]. Brave is provided with a low impact docking port, where Orion can dock to, as well as a module adapter for further expansion of the station.

In EML-2 particular attention has to be paid to the radiation protection. An accurate design of the radiation shield has been performed for Brave, due to its peculiar structure in composite material. The amount of radiation absorbed in interplanetary space is over 20 kSv per year. The NASA standard states that a maximum of 1 Sv and 1.5 Sv can be absorbed during the entire astronaut life by female and male respectively. A design constraint has been fixed to a total radiation level of 0.5 Sv per year. Careful material selection and structure design is required to meet this constraint. For this purpose a detailed campaign of analyses has been performed using ESA Spenvis tool [28]. In order to be conservative against the great amount of uncertainties, a worst case scenario is simulated. A period of maximum solar activity is selected and the radiation dose is computed using isotopic particles source and isotropic shield.

The external main structure of Brave is composed of a Boeing Fluted Core Sandwich wall [37]. Without any additional protection the radiation dose per year would be approximately 0.8 Sv, which is unsatisfactory. Furthermore the structure must be protected also by the possible threat of micrometeorites.

The debris shield is made by a layup of Nextel and Kevlar for a total thickness of 4 mm. Nextel is a ceramic material and has also a good content of aluminum, which has been expected to further increase the radiation shielding properties. In order to slow down both solar particles and cosmic radiation low atomic number material must be used [26]. The internal empty volume of the sandwich allows to introduce an additional protection made by polyethylene for maximum thickness up to 3 cm. By performing a parametric study the optimal result has been obtained with a total thickness of 2.5 cm. In the worst case scenario a total of 0.448 Sv per year are absorbed by the crew. The protection could be further enhanced using up to 3 cm of polyethylene foam. However, this configuration would not allow the use of the Falcon Heavy launcher, due to payload mass limitation, making the SLS the only viable option. Further studies in this field are required, in order to deliver the safest and lightest radiation protection for the crew.

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### 4.2 Service Module (Companion)

Companion is the space station service module (Figure 1 and Figure 3), providing the Environment and Control Life Support System (ECLSS) for up to 3 crew members, the toilet service, the exercise machines for the astronauts and access to different space station areas. The use of an inflatable air lock based on BEAM design allows astronauts to perform EVAs [3]. Companion includes a Cupola where robotic operation can be performed using a robotic arm, based on the design of the International Space Station (ISS) Canadarm, [5], or tele-operating the rovers on the lunar surface. Companion is designed to be attached to the inflatable airlock for EVA, the B330 inflatable module (Tortuga), an emergency Orion capsule (if one were to be launched and used by the crew) and, finally, a docking hatch where the lunar ascent module can dock. The structure of Companion is similar to that of the ISS Node-3 [7]; an additional mass is considered to adapt it to the mission constraint, considering also the radiation protection. The liftoff mass of this module is approximately 27800 kg [44].

### 4.3 Inflatable Module B330 (Tortuga)

The last module to arrive in EML-2 is the inflatable B330 from the private company Bigelow Aerospace, Tortuga (Figure 4). Tortuga has an estimated mass of 20000 kg for a total habitable volume of 330 $m^3$ [44].

It is assumed that the B330 technology is going to be flight proven in 2024. Current findings indicate that inflatable habitats offer good levels of protection for crew, from both radiation and micrometeorites. Tortuga provides additional space for more crew members, space for science and engineering experiments, and a dedicated area for the tele-operation of the lunar rovers (Figure 5).

### 4.4 Interior Design

The interior design of HOPE is realized according to NASA-STD-3001 Space Flight Human-System Standard [31]. The organization of the space (vicinity and/or separation of specific activities) is designed to ensure the well-being of the crew members, their physical and psychological health and the efficient transit between the three modules. Storage racks are designed based on International Standard Payload Racks [27]. This standardized system provides an easy-arranged interior design and the accessibility to every equipment. In Brave and Companion the racks are located on the four sides of the modules, creating a rectangular free space core.

The idea of creating an artificial orientation, in order to provide a vertical feeling of "up" (ceiling) and "down" (floor) is a main guideline of functional interior planning. This sensation is increased by locating the main activities, such as working and exercising and hygiene facilities on opposite sides of the modules, to give a sensation of right and left spaces. The space on the floor and ceiling is used for member-use storage and some access demanding equipment (water or air supply).

**Brave.** The interior design of Brave is shown in Figure 2. Brave is designed for the private needs of the crew and for some of the group activities. At the end of the module (which corresponds with the end of the whole station) there are 3 quarters (volume 4.14 $m^3$) for each astronaut; they are visible on the left-hand side of Figure 2. These private areas include individual equipment and storage areas (personal hygiene, sleeping bag, leisure clothing and private medical care). Additionally they can be used as shelters against Solar Particle Events. The radiation protection is provided by equipment such as water tanks, waste tanks and storage items which are located next to private modules.

To ensure an optimal acoustic isolation (a big issue for mental health), the private quarters are separated from the galley and group-activity space by wardroom with additional stowage and equipment sector. The common area takes most of the habitable volume (over 45 $m^3$). The galley is used for dining, group meeting and station operations control. It is equipped with food processing system, water supply and collapsible furniture. When the galley is not in use, the mobile furniture might be shifted to change the volume to an open space. A complement to this working area is provided by communication and control equipment located on two opposite walls. The galley contributes to the integration of the crew members, thanks to the group and working activities.

**Companion.** The interior design of Companion is based on the ISS Node 3 Tranquility, [32], and it is shown in Figure 3. Similarly to Brave, most of the storage and technical control equipment are placed on the "floor" and "ceiling" of the module. The remaining space on either side of the module is designed for exercise equipment and Waste Management Supplies. The activities connected with these areas are related to dirt and smell issues. Due to this problem they are isolated in this module and share space only with stowage, technical equipment and ECLSS. The remaining space in

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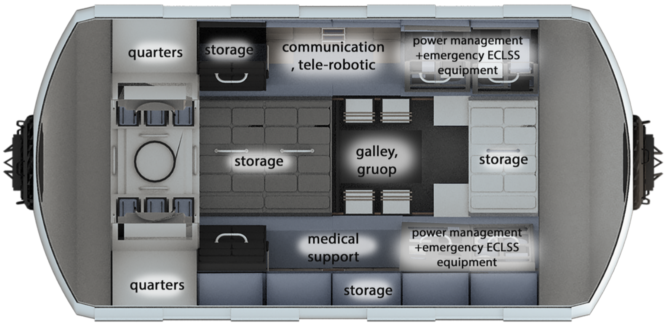


**Figure 2.** *Brave internal view.*

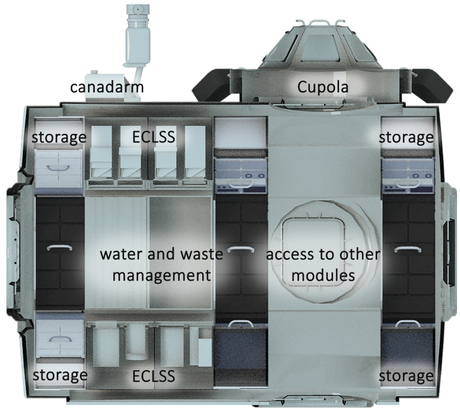


**Figure 3.** *Companion internal view.*

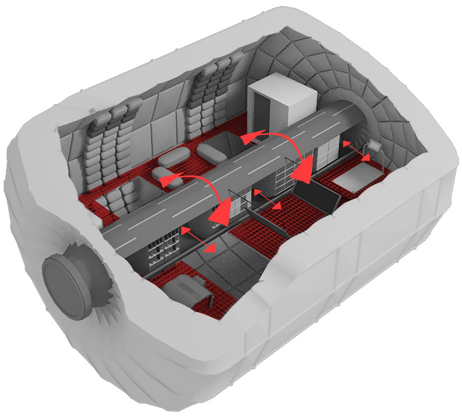

**Figure 4.** *Tortuga.*

Companion is an open space which provides access to Orion, the Cupola and other possible modules.

**Tortuga.** The interior of Tortuga is organized as a single open space. The only separations are wall-panels for the private leisure areas and an open-work "floor" separating top store from lower store . According to the Bigelow B330 inflatable module system specification, along the main axis of the module there is a core, used in Tortuga to hold the technical equipment . The access paths to every part of the module lead around the core, in two transit segments determined by floor's holes. The top store is used for group activities, (it could, for example, hold a second galley, if the number of crew members were to increase), leisure and entertainment and to tele-operate equipment on the surface of the Moon. The rest of the space is used for the storage of the exoskeleton and the equipment required for Human-Robotic operations on the lunar surface (Figure 5 and Section 7). The lower store is designed for private quarters and storage. Personal areas are located at the ends of the module. They are isolated from shared space with small storage-bags covering walls.

### 4.5 ECLSS

The ECLSS of HOPE must be able to:

- control temperature, pressure, humidity and ventilation;
- revitalize the atmosphere (removal of carbon dioxide, monitoring of oxygen and other gases level, ventilation);
- recover and manage water and waste;
- guarantee the safety of the crew (radiation shielding, fire detection).
- guarantee physical and psychological support.

All these capabilities must be performed for the entire duration of the mission without failures. Thus the ECLSS has to provide service for 80 days (that is, mission time multiplied by a safety factor of 2). Furthermore, the system has to be available to be used in future missions. In order to satisfy these points, a system based on the the ISS ECLSS is used for HOPE. Appropriate modification needs to be applied to the ISS ECLSS in order to account for the different radiative environment (absence of the Earth's magnetic field protection) and to introduce new technologies. Furthermore the longer resupply times for a station in EML-2

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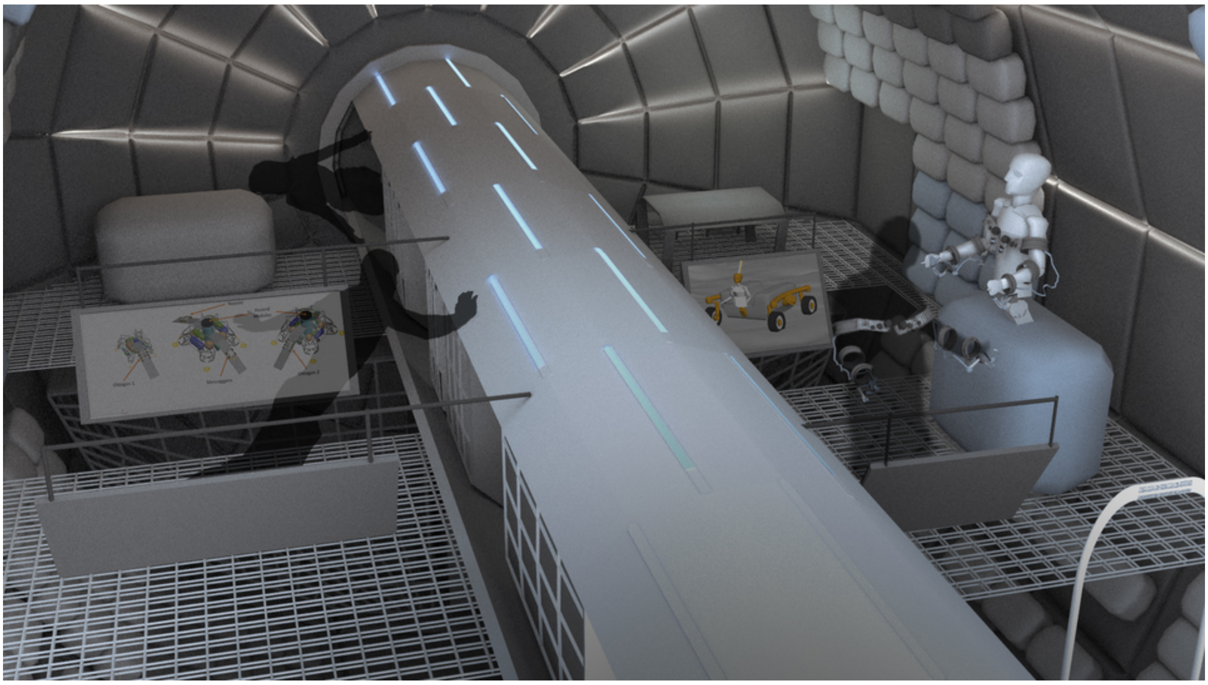

FIGURE 5. *Tortuga internal view.*

with respect to a station in Low Earth Orbit have to be considered. Therefore, a new generation of items designed for long deep space mission are necessary. A key feature of the ECLSS of HOPE is the capability of recycling a high percentage of waste, so as to make the station almost autonomous and to reduce the number of resupply missions. In the following a list of the main ECLSS components is given [44].

**Water reclamation system.** This is a key element of the ECLSS of HOPE. It provides clean water by reclaiming waste-water (crew-member urine and humidity condensate) [45]. By doing so, the mass of water and consumables that would need to be launched from Earth can be greatly reduced. The system works by reclying pretreted urine and flush water, coming from the Waste and Hygiene Compartments, to produce purified water, using the Urine Processor Assembly (UPA). In addition, the Water Processing Assembly (WPA) processes UPA distillate and produces iodinated water, delivered through a potable water bus to the Oxygen Generation System.

**Oxygen generation system.** The Oxygen Generation System (OGS) produces oxygen for breathing air for the crew and to replace the oxygen lost during airlock depressurization and carbon dioxide venting or due to module leakage [45]. The OGS uses water from the WPA; it electrolyses the water to produce oxygen (delivered to the cabin atmosphere) and hydrogen (vented over-board or used by the Carbon dioxide removal assembly). In addition, storage tanks system for the oxygen and nitrogen gases are located on the Airlock to compensate for leak in the system.

**Carbon dioxide removal assembly (CDRA).** This system is designed to remove carbon dioxide from the space station. It works by causing the hydrogen produced by the OGS to react with the carbon dioxide removed from the cabin atmosphere, to produce water and methane [45]. Due to the lack of experience in managing and storing safely methane on-board, methane is ejected from the station. The water produced in the process is instead fed to the WPA for processing. A number of lithium-hydroxide canisters are available on-orbit to support carbon dioxide removal in case of complete CDRA failure.

**Pressure, temperature and humidity control**. Each module of HOPE is equipped with a fan and with heat exchanger and pressure sensors linked to tanks to control temperature, humidity and pressure inside the station.

**Air Contamination Control (ACC).** This system is composed of a Trace Contaminants Control Assembly

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(TCCA) and a Major Constituent Analyser (MCA), [6]. The TCCA checks the cabin air for concentration of trace contaminants; it does so by using a charcoal bed (for the removal of high molecular weight contaminants), a high temperature catalytic oxidizer (for low molecular weight contaminants) and a lithium-hydroxide sorbing bed, [6]. The MCA is a mass spectrometer; it is used to monitor the partial pressures of oxygen, carbon dioxide, hydrogen, methane, nitrogen and water vapour in the atmosphere of the cabin [6].

### 4.6 Private Sector Involvement

The emergence and rapid growth of private companies into the space sector has shown that there is a significant opportunity for further expansion. SpaceX is a clear example of successful private sector cooperation with space agencies. Bigelow Aerospace are also forging relationships with traditional space exploration, using the ISS to test their technologies. The ISS pioneered multinational cooperation in space exploration; the next step is the further integration of the private sector. HOPE provides a perfect stepping stone for this cooperation. It is a proving ground for private sector proprietary technologies, which not only require testing, but also benefit from the extensive experience of space agencies. Furthermore, the association with trusted space agencies will give private companies and their technologies a level of recognition they would otherwise be unable to achieve. The private sector are constantly seeking new areas to expand their operations, and HOPE can provide an opportunity for cooperation.

## 5 Landers

In order to realize the objectives of the mission, three landers are required, one for each of the landing sites defined in Section 8. The first lander, La Pinta, delivers Nozomi, a construction rover, and Messaggero, a humanoid rover, to the north region of the Schrodinger Crater. The second lander, La Niña, delivers Oktagon 1, an 8-wheels scientific rover, to the east region of the Schrodinger Crater. The third lander, La Santa Maria, delivers Oktagon 2, the second 8-wheels scientific rover to the Daedalus Crater.

Due to the nature of the mission, the landers have to provide high autonomous landing accuracy and autonomous Hazard Detection and Avoidance (HDA). According to [33] and to the lander types categorization given by [17], the best lander type to provide high accuracy and soft landing for unknown terrain is the legged lander type; therefore this has been chosen as as the baseline for the landers of HECATE.

The baseline structure bus for the lander body is a typical octagonal pallet lander with four legs that incorporate crushable honeycomb for shock attenuation after the touchdown. The electronic systems are placed together with the thermal control subsystem at the side of the lander. The rovers are attached to a deployable ramp and secured within the lander by pyrotechnic bolts. The rovers are deployed to the lunar surface by the deployable ramp that unfolds and lowers softly to the lunar surface after the discharge of the pyrotechnic bolts. All the landers consist of a Lunar Descent Module (LDM). La Pinta and La Niña also carry a Lunar Ascent Module (LAM) which includes the sample return capsule. Table 4 shows preliminary estimation of the mass budget for all of the landers assuming a $\Delta V$ for lunar landing of 1.72 km/s, [44].

The propulsion makes use of a liquid bi-propellant, N2O4/MMH, divided among two tanks for the fuel and four tanks for the oxidizer for La Pinta and La Niña, and one fuel tank and one oxidizer tank for La Santa Maria. The Main Engine Assembly (MEA) is mounted at the bottom of the lander and aligned symmetrically so the thrust vector runs through the center of gravity. The total thrust level in vacuum provided by the MEA and the number of clustered thrusters of each of the lander are: 14 kN (4.5 kN x 4) for La Pinta, 6 kN (1.5 kN x 4) for La Niña and 4 kN (1 kN x 4) for La Santa Maria. Helium gas is used as suppressant.

## 6 Rovers

Mission HECATE lands four vehicles on the surface of the Moon: Messaggero, Oktagon 1, Oktagon 2 and Nozomi.

There are two main factors that influence the vehicle design choice: lunar regolith and lunar gravity (about one sixth of Earth's gravitational acceleration). Lunar regolith is the layer of loose material covering the surface of the Moon; it causes challenging driving conditions. It includes glassy, spheroidal particles which are drops of melted lunar material formed from meteorite impacts [41]. The spheroidal nature of the particles reduces the friction by making slipping easier. To overcome this problem, careful attention has to be paid to the tread on the tyres. It should maximise the grip and friction to reduce slip when drive is applied [36]. The

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| La Pinta | | La Niña | | La Santa Maria | |
|---|---|---|---|---|---|
| Wet mass | 7270 | Wet mass | 3220 | Wet mass | 1558 |
| Propellant mass | 4700 | Propellant mass | 2085 | Propellant mass | 1009 |
| Total payload mass | 1200 | Total payload mass | 620 | Total payload mass | 300 |
| - Nozomi | 550 | - Oktagon 1 | 220 | - Oktagon 2 | 220 |
| - Messaggero | 250 | - Ascend module | 400 | - Telescope | 80 |
| - Ascend module | 400 | | | | |

Table 4. *Mass break-down for the landers (masses are in kg).*

porosity of the soil is another interesting lunar property. Due to the small gravitational acceleration it is unlikely for the particles to form a dense structure.

In the following subsections the design of the "MOON" rovers, realized taking into account the effect described above, is described.

### 6.1 Exploration Rovers - Oktagon 1 and 2

The wheels of the lunar rovers Lunokhods [12] and LRV [14] were made from metal mesh and had favourable characteristics when used on lunar soil. The "MOON" rovers uses similar wheels to those of Lunokhods. To minimise surface pressure there are two options: many small wheels (a characteristic similar to robots with tracks) or a few large diameter wheels [36]. Oktagon 1 and Oktagon 2 are Eight Wheeled Exploration Rovers (EWER). The suspension of this kind of rover is similar to that of Lunokhods. However, their design improves upon the original by implementing proper turning capability instead of relying on skid-steering. This is achieved by having four independent bogies, each with two wheels whose relative angles can be controlled. Independent suspension is desirable because when the rover is tele-operated the user often wants the capability to drive at the minimum speed of human walking pace (approximately 5 km/h). This is a relatively high speed for lunar locomotion and generates lots of unpredictable dynamic impacts. Independent suspension is better able to absorb these impacts and facilitates more accurate control of the rover.

During the exploration various gradients of terrain are going to be encountered. EWER should be capable of traversing a slope of up to 30 degrees; since the stability depends on the center of mass it is desirable for both rovers to be as low to the ground as possible.

The rovers are expected to return samples to HOPE. Therefore it is unnecessary for them to have many onboard testing equipment, thus reducing the weight and complexity of the rover. The estimated mass per rover is 220 kg. The design of the rovers accounts for transportation by considering the form taken when in storage. A single use mechanism is used to take the robot from a small size to operation mode by using a mechanism consisting of springs and pawls of solenoids [44].

The torque required to drive and turn the rover is calculated with the estimation that Oktagon needs to transport up to 10 kg of samples. Calculations have shown that to move at speeds up to 5 km/h, each drive needs an approximate power of 50 W. Therefore, the total power when all eight drives are at maximum is 400W. Typical small Radioisotope Thermoelectric Generators (RTG) can produce 1200 Wh/day [16]. RTGs are suitable because the rovers are not planned to be in the proximity of humans. That means that with maximum sample capacity, on the steepest slope the robot is designed to operate for up to three hours per day. This is a worst case scenario. However, the onboard drill has some power use when taking samples so the amount of material collected affects the operational time of the robot.

### 6.2 Humanoid Rover - Messaggero

Messaggero is a humanoid rover. Examples of existing humanoid mounted rovers include ESA's Centaur [8] and NASA's Robonaut [15]. Robonaut is unlike other space robotic systems in that it is designed for tasks requiring dexterity, not to move bulky objects. Its humanoid shape allows it to use tools designed for human astronauts allowing it to work side by side with its organic counterparts. The torso can be attached to a wheeled platform such as Centaur 1 to allow movement over long distances. ESA's Centaur shares the same name as the wheeled platform but is an entirely sepa-

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rate project. It is also capable of high precision tasks. This human robotic interaction is seen as a vital part of of space exploration for long term projects.

### 6.3 Construction Rover - Nozomi

Recently ESA has proposed constructing a base with lunar soil on the Moon [4]. The "printer" consists of a robot that acquires lunar regolith and converts it into a material suitable for onboard nozzles to print with. It does this by placing layer upon layer over a long period of time, slowly building the desired structure.

The technology needed to build structures using additive manufacturing in a non-terrestrial environment is still in its infancy with much further development needed. For HECATE, it is proposed that a prototype construction robot, Nozomi, is deployed as an early stage feasibility test.

## 7 Human-Robotic Interaction

To achieve HECATE mission goals, human-robotic interaction hardware and software are available to the astronauts inside HOPE. All robots part of the HECATE mission are designed to be autonomous and capable of operating on their own. However, at times it may be beneficial for a human operator to take control through a tele-operation and human-robotic interaction. For example, a collection of rocks have been found but the payload capacity of the robot is such that only one can be carried.

Artificial intelligence is progressing but currently a trained human has a better understanding of complicated scenarios where a wide variety of tasks must be performed. The main benefits of human-robotic interaction include less risk to humans, lower costs and the ability to have a presence in multiple locations simultaneously.

Current technology requires an operator to make some physical input to a controller. In return, the system may provide feedback to the operator to assist his actions. Four technologies have been chosen from many to be included on HOPE: Gesture Tracking, Exoskeleton, Virtual Reality and Auditory Feedback. They have been selected not only because they are suitable for the job but also because HECATE mission should further and improve their development.

Gesture tracking is used for simple control motions of the "MOON" rovers, such as basic locomotion maneuvers. The main advantage of this method is the minimal amount of setup for the operator. No devices must be prepared or attached so the operator can multi-task and only apply commands when required. The hardware is similar to that of Microsoft's Kinect platform, consisting of a camera and IR structured light depth camera.

The Exoskeleton located inside Tortuga is used for more complex operations involving Messaggero (the humanoid rover). The astronaut wears hardware that tracks the full six degree of freedom (6DOF) movements of his arm and sends commands to the robotic arm to replicate the action. Sensors on the robotic arm is used to provide tactile feedback to the operator back in Tortuga.

The virtual reality environment has a direct practical use in operations involving Messaggero, but crucially it is designed to increase the psychological and physical well-being of the astronauts. Perhaps this is not essential for the HECATE mission but in the future space voyages are going to take a long time; a round trip to Mars is predicted to last at least two and a half years. Proving the viability of the technology in missions like HECATE is important and HOPE offers a platform to research and improve the hardware.

Finally auditory feedback is available to provide information to the operator when controlling the robots during complicated task. Binaural feedback keeps the operator informed of the robot's state and sound warnings when necessary.

## 8 Scientific Objectives

To realise the scientific objectives of mission HECATE, the "MOON" rovers are expected to land inside the Schrodinger basin and Daedulus Crater on the far side of the Moon.

### 8.1 The Schrodinger Basin

The US National Research Council (NRC) has identified eight scientific concepts and thirty-five prioritized goals for future human and robotic exploration of the Moon [42]. The Schrodinger basin is a geologically rich area and a sample return from this region would address many of objectives of the NRC.

It is located on the lunar far side (latitude -75°, longitude 132.5°) and it has a diameter of approximately 320 km; its floor, at its deepest points, is 4.5 km beneath the crater's rim [40]. Schrodinger is the second youngest basin on the Moon and it is inside the oldest and largest lunar basin, the South Pole-Aitken. Because of this, a

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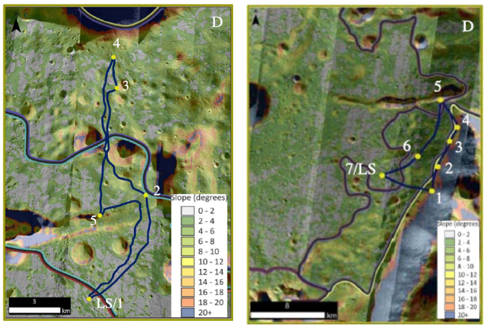


**Figure 6.** *SBLS1 (left) and SBLS2 (right) traverse slope map, [40].*

mission to Schrodinger would permit the rovers to recover samples from both basins, allowing to test of the lunar cataclysm hypothesis and to determine the age of the oldest lunar basin, meeting two of the highest NRC science priorities [42], [40]. Two of the three landing sites of the mission are located within the Schrodinger basin.

**Landing Site SBLS1.** The first lunar mission is planned to land within the peak ring of Schrodinger, at approximately -73.35°latitude and 134.47°longitude. This landing site is identified as Schrodinger Basin Landing Site 1, SBLS1. Messaggero and Nozomi land at SBLS1. The considered traverse for Messaggero in SBLS1 is 37 km long and five main sites for sampling have been identified as represented in Figure 6, [40]. The traverse shown in Figure 6 is used as a baseline for the operations of Messaggero. Astronauts tele-operating the rover from HOPE use data from an Alpha Particle X-Ray Spectrometer (APXS) to move Messaggero to different locations on the surface of the Moon, depending on the data obtained. Operations of the APXS takes 4 hours with an additional 0.5 h to position the instrument, [40]. The high resolution visible light camera has been selected in order to obtain images of the surface and provide geological information on the collected samples.

**Landing Site SBLS2.** The second landing site, Schrodinger Basin Landing Site 2 (SBLS2) is located at latitude -75.50°and longitude 141.37°. Oktagon 1 operates a baseline traverse in SBLS2 as shown in Figure 6; the route is 28.8 km long and considers seven main sites for scientific exploration. The estimated traverse minimum time is 9.1 days [40]. As for Messaggero, data from APXS and the on-board camera gives the astronauts information about the best place for sampling.

### 8.2 3D Printing

The landing in SBLS1 is exploited also for technology demonstration of 3D printing of the lunar surface, a concept of particular interest for future long term human mission to the Moon. With the aid of tele-operated Messaggero, a radiation sensor is placed under a layer of 3D printed regolith, to assess the radiation shielding properties of the 3D printed material. Nozomi has been designed also to print several specimens, returned to HOPE and then to Earth for structural analysis.

### 8.3 Telescope Deployment on Daedalus Crater

A unique science opportunity presented by operations on the far side of the Moon is the deployment of a low frequency radio telescope. The position on the far side takes advantage of the Moon acting as a shield for radio noise coming from the Earth. This reduction in noise allows the detection of extremely faint signals produced by neutral Hydrogen during the Cosmological Dark Ages.

A concept for a lunar surface antenna composed of numerous flat radio antennas that can be easily unfurled on the lunar surface has been developed [9]. The 3-armed, Y-shape flat polyimide film antenna design allows simple deployment by Oktagon2 of 3 antenna components. The best location for the positioning of the telescope has been identified as the Daedalus crater, located at latitude -5.9°and longitude 179.4°[43, 1].

## 9 Mission Cost

A preliminary analysis of the cost of mission HECATE has been realized. Margins are employed to account for uncertainties in the design process. This can be due to insufficient data, low TRL and to increase safety. Margins are applied according to NASA/SP-2007-6105 to individual elements based on the level of uncertainty and criticality estimated by the designer and range from 5% to 25%. Additionally, a 20% margin is applied to the overall system budget. Margins apply to mass, power, volume and cost estimates. Operational cost is estimated at $3.5B per year. The total cost of the mission is approximately 38B$. Table 5 summarizes HECATE's costs.

## 10 Conclusions

This paper highlights the critical steps of a mission architecture that allows humans to explore the far side

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| Element (Number of elements) | Cost [M$] |
|---|---|
| Launch Vehicles (5) | 10270 |
| Orion MPCV (1) | 1300 |
| Brave (1) | 4120 |
| Companion (1) | 6410 |
| Tortuga (1) | 4000 |
| "MOON" rovers (4) | 750 |
| Landers (3) | 2470 |
| Operational cost (2.5 years) | 8750 |
| Total cost | 38070 |

**Table 5.** *HECATE's costs in $FY15.*

of the Moon as well as creating a space infrastructure, HOPE, that can be sustainably resupplied to enable further exploration of our Solar System. The emphasis of this paper is primarily on the space station, HOPE, and how its strategic location and role in the Earth-Moon system can be utilized for exploring the Moon and for deep space exploration. Along with a detailed description of HOPE, the mission analysis for HECATE's architecture, the scientific values of exploring the Moon using tele-robotic operations, and the overall cost of the mission are discussed in this paper. Thus, this demonstrates that HECATE is a feasible and sustainable mission aimed at furthering the presence of humanity on the Moon, Mars, and beyond.

## References


[1] Astronomers plan telescope on Moon. https://goo.gl/6AgFCp. Accessed: 2016-02-10.

[2] Bigelow B330. https://goo.gl/Ra8qCv. Accessed: 2016-02-10.

[3] Bigelow BEAM. https://goo.gl/j3P995. Accessed: 2016-02-10.

[4] Building a Lunar Base with 3D Printing. https://goo.gl/RYdajn. Accessed: 2016-02-10.

[5] CANADARM. https://goo.gl/5kPd3v. Accessed: 2016-02-10.

[6] ESA Environment Control and Life Support System (ECLSS). https://goo.gl/8SFsKC. Accessed: 2016-02-10.

[7] ESA ISS - Node 3: Connecting Module. https://goo.gl/gPKXvv. Accessed: 2016-02-10.

[8] Interact Space Experiment. http://esa-telerobotics.net/. Accessed: 2016-02-10.

[9] Lunar Radio Array. https://goo.gl/prGhmK. Accessed: 2016-02-10.

[10] NASA Orion Spacecraft. https://goo.gl/1FRMfJ. Accessed: 2016-02-10.

[11] NASA Space Launch System. https://goo.gl/rtydyT. Accessed: 2016-02-10.

[12] Rovers – learning from Lunokhod. https://goo.gl/vEEhLe. Accessed: 2016-02-10.

[13] SpaceX Falcon Heavy. https://goo.gl/cYYXog. Accessed: 2016-02-10.

[14] The Apollo Lunar Roving Vehicle. https://goo.gl/XTPpLz. Accessed: 2016-02-10.

[15] R. O. Ambrose, H. Aldridge, R. S. Askew, et al. Robonaut: NASA's space humanoid. *IEEE Intelligent Systems*, (4):57–63, 2000.

[16] T. S. Balint. *Small-RPS enabled Mars rover concept*. Citeseer, 2004.

[17] A. Ball, J. Garry, R. Lorenz, and V. Kerzhanovich. *Planetary landers and entry probes*. Cambridge University Press, 2007.

[18] E. A. Belbruno and J. K. Miller. Sun-perturbed Earth-to-Moon transfers with ballistic capture. *Journal of Guidance, Control, and Dynamics*, 16(4):770–775, 1993.

[19] J. O. Burns, D. A. Kring, J. B. Hopkins, et al. A lunar L2-farside exploration and science mission concept with the Orion Multi-Purpose Crew Vehicle and a teleoperated lander/rover. *Advances in Space Research*, 52(2):306–320, 2013.

[20] J. H. Connolly and M. Arch. NASA Standard 3000 Human Systems Integration Standards (HSIS) Update. In *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, volume 49, pages 2018–2022. SAGE Publications, 2005.

[21] R. W. Farquhar and A. A. Kamel. Quasi-periodic orbits about the translunar libration point. *Celestial Mechanics*, 7(4):458–473, 1973.

[22] J. C. Fikes. Composite Cryotank Technologies and Demonstration. *NTRS*, 2014.

[23] D. C. Folta, N. Bosanac, D. Guzzetti, et al. An Earth–Moon system trajectory design reference catalog. *Acta Astronautica*, 110:341–353, 2015.

[24] R. F. Gibson. A review of recent research on mechanics of multifunctional composite materials and structures. *Composite structures*, 92(12):2793–2810, 2010.

[25] B. N. Griffin, D. Smitherman, K. J. Kennedy, et al. Skylab II: A Deep Space Habitat From a Space Launch System Propellant Tank (AIAA2012-5207). In *AIAA Space 2012 Conference & Exhibition*, 2012.

[26] S. Guetersloh, C. Zeitlin, L. Heilbronn, et al. Polyethylene as a radiation shielding standard in simulated cosmic-ray environments. *Nuclear Instruments and Methods in Physics Research, Section B: Beam Interactions with Materials and Atoms*, 252(2):319–332, 2006.

[27] H. Hashimoto, T. Fukatsu, Y. Ano, et al. Development of international standard payload rack structure for space station science operations. *AIAA98-0466*, 1998.

[28] D. Heynderickx, B. Quaghebeur, and H. Evans. The ESA Space Environment Information System (SPENVIS). In *IAF abstracts, 34th COSPAR Scientific Assembly*, volume 1, page 475, 2002.

[29] ISECG. The Global Exploration Roadmap. August 2013.

[30] T. F. Johnson, D. W. Sleight, and R. A. Martin. Structures and design phase I summary for the NASA composite cryotank technology demonstration project. In *54th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference*, page 1825, 2013.

[31] E. Jones and K. Shiva. NASA Technical Standards Program. *NASA STD-3001*, 2.

[32] H. Jones. Mission Design Drivers for Life Support. In *41st International Conference on Environmental Systems*, page 5037, 2011.

[33] K. Konstantinidis, C. L. F. Martinez, B. Dachwald, et al. A lander mission to probe subglacial water on Saturns moon Enceladus for life. *Acta Astronautica*, 106:63–89, 2015.

[34] M. Landgraf, J. Carpenter, and H. Sawada. HERACLES Concept – An International Lunar Exploration Architecture Study. 2015.

[35] D. Lester and H. Thronson. Low-latency lunar surface telerobotics from earth-moon libration points. *American Institute of Aeronautics and Astronautics Space*, 2011.

[36] K. Lewandowski. Pojazdy na Ksiezycu (Vehicles on the Moon). 2001.

[37] S. Y. Lin, S. C. Splinter, C. Tarkenton, et al. Fabrication and Testing of Durable Redundant and Fluted-Core Joints for Composite Sandwich Structures. *SAMPE Journal*, 49(4):30–39, 2013.

[38] L. Narici, V. Bidoli, M. Casolino, et al. The ALTEA facility on the international space station. *Physica Medica*, 17:255–257, 2001.

[39] E. Perez et al. Ariane 5 User's Manual. *ArianeSpace Evry-Courcouronnes Cedex-France*, 2008.

[40] N. J. Potts, A. L. Gullikson, N. M. Curran, et al. Robotic traverse and sample return strategies for a lunar farside mission to the schrödinger basin. *Advances in Space Research*, 55(4):1241–1254, 2015.

[41] O. D. Rode, A. V. Ivanov, M. A. Nazarov, et al. *Atlas of photomicrographs of the surface structures of lunar regolith particles*. Springer, 1979.

[42] D. H. Smith, C. F. Pieters, and G. A. Paulikas. The Scientific Context for the Exploration of the Moon. In *Bulletin of the American Astronomical Society*, volume 38, page 589, 2006.

[43] Y. D. Takahashi. New Astronomy from the Moon: a Lunar Based Very-Low Frequency Radio Array. In *IAF abstracts, 34th COSPAR Scientific Assembly*, volume 1, page 715, 2002.

[44] Team HECATE. Human Exploration of Cis-Lunar Space via Assets Teleoperated from EML2. Technical report, ESA Moon Challenge, November 2015.

 DOI: 10.5281/zenodo.202192

[45] D. E. Williams, J. R. Dake, and G. J. Gentry. International Space Station Environmental Control and Life Support System Status for the Prior Year: 2010-2011. In *42nd International Conference on Environmental Systems (San Diego, CA, USA)*, pages 1–24, 2012.

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# A Feasibility Study for A Short Duration Human Mission to the Martian Surface

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**Abstract.** A feasibility study is carried out for Mission MILESTONE, which is a short duration mission with the aim of establishing a long permanence outpost for subsequent exploration. This paper presents the results of this study, both the overall system architecture and the results of detailed investigations into certain aspects of the mission. The Mission MILESTONE (Mars Initial Landing ExpeditionS Towards a New Era) feasibility study focuses on the mission stages from Low Mars Orbit onwards only, and does not carry out a detailed investigation into the Earth-Mars transit. An 180 day transit is assumed each way, with the intention of residing on the surface for 60 days. As the mission is intended as a pre-cursor to exploration missions, it is focused on the establishment of a habitable environment to ensure the supply of sufficient resources required to sustain human life. During this first manned mission to the Martian surface there will also be technology demonstrations, increasing technology readiness levels for the benefit of future missions. This paper first of all sets out the mission architecture and objectives. It then details the results of the major investigations carried out into key components of the mission and outpost. Finally, the main conclusions of the feasibility study are drawn.

## 1 Introduction

The next frontier of human space exploration is the exploration of Mars, and the SEEDS (SpacE Exploration and Development Systems) course project for 2015 considers an initial human landing on the Martian surface. SEEDS VII is an international, multidisciplinary group comprised of students from both the Politecnico di Torino and the University of Leicester. The project takes place over three stages: in Turin working in collaboration with ALTEC and Thales Alenia Space; in Toulouse with assistance from ISAE; and in Leicester within the University of Leicester Space Research Centre.

The SEEDS VII project covers the second step of "Conquest by Humans of Mars in Five Steps". The

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**Figure 1.** *Mission MILESTONE Insignia*

summary of the findings and the proposed mission to accomplish this task is MILESTONE: Mars Initial Landing ExpeditionS TOward a New Era. The overall aim for the mission was given as "The initial descent, permanence and departure of humans on/from Planet Mars". Mission MILESTONE will be an early stage mission, which will create an outpost on Mars for further human exploration by subsequent missions. This was determined to be the most cost-effective method, as a substantial outpost would be required to sustain human life on Mars, thus a multi-mission outpost is designed to allow sufficient time for experimenting to build a future permanent outpost. Mission MILESTONE's insignia can be seen in Figure 1, and depicts the Monolith from Arthur C. Clarke's novel "2001: A Space Odyssey" approaching the Martian surface. The use of the Monolith pays tribute not only to the media that inspires space exploration but also the work of previous Mars missions. Beneath the insignia is the motto of the mission: "The first human expedition to the Martian surface".

## 2 Mission Summary

The mission statement for Mission MILESTONE is "To descend humans to the Martian surface; to ensure their survival through the establishment of a long permanence outpost; to conduct in-situ scientific operations and exploration; and to allow for their ascent from the Martian surface".

This statement encapsulates the key mission objectives, and the objective of "conducting in-situ scientific operations" will be expanded into a number of scientific objectives in Section 3.

Mission MILESTONE will take place after Mission Orpheus [3], which was designed by SEEDS VI and is intended to take place in 2036. The mission will build on the scientific and engineering knowledge obtained during Mission Orpheus, including the use of the Crew Interplanetary Vehicle (CIV) as a crew transfer vehicle. As Mission MILESTONE is expanding on Mission Orpheus, the interplanetary transfer will not be considered, and the mission is considered to begin and end in Low Mars Orbit (LMO). Mission MILESTONE will take the form of a split mission, with the cargo modules being launched in two windows in 2039 and 2041, and the crew being launched in 2042. These dates were selected using research presented in *Casalino et al.* [12]. The cargo modules will be collected at the outpost location autonomously prior to the crew launch. In order to ensure mission feasibility,the cargo launches will be constrained to using either a Super Heavy Class launcher (e.g. an SLS-2B [27]) or a Heavy Class launcher (e.g. a Falcon Heavy [37]). There will be a total of 15 launches, with 8 Heavy and 7 Super Heavy launches.

The crew of MILESTONE will undertake a 60 day stay in the Martian environment, which includes the transits to and from Low Mars Orbit. The main objectives of the crew phase of Mission MILESTONE are to assemble the outpost and to conduct scientific activities and exploration, including demostrating in-situ resource utilisation and food production.

A large outpost has been designed, as a key objective of Mission MILESTONE is to provide a habitable environment sized for a long-duration future mission. The overall configuration can be seen in Figure 2, and the modules shown are: two habitable modules, which provide the main living quarters; two greenhouses for food production; a laboratory for conducting in-situ science; two EVA modules to allow access to the Martian surface; and a node to connect these modules. In addition, the Mars Descent Vehicle will allow the crew to reach the Martian surface, and the Mars Ascent Vehicle will transport them back to the Crew Interplanetary Vehicle (CIV) in Low Mars Orbit. The power plants will power the outpost using nuclear and solar power, and the In-Situ Resource Utilisation will help reduce the dependence on Earth in future missions. Finally, the rovers will give both the modules and the crew mobility.

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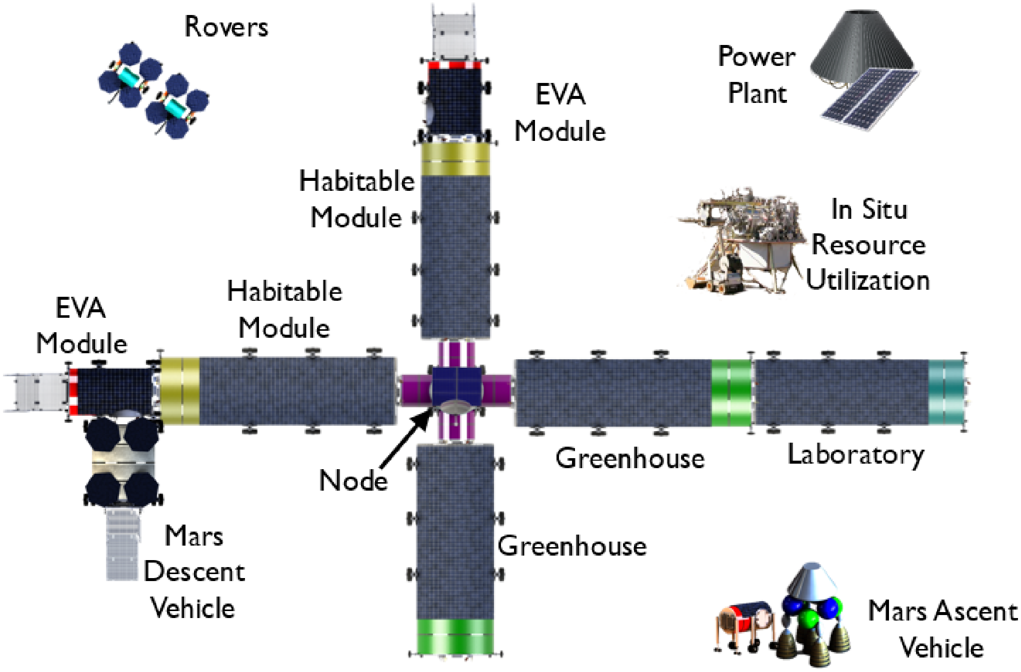


FIGURE 2. *Overall outpost architecture*

Mission MILESTONE will land in Amazonis Planitia, in a region centred on 15N, 155W and at an elevation of -3.5 km MOLA [29]. The region is thought to be a Noachian impact basin, with Hesperian lava flow and most recently an Amazonian surface [16], with around 6% water content [39]. The region is of geological interest, and also has a volcanic history which may have caused fossils or extant life to be pushed nearer the surface [16].

The mission will deploy four static landers in addition to the modules being discussed, which will be discussed in Section 3. These will be located at Isidis Planitia (12N, 87E), Chryse Planitia (27N, 40W), Elysium Planitia (3N, 155E) and Candor Chasma (7S, 71W). Each of these landing sites were selected in line with the scientific objectives for Mission MILESTONE, and are locations that could be appropriate as future human landing sites.

## 3 Scientific Objectives and Operations

The crucial justification for a human mission to the Martian surface is the expected increased scientific return. Having humans on Mars will provide a unique opportunity to understand the biological effects of the Martian environment on humans, which is essential for future manned missions and even possible colonisation. Another advantage, is to the ability of humans that are performing in-situ sample gathering can discern interesting or unusual features among a large variety of samples, which is difficult to achieve remotely. In addition, a greater variety of scientific experiments can be performed with ever more complexity, and higher risk instruments being able to be taken due to the ability of humans to perform in-situ repairs.

### 3.1 Scientific Objectives

The science objectives for Mission MILESTONE are as follows:

1. *To study the physiological and psychological impact of a Mars surface mission*
2. *To perform in-situ investigations into the Martian environment to support future exploration*
3. *To collect data to support the identification of landing sites for future human missions*
4. *To study the origins and evolution of Mars*

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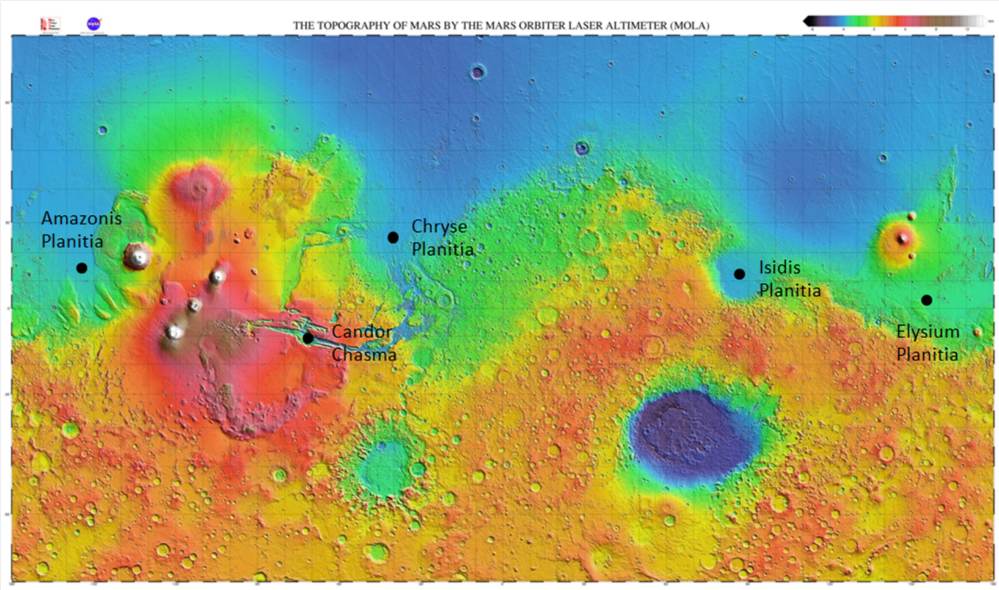


**Figure 3.** *Map of MILESTONE landing sites. Image adapted from MOLA topographic map [30]*

To achieve these scientific objectives, a scientific architecture comprising of a laboratory module, four static landers, scientific payloads for the rover, human deployable assets and entry probes for each modules (Section 3.2).

### 3.2 Scientific Payloads

**Laboratory Module**: In accordance with the outpost layout, the laboratory module will be the same dimensions as the other modules and consists of a rigid and inflatable sections. The rigid section of the module has two bulkheads which forms the decontamination room; dividing non-hazardous experiments and experiments or samples that have been exposed to the Martian environment. The laboratory module has a dedicated sample delivery and return, in order to decrease the risk of forward and backward contamination.

**Static Landers**: Prior to the descent of the crew onto the Martian surface, the Crew Interplanetary Vehicle will deploy four identical static landers to the locations mentioned previously.

The landed mass of each of the static landers are 162.7 kg with a science payload of 34.2 kg and a maximum power of 142.8 W. The landers will transmit scientific data to the Outpost Control Centre via a 4G-LTE (see Section 11) The scientific payload consists of the following (with the reference instrument cited): 5 metre depth mole [7]; gamma ray neutron spectrometer [24]; mole head gamma ray spectrometer [35, 2]; sub-surface seismometer [6]; environmental monitoring suite [17]; laser induced breakdown spectrometer [41]; rock abrasion tool [18]; alpha particle x-ray spectrometer [23]; Raman laser spectrometer [32]); magnetometer [21]; robotic arm [5]; panoramic camera [13] and a radiation assessment detector [19]. One of the unique features of the static landers is the mole capable of reaching depths of 5 metres, with a mole head gamma ray spectrometer based on an instrument proposed in *Skidmore et al., 2009* [35].

**Rover Scientific Payload**: In order to meet the scientific objectives of Mission MILESTONE and reduce the mass and power required, three different scientific payloads have been specified for the rover; a permanent payload, a planetary science payload and an environmental measurements payload. The permanent payload for the rover contains instruments that will provide scientific data for the duration of the rover lifetime, and includes a number of sensors primarily for aimed at radiation and magnetic monitoring. The permanent payload has a mass of 4 kg and requires a power of 13.5 W.

The planetary science payload contains many instruments included on the static landers, as mentioned previously. However, instead of having a mole, the rover planetary science payload will have a core drill capable

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of drilling to depths of approximately 5 m. Although having such a large core drill is a risk, humans can carry out repairs, and it was required due to the reduced operation time compared to the mole [34]. The total mass of the payload is 120 kg and has a power of 1.3kW.

The environmental measurements payload on the rover will consist of pressure, temperature and humidity sensors, together with a sonic anemometer for measuring wind speed. The payload has a total mass of 1.6 kg and a power requirement of 5.5 W.

**Human Deployable Assets**: Human deployable assets (HDAs) will be deployed by the crew of Mission MILESTONE and will be located in the area around the outpost location. The human deployable assets consist of mini-greenhouses, and radiation and environmental monitoring HDAs.

The mini-greenhouses can be used to monitor the growth of plants whilst exposed to various aspects of the Martian environment; for example using Martian soil. The mini-greenhouse has a total mass of 58 kg.

The atmosphere and radiation monitoring HDAs will consist of atmospheric sensors based on the LIDAR instrument used on the Phoenix lander [10], and a variety of radiation monitoring instruments.

**Entry Probes**: The entry, descent and landing system (discussed in Section 4) is largely dependent on the Martian atmospheric density, and therefore it is necessary to monitor this accurately. To achieve this, entry probes are used. The probe will use the same trajectory as the cargo modules and will be equipped with an accelerometer to calculate the acceleration over the descent. It will send the recorded data to the communications satellite via Ka-band.

**Scientific Timeline**: Due to the large number of experiments expected to be performed during Mission MILESTONE, and to estimate the science return of the mission, a science timeline was produced. The scientific activities stage of the mission will last approximately 40 days. With four to six EVAs with the rover and two crewmembers possible in this time, the total number of samples that can be fully analysed is 81. After these samples have been fully analysed, the more scientifically interesting will be selected for sample return to Earth.

## 4 Entry, Descent and Landing

For Mission MILESTONE, a unique entry, descent and landing (EDL) system has been established, due to the large mass of the modules landed on the surface. The unique features of this EDL system is the use of a 23 m diameter, *Hypersonic Inflatable Aerodynamic Decelerator (HIAD)*, and the modules having wheels and shock absorbers.

First of all it is assumed that a module with a thermal protection system (TPS) is in a stable, 200km altitude Mars orbit. After a Hohmann transfer has been performed, to take the module's orbit to an altitude of 100 km. the HIAD is inflated. The HIAD will cause an aerobraking manoeuvre in the Martian atmosphere, down to an altitude of -2 km MOLA. After this, the TPS and the HIAD will be ejected; and the main thruster will be activated, causing a constant flight path angle descent to an altitude of -2.8 km MOLA. At this level, the main thruster is ejected and the secondary thrusters are activated, causing a vertical descent down to 15m above the landing site, where the module will hover. At this stage, the secondary thrusters are then employed to achieve a horizontal speed to avoid the 15m diameter hole caused by the retro rockets, with the wheeled landing devices activated.

The altitudes of each stage of the entry, descent and landing were optimised using computer simulations, with the diameter of the HIAD also optimised. The results of these simulations, and the establishment of the EDL system described, were then constraints on other aspects of the mission, such as the altitude of the landing site. The maximum altitude of the landing site due to the constraints of the EDL system, is -3 km MOLA. In addition, the simulations provided the estimate for the 10 km x 3 km landing ellipse of each module. For the mass of each module, the mass of the EDL system can be calculated easily, as it was found that the mass of the module and mass of the EDL system had a linear relationship. For example, for the habitable module which has a mass of 29.5 tonnes, the EDL system has a mass of approximately 10 tonnes.

## 5 Power

Each module will have an Automated Electrical Power System (AEPS) to maintain the modules temperature and communication links between the cargo period and the crew arrival. The AEPS supplies power using hybrid thermal-electric solar panels [28] located on each module.

During the manned period of the outpost power to the habitable modules, greenhouse modules, laboratory, node, EVA modules and ISRU plant will be provided

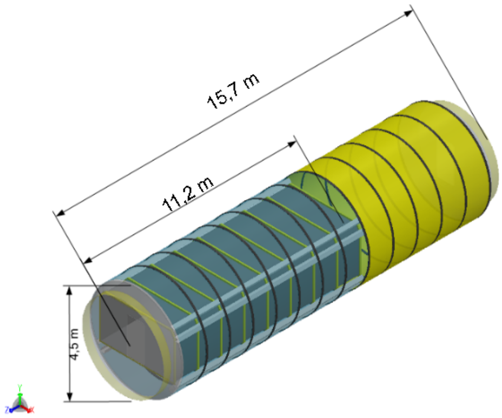


Figure 4. *The dimensions of the module*

by a centralised power source. The Mars Ascent Vehicle and Mars Descent Vehicle will provide their own power as a contingency measure with the MDV operating as contingency shelter and the MAV as an escape vehicle should the main outpost fail. The rovers will have their own power source for nominal use but may be recharged from the centralised power source should the need arise.

The central power system consists of a set of 19, 300 $m^2$ self-deploying solar arrays utilising regenerative fuel cells, an 85 kWe Brayton conversion fission reactor and a distribution system. The solar cells have been sized so that independently they can provide power at any point over the Martian year for single habitable module's life support and a connected EVA module (11kWe). The cells are static, southward facing and have a tilt angle of 35°.

The nuclear reactor is a modular heat pipe reactor design [8]. Both heat transfer and heat rejection are performed with heat pipes. The heat pipes are a sealed system with low maintenance, modularity and inherent redundancy. To reduce the harmful radiation dosage that the crew may receive as a result of the reactors fission products the reactor will be positioned 100 m from the outpost and employ a shadow shield. The shadow shield is a layered tungsten, to shield from gamma rays, and lithium hydride to shield from neutron leakage [9]. In the area covered by the shield, radiation can be reduced to near Martian background levels.

The combination of solar and nuclear presents a diverse and robust system. A totally solar solution would be too massive for an SLS-2B and a single nuclear reactor requires days for the fission products to stop emitting after being turned off, leaving the choice of being exposed to high radiation or foregoing power for days. The proposed configuration will cover the outpost in nominal conditions and supply a meaningful power production from each system independently whilst conforming to the launcher constraints.

## 6 Module Design

The primary structure of the modules for Mission MILESTONE incorporates both rigid (blue) and inflatable (yellow) sections to utilise a greater volume with a limited launch mass. The inflatable section of the primary structure can be packed up in the longitudinal direction to 60% of its inflated size. Whilst the module is in the launcher fairing, the inflatable part is totally packed and all the subsystems for the module are mounted in the rigid part. Once the modules are landed on the Martian surface and fully inflated, the subsystems are redistributed along the entire length of the module. In the inflatable part, the secondary structures (floor and ceiling) are mounted by the crew in order to utilise the entire living volume. It is expected that the assembly of all modules and the connection to the power supply would take 12 days. An identical structure is used for all the modules in Mission MILESTONE, excluding the Node.

The overall length of the modules, whilst the inflatable section is packed, is restricted by the fairing size of the SLS-2B [27]. As a result the modules have a packed length of 13m and a diameter of 4.5m. The module length when it is fully inflated is 15.7m. The total living volume is 147 $m^3$, when the module is fully inflated and the secondary structure has been assembled. The dimensions of the module are shown in Figure 4.

The primary structure for the rigid section of the modules comprise of the shell, rings and longerons; whilst the inflatable section comprises of the inflatable shell, rings, and extendable longerons when inflated. The rigid shell of the module is made from aluminium with a Kapton layer for insulation, the rings and longerons are made from aluminium-6061. The inflatable shell is made from layers of BetaCloth, Kapton, Kevlar, Polyamide and Nomex. The module also has end caps that are used to close the module volume and provide the ability for standard connection interfaces. The detailed structure of the module is shown in Figure 5. The total mass of the primary structure is approximately 11.5 tons and the total mass of the secondary

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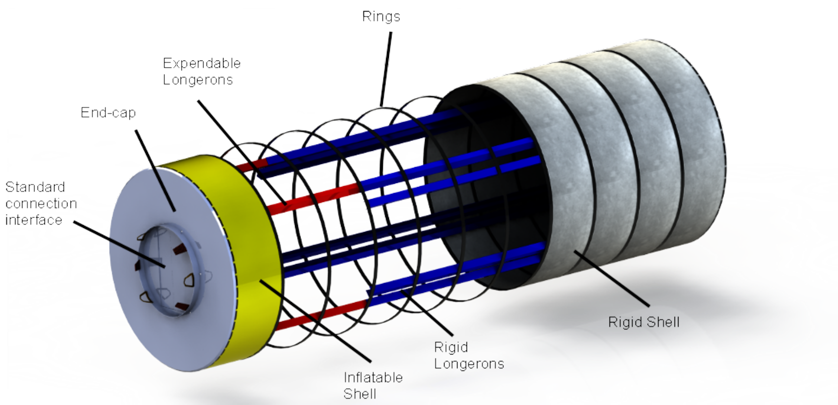


**Figure 5.** *Primary structure elements of the modules*

structure is approximately 1.2 tons.

## 7 Radiation Protection

A radiation protection system for the primary habitable module used in Mission MILESTONE has been established. The majority of the radiation exposure will be during the cruise phase from Earth to Mars, with no atmosphere providing protection from galactic cosmic rays (GCRs) and solar particles (SPs). The atmosphere of Mars is thin compared to that of Earth and provides only the equivalent shielding from 16 cm of water [22].

A forward Monte Carlo simulation of the radiation environment on the Martian surface was modelled using SPENVIS MEREM models on the Geant4 platform [1, 15, 33]. The sensitive elements of the simulation were modelled as 'humans' made of water located in a geometric model of the habitable module as it was designed at the time. The radiation protection employed was using a layer of water within the shell of the module and this thickness was varied during to simulate the effect that this water layer had. The relative effect of this water layer was analysed to accommodate for changes in the module design and is shown in Figure 6.

The water thickness of 10.41 cm, was determined by being supplied by any excess water from buffers for the habitable modules and the greenhouses. As can be seen in Figure 6 this thickness of water used for radiation protection would reduce the relative dose to 69.31% of the dose without any protection besides the module structural components. The 30% reduction in the dose received by crew members on Mission MILESTONE is considered acceptable. However the dose received during the surface stay phase of a Mars mission is minimal compared to the transit phase, thus research should be focused on reducing the radiation dose received during transit [20].

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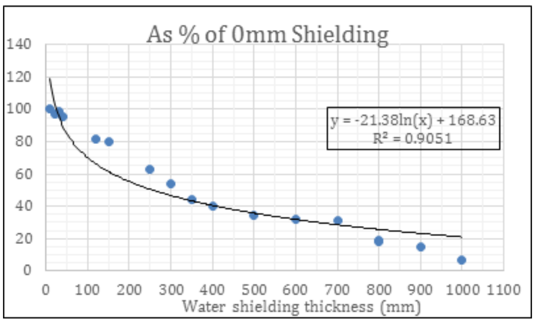


**Figure 6.** *The effect of the water shielding layer to reduce radiation dose*

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## 8 Habitable Module

The habitable module will be the living quarters for the crew of Mission MILESTONE. There will be two habitable modules at the outpost, each capable of housing six crew members for 60 days. Two have been considered for redundancy, but in a nominal mode of operation, each module will house three crew members. The landed mass of each habitable module is approximately 29.5 tonnes.

The primary habitable module for Mission MILESTONE will also contain the outpost control centre, which is responsible for controlling the operations of the outpost and will be the centralised communications terminal.

### 8.1 Environmental Support and Life Support Systems (ECLSS)

The ECLSS employed in the habitable module is the baseline design for other systems used throughout all the modules of the outpost, and is thus only discussed here.

The air revitalisation subsystem is responsible for keeping an appropriate amount of oxygen in the modules atmosphere, and removing CO2. This subsystem consists of an oxygen generation assembly which uses electrolysis, the carbon capture assembly which uses pressure swing adsorption technology and the carbon reduction assembly which consists of a Sabatier reactor.

The atmosphere management, thermal humidity control and atmosphere control and supply subsystem will keep the atmosphere inside the modules at a pressure of 90.5 kPa; reducing the ratio between the outpost atmosphere and the EVA suits to less than 1.2, eliminating the need for pre-breathing for EVAs [26]. In order to aid the fire detection and suppression subsystem, the oxygen can be removed from the atmosphere and the pressure halved during periods of unmanned operations at the outpost.

The fire detection and suppression (FDS) subsystem is essential because flammability range and spread are estimated to have a peak at approximately the Martian gravity environment [38]. The FDS will use portable water-foam fire extinguishers during manned phases of operation, and the generation of an inert atmosphere during unmanned phases. However, the greenhouse cannot be kept inert for long periods and as a result will use an automated system to isolate itself and provide an inert atmosphere if needed.

The water recovery system that the habitable module will use is based on the current International Space Station (ISS) water recovery system, which can recover up to 87% of the water content from waste streams [11].This will need to be supplemented with approximately 1.5 tonnes of water bought from Earth, to provide the 30 kg/day per crew member [43]. Other systems can recover more water content from waste streams but require a larger intake of resources, such as oxygen, and have been deemed unfeasible for a Mars mission.

The waste management subsystem for the habitable modules will use a heat melt compactor, which will produce compressed tiles of waste that can either be incinerated or can be used for additional radiation shielding for the habitable modules. Each habitable module will have its own trash compactor, with greenhouse having its own waste management system, discussed in Section 9.

### 8.2 Crew Utilities

The crew utilities are the support structures and equipment that the crew will interact with inside the habitable module. The utilities have been divided into subsystems to cover the different functions needed by the crew: food and galley, waste collection services, hygiene, clothing, personal, housekeeping, operational supplies, sleep accommodation and crew health care. The total mass of the utilities is 5.34 tons with 1.80 tons being consumed by 60 day mission and 3.55 tons remaining for future usage.

## 9 Greenhouse Module

The greenhouse modules have been introduced with the aim of providing a method of food production for future long duration missions. They will only be tested during Mission MILESTONE, but will provide 1.64 kg of fresh food per crew member per day in subsequent missions.

The greenhouse modules share the same primary and secondary structure with the Habitable Module, but additionally have a tertiary structure which consists of a series of four racks, extended along the length of the rigid part and separated with two corridors. The driving factor for the size is the cultivable surface: the configuration assumes the average height available for each plant is 58 cm. This height will guarantee a better visibility and accessibility to each plant, but also a slightly higher distance from the LED during growth.

The greenhouse will use a gravity-assisted nutrient

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film technique (NFT) hydroponic growth system. In NFT, plant roots are kept in contact with a few centimetres of water and nutrients which is continually cycled around the system. It is possible to grow most crops with NFT, including potatoes which usually require a solid growth substrate to grow successfully [42]. The benefit of this system is that the steady stream of water and nutrients past the plant roots allows them to absorb as much water as they require, before the water returns to a tank where more nutrients are added as a salt solution.

From Earth-based studies [36], 1 l/min of water flux is required in NFT systems. A water recovery system based on that used in the Habitable Modules will be used, in combination with water recovery from the waste management systems. The greenhouse requires a total of 31.2 kg/day of water to be introduced from external sources (i.e. ISRU), with a further 14.5 kg/day being recovered.

A waste management system was devised which maximises the resources recovered from the modules and minimises the unusable waste produced. The waste from both the greenhouses and the other modules is sterilised, dried and condensed before being incinerated. It is therefore possible to extract CO2, H2O from the process, and use excess O2 produced in the greenhouse to minimise the inputs required.

A dexterous multifunction robot is envisaged in each module to partially automate all the operation needed to be performed in the greenhouse, from the planting of the seeds and moving the plants from germinator trays to growing trays, to helping in checking the growth and the maturation of the fruits.

The crew diet was decided from a number of considerations, one of which was the required dietary inputs stated by NASA [4]. A number of diets were compared, and the diet chosen requires the smallest area of greenhouse by introducing a number of high calorie and fat foods which would be brought from Earth. The total diet provides 2.2 kg of food per astronaut per day, with 560g of this being provided from Earth. The food from Earth includes high calorie foods and dried wheat, rice and beans, as these were deemed too resource-consuming to grown in the greenhouse. The total requirement of food for transport from Earth is 1875 kg, which provides 76% of the calorie content per crew member per day.

In order to ensure sufficient food provisions for a 500 day mission, three contingency considerations were made. These were to double the food being transported from Earth, to divide the cultivated area over two modules, and to transport the lyophilised equivalent of two months' worth of crops to provide an additional month of food in each greenhouse module. This configuration minimises the volume and mass and provides 30 days of food to allow for failure repair in the worst case scenario of complete failure of production in both greenhouse modules.

## 10 Rover

In order to provide mobility for both the modules and the crew themselves, two transport rovers are included. These will be capable of both autonomous travel for collection of the cargo modules, and driven operation so that the crew can travel at higher speeds.

However, as Mission MILESTONE is also providing infrastructure for future missions, the Mars Descent Vehicle (MDV) can be combined with the rover to be used as a long-duration, pressurised exploration vehicle. It contains all the necessary life support systems for multiple-day exploration, as the crew will live in the vehicle immediately after reaching the Martian surface.

The rovers have been designed to autonomously collect the cargo modules ahead of the departure of the crew. The power source required has been sized considering the two launch windows for the cargo mission. All the modules have to be in position and working before the crew departure, so this leaves around 640 days for the first window, and only 90 days for the second one. The worst case scenario involves one rover collecting eight modules in 90 days (after the second window), and therefore covering around 280 km, which requires a collection velocity of 0.13 km/h if the rover operates continuously. The power is supplied by 3.7 kW of regenerative fuel cell (RFC) charge power, which are charged from four 1.9m radius solar arrays in a flower configuration. The total mass of solar arrays is 93.5 kg.

Once the crew have landed on Mars, the rover will collect the MDV and transport the crew to the outpost location. An allowance of six hours was used to size this transfer, which results in a speed of 3.6 km/h. This was the limiting case on the power requirements, due to the large mass being transported, and led to a total mass of 7.8 tons for each rover (including all subsystems). Each of the modes of operation, including this and the initial autonomous collection, can be seen in Table 1.

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| Mode of Operation | Power Source | Working Period | Average Speed | Daily Range |
|---|---|---|---|---|
| Autonomous Collection (with module attached) | RFC + Solar Arrays - 3.42 kW | 24 hours, continuously | 0.13 km/h | 3.12 km |
| Autonomous Exploration (without module attached) | RFC + Solar Arrays - 3.42 kW | 24 hours, continuously | 0.68 km/h | 16 km |
| Autonomous Collection of MDV | RFC - 41.3 kW | 7 hours, recharge needed | 3.6 km/h | 25 km |
| Autonomous Exploration - Maximum Range (only Rover) | RFC - 16.2 kW | 24 hours, recharge needed | 3.2 km/h | 77 km |
| Manned Exploration - Maximum Speed (Rover + 2 Astronauts in suit) | RFC - 92 kW | 4.2 hours, recharge needed | 17.5 km/h | 74 km |

**Table 1.** *Modes of operation for the rovers*

## 11 Communications

Two architectures for the communication system have been determined, one for the cargo mission (Figure 7) and another for the crew mission (Figure 8). The architecture is based on an adaptation of Earth cellular networks for the Martian surface, using 4G LTE links between on-surface elements, and using orbital elements to relay communication back to Earth. Both surface and orbital elements of the Earth Ground Station are used, in the form of modified Tracking and Data Relay Satellites (TDRS) for optical communications and the Deep Space Network (DSN) for Ka-band communications.

The architecture for the cargo mission can be seen in Figure 7, and demonstrates the nominal situation (shown as solid lines) and a number of contingency links (shown as dotted lines). The contingency links have been introduced ensure 100% availability of the link except during solar conjunction, and operate at a lower data rate. Only three modules and one transport rover are shown for simplicity; there would actually be 12 modules and two transport rovers.

In the cargo mission, each module is equipped with an omnidirectional 4G LTE band antenna. The transport rovers are equipped with both an omnidirectional antenna and a parabolic antenna (for communication with the communication satellite).

The crew mission architecture can be seen in Figure 8, with four levels of contingency shown as well as the nominal situation. As previously, each contingency link will operate at a lower data rates, with the exception of the link between the CIV and the Earth Ground Station which will transmit data at the same rate as from the Communication Satellite to the CIV (6.63 Mbps). The three Communication Satellites are also envisaged to transmit data between themselves at this rate.

During the crew mission, contingencies two and four are envisaged to prevent single point failures in the network and cause the crew to be unable to communicate with Earth. The only modules which use parabolic antennae are the exploration vehicle (0.5 m 4G LTE), the Outpost Control Centre (2 m Ka-band) and the CIV (0.35 m optical). All other modules have omnidirectional 4G LTE antennae, and the CIV also has an omnidirectional Ka-band antenna.

The Transport Rover and Exploration Vehicle have been included as separate elements as there are different data requirements in the crew and cargo phases, and to cover the option of using the MDV for exploration (see Section 10). However, the antennae in use are the same.

The Communication Satellites provide a key part of the communication network. They will have four antennae: a 0.35 m diameter optical antenna; a 2 m diameter parabolic a 2 m diameter parabolic Ka-band antenna; and a 3 m diameter parabolic 4G LTE antenna. As the frequency of 4G LTE is only approximately 800 MHz, from an Areostationary orbit the antenna has a footprint of over 10000 km (calculated based on [40]), which will be more than sufficient to cover the range of exploration without reorientation being required. The Communication Satellites will be solar powered, with regenerative

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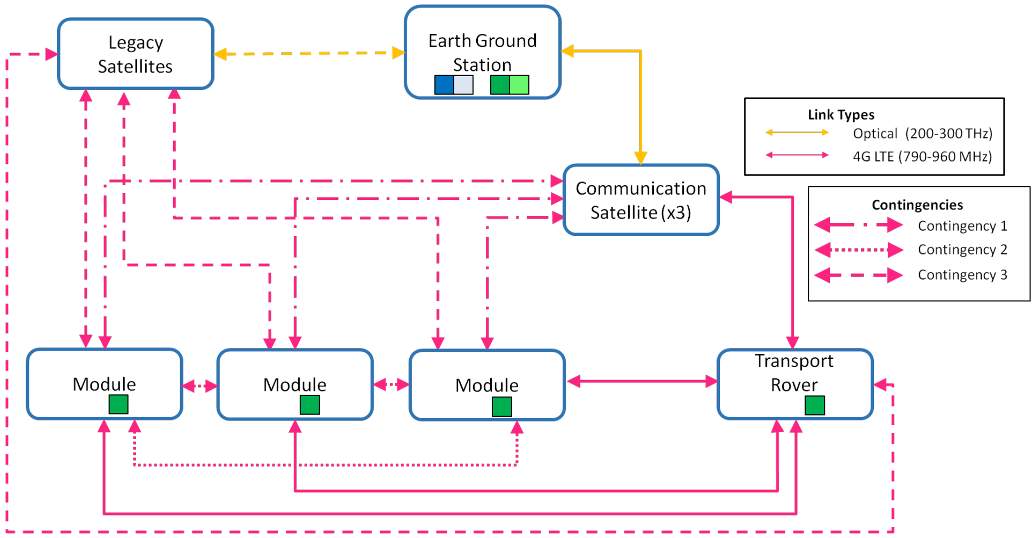


Figure 7. *Cargo mission communications architecture*

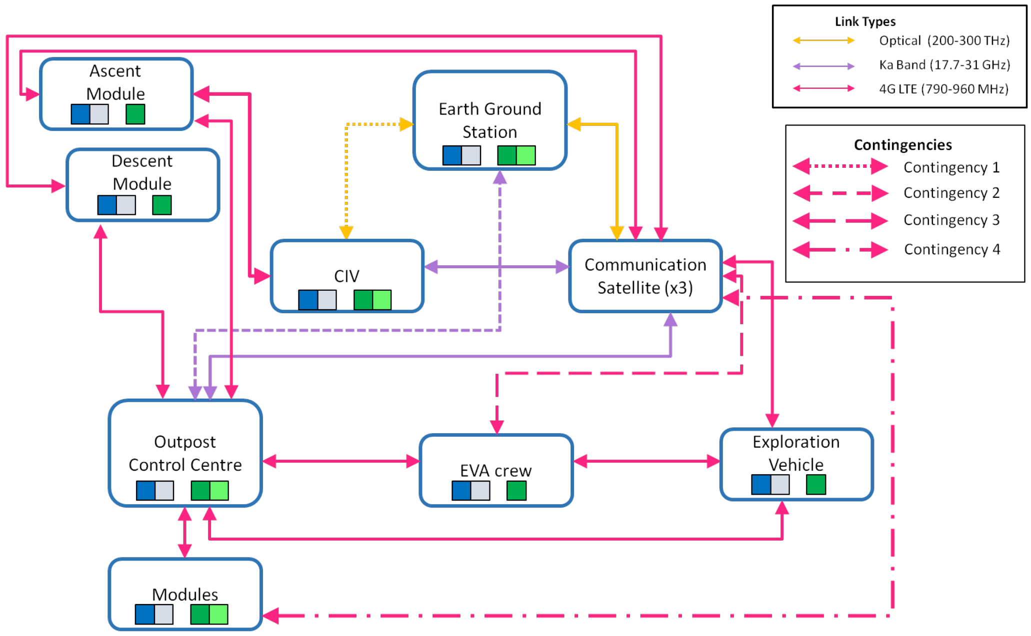


Figure 8. *Crew mission communications architecture*

fuel cells being used to provide additional power.

## 12 In-Situ Resource Utilisation

Mission MILESTONE will bring all resources necessary for the survivability of the crew for the 60 days on the Martian surface. However, due to the intention to create a long permanence outpost, it is intended to provide in-situ resource utilisation (ISRU) for a number of key resources. When the crew of Mission MILESTONE leaves Mars, the ISRU will collect all the resources that are necessary for the next mission, before the next crew depart from Earth. The physical processes used in the ISRU system are shown in Figure 7. The

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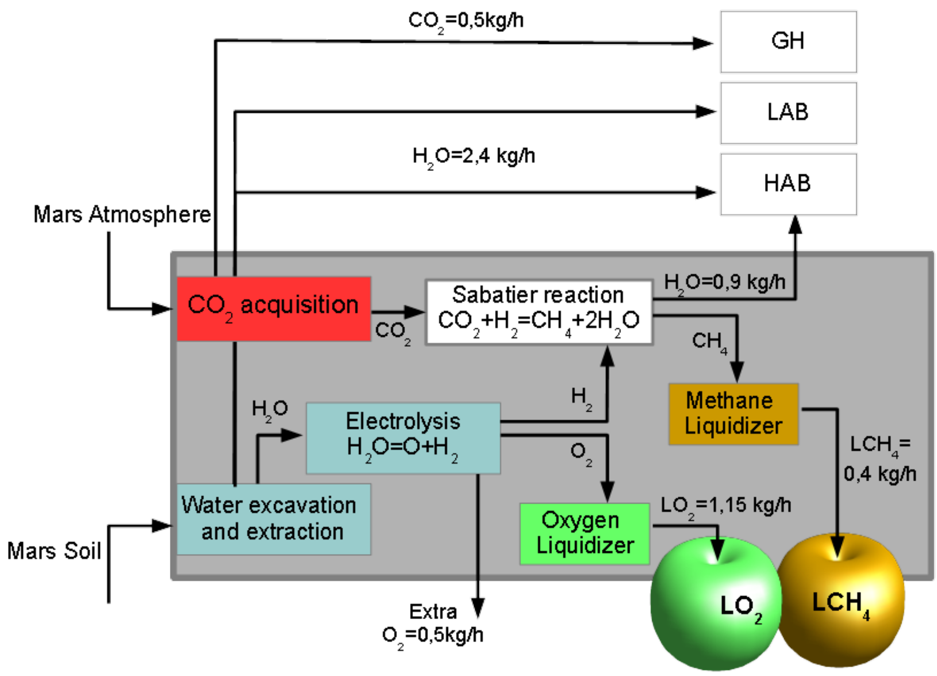


FIGURE 9. *ISRU schematic of the processes for the production of liquid oxygen and methane*

Martian soil and atmosphere are processed in order to produce the resources required, using the Sabatier reaction, electrolysis and CO2 acquisition.

The ISRU system has been sized based on the reference system discussed in Rapp, 2008 [31] . The requirements for the ISRU system have been summarised in Table 3. The requirements for the preparation of the Outpost between Mission MILESTONE and the subsequent long duration mission and the daily resupply needs for the long duration mission have been discussed. The maximum values required per hour were used to size the total system, which are those for the outpost preparation and lead to a total mass of 7.5 tons.

The system requires 60 kW of power during operation, with the largest contribution coming from the water extractor and processor. It is assumed that the system operates 24 hours a day, and that there will be 540 days between the end of Mission MILESTONE and the start of the next mission.

## 13 Ascent

A Martian Ascent Vehicle will be used to return the crew from the Martian surface to the orbiting Crew Interplanetary Vehicle. It is sized to return all 6 crew members and a supply of Martian samples. The vehicle has life support for 3 days and uses a dedicated EVA module for crew entry and exit. The EVA module will remain on the surface.

The Mars Ascent Vehicle will use 5 liquid methane/liquid oxygen burning engines comparable in design to the hydorgen burning RL-10 engines. The engines will exert 350 kN of thrust to launch the MAV which is then throttled to 150 kN to pitch the vehicle over so that it has no radial velocity from the surface of Mars. At this point a series of Hohmann transfers are initiated to bring the MAV to rendezvous with the CIV. The MAV will be shipped as part of the cargo mission, fully fueled with the propellant stored in cryocooler tanks.

The MAV will have two available launch windows a sol if the CIV performs station keeping and the MAV first launches to a 200 km parking orbit. The vehicle will autonomously dock with the CIV and the ascent vehicle will be discarded in a graveyard orbit.

The MAV total wet mass is 26 tonnes with 19 tonnes of propellant, calculated from the manoeuvers required, a capsule of 4.6tonnes, sized from a NASA parametric

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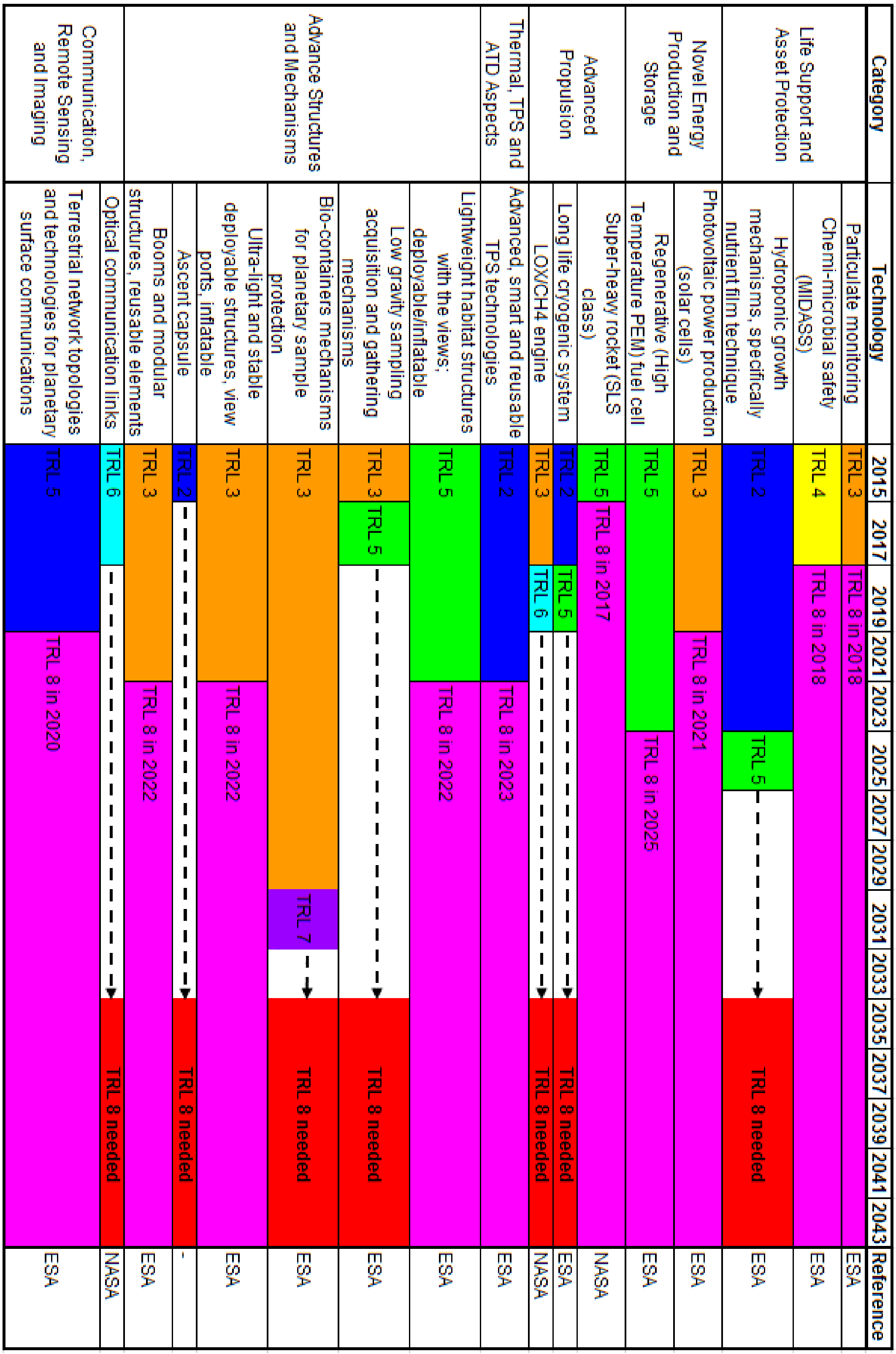


**Figure 10.** *Mission critical technologies TRL roadmap*

| Technology | Description / Capability Performance Goal | Current TRL | Final TRL | Maturation Time [Years] | Reference Agency |
|---|---|---|---|---|---|
| Water recycling system | Recycling of grey water and urine, with the possibility of also combining the water from the waste management. High efficiency and low maintenance desired. | 3 | 5 | 5 | ESA |

Table 2. *An example of an enhancing technology for Mission MILESTONE*

| Activity | | $H_2O$ [kg] | $CH_4$ [kg] | $CO_2$ [kg] | $O_2$ [kg] | $N_2$ [kg] |
|---|---|---|---|---|---|---|
| **Outpost Preparation** | Total Requirement | 42766 | 5361 | _ | 14950 | 93 |
| | Requirement per Hour | 3.3 | 0.4 | _ | 1.15 | 0.007 |
| **Daily Re-Supply** | Requirement per Hour | 3.23 | 0 | 0.2 | _ | 0.007 |

Table 3. *ISRU resource requirements*

model [25] and the remainder being the rocket engines and associated structures.

## 14 Technology Output and Roadmap

For Mission MILESTONE, a number of technologies that are required for the mission, but which are not yet fully developed have been identified. The maturity of a technology is stated by the technology readiness level, and for Mission MILESTONE, the technology readiness level for systems and sub-systems needs to be at least *TRL 8*.

As a result a number of technologies that need to be matured before the launch for Mission MILESTONE have been categorised into *mission enhancing*, *mission enabling* and *mission critical technologies*. However, it has not been determined how the technologies could be matured or whether it would be possible in the time-frame specified; they are simply presented as criteria that must be met for the mission to be possible. The current timeline for maturing technologies was identified using the *ESA Exploration Technologies Roadmaps 2015* [14] and the *2015 NASA Technology Roadmaps* [28]. Example technologies are given here; a complete list is available on request from the authors.

Mission enhancing technologies are classed as such if it would enhance the efficiency of the mission but do not determine the feasibility of Mission MILESTONE. An example of an enhancing technology is shown in Table 2. The column "Maturation Time" refers to the *Minimum Time to Mature Technology*, and is defined based on information given in the roadmaps.

Mission enabling technologies are classed as such if a future 500 day missions would not be feasible without. Examples of enabling technologies are shown in Table 4.

The mission critical technologies were also identified, and can be seen in Figure 10. Technologies are classed as mission critical if the 60 day surface stay of Mission MILESTONE would not be feasible without them.

As can be seen in Figure 10, there are several technologies that could not be identified in the *ESA Exploration Tehcnologies Roadmaps 2015* but could be found in the 2015 NASA Technology Roadmap. However, particular attention should be paid to the need for an ascent capsule as shown in Figure 10. The complete unit of an ascent capsule was not found in either the ESA Exploration Technologies Roadmaps 2015 [14] or the 2015 NASA Technology Roadmap [28].

## 15 Conclusions

Mission MILESTONE will be a short duration mission to the surface of Mars, landing a crew of six humans on the Martian surface in order to establish a long-term outpost for future exploration. The mission will take the

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| Technology | Description / Capability Performance Goal | Current TRL | Final TRL | Maturation Time [Years] | Reference Agency |
|---|---|---|---|---|---|
| Advanced shielding structures (radiation, meteoroids, dust) | Pressurized structure designs with integrated micro-meteoroid orbital debris, radiation, and permeability protection, electrical harnessing, thermal control, and sensor subsystems. | 3 | 8 | 7 | ESA |

**Table 4.** *An example of an enabling technology for Mission MILESTONE*

form of a split mission, with the cargo being launched in 2039 and 2041. The cargo mission will deliver 14 modules to the Martian surface and three communication satellites to Areostationary Orbit.

The crew mission will follow in 2042, once the modules have been successfully assembled at Amazonis Planitia, allowing a 60-day period of human surface operations and exploration.

The outpost established is intended to allow future long-duration exploration, with an aim to reducing the dependence on Earth for resources. The presence of a greenhouse and an ISRU plant will provide food, water and oxygen which are crucial to human survival.

The scientific operations taking place in Mission MILESTONE are led by four key science objectives: studying the physiological and psychological impact of a Mars surface mission; performing in-situ investigations into the Martian environment to support future exploration; collecting data to support the identification of resources for future human missions; and studying the origins and evolution of Mars. The science objectives defined the scientific architecture of the mission, in particular introducing a number of static landers to allow for scientific operations over a larger portion of the Martian surface, and a number of probes to better analyse the atmosphere in order to verify the entry, descent and landing process.

In order for Mission MILESTONE to be feasible, a number of technologies identified must be matured, with a particular focus on the mission critical technologies. However, given sufficient investment and resources, Mission MILESTONE could be a robust and important step in human space exploration.

## References

[1] S. Agostinelli et al. Geant4 - a simulation toolkit. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 506, 2003.

[2] R. M. Ambrosi et al. X-Ray and Gamma Ray Spectrometers for the Heat Flow and Physical Properties Instrument (HP3) on the ExoMars Geophysical and Environmental Package. In *Fourth International Planetary Probe Workshop*, 2006.

[3] C. R. X. Amendola and others. Orpheus: Executive Summary. Technical report, SEEDS 2014, 2014.

[4] M. S. Anderson et al. Life Support Baseline Values and Assumptions Document. Technical Report NASA/TP-2015-218570, NASA, 2015.

[5] A. J. Ball, J. R. C. Garry, R. D. Lorenz, et al. *Planetary Landers and Entry Probes*. Cambridge University Press, 2007.

[6] W. B. Banerdt and W. T. Pike. A Minuturized Seismometer For Subsurface Probing On Mars. In *Conference on the Geophysical Detection of Subsurface Water on Mars*, 2001.

[7] Y. Bar-Cohen and K. Zacny. *Drilling in Extreme Environments*. WILEY-VCH Verlag GmbH & Co, 2009.

[8] M. Berte and B. Capell. Engineering Design Aspects of the Heatpipe Power System. In *Space Technologies and Applications International Forum*. The American Institute of Physics, 1998.

DOI: 10.5281/zenodo.202213 

[9] H. Broomfield. Small Reactor Power Systems for Manned Planetary Bases. Technical Report NASA-TM-100223, National Aeronautics and Space Administration, 1987.

[10] Canadian Space Agency. Meteorological Station - Lidar. https://goo.gl/nZBgM1, July 2008.

[11] D. L. Carter. Status of the Regenerative ECLSS Water Recovery System. Technical Report 2009-01-2352, NASA, Marshall Space Flight Center, 2009.

[12] L. Casalino, G. Colasurdo, and D. Pastone. Mission Opportunities for the Human Exploration of Mars. *Planetary and Space Science*, 46, 1998.

[13] A. J. Coates et al. PanCam on the ExoMars 2018 Rover: A Stereo, Multispectral and High-Resolution Camera System to Investigate the Surface of Mars. In *46th Lunar and Planetary Science Conference*, 2015.

[14] ESA. ESA Exploration Technologies Roadmaps, 2015.

[15] ESA - Operated by Belgian Institute for Space Aeronomy. SPENVIS - Space Environment, Effects and Education System. https://goo.gl/AF8Cdo.

[16] E. R. Fuller and J. W. Head III. Amazonis Planitia: The role of geologically recent volcanism and sedimentation in the formation of the smoothest plains on Mars. *Journal of Geophysical Research*, 10, 2002.

[17] J. Gómez-Elvira et al. REMS: The Environmental Sensor Suite for the Mars Science Laboratory Rover. *Space Science Reviews*, 170, 2012.

[18] S. P. Gorevan et al. Rock Abrasion Tool: Mars Exploration Rover Mission. *Journal of Geophysical Research*, 108, 2003.

[19] D. M. Hassler et al. The Radiation Assessment Detector (RAD) on the Mars Science Laboratory (MSL). In *40th Lunar and Planetary Science Conference*, 2009.

[20] D. M. Hassler et al. Mars' Surface Radiation Environment Measured with the Mars Science Laboratory's Curiosity Rover. *Science*, 343, 2014.

[21] Honeywell International Inc. *Smart Digital Magnetometer HMR2300 Data Sheet*, 2006.

[22] O. Jäkel. Radiation hazard during a manned mission to Mars. *Zeitschrift für Medinizische Physik*, 14, 2004.

[23] G. Klingelhöfer et al. The Rosetta Alpha Particle X-Ray Spectrometer (APXS). *Space Science Reviews*, 128, 2007.

[24] A. S. Kozyrev et al. The Mercury Gamma-Ray and Neutron Spectrometer (MGNS) for the ESA BepiColombo Mission. In *Lunar and Planetary Science XXXVII*, 2006.

[25] NASA. Mass Estimating & Forecasting for Aerospace Vehicles. Technical report, National Aeronautics and Space Administration, 1994.

[26] NASA. Advanced Life Support Program - Requirements Definition and Design Considerations. https://goo.gl/jvQvm, December 1996.

[27] NASA. Space Launch System Program Mission Planner's Guide Executive Overview. Technical Report SLS-MNL-201, National Aeronautics and Space Administration, 2014.

[28] NASA. Nasa Technology Roadmaps, 2015.

[29] NASA. The Mars Orbiter Laser Altimeter (MOLA). https://goo.gl/Q8tK7b, August 2015.

[30] NASA. The Topography of Mars by The Mars Orbiter Laser Altimeter (MOLA), 2015.

[31] D. Rapp. *Human Missions to Mars - Enabling Technologies for Exploring the Red Planet*. Springer-Verlag Berlin Heidelberg, 2008.

[32] F. Rull et al. The Raman Laser Spectrometer (RLS) on the ExoMars 2018 Rover Mission. In *42nd Lunar and Planetary Science Conference*, 2011.

[33] G. Santin. Space and Planetary Environment, Planetary Surfaces: Radiation Transport Modelling Workshop. University of Leicester, 2015.

[34] Selex-ES. ExoMars Drill System. https://goo.gl/95OPhv, August 2015.

[35] M. S. Skidmore, R. M. Ambrosi, and H. Simon. Hybrid X-ray and gamma-ray spectrometer for in-situ planetary science missions. *Nuclear Instruments and Methods in Physics Research A*, 604, 2009.

 DOI: 10.5281/zenodo.202213

[36] D. Slade. Issue 04: NFT Culture. *Practical Hydroponics and Greenhouses*, 1992.

[37] Space X. Falcon Heavy Technical Overview. https://goo.gl/HvyaA1, September 2015.

[38] J. W. Thomas. Space Based Fires & Suppression Systems, April 2013.

[39] University of Arizona. Data from 2001 Mars Odyssey Gamma Ray Spectrometer. https://goo.gl/ZQdvqO, August 2015.

[40] University of Hawaii Department of Physics and Astronomy. Antenna Introduction/Basics. https://goo.gl/YCBOfG, 2015.

[41] R. C. Weins et al. The ChemCam Instrument Suite on the Mars Science Laboratory (MSL) Rover: Body Unit and Combined Systems Tests. *Space Science Reviews*, 170, 2012.

[42] R. M. Wheeler et al. Crop productivities and radiation use efficiencies for bioregenerative life support. *Advances in Space Research*, 41, 2008.

[43] P. O. Wieland. Designing For Human Presence in Space: An Introduction to Environmental Control and Life Support Systems (ECLSS). Technical Report NASA/TM-2005-214007, NASA, Marshall Space Flight Center, 2005.

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# An ISRU-Based Architecture for Human Habitats on Mars: the 'Lava Hive' Concept

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**Abstract.** We detail the overall structural architecture for a Class III Mars habitat intended for human exploration missions, constructed utilizing a robust and simple *in-situ* resource utilization (ISRU) approach we have termed 'lava casting'. The habitat concept is based on a hybrid approach, with structural elements of a central habitat arriving from Earth conventionally, while an additive manufacturing (AM) process is used *in-situ* to expand the central habitat workspace using locally sourced construction material, namely Martian regolith soil and sand. The construction process is outlined, with the advantages of our approach elucidated in terms of flexibility, achievability and the ability to provide important protection to surface assets and explorers from the Martian radiation and thermal environment.

## 1 Introduction

The use of *in-situ* building materials will become increasingly critical as human exploration activities progress beyond low Earth orbit once again, with likely destinations including the Moon and Mars [18, 10]. As human presence on these bodies is expected to follow robotic precursor missions, so must we develop new approaches to structures to accommodate them such as habitats, radiation shelters, laboratory space, greenhouses, etc. It is well understood that the use of *in-situ* resources can significantly offset required launch mass requirements and potentially provide for greater mission sustainability and new capabilities [2, 23], but the use of ISRU represents a paradigm change in mission architecture that has yet to be fully embraced or indeed demonstrated reliably outside of small field test campaigns.

Initial development of ISRU technology has focused heavily on O2 production because it is a substantial constituent of the minerals in both Lunar and Martian regoliths, and it has been shown that a hydrogen reduction process can be used to release it [2, 13]. Upon examination of the regolith composition and atmosphere of Mars, it becomes apparent that there are many resources there that could be exploited to make exploration missions sustainable and affordable. Looking beyond the astronaut's life support, the concept of using local resources for construction processes is equally desirable, with recent work in the domain of 3D printing on the Lunar surface gaining particular attention [4].

Throughout these technologies, however, there runs a streak of design complexity, whether in the chemistry

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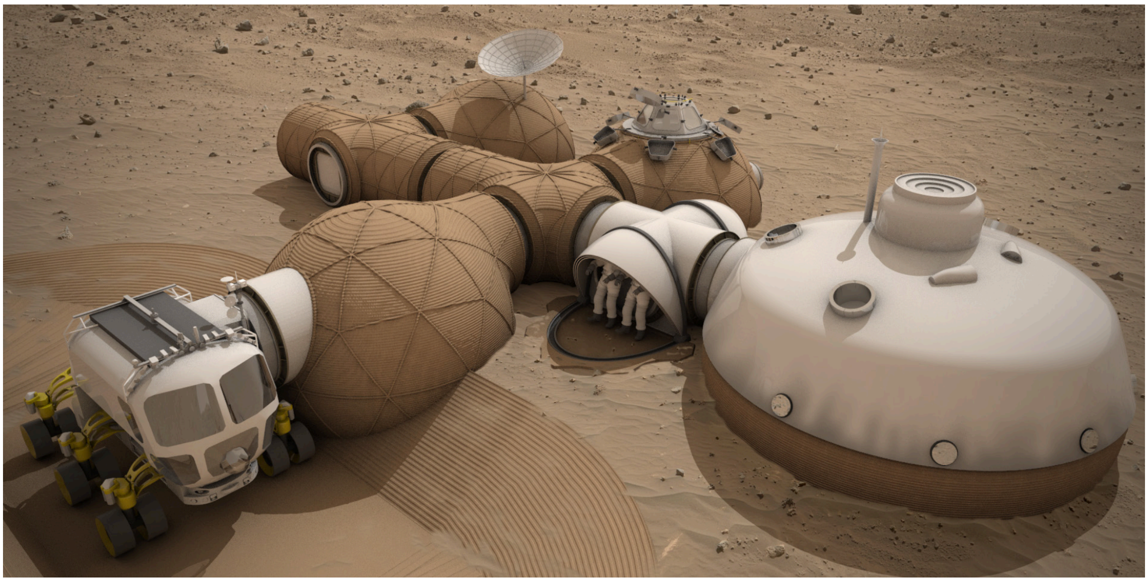

**Figure 1.** *Render of the Lava Hive concept in its linear configuration. Clearly observable is the central habitat core, with the smaller ancillary 3D printed satellite structures clustered surrounding it. Visualization: René Waclavicek, LSG, 2015*

used to release gas/mineral resources or the engineering concepts needed to access them. In many cases, such concepts require significant development with regards their technology readiness level (TRL), to the point as to exclude them from serious consideration among conservative mission plans in the near or medium term. Exploration demands an expectation of encountering the unknown, but this does not preclude a solid engineering approach to be taken based on best known science as well as a solid design principle such as 'keep it simple and straightforward (KISS)'. With this view, construction processes and technologies can act as simpler *ab initio* validators for ISRU.

In this paper we discuss the concept for our ISRU enabled Mars habitat, which we have named 'Lava Hive', and how our approach provides a potentially robust and simple approach to producing structures on Mars.

## 2 The Lava Hive Concept

Lava Hive is a modular additive manufactured Martian habitat concept using a proposed novel 'lava-casting' construction technique, utilizing recycled spacecraft materials and structures, and represents a Class III ISRU derived structure as defined by NASA [5]. The impetus for this work was our response to the NASA Centennial Challenge, calling for approaches to 3D-Printing a Mars Habitat, which was run in 2015 [19]. Key design requirements for this competition were to address ISRU and 3D printing combined, re-use or recycling of existent spacecraft structures, mission concept and overall architectural quality. This concept was awarded third place in September 2015.

Our proposed habitat concept has a number of key design elements:

- 'Re-use' of commonly discarded entry-descent-landing (EDL) systems, the reentry back plate, as part of the central habitat section, providing the housing for mission critical mission elements and personnel
- 3D printed satellite structures feeding off from the main central habitat, with configurable orientations to suit the mission requirements
- Unique use of regolith sintering combined with the novel 'Lava Cast' methodology to produce solid basalt structures for enhanced protection from the Martian radiation and thermal environment

An architectural interpretation of our concept can be seen in the Figure 1. A primary central dome, housing crew areas and mission critical systems such as life support, is connected to a number of smaller ancillary dome

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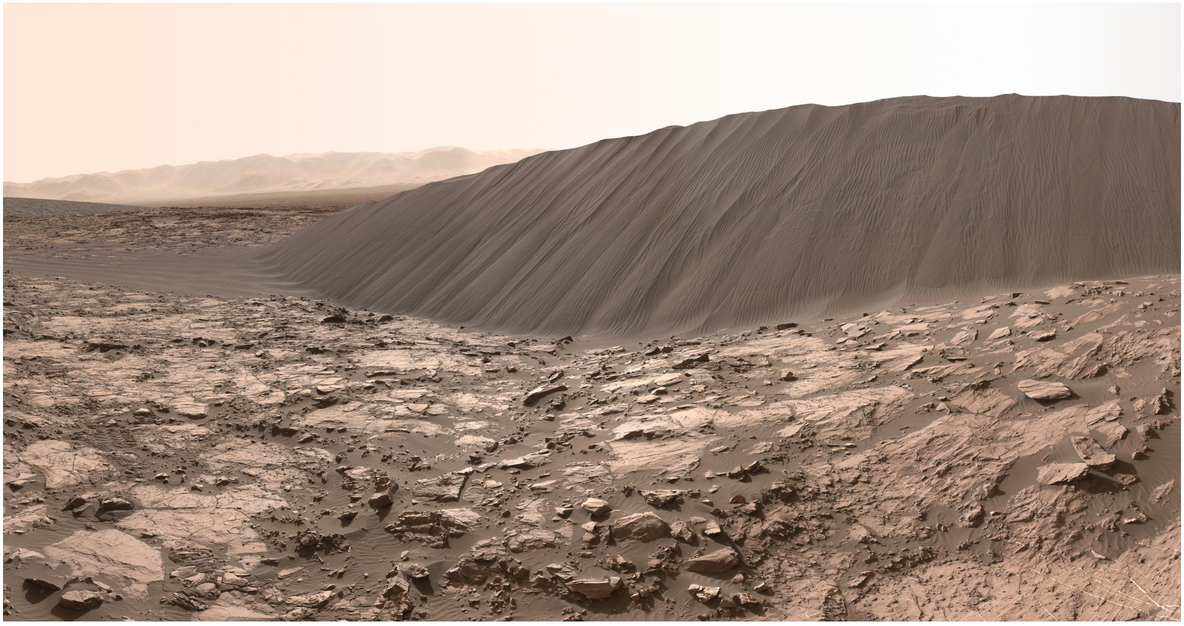

**Figure 2.** *The Namib dune periphery, visited by NASA Curiosity rover in January 2016, illustrating the ease of availability of well understood construction resources.*

structures. This central element will be brought from Earth and forms the core of the habitat. The smaller domes, connected via 3D printed passageways to the central dome, house laboratories, workspaces, garage airlock and other required mission specific areas. Our understanding and examination of state of the art technologies led us to develop a concept and fabrication approach that would erect freestanding 3D printed structures using direct energy input to Martian regolith and sand material as shown in figure 2. We purposely avoid the use of any binders or additive materials, as we consider the down mass requirement to Mars prohibitive and many aspects, such as thermal cycling, unproven for these approaches [15, 14]. A combination of sintering and melting of Martian regolith and sand emerged as our process of choice.

Architecturally, our inspiration was driven by beehive huts (Clochán) of the Irish monastic sites and by the traditional South Italian's "Trulli", Apulia's domed houses with prehistoric origins built using the abundant stone materials from the surrounding land, a true example of ISRU on Earth. In order to render the interiors of these houses hygienic and clean, a plaster made of reddish clay soil and pieces of straw mixed with slaked lime was used, similar to our proposed use of epoxy for sealing the inside of our 3D printed structures.

### 2.1 Mission Concept

On arrival to the Mars orbit, the spacecraft will detach the EDL payload containing the two surface rovers and the central habitat section. The payload will descend and land within range of the preferred site via standard parachute. Two utility rovers will also be included in this payload, which will be used for the 3D construction process to follow.

When the re-entry capsule (Fig. 3) comes to rest on site, the underside inflatable habitat will deploy, as seen in Fig. 4. This forms the nexus for the development of the other desired 3D printed structures. While it is tempting to construct the main habitat in a similar way as the ancillary 3D printed satellite domes, we assume that a terrestrially provided solution has a lower risk overall and offers a number of advantages, such as assured structural integrity as well as housing essential subsystems like environmental control and life support (ECLSS) as well as providing a reliably sealed environment. It can also act as the initial habitat for astronauts as the construction work is carried out, as opposed to remaining in orbit.

The back-shell from the EDL heat shield will be recycled as the roof of this central habitat, to reinforce and protect the inflatable structure that deploys under-

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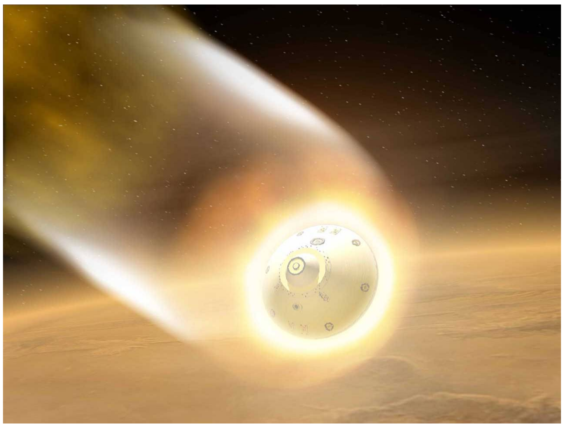

**Figure 3.** *Mars Exploration Rover aeroshell (artistic rendition [20])*

neath from hazards such as micrometeorites and radiation. Landing within range of our targeted site, the tele-operated utility rovers will be utilized to begin the preparation of the area for the expansion of the base.

## 2.2 Martian ISRU Construction Material

The surface of Mars yields a number of potential construction resources that can be readily accessed, chiefly among them is the regolith and sand. Sand dunes are among the most widespread Aeolian features present on the surface, manifesting readily as large fields or within sheltered crater impact sites. In addition to the loose surface regolith, they represent an excellent building construction material consisting of a narrow range of well-sorted, unconsolidated particles mostly comprised of pyroxene, olivine and basaltic sands.

The material within these Aeolian dunes and beds are well understood in terms of their particle size distributions from thermal inertia measurements ($500 \pm 100$ $\mu m$, medium to coarse sand [8]), as well as from terrestrial numerical and empirical modeling of their morphology [21]. The particle size and characteristics are an important consideration for understanding the dynamics of any sintering process that would be employed, and we can thus empirically validate our process with simulants found terrestrially.

The utility rovers deployed will identify and collect from the loose regolith or sand from dunes present in craters, natural beds or depressions. Transporting these to the base site, the utility rover, capable of a sintering process, will begin the production of the foundations for the smaller habitat sections.

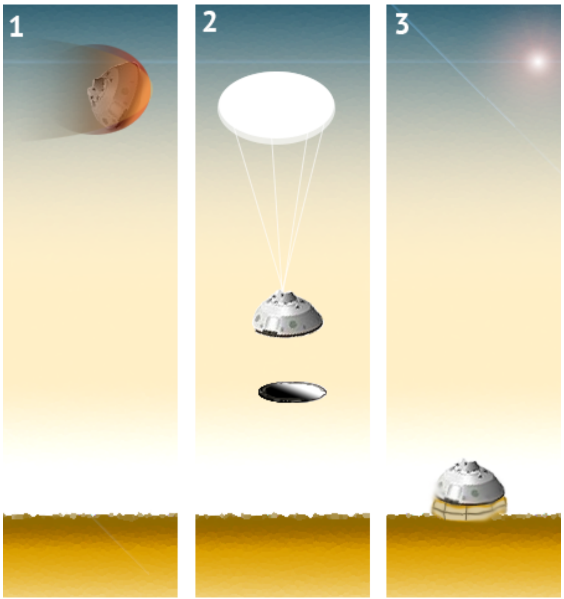


**Figure 4.** *Illustration of main habitat deployment below the back shell*

## 2.3 Fabrication via Lava Casting and Thermal Sintering

Our AM inspired fabrication process uses two distinct methods to produce a final structure. The lava-casting fabrication process is inspired by naturally occurring terrestrial processes and its feasibility has been confirmed by small-scale demonstration projects terrestrially [9]. The second process, thermal sintering, involves using heat and/or pressure to fuse fine particles and it is a well defined material process, even being demonstrated to be effective with planetary regoliths [1]. The two techniques would be used in tandem, with the sinter process producing flow channels for the lava cast technique – essentially a guide path for the basalt liquid melt 5.

Sintering of the flow channel for the Lava Cast technique would likely best be achieved via a thermal sintering approach, with a strong candidate being a laser sinter system [17, 11]. In addition to creating the flow channels, this multi-functional sinter rover would also provide a basic leveling and preparation of the foundation via sintering. Upon this foundation, the 3D printed structure would be built layer by layer.

When one cast layer has cooled, the rover begins the layering of more regolith/sand and a new channel is sin-


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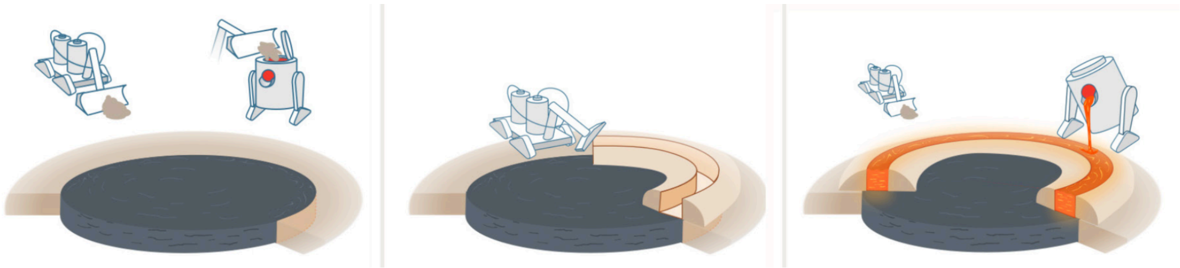

Figure 5. *Illustration of the flow channel construction process, whereby the utility rover produces a controlled path within which the lava melt can flow and be constrained.*

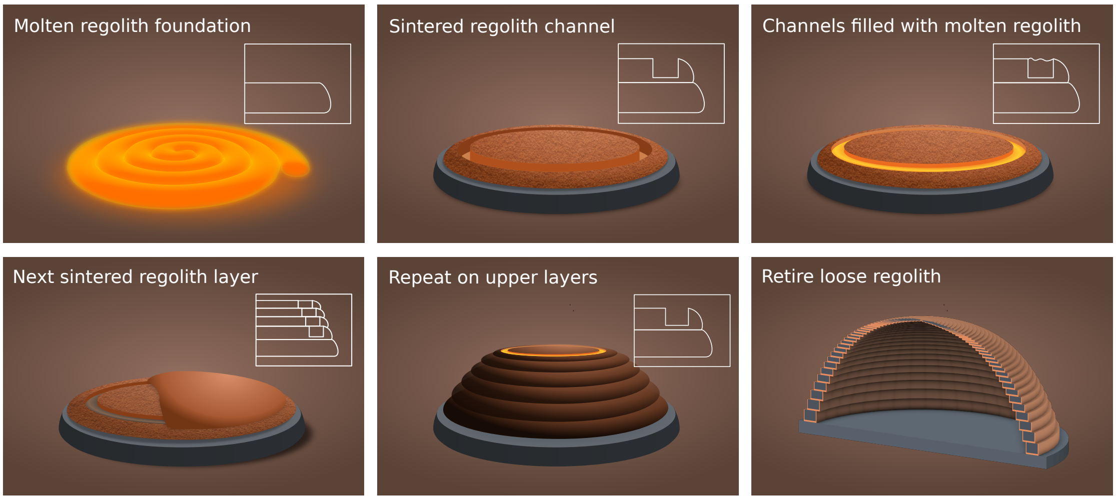


Figure 6. *Stepwise illustration of the lava casting process to produce a hemispherical shape habitat section (inset represents cross section of the process): (1) deposition of foundation base, (2) regolith is gathered and sintered to produce a flow channel, (3) molten basalt from the sand/regolith is poured into the channel and allowed to solidify, (4) the next layer of regolith is spread across, and another channel sintered, (5) layer by layer the structure is constructed, (6) loose, un-sintered regolith is excavated from the structure, revealing the completed dome.*

tered on top. This process is repeated until the dome is complete. The sintering of a channel for the lava to flow into also provides an element of control to the overall process, as it is well known that the underlying layer onto which lava flows influences the properties and final morphology [9]. The presintering of the channel would also likely reduce outgassing events during the lava pour, which could affect the porosity of the basaltic lava. Heating and control of the lava itself, while it may seem difficult, is relatively easy to achieve – lava is highly viscous yet can readily flow long distances before cooling owing to its thixotropy and shear thinning characteristics [3]. A full schematic of the fabrication process can be seen in Fig. 6.

It is envisaged that astronauts will then perform final operations either autonomously/tele-robotically from Mars orbit or from the surface (e.g. from the central habitat), installing mission elements brought from orbit (such as airlocks, internal fittings, etc). Once structurally complete, the sub-habitats will then be hermetically sealed by spraying a sealing epoxy coating on the inside surfaces of the 3D printed sections, forming a sealed environment with the main habitat.

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## 3 Advantages of Lava Casting Approach

A number of advantages are realized by utilizing this casting approach and the final basaltic rock building elements. Firstly, as a building material in terms of structural strength, it is superior to thermally induced sintered material [1]. The thermal inertia of the regolith is a key parameter that drives the surface-atmosphere exchange processes [22]. The thermal inertia is defined as $I = \sqrt{\rho \cdot c \cdot \kappa}$, being $\rho$ the density, $c$ the heat capacity and $\kappa$ the thermal conductivity. Compared to dust and sand, Martian rocks present a higher thermal inertia due to their higher $\kappa$ conductivity and density. Figure 7 compares the influence of the thermal inertia on the surface temperature on Mars. It can be seen that because of the high inertia of the Martian rocks (around 1500-1700 $\frac{J}{m^2 \cdot K \cdot s^{0.5}}$), the temperature swing experienced between day and night within such material would be much more moderate than in the case of sand, having a much lower thermal inertia (around 300 $\frac{J}{m^2 \cdot K \cdot s^{0.5}}$).

The higher density of the basaltic lava would have

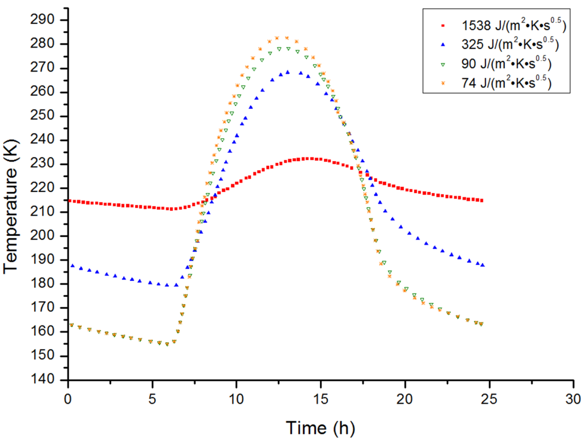


**Figure 7.** *Surface temperature profile of dust (low thermal inertia), sandy and rocky surfaces (high thermal inertia) on Mars, results based on the equations presented by Paton, M. et al. [22]*

considerable benefits in terms of providing radiation shielding on the surface environment, from galactic cosmic rays (GCR) and solar proton events (SPE). The permeability of basalt stone [24] is also superior to that of a sintered process, which is an important consideration for forming a hermetic seal. Studies of GCR penetration into Martian regolith have been numerically studied, with peak dose found to be 40 $cm$ within the regolith (density of 1.6 $\frac{g}{cm^3}$) and attenuation to 2% initial dose 5 $m$ subsurface [16]. The basaltic lava rock would have a higher density ($\sim 3.3 \frac{g}{cm^3}$) and would be a stronger candidate for radiation protection then loose regolith alone. The inner polyethelyne ($CH_2$) based sealing epoxy can also act as an additional radiation attenuator [12], where the hydrogen-rich nature of this material make it suitable for passive radiation shielding. The accurate GCR and SPE dose modeling of the basaltic layer and epoxy sealant is continuing work at this time.

## 4 Overall Layout Design Considerations

At a building scale, the 3D printed approach of this concept allows for a great deal of extensibility. Figure 8 below shows how the ancillary hive areas can be arranged in a linear manner, however the interconnections could be arranged in a web or ring configuration also depending on the mission scenario or local surface topography. In Figure 8, different layout configuration options ranging from "star", to "ring star", only "ring" and "linear" can be compared. The "star" option can expand on limited area and has drawbacks from a circulation point of view. There would need to be many habitation volumes, not just connecting tunnels, which serve as circulation space. The modules need to have numerous doors to the other modules, necessitating such structures being brought as payload. The efficient use of interior space is thus limited. The "ring" configuration uses necessary circulation space more efficiently; only two connection doors are necessary. However, the layout of the modules requires a circulation path right through the module and this space functions are limited and may only be used as public zones. The linear configuration allows a module to only have one exit and entrance, which might pose a safety concern in case of an emergency such as fire. This linear layout allows different functions and spaces such as a greenhouse and a laboratory to be used efficiently since there is no circulation path leading through this module. Each module is essentially self-contained and if malfunctioning, can be disconnected and does not disturb the functioning of the other modules or hinder the crew to reach other modules.

## 5 Habitat Design Considerations

The central habitat section (see Figs. 9 and 10) is housed under the re-used back shell and is an inflatable structure. Attached to this central section is an airlock node,

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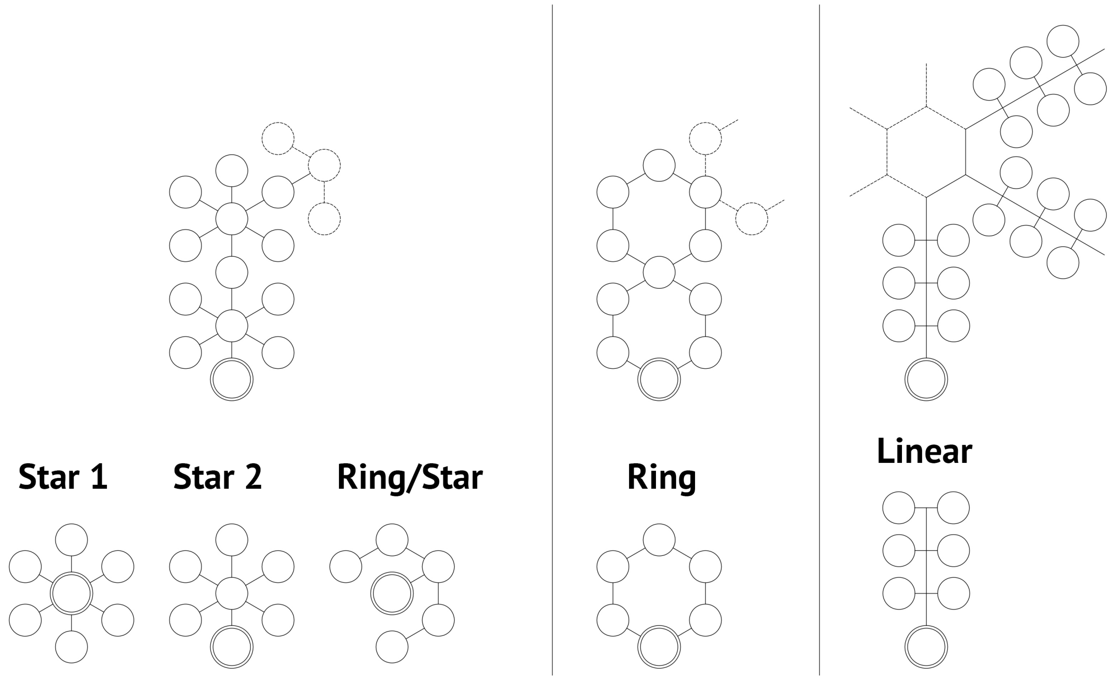


**Figure 8.** *Overall configuration options ranging from circular to linear extension possibilities. Visualization: René Waclavicek, LSG, 2015*

which then interfaces with the 3D printed ancillary structures. The airlock or suitport node allows for the capability to egress and ingress the habitat.

If mission planners will decide on a conventional airlock or on suitports is still open, the most likely scenario is to have both options. The suitport as the nominal way of stepping onto the Martian surface preventing cross contamination and an airlock in case of an emergency, e.g. should an injured astronaut need to be recovered and brought into the habitat and cannot step backwards from the suit through the port into the habitat.

The core habitation zone, depicted in Figure 9 and 10, houses private crew quarters for a nominal size of a four person crew. These offer a bed, a desk and some storage accommodation. The infrastructure parts such as the hygiene facility and the galley are in the centre of the module separating the private zone from the public area including a main installation shaft connected to the ECLSS which are located under the backshell roof. The habitation module can serve as a minimal base for the first crew.

Essential are the suitports and the workshop where a pressurized rover can be docked. The workshop can also be used as a multi-purpose space, where goods, spare parts can be stored or other activities can be performed. Since the floor is lower than in the other modules, the ceiling is higher and thus this part offers more volume.

Some of the interior might be deployable and being stowed under the backshell. Some of the interior for the laboratory (Fig. 12), or the greenhouse could be transported from the lander to the modules with a pressurized rover and installed using the docking port to reach the interior of the base.

It will become an important issue in the preparation of such missions to find efficient ways of packing and deploying interiors, even transforming some parts from other missions into usable gear. One could think of "transformers" which have different purposes, being used in a different function before becoming interior installations.

Imperative for the survival of humankind on Mars is also a greenhouse (Fig. 11). Although the size of the greenhouse envisioned for this concept is probably too small, exact growth areas are still to be determined by experts working on this topic – we need to develop robust nutrition capabilities before we can stay on Mars for longer periods.

Crucial to the crew apart from food is also sensible

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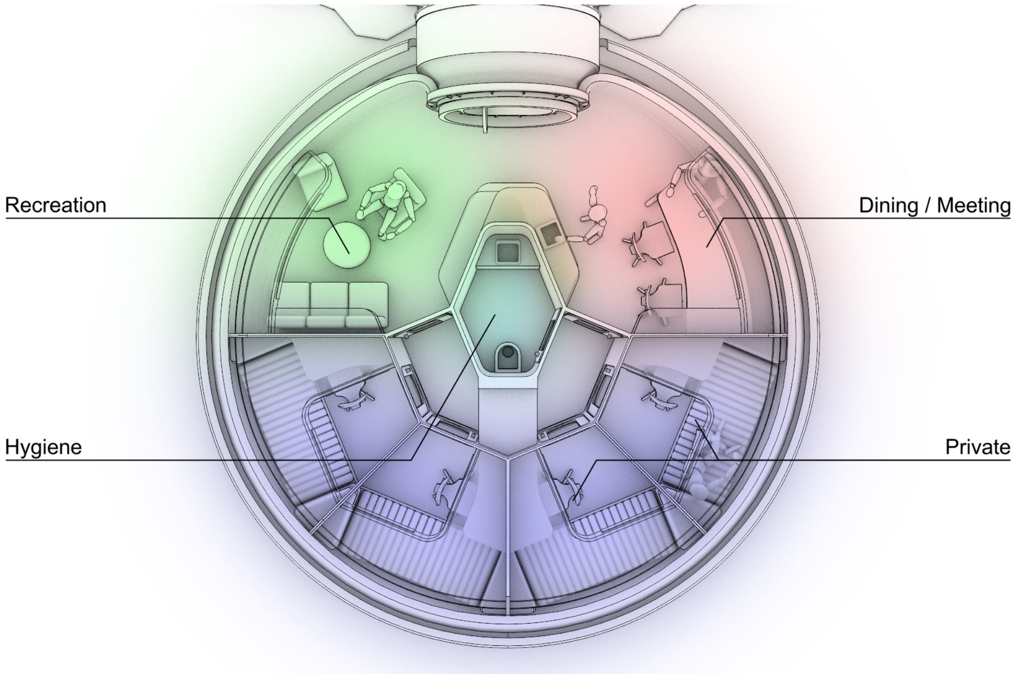


**Figure 9.** *Habitation module. Visualization: René Waclavicek, LSG, 2015*

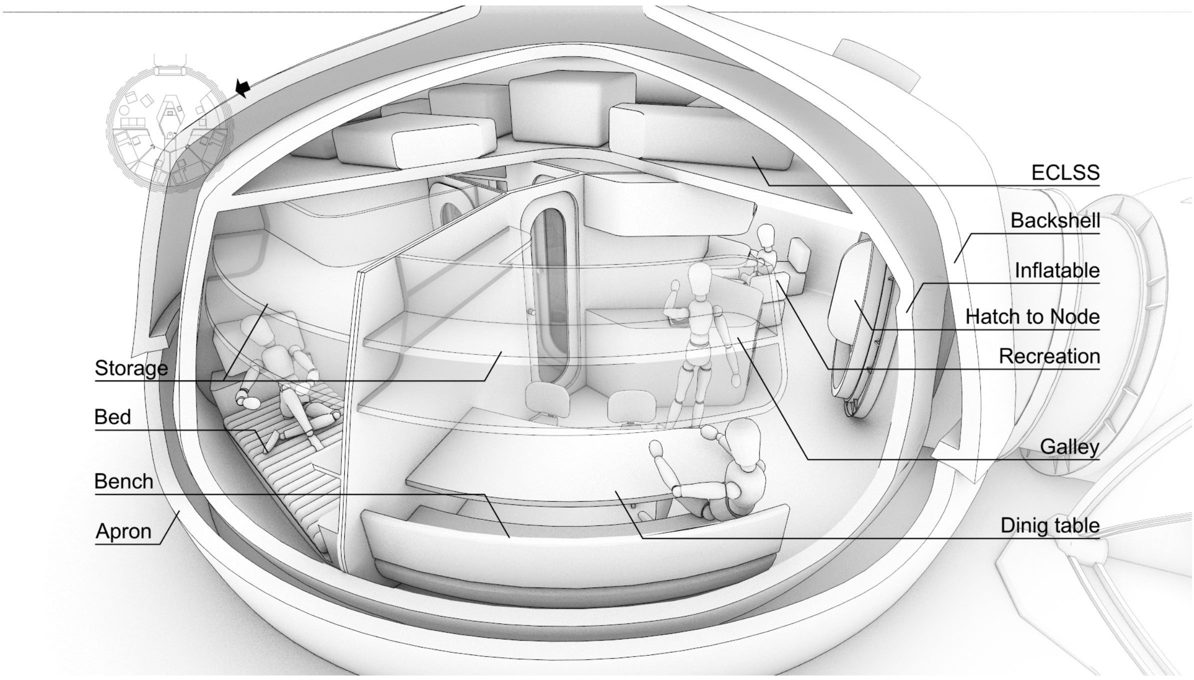


**Figure 10.** *Interior cutaway showing the living area and on the left a view into a crewquarter. Visualization: René Waclavicek, LSG, 2015*

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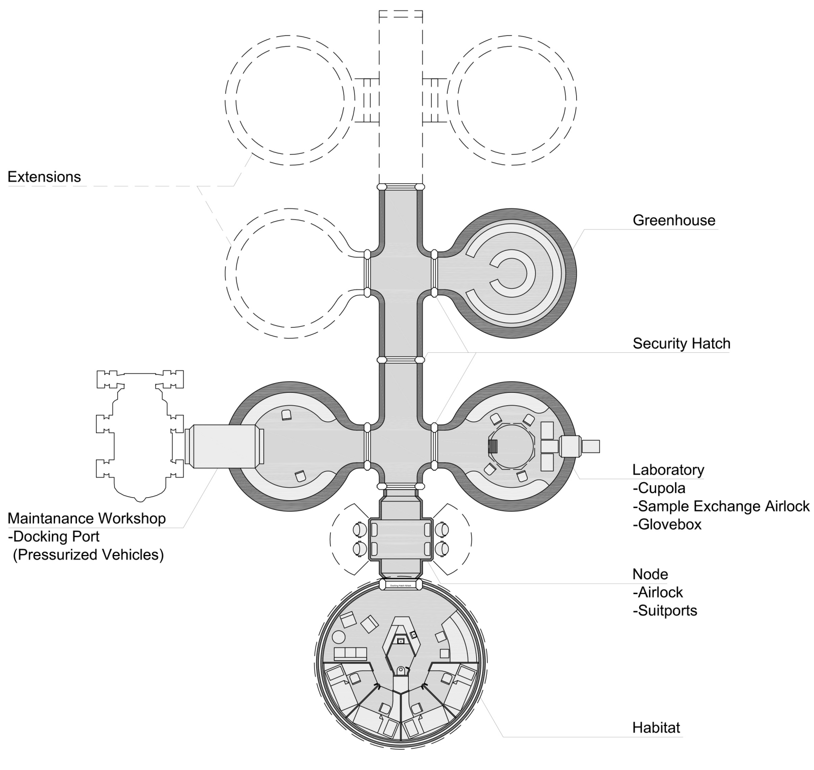


Figure 11. *Linear layout of Lava Hive concept, stemming from the habitat section. A pre-fabricated airlock node acts as the interface between the terrestrially delivered structures and the in-situ 3D printed elements. Visualization:René Waclavicek, LSG, 2015*

work to do. While Extra Vehicular Activities (EVAs) provide only for one end of scientific investigations the astronaut team will also need some facility within the habitation zone to analyse samples.

Here the authors suggest an astrobiology laboratory as described by Marc Cohen [6, 7]. The visualization in this paper is the first in a real scenario modelled after Cohen. The layout and tools are required to prevent cross-contamination. The samples would be handled by a robotic arm (see Fig. 12) and taken through a sample exchange airlock into autoclaves and glove-boxes for inspection. Some of the samples would also be taken out again since it is assumed that only particular samples would make it back to Earth. Work desks, racks and an observation deck would complement the laboratory.

To which extent the crew will be able to directly view the outside needs to be discussed since the radiation levels on Mars might be still too high to allow real windows. In specific dedicated areas, certainly not in the habitation module, a direct observation option might prove useful and not too dangerous if shutters can be closed for more solid protection against radiation.

Additional functions to be manufactured to extend the base or to add other parts could be a non-pressurized wind and dust shelter, a sort of garage to protect tools, machinery and vehicles from the Martian environment.

## 6 Conclusion

In this paper we discuss the Lava Hive concept, a novel 3D printed habitat made from sintered and molten Martian regolith/sand. We detail the construction process using readily accessible resources, and outline the merits of our approach in terms of achievability and specific advantages. It is a modular design for an initial surface habitation mission, with the ability to expand

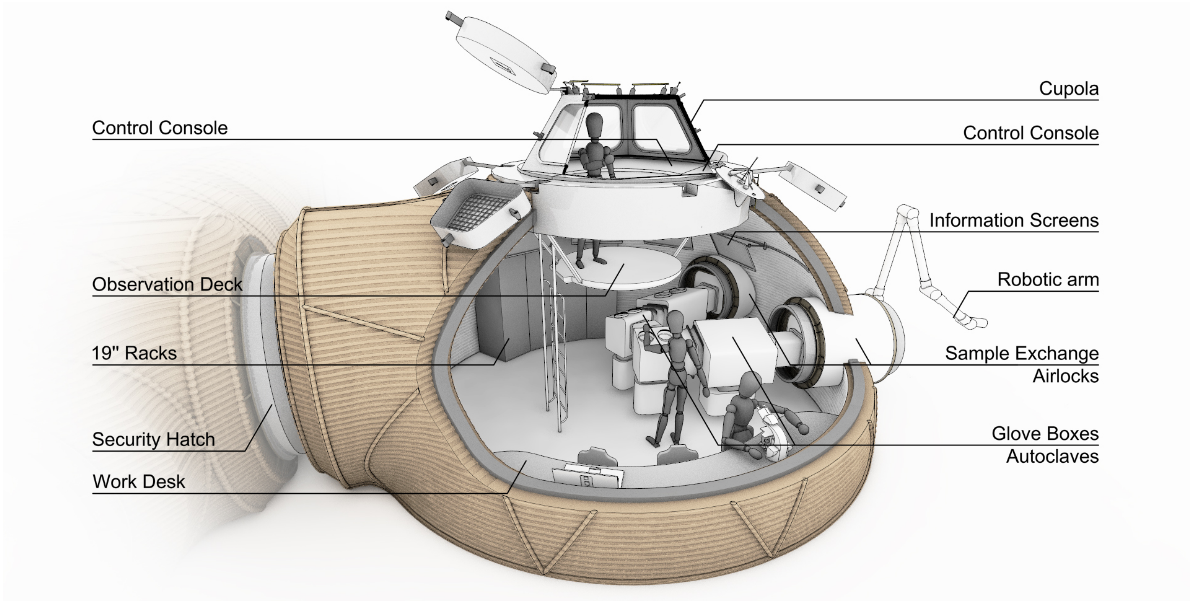


Figure 12. *Cutaway imaging of the laboratory space, with embedded cupola for site observation, sample load locks and work area. Visualization:René Waclavicek, LSG, 2015*

or adapt to changing mission requirements. In its initial state, a main habitat is connected via a central corridor to three sub-habitats made entirely from *in-situ* resources, demonstrating a new approach to a Class III habitat design realized via AM and a simple resource utilization process. The main habitat houses crew living areas and critical subsystems with the subhabitats used for experiments, Martian surface exploration preparation and maintenance. With some development, we believe this approach can be terrestrially validated using simulant regolith or sand, opening up the possibility for future mission scenarios to utilize derivations of our concept. It is planned to demonstrate aspects of the lava casting process on a small scale in order to derive material characteristics and validate the fabrication approach.

## 7 Acknowledgements

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## References

[1] C. C. Allen, J. A. Hines, D. S. McKay, et al. Sintering of lunar glass and basalt. In *Engineering, Construction, and Operations in space-III: Space'92*, volume 1, pages 1209–1218, 1992.

[2] M. Anand, I. A. Crawford, M. Balat-Pichelin, et al. A brief review of chemical and mineralogical resources on the moon and likely initial in situ resource utilization (isru) applications. *Planetary and Space Science*, 74(1):42–48, 2012.

[3] N. Bagdassarov and H. Pinkerton. A review and investigation of the non-newtonian properties of lavas based on laboratory experiments with analogue materials. *J. Volcanol Geotherm Res*, 2003.

[4] G. Cesaretti, E. Dini, X. De Kestelier, et al. Building components for an outpost on the lunar soil by means of a novel 3d printing technology. *Acta Astronautica*, 93:430–450, 2014.

[5] M. Cohen and K. J. Kennedy. Habitats and surface construction: technology and development roadmap. In *NASA conference publication*, pages 75–96. NASA, 1997.

[6] M. M. Cohen. Mars surface science laboratory accommodations and operations. In *SAE 1999-01-2142, 29 th International Conference on Environmental System, Denver, Colorado, 12-15 July 1999*, 1999.

 DOI: 10.5281/zenodo.202220

[7] M. M. Cohen. Design development strategy for the mars surface astrobiology laboratory. In *SAE, ASME, AIAA, et al, International Conference on Environmental Systems(ICES), 30 th, Toulouse, France*. Citeseer, 2000.

[8] K. S. Edgett and P. R. Christensen. The particle size of martian aeolian dunes. *Journal of Geophysical Research: Planets*, 96(E5):22765–22776, 1991.

[9] B. R. Edwards, J. Karson, R. Wysocki, et al. Insights on lava–ice/snow interactions from large-scale basaltic melt experiments. *Geology*, 41(8):851–854, 2013.

[10] ESA. European Space Agency Space Exploration Strategy . https://goo.gl/7HoXYj, 2016. Checked: 24.02.2016.

[11] M. Fateri, A. Gebhardt, and M. Khosravi. Experimental Investigation of Selective Laser Melting of lunar regolith for in-situ applications. In *ASME 2013 International Mechanical Engineering Congress and Exposition*, pages V02AT02A008–V02AT02A008. American Society of Mechanical Engineers, 2013.

[12] S. Guetersloh, C. Zeitlin, L. Heilbronn, et al. Polyethylene as a radiation shielding standard in simulated cosmic-ray environments. *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms*, 252(2):319–332, 2006.

[13] M. Hecht, J. Hoffman, and M. Team. The Mars Oxygen ISRU Experiment (MOXIE) on the Mars 2020 Rover. In *Lunar and Planetary Science Conference*, volume 46, page 2774, 2015.

[14] R. Leonard and S. Johnson. Sulfur-based construction materials for lunar construction. In *Engineering, construction, and operations in space*, pages 1295–1307. ASCE, 1988.

[15] C. Montes, K. Broussard, M. Gongre, et al. Evaluation of lunar regolith geopolymer binder as a radioactive shielding material for space exploration applications. *Advances in Space Research*, 56(6):1212–1221, 2015.

[16] P. Morthekai, M. Jain, L. Dartnell, et al. Modelling of the dose-rate variations with depth in the Martian regolith using GEANT4. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 580(1):667–670, 2007.

[17] R. Mueller, L. Sibille, P. Hintze, et al. Additive Construction using Basalt Regolith Fines. In *Earth and Space 2014@ sEngineering for Extreme Environments*, pages 394–403. ASCE, 2014.

[18] NASA. The international space exploration coordination group - global exploration roadmap:. https://goo.gl/1sCyLV, 2016. Checked: 24.02.2016.

[19] NASA. NASA Centennial Challenge – 3D Print Mars Habitat. https://goo.gl/0g4cFd, 2016. Checked: 24.02.2016.

[20] NASA. Public domain image taken from. https://goo.gl/HJY7LP, 2016. Checked: 24.02.2016.

[21] E. Parteli, K. Kroy, H. Tsoar, et al. Morphodynamic modeling of aeolian dunes: Review and future plans. *The European Physical Journal Special Topics*, 223(11):2269–2283, 2014.

[22] M. Paton, A.-M. Harri, T. Mäkinen, et al. High-fidelity subsurface thermal model as part of a martian atmospheric column model. *Geoscientific Instrumentation, Methods and Data Systems*, 2(1):17–27, 2013.

[23] G. Sanders, K. Romig, W. Larson, et al. Results from the nasa capability roadmap team for in-situ resource utilization (isru). 2005.

[24] R. Schultz. Brittle strength of basaltic rock masses with applications to venus. *Journal of Geophysical Research: Planets*, 98(E6):10883–10895, 1993.

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Acta Futura

# Concept Design of an Outpost for Mars Using Autonomous Additive Swarm Construction

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**Abstract.** Designing an outpost for a long-duration scientific expedition to an extreme environment such as Mars requires the basic qualities of functionality, comfort, and security. In this paper we assess: the key environmental conditions that govern the functionality of a Martian habitat; what it takes to design and build a comfortable home for a crew of four for 500 days with limited communication with Earth; and most critically, how to ensure mission success, safety, and robustness through increased redundancy. These factors are collected here into a conceptual design proposal, along with details of the deployment and multi-robot additive regolith construction system. This work is part of ongoing research at F+P specialist modelling group on robotics, large-scale additive construction, and architecture for extreme environments.

## 1 Introduction

As we move towards public or privately-funded human expeditions to Mars over the next few decades, it is necessary to consider what type of a home can be provided for astronauts on the surface of the planet; and that this endeavour should involve a broader multi-disciplinary basis. In this paper our primary objective is to suggest that we have the technology to go beyond deploying a purely functional scientific base, as is perhaps the convention [7, 9]. Rather we propose to build a place for living, suitable for continued multi-mission occupation and development. It is more than likely that each successive expedition will incorporate feedback from the last into an evolving design. Any future colony is therefore likely to be a mixed system of technologies and habitats of increasingly advanced and successful design, the parents of which will be theoretical or prototyped closer to home.

Surface habitats can be one of three classes: Class I are single pre-fabricated pressurised module, such as the Apollo Lunar lander; Class II are multiple such modules connected together; and Class III combine multiple modules plus structures built from in-situ materials [10]. Extending this, Class IV would be constructed solely from local materials, and Class V the construction machines would themselves be fabricated in-situ.

Here, the proposed Class III outpost is a composite of light-weight inflatable pressurised modules [11] and a multi-robot additive construction system to compile local regolith into a protective heavy-weight shield. Although the pressurised elements are better suited to high accuracy fabrication possible under tightly controlled conditions on Earth, the compressive heavy-weight pro-

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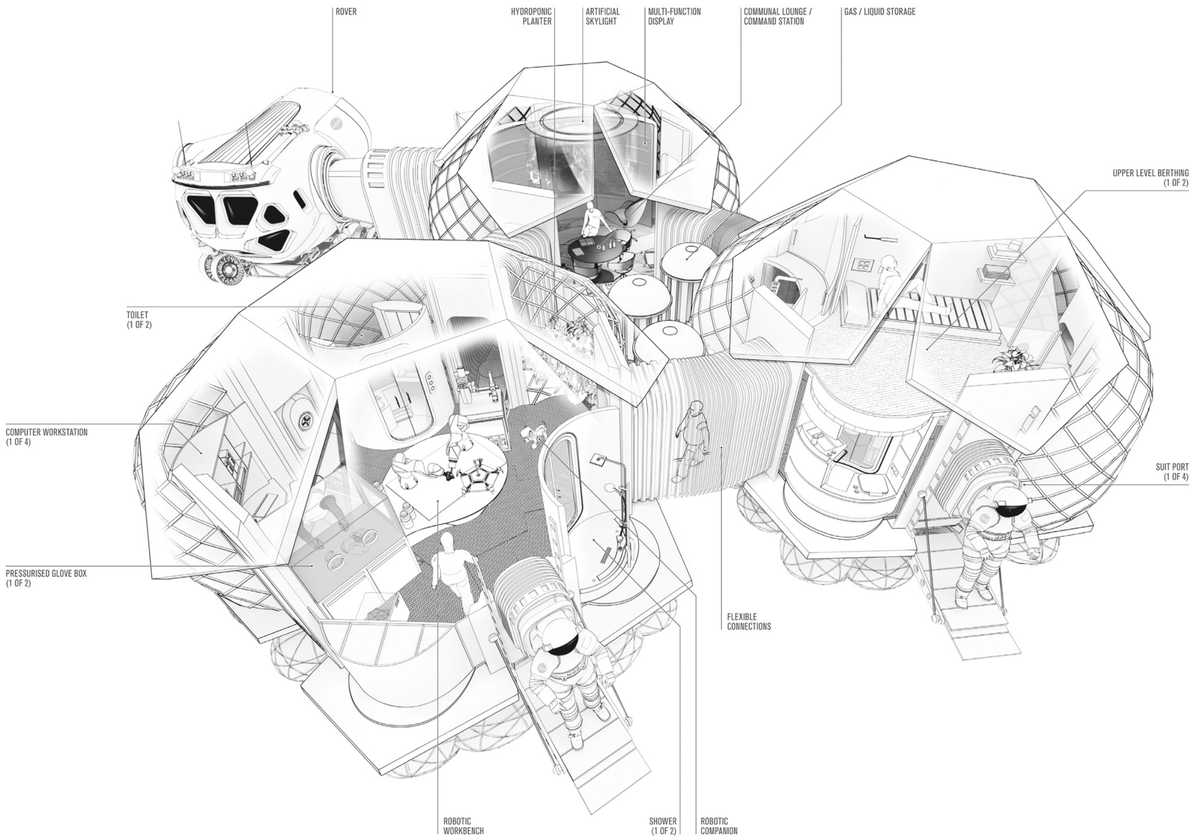


**Figure 1.** *Outpost design (axonometric view)*

tective shield can be more heterogeneous. Therefore delivery of construction robots is lighter, more compact and flexible than sending an equivalent item from Earth. Others have also considered additive regolith construction processes for extra-planetary missions [6, 10, 12], along with other entries in NASA's 3D Printed Habitat Centennial Challenge.

The habitat (Figure 1) is divided into a network of connected deployable spaces with 120 $m^2$ habitable floor area divided into three modules. Each module has ~30 $m^2$ (plus two modules have upper mezzanine levels of ~15 $m^2$ each) and ~100 $m^3$ habitable volume. The services for each includes 2.5 $m^3$ of bulkhead required for the Environmental Control and Life Support Systems (ECLSS) which is located in the hard elements.

Conventionally, each module would be assigned a single specific task and the required equipment designed to fit [27]. Here, each of the modules is identical and is deployed empty; to be filled with specific equipment on arrival of the crew. Each module can operate independently to provide basic life-support should another fail, and together provide a more comfortable environment.

### 1.1 Mission Architecture

The base and construction system is delivered prior to human arrival via two cargo ships containing: the deployable habitation units with their construction robots; a Radioisotope Thermoelectric Generator (RTG); and the In-Situ Resource Utilisation (ISRU) module. These are to be delivered by launches of two heavy-lift rockets followed by a ~210 day transit [7]. On arrival in orbit, the subsequent stages of the delivery and deployment are as follows:

***Entry, Descent, Landing***

Descent of the modules will follow a similar method to the Pathfinder mission [3] with a combination

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of ablative heat shield, solid retro-rockets, supersonic parachute, and finally air bags softening the final few metre drop. The modules have a dodecahedron shape (∅4.6 m), with each of the 12 faces covered in six inflated spheres (∅1.35 m). The EDL will happen in two phases: first the robots will be delivered to the surface for site selection and preparation; followed later by the habitat modules.

*Surface Navigation*

When developing the air bag system for the Pathfinder mission, rigorous drop-tests were conducted on various terrains, ranging from flat surfaces to steep, rocky inclines. This led to the use of multiple thin fabric layers rather than a single thick one. This greatly improved the strength since the outermost layer tore, absorbed energy, and created a soft protective buffer for the inner layers [5]. This study leads us to believe that the air bag system can be used for a secondary function post-EDL for positioning the modules.

Once stationary on the surface, the individual modules may be distributed within a landing radius of a few kilometres, and so it is necessary for them to navigate together. A sequenced inflation-deflation of the 72 external air bags starts a controlled roll of the modules to a shared target. The objective is to get within close proximity of one another (<2 m) for the airlocks to connect. In order to ensure the modules face the correct way up, the individual rolling paths can be controlled over the journey to be slightly longer or shorter as required.

*Robotic Site Preparation*

The multi-robot system consists of three classes of robot deployed prior to the habitat modules (Figure 3): one large digger (RAC-D ~1 m); five medium transporters (RAC-T ~0.4 m); and fifteen small melters (RAC-M ~0.25 m). For system diversity, robot movement is by wheels, tracks and legs respectively.

The first task for the robot system once at the site is to excavate a 1.5 m deep hole for the habitat to sit within. The RAC-D robots will dig the loose regolith from the surface layer by layer, which will be moved nearby into protective berms by the RAC-T robots. The volume of excavated regolith is roughly equal to the amount to be printed on the shield.

*Habitat Deployment and Connection*

Once the site is prepared, and the three modules are gathered together, the small inflatable spheres surrounding the habitat partially deflate. The upper faces of the dodecahedron module fold up and lock in position, similarly for the lower faces to form the foundation which can fit to a rough landscape to ensure the interior floor is level. Subsequently, the core, shaped as a pentagonal prism, expands outwards (Figure 2).

Each of the five vertical faces of the core is either a connection or a window which will move to the outer perimeter along with the inflated skin. Once inflated the hard outer connections lock into the upper and lower pentagonal faces, and the connector airlocks extend outwards to connect to one another. Figure 2 shows this process of the modules in their prepared site, unfolding, inflating, and connecting. The three deployed habitat modules are now ready for the regolith shield to be constructed on top.

## 2 Extreme Environments

The first considerations in the design of a habitat are the challenges and affordances of the natural environment in which it is situated [4]. Although Mars has the closest similarities to Earth of any of the planets in the solar system, its environment is relatively inhospitable and presents challenges to human survival. In this section we assess how various environmental aspects will affect the design.

### 2.1 Site Selection

For solar power to be most effective and smaller temperature variations, an outpost should ideally be located nearer the equator. The multitude of scientifically interesting sites across Mars are situated in a broad range of topographical environments [7], from plains to caves, valleys, volcanoes, cliffs and craters. Special regions are less likely to occur in circum-equatorial regions [20] and the availability of ground-ice is likely to be greater in higher latitudes.

The system design and the outpost itself can be potentially applied to this broad range of cases. Whilst a specific site is not being selected, the broad 'river' estuary topography may offer certain benefits. The network of channels gives a directional catchment area for the EDL to focus on, although it may be more rugged terrain. After landing, the modules will navigate 'down-stream' to

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FIGURE 2. *Habitat module deployment: (right to left) unfolding, inflation, and connection.*

a larger plain (for example, around 25°N 60°W).

### 2.2 Radiation

Due to the lower density atmosphere, lack of clouds, ozone and a magnetosphere, Mars receives more solar particle events (SPE) and galactic cosmic radiation (GCR) than Earth. Periodic radiation from SPE is especially harmful for humans, although these can be detected, given warning time, by solar observation. The constant bombardment of high-energy GCR particles delivers a lower yet steady dose rate compared with large SPEs that can deliver a very high dose over a short time. The GCR contribution to dose becomes more significant as the mission duration increases [17]. Mitigating radiation exposure for the crew is a serious consideration for the health and life-expectancy of the crew, and is the primary reason for the protective regolith shield.

### 2.3 Temperature

It is commonly reported that the temperature on Mars can reach a high of about 20°C at noon at the equator in the summer, or a low of about -153°C at the poles. In the mid-latitudes, the average temperature is about -50°C with a night-time minimum of -60°C and a summer midday maximum of about 0°C [22].

Due to the low density of the atmosphere, temperature is primarily governed by solar heating, and infrared cooling to the atmosphere and space, rather than conductive and convective heat transfer with the atmosphere. This means radiative fluctuations, on a momentary, daily and yearly basis, are more varied and must be balanced with both adaptive thermal control systems and the heavy weight thermal mass of a regolith shield.

### 2.4 Ingress/Egress

It has been widely acknowledged that dust/dirt management is likely to be a key issue for long duration surface missions. The small particle size of the regolith could lead to contamination of the habitat and potential health risks to the crew. It is therefore important to control the ingress of dust. The suitport system [18] solves this issue, as well as removing the need for large airlocks, by having the spacesuit mounted externally. For EVAs the crew can climb into the back of the suits directly from the inside and detach themselves. The pressurised rover and conventional airlocks offer alternative points of entry if necessary.

Due to the low atmospheric pressure, high speed winds have minimal force yet are capable of transporting large amounts of electrically-charged dust over great distances. The deposition of dust around airlocks could potentially lead to difficult ingress/egress, therefore airlocks are distributed at various positions and angles to avoid entrapment. Suitports are used as the primary EVA method instead of traditional airlocks to remove risk of contamination of the interior with dust, and the exterior with bacteria.


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### 2.5 Meteorites

The Martian atmosphere gives a certain degree of protection from micro-meteorite impact [28], however since the habitat is a pressurised volume, additional layers are needed to avoid breaches. The regolith shield gives an additional protective layer from micro-meteorites.

### 2.6 Life-support

Pressurised vessels are prone to breaches with the great pressure differential between inside and out. With atmospheric pressure 100-times less than Earth, a strong boundary is required which can withstand its occupants' activities. The tensile strength required to maintain this internal pressure is difficult to achieve with regolith which is more suitable for compressive structures [19]. Therefore a pre-fabricated multi-layered, woven Kevlar inflatable skin provides this pressure boundary.

Finally, for long duration missions it is important to maximise use of environmental resources for collection of energy, and production of life support consumables and rocket propellant. The In-situ Resource Utilisation (ISRU) unit which accompanies the habitat prior to human arrival has time to collect and process atmospheric carbon dioxide and potentially near-surface water ice [15]. Delivering the technology to produce propellant for crew return and life support consumables will be easier than delivering the gases/liquids themselves. Power for this processing will be delivered with the ISRU in the form of a Radioisotope Thermoelectric Generator (RTG) unit, to be supplemented by photovoltaic cells on crew arrival.

A human mission to Mars must necessarily be power-rich, in that life-support (ISRU) and everyday (primarily extra-vehicular) activities will require relatively high power when compared to previous low-activity missions. In this vein, power generation capability should be maximised at the mission outset to available weight limits, then expanded upon and diversified when possible on future missions.

## 3 Shelter

The second component of the concept design that we consider is security, in terms of both crew safety, peace of mind, and mission success in relation to the environmental conditions. Safety is arguably the most fundamental and primitive aspect of a home. Shelter from wild animals, storms, enemies, and the cold has for thousands of years defined our homes. Protection from environmental conditions on Mars leads us to consider the necessity of a heavy-weight regolith shield.

A shield built from surface regolith has many advantages: protection from cosmic radiation, solar flares, dust storms, meteorites, and temperature variations; as well as increasing the durability of the light-weight habitat modules. Additionally, other protective structures can be built, such as berms, and other infrastructure like landing pads and roads.

### 3.1 Swarm Robotics

The construction system is comprised of three types of robot, each specialising in either excavation, transportation, or melting (Figure 3). The traditional approach to mission robotics is to consolidate risk and complexity into a single fate-sharing machine, with built-in redundancy (e.g. 'over-engineering' and system duplication). However, distributing risk across multiple specialised, simpler robots has the advantage of isolating risk to individual units. Given enough robots, there is also the potential for emergent behaviour, i.e. group behaviours greater than the sum of the individual behaviours [23, 24].

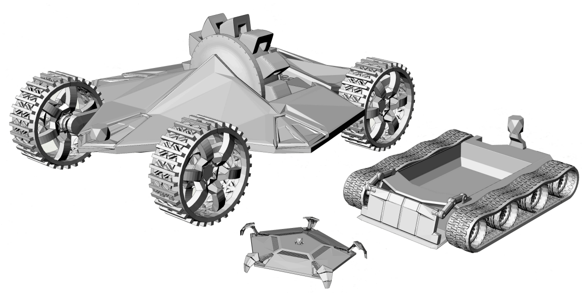

**Figure 3.** *Construction robot classes: (large to small) RAC-D excavator, RAC-T transporter, and RAC-M melter.*

Due to communications delays from Earth the robot control must be highly autonomous, with each individual being capable of decision-making and following rules. In the near future, it is predicted that computational intelligence and robotic technology will be sufficiently advanced to allow for a distributed system of autonomous intelligent machines. The system is capable of adapting to uncertain operating environments, of self-management and sys-

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tem awareness, and of following high-level commands such as 'explore', 'gather materials' or 'construct habitat'.

### 3.2 Additive Regolith Construction

The autonomous and generative additive construction method relies on rules and objectives, meaning that the outcome is more adaptive and open-ended. The regolith additive construction (RAC) approach is adapted for the low accuracy likely to be achieved from using variable materials at an uncertain site with autonomous robots in the field. The reliability of the RAC is in its simplicity, implemented by the three classes of robot: the strategy is to 'dig, move, and melt' regolith. The large digging robots will extract loose regolith in close proximity for the medium-sized mover robots to transport to the habitat. As the regolith is deposited, the smallest melting robots have a 200W microwave (2.45GHz) print head to bond one layer at a time [1]. The regolith is positioned into rough layers by the transporter robots, with the thickness continuously measured. Once a thin layer of regolith is in place, the third class of smallest robots selectively melts patches into a hard crystalline material (Figure 4).

For protection from radiation over long-term periods, rather than transporting heavy shielding from Earth, the construction of a regolith shield is a logical alternative [13]. The largest reduction in dose equivalent (rem) occurs in the first 20 g/cm$^2$, so assuming a regolith density of 1.5 g/cm$^3$ the regolith depth should be at least 15 cm [21].

Whilst this is a minimum depth to ensure the crew does not receive 'career limiting' doses, the design includes 1.5 m above the work/sleep modules for general protection from cosmic radiation, and 2.5 m above the communal space for protection from solar flares during periods of increased solar activity.

The form of the regolith shield is driven by two key criteria, which become the operational rules for the individual robots. The first criteria is the minimal thickness of regolith needed to protect the inhabitants from radiation. The second criteria is the ability of all construction robots to transfer themselves to the highest layer printed so far during the construction process. As a result, multiple ramp structures blended into the overall form are introduced next to every opening of each module (airlocks, windows and suitports). Because of their location, they also serve as an extra protection of these openings.

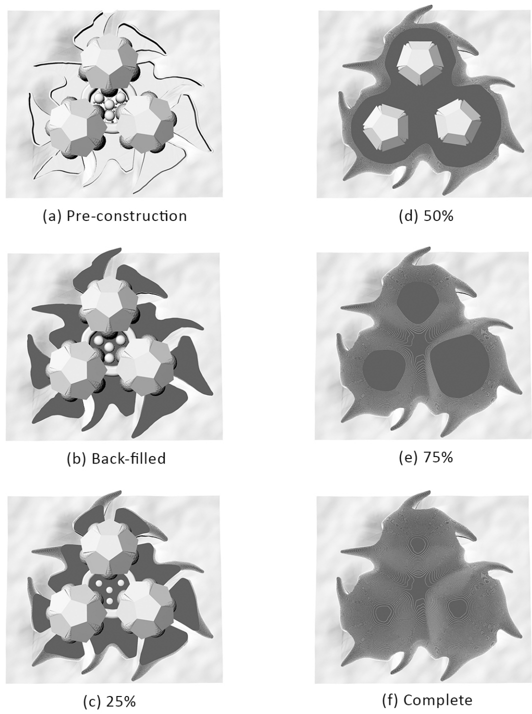


FIGURE 4. *Progression of regolith construction.*

## 4 Comfort

The interior of the habitat will be the home for the four crew during their stay on Mars and should be, as a minimum, functional for the activities that can be expected and flexible enough to accommodate those that are unexpected. As the three initial habitat modules are deployed, connected and shielded, the concept was for the modules to be like an unfurnished apartment; all services are included but the furniture and more delicate internal equipment must be delivered with the crew. This has two benefits: first, that when the crew arrive they have an empty habitat that they can shelter in; and secondly that all of the interior can be configured or replaced as needed.

The use of three smaller modules instead of a single large one means that, in the circumstance that one is damaged, the other two would be adequate for continuing the (perhaps cramped) mission.

### 4.1 Private vs. Public

Sharing confined spaces for prolonged periods of times can potentially lead to conflict and psychological stress,

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therefore it is important to manage the relationship between private and communal space [25]. The three modules, although identical on deployment, are differentiated during fit-out.

Module A, with full-height volume, is designated as the communal space, with exercise, cooking, communication and meeting space for four people (Figure 5). The

**Figure 5.** *Module A: communal space.*

other two modules B and C are designed for laboratory, work, toilet and cleaning facilities for two people on the lower levels (Figure 7), and individual private berthing quarters on the upper levels (Figure 6). This creates clear spaces for social interactions with the opportunity for privacy but not isolation [8].

**Figure 6.** *Module B/C upper: private quarters.*

### 4.2 Lighting

Humans have 24-hour day-night cycles hard-wired into them which should be maintained for long-term health and productivity [26]. Although there are a few small physical windows on airlocks for direct views out, the majority of lighting will be artificial. Circadian rhythm

**Figure 7.** *Module B/C lower: work space.*

lighting will adapt light levels and colour temperature throughout the day.

There will be a central 'skylight' in each module as primary lighting feature. The skylight will mimic the sun and the atmosphere using nanoparticles integrated into the transparent element [14] creating the perception of infinite depth improving the visual quality and comfort of the astronauts.

### 4.3 Surface Finishes

As with lighting, surface materials play a subtle but important role in occupants' enjoyment of an environment. Beyond strict functionality, materials can range from warm and natural through to cold and artificial. Throughout the habitat, natural materials have been placed in selected locations to create a greater feeling of home and, since monotony is a potential psychological issue, for visual and tactile stimulation [2]. For instance, wood veneer is placed on work surfaces, communal floors, and ladder steps; colourful woven fabrics and tatami mats are used in the sleeping quarters.

### 4.4 Acoustics

An additional source of psychological stress is the continual mechanical noise of life-support systems [25]. In this context, this can be particularly stressful as it is a constant reminder of the necessity of the life-support systems. Material selection is a simple way to reduce reverberation, with micro-perforated surfaces, soft finishes and vegetation on walls and ceilings.

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## 5 Field Tests

There are a number of sites on Earth which have specific semblances to the Martian landscape, but the Atacama Desert to the west of the Andes has perhaps the most similar character [16]. The extremely arid and cold climate, isolation from human activity, similar soil, lack of microbial life, and desert landscape are the primary dominant features which would make for an interesting preliminary experimental site. Various analogous topographical features also exist for testing, such as plains, cliffs, caves and valleys.

Figure 8. *Outpost design*

It is envisaged that the developmental journey to Mars will probably, after Earth field tests, first involve testing technologies on the Moon. This test environment closer to home has many advantages, such as near-instant communication and far shorter journey time. However whilst the delivery components of the Mars mission architecture may not be applicable to a zero-$g$, no atmosphere scenario, the robotic additive construction can be rigorously tested.

The next developmental steps can be broken down into four parts: i) operation of the robotic system (detailed robot specification, autonomous control, communication, power beaming); ii) the additive construction process (material characterisation, filtering, melting process, layering); iii) the design of the habitat module itself; and iv) integration of the previous three components in the field.

Field tests on Earth may also pave the way for establishing whether this construction process is also applicable to terrestrial construction projects, such as in extreme environments or for infrastructural or disaster relief.

## 6 Conclusion

Building on new frontiers demands reliable and tested solutions, whilst at the same time novel techniques are required to overcome unique challenges. In this context, the outpost design is an exploration of integrating existing viable space architectures and emerging robotic construction technologies. A semi-autonomous multi-robot construction system is used to collect and assemble a highly robust Mars habitat prior to arrival of the first crew. The use of regolith additive construction and inflatable architecture provide an adaptive and open-ended strategy to master broad uncertainties in the terrain and resources of Mars.

## Acknowledgements

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## References

[1] M. Barmatz, D. Steinfeld, M. Anderson, et al. 3d microwave print head approach for processing lunar and mars regolith. In *Lunar and Planetary Science Conference*, volume 45, page 1137, 2014.

[2] I. Biederman and E. Vessel. Perceptual pleasure and the brain: A novel theory explains why the brain craves information and seeks it through the senses. *American Scientist*, 94(3):247–253, 2006.

[3] R. D. Braun and R. M. Manning. Mars exploration entry, descent and landing challenges. In *Aerospace Conference, 2006 IEEE*, pages 18–pp. IEEE, 2006.

[4] H. G. K. Broughton and I. I. H. Vi. Antarctic Research Stations: Parallels for Interplanetary Design. pages 1–12, 2010.

 DOI: 10.5281/zenodo.202236

[5] D. Cadogan, C. Sandy, and M. Grahne. Development and evaluation of the mars pathfinder inflatable airbag landing system. *Acta Astronautica*, 50(10):633–640, 2002.

[6] G. Cesaretti, E. Dini, X. De Kestelier, et al. Building components for an outpost on the lunar soil by means of a novel 3d printing technology. *Acta Astronautica*, 93:430–450, 2014.

[7] B. G. Drake, S. J. Hoffman, and D. W. Beaty. Human exploration of mars, design reference architecture 5.0. In *Aerospace Conference, 2010 IEEE*, pages 1–24. IEEE, 2010.

[8] S. Häuplik-Meusburger. *Architecture for astronauts: an activity-based approach*. Springer Science & Business Media, 2011.

[9] S. J. Hoffman. The Mars Surface Reference Mission: A Description of Human and Robotic Surface Activities. Technical report, 2001.

[10] A. S. Howe, C. McQuin, J. Townsend, et al. Faxing Structures to the Moon: Freeform Additive Construction System (FACS). *AIAA*, 5437:10–12, 2013.

[11] K. J. Kennedy, J. Raboin, G. Spexarth, et al. Inflatable Structures Technology Handbook. In *Habitation*, volume l. 2000.

[12] B. Khoshnevis, M. P. Bodiford, K. H. Burks, et al. Lunar contour crafting—a novel technique for isru-based habitat development. In *43rd AIAA Aerospace Sciences Meeting and Exhibit—Meeting Papers*, pages 7397–7409, 2005.

[13] J. Kozicki. Human friendly architectural design for a small martian base. *Advances in Space Research*, 48(12):1997–2004, 2011.

[14] P. Marks. Blue skies on tap, whenever you need them. *New Scientist*, 222(2965):21, 2014.

[15] A. C. Muscatello and E. Santiago-Maldonado. Mars In Situ Resource Utilization Technology Evaluation. *50th AIAA Aerospace Sciences Meeting Including the New Horizons Forum and Aerospace Exposition*, 2012.

[16] R. Navarro-González, F. A. Rainey, P. Molina, et al. Mars-like soils in the atacama desert, chile, and the dry limit of microbial life. *Science*, 302(5647):1018–1021, 2003.

[17] D. Rapp. Radiation effects and shielding requirements in human missions to the moon and mars. *International Journal of Mars Science and Exploration*, 2:46–71, 2006.

[18] B. Romig and C. Allton. First generation suit port development and testing. *Johnson Space Center Engineering Directorate Biennial Report*, 2009.

[19] F. Ruess, J. Schaenzlin, and H. Benaroya. Structural design of a lunar habitat. *Journal of Aerospace Engineering*, 19(July 2015):133–157, 2006.

[20] J. D. Rummel, D. W. Beaty, M. A. Jones, et al. A new analysis of Mars "special regions": findings of the second MEPAG Special Regions Science Analysis Group (SR-SAG2). *Astrobiology*, 14(11):887–968, 2014.

[21] L. C. Simonsen and J. E. Nealy. Radiation protection for human missions to the moon and mars. Technical report, National Aeronautics and Space Administration, Hampton, VA (USA). Langley Research Center, 1991.

[22] J. E. Tillman. Mars temperature overview. https://goo.gl/k0ofvT, 2009.

[23] W. Truszkowski, M. Hinchey, and J. Rash. NASA's Swarm Missions: The challenge of building autonomous software. *IT Professional*, (6.5):47–52, 2004.

[24] W. Truszkowski, M. Hinchey, J. Rash, et al. Autonomous and autonomic systems: A paradigm for future space exploration missions. *IEEE Transactions on Systems, Man and Cybernetics, Part C (Applications and Reviews)*, 36(3):279–291, 2006.

[25] D. A. Vakoch. Psychology of space exploration. *Washington (DC): NASA*, 2011.

[26] A. R. Webb. Considerations for lighting in the built environment: Non-visual effects of light. *Energy and Buildings*, 38(7):721–727, 2006.

[27] A. Whitmire, L. Leveton, H. Broughton, et al. Minimum acceptable net habitable volume for long-duration exploration missions. 2015.

[28] S. Wright. Infrared analyses of small impact craters on earth and mars. *University of Pittsburgh. Archived from the original on June*, 12, 2007.

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**Acta Futura**

# A Deployable Telescope Concept for Sub-Meter Resolutions

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**Abstract.** The use of synthetic aperture elements enables the development of telescopes with sub-meter resolution and considerably smaller launch volume, mass and thereby costs. As such, a space concept study yielded a competitive MicroSat Fizeau optical design with 25 cm ground resolution at 500 km orbital altitude. Its full-field Korsch design was optimized for compactness and wave-front quality. The primary mirror uses three aperture segments folded alongside the instrument during launch combined with a secondary mirror mounted on a deployable boom. A high image quality in space requires tight tolerance control of all mirror segment positions. Therefore, an alignment budget was derived using a sensitivity analysis.

Silicon Carbide mirror segments, Invar deployable arms and a main housing with active thermal control, enable operations with high thermal-mechanical stability. In orbit, the diffraction limited performance is controlled by a calibration system using interferometers and capacitive sensors to characterise the system. Actuators beneath the primary mirror segments correct their position to meet the required operational accuracy ranges. During operations, a passive system uses a phase diversity algorithm to retrieve the residual wave-front aberrations and de-convolve the image data yielding the required end-to-end imaging performance. A rough first order bottom-up design using interferometers and capacitive sensors was made to comply with the top-down driven and required mirror rotation and alignment tolerance budgets down to 200 nrads and 100 nm. This indicated the potential compliance of top-down and bottom-up system engineering budgets to validate the healthy system design concept and to push it towards a robust design.

## 1 Introduction

High resolution Earth Observation (EO) data has become invaluable for a wide variety of applications, ranging from defence and security to environmental monitoring, precision farming and disaster response [25].

Presently, high resolution imaging data is captured by large, heavy and expensive EO systems such as GeoEye, Quickbird, Worldview and Spot [9, 4]. As a result, data produced by these satellite systems is also very expensive. Moreover, the number of systems capable of capturing imagery at a high resolution is still limited, while the swath width of these systems is typically small. This means that for many regions on Earth, frequently updated imagery is simply not available.

The goal of this work is therefore to design a deployable optical system that can reach similar resolutions as state-of-the-art EO systems, while using a fraction of

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Table 1. *Design Specifications of the Deployable Telescope*

| | | |
|---|---|---|
| Pupil Baseline | | 1.5 m |
| Focal Length | | 11 m |
| Swath Width | | 5 km |
| Field of View | | 0.57° |
| Aperture Area | | 0.65 m |
| GSD | Panchromatic (450-650 nm) | 25 cm |
| | Blue (450-510 nm) | 100 cm |
| | Green (520-580 nm) | 100 cm |
| | Yellow (580-630 nm) | 100 cm |
| | Red (630-700 nm) | 100 cm |

the volume and mass. The launch costs of such a system are therefore expected to be substantially smaller, which will ultimately result in a much lower cost per image. In Table 1, the main optical properties are listed that have been used as a starting point for the design. The ground resolution target and orbital altitude were derived from the Worldview-3 specifications [6], the recently launched 2800 kg EO satellite.

The paper is structured as follows. First of all, in Section 2, the systems engineering approach will be described that was used for designing a synthetic aperture system. Secondly, in Section 3 the optical design process is discussed. The section includes a trade-off between two synthetic aperture approaches. A conceptual mechanical design of the telescope is presented in Section 4 and in Section 5, its calibration aspects are discussed.

## 2 Systems Engineering Approach

Designing a synthetic aperture instrument for operation in a harsh and dynamic space environment is a complex task, particularly if the instrument instrument needs to be unfolded in orbit. To ensure that the instrument can meet its required optical performance, independent lightpaths must be phased to a fraction of a wavelength. This difficult task is further complicated by the fact that the telescope will be operating in a Low Earth Orbit (LEO), where thermal loads in are changing continuously. Active optical control and on-board metrology systems are therefore indispensable to accomplish such a task. Such systems must be used to measure and correct offsets in the position and orientation of critical optical elements.

Given the complexity of this design problem, coming up with a feasible design requires a sound systems engineering approach. The approach which was used in this project can be characterized by the simultaneous application of bottoms-up and top-down system engineering principles.

From a top-down perspective, an optical design was created based on a set of top level requirements given in Table 1. Successively, an alignment budget is derived by performing a tolerance analysis. The budget takes into account potential image quality improvements that can be obtained using image processing algorithms, thus resulting in a somewhat more relaxed alignment budget, compared to a budget that would result from a tolerance analysis in which a diffraction limited performance must be achieved before any image processing comes into play. In a previous paper [8], the top down approach was already touched upon.

In the bottoms up approach achievable accuracies of the metrology and actuation systems are derived by performing a thorough analysis of these systems. In this analysis, limitations imposed by manufacturing effects, sensor noise, platform instabilities and temperature fluctuations are estimated and quantified.

Approaching the design problem from the top and bottom simultaneously, rather than sequentially, has several advantages. The main advantage is that the consequences of top level design choices on a subsystem level are already apparent in very early stage of the project. In a project phase where high level design choices are still somewhat flexible, this will allow for adjustments to be made to allow for a more feasible instrument design. A feasible design is obtained if the top-down alignment budget can be met with the achievable accuracies of the calibration system.

## 3 Optical Design and Trade-Off

When designing a synthetic aperture instrument, two main design architectures can be implemented [19].

In the **Michelson synthetic aperture**, a single large telescope is replaced by a number of afocal telescopes that are spread out across the pupil plane of the telescope. The telescopes produce collimated, magnified beams that are directed towards a beam combiner. The beam combiner focusses the light of each of the afocal telescopes onto a common image plane. A prominent Earth based example of a Michelson synthetic aperture are the Large Binocular Telescope [12]. A conceptual design of a Michelson synthetic aperture instrument will be described in Section 3.1.

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The **Fizeau synthetic aperture** is similar to a conventional telescope. However, instead of a single monolithic primary mirror, a Fizeau synthetic aperture features a segmented primary mirror. The advantage of a segmented primary mirror is that these segments can be stowed in a compact volume during launch, to be spread across the baseline of the instrument after reaching orbit. An Earth based example of the Fizeau synthetic aperture is the Gran Telescopio Canarias (GTC) [13], while the planned James Webb Space Telescope is a prominent space-based telescope following the same design principles. In Section 3.2, a concept for a Fizeau synthetic aperture instrument is described in further detail.

A trade-off between the two approaches was performed, the results of which are described in section 2.

### 3.1 Michelson Synthetic Aperture

A fully reflective design for a Michelson synthetic aperture was created, which uses a set of 12 afocal telescopes that are distributed in an annular configuration across the pupil plane. Each of the afocal telescopes has an aperture diameter of 250 mm and an obscuration ratio of 0.4. The angular magnification of the telescopes is 5x, which was chosen to ensure that a compact beam combiner can be used. As a beam combiner, a full-field Korsch design was chosen, since it allows for a diffraction limited performance over a wide angular FOV. The use of glass components was deliberately avoided for two reasons. First of all, chromatic aberrations will complicate the image processing algorithms that are needed to obtain a good image quality. Secondly, the lower mounting stability of glass components when compared to mirror elements, would result in larger mechanical uncertainties.

Designing a Michelson Synthetic aperture for a wide Field of View (FOV) is a complex task, since raytrace applications such as Zemax do not natively support optimization through multiple parallel light paths [18]. The complexity lies in the fact that instrument must be modelled using non-sequential elements which, depending on the aperture configuration, can lead to a failure of many optimization operands. The beam combiner and afocal telescopes must therefore be designed separately, meaning that the interaction between the two components must be well understood.

The beam combiner, afocal telescopes and the system as a whole must meet a number of requirements to ensure that a diffraction limited performance can be reached over a wide FOV [22]. First of all, both the afocal telescopes and the beam combiner have to be designed to produce a diffraction limited image quality over the full FOV. Secondly, the principle of homothetic mapping must be applied, i.e. the entrance pupil of the beam combiner should be an exact demagnification of the entrance pupil of the array of telescopes.

Finally, the afocal telescopes must be designed to produce a specified amount of distortion, known as sine-law distortion. As described in [27] this ensures that for off-axis fields, the wavefronts originating from each telescope remain in phase.

To ensure that the afocal telescopes have the appropriate amount of sine-law distortion, without sacrificing the wavefront quality, the afocal telescopes use aspheric mirrors. The shape of these mirrors can be described as a conic with 4 higher order terms. In Figure 1, a three dimensional view and a cross-section of the concept are shown. In the figure, the 12 afocal telescopes can be seen. They are spread in a circle with a diameter of 1.5 meter around the beam combiner. The beams originating from the afocal telescopes cross in the centre of the instrument before entering the beam combiner, which is needed because the afocal telescopes flip the image.

In Figure 2, the optical performance of the Michelson Synthetic Aperture is shown. The point spread function (PSF) is given for the most off-axis field, where the performance is worst. Both the polychromatic point spread function and the modulation transfer function (MTF) curves show that the system delivers a nearly diffraction limited performance for the full field of view. For the chosen aperture configuration, this leads to an MTF at the Nyquist frequency of approximately 10%. A slight degradation in MTF is observed when going to the outermost fields, at field angles of +/- 0.1° . However, this drop remains limited to just 3% at low spatial frequencies (< 30 cycles/mm), while at higher frequencies almost no loss in resolving power is observed.

The full FOV that can be obtained with the Michelson system is limited to 0.2° , corresponding to a swath width of 1.75 kilometre. It falls short of the design goal of 5 km, given in table 1. A small extension in the FOV may be achieved with the current optical design. However, to reach the FOV goal, a substantial redesign of the afocal telescopes as well as the beam combiner is required. Steps that can be taken to achieve a wider field of view are reducing the angular magnification of the afocal telescopes, reducing the aperture diameter of these telescopes or using more, or more complex, optical elements. These steps will either lead to a substantially

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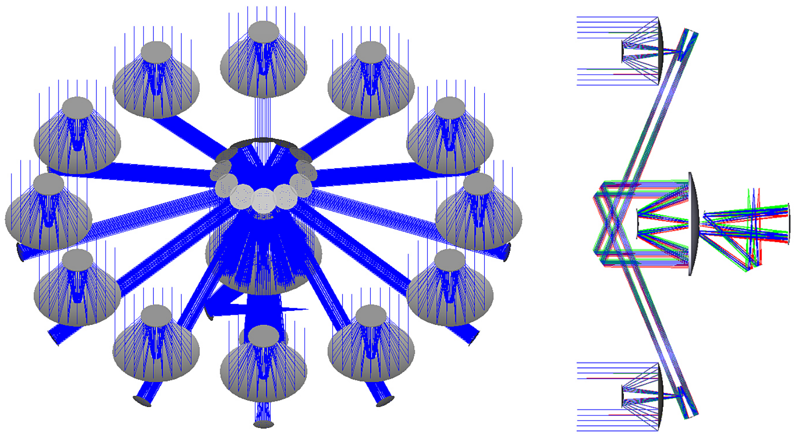

Figure 1. *Optical Lay-out of the Michelson Synthetic Aperture*

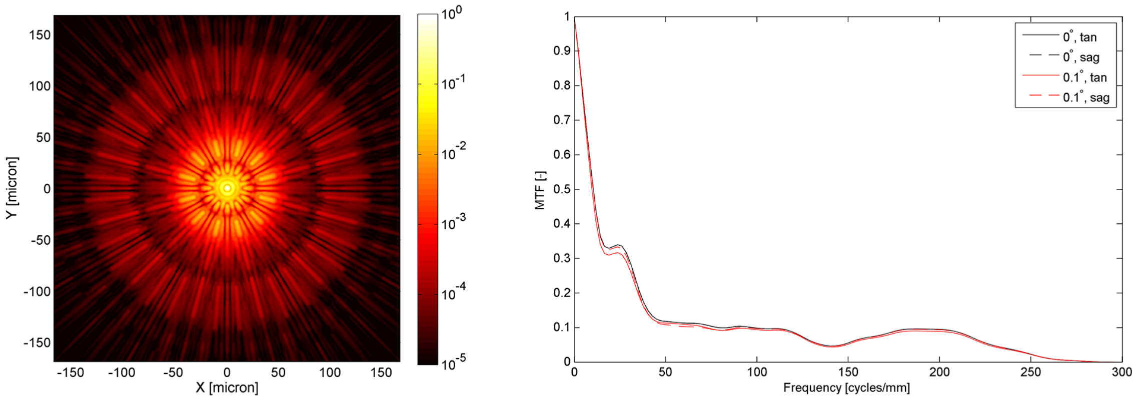


Figure 2. *Polychromatic PSF and MTF of the Michelson Synthetic Aperture*

larger telescope, a reduction in aperture area or an increase the complexity. Therefore, it was decided not to undertake a redesign effort, since it would not change the outcome of the trade-off.

Compared to a conventional telescope, a reduction in launch volume of the telescope is mostly achieved by reducing the length of the telescope. Given the dimensions of the afocal telescopes, it is hard to design a mechanism which would allow them to be stowed in a more compact volume, since this would quickly lead to volume conflicts. Thus, it is not envisioned that using deployment mechanisms will lead to a more compact launch volume for a this instrument.

### 3.2 Fizeau Synthetic Aperture

Designing a Fizeau synthetic aperture system is a lot more straightforward than designing a Michelson system. The only difference between a Fizeau system and a conventional telescope, after all, is the shape of the entrance pupil. As a starting point for the concept, a full-field Korsch telescope [15, 16] was chosen for its compact size, good image performance and low distortions.

The primary mirror was split into rectangular segments, which can be folded towards the instrument body during launch. It was chosen to split the primary mirror into three segments, following an MTF analysis. Even though an increase in the number of segments leads to a slightly higher MTF at the Nyquist frequency

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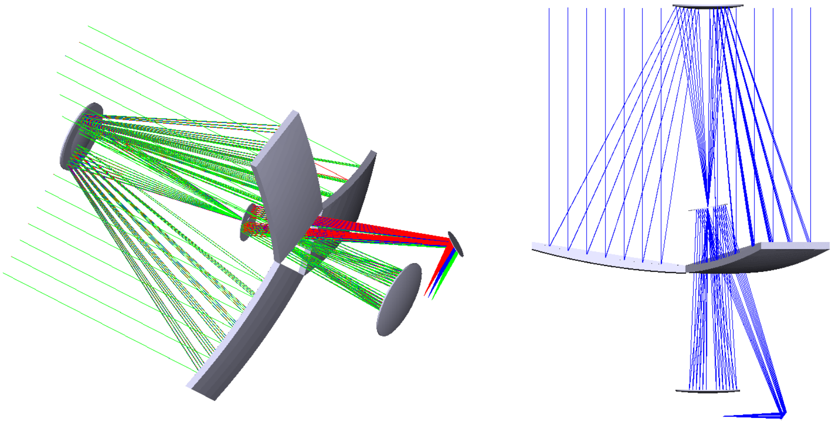

**Figure 3.** *Optical Lay-out of the Fizeau Synthetic Aperture*

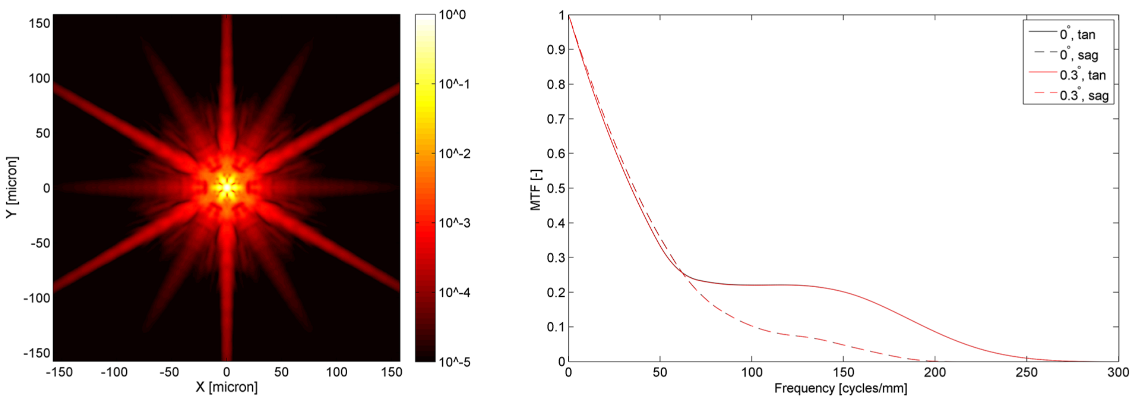


**Figure 4.** *Polychromatic PSF and MTF of the Fizeau Synthetic Aperture*

of the detector, this increase is accompanied by a loss in contrast at lower spatial frequencies. Additional advantages of using three segments are the more compact stowed volume of the instrument as well as the increased simplicity of the deployment mechanisms.

The secondary mirror is placed on an extendible boom, further reducing the stowed size of the instrument. The design was optimized for a short distance of 1.1 meter between the primary mirror segments and the secondary mirror, to reduce mechanical uncertainties in the extendable arm. With this length, the obscuration of the telescope could be kept at 0.25. A further reduction in length led to a larger obscuration ratio, increased aberrations and results in stricter alignment tolerances on the secondary mirror.

In Fig. 3 the optical lay-out of the Fizeau system is shown, while Fig. 4 on the next page shows the optical performance of the system.

As shown in Figure 4, the Fizeau synthetic aperture concept delivers a diffraction limited performance for the full field of view of 0.6° . In the MTF chart only one curve is visible, since the MTF curves overlap for the centre and the edges of the field (+/- 0.3° ) for the full frequency range. There is a considerable variation in MTF depending on the direction, which is a logical consequence of the pupil configuration. However, for all spatial frequencies up till the Nyquist frequency of the detector (90 cycles/mm), the Fizeau system has a higher MTF than the Michelson system.

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TABLE 2. *Trade-off between the Michelson and Fizeau systems. Scores between 0 and 5 were awarded for each trade-off criteria.*

| Criteria | | Weight | Values | | Scores | |
|---|---|---|---|---|---|---|
| | | | *Michelson* | *Fizeau* | *Michelson* | *Fizeau* |
| *Stowed Volume* | | 30 | 1.06 $m^3$ | 0.37 $m^3$ | 3 | 5 |
| *MTF* | *@ 50 mm-1* | 10 | 0.15 | 0.40 | 3 | 5 |
| | *@100 mm-1* | 10 | 0.08 | 0.17 | 2 | 4 |
| *Effective Aperture Area* | | 20 | 0.36 $m^2$ | 0.57 $m^2$ | 2 | 3 |
| *Complexity* | | 10 | - | - | 2.3 | 2.7 |
| *Field of View* | | 8 | 0.2° | 0.6° | 2 | 5 |
| *Thermo-Mechanical Stability* | | 8 | - | - | 2 | 3 |
| *Straylight Sensitivity* | | 4 | - | - | 4 | 2 |
| *Weighted Average* | | | | | *2.5* | *4.0* |

### 3.3 Trade-off

A trade-off was performed between the two concepts. Below, a general description is given of the trade-off criteria and the relative performance of the concepts. The results of the trade-off are given in Table 2. A detailed description of the trade-off and the scoring systems that have been used are beyond the scope of this paper and is available for download at [7] .

- **Stowed Size:** The stowed size was the most important criteria in this trade-off, as a compact launch volume greatly reduces the launch cost of the instrument and is a very important factor in bringing down the mass of the instrument. Therefore, it was given a high weight of 30%. The mass was not explicitly included in this trade-off, since it is strongly correlated with the instrument volume. In addition, large space structures are often constrained by volume rather than mass [21]. On top of that, it is very hard to get a reliable estimate at this stage of the project. With a stowed volume of 0.37 $m^3$, calculated using CATIA, the Fizeau system is considerably more compact than the Michelson system, which has an estimated volume of 1.06 $m^3$. Note that both systems are substantially more compact than a conventional telescope designed for the same ground resolution. Such a system is estimated to have a volume of at least 3.4 $m^3$, computed by taking the bounded volume of the full-field Korsch design of the Fizeau system.

- **MTF:** The average MTF of both concepts was compared at the Nyquist frequency of the detector as well as half this frequency. As demonstrated in Fig. 3 and 4, at both spatial frequencies, the Fizeau system has a higher MTF and as such receives a higher score. MTF was given a high weight of 20%, since it is an important metric describing the image quality. It was not rated as highly as the launch volume, however, since some performance may be sacrificed if the cost of the instrument is brought down significantly.

- **Effective Aperture Area:** For this trade-off the effective aperture was defined as the product of the total aperture area and the system transmission. The parameter can be seen as driving for achieving a good Signal-to-Noise (SNR) ratio. The Michelson system has substantially more optical elements in its optical path, resulting in a lower transmission, as well as a slightly smaller aperture area. Therefore, it receives a lower score. Like MTF, the effective aperture area is given a high weight of 20%.

- **Complexity:** The complexity of the two systems was compared on the basis of the number of optical components, the complexity of the surface types, the dimension of the largest optical component and whether or not the system uses moving parts. All in all, the complexity of the Fizeau system was determined to be lower than that of the Michelson system, primarily due to a much smaller amount of total parts. The Michelson system features 77 optical components, while the Fizeau has only 7. Complexity is given a weight of 10%, since it can lead to high system cost, but may be tolerated if it results in a substantially better performance in the other criteria.

- **Field of View:** With a full field of view of 0.6°, the Fizeau system has a wider field of view than the Michelson system, which can only reach 0.2°. A further increase in field of view is possible for the Fizeau system, while large design changes are needed for the Michelson system. Should the

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Michelson system be redesigned, it will likely increase in size and complexity. Thus, it is expected that this would not increase its overall score. The field of view is given a relatively low weight of 8%, since the primary goal of a high-resolution imager is not to obtain a complete ground coverage, but rather to observe specific regions of interest. Thus, for many applications, a small swath width may suffice.

- **Thermo-Mechanical Stability:** The thermo-mechanical stability of the Michelson is expected to be much more critical than that of the Fizeau system, primarily due to the long path lengths between the afocal telescopes and beam combiner as well as the large number of components. In addition, an active control system for the Michelson system will require the addition of several optical components, while for the Fizeau system direct actuation of the optical components is possible. The thermo-mechanical stability is given a weight of 8% in this trade-off. The main reason for choosing this weight was that the design philosophy used in this study is to develop a system that can function despite the inherent instabilities and uncertainties associated with such an instrument.
- **Straylight Sensitivity:** The Michelson system features multiple intermediate images, which can be used for the placement of a field stop and has small apertures that can be effectively baffled. While the Fizeau system also has a field stop, its aperture is much larger and therefore much more difficult to baffle. As such, the system is expected to be more sensitive to straylight. Straylight is given a low weight of 4%, because at this point, only a qualitative analysis has been performed, which is not detailed enough to be a major design driver. In the qualitative analysis, potential straylight issues and possible mitigation strategies are compared for both concepts. A more quantitative study of the straylight characteristics of a deployable telescope is subject to future research.

As shown in Table 2, the Fizeau was a clear winner of the trade-off and was therefore used as the basis for further development. In the detailed optical design phase, very few changes were made to the design, since a diffraction limited optical performance was already achieved. In Table 3, a summary is given of some key performance parameters that can be obtained for the final optical design. The SNR values have been calculated for two different Earth reflectances (ER) and sun zenith angles (SZA) under the assumption that a detector with 128 Time Delay and Integration (TDI) stages is used. At the time of writing, linescan detectors with up to 256 TDI-stages are available [5].

TABLE 3. *Key performance parameters of the final optical design*

| | | |
|---|---|---|
| Strehl Ratio | | >0.99 |
| MTF | @ 100 $mm^{-1}$ | 0.10 (s) / 0.23 (t) |
| | @ 50 $mm^{-1}$ | 0.33 (s) / 0.32 (t) |
| SNR | ER: 0.3, SZA: 60° | 100 |
| | ER: 0.5, SZA: 23.5° | 150 |

### 3.4 Sensitivity Analysis

While the nominal optical performance of the deployable aperture telescope is excellent, this is by no means a guarantee for a good performance in the harsh and dynamic space environment. The telescope will be operating in a low Earth orbit and will go in and out of eclipse every 100 minutes. As such, the instrument will be subjected to continuously changing heat loads, which can affect the position and shape of the optical components. To analyse the sensitivity of the design to such changes, a tolerance analysis has been performed. The main goal of this analysis was to create an alignment budget which must be met to ensure a good end-to-end image performance. It was determined using extensive simulations that such a performance can be met, on the condition that the peak-to-valley wavefront error stays below 7 waves. If this condition is met, the passive calibration system to be described in Section 5 of this paper can be used to retrieve the wavefront and correct the image.

In order to keep the wavefront error below the stated value, the elements must be positioned with the accuracies given in table 4. The directions of the axes used in this table are as follows: for the primary mirror segments, the X-axis is parallel to the long side of the segment, while the Y-axis is parallel to the short axis. The Z-axis for all optical elements is parallel to the optical axis of the telescope. The budget was established following a sensitivity analysis in which the effect of offsets in every degree of freedom were analysed.

As can be seen, particularly for the primary mirror segments, the tolerances are very tight. Especially the tolerances on the positioning in the Z-direction and the tilts around the X- and Y-axis will be very challenging;

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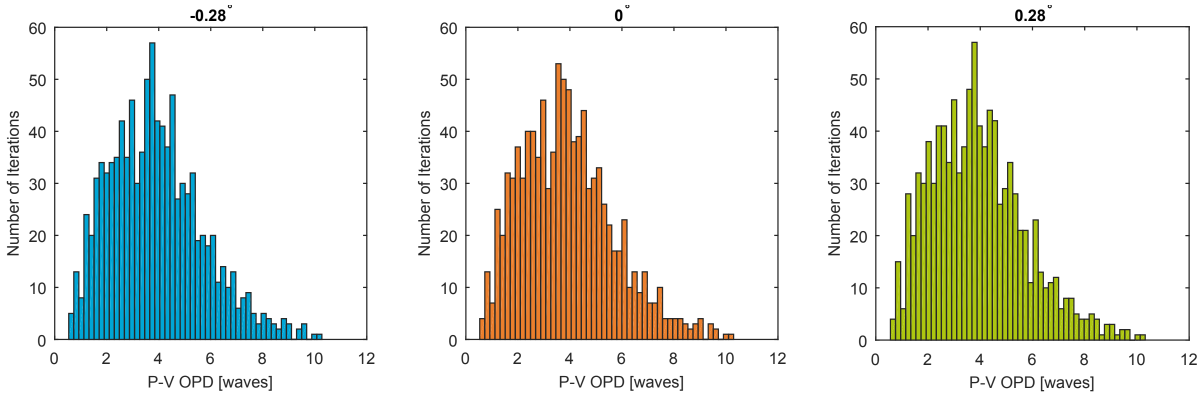


**Figure 5.** *Histogram of P-V wavefront error for 1000 Monte Carlo iterations*

it is clear that these values cannot be reached with a fully passive system. Therefore, underneath the primary mirror, actuators must be placed to ensure that the tilt and piston error of the segments can be controlled.

**Table 4.** *Required position and orientation tolerances of the primary mirror segments (M1), secondary mirror (M2) and tertiary mirror (M3)*

| Element | Position (μm) | | | Tilt (μrad) | | |
|---|---|---|---|---|---|---|
| | *X* | *Y* | *Z* | *X* | *Y* | *Z* |
| M1 | 1 | 2 | 0.1 | 0.4 | 4.5 | 0.2 |
| M2 | 4 | 4 | 2 | 17 | 17 | 50 |
| M3 | 10 | 10 | 5 | 17 | 17 | 50 |

The tolerances on the secondary and tertiary mirror are less challenging to meet. Even though the tolerances on the secondary mirror are approaching the limits of a passive system, an active system is not foreseen here. Should it prove impossible to design a deployment mechanism that can meet the tolerances, the errors in its position can be effectively compensated by the actuation system controlling the primary mirror segments.

A Monte Carlo simulation was run to check the wavefront error that could be achieved with the stated budget. A total of 500 runs was performed. In the histogram of Figure 5, the results of the analysis are given for three field of view. It was found that in 90% of the cases, the P-V wavefront error remains smaller than 6.3 waves for the complete field of view.

## 4 Mechanical Design

Using CATIA®, a conceptual mechanical design has been created for the deployable aperture telescope. In Figure 6, two views on the instrument are shown. A compact and lightweight design has been created. In the stowed configuration, the design fills a hexagonal envelope with sides of 35 cm and a height of 1.1 meter. Currently, the nominal mass of the instrument is estimated to be 75 kg. This figure includes the weight of the deployment mechanisms, the optical components, the instrument housing structure and the calibration mechanisms. It does not include the deployable baffle structure and the weight of the electronics.

On the left side of Figure 6, the backside of the lightweighted primary mirror panels is shown. The mirror panels will be made using a Silicon Carbide (SiC) substrate. This material has been chosen on the basis of its low Coefficient of Thermal Expansion (CTE), high thermal conductivity, high stiffness and excellent lightweighting possibilities. Areal densities as low as 7.1 kg/m$^2$ have already been demonstrated [26]. The low CTE of SiC makes the system quite tolerant to a thermal offset of one the segments; when relying on phase retrieval algorithms, a good performance can be achieved for a temperature range of up to +/-5° with respect to the desired operating temperature. This alleviates the requirements on the thermal control subsystem to a great extent compared to when an aluminium mirror would be used. For this material, the allowable temperature range would be 10 times smaller.

The primary mirror segments have been mounted on arms via three whiffles. This set-up was chosen to reduce load concentration at the connection points on the

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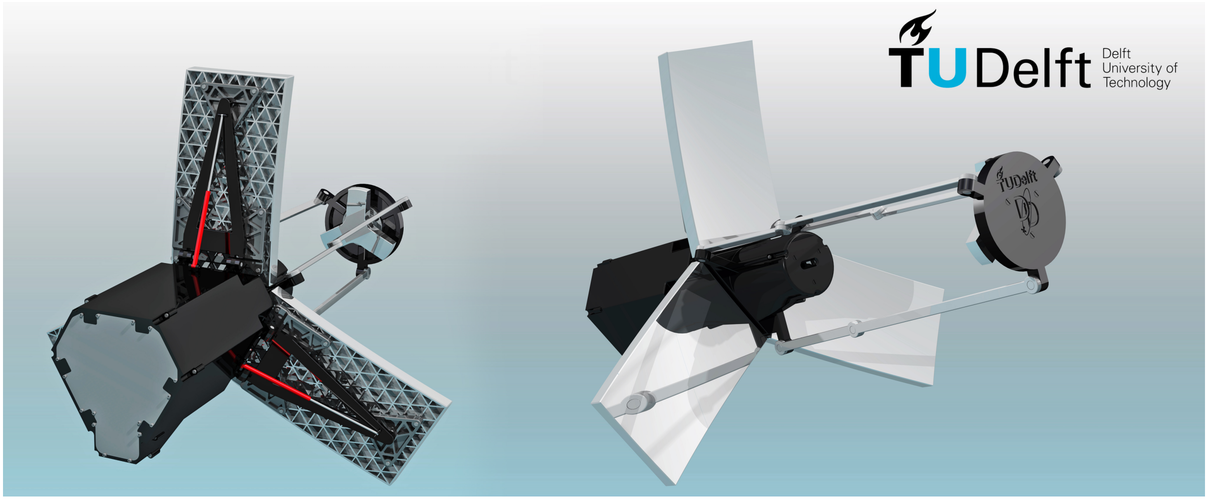


**FIGURE 6.** *Two views on the deployable aperture instrument*

mirror substrate, while also allowing for Between the whiffles and the arms, actuators can be placed to control the tilt and vertical position of the mirror segments. The arms can fold downwards in the stowed configuration. Doing so, leads to the most compact stowed configuration. The arms are supported by an extending rod for additional stability during the measurements.

Not shown in Figure 6 is the deployable baffle, which will be added to shield the instrument from straylight. During launch and integration of the satellite, the baffle will serve the additional purpose of shielding the sensitive reflective surface of the primary mirror segments from impacts. Currently, inflatable structures are being considered, but the design of this is a subject of future research.

The secondary mirror has been connected to the main housing via three deployable Invar arms. The arms feature a hinge in the centre to allow the mirror to be folded towards the main housing. This type of deployment mechanism is also found in the conceptual design of the International X-ray observatory (IXO) [1]. In the stowed configuration, the arms fit within the gap that is left when the primary are folded downwards. The arms have been positioned in such a way that they do not create any additional obscuration of the entrance pupil.

The main housing connects the primary and secondary mirror mechanisms to the other optical components. The temperature of the housing will be actively controlled using small heaters to ensure that the thermal gradients within the housing remain minimal. An active system is preferred here, since deformations in the tertiary mirror are highly undesirable, since they will lead to field dependent aberrations. Such aberrations are difficult to correct and will therefore complicate the calibration procedure.

In Figure 7, the deployment sequence of the instrument is shown. The secondary mirror will deploy first, followed by the primary mirror segments. Since the speed of deployment is not critical, only a small force is needed to drive the deployment. As such, motors placed on the hinges of the mechanisms can be used to deploy the mirror segments.

## 5 Calibration Strategy

As shown in Section 3.4, the deployable aperture system is very sensitive to misalignments of its optical elements. As such, a well-defined calibration strategy is of vital importance to ensure that a good image performance can be reached. In the left panel Figure 8, a schematic overview is given of the proposed calibration strategy.

The calibration strategy can be split up into two phases. The first phase will occur directly after launch and may be repeated periodically to correct for long-term drifts. The main goal of this calibration phase is to ensure that the optical components are positioned with the accuracies defined in table 4, which will result in a peak-to-valley wavefront error of 7 waves. The remainder of the wavefront error will be retrieved during operations using phase diversity techniques.

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**Figure 7.** *Deployment Sequence*

As an input to the calibration system, range measurements using capacitive sensors will be combined with interferometric measurements of a number of control points on the optical elements. In addition, measurements of stars can be used to estimate the wavefront errors of the telescope. To do so, wavefront retrieval algorithms, such as the Gerchberg-Saxton algorithm, can be used [10].

### 5.1 Metrology and Actuation Systems

The onboard metrology system of the deployable telescope is still in an early stage of development. A brief summary of the current design baseline will be provided in this section. Further details can be found in [24]. The currently proposed system will consist of two main components

First of all, capacitive edge sensors will be placed on the edges of the mirror segments, to measure offsets of the mirror segments relative to one another, and relative to the main structure. Such sensors are commonly applied in ground-based astronomical telescopes, such as the Thirty Meter Telescope that is currently under development [23]. In future iterations of the design, the shape of the mirror panels will be adjusted to create larger adjacent surface areas between two mirror segments, thereby allowing for more accurate measurements of the relative alignment of each of the mirror panels.

Secondly, an interferometric system will be used to measure the position of several reference points located on the surface of the primary mirror panels. These reflectors can be either corner cubes, or, as described in [14] retro-reflective gratings. Such gratings can be manufactured directly onto the mirror surface or can be attached later. By tuning the grating such that it has a low diffractive efficiency, the impact of the gratings on the amount of straylight is negligible. By tuning the power of the laser, the measurements will have a sufficient SNR, despite the low grating efficiency.

A preliminary system model was developed to assess whether the accuracies of the metrology baseline are sufficient to meet the top down budget defined in Table 4. Using the model, a detailed bottoms-up budget was defined, which includes a wide variety of error sources, such as sensor noise, misalignments of retro-reflectors and capacitive sensors, thermal fluctuations and laser instabilities. From the model, it follows that with realistic, achievable, alignment tolerances, thermal stabilities and sensor noise values, the budget given in Table 4 can be met with sufficient margin. This became clear by the results of a first order bottom-up measurement and actuator system design using interferometers and capacitive sensors. This showed compliance with the top-down driven and required mirror rotation and alignment tolerance budgets down to 200 nrads and 100 nm. Finally, this indicated the potential compliance of top-down and bottom-up system engineering budgets to validate a healthy system design concept and to push it towards a robust design.

After the metrology system has determined the position of the key optical components, actuators can be used to correct the position of the primary mirror segments. A more detailed analysis of the actuator system still has to be performed. Actuators designed for terrestrial astronomical telescopes can meet the requirements, both in terms of their stroke and accuracy [17]. However, more research is needed to determine whether or not this technology can be adapted for usage in space.

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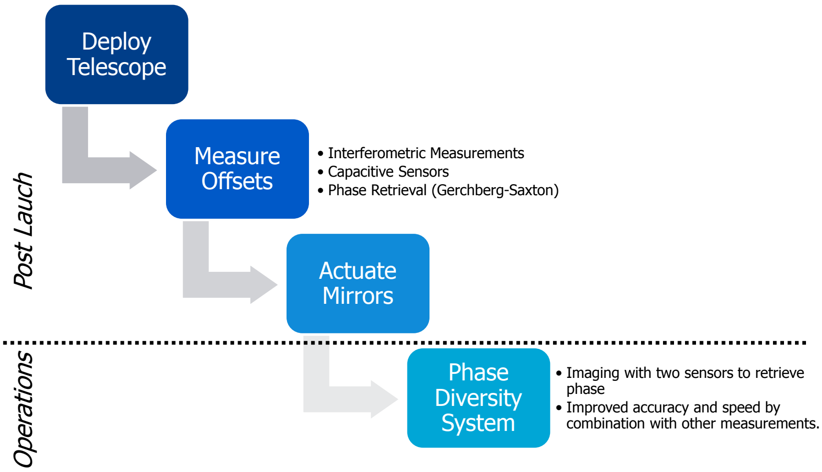


FIGURE 8. *Calibration Strategy*

### 5.2 Phase Diversity

During operations, a phase diversity will be used to recover the residual wavefront error and subsequently correct the image. In a phase diversity system, two detectors are used to capture the same image. The second detector is placed at a known defocus distance with respect to the first detector. Phase diversity is based on the principle that there is a known difference between the generalized pupil function at the first detector and the second detector. The generalized pupil function $H(x, y)$ is given by Equation 1 [11],

$$H_n(x,y) = P(x,y)\exp\left\{j\frac{2\pi}{\lambda}\left(W(x,y) + W_{defocus}(x,y)\right)\right\} \quad (1)$$

where $P(x, y)$ is the binary pupil function, $\lambda$ is wavelength and $W(x, y)$ is the unknown wavefront which will be estimated. $W_{defocus}(x, y)$ is the known defocus contribution to the wavefront; for the detector placed in the nominal focus, this term equals zero. To ensure a stable convergence in the presence of noise and a decrease in computing time, it is convenient to parameterize the wavefront by a set of aberration parameters $\alpha$. For this application, the wavefront coming from each of the three segments is parameterized with a set of 17 Zernike terms. It has been shown that by maximizing the cost function $L_m$, given in Equation 2, an estimate can be obtained for the wavefront parameters $\alpha$ [20].

$$L_m(\alpha) = -\sum_{u \in \chi} \frac{|D_1(u)S_2(u) - D_2(u)S_1(u)|^2}{|S_1(u)|^2 + |S_2(u)|^2} \quad (2)$$

$D_1$ and $D_2$ in Equation 2 are the Fourier transforms of the images obtained with the first and second detector, while $S_1$ and $S_2$ are the Fourier transforms of the estimates of the PSF at the first and second detector. The variable $u$ is used for the spatial frequency. The summation is done over the set of spatial frequencies $\chi$ within the passband of the instrument.

Two implementations of phase diversity were considered, as illustrated in Figure 9 In the first approach, which is generally shown in literature, a beam splitter is placed close to the focal plane, reflecting half of the light to the second detector which is placed at a known defocus distance. In the second approach, the second detector is looking at a slightly different field than the primary detector.

A major advantage of the second approach is that the two detector do not need to share the light coming from the telescope, resulting in twice as much signal on the detector. One issue which could cause the phase retrieval to fail is that the unknown component of the wavefront is different at the two detector locations due to spatial variations. However, since both detectors will be placed very close to one another, this effect is expected to be very small, as was later confirmed by a Monte Carlo analysis.

To validate the principles of the phase diversity, an

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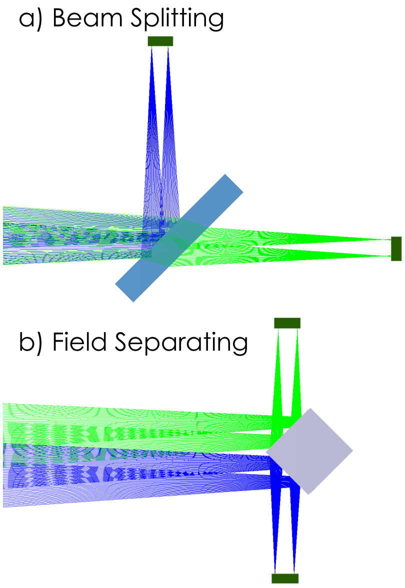


FIGURE 9. *Two implementations of a phase diversity system*

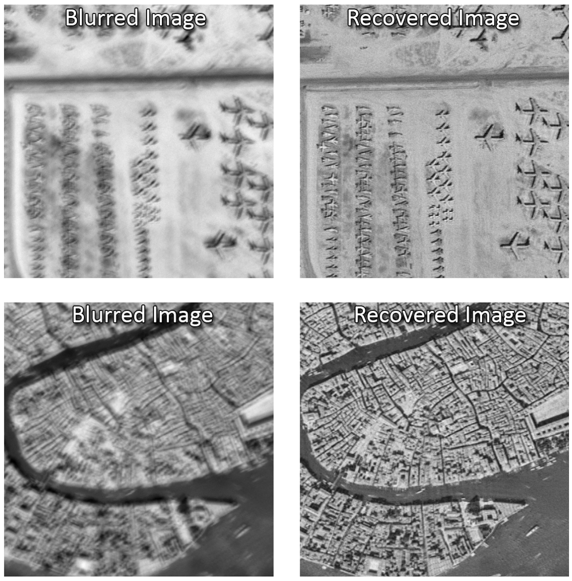


FIGURE 10. *Results of the end-to-end simulation. Both images were obtained with field-separated phase diversity.*

end-to-end analysis was performed using a combination of Zemax and Matlab modules. Perturbations were added to the optical model based on the budget given in table 4, after which wavefronts for both detectors were retrieved. The wavefronts were used to simulate the two images. Representative image noise was added before using the images in the phase diversity algorithms.

In Figure 10 some results of this analysis are shown for two different scenes. The blurred pictures show the image quality, or the lack thereof, of a system with a peak-to-valley wavefront error of 6 waves. The recovered images have been obtained when deconvolving the blurry image using the retrieved wavefront.

The success of the phase diversity process is evaluated by calculating the Residual Strehl ratio, $S_res$. The Residual Strehl Ratio is calculated using the difference between the recovered wavefront and the actual, modelled wavefront error. It can be calculated using Equation 3

$$S_{res} = \frac{\max_{x,y}[p_{res}(x,y)]}{p_{diff}(0,0)} \quad (3)$$

where $p_{res}$ is the PSF calculated with the residual wavefront error and $p_{diff}$ is equal to the diffraction limited PSF. If a Residual Strehl ratio of 1 is reached, the wavefront has been recovered perfectly. For values above 0.8, the difference between the recovered wavefront and the actual wavefront is smaller than the diffraction limit. As such, image restoration with the recovered wavefront will result in a nearly diffraction limited image. For values above 0.4, already a vast improvement in image quality can be observed, although some artefacts may be visible.

The analysis was repeated 120 times for different combinations of alignment errors, for both implementations of phase diversity. In Figure 11, a histogram is shown of the residual Strehl ratios obtained with the analysis. It was found that in 70% of the analysed cases the wavefront was retrieved successfully and most detail lost due to misalignments was recovered. Furthermore, the success rate of the algorithm was almost the same for the beam splitting implementation and the field separated implementation of phase diversity. It should be noted here that both simulations were performed using the same Signal-to-Noise ratio. Although field separated phase diversity can result in lower image noise, it may be preferable to bring down the number of TDI stages. For the 30% of the cases in which the algorithm failed to converge, no systemic effects were observed. It is expected that with future refinement of the algorithms, using several techniques described in literature [3, 2], the success rate can be increased significantly.


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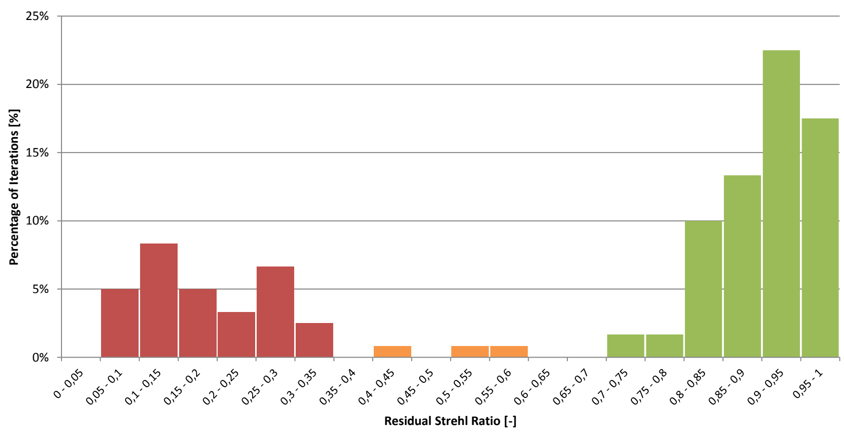


**Figure 11.** *Histogram of the residual Strehl ratio obtained with 120 iterations. The beam-splitting implementation of phase diversity was modelled here.*

## 6 Conclusions and Future Work

Sub-meter resolution imagery has become increasingly important for disaster response, defence and security applications. This paper presents a promising concept for a deployable aperture instrument, which can deliver such images whilst using a fraction of the mass and volume compared to conventional telescopes. End-to-end performance simulations of the instrument and its calibration system show promising results. A good image quality was obtained, within the limitations of a synthetic aperture solution, despite inherent instabilities occurring in a deployable system. Compared to a conventional telescope with an annular pupil, the contrast and SNR ratio will be lower, but this limitation in performance is compensated by a reduction in launch volume of a factor 4.

The actual bottom-up and top-down system engineering budgets comply and validate a healthy design concept. These budgets will be continuously refined in a stepwise systematic approach to keep the system engineering process in tight control.

Future work will consist of the further optimization of the performance of the telescope and the continuation of the mechanical design efforts. A detailed design of the mirror mounts, deployment mechanisms and actuators will be created. Key components of the system will be bread-boarded and a detailed analysis of the thermo-mechanical stability of the system will be performed.

Other topics that will be addressed in the near future are the further development of the metrology and actuation subsystems to be used in the post-launch calibration phase and the refinement of the phase diversity algorithms. In addition, alternative calibration approaches will be investigated, such as the alignment of the telescope through optimization of a sharpness criterion. This strategy could allow for a more robust and simple calibration procedure in orbit. Part of the work will be done within the scope of a PhD research project that is funded by ESA NPI, TNO and the Delft University of Technology. A continuously refreshing team of MSc students will work on the development of the system together with experts from diverse parties.

## References

[1] M. Bavdaz, P. Gondoin, K. Wallace, T. Oosterbroek, D. Lumb, D. Martin, P. Verhoeve, L. Puig, L. T. Soto, and A. Parmar. IXO system studies and technology preparation. In *SPIE Optical Engineering+ Applications*, pages 743702–743702–9. International Society for Optics and Photonics, 2009.

[2] A. Blanc, L. M. Mugnier, and J. Idier. Marginal estimation of aberrations and image restoration by use of phase diversity. *JOSA A*, 20(6):1035–1045, 2003.

[3] M. R. Bolcar. *Phase diversity for segmented and multi-aperture systems*. ProQuest, 2009.

DOI: 10.5281/zenodo.202244

[4] S. I. Corporation. Satellite sensors (0.31m - 2m). https://goo.gl/d2NU8p. Accessed: 2016-04-29.

[5] T. Dalsa. Piranha hs hs-s0-12kxx, 2011.

[6] DigitalGlobe. Worldview-3 data sheet. https://goo.gl/U7ekBW, Accessed: 2016-04-29.

[7] D. Dolkens. A deployable telescope for sub-meter resolutions from microsatellite platforms. Master's thesis, Delft University of Technology, 3 2015.

[8] D. Dolkens and H. Kuiper. A deployable telescope for sub-meter resolutions from microsatellite platforms. In *International Conference on Space Optics (ICSO)*, Tenerife, Spain, 10 2014.

[9] A. DS. Satellite imagery - the constellation. https://goo.gl/hBb9l0. Accessed: 2016-04-29.

[10] J. R. Fienup. Phase retrieval algorithms: a comparison. *Applied optics*, 21(15):2758–2769, 1982.

[11] J. E. Harvey and C. Ftaclas. Field-of-view limitations of phased telescope arrays. *Applied optics*, 34(25):5787–5798, 1995.

[12] P. M. Hinz, J. R. P. Angel, D. W. McCarthy Jr, W. F. Hoffman, and C. Y. Peng. The large binocular telescope interferometer. In *Astronomical Telescopes and Instrumentation*, pages 108–112. International Society for Optics and Photonics, 2003.

[13] L. Jochum, J. Castro, and N. Devaney. Gran telescopio canarias: current status of its optical design and optomechanical support system. In *Astronomical Telescopes & Instrumentation*, pages 621–631. International Society for Optics and Photonics, 1998.

[14] S. J. Kishner. High-bandwidth alignment sensing in active optical systems. In *San Diego,'91, San Diego, CA*, pages 215–229. International Society for Optics and Photonics, 1991.

[15] D. Korsch. Anastigmatic three-mirror telescope. *Applied optics*, 16(8):2074–2077, 1977.

[16] M. Lampton and M. Sholl. Comparison of on-axis three-mirror-anastigmat telescopes. In *Optical Engineering+ Applications*, pages 66870S–66870S. International Society for Optics and Photonics, 2007.

[17] K. R. Lorell, J.-N. Aubrun, R. R. Clappier, S. W. Miller, and M. Sirota. Design of a prototype primary mirror segment positioning actuator for the thirty meter telescope. In *SPIE Astronomical Telescopes+ Instrumentation*, pages 62672T–62672T. International Society for Optics and Photonics, 2006.

[18] L. Mugnier, F. Cassaing, G. Rousset, F. Baron, V. Michau, I. Mocœur, B. Sorrente, and M. Velluet. Continuous high-resolution earth observation with multiple aperture optical telescopes. In *Proceedings of the OPTRO 2005 International Symposium*, 2005.

[19] L. Mugnier, F. Cassaing, B. Sorrente, F. Baron, M.-T. Velluet, V. Michau, and G. Rousset. Multiple aperture optical telescopes: some key issues for earth observation from a geo orbit. In *5th International Conference On Space Optics*, volume 554, pages 181–187, 2004.

[20] R. G. Paxman, T. J. Schulz, and J. R. Fienup. Joint estimation of object and aberrations by using phase diversity. *JOSA A*, 9(7):1072–1085, 1992.

[21] L. D. Peterson, J. D. Hinkle, and S. Ismail. Deployable optics for earth observing lidar instruments. In *Earth Science Technology Conference Proce. NASA ESTO Earth Science Technology Conference, Palo Alto, CA*, 2004.

[22] G. Rousset, L. Mugnier, F. Cassaing, and B. Sorrente. Imaging with multi-aperture optical telescopes and an application. *Comptes Rendus de l'Académie des Sciences-Series IV-Physics*, 2(1):17–25, 2001.

[23] C. Shelton, T. Mast, G. Chanan, J. Nelson, L. C. Roberts Jr, M. Troy, M. J. Sirota, B.-J. Seo, and D. R. MacDonald. Advances in edge sensors for the thirty meter telescope primary mirror. In *SPIE Astronomical Telescopes+ Instrumentation*, pages 701210–701210. International Society for Optics and Photonics, 2008.

[24] S. Sridharan. Sensor measurements and error budget analysis for a deployable multi-aperture space telescope. Master's thesis, Delft University of Technology, 11 2014.

[25] SSTL. Applications of earth observation. https://goo.gl/qhQccL1. Accessed: 2016-04-29.


 DOI: 10.5281/zenodo.202244

[26] H. P. Stahl, D. T. Leisawitz, and D. J. Benford. Mirror requirements for safir. In *Astronomical Telescopes and Instrumentation*, pages 1613–1616. International Society for Optics and Photonics, 2004.

[27] T. W. Stuhlinger. All-reflective phased array imaging telescopes. In *1990 Intl Lens Design Conf*, pages 438–446. International Society for Optics and Photonics, 1991.