German Network for Lunar Science and Exploration

Application for an Affiliate Membership of the NASA Lunar Science Institute

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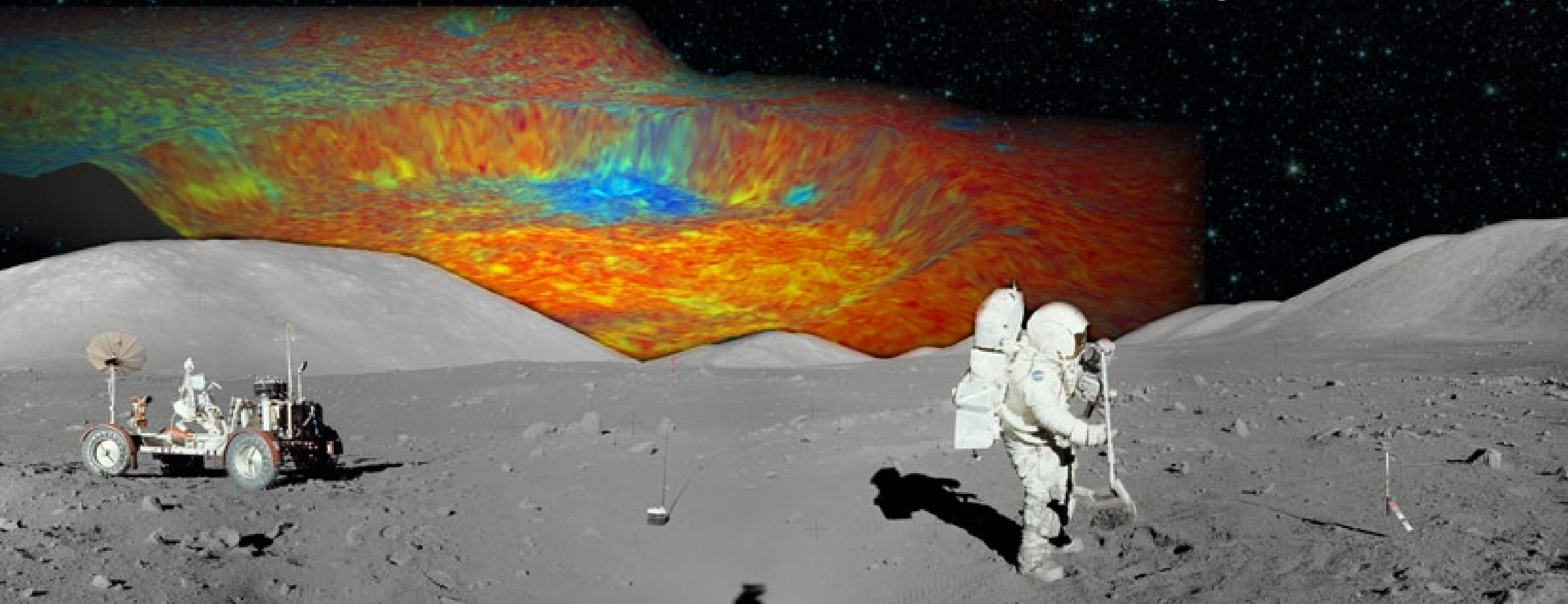
The full list of members of the German Network for Lunar Science and Exploration ist given in Annex 1.



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The full list of members of the German Network for Lunar Science and Exploration is given in Annex 1

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Executive Summary

This proposal summarizes the German activities in lunar research and exploration with respect to an application for an affiliate membership of the NASA Lunar Science Institute.

This is based on the understanding of the Deutsches Zentrum fuer Luft- und Raumfahrt (DLR) that subsumes all activities in preparation for and in realization of robotic and human missions to the Solar System in order to discover and to explore celestial bodies. In accordance with the Global Exploration Strategy (GES) the Moon is the next logical step for our exploration activities. Space exploration aims at increasing the sphere of influence of humans beyond low Earth orbit. The development of new technologies and infrastructures is vital.

From DLR's point of view the ten most important lunar exploration objectives are the following:

1. Develop and validate navigation and communication capabilities
    - Autonomous GNC
    - Moon-Earth communication
    - Communication and navigation on the Moon (e.g. Moon Positioning System)
2. Demonstrate descent and landing capabilities
    - Soft precision landing
3. Develop and validate surface mobility including advanced robotic technology
    - Robotic assembly
    - Autonomous rover with scientific P/L
    - Climber
    - Drill
4. Provide life support systems and habitats
    - Closed loop life support systems
    - Bioreactors
    - Agricultural systems
    - Research and counter measures of biomedical effects
    - Construction and infrastructure engineering
5. Develop and validate power supply systems
    - RFCS
6. Prepare Lunar Resource Utilization
    - Characterize resources (e.g. dating of samples)
    - Mapping of lunar resources
    - Demonstrate the feasibility of ISRU technologies for Hydrogen, Nitrogen, and Oxygen
7. Characterize the lunar environment
    - Characterize lunar atmosphere and monitor space weather
    - Mapping of lunar surface (Lunar information system)
    - Monitor seismological activities
    - Identify effects of lunar dust
    - Characterize thermal environment and volatile content (HP3)
    - Sample return capabilities
8. Characterize thermal environment and volatile content Mitigate environmental hazard
    - Monitoring of space weather and radiation
    - Monitoring of space debris
    - Dust mitigation

- Research on impacts of long-term exposure
- Radiation protection

9. Improve knowledge of lunar Geology
   - Identify sampling sites
   - Lunar structure
   - Lunar interior
   - Volcanic evolution
   - Origin of remnant magnetization
   - Subsurface stratigraphy
   - Lunar mineralogy and chemistry
   - Transition regolith/megaregolith

10. Satisfy public engagement
    - Two-way interaction with live video streams
    - Involvement of educational institutions
    - P/L capacity for educational experiments

In particular, this leads to the following collaboration objectives with NLSI Ames and other NLSI nodes:

Science of the Moon, on the Moon and from the Moon

Near-term

- Understanding of the lunar surface geology and interior in terms of a comparative data evaluation approach based on past and current mission contributions and its results.
- Understanding of the specific nature of the lunar regolith as the uppermost surface reflecting the lunar geochemistry and as an available source for materials.
- Understanding the lunar dust and plasma environment by simulation experiments in the laboratory.
- Understanding the Moon's origin in context with the evolution of the Earth-Moon-System.

This research will rely on the data bases already existing or to be collected in the near-future as a result of ongoing or confirmed international missions.

Long-term

- Precise highest resolution geological, geophysical, and geochemical global mapping of the Moon
- Monitoring of the lunar dust, particles, and fields environment
- In-situ and rover exploration on the lunar surface and subsurface in terms of heat flow, seismicity and rock/soil and volatile analysis.
- Sample return
- Astronomy from the Moon

This research will rely on upcoming robotic missions and lunar networks.

Exploration of the Moon

Near-term

- Development of exploration tools in terms of in-orbit and in-situ robotic vehicles and instrumentation.
- Development of lunar road maps for mobility resource utilization on the Moon.
- Earth-Moon communication and data transfer.
- Development of biomedical support systems and lunar environment simulation for human applications.
- Outreach: the Moon as part of Earth

Long-term

- Development of tools for resource utilization on the Moon.
- Concepts for lunar infrastructure engineering.
- Development of life support systems and being on the Moon

In detail we plan to interact with the NLSI community with respect to all objectives presented in chapter 2 of this proposal. In the near-time we will focus onto the following major topics:

- Continue our collaborations in ongoing missions and common data processing and evaluation projects, continue our participation in proposed lunar missions and continue our work in international groups dealing with lunar exploration (cf.2.4)
- Continue our scientific work for understanding the lunar geosciences and the lunar environment as described in 2.1
- Develop strategies for global lunar mapping and provide lunar data bases as road maps required for future lunar exploration mainly focusing on topographic, spectral, thermal, gravitational, radiation and cosmic dust distribution data sets. These work will be based on our experience with space missions such as stereo mapping of Mars, Moon, asteroids, icy satellites, spectral mapping of Mars, Venus, Moon, icy satellites, asteroids and comets, dust monitoring in the outer solar system and gravimetry of the Earth (cf. 2.2.1 and 3)
- Develop models of the lunar interior and origin (cf. 2.1)
- Collaborate in the development of soft lunar landing and mobility (cf. 2.2.2 and 2.2.3)
- Collaborate in the development of strategies for the power support of lunar surface operations (cf. 2.2.3.5)
- Collaborate in the development of strategies of Moon/Earth communication and on the Moon navigation (cf. 2.2.2.6 and 2.2.3.4)
- Collaborate in the characterization of the lunar environment (cf. 2.2.1.6, 2.2.1.7, 2.2.1.8.1, 2.2.2.5, 2.2.5.4)
- Collaborate in the development of life support systems (cf. 2.2.4)
- Collaborate in the development of strategies for lunar resource utilization (cf. 2.2.4)
- Collaborate in correlating on Earth lab capabilities (e.g. cross calibration of standards, cf. 2.2.5)
- Collaborate in the effort fostering the public interest in science of the Moon, on the Moon and from the Moon (cf. 4)

In the spirit of fostering collaboration between NLSI partners we envisage to exchange scientists, both senior scientists and young researchers, to provide experience and increase scientific and technical knowledge to the above topics, as well as improving the background and educating the next generation of scientists. The exchange of scientists foresees visits at NLSI in Ames and other partner institutions as well as DLR to host scientists from NLSI partners.

Members of the German Network of Lunar Science and Exploration are research institutions, universities and industrial companies (see Annex 1) that are involved in lunar research and technology development. On request of the Deutsches Zentrum fuer Luft- und Raumfahrt (DLR), the Institute of Planetary Research in Berlin is coordinating the lunar science and exploration activities related to this proposal.

1 Introduction

The Moon is an integral part of the Earth-Moon system, it is a witness to more than 4.5 b. y. of solar system history, and it is the only planetary body except Earth for which we have samples from known locations. The Moon is our closest companion and can easily be reached from Earth. Consequently, the Moon was the first logical step in the exploration of our solar system before we pursued more distant targets such as Mars and beyond. The vast amount of knowledge gained from the Apollo and other lunar missions of the late 1960's and early 1970's demonstrates how valuable the Moon is for the understanding of our planetary system. Even today, the Moon remains an extremely interesting target scientifically and technologically, as ever since, new data have helped to address some of our questions about the Earth-Moon system, many questions remained.

Understanding the origin and evolution of the terrestrial planets including Earth requires information about early differentiation, volcanism and related tectonics. However the physics and chemistry of these processes and their chronological sequences are not completely known. The Moon's composition is, due to the lack of water and its restricted geological active phase, relatively simple and thus provides insight into planetary processes that are much more obscured on other bodies. In particular, Earth and Venus exhibit extremely young surfaces, containing almost no record of the early evolution of a planet. Thus, evidence of how planets differentiate, of how early magma oceans operate, as well as of secondary differentiation and initial volcanism, is restricted to the Moon. Earth and Moon form a common planetary system that is unique among the terrestrial planets. Both bodies exchange gravitational energy. Is there a direct correlation of the specific evolution of Earth including life and the existence of the Moon? The Moon is thought to be the product of an early planetary collision of a Mars-sized body with Earth. However this model needs to be confirmed by measurable "ground truth". Dating of planetary surface and thus of planetary processes like emplacement of lava, collision events, and breaking of the crust depends on the distribution and frequency of impact craters. This statistical method is based on the long record of impacts known from the lunar surface and correlations with the absolute age of lunar samples. However, particularly small impact craters that are needed to improve the accuracy of this dating method have not been mapped out globally. As the Moon has no atmosphere its surface will not only collect impacts of smallest scale but is hit by projectiles with sizes down to the particles of the solar wind. The surface debris called regolith has thus collected information about activities in our space environment over time since the beginning.

A necessary further step in investigating the Moon is obtaining a global and integrated view of its geology, geochemistry and geophysics at highest resolution down to meter scale. In particular, we need to significantly improve our understanding of the lunar surface structure and composition, surface ages, mineralogy, physical properties, interior, thermal history, gravity field, regolith structure, radiation environment, and magnetic field. Low altitude orbiting spacecraft as well as in-situ experiments carried by lander and rover and equipped with a wealth of advanced technology instrumentation, can achieve such a goal.

Therefore, returning to the Moon is the critical stepping-stone to further exploring our immediate planetary neighborhood. In this concept study, we present scientific and technological arguments and objectives for the German lunar science and exploration approach which is in accordance with the high priority objectives of NASA in context with the ISECG NASA, JAXA, ASI, CSA, DLR, and ESA defined the following 15 coals for lunar exploration:

(1) Embrace a long-term strategic view for enhancing and expanding global partnerships for sustainable exploration of the Moon and beyond.

(2) Maximize early international partnership opportunities for lunar exploration.

(3) Use lunar exploration as a stepping stone for the demonstration of technologies, operational concepts, and cooperation approaches for Mars and other destinations.

(4) Take maximum advantage of ISS assets and other opportunities in LEO to advance technologies and capabilities for exploration beyond LEO.

(5) Develop, demonstrate and apply innovative capabilities, technologies and processes for improving resource and energy management and environmental protection, driven by the challenge of sustaining human life and operations in the hostile environment of space and the lunar surface.

(6) Develop a flexible, robust and reliable architecture that allows humans to safely explore the moon.

(7) Stimulate economic development and industrial innovation to enhance global economic prosperity via exploration of the Moon.

(8) Understand the origin and evolution of the Moon

(9) Interpret the uniquely preserved record of solar system evolution on the Moon and its relation to the origin and evolution of life

(10) Extend human presence in the solar system and improve the health of humans on Earth, by understanding and mitigating the risks to astronaut health in the lunar environment.

(11) Maximize science return by leveraging human-robotic partnership for lunar exploration and/or capabilities developed for lunar exploration.

(12) Develop innovative tools, means and methods to enable the public to engage interactively in human exploration.

(13) Inspire the next generation to embrace the tools of exploration: science, technology, engineering, mathematics and a sense of curiosity.

(14) Engage the public on the broader rationale and benefits of exploration.

(15) Achieve early, frequent and inspiring milestones relevant to the partnership, and to the public.

The German initiative for Lunar Science and Exploration originated from a national conference "Exploration of our Solar System", held in Dresden in November 2006. Major result of this conference was that the Moon is of high interest for the scientific community for various reasons, it is affordable to perform missions to the Moon and it insures technological and scientific progress necessary to assist further exploration activities of our Solar System. Based on scientific proposals elaborated by German scientists in January 2007, a Lunar Exploration Orbiter and in-situ-science concepts were defined. Further analyses were initiated by DLR in the frame of industrial studies of an orbiter as well as lunar landing and surface mobility concepts.

Partners of the German Network of Lunar Science and Exploration (GNLSE) are research institutions, universities and industrial companies (see Annex 1) that are involved in lunar research and technology development. On request of the Deutsches Zentrum fuer Luft- und Raumfahrt (DLR), the Institute of Planetary Research in Berlin is coordinating the lunar science and exploration activities related to this proposal.

2 Themes of the scientific work currently being undertaken and plans for interacting with the NLSI community

2.1 Main scientific objectives

2.1.1 Lunar geological evolution

2.1.1.1 Geomorphological and compositional mapping: global distribution of materials

The striking albedo difference between bright and heavily cratered highland terrains and the dark, flat and less densely cratered mare terrains is already obvious from Earth. This albedo change marks major differences in the composition and origin of the surface material as well as of morphological surface features. The highlands are mainly formed by pristine ferroan anorthositic rocks and the magnesium-suite rocks including norites, dunites, troctolites and gabbronorites. Less abundant are alkali-suite rocks and the KREEP basalts which are enriched in potassium, rare Earth elements and phosphor. The dark mare terrains are covered by younger basaltic volcanic rocks including lava flows and pyroclastic deposits.

The dominant geologic processes in shaping the lunar surface are impact processes. Mare terrains are large impact basins which provided the pathway for subsequent volcanic activities. The most prominent lunar impact feature is the South-Pole-Aitken basin with a diameter of about 2500 km which is the largest impact basin known in the solar system. Its basin floor is not filled by mare volcanism and its composition and origin are under debate. Impact processes are discussed in detail below.

Beside impacts, volcanism and tectonism are the main geologic processes responsible for the shape of the lunar surface. Geomorphologic features of volcanic origin include lava flows of the mare basalts, volcanic domes, cones and sinuous rills. Highland features of probable volcanic origin are the non-mare domes like the Gruithuisen domes and the light plains. Accurate assessment of volumes and lava rheologies requires data with high spatial and vertical resolutions. Finally, tectonism is the third geological process responsible for the inventory of lunar morphological features including faults, graben and wrinkle ridges. Tectonic features related to both extension and compression can be found.

The canonical view of a relatively simple thermal evolution of the Moon, and with this a four phase hypothesis, can easily be summarized: (i) a relatively quick assembly of our satellite from a biased mix of vaporized and pulverized materials originating both from a giant impactor and from the proto-Earth itself; (ii) development through mineralogical differentiation of an anorthositic solid crust accompanied by the sinking of mafic minerals from a magma ocean followed by a later concentration of KREEP materials at depth; (iii) surfacing of melts from this heterogeneous interior triggered and facilitated by crustal weakening and excavation due to massive impacts; (iv) production of impact melts (presumably with compositions related to the target materials). This mainly contributed to the formation of the crust and the evolution of the surface.

The uppermost lunar surface mainly consists of debris, fragments, and various glass welded fractions ultimately derived from the primordial anorthositic crust, augmented by extrusive products of varying compositions, excavated materials from depth, extralunar materials, such as meteorites, solar particles, etc., and impact-generated products ranging in size from micro-regolith to massive melt sheets. Nevertheless, the lunar surface mineralogy remains simple compared to those of other planetary bodies such as the Earth, Mars and Venus, due to the depletion of key volatiles in the primordial mix, in particular H_2O and OH. Furthermore, the surface has remained virtually unmodified for the last 1.2Ga and most is more than 4Ga old. In short, the whole lunar surface mineralogy-petrology can be simplified and has been characterized by four main mineral phases: plagioclase, pyroxene(s), olivine, and ilmenite, with other oxides as accessory mineral. As on most planetary bodies, these minerals combine in endless fractional permutations and their relative concentrations in discrete uniform parageneses (i.e. rocks) allow us to classify them into distinct petrological groups, albeit within a continuous compositional spectrum. For instance, a rock containing a large fraction of plagioclase will be classified according to the type and fraction mass of its mafic component: orthopyroxene will give 'norite', clinopyroxene 'gabbro', and olivine 'troctolite'. Since the presence and ratio of the mafic components relate to the particular thermal and compositional environment where the melt was produced, establishing their spatial and volumetric distribution, especially where they are accessible only by remote sensing, it is of obvious and great value.

The spectral characteristics of the main mineralogical species are reasonably well understood across the whole diagnostic spectrum (UV-IR), including the visible to near infrared. In particular, laboratory studies have published both theoretical and actual spectral plots of the constituent minerals. Additionally, several studies have looked into the variations of spectral absorption characteristics when, as in real life scenarios, minerals are admixed. Different techniques claim some degree of success (e.g. MGM) in unscrambling the absorption curve variation and translating it into not just the detection of certain phases, but also their quantitative fractional estimates. In reality, what is verified, simulated, and learned under controlled laboratory conditions cannot be easily applied to real life observations using similar instruments observing from space. For a start, as on the Moon, surface materials are not conveniently sorted by grain size on a flat surface in a controlled thermal and illumination environment.

Remote sensing of the lunar surface, compared to laboratory analysis of returned samples and lunar meteorites, need to take into account infinite variations in terrain topography (e.g. shadowing) and shifting angles of illumination. To complicate matters even further lunar soils may not be entirely representative of the underlying bedrock typology. They are the result of countless violent impacts and admixing, which have modified both their spatial and mineralogical distribution. Lastly, returned lunar samples, on which instrument calibration is dependent on, offer a rather biased representation of surface materials (e.g. they were all collected within a 50 degree latitudinal range on the nearside); furthermore, realistic regolith simulants are notoriously difficult to produce.

The main products of the continuous weathering processes acting on lunar surface materials, glass (sometimes the major constituent fraction in a lunar samples), and native iron, combine in increasing reflectance toward longer wavelengths and weaken, even altogether cancel out, diagnostic absorption characteristics in the NIR and beyond. The longer a surface material is exposed to space elements, the 'deeper' the red continuum will affect its reflectance imprint. For this reason low spatial resolution orbiting and telescopic observations in the NIR have trained their instruments mainly on relatively 'fresh' crystalline soil samples, such as on gravitationally exposed sloping surfaces or fresh crater ejecta. Nevertheless, the scientific yield has been rich: e.g. exposed surface materials containing large fractions of olivine and orthopyroxene, reflecting, as in the case of excavated materials, the compositional stratigraphy of the underlying subsurface, sometimes to considerable inferred depths.

2.1.1.2 Stratigraphic relations based on impact chronology

The chronology of geologic events on the Moon is based on radiometric ages determined from Apollo and Luna landing site samples, regional stratigraphic relationships, and crater degradation and size-frequency distribution data for units largely defined prior to the end of the Apollo program. For example, accurate estimates of mare basalt ages are crucial to place constraints on the duration and the flux of lunar volcanism as well as on the petrogenesis of lunar mare basalts and their relationship to the thermal evolution of the Moon. The internal thermal history and evolution of a planetary body is reflected in the timing and extent of volcanism on its surface (Head and Wilson, 1992). Thus, investigations of the ages and compositions of volcanic products on the surface provide clues to the geologic and thermal evolution of a planet. In preparation for and following the American and Russian lunar missions, extensive work on the lunar stratigraphy has been done, for example by

Wilhelms (1970, 1987, Shoemaker and Hackman (1962), and Wilhelms and McCauley (1971)). Based on this early work we know that the lunar highlands are generally older than the mare regions (e.g., Wilhelms, 1987), that mare volcanism did not occur within a short time interval but shows a substantial range in ages (e.g., Shoemaker and Hackman, 1962; Carr, 1966), and that there is significant variation in the mineralogy of basalts of different ages (e.g., Soderblom et al., 1977; Pieters et al., 1980). Compared to Earth we only have a small number of samples of the Moon that can help us to decipher its geologic history and evolution. For example, accurate radiometric ages for lunar mare basalts, which cover about 17% of the lunar surface (Head, 1976; Head and Wilson, 1992) are available only for the spatially very limited regions around the Apollo and Luna landing sites (e.g., BVSP, 1981; Stoeffler and Ryder, 2001, and references therein). As most lunar mare basalts remain unsampled even after the Apollo and Luna missions (e.g., Pieters, 1978; Giguere et al., 2000), absolute radiometric age data for the majority of basalts are still lacking. Fortunately, we can derive relative and absolute model ages for these unsampled regions with remote sensing techniques. For example, inspection and interpretation of superposition of geologic units onto each other, embayment, and cross-cutting relationships within high-resolution Apollo and Lunar Orbiter images were used to obtain relative ages for lunar surface units (e.g., Shoemaker and Hackman, 1962). In addition it has been shown that crater degradation stages and crater size-frequency distribution measurements, calibrated to the landing sites, are useful to derive relative and absolute model ages (e.g., Hartmann, 1966; Greeley and Gault, 1970; Neukum et al., 1975a; Neukum and Horn, 1976; Boyce, 1976; Boyce and Johnson, 1978; Wilhelms, 1987; Neukum and Ivanov, 1994; Hiesinger et al., 2000, 2001, 2002, 2003, 2009; Morota et al., 2008; Haruyama et al., 2009). Crater size-frequency distribution measurements are a statistically robust and accurate method to derive absolute model ages of unsampled regions on the Moon and other planetary surfaces. One of the major goals of stratigraphic investigations is to date geologic units, integrate them into a stratigraphic column, which is applicable over the whole planet, and to calibrate this column with absolute ages.

Over more than 10 years, we have dated basalts in Oceanus Procellarum, Imbrium, Serenitatis, Tranquillitatis, Humbodtianum, Australe, Humorum, Nubium, Cognitum, Nectaris, Frigoris, and numerous smaller occurrences like impact craters and sinus and lacus areas. Our investigations showed that (1) in the investigated basins lunar volcanism was active for almost 3Ga, starting at about 3.9-4.0Ga and ceasing at ~1.2Ga, (2) most basalts erupted during the late Imbrian Period at about 3.6-3.8Ga, (3) significantly fewer basalts were emplaced during the Eratosthenian Period, (4) basalts of possible Copernican age were only found in limited areas in Oceanus Procellarum. Our results confirm and extend the general distribution of ages of mare basalt volcanism and further underline the predominance of older mare basalt ages in the eastern and southern nearside and in patches of maria peripheral to the larger maria, in contrast to the younger basalt ages on the western nearside, i.e., in Oceanus Procellarum.

2.1.1.3 The distribution of feldspars and implication for the evolution of the primary crust

Some major findings based on the early inspection of Apollo samples were that (1) anorthosite is common in the lunar highlands and (2) lunar anorthosite is highly anorthitic. Thus, plagioclase in lunar highlands rocks has typically a composition of An_{96}, which is much higher than what is typically found in plagioclase in terrestrial rocks. For example, the composition of plagioclase in terrestrial massif anorthosites is typically in the An_{35} to An_{65} range. Ultimately, the high plagioclase contents in lunar rock samples reflect the Moon’s depletion in volatile elements like sodium. In addition, compared to terrestrial standards, the *Mg´* of pyroxene and olivine in lunar anorthosite is much more ferroan than in terrestrial rocks of such high Ca/Na ratio and any other nonmare lunar rocks, such as impact-melt breccias and troctolites ($En_{44–76}$) (e.g., Lucey et al., 2006 and references therein). Consequently, lunar anorthosite with a plutonic or relic plutonic textures has been called *ferroan anorthosite* (e.g., Dowty et al., 1974a, and b).

The ferroan-anorthositic suite or *FAS* (Warren 1993) consists of ferroan anorthosites (>90% plagioclase) as well as their more mafic but less common variants, ferroan noritic anorthosite and ferroan anorthositic norite. Some ferroan anorthosites contain olivine, but pyroxene usually predominates. While usually heavily brecciated, a number of samples suggest that lunar ferroan anorthosites are coarse-grained intrusive igneous rocks, formed during slow cooling at some depth below the surface. The high concentration of plagioclase feldspar in ferroan anorthosites indicates that they are cumulate rocks, produced by the separation and accumulation of crystals from the remaining melt. Geochemically, ferroan anorthosites have very low concentrations of both FeO and incompatible trace elements, for example Th, compared to other lunar rocks (e.g., Lucey et al., 2006 and references therein).

From the Apollo landing sites, several large rocks were brought to Earth that are nearly monomineralic plagioclase (e.g., Warren 1990) and outcrops of “pure” anorthosite can be identified in Earth-based and spacecraft observations (Hawke et al. 2003; Otake et al., 2009). However, Lucey et al. (2006) argued that its perceived importance to lunar crustal formation may have been overestimated. While the large “Genesis Rock” (sample 15415, e.g., Ryder 1985) was found at the Apollo 15 site, and while ferroan anorthosite is the most common pristine rock type at the Apollo 16 site, it is uncommon to rare at other sites. Consequently, Lucey et al. (2006) argued that because (1) the Apollo 16 mission was the only Apollo mission that landed on feldspathic highlands distant from any mare region, (2) highly feldspathic (typically >98% plagioclase) ferroan anorthosite was ubiquitous at the site, and (3) we did not learn about the first feldspathic lunar meteorite until long after the Apollo program ended, the idea persists that the lunar highlands are dominated by ferroan anorthosite and that the FAS component of the crust is highly feldspathic. However, the feldspathic lunar meteorites, orbital geochemistry, as well as regolith samples from Apollo 16 and Luna 20 suggest that highly feldspathic ferroan anorthosite is not necessarily typical of the highlands surface, at least, not on the Moon’s near side (e.g., Lucey et al., 2006 and references therein). Instead, most feldspathic lunar meteorites are more mafic than the feldspathic material of the Apollo 16 regolith (Korotev 1996, 1997; Korotev et al. 2003). In addition, the high *Mg´* of the upper feldspathic crust (70±3), which at the surface is at the high end of the range for FAS rocks, implies that magnesian feldspathic rocks are the source of a significant fraction of the plagioclase in the lunar highlands (e.g., Lucey et al., 2006 and references therein).

2.1.1.4 Impact processes

Mainly two processes: space weathering and impact “gardening” have re-shaped the face of the Moon. Cratered landscapes and impact basins are sufficient evidence of the bombardment from space over time. The lunar surface is the ideal place to study craters and the populations of solar-system objects forming them. The Moon also is the closest celestial body such that sample return is not too expensive. This has allowed precise age determinations and will allow so in the future. Photogeological age determination with the help of crater statistics works mostly because of the calibration with the help of isotopic ages. Indirectly this allows to test dynamical models of the impactor population and consequently of the formation of the solar system. Impact cratering is a basic process for planetary science but physical models are far from complete. No atmosphere stops the flow of ejecta material from large lunar craters so it is distributed more globally and the main mode of transport is ballistic. Secondary craters are formed by large ejecta blocks returning to the surface, whereas the finest material is often deposited in the form of rays. The entire surface is covered with the material from large basin-forming events. A number of geochemical and mineralogical signatures of meteorite impact are known but not all such phenomena are thoroughly understood. In this respect it is easier to find answers on the Moon than on a geologically active planet like Earth. On our planet the atmosphere protects from hypervelocity impacts of objects below a threshold size. In contrast details about the small-size end of the impactor population can be found from the in-situ investigation of small lunar craters. Even direct observation of the impact of micrometeorites seems to be feasible.

Geochemical consequences are important and from in situ exploration of lunar craters understanding of the mineral formation in the aftermath of a large impact will improve substantially. Our contribution will be the attempt to improve physical models for hypervelocity impact processes. This includes hydrodynamic, gas-dynamic, statistical and stochastic models dealing with the causes and consequences. It will also be our goal to improve the state of the art of impact simulations as well as to identify physical causes for distinct observational phenomena. The outcome of many individual events has to be abstracted to adequately describe planet formation as a whole. Physical models will also be developed to understand compositional changes.

Important constituents of the lunar environment are neutral gas, plasma, and ejecta particles that are generated by meteoroid impacts onto the lunar surface. The characterization of these components has gained importance because of their effects on the expected enhanced human and robotic activity on the lunar surface. Lab experiments using electrostatic dust accelerators are planned to study hypervelocity impact cratering and associated phenomena in detail.

2.1.1.5 The regolith structure, physical properties and stratigraphy

Impact processes at all scales and the interaction of the lunar surface with the solar and cosmic radiation are responsible for the formation and evolution of the lunar regolith. In the early history of the Moon, large-scale impactors bombarded the lunar surface and shattered and fragmented the lunar crust down to depths of several kilometers. Ejecta were broadly distributed and produced a chaotically structured impact debris layer, the megaregolith. The size distribution of impactors changed drastically at the end of the heavy bombardment and smaller projectiles dominated the evolution of the lunar surface. The impacts generated a layer of loose, fine-grained and poorly sorted material, the lunar regolith. While small-sized impacts homogenize the regolith by continuously turning over the surface layer, larger impactors are able to excavate fresh and unweathered material from the subsurface resulting in a layered structure with numerous discontinuities.

Thickness estimates for the regolith had been deduced from the analysis of impact craters and from modeling yielding a thickness of only a few meters in the mare areas and up to 15m in the highlands. Radar observations from Earth gave an average regolith thickness of 5-12m. Recently, radar observations from Kaguya, Chandrayaan-1 and LRO have revealed further insight into the complex structure of the lunar regolith. The mare regions, for example, exhibit an alternating sequence of compact basalts and loose regolith indicating periods of exposure and erosion after the emplacement of a volcanic layer. A better understanding and mapping of the lunar regolith structure and stratigraphy are essential for unraveling the geologic evolution of the lunar surface and in preparation of any future exploitation.

Due to the lack of a magnetic field and the very tenuous lunar atmosphere, the lunar surface is directly exposed to space weathering processes caused by the continuous bombardment of particles from space including micrometeorites, energetic particles of the solar wind and cosmic radiation. An increasing exposure to space weathering results in an intensified physical and chemical alteration or maturation of the lunar regolith, which involves numerous processes like lithification, mechanical comminution, melting, vaporization, formation of agglutinates, ion implantation, and sputtering. This may result in the accumulation of scientifically or even economically interesting materials like trapped solar wind particles to decipher the history of our sun, ^{3}He, metallic iron or hydrogen/water. Space weathering is also responsible for changes in the optical properties of the lunar regolith which have to be taken into account in analyzing remotely sensed data.

Proposal team members are actually studying the properties and characteristics of the lunar regolith by analyzing high-resolution LROC imagery of impact craters and spectral observations in the VIS-NIR by SIR-2 and HySi. Moreover, laboratory spectral measurements of lunar analogue materials are performed in the thermal infrared to better understand the spectral characteristics of the lunar regolith in this wavelength domain and to help in the design of a mid-infrared lunar mapping spectrometer. A further extension of the wavelength range investigated in the laboratory towards the UV is in preparation.

2.1.2 Modeling of the lunar interior

2.1.2.1 Lunar Interior Gravity

There are many open questions regarding the present constitution, origin, and evolution of the Moon that would be best addressed in the frame of a network mission. A higher temporal resolution and precision than with ground based and space techniques alone can be achieved by emplacement of a geophysical network of one or several soft-landed surface stations on the Moon. During the Apollo missions, the US astronauts deployed a small 4-station geophysical instrument network that operated successfully until 1977. The Apollo experience suggests that there is much open science potential in such network data to further our understanding of the Moon's internal structure, its environment, and the dynamics of the Earth-Moon system. Due to the proximity of the Moon, a network could return new science data very rapidly after launch. It is conceivable that data packages from the Moon can be received by small meter-size receiving antennas (e.g. DLR Weilheim, DLR Neustrelitz), within a time window of 2-3 hours per day. A network offers great potential for international cooperation, as several nations are currently planning and preparing Lunar missions. The Lunar experience could be a test bed for future global geophysical/geodetic networks on other planets.

The precise knowledge of the lunar gravity field in terms of accuracy and resolution is crucial for understanding the internal structure and evolution of the Moon. A high accuracy and high resolution gravity field with a global mean error better than 0.1mGal for half-wavelengths of 50km would allow to precisely

- determine the structure of the lunar crust by inversion of topography and gravity information,
- investigate heterogeneity and elasticity of the lunar mantle,
- investigate the reason for the shift between the center of mass and center of figure of the Moon,
- improve the characterization of the size, physical state and composition of the lunar core,
- determine lunar Love numbers as a measure for the tidal distortion of the Moon from time-varying gravitational perturbations,
- determine the rotational state and physical librations of the Moon,
- draw conclusions on the origin of the Moon and early Earth history,
- investigate the Earth-Moon system as a whole,
- possibly conduct relativistic studies in the Earth-Moon system.

2.1.2.1.1 Tidal Instrument Suite

Important clues on the constitution of the lunar interior can be gained by monitoring tidally-induced surface deformations from orbiting and landed spacecraft and Earth-based, highly precise lunar laser ranging observations. In addition to the Apollo lunar seismic data record, those observations could provide useful constraints on mantle elasticity and size, composition and physical state of a lunar core. A major advantage is that the tidal forcing function for a synchronously rotating satellite like the Moon is exactly known. Tidal measurements may be significantly impeded by instrumental drift, instrument coupling to the surface, and local sources of noise. Key tidal parameters such as degree-2 body tide Love numbers are mainly related to the constitution of the deep interior of the Moon and can be retrieved from monitoring tidally-induced changes of local gravity and surface tilt by operating a gravimeter and tiltmeter, respectively, at the lunar surface. A most promising approach would involve time-varying gravitational field observations from an orbiting spacecraft combined with long-term monitoring of tidally-induced gravity changes at the lunar surface.

2.1.2.1.2 Laser Beacons

Laser reflectors near the Apollo and Lunochod landing sites have been in use for Earth-Moon ranging up to the present day. Owing to the complexity of the observational task, only a handful terrestrial Laser ranging stations are capable to routinely carry out the measurements, among them the "Fundamentalstation Wettzell", Germany. We propose a Lunar ranging experiment of the next generation. On the Lunar nearside laser "beacons" shall be deployed, shooting short Laser pulses towards Earth. We estimate that the received pulse strength from a 50mJ Laser on the Moon illuminating the entire Earth (like the one that is currently being developed in Germany for the Laser Altimeter on BepiColombo, BELA) is 3 orders of magnitude larger than a ranging signal returning from the Lunar retroreflectors. Such laser shots could be received by most of the stations within the International Laser Ranging Station (ILRS) network. From observations by multiple stations, systematic measurement errors can be identified and removed. We propose to deploy Laser beacons near the poles or the equatorial limb as these locations are best suited for the tracking of Lunar librations in latitude and longitude. Lunar ranging data will further our understanding of the Moon's internal structure, the dynamics of the Earth-Moon system, and fundamental physics. For example, from the tidal response at the expected mm accuracy, elastic parameters of the Lunar interior can be modeled. Inferences can be made on a solid or liquid Lunar core and its size and oblateness. In addition, parameters from gravitational physics, e.g., the time-stability of the gravitational "constant", or the strong equivalence principle (Nordtvedt-effect) could be modeled with vastly improved accuracy. To complement the experiment, we propose to deploy small radio transmitters along with the Lasers. While the position of the Lasers forms anchor points in the Lunar-fixed coordinate system, the radio transmitters will firmly tie Lunar coordinates into the radio-defined stellar Quasar coordinate system.

2.1.2.1.3 Magnetic Field Monitoring

A Lunar Surface Magnetometer was included in the ALSEP experiment packages of Apollo 12, 15, and 16. There are significant variations in the strength of the Moon's intrinsic magnetic field on regional scales, indicating the presence of strong localized magnetic field sources in the crust. There is no evidence for a dipole field. Variations in the observed magnetic field strength – as the Moon moved through the Earth's magnetic field – have helped constrain how the Moon's electrical conductivity varies with depth. Limits on the size of the Moon's iron core and on temperatures within the mantle can be given. Temperature estimates from electromagnetic sounding approach the melting point at a depth between 800 and 1500 kilometers, in agreement with the observed attenuation of seismic waves. The magnetometer observations are consistent with a core that is up to about 450 kilometers in radius.

2.1.2.2 Lunar heat flow

Planetary heat flow is a fundamental parameter characterizing the thermal state of a planet. The heat extracted from the lunar interior is a fundamental boundary condition for models of the thermal evolution of the Moon and closely connected to the past and present temperature distribution in the lunar interior. The Moon has been magmatically active for a large part of its history and Mare volcanism has been surprisingly long-lived. Knowledge of the lunar heat flow would allow us to address question connected to the generation of partial melt in the lunar mantle and better understand the timing and extent of lunar volcanism.

Although the Moon does not currently possess an internally generated magnetic field, its crust exhibits regions of weak remanent magnetization. The origin of this magnetization is under debate, but a former internally generated magnetic field is one possible source. Internal magnetic field generation requires the presence of a highly conductive fluid in the lunar interior and motion within this fluid. This could have been provided by a liquid core early in lunar history. Motion within the core would have been driven by either thermal or chemical convection caused by core freezing. These processes depend on the amount of heat extracted from the lunar interior and the knowledge of the rate of heat loss places constraints on models of lunar magnetic field generation.

The heat flow from the lunar interior is provided by heat liberated by the decay of radioactive elements in the lunar mantle and secular cooling, i.e., heat loss of primordial heat acquired during accretion. Therefore, lunar heat flow is closely connected to its bulk chemical composition in terms of the abundance of the heat producing elements K, Th and U and knowledge of the average heat loss of the Moon would directly constrain the abundance of these elements. Questions of the lunar bulk composition are also relevant to the accretional history of the Moon itself and the history Earth-Moon system.

Among the many ways to investigate a planetary body, measuring heat flow as a function of position is one of the few ways by which we can address questions of lateral heterogeneity in the deep interior. On Earth, variations of the surface heat flow are due to the effects of crustal composition and thickness, tectonic activity, terrene age, climatic effects, and hydrothermal circulation. On the Moon, the primary variations are likely due to differences in crustal composition and the thickness of the megaregolith and lithosphere. Measurements by the gamma ray spectrometer onboard the Lunar Prospector spacecraft indicate that the distribution of heat sources on the lunar surface is highly non-uniform and abnormally high K, Th and U abundances are found around the Oceanus Procellarum, a region known as the Procellarum KREEP terrain. However, gamma ray spectroscopy probes but the first half meter of lunar regolith and the depth extent of the anomaly is unknown. This question could be addressed by investigating the surface heat flow.

The question of the distribution of heat producing elements in the lunar interior and the degree of differentiation in terms the crustal enrichment of radioactive elements can also be addressed by measuring heat flow. A determination of the mantle heat flow in regions of very thin crust like, e.g., the South Pole Aitken Basin, as compared to the nearside and farside Feldspathic Highlands, would allow us to constrain the crustal contribution to the surface heat flow and learn about the crustal enrichment of K, Th and U.

While tens of thousands of terrestrial measurements have been made to constrain heat flow on the Earth (Pollack et al. 1993), to date only two independent measurements have been performed to constrain heat flow on the Moon (Langseth et al. 1976). Measurements were obtained at the Apollo 15 and 17 landing sites, situated on the boundary of the Procellarum KREEP terrain and differed by 25%. This relatively large spread has given rise to some debate and different theories concerning its origin have been proposed. It is generally accepted that the lateral and possible vertical variation of the concentration of heat producing elements plays a dominant role (Wieczorek and Phillips, 2000), and it has been speculated that the observed differences may be connected to different thicknesses of the Th-enriched Imbrium ejecta-blanket at the two locations (Hagermann and Tanaka, 2006). However, irrespective of the cause for the large spread, it is evident that the present ambiguities make estimates of the global lunar heat loss unreliable and many questions concerning the thermal state of the Moon remain unresolved.

Therefore, additional measurements are required. These experiments need to be carefully planned and executed: Measurements should be made at depths that extend below the penetration depth of the annual thermal wave and long term measurements are desirable. To help obtain straight-forward results, heat flow measurements should also be taken well away from terrene boundaries to minimize heat flow focusing effects (e.g., Warren and Rasmussen, 1987).

To summarize, a determination of the lunar heat flow will allow us to address the following questions:

1. What is the average rate of heat loss from the Moon?
2. How did the Moon thermally evolve and how does this tie into the magnetic field and magmatic history of the Moon?
3. Do different lunar terrenes (Procellarum KREEP Terrene, Feldspathic Highland Terrene, Mare, South Pole Aitken Basin) have unique heat flow budgets?
4. What is the bulk composition of the Moon in terms of heat-producing elements?
5. What are the implications of these differences for the chemical, thermal and magmatic evolution of the Moon?
6. What is the degree of differentiation between the crust and mantle in terms of radioactive elements and what does this tell us about the formation of the Moon and the Earth-Moon system?

2.1.2.3 Implications from seismology

Seismology is the only direct way to assess the actual interior of a planet. The subdivision of the Earth's structure into crust, mantle, outer core and inner core was discovered by evaluation of seismological data in the beginning of the 20^{th} century. Today, 3D seismic tomography is able to provide pictures of upwelling plumes and down going slabs in the entire mantle of the Earth. Thus it provides important constraints to the geodynamical evolution of the planet, hence to our understanding of the planetary heat engine.

The Moon is the only other body in the solar system on which seismological experiments were conducted successfully. From the Apollo data, we learned that the lunar seismicity is fundamentally different from that of the Earth. Lunar seismicity correlates strongly with the tidal cycles caused by the Earth and the Sun. But neither the spatial nor the temporal pattern of lunar deep quakes is well understood. The shallow lunar quakes still remain enigmatic. They are relatively strong, but very rare, such that the almost eight years of continuous Apollo data could not reveal a specific pattern.

To us, the most important questions to be answered by future lunar seismological experiments are the following:

- How are the lunar deep quakes coupled to the tidal periods? Geodynamical modeling suggests that the deep interior, around 900km depth, is too hot for brittle failure, but this is the depth in which the deep quakes concentrate. What is the mechanism behind these quakes?
- Is the lunar deep seismicity distributed uniformly over the Moon? The current literature suggests that almost all deep sources are on the near side, whereas the lunar far side remains inactive. Is this an observational artifact, or is the far half of the Moon fundamentally different from the near half?
- Did the spatial pattern of deep seismicity change since the shutdown of the Apollo experiment? Are the clusters that were active in the 1970s still active? Are spatial changes diffused or do they reflect a migration process?
- Are the shallow quakes related to geological features visible on the surface? Do they express tectonic processes like lithospheric shrinking due to secular cooling, are they related to the Mare-Highland boundaries, or are they produced by impacts of strange matter particles originating outside the solar system, as statistical analyses suggest?

- Do the shallow quakes also occur in distinct periods, or are the randomly distributed in time?
- Does the Moon have a liquid core? How large is it? Geodetic and magnetic observations pose constraints, but seismology could provide a direct measurement.
- Does the 500km-discontinuity suggested by some seismic mantle models and interpreted as bottom of an ancient magma ocean really exist? Is it a global feature, suggesting a global magma ocean, or is it related to near side provinces only?
- Can the crustal and lithospheric thicknesses assumed in gravity modeling be confirmed by direct measurement? What are the spatial variations?

The Moon is tectonically active. From 1972 – 1977 a 4-station seismic network operated at the Apollo landing sites and detected more than 12,000 seismic events. These fall into three main groups, the tidally triggered Deep Moonquakes, tectonically-driven Shallow Moonquakes, and Meteoroid Impacts. The data give us the opportunity to study the lunar interior structure by inversion of seismic wave arrival times and seismic amplitudes. Major findings of the Apollo network include the identification of the lunar crust. The impact data give us a chance to study the present-day lunar meteoroid flux. Proposal team members at University Muenster and DLR have been involved in the analysis of the Apollo seismic data, supported by DFG (German Science Foundation) and DLR.

Networks of control points and accurate maps constitute important reference and planning tools for any aspects of lunar science and future exploration. While coordinates near the Apollo landing sites are firmly established, coordinate knowledge deteriorates rapidly towards the lunar farside and the polar areas. Camera data which often suffer from pointing uncertainties have to be analyzed by photogrammetric techniques and processed to warrant co-registration with the Lunar-fixed coordinate system. Stereo images may be processed to derive Digital Terrain Models.

Images obtained by the Clementine spacecraft have been used as a basis for global maps. The stereo camera on board the Kaguya spacecraft has obtained global topographic coverage. Using its onboard instrument LOLA (Lunar Orbiting Laser Altimeter), the Lunar Reconnaissance Orbiter will obtain a global topographic model. LRO's Narrow Angle Camera (NAC) will collect stereo data, from which high-resolution (1-3m) Digital Terrain Models may be produced. Analysis of the LOLA pulse characteristics can also be used to study surface roughness and albedo.

Members of this proposal team from DLR, FUB, and TUB have been involved in the development of a sophisticated photogrammetric software system and have a profound working experience in the analysis of planetary stereo images (Jaumann et al., 2007). Work has been done for the Moon. Members of the proposal team are members of the Kaguya and the LOLA teams have access and a work experience with the Laser altimeter data.

2.1.3 Lunar environment

2.1.3.1 Implication from a magnetosphere

Due to the absence of a global lunar magnetic field the Moon does not exhibits a magnetosphere as planets Earth or Mercury. This implies that the magnetized solar wind plasma or the terrestrial magnetotail plasma directly impinges onto the surface of the Moon. Two types of interaction need to be considered in this respect, that of the magnetic field with the Moon and that of the plasma particles with the Moon.

While most solar wind ions are implanted into the lunar dust, a significant fraction is also backscattered and emitted by energetic neutral atoms. The impact of energetic solar particles onto the surface also leads to significant charging of the lunar surface, causing levitation effects and other processes at the surface. The impact of multiply charged solar wind ions on the lunar surface can also result in soft X-ray and extreme ultraviolet photon emissions. All these processes will eventually result in non-homogenous ageing of the surface. The lunar dayside surface is thus a complex surface where the fundamental processes of direct interaction between space plasmas and planetary bodies can be observed par excellence. Space weathering processes can ideally be studied here.

On the nightside a clear and obvious plasma void is created, the lunar wake structure that extends many lunar radii behind the Moon. Plasma adjacent to this void will expand into this depleted region. As electrons and ions diffuse into this region, the quasi-neutrality of the plasma is violated here and significant electric fields are generated. The lunar near-surface electric field in the vicinity of the terminator is very complex, with a surface polarity change from dayside-positive to nightside-negative potentials and the formation of intensely negative potentials due to the low plasma density and increased temperatures in the trailing lunar wake region. Electrically charged dust is influenced by these fields. The magnetic field is enhanced within the optical lunar shadow and depressed near the edge of the shadow.

In regions where the crustal magnetic field is large mini-magnetospheres develop. The Reiner Gamma magnetic anomaly, when exposed to the solar wind, is significantly distorted. Magnetic field amplifications observed are too large to present direct measurements of crustal field and must be caused by the interaction of the solar wind plasma with these magnetic anomaly regions. In these mini-magnetospheres increases in low-energy electron energy fluxes are often observed, consistent with an increase in plasma density across a shock surface. Also observed is low frequency wave activity in the magnetic field data, often associated with electron energization up to keV energies. Observations, however, also indicate that fully formed lunar mini-magnetospheres are rare and difficult to observe from space.

The interaction of the solar wind magnetic field with the Moon depends very much on the electrical conductivity structure in the lunar interior. If the conductivity would be zero the interplanetary magnetic field would just pass through the Moon. If the conductivity would be infinite, the field would never be able to penetrate and magnetic field draping would be very significant. As the lunar interior exhibits a finite electrical conductivity the interplanetary magnetic slowly diffuses through the Moon. The induced magnetic field gives rise to draping effects, observable in space. Furthermore, the transfer function between the inducing field and the induced field has been used to determine the lunar conductivity structure and the size of the lunar core.

Future, detailed observational and numerical studies will be necessary in order to understand the complex physics of the Moon - solar wind interaction region. Understanding these processes allows concluding about the lunar interior structure and the exogenic lunar surface modifications. At present, the Moon represents the only natural laboratory available to us to study solar wind interaction with small-scale crustal magnetic fields, though simulation results and theoretical work can also help us understand the physical processes at work.

2.1.3.2 Lunar Dust environment

Like any atmosphere-free body of the solar system the Moon is shrouded in a cloud of dust particles that have been lifted by meteoroid impacts from its surface. The dust particles, so-called ejecta, move on ballistic trajectories, most of which re-collide with the lunar surface. Because the cloud particles are small samples of the upper layers of the lunar surface, measurements of the cloud particle composition and dynamical properties provide spatially resolved mapping of the lunar surface composition. Modern, next-generation dust cameras allow to measure even trace amounts of water ice, or organic compounds embedded in the ejected grains can be quantized with high accuracy. The analysis of surface ejecta by a dust camera is complementary to studies by remote sensing methods (e.g. by infrared spectroscopy), which is often not unique. To illustrate the capability of a dust camera, the figure below shows an example of a mass spectrum of a 0.6 μm orthopyroxene particle recorded with the LAMA impact mass spectrometer.

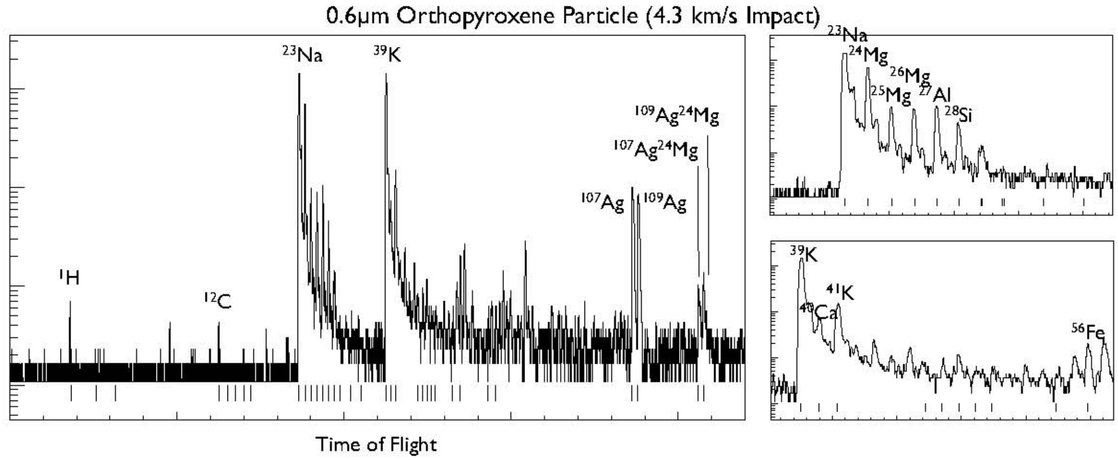


Figure 1: Mass spectrum of a 0.6 μm orthopyroxene particle impact onto a silver target recorded with the LAMA reflectron spectrometer at the Heidelberg dust accelerator facility. The right column shows expanded views of the spectrum around the ^{23}Na (top) and ^{39}Kline (bottom). The impact speed was about 4kms^{-1}.

The density of the lunar dust exosphere depends on the flux, speed and size distribution of the interplanetary and interstellar micrometeoroids at 1AU as well as on the properties of the lunar surface. Assuming a meteoroid mass flux of $5.9 \cdot 10^{-16}$ kgm^{-2} s^{-1} and an average meteoroid speed of 17.9kms^{-1}, one finds that a 0.1m^{2} dust detector on a satellite orbiting the Moon at 50 km altitude will detect about 100 ejecta particles per day.

The electrostatic levitation and transport of lunar dust remains an interesting and controversial science issue from the Apollo era (Colwell et al., 2007). There were several in-situ and remote sensing observations that indicate that dusty plasma processes are likely to be responsible for the mobilization and transport of lunar soil. Images taken by the television cameras on Surveyors 5, 6, and 7 showed a distinct glow just above the lunar horizon referred to as horizon glow (HG). This light was interpreted to be forward-scattered sunlight from a cloud of abundant dust particles above the surface near the terminator.

A photometer onboard the Lunokhod-2 rover also reported excess brightness, most likely due to HG. From lunar orbit during sunrise the Apollo astronauts reported bright streamers high above the lunar surface which were interpreted potentially as dust phenomena. The Lunar Ejecta and Meteorites (LEAM) Experiment was deployed on the lunar surface by the Apollo 17 astronauts in order to characterize the lunar dust environment. Instead of the expected low impact rate LEAM registered hundreds of signals associated with the passage of the terminator which swamped any signature of primary impactors of interplanetary origin. It was suggest that the LEAM events are consistent with the sunrise/sunset-triggered levitation and transport of charged lunar dust particles.

The issue of dust mobilization and transport of lunar soil is also of great engineering importance in designing human habitats and protecting optical and mechanical devices. As a function of time and location, the lunar surface is exposed to solar wind plasma, UV radiation, and/or the plasma environment of our magnetosphere. Dust grains on the lunar surface collect an electrostatic charge and contribute to the large-scale surface charge density distribution. They emit and absorb plasma particles and solar UV photons, and provide an electromagnetic interface to the lunar interior. These processes are relevant to: (a) understand the lunar surface environment; (b) develop dust mitigation strategies; (c) understand the basic physical processes involved in the repeated build-up and collapse of dust loaded plasma sheaths. It is planned to study these dust plasma interactions in the lab and to develop instrumentation to characterize the dusty plasma on the lunar surface.

2.1.3.3 Radiation Environment

Each celestial planet is embedded in the space radiation environment composed of energetic particles of galactic and solar origin. These particles are modulated by interstellar magnetic fields, the solar magnetic field and the magnetic field of the planet (if the latter exists and is strong enough to deflect charged particles) before they interact with the molecules and atoms of the planetary atmosphere and soil. This causes a radiation environment on the planet's surface comprising a complex mixture of primary radiations and secondary radiation of all types of radiations and a wide energy range. In addition, there are emissions from primordial lunar radio nuclides.

The galactic cosmic rays are composed of energetic particles which cover a broad spectrum of energy and mass values. About 98% are atomic nuclei and 2% electrons and positrons. The nuclear component consists of about 87% protons, about 12% α particles and about 1% nuclei of $Z>2$, the so-called HZE particles. These nuclei are stripped off all their orbital electrons and have traveled for several million years through the galaxy before entering the solar system. When these charged particles enter the solar system, they interact with the outbound streaming of the solar wind and the interplanetary magnetic field which vary with the solar activity. In interplanetary space, the annual radiation dose amounts to ≤ 0.1Gy/a depending on mass shielding with the highest dose at 0.15g/cm² shielding. Cosmic ray fluxes are not constant; they vary between two extremes which correspond in time with the maximum and minimum solar activity. Solar activity and cosmic ray fluxes are anticorrelated.

Besides electromagnetic radiation, the sun emits continuously particle radiation, consisting mainly of protons and electrons, the so called solar wind. The intensities of these low energy particles vary during the 11 year solar cycle by 2 orders of magnitude of about 10^{10} and 10^{12} particles cm^{-2} s^{-1} sr^{-1}. The related energies are so low (for a proton between 100eV and 3.5keV), that the particles will be stopped within the first few hundred Angstrom of tissue. Occasionally, the surface of the sun releases large amounts of energy in sudden local outbursts of gamma rays, hard and soft X-rays and radio waves in a wide frequency band. In these solar particle events (SPEs) large currents and moving magnetic fields in the solar corona accelerate solar matter. Coronal particles with energies up to several GeV escape into the interplanetary space. They spiral around the interplanetary magnetic field lines. Within the ecliptic plane field lines expand from the sun into the interplanetary medium like the beam of a rotating garden hose. They connect the Earth with a certain spot on the western part of the sun. The number and energy spectrum of particles observed in SPEs at Earth depends on this connection. SPEs show an enormous variability in particle flux and energy spectra and have the potential to expose space crew to life threatening doses. Their occurrence is linked to the solar cycle with a higher probability at the end of a solar maximum.

In the vicinity of a planet, the flux of primary nuclei is modulated by the magnetic field of the planet, if it exists. This causes, on one hand, deflection of particles having low energies, the so-called cut-off effect; and on the other hand, capture of solar wind light particles forming the radiation belts. There are also several indications for a weak intrinsic magnetic field of Mars, especially from observations on Phobos 2 and Mars Global Surveyor. The Moon has no global magnetic field, but some surprisingly high local magnetic-field intensities are detected.

In colliding with the nuclei of molecules of lunar soil, the primary cosmic ray particles loose energy in ionization interactions and generate secondary radiation, like hadrons (e.g. protons, neutrons, π and K mesons) and leptons (e.g. muons and electrons). These secondary particles undergo further interactions or decay into other particles increasing the complexity of the radiation field.

On Earth, the galactic cosmic radiation contributes about 1/6 of the annual terrestrial dose of natural ionizing radiation which amounts to 2.4mSv/year. (The highest natural radiation dose on Earth is received in Kerala, India with 13.0mSv/year). Particle fluxes on Moon and Mars are calculated, for example, by Clowdsley (2003, NASA Langley). The total dose equivalents calculated from these spectra give roughly for a point on the lunar surface for GCR values of some 380mSv/year (solar Minimum) and 110mSv/year (solar Maximum) and for a worst case SPE 900mSv; the contribution of neutrons to these dose equivalents by about 27mSv/year, 10mSv/year and 20mSv.

The stochastic solar particle events are efficiently absorbed by the atmospheres of Venus and Earth, but this is not the case for the Moon. During a worst case SPE the radiation exposure in a space suit can reach about 2Sv causing serious early radiation effects or even death. For a stay of humans on Moon dwellings or shelters built from regolith are therefore needed to be safe. Even more of concerns are solar particle events occurring during the cruise to Moon where even higher doses can apply. The hazards due to SPEs have been identified as one of the major risks in the performance of human interplanetary missions.

An additional radiation environment comes from emissions from the planetary surfaces due to the primordial radio nuclides ^{40}K, ^{235}U, the ^{238}U series and the ^{232}Th series. The abundance of radio nuclides on Mars has been assessed from that found in the Martian meteorites. It contributes a total of 0.3mSv/a to the dose equivalent which is less that 1% of that resulting from cosmic rays.

Models and simulations exist that describe the approximate radiation exposure in space and on the lunar surface. The knowledge about the radiation exposure at the Moon surface caused by the charged particles of galactic and solar origin comes only from calculations from radiative transfer models based on a few radiation measurements outside the Earth orbit and on the lunar surface during the Apollo missions. Therefore, these models need to be validated with observations using appropriate radiation detector devices.

Characterization of New Shielding Materials:

- Analyze shielding and secondary radiation production processes, considering geometry, materials and radiation sources, using computer codes
- Expand data base for nuclear cross sections
- Improve computer codes (heavy ion transport, neutrons, 3D)
- Define combinations of flexible materials for the future habitat structures; candidate materials are multi-layers, including Beta cloth (glass fiber), Mylar, Kevlar, Nextel, Combitherm and polyethylene , graphite nanofibres
- Define reference multilayer configuration(s) for testing on flight experiments (e.g. MATROSHKA)
- Procure detailed material data for simulations with different radiation analysis tools
- Provide materials for testing in ground laboratories (Brookhaven, Chiba, GSI) and support test execution
- Perform iterations, proposing improved and alternative shielding solutions (composition, thickness, configuration and architecture) and improvement of S/W tools and models
- Compare flight dose and particle flux data with ground test and simulation results, correlate and tune models
- Based on simulations and tests, evaluate the equivalent doses to the crew for the defined LEO missions and compare them with the established radiation dose thresholds.

2.1.3.4 Particle flux and radiation

2.1.3.4.1 Interaction with the surface

Galactic cosmic rays (GCR) and solar energetic particles (SEPs) interact with the lunar surface and produce a radiation environment quite different from what we measure on Earth. The relatively constant flux of the high-energy (GeV/nuc) GCR produces secondary products inside lunar material which are commonly used to date soil samples and rocks which are still available from the Apollo (and some Russian sample-return-) missions. Constancy of the GCR flux is a probably unfounded assumption, recent work (e.g., Shaviv, 2002) indicates that the present-day cosmic ray flux is slightly (24%) higher today than the average flux over the past 150-700Myrs with variations between 25% and 135% around the current value. Obviously, the uncertainties in dating of lunar samples have implications for under-standing lunar geology and surface processes. Therefore, an accurate understanding of the cosmic-ray interaction with lunar soils – present and past – is crucial to the overall goal of better understanding the Earth-Moon system and its implications for the % history and evolution of the solar system.

The interaction of low-energy particles (keV/nuc – MeV/nuc) with lunar soils changes their appearance through the process of “space weathering” by which even the soil chemistry can be altered (see, e.g., Hapke, 2001, for a review).

Figure 2 shows the GCR radiation field on the lunar surface for the 1977 solar activity minimum (solid lines) and the 1990 maximum conditions (dashed lines) (Clowdsley et al., 2003). The primary GCR flux (labeled with Z >0) peaks at energies around 300-500 MeV/nuc, but the dominant population comes from neutrons (Z=0) which are created in nuclear reactions between GCR and lunar soil nuclei. This situation is quite different from that at Earth surface, where the secondary flux is dominated by muons which are created high up in the atmosphere. Moreover, the Earth is shielded by its magnetosphere and atmosphere, resulting in a maximum secondary particle production at around 20km altitude. On the Moon, this occurs at or just below the surface further reinforcing the need for an accurate understanding of the interaction of GCRs and SEPs with the lunar surface.

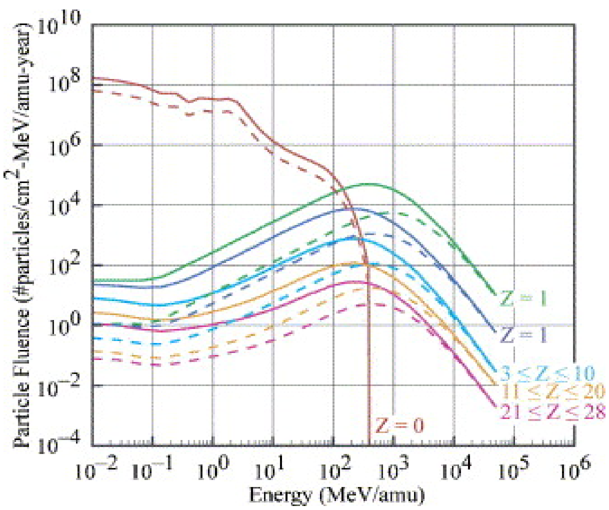


Figure 2: The GCR radiation field on the lunar surface during the 197 solar activity minimum (solid lines) and the 1990 solar activity maximum (dashed lines) (Clowdsley et al., 2003).

2.1.3.4.2 Constraints for manned mission

The Apollo missions performed various measurements of the lunar radiation environment with a multitude of sensors and technologies. However, only passive detectors were used on the lunar surface. Such detectors can only measure total doses integrated over the time period between activation and readout of the sensor. Active instruments, which give time series measurements, were only used in orbit and the measurements were only transmitted to Earth to a very limited extent due to problems with telemetry and other issues. Thus, continuous series of data are rare; moreover, they only contain absorbed dose rates, and no information is available on equivalent or effective doses as are required to determine the radiation exposure of astronauts.

Despite being within the Earth's magnetosphere for some fraction of its orbit, the shielding against radiation thus offered is only marginal (Huang et al., 2009) and a manned station on the Moon would have to be buried deep within the regolith. The depth is determined mainly by the dose due to secondary neutrons which is only weakly attenuated by the dry lunar soils (see Fig. 3 from Tripathi et al., 2006).

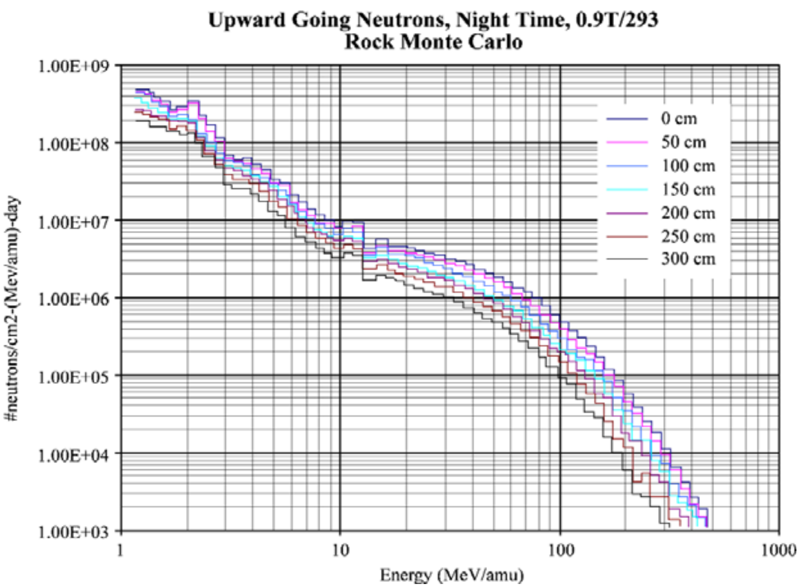


Figure 3: Upward flux of secondary (GCR-induced) neutrons for various soil thicknesses (Tripathi et al., 2006)

2.2 Enabling technologies and techniques

2.2.1 Remote sensing by lunar exploration orbiting (the LEO case)

In order to address the open questions of the Earth-Moon system a necessary further step in investigating the Moon is obtaining a global and integrated view of its geology, geochemistry and geophysics at highest resolution down to meter scale. In particular, we need to significantly improve our understanding of the lunar surface structure and composition, surface ages, mineralogy, physical properties, interior, thermal history, gravity field, regolith structure, and magnetic field. Low altitude orbiting spacecrafts, equipped with a wealth of high-resolution remote sensing instrumentation, can achieve such a goal. Highest resolution geological, geochemical and geophysical mapping will provide the absolutely needed information to plan landings and future utilization of the Moon.

Many space-faring nations have realized and identified the unique opportunities related to lunar exploration and have planned missions to the Moon within the next few years. Among these missions, a Lunar Explorations Orbiter (LEO) would be unique, because it should **globally** explore the Moon in unprecedented spatial and spectral resolution: 1.25m in stereo, 12m spectrally in the UV to NIR (0.2–3µm), 200m in the thermal infrared (7–14µm), subsurface sounding at 6 m resolution, and 20 km resolution for lunar gravity with an accuracy of < 0.1mGal. Therefore, LEO would significantly improve our understanding of the lunar surface composition, surface ages, mineralogy, physical properties, interior, thermal history, gravity field, regolith structure, and magnetic field. The concept of lunar exploration orbiters would gather unique, integrated, interdisciplinary data sets that are of high scientific interest and would provide an unprecedented new context for other international lunar missions.

The most visible mission goal for exploration orbiters would be the global mapping of the lunar surface with high spatial as well as spectral resolution. Therefore, in addition to a stereoscopic global mapping in the meter range, a screening of the electromagnetic spectrum within a very broad range should be performed. In particular, spectral mapping in the ultraviolet and mid-infrared would provide insight into mineralogical and thermal properties so far unexplored in these wavelength ranges. Fine scale analysis of the lunar regolith by radar sounding would provide structural information about regolith layering. The determination of the dust distribution in the lunar orbit would provide information about processes between the lunar surface and exosphere supported by direct observations of lunar flashes. The geophysical properties of the Moon should be investigated by recording the magnetic and gravitational field with so far unrivalled accuracy due to a low orbit, stable sub-satellites and specific tracking. Measuring of the radiation environment should finally complete the exosphere investigations. Combined observations based on simultaneous instrument adjustment and correlated data processing should provide an integrated geological, geochemical and geophysical database that enables

- the exploration and utilization of the Moon in the 21st century;
- solutions to fundamental problems of planetology concerning the origin and evolution of terrestrial bodies;
- understanding the uniqueness of the Earth-Moon System,
- the absolute calibration of the impact chronology for the dating of solar system processes.
- deciphering the lunar regolith as record for space environmental conditions.
- mapping lunar resources.

Lunar exploration orbiting should feature a set of unique scientific capabilities w. r. t.: (1) 100% global coverage of he lunar surface for remote sensing with stereo resolutions of close to 1 m and spatial resolution of all spectral bands of <200m in the MIR down to <12m in the UV. (2) Besides the VIS-NIR spectral range so far uncovered wavelengths in the ultraviolet (0.2–0.4µm) and mid-infrared (7-14µm) should be globally mapped. (3) Global coverage and subsurface detection of the regolith with vertical resolutions of about 3m down to a few tens of meters (high resolution Synthetic Aperture Radar with 25cm wavelength) and on mm-scale within the first 2m (microwave-instrument) should investigate the regolith's structure. (4) Detailed measurements of the global lunar gravity field <0.1mGal accuracy at 20km spatial resolution and magnetic field with 0.1nT accuracy from a low orbit (~50km) using two sub-satellites and simultaneous Earth tracking, supported by a radiation monitor and two independent magnetometers, should provide high precision and, in addition, should enable to geophysically investigate the lunar far side. In summary, the overall lunar exploration by orbiting scientific objectives and major measurement requirements are as follows:

<u>Scientific Objectives for exploration orbiting</u>

- Provide an integrated geoscientific global data base for the future exploration and utilization of the Moon
- Solve fundamental problems of planetology
  - The origin and geoscientific evolution of the Moon as baseline for the understanding of the terrestrial planets.
  - Uniqueness of the Earth-Moon System.

- Surface-space interaction and space environment.
- Absolute calibration of the impact chronology for the dating of solar system processes.
- Regolith as record for space environmental conditions.

- Map lunar Resources in a cartographical, geological, mineralogical, geophysical sense.
- Provide a high-resolution road map for further exploration.

Major Measurement Requirements for exploration orbiting

- Global coverage in all wavelength ranges
- Spectral coverage: *X-Ray, UV, VIS, NIR, MIR, Microwave, Radar*
- Highest spatial resolution with ground sampling distances (at 50 km orbit altitude, c.p. Fig. 4):
  1.25m stereo,
  12m (UV),
  24m (VIS, NIR),
  < 200m (MIR, < 1km thermal),
  ~ 6m (Radar),
  ~ 6km (Microwave, X-Ray)
- Subsurface sounding
  - *few meters deep with mm resolution (Microwave)*
  - *up to hundred meter deep with m resolution (Radar)*
- Physical characterization of the regolith (composition, physical properties, thermal, polarization, scattering, maturity, space weather interaction, particle properties)
- Global gravity with 0.1mGal accuracy at 20km spatial resolution
- Magnetic field globally with 0.1nT accuracy at 20-80km altitude
- Characterization and monitoring of the lunar space environment regarding radiation, dust and magnetic field

An overview of the complementary lunar surface mapping as a function of wavelength and ground sampling distance is given in Fig. 4. The German instruments (Fig. 4) as described below are already developed and operate on different planetary mission or are under development. Different spectrometer instruments cover a broad range of wavelengths from X-ray to the thermal infrared in order to decipher the composition or the lunar surface with respect to its elemental as well as its mineralogical composition. In each wavelength range of the electromagnetic spectrum, distinct physical processes are responsible for the scattering, absorption and/or emission of radiation and the measurements are highly complementary:

1. X-Ray Fluorescence measures the emission of X-rays due to the excitation by solar X-ray radiation and is diagnostic for the abundances of elements like Na, Mg, Al, Si, K, Ca, Ti, Mn, and Fe.
2. In the UV, spectral features are caused mainly by charge transfers between (i) oxygen and metal atoms and (ii) metal to metal atoms
3. In the VIS to NIR, spectra are dominated by crystal field transitions within distorted d-shells of the transition metals and especially diagnostic for the mafic mineral groups of olivine and pyroxene.
4. In the thermal infrared, spectral features are related to vibration modes of the silica-oxygen bonds and diagnostic for the silica-related mineralogy

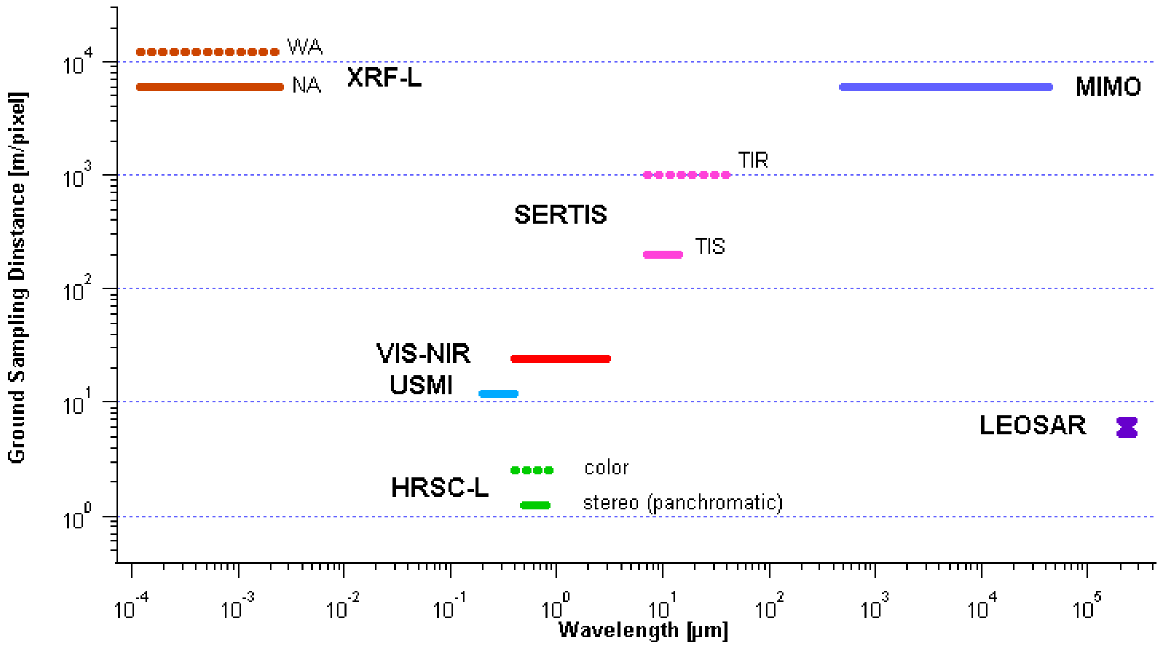


Figure 4: Lunar surface mapping as a function of wavelength coverage and ground sampling distances.

Descriptions of the lunar exploration orbiter instruments developed or under development in Germany are following below.

2.2.1.1 Global Geomorphological Mapping by stereo imaging (HRSC-L)

Main science goal of the high resolution stereo camera (HRSC-L) imaging experiment is to analyze the geology and geomorphology of the lunar surface in order to decipher its formation and evolution as a key for the understanding of planetary crust formation. HRSC-L would acquire morphologic, topographic, multispectral and physical image data at high spatial resolution (< 1m) for the detailed and **global** mapping of the lunar surface. HRSC-L is derived from the Mars Express HRSC instrument that operates successfully in Martian orbit since 2004. The major science objectives of the HRSC-L experiment would be

- Global 3D structural mapping at high spatial resolution (<1m/pixel)
- Detailed and global geologic mapping of the lunar surface
- Investigating lunar volcanism and volcanic processes throughout the lunar history with special emphasis on
  - Extent and volume of volcanic materials
  - Eruption styles and depositional processes
  - Eruption rates and rheologic properties of volcanic material
  - Formation ages of volcanic materials and variations in volcanic processes over time
  - Are small structures like Ina D really erosional morphologic features in the lunar regolith caused by gas eruptions and of late-stage volcanic origin?
  - Nature and occurrence of pre-mare and highland volcanism
- Investigating lunar tectonism on a global scale with special emphasis on quantifying the amount of extension and compression, characterizing tectonic processes involved and their

evolution over time, and determining the thickness of the lunar lithosphere at the time of tectonic activity

- Detailed analysis of lunar impact structures, impact melts, the impact process itself and the degradation of impact structures over time
- Determination of the lunar impact rate and refinement of the lunar chronostratigraphy with special emphasis on the
    - Crater production rate over time and the question of a possible cataclysm
    - Actual impact rate by comparing HRSC-L imagery with old high-resolution image data (mainly Lunar Orbiter, Apollo)
    - Refinement of the crater-size frequency distribution and age determination by means of crater statistics
    - Improvement of the lunar chronostratography
- Investigating the lunar regolith with special emphasis on
    - Surface weathering, optical alteration and soil maturity
    - Investigating the physical characteristics and texture of the regolith by means of photometric and linear polarization measurements
    - Localizing outcrops and occurrence of boulders
    - Erosional processes and the degree of lateral and vertical mixing of material
    - Detailed investigation of recent erosional structures (impact, outgassing, mass wasting)
    - Mapping lunar resources
- Refinement of the lunar geodetic control network

Key elements to meet these science objectives are global coverage, high spatial resolution of about 1m/pixel in b/w and the simultaneous observation in quintuple stereo. The high spatial resolution is necessary to resolve and investigate also small-scale surface features globally. The large variations in a low altitude orbit would be beneficial for imaging and allow observations of large fractions of the lunar surface at spatial resolutions down to 0.6m/pixel. This resolution is similar to the spatial resolution of the camera experiment onboard LRO which, however, is aiming to observe only about 10% of the lunar surface and without stereo information. All other camera instruments actually operating have much lower spatial resolution and only double (Selene) or triple (Chandrayaan) stereo. The topographic information derived from stereo data is crucial to quantify heights and 3-dimensional parameters like volumes or derived parameters like eruption rates and erosional processes. The multispectral imaging capability of HRSC-L would allow to map compositional variations of the lunar surface and to determine the soil maturity; the Fe-content, and (less-accurate) the Ti-content similar to the methods applied to Clementine image data. Unique features of HRSC-L are the photometric (i.e. multi-phase angle) and polarimetric imaging capabilities, which would provide independent but partly overlapping information about the texture and physical properties of the lunar regolith (e.g. macroscopic roughness, grain sizes, compaction, porosity). HRSC-L is perfectly suited to provide the morphologic, geologic and topographic context information for the entire suite of orbiter instruments as well as for experiments on other missions and the preparation of future lander missions. Synergies and complementarities to other orbiter instruments are manifold with

- Mapping the mineralogical and elemental composition jointly with the imaging spectrometers and XRF-L; HRSC-L would define the geomorphological units, provide the topography and parameters for the photometric correction, and would map compositional variegations mainly due to Fe, maturity, and Ti at much higher spatial resolution;

- Investigating the lunar regolith with respect to composition and maturity jointly with the imaging spectrometers (USMI, VIS-NIR, and SERTIS) and XRF-L, determining the physical and textural characteristics of the uppermost regolith layer jointly with SERTIS, MIMO, LEOSAR and RaPS, while the radar and microwave instrument would provide the vertical structure of the regolith. Complementary compositional information would be provided by RadMo and LEOPARD;
- Joined analysis by SPOSH, LEOPARD and HRSC-L of larger, recent impact events where HRSC-L would search for modifications of the surface after the detection of a large flash event;
- The improved topographic information obtained by HRSC-L and LEOSAR would be an important input for the analysis of PRARE-L gravity measurements to determine the thickness of the lunar crust.
- HRSC-L would provide the geological, geomorphological and topographic context for the magnetic field measurements.

2.2.1.2 Global Compositional Mapping by spectral imaging (XRF-L, USMI, VIS-NIR, SERTIS)

The XRF experiment would map the composition of lunar surface materials with respect to the main rock-forming chemical elements on a 'global', i.e., lunar-wide, scale. This goal would be achieved by measuring the emission of rays in a spectral range of 0.5eV-10keV, which have been excited by solar radiation. The instrument design makes use of innovative semi-conductor technology with a spectral resolution of 160eV @ 6keV and of a special set of collimators.

Main objectives are

(a) mapping of the global distribution of chemical elements, i.e., Na, Mg, Al, Si, K, Ca, Ti, Mn, Fe, using two spatial-resolution modes, one at 12km per pixel and one at 6km per pixel;

(b) detailed mapping of the chemical composition of volcanic features and plains;

(c) detailed mapping of the Apollo and Luna landing sites;

(d) detailed mapping of the chemical composition of impact-crater interiors and ejecta blankets for subsurface compositional information.

This would provide an understanding of the crustal chemical composition on a global scale and provide information on the evolution of lunar surface materials and surface features that were formed during the period of formation of the ancient lunar crust and during periods of extensive volcanism.

XRF measurements would furthermore be of utmost importance for the calibration and interpretation of (a) measurements in the visible spectral range as well as (b) for measurements performed by radar instruments.

Despite the abundance of geochemical analyses conducted thus far on returned lunar surface material by the Apollo and Luna missions, such samples do not provide a representative view of the lunar geochemical surface composition and can only be marginally taken as a basis for the understanding of the lunar evolution. Global-scale, quantitative, and therefore absolute, measurements of the chemical composition have not been conducted thus far.

Notwithstanding the proximity of the Moon to the Earth, selective in-situ measurements as well as several low-resolution and spatially fairly limited mapping attempts of the lunar chemical composition through remote-sensing instruments could not answer all of the important questions regarding the evolution of the Moon and distribution of surface units as defined by their key chemical elements.

In a more limited way and in dependence of the intensity of solar x-ray radiation, the geochemical contribution of asteroid bombardment could be estimated by measuring Ni concentrations. The proposed XRF measurements would furthermore help estimate the economic potential and possible economic resources for the support of future lunar and non-lunar missions, especially for the development of lunar bases.

During the mission, resampled maps at various resolutions (6-12 km/pixel) as well as energy-spectra containing information on key elements would be produced. For calibration purposes, XRF-L would also provide quantitative information for other spectral imaging instruments.

The reflection characteristics of solid surfaces in the UV spectral range can be used to constrain the mineralogical, petrologic, and chemical composition of geologic material or, in combination with observations in the visual and IR, to determine it in greater detail. Laboratory research of lunar material and other minerals shows that in this wavelength range characteristic features exist for many minerals relevant for planetary geological science.

The spectral dependence of the reflectivity of solid surfaces is determined by many factors (weathering, grain size, crystallization sequence, material composition) whose deconvolution can often be achieved only by observation over the entire spectral range from the UV to the IR with adequate spectral resolution.

Lunar material was analyzed in the laboratory in the 1970s and 1980s. Lunar rock like KREEP (mainly pyroxene and plagioclase) or basalt with low or high titanium content as well as others often show a steep characteristic absorption edge in the range 250 to 400nm. For lunar soil these absorption edges are less pronounced. Just by combination with observations at longer wavelengths (VIS and IR) the potential for identification can be significantly enhanced.

Recent laboratory research in the UV range reveals relations of the spectral shape with the minerals. One example is feldspar. Another example is ilmenite that, in contrast to other minerals, shows a characteristic absorption minimum between 400 and 500nm and, hence, can be distinguished from other lunar minerals in the UV. In titanium-rich basalts titanium is mainly stored in ilmenite, so that in this case the UV-to-VIS ratio is hardly affected by other minerals. On the other hand, in titanium-poor soil one has to consider that the effect of some titanium-poor or even titanium-free minerals (chromite or ulvoespinel) on the reflection spectrum is very similar to that of ilmenite and, thus, can severely corrupt estimates of the ilmenite content if the spectral resolution is too low.

Space weathering on the lunar surface by influences of the Sun (solar wind and UV radiation) and by cosmic particle radiation acts to make the spectra redder in the IR as well as to make them bluer in the UV. The increased blue coloring is strongest in the range 300 to 400nm, because here the above mentioned absorption edge is being degraded. Therefore, quantitative observations in the UV can also be used for a relative age determination of the material on the lunar surface.

A UV spectrometer to characterize the mineral composition and to determine the degree of weathering in the wavelength range 200 to 400 nm does not need to have a high spectral resolution because all phenomena cover broad bands over several 10nm. A resolution of $\lambda/10$ is sufficient.

USMI would provide UV data, which would be complementary to other instruments that shall perform observations from the visual to the thermal infrared. Combined with the geological and morphological mapping by HRSC-L in the visual, and the mineralogical measurements of VIS-NIR in the near infrared, and SERTIS in the medium infrared, USMI would enable to determine, spatially highly resolved, the distribution of the principal minerals on the lunar surface by a broad, up to now never achieved coverage of the electromagnetic spectrum. The strived resolution of about 12m on the lunar surface represents a quantum leap in the multi-spectral mapping of the lunar surface (up to now about 100 to 400m) and would yield significant progress in detection of the surface mineralogy, because the spatial smearing of spectral signatures would be strongly reduced.

Reflectance spectra in the visual and infrared wavelength range of natural surfaces contain important compositional information, which is derived from the position, shape, and strength of absorption bands in the spectra. Remotely sensed reflectance spectra of planetary surfaces contain therefore compositional information due to the convolution of the reflectance spectra of the individual components in the surface material.

The extraction of mineralogical information from these data is hindered by the complexities introduced by particle size effects, variations in viewing and illumination geometry, surface roughness, and regolith or weathering alteration on reflectance spectra. The prime goal of the VIS-NIR instrument is to generate a new data set of the lunar surface with high spatial and spectroscopic resolution, which allows one to disentangle those effects. The VIS-NIR imaging mapping spectrometer would map the lunar surface mineralogy with a spatial resolution of approx. 24m in the visible to near-infrared range of 0.4-2.5µm (goal 0.4-3.0µm). What can a NIR lunar spectrum of a relatively morphologically featureless mare or highland area reveal about its geophysical characteristics? Very little, especially if viewed in isolation. Maybe one could detect the un-weighted presence of a pyroxene and/or olivine. With a very good set of high-resolution spectral data, we might even infer the likely fraction of Ca-rich or Ca-poor pyroxene. Mineral detection is especially challenging when dealing with extremely weak absorption features, as in mature soils, and by the fact that telescopic observations have to deal with shifting illumination regimes, atmospheric conditions, and low spatial resolution. However, in high-resolution spectrometric observations from space where good spatial resolution is combined with good spectral resolution, NIR spectrometry starts to show it strength. With the SIR-2 instrument on Chandrayaan-1 we now have delivered the wanted high-resolution data, both in spectral as in spatial terms. The SIR-2 point spectrometer which operated in 256 wavelength bands between 0.9 to 2.4 microns, took its reflectance readings in closely spaced time intervals along a circular polar lunar orbit from ~100km of altitude and ~200km, respectively. This translates into a stuttered spectral analysis along an orbital path with gaps of ~300 meters between successive readings; in other words, a given terrain is sampled across a latitudinal path with a geographical coverage of 2 over 5. The SIR-2 high-resolution NIR instrument can detect within a high degree of accuracy relative differences in exposed surface materials in respect to: maturity - (overall reflectivity or brightness, i.e. degree of weathering); mineralogy – (presence and species of pyroxene, olivine, and, in certain circumstances plagioclase); and, possibly, morphology - (average grain size, i.e. roughness of surface). Since the SIR-2 instrument acquired a total of over 12 Mio. spectra from 1026 orbits, collected on a global scale including relatively unexplored areas such as the lunar farside and the poles, there is huge potential for a wide and extensive mapping of key mineral phases and soil characteristics. Ongoing work combines high-resolution data from HySi, the spectrometer imager on Chandrayaan-1 with the SIR-2 data, thus extending the sampled wavelength region down to the visible (424nm) to cover the mineralogically important one micron range. Near infrared spectroscopy has come of age. In the next few years, the whole SIR-2 data set, together with the upcoming high resolution lunar mapping efforts, will play a key role in building a reliable and rigorous framework as a basis for improved mineralogical remote sensing investigations, which will also find synergy with parallel research on Mercury and asteroids.

This characterization of the lunar crust has to occur within the context of its lunar geological evolution. Data delivered by VIS-NIR, the HRSC-L camera and the thermal imaging instrument SERTIS are therefore intimately linked. The analysis of the mineralogical composition of the lunar surface is equally important in the highland areas as well as in the mare regions, where the diversity and extent of the basaltic volcanism needs to be explored.

The search for volatiles is another key objective for VIS-NIR. Measurements taken by earlier flown lunar missions indicated that the lunar poles contain deposits of hydrogen, which have been interpreted to exist in the form of water ice. The fact that lunar soils release water only at temperatures above 150°C indicate that even the sunlit surfaces near the lunar poles never come close to such temperatures, and the permanently shadowed areas are of course much colder. This paves the way for the possibility that on the Moon water deposits from the outer space brought in e.g. by comets could still be found in the lunar polar regions.

Despite the achievements made in recent years in understanding the effects which influence the reflectance spectra, an accurate determination of the composition of planetary surfaces using remotely sensed reflected sunlight has also remained a challenge because a quantitative abundance determination requires a clear understanding of the effects of space weathering and the effect of the illumination/viewing geometry on the remotely sensed surfaces.

Space weathering, defined as the aggregate of the physical and chemical changes that occur to material exposed on the surface of an airless body, is therefore another key research theme of VIS-NIR. Space weathering is important for the planetary remote sensing studies because it causes major changes in the optical properties of the surfaces. On the Moon, space weathering lowers the albedo, reddens the spectral slope, obscures absorption bands, and generates the characteristic magnetic electron spin resonance of the lunar regolith. Within this context is also the joint interest of VIS-NIR and HRSC-L in identifying fresh small craters, which for VIS-NIR are particularly interesting because they reveal a surface not affected on the same scale by space weathering.

The investigation of the influence of the viewing geometry on the reflectance spectra, which can be explored in great detail from a lunar polar orbit under a wide range of observation conditions, will lead to a quantitative investigation of the correct shape of the phase function to be used in remote reflectance spectroscopy.

In the mid-infrared the SERTIS instrument would address the following scientific goals:

- Identification of rock-forming minerals, mainly feldspars
- Determination and cartographic mapping of the lunar surface mineralogy with a spatial resolution of <100m
- Investigation of the surface composition of the Moon
- Correlation of mineralogy and morphology together with the HRSC-L camera and the VIS-NIR spectrometer
- Study of central peaks and ejecta material of impact craters
- Study the evolution of the lunar volcanism and magma composition
- Study the effects of "Space Weathering" – Comparison with VIS-NIR spectra
- Direct comparison of the mineralogy of Mercury and the Moon
- Global measurement of the surface temperature
- Global mapping of the thermal inertia of the lunar surface
- Global determination of physical regolith properties such as grain size and texture

In 2006-2007 the "Committee on the Scientific Context for the Exploration of the Moon" of the National Research Council of the National Academies prioritized important scientific objectives for NASA. Five out of the 15 high-priority objectives can be addressed with SERTIS, including: (1) Key planetary processes are manifested in the diversity of lunar crustal rocks; (2) The lunar poles are special environments that may bear witness to the volatile flux over the latter part of solar system history; (3) Lunar volcanism provides a window into the thermal and compositional evolution of the Moon; (4) The Moon is an accessible laboratory for studying the impact process on planetary scales;

and (5) The Moon is a natural laboratory for regolith processes and weathering on anhydrous airless bodies.

2.2.1.3 Global Sub-Surface Mapping by radar and microwave imaging (LEOSAR, MIMO)

Remote sensing with imaging Synthetic Aperture Radar (SAR) has become a well established technique in Earth and planetary observations. Active microwave techniques have the advantage to be independent of solar illumination and can therefore observe regions where insufficient illumination restricts the use of optical systems. With proper selection of the wavelength, for LEOSAR its L-band 23cm wavelength, the SAR signal has the capability to penetrate deep into subsurface regions. The depth is depending upon the rock abundance and bulk chemistry, the signal gets scattered back to the sensor from subsurface rocks, voids, or interfaces at layers with different scattering properties. The use of new imaging techniques with sophisticated digital processing would provide new and powerful observation tools. SAR systems can deliver wide swath, high resolution (both geometric and radiometric) radar images comparable to and complementing the optical images from high resolution cameras.

Radar measures the reflected energy in the microwave region and can therefore measure in three dimensions the electrical and structural properties of the surface or subsurface area. Penetrating several meters deep into the subsurface and using polarimetry, tomography and advanced digital processing techniques, many geology features can be imaged to detect surface subtle motion due to Earthquakes or volcanic activities and to get a detailed understanding of the structure and the properties to provide better estimates for vehicle landing and planning of space habitats. The detection of water or ice in surface or subsurface regions with polarimetric radar system is an already demonstrated capability. Due to the relative stable surface of the Moon, repeat pass data acquisitions can be used to produce high resolution digital terrain models of the surface and subsurface with radar interferometry.

SAR systems with their large antennas have been bulky and heavy instruments asking for a lot of energy and data transmission capabilities. But new lightweight radar technologies with membrane and printed array antennas, with direct digital down conversion, with advanced data compression and onboard digital signal processing and tiny solid state memories with huge storage capacity have now opened new possibilities for lunar remote sensing missions.

The main science objectives and prime questions to be answered are:

- Thickness of the lunar regolith and topography of its base;
- Physical properties of the lunar regolith in the radar wavelength range;
- Structure and layering within the lunar regolith;
- Presence of buried impacts and their ejecta blankets; vertical profiling of surface impacts and their ejecta;
- Thickness of volcanic deposits;
- Layers and structures in the megaregolith.

Microwave observations (MIMO) would provide a global map about the composition, structure and the physical (electrical and thermal) properties of the lunar regolith down to a depth of 1 to 2 meters (and where appropriate about the thickness of the regolith) and determine the lunar heat flux with higher accuracy than before. Furthermore MIMO would search for water ice and with very high sensitivity for water vapor in the vicinity of polar craters in which up to 4 billion tons of frozen water are believed to be stored. In both cases the method of passive microwave remote sensing would be applied. Observing the Moon in 5 spectral bands between 7 and 557GHz (~ 43mm to 0.5mm) with vertical and horizontal polarization and under 3 angles of incidence would provide subsurface temperatures within the depth range mentioned above. Additionally to the 5 MIMO bands the

LEOSAR receiver can provide information about the microwave brightness of the Moon at 23cm wavelength. These observations would constrain thermophysical models and in particular the following parameters:

- The thermal albedo factor, i.e. the emissivity of particles with form the regolith (from dual polarization microwave brightness's).
- The conductivity ratio, i.e. the relative impact of IR-radiation and solid state conductivity (from thermophysical modeling and the measured microwave brightness.
- The thermal inertia (from thermophysical modeling of the measured lunar microwave brightness).
- The dielectrical properties of the medium (from the polarization of the microwave emission and the thermal inertia), i.e. the refractive index and the microwave opacity.
- The temperature and the thermal diffusion

From these parameters boundary conditions about the particle size, the elemental and mineralogical composition can be derived.
MIMO is complementary to other instruments like LEOSAR and the near and thermal IR spectrometers.
The combination would provide for the first time deep insight (literally) into the regolith parameters described above and help to understand the regolith as a potential supplier of resources and energy. Both are very important in the context of future landing and lunar exploration missions

2.2.1.4 Geophysical Mapping of the gravity and magnetic properties (PRARE-L and LunarMag)

The precise knowledge of the lunar gravity field in terms of accuracy and resolution is crucial for understanding the internal structure and evolution of the Moon. All currently available lunar gravity field models are mainly based on the analysis of relatively imprecise radio tracking data of orbiting spacecraft, which include data from the Lunar Orbiter, Apollo, Clementine, and Lunar Prospector missions. Additionally, due to the synchronous rotation of the Moon around the Earth, all derived models lack information from the far-side. The most recent and probably best model available is the JPL Lunar Prospector mission result LP150Q that can resolve small-scale features up to 36km half-wavelength with an approximate accuracy of about 30mGal on the near-side, but the model errors are definitely much larger (up to 200mGal) on the far-side.

These deficiencies have been partly overcome with the Japanese SELENE mission, launched on September 14, 2007, realizing for the first time the high-low-satellite-to satellite tracking principle. The overall SELENE goal was to derive an improved (one order of magnitude up to degree and order 30) and homogeneous (incorporating data on the far-side) lunar gravity field up to degree and order 75, where most of the coefficients shall be derived without a priori constraints. An important mission goal was reached in 2008 with the almost complete coverage of the lunar far-side. From the acquired data sets, a preliminary global field solution up to degree and order 90 (SELENE Gravity Model SGM90d) was deduced with significant improvement up to degree 60 over previous gravity field solutions. The SELENE (Kaguya) gravity field solution indicates variable styles of compensation on the lunar near- and farsides, implying that the lithosphere on the lunar near-side underwent more intense thermally-induced modification than previously thought. Contrary, relatively rigid lithosphere supports basin topography and mantle uplift on the lunar far-side.

This will be a clear improvement, but the resulting lunar gravity field model will not be sufficient to answer fundamental questions such as to

- determine the structure of the lunar crust by inversion of topography and gravity information,
- investigate the heterogeneity and elasticity of the lunar mantle,

- investigate the reason for the 1.9km shift between the centre of mass and centre of figure of the Moon,
- improve the characterization of the size, physical state and composition of the lunar core or
- determine lunar Love numbers, which account for the tidal distortion of the Moon, for the first time precisely from time-varying gravitational perturbations.
- In addition, it would be highly desirable to
- draw conclusions on the origin of the Moon and early Earth history,
- improve the orbit determination and operations of an lunar exploration orbiter and all other historic and future lunar missions,
- investigate the Earth-Moon system as a whole and in detail the librations of the Moon, or
- conduct relativistic studies in the Earth-Moon system.

Therefore, the minimum and desired scientific goals of the PRARE-L low-low SST experiment is to

- derive a high accuracy and high resolution global lunar gravity field with a global mean error of 0.1mGal for a half-wavelength of 50km and to improve the current precision of the lunar Love number for degree 2 (minimum scientific goals)
- increase the spatial resolution to 20km, and, for the first time, to determine the lunar Love numbers up to degree 3 (desired scientific goals)

The lunar gravitational potential model shall be characterized by coefficients of a spherical harmonic expansion.

The Moon does not possess a global magnetic field. However, all measurements indicate that the rocks of the lunar crust are magnetized. This indicates dynamo processes in the young lunar core, causing this observed magnetization. A detailed and global map of the lunar vector magnetic field does not yet exist. Such a map will give far-reaching information and insight into the structure and dynamics of the lunar crust.

Measurements made onboard the NASA spacecraft Lunar Prospector provide a first overview of the crustal field and yield a couple of interesting scientific results. However, the problem of the Lunar Prospector and all other earlier measurements is the contamination due to solar magnet and magnetospheric magnetic fields. Both, the crustal contributions and the external fields are of comparable magnitude. This requires a careful separation of both contributions.

Thus, for the Lunar Exploration Orbiter an experiment – LunarMag – is proposed with magnetic field measurements performed on two spacecraft. This allows the application of gradient measurements to separate the external contributions from the crustal magnetic field. Two fluxgate magnetometers would be used, much as they are currently operated onboard the Rosetta, Venus Express, and Themis spacecrafts. The necessary measurements need to be performed on a quasi-polar orbit (85°-90°) to ensure global coverage of the lunar surface. As the crustal magnetic fields are weak, the altitude of the spacecraft shall not be larger than 70km.

The origin of the lunar magnetic field is still a matter of debate. An earlier lunar dynamo is the most probable cause for this field. However, also impact generated magnetization is under discussion. Alternatively, transient magnetic fields, generated by compression of the interplanetary magnetic field during the impact of a comet, could contribute to the lunar magnetic field.

In recent years local magnetic field anomalies and their interaction of the interplanetary medium have received much attention. As the Moon does not posses any atmosphere the solar wind plasma can reach the surface. In regions with strong magnetic field anomalies, however, impingement on the surface is modified by the magnetic field, a local magnetosphere is created. Areas sheltered by such mini-magnetospheres shall exhibit pronounced differences. Known albedo structure can be explained this way.

These short discussions demonstrate that the lunar magnetic field leaves many open questions. A detailed global map with the external field well separated will help to understand the complex physical processes associated with the lunar magnetic field. Close cooperation and synergies with gravity field measurements as well as topographic and photogrammetric mapping of the lunar surface is anticipated.

2.2.1.5 Environmental Monitoring (LEOPARD, RadMo, RaPS, IRAS)

The Moon is wrapped into a dust envelope produced by hypervelocity impacts of micrometeoroids or interstellar grains. A more or less constant flux of fast projectiles strikes the lunar surface, and produces secondary material, and a fraction of it leaves the surface forming the dust envelope. The ejecta particles populating the dust envelope carry precious information about the composition of the lunar surface, the properties of the regolith, as well as about the impactor flux itself. Furthermore, measurements of the dynamic properties of the ejectas provide deep insight into the lunar dust production mechanism.

For deployment on the lunar surface a Lunar Dust Transport Package is being developed to investigate dusty plasma processes on the lunar surface. We are designing a combination of in situ and remote sensing observations to address the temporal variation of the spatial and size distributions of the levitated/transported dust grains, as well as to characterize the surface plasma environment. This package includes cameras, plasma and electric field booms, and instrumentation to measure the size, speed and the charge of the mobilized dust grains as well as a dust telescope for characterizing the micrometeorite flux onto the lunar surface. This suite of instruments could also contribute to fundamental astrophysical observations by measuring the size, speed, and the composition of interplanetary and interstellar grains bombarding the Moon.

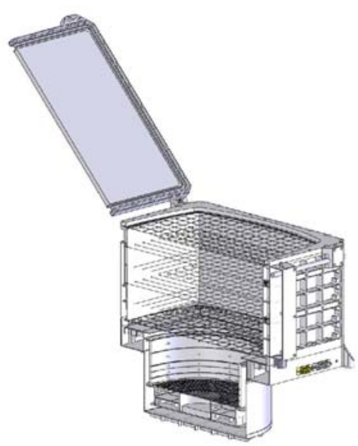
The main scientific goal of the dust camera LEOPARD is the characterization of the lunar dust envelope by measuring with unchallenged accuracy the mass, speed vector, electrostatic charge, and the chemical composition of individual ejecta particles. Because the dynamics of a lunar dust grain after ejection from the surface are dominated by the Moon's gravity knowledge of the velocity vector of a detected particle allows us to identify its starting point on the Moon. Thus, the chemical composition of the grain inferred from the simultaneously measured mass spectrum can be associated with the mineralogy of the particle's site of origin on the surface. Measurements of the electrostatic grain charge provide information about the electric potential of the lunar surface as well as about the interaction of the dust particles with the solar wind plasma. The strength and the directionality of the impactor flux onto the Moon can be inferred from the spatial distribution of the cloud particles. Even weak projectile streams from so far undiscovered sources may be identified by the induced slight asymmetries of the dust cloud. The LEOPARD measurements aim to determine the lunar dust production rate as well as the lunar mass loss. Furthermore, our knowledge of the properties of the interplanetary flux at 1AU would be significantly improved by the LEOPARD data. In the course of the mission LEOPARD would also register a few interplanetary grains (IDPs) as well as interstellar dust (ISD) grains. Interstellar grains are of particular interest because no compositional in-situ data of interstellar matter has been acquired so far.

The LEOPARD in-situ measurements of the elemental composition of the lunar fines are complementary to the characterization of the mineralogy of the lunar surface by remote sensing instruments. Of particular value are LEOPARD data of dust particles produced by impact events registered by the SPOSH camera. By combining the SPOSH data, images of the impact site before and after the event, and the LEOPARD data new insights into the cratering process would be obtained.

The LEOPARD data set of an individual dust impact consists of the mass, speed vector, electrostatic charge, and chemical composition of the grain. Based on this data, higher-order products such as the density profile of the lunar dust envelope and maps of the lunar surface composition would be generated.

Dust grains splashed off the lunar surface collect charges from the solar wind plasma. Furthermore, photo-electrons are produced by the solar UV radiation. At equilibrium the electrostatic potential of the lunar fines is independent of the grain size. The LEOPARD Langmuir probe measures the electrostatic potential, while the LEOPARD trajectory sensor determines the amount of electric charges on the grain. The combination of these two measurements provides a mean to determine the grain size with unchallenged accuracy. Due to the low plasma densities, dust particles lifted off night side of the Moon almost preserve their initial charge. Thus, night side measurements of the probe and the trajectory sensor provide precious information about the lunar surface potential. Furthermore, the Langmuir probe measures the local density and temperature of the plasma electrons in the vicinity of the Moon.

A *Dust Camera* consists of two sub–instruments, a *Trajectory Sensor* (TS) and a *Mass Spectrometer* (MS). The camera is an in-situ instrument detecting and analyzing individual impacts of sub-micrometers and micrometer sized grains. First, the charged grain passes the TS, which derives the particle's speed vector from the charge signals induced on the sensor's array of charge-sensitive wires. This subsystem determines in-situ the grain's speed, mass, primary charge, and trajectory. Assuming a free-floating grain potential of +5V and a minimum signal-to-noise ratio of 10d, the TS is sensitive to grains larger than 0.3μm. Then, the grain hits the plane target of the MS at the bottom of the instrument generating an impact plasma which is analyzed in a time-of-flight reflectron-type mass spectrometer, whose mass resolution $\Delta M/M$ is of the order of 200. Although the ejecta impacts may occur with rather low velocities (~ 2kms^{-1}), the collisions still produce a sufficient amount of plasma to analyze.



The figure shows the LEOPARD dust camera with the four plane sofwires of the Trajectory Sensor (top) and the time-of flight mass spectrometer at the bottom. The ions generated by the grain's collision with the impact target are focused on the ion detector in the centre. Data acquisition is triggered by the plasma electron signal measured at the impact target and/or by the ion signal registered at the ion sensor.

Radiation monitoring (RadMo, IRAS) has two scientific objectives. Its primary objective is to prepare manned missions to the Moon by determining the lunar radiation environment, its secondary objective is to determine the abundances of elements and water on the lunar surface. Dosimetric data from RadMo are a crucial piece of information to ensure effective radiation protection of astronauts on future manned missions, but also of experiments utilizing radiation-sensitive parts. The radiation dose induced by the galactic cosmic radiation (GCR) expected during a long-term stay on the Moon already exceeds the allowed limits on Earth. Solar Particle events can greatly enhance the instantaneous radiation dose by orders of magnitude – be it on the way to the Moon or on the lunar surface. Therefore, an accurate characterization of the lunar radiation environment is a requirement for future manned missions to the Moon. Moreover, the expected results would allow a better understanding of requirements on smart shielding materials for spacecraft and habitat construction. Interestingly, accurate radiation measurements from the Apollo days are not available (for technical reasons).

The lunar radiation environment has important implications for dating lunar samples with cosmogenic nuclei. Such studies normally assume a constant GCR flux in the past and make no attempt to characterize the influence of solar particle events on these investigations. Thus, we expect RadMo results to provide an important input into models determining ages of lunar samples. Radiation is also an important ageing agent for lunar soils.

RadMo's secondary objective is to determine the abundances of key elements and of water on the lunar surface. The interaction of the GCR and of solar particles during a solar particle event with the lunar surface results in a secondary radiation component, which also consists of neutral particles, neutrons and gamma rays. These need to be measured not only for astronaut-safety purposes, but their measurement also allows a determination of the abundances of the mineralogically important elements such as O, Si, Ti, Al, Fe, Mg, and Ca. A sufficiently sensitive instrument can also determine the abundances of radioactive elements such as Th, U and K.

This secondary radiation component, especially the neutral one, is also an important unknown in the expected radiation dose for astronauts. As electrically neutral particles, neutrons have a small cross section for interacting with nuclei. Therefore, they can easily penetrate a spacesuit or a spacecraft. However, the path of a neutron through an astronauts body is much longer than through a spacesuit and, hence, the probability of the neutron interacting with the astronauts tissue is much higher than with his spacesuit. In fact, the high water (proton) content of human tissue allows for maximum energy transfer from neutrons to tissue, thus increasing the total dose suffered by the astronaut in a way that is still badly understood. On the other hand, high energy gamma rays also easily penetrate spacesuits, and the similar arguments apply as for neutrons. Their effect resembles that of high energy (relativistic) electrons. Therefore, measurement of the secondary radiation component is also important for RadMo's primary scientific objective.

The global spatial and temporal variation of the lunar albedo and infrared field is not known with sufficient accuracy. Especially for the far side no information is available in the current models. Additionally, the radiation pressure, which is the sum of the direct solar radiation and the albedo and infrared radiation of the Moon, acts as a non-gravitational force on the LEO identical sub-satellites (LSS) and needs to be taken into account for lunar gravity field determination. Finally, the degradation of the thermal characteristics of LSS surface areas during mission lifetime is not known, but has significant influence on the radiation pressure force.

Therefore, the scientific goals of Radiation Pressure Sensor (RaPS) measurements onboard the LSS are to:

- derive the global lunar albedo field and its temporal variation during sub-satellite mission lifetime with an error less than 8% (local value, related to 10s interval) and 3% (orbit average value),
- derive the global lunar infrared field and its temporal variation during sub-satellite mission lifetime with an error less than 5% (local value, related to 10s interval) and 2% (orbit average value),

- derive non-gravitational accelerations to be used in PRARE-L analysis as the sum of Moon albedo and infrared and solar radiation with 10s (TBC) sampling rate and $5\text{-}10^{-10} m/s^2$ (TBC) accuracy,
- observe the degradation (change of optical/thermal properties over sub-satellite mission lifetime) of sub-satellite surface areas and materials with an area percentage of over 5% to be taken into account in surface pressure vector determination and for future satellite and mission design with an error for reflectivity and absorption (alpha and epsilon) of less than 10%.

Besides these scientific applications, RaPS would contribute as a Coarse Moon and Sun Sensor (CMSS) to the Attitude and Orbit Control System (AOCS) of the LSS. Additionally, the a posteriori separation of the lunar albedo and infrared components from the Earth infrared and albedo contribution and from the direct solar radiation would enable studies of the magnetic field of the lunar crust by analysis of the thermal variations of the lunar surface (LUNARMAG synergy).

The RaPS derived data would be generated at a coarse resolution (compared to SERTIS and MIMO derived data). Its advantage, however, is that it is generated during all seasons and daytimes and from the integral of all radiated wavelengths. Thus RaPS can be used to correlate between the other measurements and to extrapolate these measurements during their off-times.

The main goal of RaPS is to improve the PRARE-L gravity measurement performance. Possibly it can amend the results of other TBD instruments in addition.

Meteoroids impacting the Moon release a small portion of their impact energy in the form of optical flashes. This phenomenon could be confirmed by terrestrial telescopic observations only recently. Our experiment is designed to capture and to study the characteristics of a large number (>1000) of these events. Earth-based observations are to be carried out in parallel (but independently from LEO operations) for coverage of larger areas to catch the more rarely occurring large impact events.

Comprehensive statistical analysis would be carried out to obtain a characterization of the meteoroid population in the Earth-Moon system, in terms of total flux, size frequency distribution, orbits, clustering, and meteoroid physical characteristics. Comparisons would be made with other observational data sets, each of which has its own strengths and weaknesses: the present-day lunar cratering rate, the seismic detection rate of lunar impacts, the observed rates of meteors in the Earth's atmosphere, and NEO statistics.

In addition, light curves and spectral data from the expected events would be examined and modeled to develop an understanding of the physical processes during impacts.

While the main observational targets of the camera are the nighttime impact events, SPOSH-L has also limited capability to detect and observe large daytime impacts and other Lunar Transient Phenomena (LTPs) in sunlight conditions.

There would be important synergies to the dust camera LEOPARD, which is designed to observe dust, ejected from impacts on the lunar surface. From joint observations of impact events, a comprehensive understanding of the impact events could be developed. In addition, the HRSC-L camera is intended to identify fresh craters and therefore can supply an independent estimate of the crater-forming rate on the Moon.

The main product from the experiment is a large catalogue of >1000 impact events per year, including times, lunar locations, and optical magnitudes of impact events. For more detailed analysis, individual image frames (VIS and IR) and light curves in different spectral bands for each impact would be available.

2.2.1.6 Meteoroid impact detections (SPOSH-L)

A camera breadboard has been developed jointly by German Aerospace Center (DLR) and Jena Optronics, dedicated to imaging of faint transient noctilucent phenomena on dark planetary hemispheres, such as electric discharges, meteors -- or lunar impact flashes. SPOSH (Smart Panoramic Optical Sensor Head) is equipped with a highly sensitive 1024 x 1024 CCD chip and has a custom-made optical system which combines high light-gathering power and a wide field of view of 120 x 120º. Images can be obtained over extended periods at high rate to make monitoring for transient events possible. To reduce data rate, only those images (or relevant portions) are returned to the user that contain events. The camera has a sophisticated Data Processing unit (DPU) prepared to interface with a spacecraft system, for image processing and event detection at high rates up to 2 per sec. Over the past years, the team has routinely carried out outdoor tests that demonstrate that the camera has excellent low light level performance, as well as excellent radiometric performance and geometric accuracy over the large field of view. The camera opens up opportunities to study the current lunar impact flux from a lunar orbiting mission and was proposed to fly on LEO.

2.2.1.7 Monitor Space Weather

The IRAS instrument – a lightweight radiation spectrometer with a mass smaller than 0.6 kg developed for ExoMars - is capable to characterize the radiation field concerning particle fluences, dose rates and energy transfer spectra for ionizing particles. In addition, it allows determining the dose contribution of secondary neutrons from particle interactions with the lunar soil.

It can provide, for the first time, a detailed, continuous and long-term characterization of the Moon surface radiation environment, space weather (ionizing, neutrons) and is essential for:

- Assessing Moon surface radiation environment
- Identifying and quantifying hazards to humans
- Providing ground truth for Moon environment models.

2.2.1.8 Modular Orbiter Concept (German Instrumentation Options for joint NASA-DLR Lunar Missions)

An extensive suite of instruments to study nearly every aspect of the lunar geology, environment and topography is set for implementation in the timeframe of 2012-2015. Originally foreseen for the “Lunar Exploration Orbiter”, these instruments have been developed by the German planetary science community in co-operation with industry to phase A level and beyond. In the following, three exemplary concepts to salvage the technically successful developments are introduced.

2.2.1.8.1 Lunar Environment

To analyze the lunar radiation and dust environment two instruments, the Radiation Monitor (RadMo) and the particle detector (LEOPARD), exist. Due to the very advanced development, both instruments could be launched as early as 2012/2013.

RadMo is based on the RAD instrument of the Mars Science Laboratory (MSL) and consists of three sensor heads containing the detectors and an electronic box. The sensor heads are the High Energy Telescope (HET), the Thermal Neutron Sensor and the Non-Thermal Neutron Sensor (NTNS). Similar to RAD, RadMo utilizes different scintillators and anti-coincidence shields to characterize the lunar radiation environment including neutrons, charged particles such as protons and alpha-particles, gamma-rays and also heavy ions (e.g. up to Fe).

LEOPARD has a unique approach to simultaneously measure the direction, speed and mass of dust particles in the Moon’s vicinity by combining a trajectory sensor and an impact mass spectrometer in one instrument. A charged (due to solar UV radiation) dust particle that passes the trajectory sensor, which consists of several filaments forming a three-dimensional array, induces a charge in each of the filaments. By measuring these charges the trajectory can be reconstructed. Supplemented by the data of the impact mass spectrometer, which is similar to those flown e.g. on Cassini, a complete data set for each dust particle can be retrieved.

Additionally to RadMo and LEOPARD, the LunarMag instrument could also be included which has a similar high development status compatible with a very early launch date. More detail on this instrument is given in the section on the Lunar Geology Concept (see 2.2.1.8.3).

2.2.1.8.2 Lunar Topography, Geomorphology and Composition

Covering almost the entire spectral range from the X-Ray and UV to the thermal infrared in combination with active and passive microwave, a complete set of surface mapping instruments has been developed:

- XRF-L: Measurement of surface x-ray fluorescence in the energy range of 0.5-10keV
- USMI: Multispectral imaging from 200-400nm with 12m GSD
- VISNIR: Narrow-band multispectral imaging from 400-3000nm with 24m GSD
- SERTIS: Imaging spectrometer and radiometer with 200m GSD in range 7-14µm
- MIMO: Microwave radiometer with 5 bands (7, 24, 60, 183, 557GHz) and three observation angles (0°, 45°, 60°)
- LEOSAR: L-band SAR with 12km swath and 6 m resolution in single look
- HRSC-L: High-resolution stereo camera with 1.25m GSD and five stereo angles from -18.9° to +18.9°

Any (sub-) set of these instruments can be adapted for a joint mission. Obviously, the optical instruments require an orbit with sufficient illumination and a suitable altitude range. Especially, for maintaining the high performance in spatial resolution, the orbit should be circular and around 50km. When aiming at higher orbits, the instruments, i.e. the optics, have to be adapted and some performance degradation has to be accepted. Nevertheless, especially the instruments that utilize a previously not or not sufficiently covered spectral range (USMI, SERTIS, VISNIR and MIMO) are of high interest also on higher orbits. For the HRSC-L and for LEOSAR a low circular-orbit with limited altitude variation is mandatory (25-150km). In order to gain global coverage, a lifetime of about 4 years is required to map the entire lunar surface at adequate illumination.

2.2.1.8.3 Lunar Geology

A dedicated pair of sub-satellites has been developed to measure the Moon’s gravity field and magnetic field. The concept is based on satellite-to-satellite tracking (Low-Low SST) with microwave range and range-rate instrumentation PRARE-L for gravity and two boom-mounted magnetometers LunarMag for the magnetic field. By separating the essential systems for the science phase in a low lunar orbit from the required orbit maneuvering systems, e.g. for lunar orbit capture and orbit lowering, as well as from systems that require deployed solar arrays, the potential sources of disturbance for the gravity field measurement can be minimized; hence, the system is compatible with any mission capable of deploying the two sub-satellites in a low lunar orbit. Furthermore, magnetic cleanliness has only to be assured for the sub-satellites and not for the entire mission.

The key features of anticipated individual orbiter missions are summarized below.

Lunar Environment	
Key-features	Precise characterization of neutron-, gamma- and particle radiation in an energy range relevant for characterization of human exposure (RadMo, IRAS) Precise measurement of dust particle trajectories, charge and mass (LEOPARD)
Development Status	Bread-boarding of the instruments with all key-elements. (RadMo, LEOPARD) Advanced design and development of the flight-instruments. (RadMo, LEOPARD) Resource adaptation widely possible. (RadMo)
Required Orbit	Low circular lunar orbit (<150km) or elliptic lunar orbit with low perigee (<150km) Lifetime > 1 year
Resources	Mass: 7.5kg (RadMo) + 6.5kg (LEOPARD) + 0.6kg (IRAS) Power: 12W (RadMo)+ 16W (LEOPARD) + 4W (IRAS) Volume: 150x230x135mm, 150x150x50mm, 250x130x130mm (RadMo) + 320x370x350mm (LEOPARD) + 112x100x99,5mm^3 (IRAS) Data rate: 116kbit/s (RadMo) + 3kbit/s (LEOPARD)

Lunar Topography, Geomorphology and Composition	
Key-features	High-resolution topographic mapping (HRSC-L) Mapping of lunar surface mineralogy: • 200-400nm with 20nm bands (USMI) • 400-3000nm with 10nm bands (VISNIR) • 7-14µm (SERTIS) Mapping of the thermal albedo factor, in 5 bands of 7, 24, 60, 183 and 557GHz (MIMO) Mapping of the lunar surface and subsurface at L-band with 6 m spatial resolution (LEOSAR) Mapping of element concentration of Na, Mg, Al, Si, K, Ca, Ti, Mn and Fe with 6 km spatial resolution in energy range 0.5-10keV (XRF-L)
Development Status	Consolidated instrument concepts (HRSC-L, SERTIS, USMI, MIMO, LEOSAR) Established instrument concepts (VISNIR, XRF-L)
Required Orbit	Low circular lunar orbit with limited altitude variation (25-150km), sufficient illumination and adapted orbit spacing for coverage Lifetime > 1 year
Resources	Mass: • 26kg (HRSC-L) • 20kg (VISNIR) • 22kg (LEOSAR) • 27kg (MIMO) • 3.5kg (SERTIS) • 5.5kg (USMI) • 13kg (XRF-L) Power (average):

- ~100-130W (HRSC-L) depending on duty cycle
- 40W (VISNIR)
- 20W (LEOSAR)
- 54W (MIMO)
- 15W (SERTIS)
- 34W (USMI)
- 30W (XRF-L)

Data rate:

- 250MBit/s (HRSC-L)
- 65MBit/s (VISNIR)
- 396MBit/s (LEOSAR)
- 16kbit/s (MIMO)
- 0.4MBit/s (SERTIS)
- 12.9MBit/s (USMI)
- 2.5kbit/s (XRF-L)

Lunar Geology	
Key-features	Independent sub-satellites for release in low lunar orbit Highly accurate recovery of the lunar gravity field with accuracy 0.1mGal at 20km resolution (PRARE-L) Magnetic field with 0.1nT accuracy (LunarMag)
Development Status	Consolidated concept based on heritage design of ACES (PRARE-L) Sophisticated design with several heritage instruments (LunarMag)
Required Orbit	50 km circular long-term stable (i=85°) lunar orbit Lifetime > 2 years
Resources	Mass: 2x 128kg (entire satellite) Power: independently powered Volume: 1500x1000x670mm plus 4m boom Data rate: independent downlink

2.2.2 In-situ Exploration

2.2.2.1 Geological context characterization and sample identification by combined stereo and microscope imaging and LIBS-Raman analysis

2.2.2.1.1 Stereo and microscope imaging

During lunar surface operation the geologic context must be, either for lander or rover acquired in terms of multispectral panoramas of the landing area, stereo images of sample-acquisition worksite, and monitor sample acquisition and transfer. Therefore panoramic color stereo imaging as well as high-resolution zoom in imaging is required.

The specifications for such cameras are shown in Table 1. Despite the absence of skylight to illuminate shadows on the Moon, the lander/rover modules alone will scatter thousands of watts of solar illumination, providing irradiance levels within the shadows conservatively estimated at 1% of direct sunlight.

Table 1: Surface Stereo Panorama Camera Specifications

	WAC/HRC
Ops Phase	Surface
Features	wide-angle stereo high res mono
Pointing	Pan/tilt mast
FOV [deg]	34 x 34 / 5 x 5
Pixels (VNIR CCDs)	1024 x 1024
Spatial Resolution	2.0 / 0.2 mm @ 3 m
Spectral Bands	up to 12
SNR	> 200
Calibration	TBD
CBE mass w/elec.	1.8 kg
CBE power w/elec	8 W
Total DataVol(Mb)	8249
Design Temp (°C)	-70 to +70
Pred. Temp (°C)	~ -10

A Site Imaging System is derived from the panoramic camera system derived for ExoMars (see Figure 5) and consists of two camera systems; Wide Angle stereo Cameras (WACs) and a High Resolution Camera (HRC).

The WACs have 34° Fields of View (FOVs) and a 1064 x 1064 pixel Charge Coupled Device (CCD), with a 14 bit dynamic range. Both WACs include a filter wheel with 12 filters and are separated by 150mm. The detailed filter characteristics are not yet defined but their wavelength range will be between 430 and 900nm. Use of the optical filters provides information on the mineralogical composition of imaged terrain.

The HRC consists of a single camera head with a 1064 x 1064 pixel Complementary Metal Oxide Semiconductor (CMOS) device providing Red Green Blue (RGB) color images. The HRC's FOV is 5°. The HRC's dynamic range is 16 bit.

All SIS cameras have a read-out time of less than 1s. The system level characteristics of the SIS are given in Table 2.

Table 2: Main characteristics of the Site Imaging System
(The mass of the mast is not included.)

Unit	Mass (kg)	Power (W)	Data (Mbit)	Dimensions (mm)
WAC and filter wheel	0.4	1.85 (3.35 peak)	2 x 15 / stereo image	WAC: 50 x 50 x 70 mm (sensor box) + cylinder of 80 mm (diameter) x 20 mm (filter wheel thickness)
HRC	0.3	0.9	20 / image	55 x 45 x 180 mm
Electronics	0.3	3 x Eurocard		

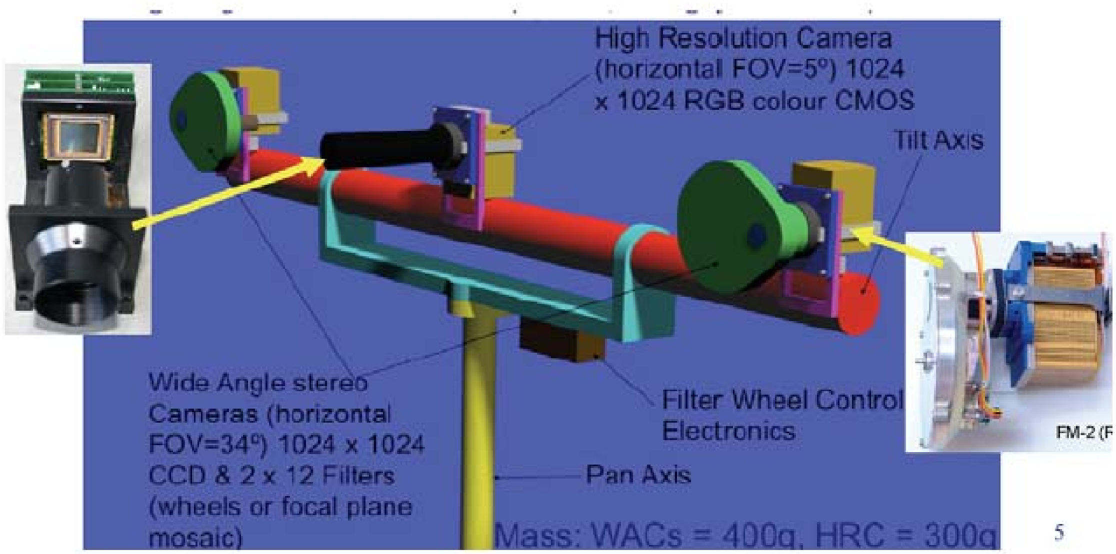


Figure 5: Concept of the ExoMars PanCam

The cameras shall be accommodated such that they can be moved azimuthally through 360° and tilted from zenith to 60° below the local horizontal. This allows the imaging of panoramas and objects from close to the lander to the horizon and also allows for observation of stellar targets for calibration.

The WACs and HRC shall be aligned to an accuracy of 1 arc minute ad shall have an alignment knowledge of better than 0.1 arc minutes. The pointing accuracy for the camera shall be less than 3 arc minutes with a goal of 1 arc minute. It shall be possible to measure the pointing position to an accuracy of 1' or better.

The cameras shall be mounted at a height greater than 1.5 m from the surface. The cameras' FOVs shall be unobstructed by the lander's structure including the high gain antenna. Any deployment arm on the lander shall include an inspection mirror to allow the camera to obtain images of otherwise inaccessible areas of the lander itself for technical inspections.

The camera electronics are shall be accommodated in the lander. The electronics include two Eurocard PCBs, plus a third Eurocard PCB providing the local memory.

The operations for the SIS are assumed to be the following:

- Provide one complete panorama, unfiltered as soon as possible after landing. A single panorama can be assumed to require 30 stereo images (one stereo image is two WAC camera images, one from each).
- Provide one panorama with each of the 12 filter wheels in place.
- Once these panoramas have been obtained it shall be assumed that two WAC stereo images and two high resolution images shall be recorded every 24 hours.
- In addition one full panorama shall be made per 24 hours for phase angle studies.
- The instrument shall operate only during periods of illumination.

2.2.2.1.2 LIBS-Raman Analysis

Close-up Laser Induced Breakdown Spectrometry (LIBS) measures the abundances of major, minor and trace elements down to 10ppm and contributes to understand the geologic/geochemical setting of the landing area and its history. Raman Spectroscopy provides detailed information on the minerals and their assemblages of at least 90% of the components of soils, coarse fines and rocks and thus defines petrogenetic processes, telling other aspects of the history of the landing site. Both methods are not only scientifically complementary, but also technically: They can be combined with substantial synergetic benefits by sharing electronics and more importantly a common optical spectrometer (Jessberger et al., 2003). The spectrometer, however, for Raman needs “darkness” (funnel) and high sensitivity, while LIBS needs a wide wavelength range from about 200nm to 800nm. Presently both methods are being developed for space application with a spatial resolution of ≈50µm (Jessberger et al., 2003; Knight et al., 2000; Bertrand et al., 2001a, 2001b; Jessberger and Bertrand, 2003; Bertrand et al., 2003a, 2003b; Bianco et al., 2006; Colao et al., 2004; Maurice et al., 2005; Sallé et al., 2005; Tarcea et al., 2008). The attractive addition of a microscope and of pointing or scanning capabilities with autonomous or remote control would greatly enhance the scientific return. The small analyzed volume of $50\times50\mu m^2$ area with ≈5µm depth (LIBS) and «1µm depth (Raman) of such a combined instrument could ideally augment presently active (on Mars) instruments like APXS and Moessbauer spectroscopy, which have information volumes of 4×4 cm^2 area and 10 µm depth.

LIBS allows for depth profiling and removes dust layers on rocks and coarse fines e.g. these “cleaned” surfaces subsequently may be studied again by an optical microscope, by Raman and LIBS. Other important features of LIBS are (Rauschenbach et al., 2010a, 2010b; Rauschenbach et al., 2009):

- determines quantitatively the concentrations of major, minor and trace elements within minutes;
- allows hundreds of micro-analyses during a mission and thus truly “explores” in detail the complete landing area as accessible by a rover;
- analyses lunar rocks, dust and especially many coarse fines, impact transported specimens of distant geologic units thus greatly expanding the “view” of the mission;
- detection limits for almost all elements are a few ppm (not yet maxed out!);
- detects water as ice as well as pore water, both potential lunar resources (Rauschenbach et al., 2008; Lazic et al., 2007);
- no sample preparation is needed;
- enables depth profiling up to 2mm;
- minerals as well as rock types can be identified by chemometric methods;
- the modular design make it highly versatile – one “bulky” instrument module with the spectrometer and electronics inside a rover serves many “light-weight” optical heads;
- a LIBS-alone instrument with TLR = 5 weighs only ≤1kg.

At DLR a Raman-microscope is available. This system combines confocal reflection microscopy, atomic force microscopy and confocal Raman spectroscopy. It can provide information on sample structure and composition and allows direct measurements of rocks, ices, brines, and mixtures using very little laser energy. This allows study properties of extraterrestrial material and planetary analogue material. With DLR´s Laser Induced Breakdown Spectrometer (LIBS) it is possible to determine the elemental composition of extraterrestrial material and planetary analogues with high lateral resolution and depth profiling. The Raman as well as the LIBS system is equipped with a planetary simulation chamber. This allows analysis under planetary conditions, i.e. at the pressure, temperature and atmospheric composition, which prevail on the planet of interest.

The Institut fuer Planetologie in Muenster, in cooperation with the DLR institute and industrial partners, has developed a lightweight (216g) LIBS laser and a miniaturized optical spectrometer

(Pavlov et al., 2010). In addition, it focuses on the further technical as well as systematic methodical development of LIBS for planetary applications. An example for their cooperative efforts: they have shown that LIBS is able to quantitatively determine the elemental composition of deep (some cm) dust layers in water ice (Pavlov et al., 2010; Schroeder et al., 2010).

Within the ExoMars project, German industry developed a Raman optical system and a compact LIBS laser for the ExoMars Raman/LIBS spectrometer. Both industry activities have demonstrated breadboards, with a TRL 5 in 2009. The RAMAN development for ExoMars is ongoing in the German industry (Hofmann et al., 2009).

2.2.2.2 ^{40}Ar-^{39}Ar in situ dating of the lunar surface

The time scale of any geologic process determines its very nature. Therefore, one of the highest-priority science goals of planetary exploration is elucidating the absolute chronology like internal differentiation processes or the surface evolution by volcanism and impact cratering. Radioisotope dating of the Apollo samples enabled to link impact crater counting to absolute chronology, not only for the Moon but also for other terrestrial planets (Turner 1977, Jessberger et al. 1974, Hiesinger et al. 2000, Hiesinger and Head 2006, Neukum et al. 2001, Stoeffler and Ryder 2001).

In situ radiometric dating at landing sites on the Moon could contribute to test the cataclysm hypothesis, to determine the age of the South Pole Aitken basin, or to date very young basalts (~1.2Ga) south of the Aristarchus Plateau, which likely mark the end of active volcanism on the Moon (Hiesinger at. all 2000, Hiesinger and Head 2006). However, no autonomous instrument for in-situ dating of planetary surfaces – though of vital scientific interest – has been developed up to now. Particularly promising seems ^{40}Ar-^{39}Ar dating of neutron-activated samples, which is one of the most reliable radioisotope methods to date impact metamorphosed rocks, thus capable to constrain lunar, asteroidal or terrestrial cratering histories (Turner 1977, Jessberger et al. 1974, Hiesinger et al. 2000, Hiesinger and Head 2006, Neukum et al. 2001, Stoeffler and Ryder 2001, Trieloff et al. 1998, Korochantseva et al. 2007). Dating basalt with the ^{40}Ar-^{39}Ar method generally is even more straightforward.

Based on a recent DLR funded study in cooperation with an industrial partner (Burfeindt et al. 2009, Trieloff et al. 2009, Hofmann et al. 2008), the development of a compact in-situ radiometric dating instrument appears to be feasible. ^{252}Cf (half live 2.6yr) would serve as a neutron source, while sample collection and transport between the neutron irradiation unit and the analysis unit would be performed robotically. After irradiation, the noble gases He, Ne and Ar would be extracted from samples by stepwise heating in a furnace and analyzed by mass spectrometry. The determination of the isotopic compositions of argon (^{40}Ar from in-situ decay of ^{40}K) will allow dating impact metamorphism and crystallization. Additionally, cosmic ray exposure ages can be calculated from the easily determined concentrations of cosmogenic nuclides (e.g., ^{3}He, ^{21}Ne, ^{38}Ar) and together with solar wind implanted noble gases yield information on small cratering events or regolith reworking. The addition of a small γ-spectrometer would allow classical neutron activation analysis of the samples, i.e. the determination of the concentrations of major and minor elements.

Advantages of stepwise-heating for in-situ ^{40}Ar-^{39}Ar dating, compared to conventional K-Ar or Rb-Sr dating, are

- no need for sample preparation or mineral separation
- the ability to recognize disturbances of the system, e.g., presence of inherited ^{40}Ar or late partial loss of ^{40}Ar
- the possibility to identify different events that influence the age of a sample, e.g., original crystallization and later mild reheating

- the simultaneous dating of high temperature events (affecting the ^{40}Ar budget of a rock by thermal diffusion) and low grade events leading to surface exposure (causing accumulation of cosmic ray induced nuclides)
- the simultaneous chemical characterization of the dated samples by ^{37}Ar from Ca, ^{39}Ar from K, and by γ-spectrometry of a number of other elements.

2.2.2.3 Sub-surface properties monitoring by HP^3 (Heat Flow and Physical Properties Package)

The German Aerospace Center is involved in the development of an instrument for in-situ measurement of lunar heat flow and to investigate the mechanical, electrical and thermophysical properties of the lunar regolith. This so-called Heat Flow and Physical Properties Package (HP^3) (Spohn et al. 2001) consists of temperature sensors, heaters and electrical sensor that will be emplaced into the lunar subsurface by means of an electro-mechanical hammering mechanism. Motion and tilt sensors are included to determine the position of the instrument in the ground. The instrument is foreseen to penetrate at least 3m into the lunar regolith and perform depth resolved measurements of the soil's thermal conductivity, thermal diffusivity, temperature, electrical conductivity and relative permittivity. From these measurements, the surface planetary heat flow can be directly deduced and the measurement of electrical properties will allow us to constrain the soil porosity and - to some extent - chemical composition. Furthermore, an analysis of the achieved soil intrusion as a function of time will constrain the soil's cohesion, internal friction angle and density. In this way, the stratigraphy of the landing site can be characterized to the penetrated depth in great detail, identifying soil compaction with depth and possible layering.

The HP^3 instrument consists of four functional subunits, which are shown in Fig. 6: The mole houses the electro-mechanical hammering mechanism to provide capability for penetration into the regolith. The payload compartments incorporates motion and tilt sensor heads, soil heaters/sensors for the soil thermal conductivity experiment and electrodes, as well as the necessary electronics to perform the permittivity and electrical conductivity measurements. The instrumented tether, which is trailed behind the payload compartment, provides the power and data link to the surface and acts as a carrier for temperature sensors. The support system stays on the surface after deployment and provides secure storage of Mole, Payload Compartment and Tether during all flight phases. It also serves as the mounting locale for the instrument's back-end electronics.

The instrument has been pre-developed in two ESA funded precursor studies and has been further developed in the framework of ESA's ExoMars mission. The current readiness level of the instrument is TRL 5.62 (ESA PDR Apr. 2009) which has been achieved with several Breadboards developed and tested between 2004 and 2009. As no drilling is required to achieve soil penetration, HP^3 is a relatively lightweight heat flow probe, weighing less than 1800 g.

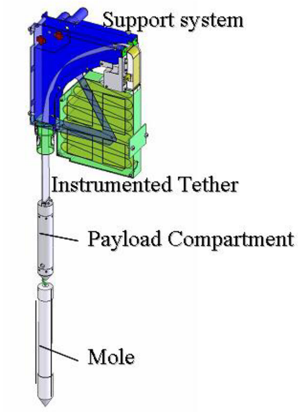


Figure 6: Schematics of the HP3 instrument showing the functional subsystems (left).
HP3 Breadboard during 2.3 m soil intrusion test. The Support System is positioned at the top of soil cylinder (right).

After deployment of the instrument onto the lunar surface, instrument operation will be split into two phases. During the penetration phase soil intrusion is achieved by means of the electro-mechanical hammering mechanism. The net hammering time is expected to be ~12h to reach the final depth of 3m, but hammering will be interrupted at intervals of 0.5m to conduct thermal conductivity and electrical measurements. After the final penetration depth has been reached, the instrument will switch to the monitoring mode. This mission phase basically consists of column temperature readings and occasional permittivity experiments and lasts to the end of the mission.

HP3 will measure temperatures using copper based resistance temperature detectors (RTD's), which are mounted on the tether and will allow for determination of the column temperature profile with high spatial resolution. The thermal gradient in the regolith is then obtained from the combination of temperature and position measurements, i.e., the deviation of the mole path from the vertical and the amount of paid out tether. The basic principle applied to determine the thermal conductivity is the controlled injection of a specified amount of heat into the medium and a measurement of the subsequent temperature increase of the heater, the self-heating curve. We focus on transient methods because of the finite time available for the measurements, the specific HP3 geometry, and the lesser dependence on contact resistance of these methods compared to steady state methods. In case of HP3, we use a modified version of the line heat source (LHS) method (Hammerschmidt and Sabuga, 2000, Jaeger, 1956). An independent measure of the regolith's thermophysical properties will be obtained by a measurement of the attenuation of the amplitude of the diurnal and annual temperature waves.

The electrical properties of the regolith will be determined by applying and alternating current to the payload compartment's transmitter electrodes, and the induced voltage will be measured by two receiver electrodes also mounted on the outside of the payload compartment (Sohl and Spitzer, 2008). Coupling to the regolith is non-galvanic and the amplitude and phase shift of the induced signal at the receiver electrodes can be directly inverted to give the soil's electrical conductivity and relative permittivity.

2.2.2.4 Seismology

In recent years, seismological work at the DLR Institute of Planetary Research focused on the question of Moonquake location, since source location is the most fundamental problem in classical seismology. A new method (named "LOCSMITH", Knapmeyer, 2008) for location with insufficient data from very sparse station networks (as Apollo) was developed and used to relocate the known lunar deep quake clusters (Sonnemann, 2005a,2005b, 2006; Hempel et al., 2009a, 2009b,2009c). The advantages of the new method are the determination of the location uncertainty under conditions

where the usual assumption of Gaussian distributions does not hold, and the strongly reduced dependency on starting solutions, i.e. on a priori assumptions about the outcome. We were able to constrain the locations of several previously unlocated quake clusters, i.e. for clusters for which standard methods fail. By a re-assessment of the location uncertainties of all other clusters we found that the existing travel time observations do not rule out that many of them occurred in the far half of the Moon. We have correlated the shape and extent of the location uncertainty volumes with anelastic attenuation (Hempel, 2009c), and thus find likely source areas for quake cluster for which seismic travel times alone are not sufficient for location. To determine the seismicity level in the far half, more seismometers in a dedicated, truly global network geometry would be necessary. Both the non-linear determination of location uncertainties and the connection with the attenuation model can be useful for the selection of landing sites of a future lunar seismic network.
We are currently working on the orientation of the lunar deep quake mechanism, i.e. on the determination of the three angles that define a seismic fault plane solution. The relation between the source orientation and the tidal stresses is an important clue for the understanding of the physics behind Moonquake periodicities. This is project done in a project together with USGS, Flagstaff, AZ.

The Max Planck Institute for Solar System Research has developed the prototype of a deployment and leveling system for a broadband seismometer for planetary applications. It provides autonomous leveling of the seismic sensors fixed on a Lander as well as after deployment to ground. It includes its own lock system for launch, landing and release after landing. The drives and the deployment structure are designed to allow leveling over a wide temperature range to cover day and night measurement. The deployment structure is developed with special regard for a transfer function without eigenfrequencies up to 200Hz. This allows simultaneous measurement of very broad band sensors (VBB) and short period (SP) sensors integrated at the same structure. Up to three VBB and three SP sensors can be accommodated with a total weight of up to 2kg.

2.2.2.5 Mitigate environmental hazard

Manned and unmanned missions to the Moon are likely to experience a multitude of environmental hazards, most of which have already been alluded to. While humans or robotic equipment can be protected against most hazards by state-of-the-art engineering solutions, two stand out because of their random nature – micrometeoroid impacts and radiation damage due to solar particle events. Because of the relative constancy of the GCR flux, radiation hazards due to GCRs can be mitigated by design criteria. Solar energetic particles which lead to radiation hazards are accelerated in gradual events, probably by shocks or compression regions in the solar corona. Electrons which are also accelerated are much faster than the heavier ions and arrive at Earth or Moon with nearly the velocity of light. Thus, measurements of energetic electrons can be used as an early warning system for the arrival of energetic ions which pose a much more dangerous radiation hazard (see Fig. 7, Posner et al., 2009). Warning times are on the order of tens of minutes which are not a lot, but may be enough to reach an underground shelter. Hazards due to micrometeoroid impacts are near-impossible to predict and prevention must rely on minimizing time spent in unsheltered locations.

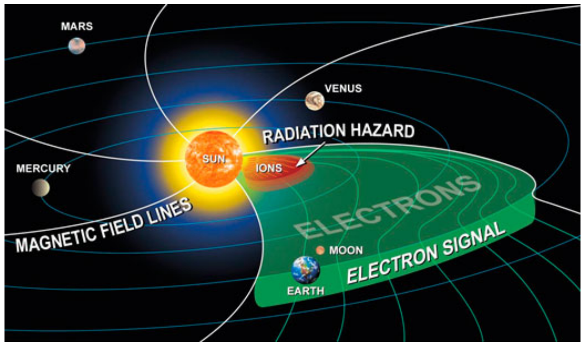


Figure 7: Illustration of the working principle of the Relativistic Electron Alert System for Exploration (REleASE). Ten minutes into a solar energetic particle event, the radiation hazard is still confined to a region (red) close to the Sun when light-speed solar electrons reach the Earth-Moon system. A warning system outside the Earth's magnetosphere receives the signal and translates it in near real time into a hazard warning of upcoming ion intensity. Between 20 minutes and an hour later, hazardous energetic ions would begin to engulf the Earth-Moon system. Promptly warned, astronauts would have time to prepare for and avoid the hazard. Depending on the circumstances, reliable and accurate warnings can significantly reduce astronauts' radiation exposure (Posner et al., 2009).

2.2.2.6 Moon-Earth communication

2.2.2.6.1 Channel Coding

In the context of space exploration missions, channel coding represents a key component for the communications subsystem. Space communication links are in fact characterized by large propagation distances and hence by large attenuations (leading to low link margins). Channel coding (i.e., the use of error correcting codes) permits to cope with the high unreliability of the link, correcting errors and increasing the amount of useful information. In space communications, efficient codes (i.e., codes operating in proximity of the Shannon limit) are extremely appealing. Recently, CCSDS investigated the recommendation of near-Shannon limit error correcting codes based on sparse matrices (low-density parity-check codes, LDPCC). LDPC codes are large block codes for which fast iterative decoding is possible, allowing data rates in the order of 10-100 Mbps, which may be appealing for future Moon-Earth links (according to the Moon missions requirements discussed within the Channel Coding Working Group of CCSDS). The KN institute of DLR (DN section) is currently involved in the design of LDPC codes for satellite communication standards, and in the development of fast LDPC decoders. Furthermore, our section is leading the activity of CCSDS on the adoption of long erasure codes (LECs). LECs are usually applied to recover packet losses in wireless links, even in presence of outages and/or link disruptions, and are particularly suited for free-space optical communications, and in the DTN context. DLR recently proposed a LEC scheme able to almost achieve the ultimate communication bound, with a decoder implementation working at 1.6Gbps.

2.2.2.6.2 Networking Issues: Delay Tolerant Network Applications

The need for continuous connectivity amongst the nodes deployed on the Moon surface and the Earth stations introduce some networking challenges in view of the heterogeneous operative conditions present on the Moon. In particular some attention has to be paid when nodes are located on the "hidden" face or exploring craters, thus missing the line-of-sight with the other communication devices. In these cases, continuous connectivity cannot be guaranteed, and data communication may suffer from unpredictable interruptions. A possible solution to this problem is then given by the Delay Tolerant Network architecture (whose benefits are being investigated at the KN institute of DLR; DN section), which exploits the mailman principle, thus offering suspend-resume facilities. In this respect, the selection of the next DTN node to which the information can then be transferred plays some role and opens the door to storage-based routing mechanisms, by taking into account that both power supply and storage availability are important, and scarce resource within each node on the Moon surface.

2.2.2.6.3 Optical Moon-Earth Communications

For a given mass, power consumption and volume, laser communications allows higher data rates than the classical RF technology. There exists today a variety of space-qualified optical terminals: near-infrared wavelengths, typically 1064 or 1550nm, offer the best performances. However, no specific modulation scheme is favored for the Moon scenario.

A communication relay from the Moon to a GEO satellite is limited by the achievable optical antenna size and mass on both spacecraft. On ground, antennas can be 10 times larger in diameter which still outperforms atmospheric channel disturbances (attenuation, scintillation and wavefront distortions). Unlike an Earth-orbiting optical relay, a network of optical ground stations can be established gradually, spreading cost over time. Because optical link is blocked by clouds, the ground station network must be used to provide an effective spatial diversity and maintain high link availability. Earth-based optical telescopes shall properly filter background noise that is caused by sky radiations during daytime and sunlight reflected by the Moon. The power budget of an optical downlink from the Moon showed that 10Mbit/s could be achieved with a 0.4m ground telescope.

2.2.3 On lunar surface operations

2.2.3.1 Lander Concepts

Based on ESA studies a comparative assessment with NASA has been performed in order to determine if ESA and NASA lunar architecture concepts could complement, augment and enhance their respective exploration plans. After assessing different options, a European contribution to the NASA led lunar exploration initiative has been identified in the form of an autonomous European Lunar Lander, capable of delivering payload to the lunar surface which might include infrastructure, logistics and consumables for the later human presence on the Moon, as well as payloads directly supporting independent European exploration objectives (future Lunar Lander in a cooperation scenario). In this context an adequate predevelopment and demonstration program is seen absolutely mandatory. In particular, it has to be ensured that the TRL of the key enabling technologies and the IRL of the subsystems has reached a reliable status (TRL 5) before entering the Lander procurement phases. Figure 8 depicts the generic approach improving TRL and IRL highlighting the essential milestones "Terrestrial Landing Demonstrator" and "Precursor Lunar Lander" (NEXT LL).

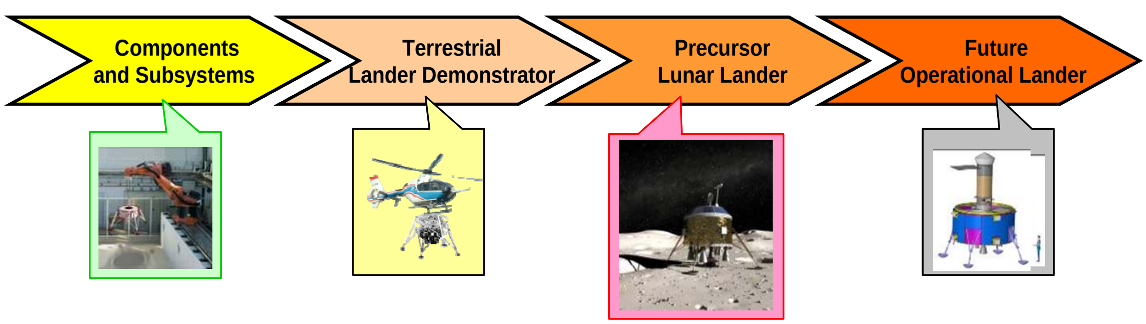


Figure 8: Development Logic Lunar Lander

Several studies have been performed to investigate at Phase A level a Precursor Lunar Lander mission with in-situ science and mobility, demonstrating soft precision landing with hazard avoidance. In particular the proposed mission concept

- demonstrates a fully autonomous soft and precision landing on landing legs with a precision better than 200m (3-σ)
- shows the ability for autonomous selection of a safe landing site including the capability for hazard avoidance
- offers the opportunity to perform scientific measurements on a region of the Moon that has never been explored before, e.g. at the South Pole
- provides the servicing for the scientific instruments in terms of safe transport to the Moon, deployment of the instruments to Moon surface, if required, and the necessary interfaces and equipment for power supply, data management and communication during surface operations.

The assessments are given for two optional mission concepts which are

- A Single Stage Lander providing a Lander-only payload capability of **60kg** landed on the surface of the Moon. After launch with a Soyuz 2.1B Fregat into HEO the direct transfer to the LLO and the descent and landing are managed by the Lander's own propulsion system. The payload capability is compliant to the requirements of an instrument package of 24.4kg including all service needs.

- A Dual Stage Lander providing the capability of a Lander + Rover Light shared payload of **115kg** landed on the surface of the Moon. Lunar transfer from GTO to LLO is performed by a separate Transfer Module. Within this scenario, in addition to the instruments, a rover of about 57kg including 4.6kg payload can be served.

Main Characteristics	
Transfer concept	• Single Stage Lander • Direct transfer to HEO
Dimensions	• Diameter: 2400nm • Height: 2800mm • Footprint Rad. 2700mm
Mass Figures	• Launch mass: 2111kg • Dry mass on Moon: 741kg
Propulsion System	• 5 x EAMs (500N) • 6 x 220 N thrusters • ACS system
Lander PL Capability	• **60kg**
Surface PL Needs	• **55.8kg** (24.4kg Instruments Priority 1 + 24.4kg Services + 7kg CLIE)

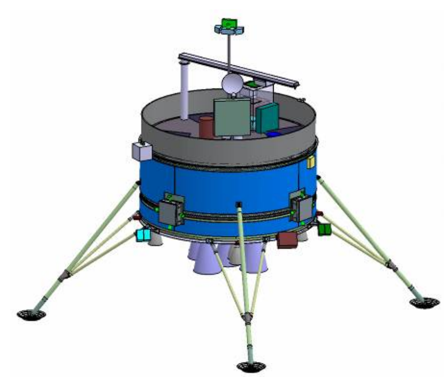


Figure 9: Lander-only Scenario and Concept

Main Characteristics (Lander)	
Transfer concept	• Dual Stage Lander • Transfer to GTO / GTO - LLO
Dimensions	• Diameter: 2770mm • Height: 2570mm • Footprint Rad. 2890mm
Mass Figures	• Launch mass: 2896kg • After TM sep. 1403kg • Dry mass on Moon: 700kg
Propulsion System	• 5 x EAMs (500 N) • 6 x 220 N thrusters • ACS system
Lander PL Capability	• **115kg**
PL Needs	• **113kg** (24.4kg Instruments Priority 1 + 24.4kg Services + 7kg CLIE + 57.8kg Rover)
Main Characteristics (Rover)	
Dimensions	• Stowed envelope: 952 x 741 x 273mm • Depl.: 857 x 741 x 1185mm
Mass Figures	• Total mass incl. PL **57.8kg**
Rover PL Capability	• 4.6kg Rover PL

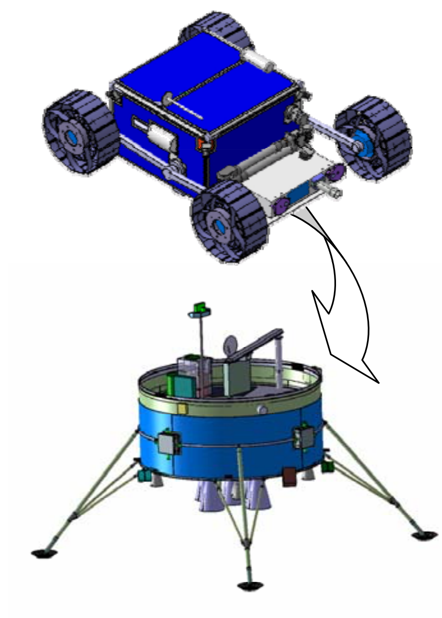


Figure 10: Lander + Rover Scenario and Concept

The NEXT Lunar Lander Mission was continued by a further study investigating a different candidate LL mission considering a shared Ariane-5 launch instead of a Soyuz launch. The phase B is now under preparation expected to start in the second quarter of 2010.

2.2.3.2 Soft Precision Landing

The demonstration of a soft, precise and safe landing on the lunar surface is priority for a first landing mission. This is in itself key for future exploration missions, and is one of the most critical elements to demonstrate to international partners Europe's capability to contribute significantly to international exploration of the Moon.

The Descent and Landing phase starts about 1:20h prior to touchdown when the Lander is on its final orbit about half way around the Moon. The Lander will pass the periselenium in a retrograde attitude and start a full thrust braking maneuver. Applying full thrust and an optimized pitch program the Lander will start a fuel optimal descent to the landing area.

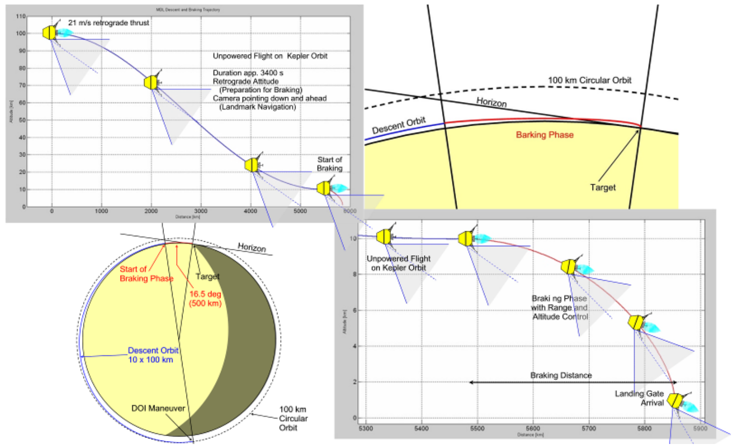


Figure 11: Summary of D&L Phases

Range, altitude, and cross track controls are performed by small thrust modulations and pitch angle feedback control, switching some of the auxiliary engines on and off at a slow rate. The full thrust braking maneuver will deliver the Lander to the “approach gate” when thrust is throttled back and the Lander starts to pitch over to almost vertical attitude to be kept during final approach. This point is passed about 75s prior to touchdown. About 15 seconds earlier, i.e. 90s prior to touchdown, the Lander passes “high gate”, which is defined by achieving visual contact to the landing area sufficient for landing site evaluation (slant range for image resolution, elevation for visibility). At high gate, the Lander will be at an elevation of about 40 degrees and about 4.8km away from the landing area. From there on, the hazard avoidance system starts working, resulting in a first target re-assignment, if necessary.

Lander attitude will be coordinated with the vertical and horizontal motion of the Lander in order to keep the target area in the centre of the FOV. However, during a diversion to another location, the Lander has to change the optimal pitch angle in order to realize lateral motion. No visual contact to the target can be guaranteed for this time.

Once the divert maneuver has been executed by the Lander, visual contact to the new site is re-established and the Lander shall continue the approach to the current landing site along the optical system line of sight. A second chance for retargeting and divert is then available at about 30s prior to landing.

15s prior to touchdown, the Lander will establish a vertical attitude, maintain zero horizontal velocity and descend at a constant rate of about 1m/s average. When the first contact to ground is sensed by the landing gear, main engine cut-off (MECO) is commanded.

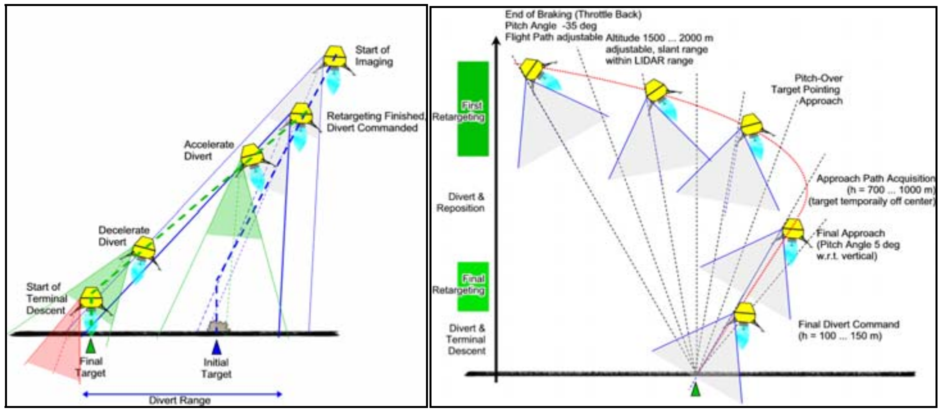


Figure 12: Final Approach and Terminal Descent (left) Pointing pitch-over after Braking (right)

The navigation concept for the NEXT Lunar landing mission is based on three different strategies which are selectively applied throughout the different mission phases

- classic deep space probe navigation
- autonomous optical navigation by means of landmarks
- the last meters vertical descent shall be performed based on IMU navigation only

While LIDAR is considered as primary sensor for Hazard Avoidance in the vicinity of the pole, it is considered as a backup or functional redundancy to the camera based navigation due to its slow update rate and the small field of view. For terminal descent, optical sensors may encounter problems due to lunar dust stirred up by the engine exhausts, such that the concept is to design the system for an IMU only terminal descent.

	Position						Attitude			
Phase	ESTRACK	IMU	RadarAlt	Camera	LIDAR		IMU	Stellar	Camera	LIDAR
Translunar Cruise	X						X	X		
Orbit Maneuvers		X					X	X		
Low Lunar Orbit	X			X			X	X	X	
Descent Orbit				X			X		X	
Powered Descent		X	X	X			X		X	
Final Approach		X	X	X	(X)		X		X	(X)
Terminal Descent		X		(X)			X		(X)	

Figure 13: Navigation Method vs. Phase for the NEXTLL Transfer Mission

Hazard avoidance shall be done primarily exploiting images acquired by the LIDAR. While the navigation camera can also be used for hazard avoidance the selection of the LIDAR as the primary hazard avoidance sensor has been made for the reason of its superiority in the presence of the illumination conditions to be expected in the vicinity of the pole. The very low elevation of the sun will result in long shadows, which makes it difficult for the camera to provide sufficient information for shape and slope estimation (shape from shading technique) The LIDAR as an active sensor is expected to provide a more reliable source of data, which is less dependant on local surface topography. Therefore, the functional redundancy capability of the two optical sensors is limited.

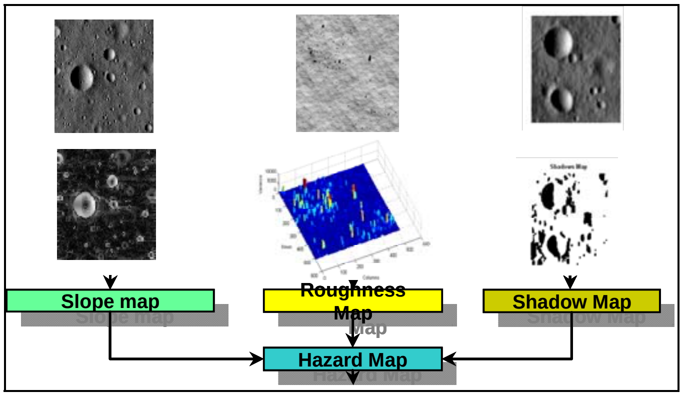


Figure 14: Camera based Hazard Avoidance Concept

ATON - Autonomous Terrain Based Optical Navigation for Landers

Together with other DLR institutes (DLR-FT, -OS, RM, SC) DLR-RY develops a demonstration hardware of an optical navigation system for autonomous, precise and safe landing on the Moon. Depending on the stage of the landing, different sensors and image processing techniques are utilized. These are tracking of known landmarks (absolute navigation), feature tracking (relative navigation), 3D data generation and analysis (absolute navigation and Hazard recognition). The sensor suite will be selected from a single navigation camera, a stereo camera and a Lidar.

To support development projects like ATON, the Testbed for Robotic Optical Navigation (TRON) is being constructed in DLR-RY. It is designed for the generation of realistic images of orbits and landing trajectories for Hardware in the loop tests of active and passive optical sensing hardware.

The prototype developed in ATON shall be qualified in TRON to a TRL of 4.

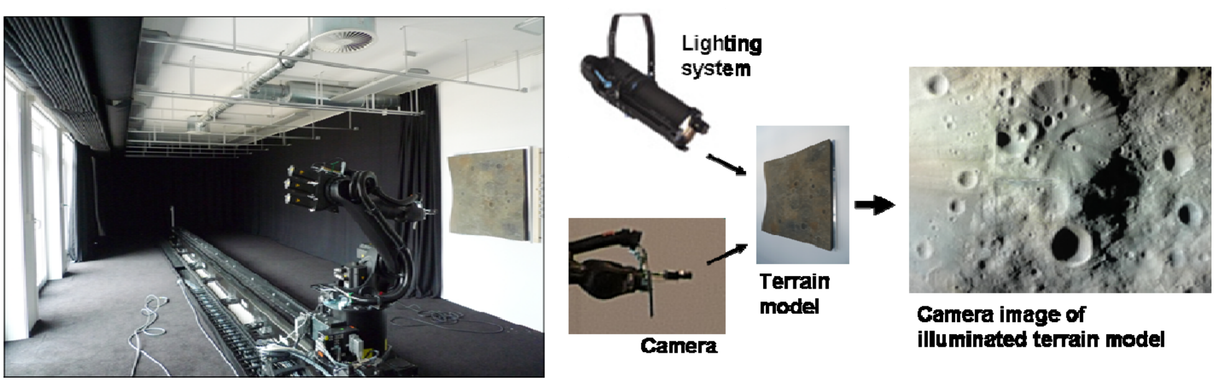


Figure 15: Current status of Testbed for Robotic Optical Navigation in DLR-RY

2.2.3.3 Concepts for Surface Mobility

2.2.3.3.1 Moon NEXT Rover Lite Concept

In the framework of the ESA Moon NEXT study the feasibility of a small rover has been investigated (Astrium UK, Stevenage, vH&S, MDA), coping with the mass constraint of about 60 kg of a precursor mission (see Lander concept Figure 10).

The rover vehicle is based on a 4 wheel active suspension platform composed of a warm box, a combination of body-mounted and deployable solar panel, and a radiator located on the top surface and at the front. The current baseline configuration is 57.8kg with the necessary maturity and systems margins and including payload. It has a stowed envelope of 192 liters and deploys to a configuration as illustrated.

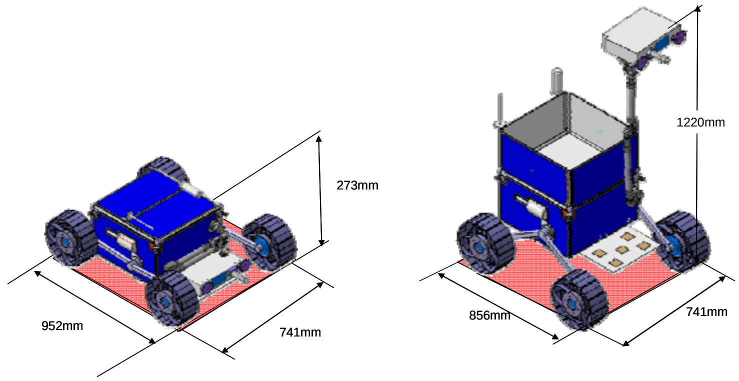


Figure 16: Rover General Configuration and Dimensions

This configuration can fully perform all the operations required of the rover over the length of the nominal mission. A dual use arm performs both the arm and mast function to provide a vantage point for the Rover Cam and the ground instruments such as the CLUPI and Raman/LIBS. In addition, should the operational constraints be altered, a number of mass saving options can be identified, e.g. limiting the range to the Lander to use a single UHF link or a non symmetrical rover to remove the use of additional solar panels. These would reduce the overall mass to the vicinity of 50kg including margins and payload.

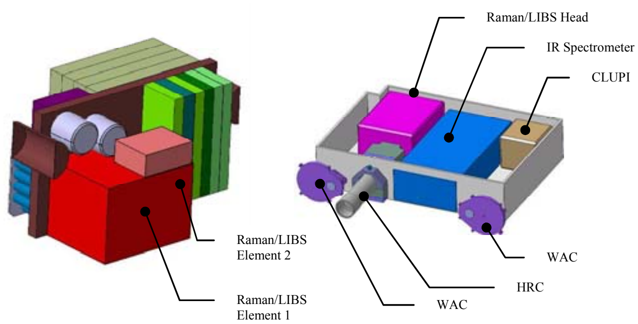


Figure 17: Payload Internal Configuration (Left) and Head Accommodation (Right)

The payload instruments and electronics are accommodated inside the warm enclosure of the rover body. However, the instrument sensors are located in the head/workbench with the IR Spectrometer and its Pelletier device connected to the head top radiator to provide the necessary thermal environment for the instruments. Due to less maturity of the dual stage Lander concept so far (chapter 2.2.3.1), and on the other hand to show the capability of mobility by limited P/L capacity, it is the intention to proceed in phase B (expected to start in early 2010) with a small rover concept (≤10kg) with innovative techniques, e.g. intelligent mobility.

2.2.3.3.2 Rover concept for the ESA Next Lunar Mission NLL

DLR-RM and DLR-RY were involved in one of the NLL Next Lunar Mission Based on Shared Ariane-5 Studies, lead by Astrium-Bremen. The DLR's tasks in Phase A CCN are to investigate the lunar rover mobility performance by making use of a DLR dynamics modeling and simulation environment for planetary rovers. This simulation tool has been developed and applied very successfully to the ExoMars rover locomotion performance prediction on rough and extreme terrains of arbitrary kind. Specific investigations in the lunar context cover the stability and gradeability performance of a 4-wheeled rover for given terrains. Performance prediction also accounts for the particular wheel design foreseen for this rover which calls for metallic flexible wheels. This is in direct heritage to the wheel concept having been proposed by DLR-RY and accepted for the ExoMars rover of ESA that is now in detailed development. Metallic flexible wheels thus far have not been used for robotic rovers but are advantageous because of their deflection under load lead to less wheel sinkage in the surface soil when compared to a rigid wheel of similar size. These results in a smaller overall motion resistance and at the same time in a smaller required wheel slip for the same net traction in comparison to a rigid wheel such as those used on current Mars rovers.

Upcoming tasks in the following study phase will use the simulation tool to optimize the preliminary rover concept w. r. t. kinematics suspension structure, mass and power consumption.

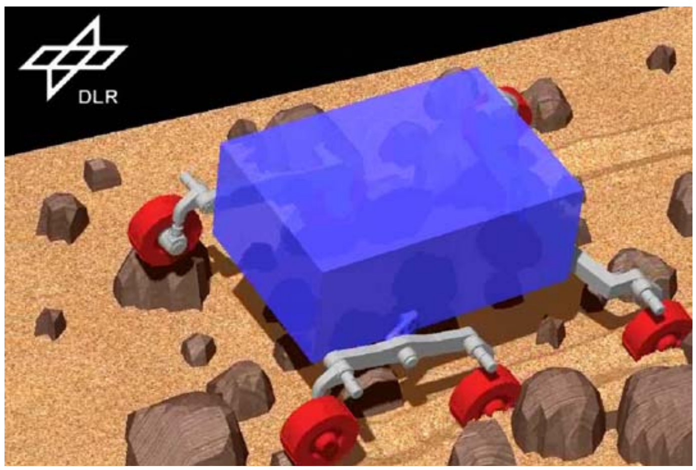


Figure 18: Simulating the entire motion dynamics of a 6-wheeled rover, with interaction between wheels and soft /hard soils.

Figure 19: ExoMars Phase B1 conceptual flight design of metallic flexible wheel (left), view of corresponding Breadboard wheel (center), and wheel undergoing single wheel test (right).

2.2.3.3.2.1 Lunar Robotic Payload scenario development

This covers scenario development, where rovers are used to give highest benefit to both scientific and technological instrumentation on Moon. Comparable earlier missions, like rover missions on Mars, can be termed ‘science-on-the-go’ approaches. Such rovers were designed to perform experiments on interesting locations with available rover science instruments and tools (MS, APXS, RAT, and MC). The payload remained integrated to the rover body throughout the mission. Future missions have to be designed more flexible, i.e. they should follow a ‘drop-and-go’ approach. Such a mission will profit from both mobility and manipulation capabilities. This approach allows deploying payloads on the Moon’s surface on certain sites for conducting experiments, e.g. radio-frequency instrumentation, ISRU demonstrators, and more. This has been done never before. Most benefit of course can be obtained from a combined approach, where we can use the mobile robot (1) as a platform for rapid deployment on several locations and (2) as a science-on-the-go system in the conventional way.

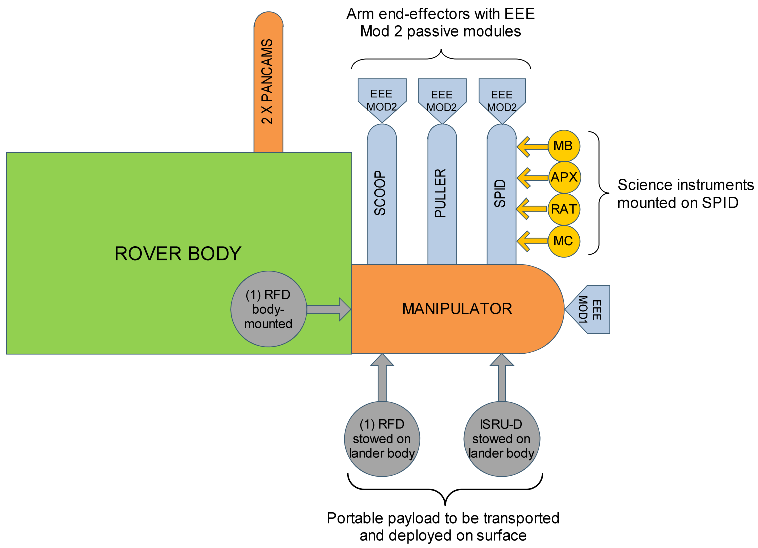


Figure 20: Functional diagram to demonstrate the combined approach.

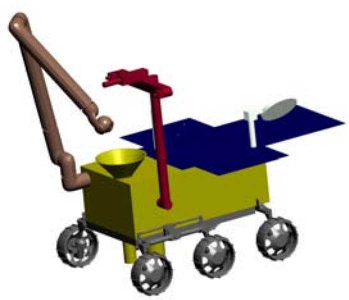


Figure 21: Six-wheeled rover with manipulation system for deploying instruments on lunar surface and for collecting regolith to fill ISRU demonstrator ovens.

2.2.3.3.2.2 Optimization of a generally wheeled mobile system

We are working on the optimization of generally wheeled mobile systems. This regards different influences to minimize mass and power consumption. It considers the scientist’s payload database, i.e.

- kind of instruments and their accommodation on the rover;
- mission user defined data and parameters, such as communication, attitude control, cabling, command and data handling system;
- rover locomotion typical data and parameters, such as mobility (wheels, actuators, suspension system, kinematic structure), thermal control sub-system, power subsystem.

Furthermore, in a separate step we optimize the rover w.r.t. to the overall motion dynamics behavior. This includes the rover as a dynamical multibody system, variations in the kinematics of the suspension systems, wheel interaction with the ground, and control aspects in order to achieve almost slip-free trajectories. Modern optimization techniques that apply are mainly based upon genetic algorithms and on multi-objective parameters methods.

2.2.3.3.2.3 Innovative mobility system design

Contrary to existing Mars applications (MER rovers, Phoenix mission) and due to the absence of atmosphere on Moon, advanced actuator systems for locomotion will benefit from their lightweight construction, high power performance, and intelligent controls by using force/torque sensing at gear output side. The DLR in-house developed brushless DC motors of high power performance, compared to brushed motors, are the only way to operate in lunar vacuum environment. Moreover, novel actuator concepts for combined wheel driving and steering have already been designed and are investigated to play a major role in low mass and low power future lunar rovers.

Moreover, wheeled systems surely will safely operate only under moderate terrain characteristics. Of strong scientific interests is to provide mobility in extreme environments, like craters, cliffs, and shadowed areas. Legged mobile systems are expected to be one of the future means to support and to realize those desires. We have developed a so-called 6-legged crawler, based on the in-house developed finger technology for our famous four-finger hand. Such a system, equipped with stereo camera and laser system for distance measurements, may almost autonomously, over wide areas, transport instrumentation to such extreme sites. In combination with intelligent walking gaits over unstructured terrain and advanced locomotion control systems (e.g. to provide compliant joints, reduce slippage) access to terrains of almost all types of characteristics may be possible. On extreme and steep slopes a combined rover and crawler system is conceivable, where the rover acts as a safe ‘mother ship’ resting at the cliff top that supports the smaller crawler inside difficult terrains being tethered by a safe rope.

Figure 22: Six-legged DLR crawler based on the finger technology for the famous DLR 4-finger hand.

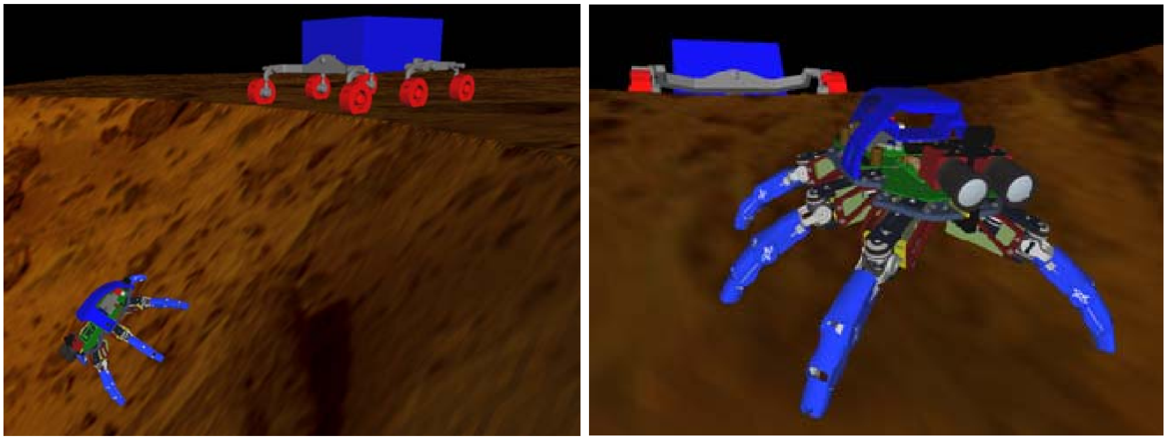


Figure 23: Combined mobile system consisting of a 'mother ship' (rover) resting on cliff top that tethers safely a 6-legged crawler operating in steep terrain.

2.2.3.4 Navigation on the Moon (Moon positioning system)

One of the major demands of processing resources on current rover designs relates to navigation. This is due to the fact that it is necessary to run a variety of processes such as image capture, storage & processing, path planning, localization using sophisticated sensor fusion techniques to ensure that the rover can operate safely and with high accuracy and progress performance.

Various algorithms and techniques have been considered including those originating from CNES, Structure from Motion and Optic Flow techniques.

The CNES algorithms are reasonably mature though they deal principally with perception (3D DEM building) and path planning. Processing loads are high and if only inadequate processing resources are available, then the rover will have to adopt a 'stop – image – move' approach (i.e. non continuous) which consumes valuable time and slows the overall progress of the rover.

The Optic Flow technique, whilst similar to Structure from Motion is not in a sufficiently advanced state of TRL for space applications to be adopted.

The Structure from Motion (SfM) technique operates in real time (given adequate resources) and is able to construct DEM's in 3 dimensions. Though quite mature, its implementation continues to evolve confidence in its robustness and performance grows. Consequently the Structure from Motion technique appears to be a very good candidate for the Moon NEXT mission.

Vision based methods	▪Tend to produce high processor loadings ▪Stereo algorithms - CNES, Structure from Motion ▪Mono algorithms - Structure from Motion, Optic Flow •Mono methods failure tolerant (with stereo pancam) ▪Sensors •Lidar based - good range & night nav compatible •Broad band (visible /IR based) – fair range & night nav compatible
Odometry	▪Wheel encoders •10% accurate but already available ▪2D/3D visual odometry •~4% accurate - require dedicated camera(s) & processing ▪Speckle Velocimetry •~1% accurate (TBC) - require dedicated camera(s) & proc.
Digital/Terrain Elevation Models	▪For path planning, hazard avoidance, traverse recording etc

Figure 24: NAV Technology Aspects

The range of available sensors and their accuracy is currently advancing at a steady rate. However, the greatest advance under development relates to the fusion of sensor data to provide a robust and accurate model of the rover environment and areas that are safe for traverse.

The baseline method of traverse and navigation for the MoonNEXT Rover is, by definition, teleoperation by human operator. Stereo or mono vision images will be relayed to Ground for the operator, as will a whole suite of sensor information including from IMU, accelerometers, tilt sensors and (bandwidth permitting) hazard cameras. Link persistence, strength margin monitoring, limited life validity of control and monitoring signals are all employed to ensure correct, timely and safe movement of the rover. Some level of autonomy is required to deal with situations when teleoperation is not adequate. Basic teleoperation will be constrained by link strength monitors to avoid the rover getting out of range or entering areas where communication is not possible. Traverse teleoperations will be monitored by on-board watchdog to avoid hazards – the most basic part of on-board autonomy for traverse operations.

Introducing more autonomy, the use of a programmed timeline incremental precision control of the rover position is important for safe placement of instruments and the conduct of science. The mix-and-match balance between teleoperations and autonomy must be matched with each operational scenario to ensure safe and successful operation of the rover without major risk. Structure from Motion (SfM) algorithmic approach for autonomous point-to-point navigation is being tested, efficient and flexible, and able to operate in both mono and stereo forms with very simple camera and image calibration required. SfM will support the provision of back-out and recover signal capability with the lowest possible risk if run over short distances and will provide a hazard avoidance monitoring capability during teleoperated driving under Ground Control.

2.2.3.5 Power supply systems

The power subsystem is in charge of the electrical power generation and distribution within the NEXT Lander spacecraft during

- distribute power to avionics equipment during the surface phase
- distribute power to equipment during all flight phases according to pre-programmed scenarios or according to specific telecommands
- manage the batteries charging by the solar array

The power system is designed around 2 independent chains, driven by the avionics architecture to provide a failure tolerance by design and avoid any failure propagation. Each power chain can be powered either by a rechargeable battery or by a solar array. Each one is controlled by one PDU that controls the power sources and distributes unregulated power to the avionics equipment.

Mission Phase	Unit	LEOP	Transfer	LLO Sun	LLO Eclipse	Descent	Landing	LD no comms	LD comms	LD Batt. Charge	DD ops	NOps1	NOps2	NOps3
Duration	hrs	1.0	120.0	1.1	0.9	1.0	0.17	454.0	28.0	18.0	16.0	180.0	2.0	2.0
OBC	W	33.0	33.0	39.6	39.6	39.6	39.6	39.6	39.6	39.6	0.0	0.0	39.6	39.6
Mass Memory	W	3.2	3.2	3.2	3.2	3.2	3.2	7.4	7.4	7.4	0.0	0.0	7.4	7.4
IMU	W	0.0	46.2	46.2	46.2	67.2	67.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Star sensor	W	0.0	4.2	4.2	4.2	4.2	4.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Sun sensor	W	0.0	2.1	2.1	2.1	2.1	2.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Radar Altimeter	W	0.0	0.0	0.0	0.0	0.0	38.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Nav Cam	W	0.0	0.0	0.0	0.0	0.0	5.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0
LIDAR	W	0.0	0.0	0.0	0.0	0.0	84.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
PDE duty cycle	W	0.0	1.0	5.0	5.0	25.0	705.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
PCDU	W	2.2	5.6	9.8	4.5	7.1	35.7	4.1	5.2	6.8	1.0	1.0	2.7	3.8
X-Bd XPNDR RX	W	25.2	0.0	0.0	25.2	0.0	0.0	25.2	0.0	0.0	0.0	0.0	25.2	0.0
X-Bd XPNDR RX + TX	W	0.0	58.2	58.2	0.0	58.2	58.2	0.0	58.2	0.0	0.0	0.0	0.0	58.2
Batt. Charge	W	0.0	10.0	118.1	0.0	0.0	0.0	0.0	0.0	100.7	0.0	0.0	0.0	0.0
Total	W	64	161	284	130	204	1036	76	108	164	1	1	76	107
System Margin 20%	W	13	32	57	26	41	207	15	22	31	0	0	15	21
Payload	W	0	0	0	0	0	0	42	42	42	11	3	3	3
Total incl. Margin	W	76	194	341	156	245	1243	133	172	227	12	4	93	131
On-top margin incl. (5 % + 1 %)	W	81	205	362	165	260	1318	141	182	241	13	5	98	139
Supply from SG	W	0	205	362	0	0	0	141	182	241	0	0	0	0
Energy from Battery	kJ	291	0	0	535	936	791	0	0	0	732	2937	709	1003
Battery self discharge	kJ	1	n/a	n/a	1	1	0	n/a	n/a	n/a	15	167	2	2
Total Energy from Battery	kJ	292	0	0	536	937	791	0	0	0	746	3104	711	1005
Spacecraft Bus Power	W	76	194	223	156	245	1243	91	130	86	1	1	90	128

Figure 25: Moon NEXT Power Budget

As can clearly be seen above, the sizing case for the solar generator is the low lunar orbit whereas the sizing case for the battery is the lunar night.

The "Heartbeat" phase where the Lander transmits its status once every other day can be more clearly seen from the power profile given in Figure 26. During lunar night activity, the battery is drained to a DOD-level of 80 % but is quickly recharged to full level during the following 17 hours of the lunar day assuming a safe C/20 charge current of 4.1 Ampere.

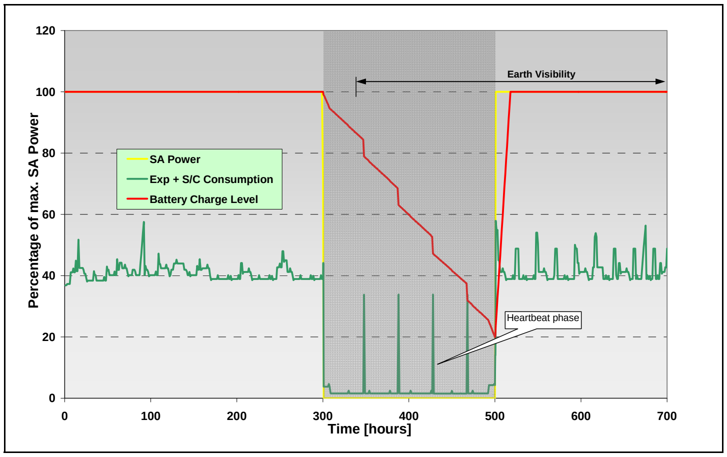


Figure 26: Power Profile

2.2.3.6 Thermal control to survive lunar night

One of the challenges to operate a surface station on the Moon is to survive the great temperature variations over day and night. Particularly, during night (lasting ~14 days) it is difficult to keep the station sufficiently warm and provide power for operations.

One possible solution is to use radioactive heaters (RHU´s), as demonstrated during e.g. the Lunokhod missions (Yelenov et al., 1971). During the Apollo missions experiments powered and heated with a radiothermal generator (RTG) were placed on the Moon and operated for many years (Apollo Lunar Surface Experiment Packages, ALSEP) (Harris, 1972). RHU´s and RTGs usually contain highly toxic plutonium-238 or polonium-210, and their use, thus, has strong influence on safety, handling and cost of the mission. For political reasons (and due to the unavailability of RTG´s in Europe) other concepts not relying on RHUs are currently investigated.

One option to keep instrumentation in a moderate temperature range is by positioning it sub-surface. Due to the low thermal conductivity of the lunar regolith, already in depths of about 20 cm the daily temperature variations are very small and the average temperature lies in a range of -20°C (Langseth et al. 1973, Lunar Sourcebook). Alternatively, concepts based on very good insulation (MLI) and a sophisticated power concept with solar generator and secondary batteries are currently studied.

It is essential for all scientific in-situ exploration relying on long term observations to solve the thermal problems, either by development (and political support) of RHUs or by applying more innovative strategies, optimizing chemical energy storage technologies as well as thermal insulation.

2.2.3.7 Laser and Radio Link Experiments

We propose to deploy state-of-the-art lunar geodesy packages on the Moon’s surface, consisting of a novel one-way laser ranging experiment, as well as microwave- and radio beacons. The ranging experiment will consist of a pulse Laser beacon pointed towards the Earth and firing short pulses at a clock controlled repetition rate. We estimate that the received signal strength from a 50mJ pulse Laser illuminating the entire Earth is approximately 3 orders of magnitude larger than a typical Laser ranging signal returning from the passive Lunar retroreflectors. Hence, such Laser shots could be received by most of the existing > 30 ILRS (International Laser Ranging Service) stations, enabling us to model systematic measurement errors, such as atmospheric travel time delay and Laser clock drift. As a result, significantly more lunar range measurements at higher accuracy and unbiased temporal coverage will become available. Small microwave and radio sources shall be deployed along with the Laser for observations of the tangential motion of the Moon with respect to the quasi-inertial kinematic reference frame of Quasar coordinates. New geodesy experiments will further our understanding of the Moon's internal structure, the dynamics of the Earth-Moon system and fundamental physics. For example, from the Moon's tidal response, inferences can be made on a solid or liquid lunar core and its size and oblateness. In addition, parameters from gravitational physics, e.g., the strong equivalence principle ("Nordtvedt-effect") could be modeled with vastly improved accuracy.

2.2.3.8 Astronomy from the Moon

Since 2005 the community has actively explored the possibility to use the Moon as a platform for astronomical observatories. In a series of workshops in Bremen, promising areas were identified, and classified into three categories:

(1) observatories uniquely requiring the Moon (low-frequency radio telescopes, large liquid mirror infrared telescopes),

(2) large space observatories which compete with formation free-flyers (e.g. optical, IR, THz interferometers), and

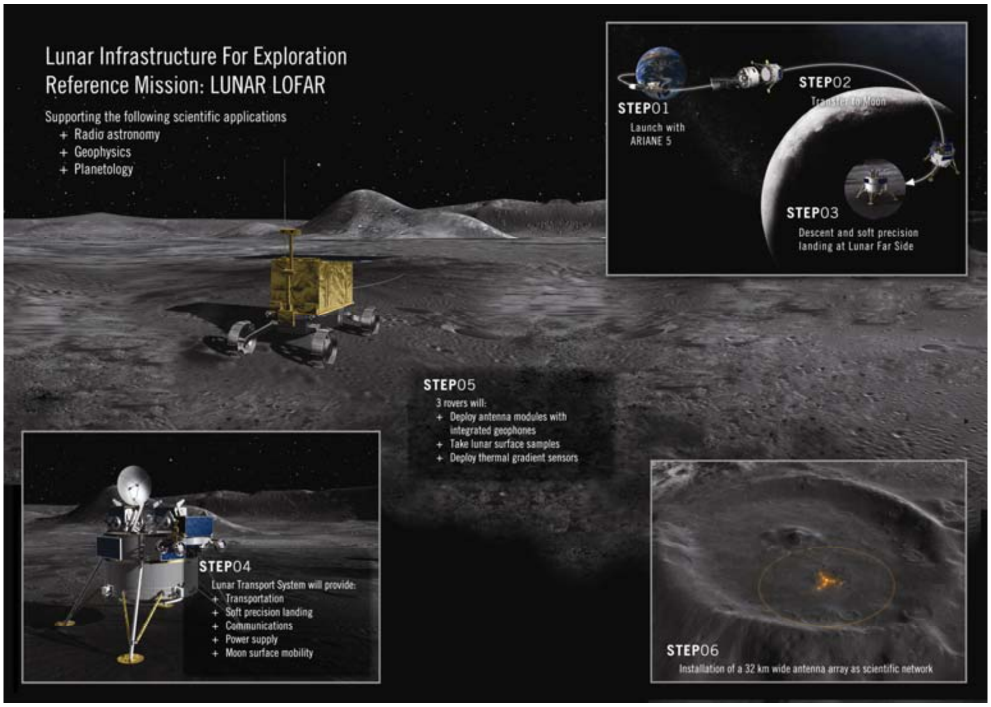
(3) smaller space observatories that may simply benefit from exploration infrastructure on the Moon (e.g., small x-ray or UV telescope).

From these initial considerations the low-frequency telescope option was then further investigated in more detail as a pathfinder application for erecting an astronomical infrastructure on the Moon. This application was considered to be the most promising one, needing the Moon as a unique stable platform outside the Earth ionosphere and also providing shielding against interfering terrestrial radiation.

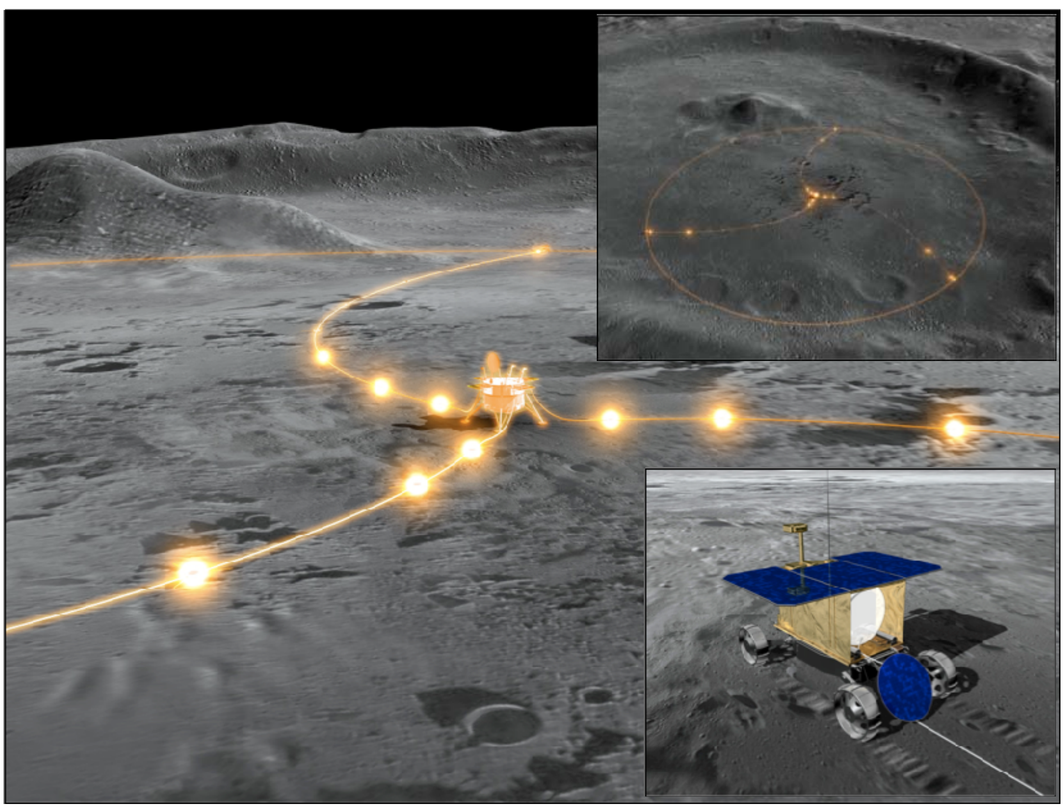
Together with German industry (EADS Space Transportation Bremen) a lunar observatory scenario was worked out in greater detail, which made use of the experience in low-frequency astronomy obtained in the construction of the LOFAR (Low Frequency Array) telescope. This telescope operates in the low-frequency regime just above the ionospheric cutoff. It is the largest of its kind and a European collaboration with the German community as the second biggest contributors in Europe and antenna fields hosted by the MPI fuer Radioastronomie (Bonn), MPI fuer Astrophysik (Garching), Astrophysikalisches Institut Potsdam, Landessternwarte Tautenburg, and the FZ Juelich (for a university consortium led by the Univ. Bochum).

The LOFAR telescope is in fact realized as a sensor network, where many simple sensors, such as low-frequency dipole antennas and geophones, share a common data network and central computing facilities. The same principle was adapted to the Moon, where an Ariane-5 - based lander would robotically deploy a sensor network consisting of self-sufficient low-frequency antenna modules, making up the radio telescope, and geophones to investigate the local underground. For low-frequency astronomy from Moon application, a detailed science case was worked out and published in the refereed literature (Falcke & Jester 2009, New Astr. Rev. 53, 1-26).

Currently further studies are being conducted to realize prototype missions, using, e.g., just two dipole antennas on a first European Moon lander (LRX – Lunar Radio Explorer). This is fed into the Lunar Exploration and Definition Team (LEDT) of the current ESA Moon lander study. On the global level the International Astronomical Union (IAU) has established a Working Group "Astronomy from the Moon" (chaired by H. Falcke), which seeks to further coordinate the global astronomy activities and in particular the radio efforts.



Scenario of a reference mission to erect a science infrastructure on the Moon, facilitating a low-frequency telescope, a geophone network, and planetary science investigations.



Low-frequency radio telescope, consisting of an Ariane-5 – based lander and a couple of robotically deployed simple dipole antenna modules.

2.2.4 Life Support Systems

2.2.4.1 Biomedical

Requirements for life support

The requirement of adequate life support systems is paramount. Firstly, oxygen partial pressure (pO_2) needs to be constantly kept above ~10kPa. PO_2 is the product of oxygen concentration and ambient air pressure. Importantly, abrupt changes in ambient pressure (or more precisely in pN_2) have to be avoided for medical reasons. The respiratory waste product, CO_2, is likewise crucial for life support, as CO_2 has both toxic and narcotic effects. Moreover, appropriate control of temperature and humidity is continuously required.

In addition to these immediate requirements, there is the obvious need for water and food supply, as well as for disposal of human waste (urine, feces etc.). Moreover, anti-microbial control, which is always important in confined environments as to be effectively carried out. An additional factor that is unique to the Moon is the occurrence of dust. Dust can cause skin reactions, and more importantly fibrosis of the lung which can ensure death in the long run. It will therefore be mandatory to implement efficient dust protection during activities outside the Moon station, and also during re-entry to the station in order to reduce the dust load in the air of the station.

Finally, it needs to be considered that human locomotion is grossly disturbed in the Moon's gravitational field. This raises fundamental questions which are of scientific interest in themselves. Moreover, the underlying problem is practically relevant, as it relates to the potential risk of falls and injury, as well as of architectural design of the Moon base.

In-situ utilization

It must be expected that activities outside a future Moon base is quite frequent, i.e. that there will by many transitions between inside and outside the station, perhaps even more than once per day. Importantly, ambient pressure is limited in space suits, as high pressures make movement and thus locomotion impossible. Therefore, an optimal regimen must be found that combines an ambient pressure that is low enough for application in space suits with an oxygen concentration that will generate an acceptable PO_2. CO_2 needs to be constantly eliminated from the air specific absorbers (e.g. $Ca(OH)_2$ or Noah). All life support systems require continuous feedback control, and appropriate back-up strategies for the case of failure.

Infrastructure engineering

It is evident from the above that appropriate sealing will be required in order to allow efficient control of ambient air pressure and gas concentrations. Moreover shielding is required to prevent heat loss and overheating, to reduce radiation exposure, to prevent water evaporation and diffusion of dust particles. Antimicrobial control can efficiently be done by UV light, which, however can be utilized only in the absence of human beings.

Design of doors, knobs, panels, work-tops, furniture etc. would have to take the specific gravitational conditions of the Moon into consideration.

Already during short visits considerable radiation exposures can occur due to Spa's. One efficient measure for the reduction of radiation exposure is provided by housing containing special shelters. These shelters may be visited during SPE activities. The housing materials have to be selected carefully, since they have to provide excellent structural properties and at the same time they should act as efficient radiation absorbers. Careful design is necessary due to the fact that the contribution to the exposure of the primary radiation components decreases with increasing shielding thickness, but the contribution of secondaries with even higher biological efficiency increases and approaches a maximum before it finally decreases. The best example is provided by the Earth's atmosphere where at atmospheric depth of about $50g/cm^2$ the radiation exposure due to cosmic ray reaches its maximum.

2.2.4.2 In-situ resource utilization

There is a strong need to investigate how robotic and manned space missions could profit from the utilization of natural resources on nearby planetary bodies. One of the most attractive options appears to be the production of propellants and life support consumables from in-situ materials. Due to the complexity and expected synergy of the considered processes, it seems quite reasonable to discuss in-situ production of life support consumables in combination with propellant production. A significant reduction of respective masses that have to be lifted from the surface of the Earth would dramatically lower mission costs. The advantage is immediately apparent from the fact that up to 90% of the total mass of conventional spacecraft consists of propellants. Depending on the degree of closure of the systems, Environmental Control & Life Support Systems (ECLSS/ALS) could also benefit from in-situ resources for the replacement of losses due to consumption, leaks or extra-vehicular activities. Typical products involved (for breathing, drinking, cooling purposes, buffer gases, potential plant growth in greenhouses, radiation shielding etc.) are O_2, H_2O, N_2, He, Ar, CO_2 and even the fine grained surface regolith. The Moon as the closest neighbor to Earth is a primary candidate for developing and testing corresponding technologies. Achieving these goals requires a detailed understanding of the lunar environment and resources as well as insights into the mining technology and chemical processing that must be used to generate the necessary products in a mass and energy efficient manner. These processes involve chemical reactions, multiphase flows, and phase changes. The scaling laws for these processes are often poorly understood even for our terrestrial environment.

The lunar surface is extremely dry and an atmosphere is practically absent. In principle, the following lunar resources could be exploited (Horneck et al. 2003):

- volatiles in the regolith including hydrogen and water with eventually enhanced quantities near the poles (according to data from the CLEMENTINE, LUNAR PROSPECTOR, Chandrayaan-1, and LCROSS missions)
- oxygen bound in silicate/oxide compounds of the lunar regolith
- in-situ materials for production of fuel components (e.g. silane, aluminum), building structures (made from e.g. metals or concrete), radiation shielding or as plant growth medium in greenhouses

The expected amount of volatiles like H, N, C, He, etc. in the regolith, which are mainly solar wind implanted and can be extracted by simple heating, is typically in the order of 10 to 100 parts per million in weight (wt. ppm) - as shown by gas release patterns from Apollo-11 samples in the temperature range from 50 to 1200°C (Gibson and Johnson 1971). Acquisition of a significant amount of those volatiles requires heating many tons of regolith to high temperatures up to 1000°C and, afterwards, cooling the extracted gas down to separate the different species by fractionate distillation (yields would be about 0.1 to 1 kg of H_2, C or N_2 per ton of regolith). It should be remembered, however, that the data base is only from samples close to equatorial sites (Apollo landing sites). Certainly, solar wind exposure and storage will depend on lunar latitude, longitude and depth within the regolith, and details of the processes involved are not yet understood and must be studied further (e.g. by modeling and in-situ investigations at different sites incl. drilling). For example, losses of implanted volatiles due to diurnal heating can be expected to be much lower in cold polar regions. Volatiles may also migrate from lower latitudes to the cold traps at the poles to be stored there for long times. The occurrence and amount of water (and OH) in the regolith near the poles - and even at lower latitudes (Pieters et al. 2009) - is a subject of ongoing investigations and discussions. From the PROSPECTOR neutron spectrometer data the average polar hydrogen content is estimated to be larger by a factor of about 2 compared to equatorial sites (Lawrence et al. 2006), corresponding to about 0.1–1 wt.% of water (if the hydrogen is in the form of H_2O) . It is, however, not clear, how much of this hydrogen is bound in H_2O molecules, and where the recently with Chandrayaan and LCROSS detected small quantities of water (and OH) stem from (perhaps produced from interaction of the solar wind hydrogen with the lunar soil via reduction of iron-oxides or other minerals – or deposited by comet impacts or of primordial origin?). Anyhow, simple extraction methods for lunar volatiles implanted in the regolith - including water - should be developed and verified in future robotic and human missions to the Moon. It is worth noting that the investigation of lunar volatiles is not only important for supply purposes but also for studying the solar wind and – possibly – comet impact history.

Recently, various studies in co-operation between German industry and Academia have dealt with the extraction of solar wind implanted particles from Moon regolith. In the so-called LUROP project, led by German industry (Kayser-Threde), a concept for a demonstrator for propellant production on the Moon has been studied (Hofmann et al. 2008, Reissaus et al. 2007). In contrast to oxygen pyrolisis, which uses lunar material and requires demanding process temperatures, the extraction of chemicals such as nitrogen and hydrogen from lunar regolith is simpler and less risky. Mid term aim is a demonstrator for propellant production on the Moon, to proof the feasibility and to prepare future production plants. A first stage demonstrator will be composed of an oven chamber in which the regolith will be homogenously heated up to temperatures around 1000°C by solar thermal energy from the sun using a foldable mirror. The reaction product will be monitored using a small compact mass spectrometer. A two years development program has been started end of 2009 by German industry and the Technical University of Munich. It aims at reaching a TRL 5 to TRL 6 in 2013. The demonstrator ("LUISE") for propellant production on the Moon is estimated to have a mass of 30kg. The running study and its activities include development test and verification of Moon regolith simulates with implanted "solar wind" particles.

The lunar surface rocks and fine-grained regolith are similar in chemical composition to terrestrial rocks, consisting mainly of silicate material with oxygen content between 40 and 45wt%. Thus, oxygen is the most abundant element on the lunar surface (but strongly bound in silicate/metal-oxide minerals and glass!). More than 20 concepts for the production of lunar oxygen have been proposed (Taylor and Carrier 1993) which include chemical, electrochemical and thermo-chemical processes. Most require several reagents and high temperatures (see Table 3). Among these concepts, *ilmenite/glass reduction with hydrogen, carbothermal reduction with methane, oxidation with fluorine,* and *pyrolysis/vapor phase reduction* have been assessed by DLR and ESA as very promising (Seboldt et al. 1999). *Ilmenite/glass reduction with hydrogen* (at ≈1000°C) seems to be the easiest process, requires only moderate temperatures and appears favored by NASA (Taylor and Carrier 1993, Rosenberg 1998). Experimental results indicate a low conversion from hydrogen into water during the reduction of ilmenite rich mare soil or volcanic glasses, whereby hydrogen diffusion into the ilmenite grains is decreasing with the ongoing reaction because of Fe- and titanium-oxide-coating. Expected oxygen yields are small (in the range of 3-4wt%) with slightly higher oxygen yields (5-6wt%) reached by using lunar glass containing up to 20wt% of ferrous(II) oxides. Considerable beneficiation of lunar soil may be necessary because an efficient processing depends on high concentrations of ferrous oxides. *Carbothermal reduction with methane* (at ≈1600°C) allows the use of unbeneficiated lunar mare or highland materials but requires relatively high temperatures. Representing a 3-step-process, it promises significant oxygen yields of about 20wt% and only few processing difficulties. *Oxidation with fluorine* (at ≈500°C) is promising due to the highest oxygen yields of all proposed processing concepts and low temperatures (fluorine is the most reactive element known and capable of oxidizing even oxygen). The liberation of oxygen from different lunar mare and highland simulants has been demonstrated to reach nearly completion (Seboldt et al. 1993, Lingner et al. 1993, Reichert et al. 1994, Seboldt et al. 1994). Recycling of fluorine from reaction products, however, is complicated, and two steps are proposed based on experiments performed in cooperation between DLR and University of Cologne (Koenies 1998): electrolysis of the extremely stable molten metal-fluorides with semiconductor-anodes (Si) releasing gaseous SiF_4, which is then combined with SiF_4 from the overall reaction to regain elemental fluorine by thermal decomposition on a platinum surface at 1600°C. This method is also capable to produce pure silicon. *Pyrolysis/vapor* *phase reduction* (at ≈1800°C) requires very high temperatures in the range of 1500°-2000°C to vaporize lunar feedstock and to induce in the gas phase thermal dissociation of oxides and/or silicates into sub-oxides and elemental oxygen. The subsequent separation of oxygen from this gas mix is proposed to be achieved by rapid quenching or other methods. Oxygen yields are expected to be in the range of 20-50% of the total oxygen content, and heat supply can be provided by concentrated solar radiation. First experiments have been carried out by Senior (1993) to identify the vapor-phase species. At DLR-Cologne, preliminary experiments were performed with JSC-1 lunar simulant exposed in vacuum to concentrated solar radiation from the DLR Solar Furnace with temperatures around 1600°-1700°C (Sauerborn et al., 2003, 2004). Oxygen in the vapor phase was identified with a mass spectrometer (Sauerborn 2005). Further work has to be carried out - especially on the separation step. Overall, the pyrolysis process is very interesting due to its capacity of providing oxygen by a simple reaction without feedstock beneficiation and additional reagents.

All described processes should be further investigated because only selected steps have been verified so far in small scale experiments. To make a decision on a preferred concept or combination of concepts, significant up-scaling including closed loop processing is necessary, considering also lunar environmental constraints. In addition, the technology in the field of power supply, cryo-storage, heat removal and especially handling of large amounts of regolith must be developed. Lunar oxygen production may be different for early and later periods: initially, oxygen might be produced by processes that are easiest to employ but with relatively low oxygen yields (e.g. ilmenite/glass reduction or carbothermal reduction); later, oxygen could be obtained with high yields by more complex processes like fluorination or pyrolysis. This could be combined with the production of useful metals and silicon.

Table 3: Processing concepts for lunar oxygen production and reagents required
**) assessed as very promising by DLR*

Oxygen processing concepts		Reagents
Solid/Gas Interaction (500°-1000°C)	Ilmenite/Glass Reduction*	H_2, CO, CH_4
	Reduction of Metaloxides	H_2S
	Oxidation with Fluorine*	F_2
	Carbochlorination	C, Cl_2
	Chlorine-Plasma-Reduction	Cl_2
	Ilmenite-Reduction Using Metals	Li; Na
Extraction from Melt (500°-2000°C)	Silicate/Oxide Melt Electrolysis	Pt (Anodes)
	Fluxed Molten Silicate Electrolysis	Pt, LiF-CaF_2
	Caustic Dissolution and Electrolysis	NaOH
	Carbothermal Reduction*	C, CH_4, CO
	Hydrofluoric Acid Dissolution	HF, H_2O
	Sulfuric Acid Dissolution	H_2SO_4, H_2O
Pyrolysis (1500°-2000°C)	Vapor Phase Reduction*	

2.2.4.3 Challenge towards lunar infrastructure engineering

Around 40 years after the first time and 37 years after the last time that astronauts landed on the Moon this satellite of the Earth has once again entered the spotlight of space research. The large space-faring nations are going to plan the manned return to the Moon and the erection of Moon stations. The Moon is regarded a springboard for long distance missions to space.

If astronauts actually are expected to stay over a longer period of time on the Moon, the question immediately arises how a base station on the Moon shall look like and by what means its construction and functional infrastructure could be realized technically.

At the Lunar Base Symposium, held on May 12th and 13th, 2009 in Kaiserslautern, Germany, scientists and engineers from space-travel related disciplines as well as civil engineers, process engineers and architects discussed how a permanent and habitable base on the Moon might look (Breit et al. 2009).

2.2.4.3.1 Survival in a hostile environment

A tremendous challenge when building a base station on the Moon will be the creation and maintenance of a living space for the astronauts in the hostile environment there. Coping with such tasks, astronauts have to be shielded against the space radiation, i.e. the high-energy gamma radiation, from which we are protected on the Earth by the geomagnetic field. There is no radiation absorbing atmosphere and no overall magnetic field that deflects charged particles. Focal point of the researchers, too, is the extremely fine and powdery Moon dust, found on the spacesuits of the Apollo astronauts. Aerospace doctors see the danger that this Moon dust could penetrate into the lungs and lead to health problems for astronauts. All of these conditions on the Moon surface impact the style of a Moon station to be built and the infrastructure systems required. Yet ample solar energy, low gravitational force, and abundant minerals on the Moon will provide favorable conditions for the development of functional infrastructure systems.

2.2.4.3.2 Infrastructure Systems

Prior to the establishment of any continuous activity, suitably shielded lunar structures must be built to house facilities and to protect personnel from the effects of solar wind, radiation, cosmic rays, and micrometeorites.

Design of structures for a lunar base differs from design of structures on Earth. There are no wind and Earthquake loads on the Moon.

Basic considerations concerning a probabilistic concept to be applied for the structural reliability of load bearing elements under specific lunar conditions include, e.g., Moon gravity = 1/6 x Earth gravity, limited life of structure, modified probability of failure.

The development of regenerative and sustainable life support systems (LSS) backed up by suitable infrastructure systems is a basic prerequisite to realize human long-term habitation on the Moon. Because of longer distance to Earth and longer transfer times new requirements appear for installation and operation and functionality in comparison to such systems already evaluated in the experienced action in the International Space Station.

The minimization of resupply mass is the crucial factor to cope with this challenge. Regenerating the basic needs oxygen, water and carbon and forming, as far as possible, a closed loop are the essential milestones for an efficient and sustainable life environment for the lunar base operating team.

Readymade solutions can not be expected from the start. Rather, it is all about the professional and creative exchange of different disciplines in science. Numerous results from ongoing research activities must be combined.

2.2.5 Terrestrial laboratories

2.2.5.1 The Noerdlinger Ries: terrestrial analogue, natural laboratory, and Apollo training site

The Noerdlinger Ries is a flat circular basin, 22-23km in diameter, which is located between the Jurassic limestones of the Swabian and Franconnian Alb, about 110km NW of Munich/Bavaria. It was formed about 14.5 m.y. ago by impact and represents one of the best-preserved large terrestrial impact structures with a well-preserved ejecta blanket. Because the Ries impact structure is one of the best-studied impact craters on Earth, it is used as an archetype for complex craters across the solar system. The structure was formerly thought to be of volcanic origin, but in 1961 Shoemaker and Chao demonstrated its impact origin. The evidence for the impact structure is based on occurrences of coesite, stishovite and other shock features (Chao and Minkin, 1977). More recently, Hough et al. (1995) detected diamonds and silicon carbide in the suevite and El Goresy et al. (2001) identified an ultradense rutile polymorph in shocked gneisses.

Extensive work, including field campaigns, geophysical measurements, seismic profiles and drilling projects (the deepest one being Noerdlingen 1973) have constrained the boundary conditions of the crater formation process. Age determinations of ^{39}Ar-^{40}Ar in moldavites and impact glasses provide an age between 14.3 and 14.5 Ma for the Ries impact event (Schwarz and Lippolt, 2002; Buchner et al., 2003; Laurenzi et al., 2003). It is thought that the impactor was a stony meteorite of about 3 km in diameter with a density of about 3.5 g/cm³ and an impact velocity of 15km/s (El Goresy and Chao, 1976, 1977; Stoeffler et al., 2002). The locations of the Ries and the adjacent Steinheimer Becken impact structures and the formation and distribution of the moldavites suggest that the impactor came from a west-southwest direction (Stoeffler et al., 2002). On the basis of analyses of the tektite (moldavite) strewn-field, the impact angle was estimated to be 30 - 45 degrees (Stoeffler et al., 2001).

The pre-impact target rocks can be divided into two main geologic units. The upper unit consisted of well-stratified sediments, mainly limestones, sandstones and shales of Triassic to Tertiary age, with a thickness of 620 to 750m (Pohl et al., 1977). The lower unit was composed of crystalline basement rocks mainly gneisses, granites and metabasites (Stoeffler et al., 2001).

The Ries impact structure consists of a central basin that is flat due to the uplift of the crystalline basement. This inner basin is surrounded by an inner ring with a diameter of 12km, which consists of uplifted basement and sedimentary megablocks (Stoeffler, 1997). The inner basin is partially filled with 300 m allochthonous crater-fill deposits (Suevite), which is overlain by 300m post-impact miocene lacustrine sediments (Arp, 2006 and references therein). The lake deposits and the allochthonous crater-fill deposits are superposed on a structural uplift of 1.5-2 km of crystalline basement, which has been inferred from geophysical data and numerical simulations (Wuennemann et al., 2005).

The megablock zone extends between the inner and outer crater rim. It consists of blocks larger than 25m that formed either as allochthonous blocks of brecciated crystalline and sedimentary rocks embedded in the Bunte Breccia or as parauthonthonous sedimentary blocks that moved into the crater during crater collapse and now form a hummocky relief (Kenkmann and Ivanov, 2006).

The ejecta deposits are composed of clastic polymict breccias (Bunte Breccia) which are located up to three crater radii from the impact center as a continuous ejecta blanket that decreases in thickness (Kenkmann and Ivanov, 2006). In the northwestern part of the basin most of the ejecta blanket has been eroded during the Pliocene and Pleistocene, leaving an asymmetric distribution of the ejecta outside the crater rim (Gall et al., 1975).

Because the structure of the Ries crater is exceptionally well-preserved and because there are numerous outcrops of impact related rocks, including breccias and impact melt, it was chosen as a training site for Apollo astronauts. Consequently, in August 1970, Alan Shepard and Edgar Mitchell were trained in the Ries crater to recognize terrestrial impact breccias in preparation of their geologic investigations of Cone Crater at the Apollo 14 landing site.

2.2.5.2 Spectral Labs for lunar and analogous sample analysis

The Institute for Planetary Research in Berlin has an expertise in spectroscopy of minerals, rocks, meteorites, and organic matter, build up in more than two decades. The available equipment allows spectroscopy from the visible to TIR range (0.5-50µm) using bi-conical reflection and emission spectroscopy. Measurements can be performed under vacuum conditions and at elevated temperatures. These activities are bundled in the Planetary Emissivity Laboratory (PEL).

The PEL has already obtained measurements on Apollo samples. A spectral database covering a wide range of planetary analogue materials has been build up in the recent years.

This facility is completed by a new laboratory for Raman and LIBS analysis of samples, including the capability to use atomic force microscopy.

2.2.5.3 Sample return capabilities

DLR is actively pursuing a program to set-up a sample return facility in Berlin. In the first step of this program the analytic capabilities have been extended. All laboratories are currently equipped with planetary simulation chambers allowing the measurements of planetary analog materials under realistic conditions for planetary bodies. This step also allows verifying the applicability of all analysis method in a future sample return facility. In the next step of the build-up all laboratories will be moved to clean room standards and first curation facilities will be set up.

2.2.5.4 Lunar environment simulation

In the past, the lunar environment has been described as dead, harsh, extreme, and hostile. While human survival and scientific exploration are challenging, it is this environment that is of scientific interest. For example, the lunar atmosphere is about 14 orders of magnitude thinner than Earth's atmosphere, totaling at about 10^4kg. The major constituents of the lunar atmosphere are neon, hydrogen, helium, and argon. Neon and hydrogen were derived from the solar wind. Helium also is mostly derived from the solar wind, but about 10% may be radiogenic and lunar in origin (Hodges, 1975). Argon is mostly ^{40}Ar that is derived from the radiogenic decay of ^{40}K. Depending on the surface temperatures, the concentrations of these gases vary. The radiation fluxes and energies typically span at least eight orders of magnitude and change with time, usually reflecting the level of solar activity, such as the modulation of galactic cosmic rays and the irregular emission of energetic particles from the Sun. The solar wind velocity is typically on the order of 300-700km/s and the particle concentrations range from 1 to 20 per cm^3 (Feldman et al., 1977). The solar wind proton flux generally ranges from 1×10^8 to 8×10^8protons/cm^2/s. The solar wind can produce sputtering and amorphous material in the uppermost (<1µm) lunar surface. Solar cosmic rays interact with the top millimeter to top few centimeters of the lunar surface by ionization energy loss. Galactic cosmic rays also interact with the uppermost few centimeters, but cascading secondary particles, especially neutrons and alpha particles penetrate meters into the ground. At the surface, the radiation produces distinct, permanent, and depth-dependent effects. The lack of a strong magnetic field and a dense atmosphere allows ionizing radiation and solar wind particles to directly interact with the lunar surface, resulting in severe space weathering effects. From the Moon it is known that space weathering processes result in a darkening of the surface, a reduction of the spectral contrast and a reddening of the spectral slope in the VIS-NIR spectral regions (e.g., Keller and McKay, 1993, 1997; Keller et al., 2000; Noble et al., 2001; Pieters et al., 1993, 2000; Hapke 2001 and references therein). Space weathering processes and the contribution of exogenic chondritic material (see, e.g., Langevin and Arnold 1977; Lewis 1988; Cintala 1992; Langevin 1997; Hapke 2001; Noble and Pieters 2003) strongly affect the chemistry and observed properties of the lunar surface. Thus, no interpretation of the composition of the Moon's true crustal composition can be made without thoroughly accounting for space weathering, maturation and exogenic deposition on its surface.

The mean grain size is also a critical parameter for interpreting surface spectra, as band depths and band shapes strongly depend on this parameter for a given mineralogical composition. Freshly excavated ("immature") material is initially coarse grained (from the mm range to rocks, even m-sized boulders) and dominated by crystalline grains. A wide variety of space weathering processes modify the size distribution, mineralogy, and optical properties of the constituents of the regolith. A direct micrometeoroid impact can result either in a microcrater (if the grain is large) or in fragmentation. Conversely, macroscopic and microscopic impacts generate fused silicate droplets which can either solidify in flight (forming glass spherules) or weld together crystalline grains (forming glassy agglutinates). Eventually, a steady state grain size distribution is reached with a median size of 60µm (McKay et al., 1991).

Lunar surface temperatures increase about 280°K from just before lunar dawn to lunar noon (Vaniman et al., 1991). Langseth et al. (1973) report that the lunar noon temperatures vary throughout the year by about 6°K between perihelion and aphelion. Estimated average surface temperatures and temperature extremes for different areas of the Moon were published by Dalton and Hoffman (1972) and Burke (1985). They investigated lower latitude craters and found that the floors of these craters may be a few degrees warmer than the walls and outer slopes. More recently, Lawson et al. (2000) used Clementine LWIR data to determine the temperature of the lunar surface. They reported latitude-dependent surface temperatures of up to 390°K. From the Apollo landing sites, for example Apollo 15, it is known that temperature varies between 92°K and 374°K (e.g., Vaniman et al., 1991). The Apollo 17 IR radiometer revealed that lunar nightside temperatures of 100°K at the antisolar meridian drop to about 90°K at the sunrise terminator. This general nightly cooling is influenced by the thermal inertia of the surface, which in turn is dependent on grain size; larger rock fragments will cool slower than fine-grained dust particles.

2.2.5.5 Lunar Laser Ranging Facility (Wettzell)

Retroreflectors deployed during the Apollo missions and those mounted on the Lunochods are in continued use for Lunar Laser Ranging (LLR) measurements up to the present day (see Dickey et al. 1994 for a summary). Range measurements at cm-level can be achieved. However, even with current technology, LLR is an extremely challenging measurement task. Among the more than 30 observatories worldwide associated with the ILRS (International Laser Ranging Service) only a few are technically equipped to carry out Laser ranging to the Moon, among them “Fundamentalstation Wettzell”, which is jointly operated by the Bundesamt fuer Kartographie und Geodaesie and the Forschungseinrichtung Satellitengeodaesie (FESG), Technical University Munich (TUM). A sophisticated LLR analysis software package and lunar motion model is in use at the Institut fuer Erdmessung (IfE), of the Leibniz University of Hannover (Mueller and Nordtvedt 1998; Mueller 2000; Mueller et al. 2006), which gives us access to a host of parameters concerning lunar physics, Earth-Moon dynamics as well as the verification of metric theories of gravity. The Wettzell station is also involved in the Laser tracking of Lunar Reconnaissance Orbiter (LRO), a novel space geodesy experiment, lead by NASA’s Goddard Space Flight Center.

2.2.5.6 Dust Accelerator Facility (Heidelberg /Stuttgart)

The Heidelberg Dust Accelerator allows the investigation of hypervelocity dust impacts onto various targets. The facility is designed to study the interaction of micro-grain impacts with target materials like planetary analogues, metals or interplanetary dust collector materials like aerogel. The accelerator provides a laboratory platform for the study of the physics of cosmic dust impacts and the design and calibration of dust sensor instrumentation for space based applications. Impact phenomena like cratering, film penetration, and generation of ejecta particles, gas, plasma, and light have been investigated in the past and are still ongoing.

Dust grain materials from nano to micron sizes are accelerated to velocities between 1 and 80 km/s, using a 2 MV Van-de-Graaff accelerator. These velocities are relevant to the study the dust properties in planetary rings of the giant planets and impact ejecta processes on the surfaces of small planetary bodies (asteroids, comets) as well as moons and atmosphereless planetary surfaces. The accelerated micro-grains pass focusing and steering electrodes and their individual speed and charge is measured by sensitive beam detectors working with charge induction. A special control hard- and software, the

Particle Selection Unit, determines the grain speed and mass and selects individual dust grains on the basis of a speed and mass window determined by the experimenter. The accelerator can be operated in a single-shot mode and in a continuous mode. Dust materials include metal powders like iron or coated microspheres like glass, organic microspheres (polystyrene) or even minerals (pyroxen, anorthite).

Impact studies that were performed at this facility played a major role in the analyses of lunar microcraters during the Apollo era. Since then several upgrades and improvements resulted in a world-wide leading microparticle accelerator facility that currently contributes to Stardust, Cassini, LADEE, and BepiColombo missions. By the end of 2010 the dust accelerator facility will be relocated to the Institut fuer Raumfahrtsysteme of the University of Stuttgart where the laboratory program will be continued.

2.3 Specific areas of near-term exchanges/partnerships and areas for longer-term interactions

Several specific near-term and long-term exchanges and partnerships with NLSI and other NLSI nodes and researchers are envisaged. Many members of this proposal are already collaborating with US and other partner universities and institutions. We expect that the NLSI status will support and cement the existing partnership and will enable new relationships. Our main interests are collaborating in:

Science of the Moon, on the Moon and from the Moon

Near-term

- Understanding of the lunar surface geology and interior in terms of a comparative data evaluation approach based on past and current mission contributions and its results.
- Understanding of the specific nature of the lunar regolith as the uppermost surface reflecting the lunar geochemistry and as an available source for materials.
- Understanding the lunar dust and plasma environment by simulation experiments in the laboratory.
- Understanding the Moon’s origin in the context of the evolution of the Earth-Moon-System.

This research will rely on the data bases already existing or to be collected in the near-future as a result of ongoing or confirmed international missions.

Long-term

- Precise highest resolution geological geophysical and geochemical global mapping of the Moon
- Monitoring of the lunar dust, particles, and fields environment
- In-situ and rover exploration on the lunar surface and subsurface in terms of heat flow, seismicity and rock/soil and volatile analysis.
- Sample return
- Astronomy from the Moon

This research will rely on upcoming robotic missions and lunar networks.

Exploration of the Moon

Near-term

- Development of exploration tools in terms of in-orbit and in-situ robotic vehicles and instrumentation.

- Development of lunar road maps for mobility resource utilization on the Moon.
- Earth-Moon communication and data transfer.
- Development of biomedical support systems and lunar environment simulation for human applications.
- Outreach: the Moon as part of Earth

Long-term

- Development of tools for resource utilization on the Moon.
- Concepts for lunar infrastructure engineering.
- Development of life support systems and being on the Moon

In the spirit of fostering collaboration between NLSI partners we envisage to exchange scientists, both senior scientists and young researchers, to provide experience and increase scientific and technical knowledge to the above topics, as well as improving the background and educating the next generation of scientists. The exchange of scientists foresees visits at NLSI in Ames and other partner institutions as well as DLR to host scientists from NLSI partners.

2.4 Plans for Interacting with the NLSI Community

In detail we plan to interact with the NLSI community with respect to all objectives presented in chapter 2 of this proposal. In the near-time we will focus onto the following major topics:

- Continue our collaborations in ongoing missions and common data processing and evaluation projects such as

  Lunar Reconnaissance Orbiter (H. Hiesinger, J. Oberst, T. Roatsch)

  Kaguya (J. Oberst)

  Chandrayaan (U. Mall)

  SMART-1 (A. Nathues)

  LADEE (R. Srama, E. Gruen)

- Continue our participation in proposed lunar missions such as

  New Frontiers Moonrise Proposal (R. Jaumann, N. Schmitz, H. Hiesinger)

  Discovery Lunette Proposal (T. Spohn, L. Richter, M. Grott, J. Knollenberg)

  ESA Moon NEXT Science Definition Team (predecessor) (H. Falcke, S. Kempf)

  NLL Next Lunar Mission based on Shared Ariane-5 Study (= ESA Moon NEXT Study) (B. Schaefer)

  ESA NEXT Lunar Exploration Definition Team (LEDT) (N. Henn, D. Breuer)

  Proposal "Continued development of a lunar geophysical instrument package" in the "Research Opportunities in Space and Earth Sciences (ROSES-2009)" Program (M. Grott)

  ESA’s topical team on “Lunar habitat” in order to develop human analogue models of lunar habitat conditions (J. Rittweger)

  Engage in parabolic flights in order to study immediate physiological effects of hypogravity equivalent to lunar conditions (J. Rittweger)

- Continue our work in international groups dealing with lunar exploration such as

  ILEWG (R. Jaumann)

  ILN (T. Spohn, R. Jaumann, L. Richter, B. Schaefer, S. Ulamec)

  IPDA Steering Group (K. Eichentopf, T. Roatsch)

  ISECG (H.-J. Kaaf, B. Schade, P. Weber, A. Boese, M. Wilde)

  Chairman of the Working Group Astronomy from the Moon of the IAU (H. Falcke)

  LUNAR (Astrophysics) node of the NLSI (H. Falcke)

  Lunar Exploration Definition Team (LEDT) of the ESA Large Lunar Cargolander study (H. Falcke)

  ESA's topical team on "Lunar habitat" in order to develop human analogue models of lunar habitat conditions (J. Rittweger)

  Engage in parabolic flights in order to study immediate physiological effects of hypogravity equivalent to lunar conditions (J. Rittweger)

- Continue our scientific work for understanding the lunar geosciences and the lunar environment as described in 2.1
- Develop strategies for global lunar mapping and provide lunar data bases as road maps required for future lunar exploration mainly focusing on topographic, spectral, thermal, gravitational, radiation and cosmic dust distribution data sets. These work will be based on our experience with space missions such as stereo mapping of Mars, Moon, asteroids, icy satellites, spectral mapping of Mars, Venus, Moon, icy satellites, asteroids and comets, dust monitoring in the outer solar system and gravimetry of the Earth (cf. 2.2.1 and 3)
- Develop models of the lunar interior and origin (cf. 2.1)
- Collaborate in the development of soft lunar landing and mobility (cf. 2.2.2 and 2.2.3)
- Collaborate in the development of strategies for the power support of lunar surface operations (cf. 2.2.3.5)
- Collaborate in the development of strategies of Moon/Earth communication and on the Moon navigation (cf. 2.2.2.6 and 2.2.3.4)
- Collaborate in the characterization of the lunar environment (cf. 2.2.1.6, 2.2.1.7, 2.2.1.8.1, 2.2.2.5, 2.2.5.4)
- Collaborate in the development of life support systems (cf. 2.2.4)
- Collaborate in the development of strategies for lunar resource utilization (cf. 2.2.4)
- Collaborate in correlating on Earth lab capabilities (e.g. cross calibration of standards, cf. 2.2.5)
- Collaborate in the effort fostering the public interest in science of the Moon, on the Moon and from the Moon (cf. 4)

3 Data mining and fusion techniques and archiving concepts

3.1 Cartographic systems (topography, gravity, composition, structure) - the lunar roadmap

3.1.1 Cartographic systems

Two different body-fixed coordinate systems are currently in use for the Moon, the Mean Earth (ME) system and the Principal Axis (PA) system. The axes of the PA system are defined by the principal axes of the Moon. In contrast, for the ME system, the *z*-axis is defined as the mean rotational pole, and the Prime Meridian (0° longitude), given by the mean Earth direction. The two coordinate systems are realized by the locations of the Laser retroreflectors and the Transmitter stations of the ALSEPs (Apollo Lunar Surface Experiment Packages), for which coordinates are precisely known. To warrant meaningful inter-comparisons of lunar mapping data, all data must be carefully referenced to either of these lunar coordinate systems. Proposal team members at DLR and TUB have a profound background dealing with these tasks.

3.1.2 Topography and gravity

Several new global topographic data sets have become available in the past years. The Japanese Kaguya spacecraft and its onboard Laser altimeter have acquired a data set involving >20 Million data points (Araki et al., 2009). Its Chinese counterpart Chang'e has acquired a data set similar in coverage and quality (Fok et al., 2009). LOLA (Lunar Reconnaissance Orbiter Laser Altimeter) is currently beginning its mapping mission and has completed a first global survey, which already exceeds the resolution of the Kaguya or Chang'e data sets. Finally, a global model (1km, Scholten et al., 2010) as well as higher-resolution (1-3m, Oberst et al., 2010) local topographic models has been produced using LRO stereo images. The proposing team is involved in these activities by team memberships (Kaguya) as well as through NASA's Participating Scientists Program.

The global lunar gravity field has been mapped by the Clementine spacecraft and the Lunar Prospector from their polar orbits. An improved gravity field solution is expected to be released by the Kaguya team. Gravity data are typically represented by spherical harmonics models, which currently reach degree and order 60. Using joint analysis of gravity and topography data, models of the lunar crust can be established. A sophisticated gravity experiment was proposed by GFZ and DLR to fly on sub-satellites of the LEO mission.

3.2 Data base of lunar resources

Utilization of lunar resources will become essential in the future for continuing lunar exploration and development, as it will help to drastically reduce transportation costs from Earth to the Moon. Possible lunar resources are concrete and glasses for the construction of habitats or shelters, oxygen and (as a by-product of oxygen extraction) metals, trapped solar wind gases and phases like hydrogen, helium-3 and nitrogen or possibly water at polar latitudes. Most lunar resources can be obtained by mining the lunar regolith. To localize and assess a possible utilization of a specific resource, the following information and mapping products would be beneficial:

- Where the specific resource is preferably enriched? (e.g. helium-3 is preferably trapped in Ti-rich regolith)
- Chemical and mineralogical composition derived from the various spectrometers
- Physical properties of the regolith like grain size distribution etc.
- Maturity (especially for trapped solar wind particles)
- Subsurface structure of the regolith

- Morphological setting and geological context

Therefore, all available data and data products shall be fed in the Lunar Information System described below.

3.3 Lunar Information System

Multiple different data sets such as optical image data, spectroscopic data, and digital terrain models are implemented in a geographic information system and used to map the lunar surface according to its geology, geomorphology, and mineralogy. That means that homogeneous surface units will be delineated from each other resulting in digital feature data sets such as polygons, lines, and points. To cross-correlate these data sets with other surface maps the digital features have to be displayed with standardized cartographic symbols. Based on these mapping results further analyses, such as the measurement of morphometric parameters, can be done.

The comprehensive results from the mapping process and the huge amount of satellite data have to be managed efficiently in a uniform system. This system includes not only a standardized map layout but also a uniform data base structure. Such a structure involves feature data sets, mapping symbols, supporting tables, a collection of individual tools, and the satellite data.

All these requirements will be realized in the Lunar Information System. Due to its standardized, uniform, and efficient data base structure it provides a well-organized environment to handle lunar scientific questions and to manage and archive the derived data and information.

4 Education and public outreach

Beyond its scientific and explorative potential the Moon is of tremendous value for all kinds of efforts in the field of Education and Public Outreach (EPO).

This has been true since the Apollo times in the 1960s, when the world-wide public has been virtually participating not only in the adventurous manned spaceflights to the Moon, but also at the EVAs on the lunar surface with their experimental activities. For the first time in the history men have been walking on an extraterrestrial surface, performing geological field trips and physical measurements, thus motivating an entire generation of engineers and scientists.

The Moon did hence not loose any of its inspiring potential as has been proofed by recent lunar missions, in particular from countries like Japan, India, or China, respectively. Of all objects in the solar system reachable by spaceflight the Moon is closest, and in the foreseeable future it will remain the only target that can be visited by astronauts. It is the sole object in the sky where surface features can be discerned by the naked eye.

Any future project to explore Earth's companion, be it an orbital or landing mission, robotic or astronautically, should make use of the Moon's outstanding potential as a prime vehicle for EPO activities.

Based on Clementine image data cartographers at DLR's Institute of Planetary Research produced the map base for this 25 meter (82 feet) diameter Moon balloon that is part of Germany's biggest ever astronomy exhibition Wonders of the Solar System at Gasometer Oberhausen, visited by 400,000 during 2009.

4.1 3D visuals and HDTV real-time viewing of the Moon

Images, or "visuals", will always play a key role in EPO efforts. Apollo photographs of planet Earth above the lunar horizon have held iconical status ever since such an image has been seen for the first time in the mid 1960s. They have so again today, for example in images presented recently by the Japanese SELENE/Kaguya mission at which a camera operated by a commercial TV station recorded high definition images for TV viewing.

Images of the bone-dry, impact-crater saturated or volcanically resurfaced Moon, contrasting with the »living planet«, Earth, have an enormous potential for common fascination. Future mission and payload scenarios with German contribution should therefore always take into consideration imaging systems that, beside their scientific design and layout, will produce visuals that transport emotional messages to the general public.

The year-long experience with the 3D-imaging system HRSC (High Resolution Stereo Camera) on ESA's Mars Express mission shows that the possibility of almost »getting in touch« with the Martian surface by 3D viewing is of unique quality. Therefore it is mandatory that a stereo-camera system providing 3D models of the lunar surface, enabling high-resolution stereo imagery in the order of every-day experience (meter-/sub-meter topography) should map the Moon globally.

Life-coverage of the lunar surface by TV-type camera(s) would be an effective add-on, in particular when taking into consideration the capability of such a system to image in (near) real time from the farside of the Moon unknown to the general public. In combination with geographical and/or geological information provided at a specific web portal, or at TV stations during nighttime hours, such a sophisticated high-definition system could contribute to increased identification with a lunar orbital mission, and its respective scientific tasks.

4.2 Outreach through German RPIF and a possible national initiative on lunar science

To visualize the fascination and suspense of the results of planetary research, the Regional Planetary Image Facility (RPIF) has been created in cooperation with NASA at the DLR Institute of Planetary Research in Berlin-Adlershof. This library of planetary photographs keeps on file all the image data transmitted by many NASA and ESA space probes and makes them accessible to the public.

The RPIF was established in 1985 under an agreement between DLR and NASA, and began to operate four years later. After working several years as part of the Remote Sensing Section at the DLR Institute of Optoelectronics in Oberpaffenhofen, the RPIF was transferred to the DLR Institute of Planetary Research in Berlin-Adlershof in 1992. The RPIF is part of an international network of image libraries coordinated by NASA. Worldwide there are 17 of these institutes, nine of which are located in the USA, five in Europe and one each in Canada, Japan, and Israel. The Berlin RPIF basically provides for the German-speaking region. The individual image libraries are in close contact via data networks. They are all linked up with NASA's Planetary Data System (PDS) and offer extensive database research options.

The library holds digital image data, spectral data, along with the relevant positional data of each space probe. To back up these data there are documentations, maps, and a selection of journals and other scientific publications. All data are documented, catalogued, and available to all users whether they are from the academic research community or from the general public. The available material mainly stems from American missions but also European and Soviet/Russians ones. It is via the RPIF that NASA shares the data both from its present and future space missions.

To facilitate the use of the RPIF and its large collection, an open-access research area is available to all users, including the general public. Access is provided to the documents from NASA, the Jet Propulsion Laboratory (JPL) and the National Space Science Data Center (NSSDC). Computerized catalogs permit data selection via a random keyword search function. Gathering information and researching data is free of charge.

The RPIF in Berlin is well established in Germany and provides infrastructure and programs to actively distribute image data of all kind to the public in the German-speaking countries of Europe. It also serves as a link to the media in general, and the communication department of DLR in particular that has one of the best online portals of all scientific organizations in Germany.

DLR is integrated in EPO activities of all major space agencies, not the least through ISECG, but also with contacts on the base of individual mission projects. DLR has an extremely good visibility in the

German public through cross-media activities, big events (exhibitions, open-door events, air-and-space fair participation), and print products.

In most of DLR’s science centers so-called “DLR School_Lab” facilities are entertained, that is, a network of laboratories for high-school level experiments in various scientific disciplines. More than 100,000 school kids per year there experience a fully tutored lecture and science-level experimental program lasting several hours. For the future it is planned to offer experiments with more “lunar” affinity, like mapping of remote-sensing image data, age determinations based on lunar impact-crater size-frequency statistics, analyses of spectral characteristics of analogs of typical lunar rocks, reflectance behavior of lunar soils, microscopic textural analyses of, for instance, impact-shattered rocks.

DLR has prepared a proposal of a nation-wide initiative to promote lunar and planetary science through an extensive educational initiative. This ready-at-hand EPO program is part of a proposed national DLR-lead German orbiter mission to the Moon that is currently on hold by the German government. Besides its scientific outline one of the principal constituents was a nation-wide EPO based competition allowing winning schools to participate (within certain limits) in the planning process, data acquisition, processing and scientific evaluation of a stereo-image experiment on the proposed lunar mission. The initiative has been well received on ministerial level of German government.

Young visitor at DLR’s 3D Mars exhibition at the United Nation’s headquarter in New York. The 3D exhibition is touring Germany, the US and Japan since 4 years. The visitor count at the end of 2009 is about 1.1 million.

Abbreviations

3D	three dimensional
ALSEP	Apollo Lunar Surface Experiment Packages
AOCS	Attitude and Orbit Control System
APXS	Alpha Particle X-Ray Spectrometer
ATON	Autonomous Terrain based Optical Navigation
BELA	BepiColombo Laser Altimeter
CCD	Charge Coupled Device
CCSDS	Consultative Committee for Space Data Systems
CMOS	complementary metal oxide semiconductor
CMSS	Coarse Moon and Sun Sensor
CNES	Centre National d'Études Spatiales
DC	direct current (electricity)
DEM	digital elevation model
DFG	Deutsche Forschungsgemeinschaft (German Science Foundation)
DLR	Deutsches Zentrum fuer Luft- und Raumfahrt
DN	Institut fuer Kommunikation und Navigation, section „Digitale Netze“
DOD	depth of discharge
DTN	Delay Tolerant Network
EADS	European Aeronautic Defence and Space Company
ECLSS	Environmental Control & Life Support System
EPO	Education and Public Outreach
ESA	European Space Agency
FAS	ferroan-anorthositic suite
FESG	Forschungseinrichtung Satellitengeodaesie
FOV	field-of-view
FT	Institut fuer Flugsystemtechnik
FUB	Freie Universitaet Berlin (Free University of Berlin)
FZ	Forschungszentrum
GCR	galactic cosmic radiation
GCR	galactic cosmic rays
GFZ	Deutsches GeoForschungsZentrum
GmbH	Gesellschaft mit beschraenkter Haftung
GNLSE	German Network of Lunar Science and Exploration
GSD	Ground Spatial Distance

GTO	geostationary transfer orbit
HEO	high elliptical orbit
HET	High Energy Telescope
HP^3	Heat Flow and Physical Properties Package
HRC	High Resolution Camera
HRSC-L	High Resolution Stereo Camera – Lunar
IAU	International Astronautical Union
IDP	interplanetary grain
IfE	Institut fuer Erdmessung
ILEWG	International Lunar Exploration Working Group
ILN	International Lunar Network
ILRS	International Laser Ranging Station
IMU	inertial measurement unit
IPDA	International Planetary Data Archiving
IR	infrared
IRAS	Ionizing Radiation Sensor
IRL	Instrument Readiness Level
ISAS	Institute for Analytical Sciences
ISD	interstellar dust
ISECG	International Space Exploration Coordination Group
ISRU	in-situ research utilization
JPL	Jet Propulsion Laboratory
KN	Institut fuer Kommunikation und Navigation
LDPCC	low-density parity-check codes
LEAM	Lunar Ejecta and Meteorites
LEC	long erasure code
LEDT	Lunar Exploration Definition Team
LEO	Lunar Explorations Orbiter
LEOPARD	Lunar Exploration Orbiter Dust Particle Detector
LEOSAR	SAR-SOUNDER Instrument
LHS	line heat source
LIDAR	light detection and ranging
LL	lunar lander
LLO	low lunar orbit
LLR	Lunar Laser Ranging

LOFAR	Low Frequency Array (Telescope)
LOLA	Lunar Orbiting Laser Altimeter
LRO	Lunar Reconnaissance Orbiter
LRX	Lunar Radio Explorer
LSS	Life Support System
LSS	sub-satellites of LEO
LTP	Lunar Transient Phenomena
LunarMag	Lunar Fluxgate Magnetometer
MDA	MacDonald, Dettwiler and Associates Ltd.
ME	Mean Earth
MECO	main engine cut-off
MER	Mars Exploration Rover Mission
MGM	Modified Gaussian Model
MIMO	Microwave Instrument for a Moon Orbiter
MIR	middle infrared
MLI	multi-layer insulation
MORO	Moon Orbiting Observatory
MPI	Max-Planck-Institut
MS	mass spectrometer
MSL	Mars Science Laboratory
NAC	Narrow Angle Camera
NEO	Near Earth Objects
NIR	near infrared
NLSI	NASA Lunar Science Institute
NSSDC	National Space Science Data Center
NTNS	Non-Thermal Neutron Sensor
PA	Principal Axis
PCB	printed circuit board
PDS	Planetary Data System
PDU	power distribution unit
PEL	Planetary Emissivity Laboratory
PL	payload
PRARE-L	Precise Range and Range-rate Equipment-Lunar Version
RAD	Radiation Assessment Detector
RadMO	Radiation Monitor

RaPS	Radiation Pressure Sensor
RGB	read-green-blue
RHU	radioactive heater unit
RM	Institut fuer Robotik und Mechatronik
RPIF	Regional Planetary Image Facility
RTD	resistance temperature detector
RTG	radioisotope thermoelectric generator
RY	Institut fuer Raumfahrtsysteme
S/W	software
SAR	synthetic aperture radar
SC	Simulations- und Softwaretechnik
SEP	solar energetic particle
SERTIS	Selenologic Radiometer and Thermal Infrared Spectrometer
SfM	Structure from Motion
SIR	near infrared spectrometer on Chandrayaan
SIS	Site Imaging System
SP	short period sensor
SPE	solar particle event
SPOSH	Smart Panoramic Optical Sensor Head
TIR	Total Internal Reflection
TRL	Technology Readiness Level
TRON	Testbed for Robotic Optical Navigation
TS	trajectory sensor
TU	Technical University
TUB	Technische Universitaet Berlin (Technical University Berlin)
TUM	Technical University Munich
UHF	ultra-high frequency
UK	United Kingdom
USMI	Ultraviolet Spectral Mapping Instrument
UV	ultraviolet
VBB	very broad band sensor
vH&S	von Hoerner&Sulger GmbH
VIS	visible
VIS-NIR	Grating Imaging Spectrometer
VNIR	visible and near-infrared

WAC	Wide Angle stereo Camera
XRF-L	Lunar-X-Ray Fluorescence Experiment

ANNEX 1 Members of the German Network of Lunar Science and Exploration

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