Lunar Mission BW1: Scientific Objectives and Small Satellite Concept

Lunar Mission BW1: Wissenschaftliche Zielsetzung und Kleinsatellitenkonzept

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Zusammenfassung

Seit dem Start von UoSat-1 (University of Surrey Satellite 1) im Jahr 1981 haben universitäre Kleinsatelliten erfolgreich die Möglichkeiten von Raumfahrtforschung und -technologie im akademischen Umfeld demonstriert. Heutzutage besteht kein Zweifel mehr, dass universitäre Satelliten in der Erdumlaufbahn wichtige Plattformen für Forschung und Lehre, sprich Ausbildung, Technologieerprobung und wissenschaftliche Experimente sind.

Schon seit Beginn des Raumfahrtzeitalters beteiligen sich Universitäten und Forschungseinrichtungen an der Erkundung von Mond und Planeten, durch Datenanalyse, Bereitstellung von Instrumenten oder im Rahmen weitergehender Forschung — bisher jedoch nicht durch Entwurf, Bau und Betrieb einer eigenen lunaren oder planetaren Raumsonde. Basierend auf dem heutigen Stand im Bereich Kleinsatellitenentwicklung, der Expertise und dem Wissen universitärer Einrichtungen sowie der Verfügbarkeit von Technologien erscheint der Entwurf, Bau und Betrieb einer eigenen Raumsonde als ein machbarer und logischer nächster Schritt.

Im Jahr 2002/03 wurde am Institut für Raumfahrtsysteme der Universität Stuttgart das Stuttgarter Kleinsatellitenprogramm initiiert. Eines seiner Ziele ist es, dass Studierende im Rahmen eines attraktiven akademischen Programmes reale Erfahrungen — quasi Raumfahrt zum Anfassen — gewinnen können. Ein Netzwerk von Partnern aus Industrie und Forschung unterstützt dieses Ziel durch ingenieurtechnische und wissenschaftliche Expertise und die Bereitstellung von Hard- und Software und finanzielle Unterstützung durch Patenschaften von Dissertationen aber auch durch die Beteiligung an der Lehre in Vorlesungen, Seminaren und Workshops.

Das Program beinhaltet derzeit vier Satellitenmissionen, aber auch Einrichtungen im Bodensegment sowie Entwicklungsprojekte von Software- und Simulations-Tools, Methoden und Datenbanken. Der Mikrosatellit *FLYING LAPTOP* wird Fernerkundungsexperimente zur Erdbeobachtung sowie Technologiedemonstrationen durchführen. Dieser Mission folgt *PERSEUS* zur Erprobung elektrischer Antriebssysteme und astronomischen UV-Beobachtungen. Diese Satelliten ebnen den Weg für weitere, komplexere Projekte: die atmosphärische Eintritts- und Rückkehrsmission *CERMIT* sowie den Kleinsatelliten-Mondorbiter *LUNAR MISSION BW1*. Das Ziel der *LUNAR MISSION BW1* ist es, den Beweis anzutreten, dass es für eine Universität, eine Fakultät oder sogar nur ein einzelnes Institut möglich ist, mit einen eigenen signifikanten Beitrag zur Erkundung des Weltraums beizutragen. Im Rahmen dieses Beitrages sollen neue wissenschaftliche Kenntnisse erbracht oder innovatives Technologien erprobt werden — sichtbar innerhalb der wissenschaftlichen und technischen Gemeinde wie auch in der Öffentlichkeit mit nachhaltigen Auswirkungen innerhalb der Raumfahrt.

Bei der *LUNAR MISSION BW1* handelt es sich um einen komplett elektrisch angetriebenen Kleinsatelliten-Mondorbiter von etwa 1 m Kantenlänge und ca. 200 kg Startmasse. Der Start als Huckepack-Nutzlast in eine geosynchrone Transferumlaufbahn ist für 2012 oder später geplant. Die Raumsonde soll dabei mittels solar-elektrischer Antriebssysteme (thermisches Lichtbogentriebwerk und magnetoplasmadynamische Triebwerke) zum Mond fliegen und in einen hoch inklinierten, niedrigen Mondorbit von etwa 100 km eintreten. Der Orbiter soll für mindestens sechs Monate Technologiedemonstrationen sowie Fernerkundungs- und In-situ-Experimente durchführen bevor die Mission mit einem Einschlag auf der Mondoberfläche endet. Während der Flugphase von mindestens 18-24 Monaten sowie dem Betrieb im Mondorbit wird die Energieversorgung mittels Solarpaneelen von rund 6 m^2 sichergestellt. Diese erzeugen eine elektrische Leistung von bis zu 1 kW, die in Lithium-Ionen-Batterien gespeichert wird. Der dreiachsenstabilisierte Satellit nutzt K_a-Band-Kommunikation und eine Bordantenne von 1 m Durchmesser zum Datentransfer zum eigenen Missionskontrollzentrum mit Unterstützung durch Bodenstationen verschiedener Kooperationspartner.

Die Programmatik der *LUNAR MISSION BW1*, basierend auf dem Status bisheriger und aktueller Monderkundung, ist ebenso dargestellt wie das Kleinsatellitenkonzept und die wissenschaftlichen Ziele dieser Mission unter Berücksichtigung von Limitierungen und Potenzialen einer universitären Arbeitsumgebung. Ein mögliches Missionsszenario mit den wesentlichen Elementen von Weltraum- und Bodensegment wird erläutert. Die Möglichkeiten aber auch Notwendigkeit eines anderen Vorgehens im Bereich Projektmanagement im Vergleich zu großen Raumfahrtorganisationen aufgrund des akademischen Umfeldes werden ausgeführt, gefolgt von einer Darstellung bisher gewonnener Erfahrungen im Rahmen dieses Projektes. Die *LUNAR MISSION BW1* wird demonstrieren, dass virtuelle Erkundung keine mögliche, machbare oder auch nur nutzbringende Option ist im Vergleich zum Entwurf, Bau und Betrieb einer eigenen Erkundungsmission, um Studierenden und wissenschaftlichem Nachwuchs reale Erfahrung zu offerieren. Nicht zu vergessen, die Gewinnung realer wissenschaftlicher Daten und weltraumqualifizierter Kleinsatellitentechnologie.

Abstract

Since UoSat-1 (University of Surrey Satellite 1) was launched in 1981 academic small satellites demonstrated successfully universities' capabilities in space science and engineering. Today it is without any doubt that academic small Earth orbiting satellites can be important educational instruments, useful technology demonstration tools and promising and serious scientific research platforms.

Since the very beginning of the space age universities and research institutes participated in lunar and planetary exploration analyzing data, providing instruments or performing further research. But usually such institutions did not design, build and operate their own lunar or planetary spacecrafts. Based on the status in the field of small spacecraft development and the expertise and knowledge of academic institutions as well as the availability of technology to design, build and operate an own probe beyond Earth orbit seems to be a feasible next logical step.

The Stuttgart Small Satellite Program was initiated in 2002/03 at the Institute of Space Systems of the Universität Stuttgart, Germany. One of its objectives is to provide an attractive academic program with real hands-on experience for participating students. A network of industrial and academic partners supports by offering engineering and scientific expertise and knowledge and providing financial support for PhD scholarships as well as involvement in lectures, workshops and seminars but also provision of hardware and software.

The program consists currently of four spacecraft missions but also ground segment facilities and the development of software and simulation tools, methods and data bases. The micro satellite *FLYING LAPTOP* will perform Earth observation remote sensing experiments and technology demonstration followed by the electric propulsion test-bed *PERSEUS* which will also perform UV astronomy. Both spacecrafts pave the way for the later complex projects: the atmospheric entry and return mission *CERMIT* and the small lunar orbiter spacecraft *LUNAR MISSION BW1*. The goal of the *LUNAR MISSION BW1* is to prove that it is possible for a university, a faculty or even an institute to make a significant contribution by its own to space exploration. The contribution should be to create new scientific knowledge or demonstrate innovative technology visible within the community and in the public as well as having an enduring efect in the space arena.

The *LUNAR MISSION BW1* will be an all-electrical small lunar orbiter of approx. 1 m cube and approx. 200 kg launch mass. Planned to be launched as a piggyback payload into a Geosynchronous Transfer Orbit (GTO) in 2012 or later the probe should use solar-electric propulsion systems (thermal arcjet and

magneto-plasma-dynamical thrusters) to be transferred to the Moon into a highly inclined circular low lunar orbit of approx. 100 km. The orbiter will perform technology demonstrations, remote sensing and in-situ research experiments for at least 6 months before impacting on the surface of the Moon. During the cruise phase of 18-24 months or more and the operations in lunar orbit solar panels of approx. 6 m^2 will generate the necessary electrical power of up to 1 kW supported by Li-Ion batteries for power storage. The satellite will be 3-axis stabilized and using a K_a band communication system and a 1 m primary dish providing broadband data transfer to the own mission control center but also supported by other partners' ground stations.

The programmatics behind the *LUNAR MISSION BW1* based on past and current lunar exploration is described as well as the small satellite concept and the scientific objectives based on the limitations and potentials of an academic environment. A possible scenario of the mission is depicted including the necessary elements of the space and the ground segment. The opportunity but also the necessity for a different approach in project management due to the academic environment is explained concluded by lessons learned. The *LUNAR MISSION BW1* demonstrated that virtual exploration is not possible - hence it is not a feasible or useful option as an alternative for building and operating an own exploration mission to provide real experience to students and young professionals and real research data as well as space qualified small satellite technology.

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Constants, Symbols, Parameters

AU	149,597,870.691 km	Astronomical unit
c	299,792.458 km/s	Speed of light
F_{AU}	1,366.1 W/m^2	Mean Solar irradiance at 1 AU
R_E	6,378.14	Mean Radius of the Earth
R_M, R_{Moon}	1,738 km	Radius of the Moon
S band	2 GHz	
K_a band	20-30 GHz	

Abbreviations

ACS	Attitude Control System
ADCS	Attitude Determination and Control System
AOCS	Attitude and Orbit Control System
APXS	Alpha Particle X-Ray Spectrometer
BW1	Baden-Württemberg 1
C&DH	Command and Data Handling
CCD	Charged Couple Device
CNSA	China National Space Administration
COM	Communication
COTS	Commercial Off-the-Shelf
CSM	Command (and) Service Module
DLR	Deutsches Zentrum für Luft- und Raumfahrt e.V. (engl.: German Aerospace Center)
ESA	European Space Agency
FEM	Finite Element Method
FIR	Far Infrared
FPGA	Field Programmable Gate Array
GNC	Guidance, Navigation and Control
GOLEM	General parametric Outline for Lunar Exploration Missions
GSLV	Geostationary Satellite Launch Vehicle
GTO	Geosynchronous Transfer Orbit
H/W	Hardware

I/F	Interface
IAA	International Academy of Astronautics
IAU	International Astronomical Union
IIR	Intermediate Infrared
IR	Infrared
IRS	Institut für Raumfahrtsysteme
	(engl.: Institute of Space Systems)
ISAC	ISRO Satellite Centre
ISRO	Indian Space Research Organisation
ISS	International Space Station
ISTRAC	ISRO Telemetry Tracking And Command Network
ISU	International Space University
JAXA	Japan Aerospace Exploration Agency
LBQ	Lunar Base Quarterly
LCROSS	Lunar Crater Observation and Sensing Satellite
LEM	Lunar Excursion Module
LEO	Low Earth Orbit
LK	Lunniy Korabl
	(engl. Lunar Craft)
LLO	Low Lunar Orbit
LM	Lunar Module
LOK	Lunniy Orbitalniy Korabl
	(engl. Lunar Orbit Craft)
LRO	Lunar Reconnaissance Orbiter
LWIR	Long-Wave Infrared
MASTER	Meteoroid and Space Debris Terrestrial Environment Reference
MDVE	Model-based Development and Verification Environment
MPD	Magneto-plasma-dynamic
MIMOS	Miniaturized Mössbauer Spectrometer
MIR	Mid Infrared
MWIR	Middle-Wave Infrared
NASA	National Aeronautics and Space Administration
NEO	Near Earth Object
NIR	Near Infrared

OLIMPIA	Outline of Lunar exploration InstruMents and Payloads for Initial Analysis
P/L	Payload
PCDU	Power Control and Distribution Unit
PDR	Preliminary Design Review
PDS	Planetary Data System (NASA)
PFS	Particles and Fields (Sub-)Satellite (Apollo Program)
PPT	Pulsed Plasma Thruster
PROP	Propulsion System
PSA	Planetary Science Archive (ESA)
PSLV	Polar Satellite Launch Vehicle
PSS	Power Supply System
RF	Radio Frequency
RKA	Federal'noe Kosmicheskoe Agentstvo Rossii (engl.: Russian Federal Space Agency, a.k.a. 'Roskosmos')
S/C	Spacecraft
S/W	Software
SEE	Single Event Effect
SEL	Single Event Latchup
SELENE	Selenological and Engineering Explorer
SEU	Single Event Upset
SMART	Small Missions for Advanced Research in Technology
STK	Satellite Toolkit
STM	Structures and Mechanisms
SWIR	Short-Wave Infrared
TBC	To Be Confirmed
TBD	To Be Defined
TCS	Thermal Control System
TIR	Thermal Infrared
TPS	The Planetary Society
VIS	Visible

Prologue

"We set sail on this new sea because there is new knowledge to be gained"

John F. Kennedy[1]

"The only way of discovering the limits of the possible is to venture a little way past them into the impossible"

Sir Arthur C. Clarke[2]

Sometimes it is difficult or even impossible to identify by date the exact starting point of a specific project because of former discussions and ideas over a longer period of time.

This project has an exact starting point: Wednesday, 4th of September 2002. After a public lecture at the local planetarium in Berlin-Schöneberg Prof. Röser asked to visit him in Stuttgart at his new university domain. Following the visit at the Institute of Space Systems (IRS) the first idea of a small Moon orbiting satellite was born in mid-October 2002. Moving from DLR Berlin to IRS Stuttgart in mid-February 2003 marked the beginning of work on the project which was named *LUNAR MISSION BW1* one month later and became part of the Stuttgart Small Satellite Program.

This report arose since February 2003 during the time in the Small Satellites Group of the Institute of Space Systems acting as project manager of the *LUNAR MISSION BW1*.

First I would like to thank my supervisor Prof. Dr. H.-P. Röser, Director of the Institute of Space Systems for all his academic and personal support, comments, suggestions and especially taking me in to Stuttgart. Also I express my gratitude to the reviewers Prof. Dr. T. Hyde (Director CASPER and Vice Provost, Baylor University, Waco, Texas, USA) and Prof. Dr. W. Peeters (Dean and Vice President, International Space University, Strasbourg, France).

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[1] Speech at Rice University, Houston, Texas, USA, September 12, 1962[41]

[2] Second Law of Prediction, from: Hazards of Prophecy: The Failure of Imagination[9]

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René Laufer
Stuttgart and Berlin, 2008/2009

Chapter 0

Introduction

"Begin at the beginning and go on till you come to the end: then stop"

King of Hearts[1]

In this chapter:

- Vision
- Structure

Every program, mission or spacecraft project has its starting point. This could be unanswered open questions, results of former missions or needs for future programs as well as political goals or commercial opportunities.

Open questions or former results are typical reasons for scientific missions concerning fundamental physics, astronomical or planetary exploration. Technology demands for future exploration programs but also verification of components for commercial spacecrafts are usual starting points for demonstration missions. Especially this is a type of project where the usage of small satellites became more and more common since the 1980s.

Obviously political goals can be a very strong justification to motivate space programs and its missions: the announcement of the human lunar landing of US-president John F. Kennedy in May 1961 being the start of the successful Apollo program is a well-known example from the cold war era in the second half of the 20th century.

[1]Disney's Alice in Wonderland, 1951, nominated for one Academy Award (Best Music) — based on: Lewis Caroll, *Alice's Adventure in Wonderland*, Macmillan & Co., Oxford University Press, 1865[37]

In an academic environment the origin could be also a matter of science policy or university's affairs. Especially these areas are often characterized by the demonstration of new technologies, research capabilities or up-to-date scientific results. To verify recent developments as well as to prove latest research results small satellites are common and affordable tools to fulfill objectives of academic programs or missions. Verification and proof are often necessary suppositions to seek for further funding to continue research and development.

0.1 Vision

In the beginning a question was raised: Is it possible for a university, a faculty or even an institute to make a significant contribution by its own to space exploration? Is this contribution able to create new scientific knowledge or new innovative technology visible within the community and in the public as well as having an enduring effect in the space arena?

Today space missions or programs are usually multinational efforts. But despite the well known scientific or commercial potential of large missions there are limitations. One is long project schedules and compromises in mission design because of the number of participating and therefore deciding nations. With a large number of instruments this could mean disadvantages for the scientific output of a single instrument because of unfavorable orbit design, limited instrument working time or influences from other experiments. Long project schedules cause low flexible response to new discoveries but also raise the problem of an expanding gap of technology level between flight instruments and current instrument development. Definitely another limitation is an increasing financial effort which is necessary because of being a multinational, long run project with many decision making processes and involved participants with more necessary communication, management and large organizational structures.

Despite of limitations in funding and cash flow, available technology, ground and on-board resources and the capability in fullfilling scientific tasks an academic environment provides potentials compared to a multinational mission. Small and lean management structures of small teams with fast decision making processes lead to short project schedules. Small teams generate high identification factor but also demand more personal responsibility of every member. Taking higher risks and accepting the limits of small payload capabilities missions designed to objectives and experiments with less compromises can be created — and because of limited funding the missions are designed to costs. An additional and important factor are highly motivated project members (students, scientists and engineers supported by senior staff) and their creativity, fresh ideas because of high identification providing real hands-on education to graduates and young professionals. Such projects are appealing to students chosing a university and generate more and better educated graduates in science and technology.

Small satellites are well known and proven tools for academic research and development in space. In 1981 the first academic small satellite UoSat-1 was launched by the University of Surrey, United Kingdom, demonstrating the possibilities of academic space science and commercial available technology despite of concerns of national agencies and industrial companies. The concerns refered (and are still referring) to the posibilities of a university to perform serious science in space. Today it is without doubt that academic small Earth orbiting satellites are useful research and technology development platforms.

Since the launch of UoSat-1 around 500 small satellites mainly in the area of communications and science were launched until the year 2000. Only a low number of small spacecrafts were equipped with propulsion systems to change orbit and only very few were launched beyond Low Earth Orbit (LEO) — none ever on an interplanetary trajectory to orbit another celestial body or touch its surface. Such missions are the next frontier and the next logical step in small satellite development extending the capabilities of academic space science and exploration beyond Earth and its environment.

Evaluating the possibility of a significant contributions it might be useful to combine the advantages of an academic environment and up-to-date small satellite capabilities. Based on the current knowledge in planetary exploration and academic small spacecraft technology the next logical step in small satellite development is a mission beyond Low Earth Orbit (LEO) to another close object of our solar system. Taking into account potentials and limits of academic small satellite projects a mission to the Moon, another neighbour planet or a near Earth asteroid or comet seem to be a feasible challenge.

Innovations within a program can focus on one specific working field like e.g. space sensor development or attitude control systems. Academic institutions are participating in lunar and planetary exploration since the very beginning of the space age providing scientific instruments, analyzing data or performing further research but usually do not design, build and operate own interplanetary space probes. Without any doubt this type of reseach and development are promising areas of space activities especially using small satellites. Also it seems possible to seek for innovations in accomplishing evolutionary steps in small satellite technology from Earth orbit towards another celestial objects. An autonomous program consisting different missions achieving various technical and scientific objectives is able to pave the way for a mission beyond Earth orbit because of gaining own experience and providing own flight heritage.

Taking advantage of low-cost piggy-back launch opportunities combined with low-cost satellite design and operations approaches of universities or institutes an academic small planetary spacecraft has to overcome disadvantages like e.g. not using a dedicated launch providing an ideal trajectory, restricted ground station capabilities or limited on-board and ground resources. On the other hand some disadvantages can be compensated, e.g. using low-cost low-mass electric propulsion systems with long travel times but also covering large distances. Especially long cruise phases provide enough flexibility in personnel resources and non-squeezed operations but also much more opportunities for incorporating hands-on education with a real spacecraft.

Evaluating different possible mission options the decision resulted in the design and development of a Moon orbiting satellite. This seems to be a feasible undertaking for a university with the necessary resources of personal, technology, funding and knowledge complemented by creativity, innovation, motivation and identification. Such a mission can demonstrate that a university is able to accomplish a space exploration endeavour autonomously. Taking advantage of the independance from large organizations like national or multinational space agencies but incorporating intense communication with experts of agencies, industrial companies as well as research institutes can keep the project small, lean and fast because of the reasons described above. A project like this would provide valuable hands-on experience to students in the technical, scientific and management area of space systems. Because there is no virtual exploration providing virtual knowledge only a real exploration mission will provide real experience and results.

0.2 Structure

The structure of this work will lead from the first broad idea of a small lunar satellite within a program to a possible mission concept resulting in the realization of the different stages of a spacecraft and other necessary elements.

Chapter 1: MISSION TARGET will provide an overview about the Moon as a potential target of space probes in comparison with other targets including information and parameters for designing a lunar mission. The description of past milestones of lunar exploration will especially focus on comparable orbiting satellites and its mission-specific data.

In chapter 2: MISSION GOALS the motivation and justification as well as goals and objectives of the Stuttgart Small Satellite Program will lead to the mission statement and the different types of objectives of the *LUNAR MISSION BW1*. Discussing possible objectives and own flight heritage will conclude this chapter.

Covering mission requirements and resulting design of the spacecraft chapter 3: MISSION CONCEPT will give details about the mission and the spacecraft.

One of the focal points will be technical and scientific payloads and its opportunity for external scientists of using and utilizing the experiments and its data.

Following the design of the spacecraft chapter 4: MISSION SCENARIO will describe all phases of the mission before and after launch of the spacecraft. Details of the ground segment and necessary steps will be provided as well as possible scientific tasks to be performed during the mission.

Space missions as complex and multidsciplinary endeavours have to be managed with respect to its resources. Chapter 5: MISSION MANAGEMENT will identify and describe potential management structures considering new approaches based due to the academic environment.

Chapter 6: PRODUCTS will show the visible outcome of the design process: the different spacecraft stages starting with the simple mock-up and leading to the flight model.

Concluding this work chapter 7: SUMMARY will provide the lessons learned and an outlook to future work.

Chapter 1

Mission Target

"I look up at the Moon and wonder, when will we be going back, and who will that be?"
James "Jim" Arthur Lovell, Jr.[1]

In this chapter:

- General Overview
- The Moon
- Cislunar and Lunar Environment
- Milestones of Lunar Exploration
- Open Questions and Modern Aspects

Every program, mission or spacecraft project has its target. Different options were evaluated of being realistic enough to be accomplished within an academic environment: Interplanetary space, Near Earth Object (NEO), Mars, Venus, Sun-Earth libration points and the Moon.

Initial analysis showed challenges which would be difficult to meet with the constraints of an academic program. In the first place orbital mechanics resulting in impulse demand (delta-v demand), flight duration and launch windows drives the satellite's design — sometimes offering just a flyby with very limited

[1]Apollo 13, 1995, nominated for nine Academy Awards (Best Art Decoration, Best Effects, Best Film Edit, Best Music, Best Picture, Best Supporting Actor, Best Supporting Actress, Best Sound, Best Writing), won two Academy Awards (Best Film Editing, Best Sound) — based on: Jim Lovell, Jeffrey Kluger, *Lost Moon: The Perilous Voyage of Apollo 13*, Houghton Mifflin, 1994[37]

opportunities for research. Leading to a large mini satellite with a dedicated (and therefore expensive) launch instead of a piggyback-launched little mini satellite some options were considered as less feasible. Longer flight durations increase e.g. system's lifetime requirements which are more difficult to meet with COTS (commercial off-the-shelf) parts and will result in increasing costs because of special hardware, extensive quailification procedures as well as long mission operations. The distances differ in two orders of magnitude challenging e.g. communication issues diminishing transfered data volume and operations. Also tasks visible within and supported by the public and expert community were evaluated. Hence planets and NEOs but also interplanetary space or libration points were judged as less feasible for different reasons resulting in the Moon as the most likely mission target.

1.1 General Overview

The Moon is the natural satellite of the Earth, our homeplanet. Certainly the Moon is one of the most observed object of the firmament - at night and in the daytime. It is observed since the dawn of mankind because of its size, brighness and of course motion and changing shape ("phases"). There is no other celestial body giving such a unique view with surface details visible to the naked eye.

Figure 1.1: Lunar map of Knowth, Ireland (left: naked eye map, right: carving from Knowth, center: both superimposed), about 2,800 BC — the earliest known depiction of the Moon[87]

Early scientific lunar observations were made and documented during ancient times: greek philosopher Anaxagoras (approx. 500 BC - 428 BC) suggested that the Moon is a spherical rocky body reflecting the sunlight, Democritus (approx. 460 BC - approx. 370 BC) supposed that mountains and valleys exist on the lunar surface. The greek explorer Pytheas of Massalia (approx. 380 BC - approx. 310 BC) reported the influence of the Moon on tides after observing changing water levels and the link to different lunar phases. Aristarchus of Samos (approx.

310 BC - approx. 230 BC) made first calculations in his work *On the Sizes and Distances of the Sun and Moon*. In the 4th century BC chinese astronomers Gan De and Shi Shen observed and predicted lunar and solar eclipses. Explaining why Sun and Moon are not eclipsing every month Shen Kuo (1031 - 1095) assumed an excentricity of their orbits to be responsible.

Mapping the Moon is mainly linked to the telescope era emerging at the beginning of the 17th century — Leonardo da Vinci (1452 - 1519) made sketches of the Moon in his notebook (see figure 1.2) and just William Gilbert (1544 - 1603) produced drawings based on naked-eye-observations. The 17th century also marked the beginning of naming surface features starting with dutch cartographer Michael Florentius van Langren (approx. 1600 - 1675) and his map from 1645, Johannes Hevelius (1611 - 1687), the father of lunar topography, and his atlas *Selenographia sive Lunae Descriptio*[2] from 1647. In 1651 the italian astronomer Giovanni Battista Riccioli (1598 - 1671) published his work *Almagestum Novum*[3] supported by his assistant Francesco Maria Grimaldi introducing a naming scheme which is still the basis of today's lunar nomenclature system of the IAU.

Figure 1.2: Lunar map (sketch) from a notebook of Leonardo da Vinci (1452 - 1519) , ca. 1500[33]

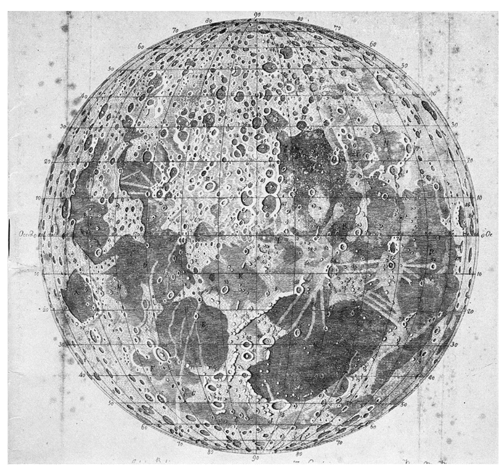

Figure 1.3: Lunar map of Tobias Mayer (1723 - 1762), from 1749 (19 cm, first map based on measured positions)[6]

With the increasing performance of telescopes the libration of the Moon was discovered exposing more than 50% of the lunar surface to a terrestrial observer.

[2]engl.: Selenography or Description of the Moon

[3]complete title: Almagestum novum astronomiam veterem novamque complectens observationibus aliorum et propriis novisque theorematibus, problematibus ac tabulis promotam

German astronomer Tobias Mayer (1723 - 1762) became recognized and famous for his lunar libration studies, charts and tables — especially introducing a coordinate system in his map of the Moon (see figure 1.3). But also analytical research went on when Italian mathematician Joseph-Louis Lagrange (1736 - 1813) was studying the three-body problem for Earth, Moon and Sun and found the Lagrangian points (also known as libration points) in 1772.

Johann Hieronymus Schröter (1745 - 1816) and his *Selenotopographische Fragmente zur genauern Kenntniss der Mondfläche*[4] from 1791 marked the beginning of the systematic mapping of the Moon and making Riccioli's naming scheme the standard for lunar nomenclature by using it. Following important milestones were Wilhelm Gotthelf Lohrmann's (1796 - 1840) *Topographie der sichtbaren Mondoberfläche*[5] from 1824, the *Mappa Selenographica* published in 1834-1836 by Johann Heinrich von Mädler (1794 - 1874) and Wilhelm Beer (1797 - 1850) who assumed that the Moon does not have any atmosphere due to the fact that surface features do not change and Johann Friedrich Julius Schmidt's (1825 - 1884) *Charte der Gebirge des Mondes*[6] with nearly 2 m diameter from 1878. The middle of the 19th century saw the first photographic (daguerreotype) images of the Moon introducing a complete new method of observation to astronomy.

Later maps are photographic images or drawings based on photographic observations like Julius Heinrich Franz's (1847 - 1913) works introducing elevation mapping, the *Photographic Atlas of the Moon* (1903) of William Henry Pickering (1858 - 1938), the *Photographic Lunar Atlas* (1960) and the *Consolidated Lunar Atlas*[7] (1967) produced by teams led by famous astronomer Gerard Peter Kuiper (1905 - 1973) or the *Berliner Mondatlas*[8] produced in the years 1964 - 1969 by the german amateur astronomers Adolf Voigt (1920 - 2007) and Hans Giebler (1897 - 1992)[9]. Today CCD sensors are the technology mainly used for ground or space-based imaging of the Moon.

Myths, legends and fairytales linked to the Moon have been told all over the world in any culture and are as old as humankind. Due to its nature as described in the beginning of this chapter the dark and bright features on the lunar near side were considered as livings (e.g. man or his face, rabbit, deer). Also the Moon was either a residence of gods or inhabited by extraterrestrials — some of the new asian lunar probes[10] are named after characters of myths. The Moon was

[4] engl.: Seleno-Topographical Fragments for detailed Knowledge of the Surface of the Moon

[5] engl.: Topography of the Visible Surface of the Moon

[6] engl.: Map of the Mountains of the Moon

[7] online available at `http://www.lpi.usra.edu/resources/cla/`

[8] engl.: Berlin Atlas of the Moon

[9] digital atlas made available on CD-ROM in 2002 by W. Tost, online available at `http://www.wfs.be.schule.de/Mondatlas/`

[10] the japanese Kaguya or the chinese Chang'E (both launched 2007)

always a romantic theme in arts like in classical music or in pop and rock but especially in countless jazz and swing songs. Also in literature and movies and to the point of comics, computer games and animations.

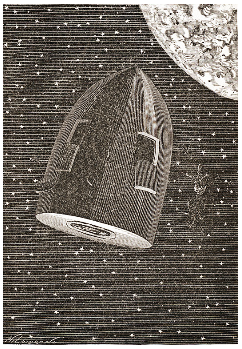

Figure 1.4: Projectile from Jules Verne's novel *De la Terre à la Lune*, 1874 edition[95]

Figure 1.5: Lunar base Clavius from the movie *2001: A Space Odyssey*, based on Sir Arthur C. Clarke's novel[10]

Above all the Moon played and plays an important role in science fiction literature and movies. Starting with Lucian of Samosata (approx. 125 - approx. 180), the father of science fiction, and a journey to the Moon as described in *Vera Historia*[11] the Moon remained a location often visited. Some later authors were Johannes Kepler (1571 - 1630), Francis Godwin (1562 - 1633), John Wilkins (1614 - 1672), Cyrano de Bergerac (1619 - 1655), Daniel Defoe (approx. 1660 - 1731), Karl Friedrich Hieronymus Freiherr von Münchhausen (1720 - 1797) and Edgar Allan Poe (1809 - 1849).

The late 19th century saw the first modern space exploration stories with relation to the interest in technology at that time — most famous Jules G. Verne's (1828 - 1905) *De la Terre à la Lune*[12] (1865, see figure 1.4) and *Autour de la Lune*[13] (1870) as well as the 1901 novel *The First Men in the Moon* from Herbert G. Wells (1866 - 1946).

In the second half of the 20th century the Moon was location for many stories of the "big three" Sir Arthur C. Clarke (1917 - 2008), Isaac Asimov (1920 - 1992) and especially Robert A. Heinlein (1907 - 1988) who wrote a large number of novels where the Moon is colonized. Bases and settlements as a logical step after the first expeditions are a frequent theme in science fiction literature and movies. In the movies the tradition of expert scientific advice came up, e.g. in

[11]engl.: True Story
[12]engl.: From the Earth to the Moon
[13]engl.: Around the Moon

1929 with Fritz Langs's famous *Die Frau im Mond*[14] introducing the countdown for a rocket launch and first generation rocket pioneer Hermann Oberth (1894 - 1989) supporting as consultant. Later examples were *2001: A Space Odyssey* (see figure 1.5) by Stanley Cubrick and Arthur C. Clarke released in 1968 with NASA advice or Ron Howard's *Apollo 13* from 1995. Another important type of art were science fact publications like the series of articles of the British Interplanetary Society or the well-known Collier's Magazine articles (*Conquest of the Moon*, 1953) providing a combination of facts, realistic visions as well as detailed concept illustrations published by engineers and scientists like Willy Ley (1906 - 1969), Wernher von Braun (1912 - 1977) and Fred Whipple (1906 - 2004) to inspire successfully the general public.

1.2 The Moon

Earth has only one large natural satellite: the Moon. Because of the minor differences in size and mass (see table 1.1) the Earth-Moon-system can be considered a double planet compared to other planet-moon-relations of our solar system.

Figure 1.6: GALILEO — Second Earth-Moon flyby, color enhanced mosaic (EM2, December 8, 1992, PIA00405, SSI camera filters 756 and 968 nm)[103]

Today's hypothesis[15] of the origin of the Moon combines different theories of creation based on data and samples from space exploration. A grazing collision

[14] engl.: Woman in the Moon, released as The Rocket to the Moon

[15] suggested first by William K. Hartmann and Donald R. Davis, Planetary Science Institute[29]

between a Mars-size body coming from Sun-Earth Lagrange point 4[16] and proto-Earth has been proposed during the very early phase of the history of our solar system. Large amounts of terrestrial mantle material was vaporized and ejected into space condensing later in Earth orbit. This and collider's mantle material formed the Moon by re-accretion with little or no metallic core. Simulations proved the possibility of such an event and fit to our current knowledge of our natural satellite but there are still open questions related to lunar origin and evolution[31, 39].

Parameter	Value	Remark
Radius (mean), R_{Moon}	1,738 km	27% of Earth radius
Area, A_{Moon}	37.9×10^6 km^2	25% of Earth land surface
Mass, M_{Moon}	7.353×10^{24} kg	$\frac{1}{81}$ of Earth mass
Density (mean)	3.34 g/cm^3	61% of Earth mean density
Gravity (mean), g_{Moon}	1.62422 m/s^2	$\frac{1}{6}$ of Earth gravity
Orbit (mean)	384,400 km	(356,400 km - 406,700 km)
Eccentricity (mean)	0.0549	(0.044 - 0.067)
Moon Sphere of Influence, $D_{SOI,Moon}$	66,000 km	
Gravitational Parameter, μ_{Moon}	4.902801076 $\times 10^{12} m^3/s^2$	
Inclination		
$i_{Orbit,Moon}$	5.15°	Ecliptic - lunar orbit plane
$i_{Equator,Moon}$	1.54°	Lunar orbit - equator plane
Orbit Revolution		
Anomalistic	27.55455 d	Pericenter to pericenter
Draconic	27.21222 d	Node to node
Sidereal	27.32166 d	Fixed star to fixed star
Synodic	29.53059 d	New Moon to new Moon
Tropical	27.32158 d	Equinox to Equinox

Table 1.1: Parameters of the Moon[31, 68, 12]

Due to the evolution of the Moon without many surface changing processes it is an excellent archive for the understanding of creation and development of planets in general and especially the Earth-Moon-System. Here we can look back to the early phase of the formation of planets and moons in our solar system at

[16] a.k.a. SEL4, lies 60° ahead of Earth on its orbit around the Sun

approx. 4-4.5 billion years ago. The evolution can be seen on the lunar surface which is mainly formed by four types (or classes) of features: craters, basins, maria and tectonic structures — starting 4.2 billion years ago until now. Maria and Terrae are areas of low (7-10%) and high (11-18%) albedo respectively and differ in chemical and mineralogical composition. Maria cover about 16% of the surface of the Moon mainly on the lunar near side visible to Earth while Terrae or Highlands constitute about 84%[31, 102].

In example the results from impact research — obvious even from Earth seen in a telescope — can be converted by using the Moon for setting up a chronology for the solar system. Still the internal structure and most of the crust is unchanged since its creation. This enables further investigation to reply to unanswered questions of the early evolution of the inner solar system.

In addition to their scientific value lunar samples provide important “ground truth” to be combined with remote sensing data. More than 2,000 samples with a total mass of nearly 400 kg of lunar samples brought back during APOLLO and LUNA missions proved that the Moon is not unchanged since its creation making it not a primitive body[39].

Figure 1.7: APOLLO 11 sample handling by Grant H. Heiken (editor, Lunar Sourcebook)[103, 31]

During the 1990s at that time new digital sensor systems obtained multi-spectral (see figure 1.8 as an example) and other data sets to contribute knowledge in the fields of lunar geology, mineralogy but also gravity and space environment research.

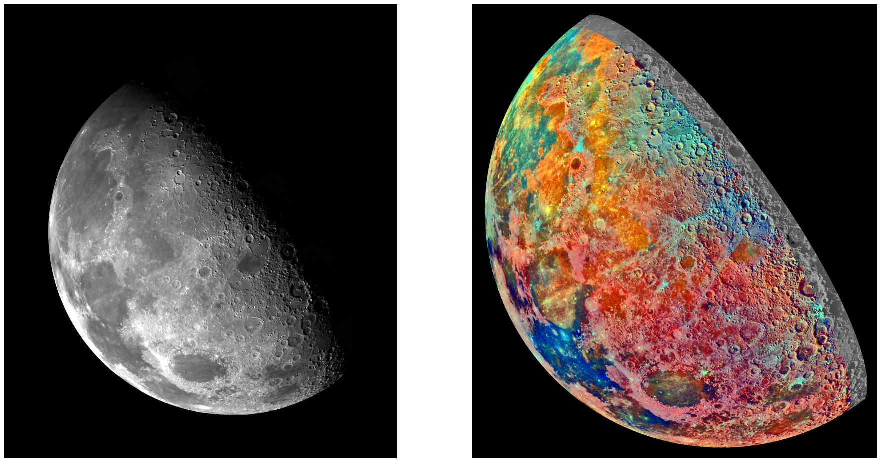

Figure 1.8: GALILEO — Moon's north pole mosaic assembled from 18 images (left) and false-color mosaic from 53 images (right) respectively indicating compositional variations (EM2, December 8, 1992, PIA00130 (left) and PIA00131 (right), SSI camera — pink: highland material, blue to orange: volcanic lava flows, dark blue: titanium rich, green and orange: less titanium)[103]

Also the Moon was and is of fundamental importance for the development of life on our homeplanet. Our natural satellite was and is stabilizing the planetary axis due to its gravitational influence and prevented extreme variations of Earth's climate. The continous evolution of life benefits clearly from the stability of the environmental conditions[46]. In addition the tides generated by the Moon's gravitation provided favorable conditions to promote and foster life.

1.3 Cislunar and Lunar Environment

The space environment either near Earth or in deep space seems to be harsh and unforgiven to satellite hardware and its operations. Main concerns are influences on satellite-ground communications, plasma and radiation as well as magnetic effects on hardware, drag perturbations due to expanding atmosphere near Earth, degradation of hardware because of radiation, atomic oxygen, micrometeoroids and space debris[77, 56]. Most effects are caused because of solar variability.

The probability of an impact of debris or a meteroroid is depending on the orbit and can be calculated with software models like ESA's MASTER (Meteoroid and Space Debris Terrestrial Environment Reference) software[13]. Calculating effects on hardware due to plasma and radiation can be done using ESA's SPENVIS (Space Environment Information System) model[4] with respect to the satellite's trajectory.

Parameter	Value	Remark
Solar irradiance	1,366.1 W/m^2	at 1 AU
Solar wind	1keV, 3-20 cm^{-3}	mainly p, at 1 AU
Solar Particle Events	10 MeV - 10 GeV	rare, sporadic
Inner Radiation Belt	p: several hundred MeV e: MeV range	max. at 2 R_E
Outer Radiation Belt	e: several tens MeV	max. at 4 R_E reaches up to 10 R_E
Plasma	0.1 eV, $10^3 - 10^5$ cm^{-3}	at LEO
Plasmasphere	1 eV, 10-1,000 cm^{-3}	at a few R_E
Plasmapause	keV range, 1 cm^{-3}	at GEO
Plasmasheet	keV range	
Galactic Cosmic Rays	100 MeV - $\gg$ 10 GeV	83% p, 13% He-4 ions

Table 1.2: Some Parameters of the Cislunar and lunar environment[77, 68] (p: protons, e: electrons, R_E: Earth radii

The spacecraft is interacting with its environment especially because of its surface area but also with its subsystems inside due to limited shielding because of mass restrictions. Surface charging is an important effect caused by plasma interaction (but also by photoemission). Discharge arcing can result in degradation effects, anomalies and component failures. Also optical surfaces and components of payloads can be affected because of degradation and contamination (e.g. because of sputtering)[51].

Radiation can cause an increase in ionization dose, degradation because of displacement damage[17] and Single Event Effects (SEE) in electronic components: charging because of high energy particles[18], bitflip data damage because of Single Event Upsets (SEU) or device damage because of Single Event Latchups (SEL). Another effect is signal background caused by cosmic ray and radiation[77, 36].

1.4 Milestones of Lunar Exploration

Being our closest neighbor in space the Moon was naturally the first target of space probes beyond Earth orbit. Less than one year after the launch of world's first artificial satellite SPUTNIK 1 in October 1957 the Soviet Union and the United States attempted to send simple robotic spacecrafts to the Moon — and failed. But only a few months later the russian LUNA 1 (January 1959, figure 1.9) and the US-american PIONEER 4 (March 1959, figure 1.10) made successful

[17] mainly by protons of 10-100 MeV

[18] e.g. $\gg$ 100 keV electrons crossing thin layer of insulation, $\gg$ 1 MeV electrons crossing material in the mm range[77]

flybys in 6,000 km and 60,000 km respectively.

Figure 1.9: LUNA 1 probe[103]

Figure 1.10: PIONEER 4 probe[103]

Both (and also later participating) nations followed mostly a typical sequence of types of missions in planetary exploration.

- Flyby
- Hard landing (e.g. impact probes, penetrators, atmospheric probes)
- Orbit
- Soft landing
- Mobile platforms (e.g. rovers, balloons/airplanes, boats/submarines)
- Sample return
- Crewed exploration
- Temporary/permanent bases (e.g. outposts, laboratories, settlements)

Table 1.3: Types of missions in planetary exploration

Each type represents an increased impulse demand (delta-v demand) and complexity than the former mission. The complexity comprises mainly an increase in number of maneuvers, number of spacecrafts involved, spacecraft mass and safety restrictions — the latter especially for human spaceflight missions. Also available technology as well as autonomy demand due to lack of direct/regular contact or lack of real time communication. Number of maneuvers and spacecraft mass drives the total delta-v demand primarily. All of these types of missions comprise several or even multiple maneuvers which are typical or even essential for planetary exploration.

- Trans target injection
- Mid-course correction
- Gravity-assist/swing-by
- Orbit insertion, aerocapture/aerobraking (at atmospheric bodies only)
- Descent, impact/surface penetration ('litho' braking), landing
- Ascent
- Approach, rendezvous, docking
- Atmospheric entry, re-entry (at atmospheric bodies only)

Table 1.4: Maneuvers in planetary exploration

Analyzing firsts and milestones of nearly five decades of lunar exploration the chronology can be divided into four phases up to now: early exploration, complex missions, new views and return to the Moon.

1.4.1 Phase I: Early Exploration (1958 - 1968)

Accomplishment of reaching the Moon for close flybys or even impacts marks the beginning of the early exploration. Main challenges to meet during this period were: the low reliability of launch vehicles resulting in many launch failures preventing most of the probes even reaching Earth orbit, low reliability of spacecraft- and ground-based navigation resulting in misled trajectories (e.g. flyby instead of impact), low reliability of subsystems resulting in lost spacecraft or uncompleted mission objectives (e.g. lost contact, non-operating payloads). In spite of the failures demonstrating the risks many firsts and other impressive accomplishments were performed during the early phase of lunar exploration. Especially the former Soviet Union was quite successful and leading nation in the space race of the cold war era.

The low reliabilities resulted in failures and therefore in a high ratio of unsuccessful missions (see table 1.5).

	Total	Successful	Unsuccessful	Remarks
by Mission Type				
Flyby	14	8 (57%)	6 (43%)	mostly launch failures
Impact	28	21 (75%)	7 (25%)	mostly orbit decay
Orbiter	19	10 (53%)	9 (47%)	mostly launch failures
Landing	23	7 (30%)	16 (70%)	mostly launch failures/impacts
by Country				
USA	29	19 (66%)	10 (34%)	successful incl. partial failures
USSR	34	15 (44%)	19 (56%)	successful incl. partial failures

Table 1.5: Overview on Phase I Missions (1958 – 1968)[85]

In 1959 the former Soviet Union conducted three important milestones of lunar exploration[85, 94, 30]: first flyby (LUNA 1, January 1959), first impact (LUNA 2, January 1959) and first pictures of the far side of the Moon (LUNA 3, October 1959). Especially the LUNA 3 mission (see figures 1.11 and 1.12) emphasized the value of space-borne remote sensing in taking and transmitting the first pictures of a region never been observable from any place on Earth.

The number of unsuccessful attempts of touching down on the lunar surface and the number of years until a sucessful first soft landing (LUNA 9, January 1966) showed the increase in mission complexity and engineering challenges. Shortly after the first robotic probe on the Moon the LUNA 10 spacecraft (March 1966) was successfully placed in lunar orbit.

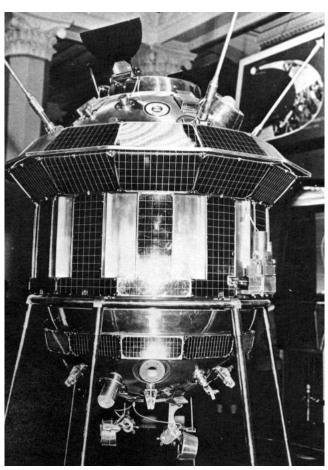

Figure 1.11: LUNA 3 probe[103]

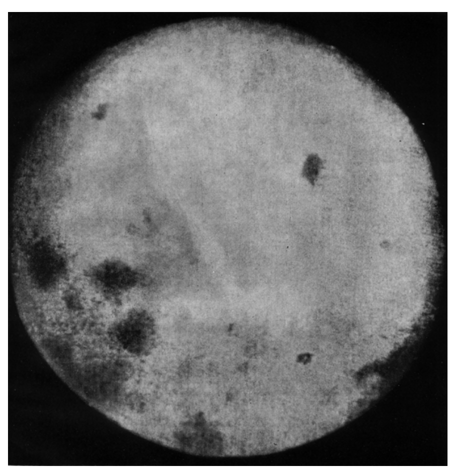

Figure 1.12: LUNA 3 — First view of the lunar far side (Luna 3-phc6, taken on October 7, 1959, image center at 15°N, 120°E)[103]

In preparation of their human lunar exploration program the USA accomplished important milestones in gaining knowledge experience and demonstrating and validating necessary technologies[94, 78]. Starting with the RANGER missions first high resolution images (finally down to meter scale) to investigate potential future landing sites were obtained during the final approach before impact. RANGER 7, 8 and 9 transmitted more than 17,000 images between July 1964 and March 1965. With the succesful SURVEYOR program (SURVEYOR 1-7, May 1966 – Januar 1968) soft landing capabilities were tested and demonstrated and first scientific experiments were performed on the lunar surface. One of the major contributions to scientific data set were done by the LUNAR ORBITER spacecrafts (LUNAR ORBITER 1-5, August 1966 – August 1967) which imaged panchromatic the Moon with resolutions from a few tens of meters down to meter scale (see figure 1.13). The resulting photographic mapping nearly covered the complete lunar surface — a data set which is still in scientific and explorative use until now.

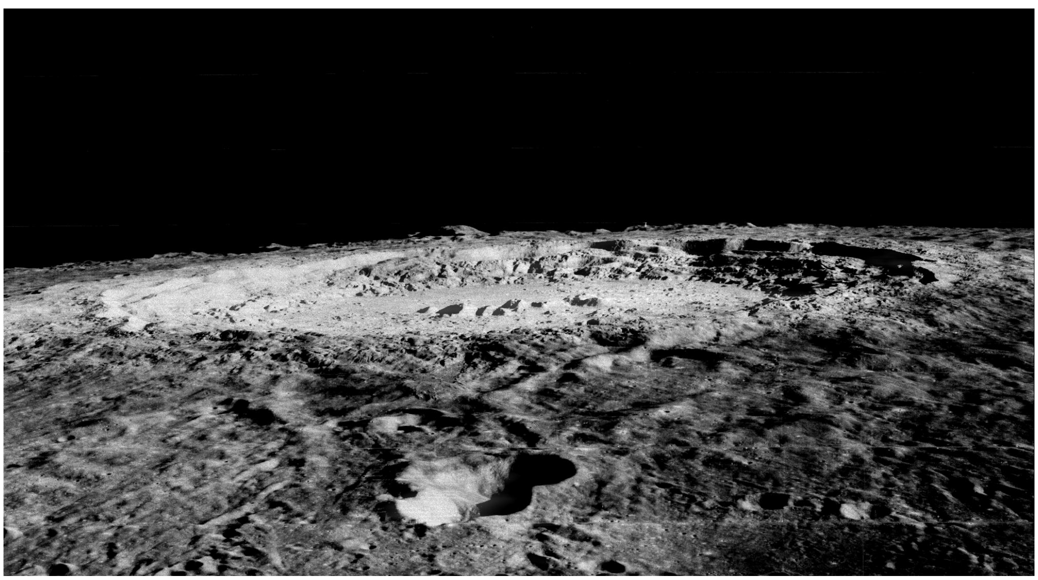

Figure 1.13: LUNAR ORBITER 2 — oblique view of Copernicus Crater with a resolution down to 1 m (PIA00094, lo2_h162/lo2_m162, taken on November 24, 1966, 93 km diameter, located within Mare Imbrium at 10°N, 340°E)[103]

Important first achievements from a mission design, engineering or scientific point of view during the early exploration phase were: reaching Earth escape velocity (LUNA 1), flyby at another celestial body (LUNA 1), impact on another celestial body (LUNA 2), imaging of another celestial body (LUNA 3), live TV network broadcast (RANGER 9), landing on another celestial body (LUNA 9), orbiting another celestial body (LUNA 10), high resolution imaging (LUNAR

ORBITER 2), surface experiments (SURVEYOR 3), surviving lunar night (SURVEYOR 5), powered take-off test (SURVEYOR 6), detection of terrestrial laser beam (SURVEYOR 7). The missions show the increased complexity of space and ground segment as well as the interaction of all elements to meet the objectives successfully. Communication, growing scientific payloads, operations and its planning as well as use of robotics characterize the status at the end of this phase.

1.4.2 Phase II: Complex Missions (1968 - 1976)

The second phase of lunar exploration is mainly characterized by the human exploration of the Moon. The US-American APOLLO program had a huge world-wide visibility in the general public but contributed also significantly to the scientific knowledge about Earth's natural satellite. The USA followed a step-by-step approach in preparation of any mission: from unmanned tests of each component of the APOLLO-SATURN system to crewed flights to low Earth orbit (APOLLO 7, 9) and finally in lunar orbit (APOLLO 8, 10).

Figure 1.14: APOLLO 8 — Earthrise (14-2383, taken on December 22, 1968)[103]

First achievements were the well-known flight around the Moon of APOLLO 8 at Christmas 1968 (see figure 1.14) — originally planned as a high Earth orbit mission but changed to a lunar orbit mission without Lunar Module to stay in the "before this decade is out" schedule and beat the Soviet Union who conducted successful ZOND mission to prepare a human circumlunar flight[65, 94].

The APOLLO missions consisted of a large number of elements within a high complex one-launch mission (see figure 1.15): launch to low Earth orbit, injection into trans-lunar trajectory, trans-lunar trajectory rendezvous to dock the Command and Service Module (CSM) with the Lunar Module (LM), insertion

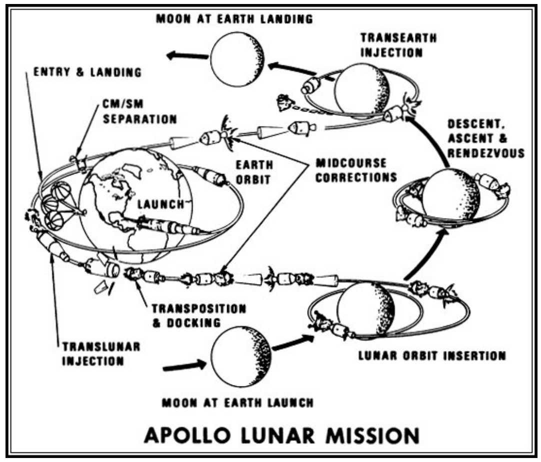

Figure 1.15: APOLLO Mission Design[103]

into lunar orbit, crew transfer, undocking of CSM and LM, descent of LM to lunar surface, soft landing, extra-vehicular activity (EVA) to walk on the Moon, ascent to lunar orbit, re-dock of LM with CSM, undock and de-orbit LM, injection into return trajectory, re-entry and landing[78].

Figure 1.16: APOLLO 11 at the launch pad LC39A (S69-38660, July 1, 1969, CSM107, LM5)[103]

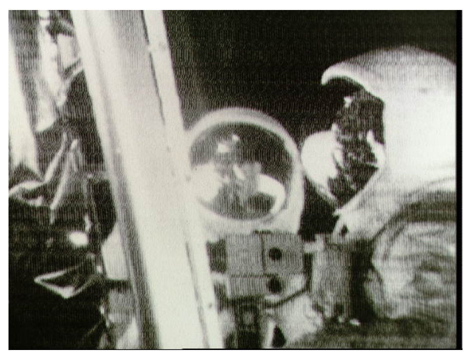

Figure 1.17: APOLLO 11 astronauts on the Moon (S69-29563, July 20, 1969)[103]

Starting with APOLLO 11 six successful crewed lunar landings were performed with 12 astronauts walking on the Moon, collecting nearly 400 kg of lunar samples, conducting around 160 hours EVA on the lunar surface, performing more than 50 experiments (many on multiple missions) including two small satellites ejected in low lunar orbit[65, 64, 85] The first human lunar landing of APOLLO 11 (see figure 1.16 and 1.17) is considered as one of the most important achievements of the 20th century. Especially the later missions (APOLLO 15, 16 and 17[28, 31, 104]) focused on science and contributed significantly to lunar geoscience culminating in the flight of the first (and still only) scientist during APOLLO 17 (see figures 1.18, 1.19, 1.20 and 1.21): Harrison Schmitt, geologist.

Figure 1.18: APOLLO 17 — Taurus-Littrow landing site (134-20435, December 10, 1972)[103]

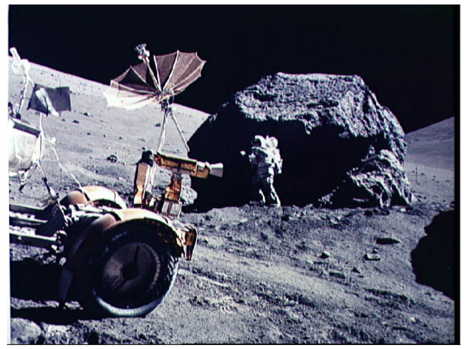

Figure 1.19: APOLLO 17 — Harrison Schmitt at North Massif (146-22294, EVA-3, station 6, December 13, 1972[103]

Figure 1.20: APOLLO 17 — lunar ascent (S72-55421, December 14, 1972)[103]

Figure 1.21: APOLLO 17 — Earth landing (S72-55834, December 19, 1972[103]

The former Soviet Union continued with its robotic exploration of the Moon during this phase — either because of being beaten in the race to the Moon but also because of technical problems with the necessary launch vehicle for a human lunar mission (N1 rocket). The robotic elements were developed as part of the preparation and planned operation of a crewed landing (e.g. Lunokhod rover)[85, 94, 30, 27]. With a heavy robotic lunar lander spacecraft three successful russian sample return missions (LUNA 16, 20 and 24) were acoomplished obtaining in total approx. 300 g of regolith from the surface as well as from drilling (see figures 1.22 and 1.23.

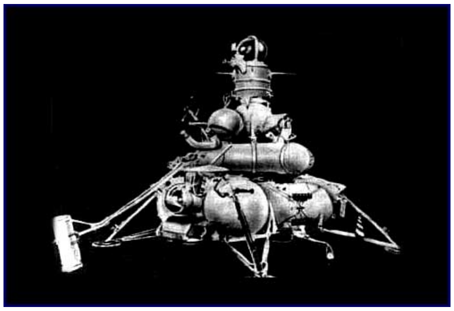

Figure 1.22: LUNA-16 sample return lander[103]

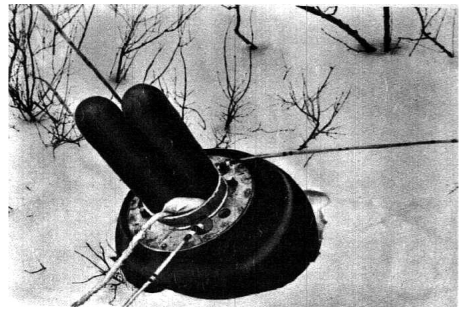

Figure 1.23: LUNA-20 sample return capsule[103]

The two russian LUNOKHOD rover missions (LUNA 17 and 21, see figures 1.24 and 1.25) demonstrated the value of heavy robotic planetary rovers for long duration operations of 10 months and 6 months respectively surviving the equivalent number of lunar nights[94, 85]. The two vehicles were moving for a distance of 10.5 km and 37 km taking nearly 100,000 images in total. With a mass of around 800 kg both rovers were able to carry also heavy scientific payloads (e.g. telescopes).

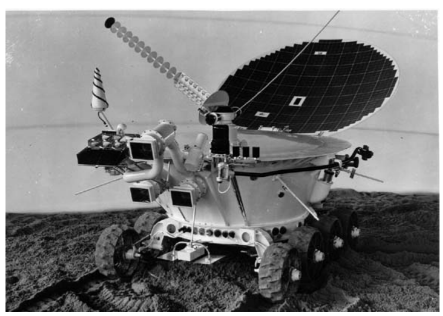

Figure 1.24: LUNOKHOD-2 rover[103]

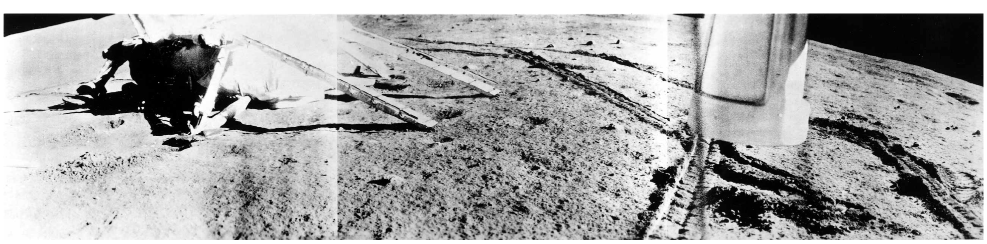

Figure 1.25: LUNOKHOD-1 panorama (3-1-600)[103]

Important first achievements from a mission design, engineering or scientific point of view during the complex missions phase were: circumlunar flight

	Total	Successful	Unsuccessful	Remarks
by Mission Type				
Flyby	6	5 (83%)	1 (17%)	
Impact	15	14 (93%)	1 (7%)	almost all orbit decay
Orbiter	27	21 (78%)	6 (22%)	mostly launch failures
Landing	14	12 (86%)	2 (14%)	
Rover	6	5 (83%)	1 (17%)	one Lunokhod lost at launch
Sample Return	15	9 (60%)	6 (40%)	launch & landing failures
by Country				
USA	10	9 (90%)	1 (10%)	Apollo 13: lucky failure
USSR	27	15 (56%)	12 (44%)	successful incl. partial failures

Table 1.6: Overview on Phase II Missions (1968 – 1976)[85]

(ZOND 5), recovery (ZOND 5), crewed lunar orbiter (APOLLO 8), crewed recovery (Apollo 8), crewed lunar landing (APOLLO 11), robotic sample return (LUNA 16), robotic rover (LUNA 17/LUNOKHOD 1), crewed rover (APOLLO 15), scientist on the Moon (APOLLO 17).

Especially the high number of failures (see table 1.6) of sample retun missions showed the complexity and risks of such a type of robotic mission — an important lesson learned for future Mars sample return missions.

1.4.3 Phase III: New Views (1989 - 2001)

After a long break new data from the Moon were returned by the GALILEO spacecraft on its way to Jupiter during the gravity-assist maneuvers at Earth and performing close flybys at the Moon. The first multispectral images using digital CCD sensor technology raised new interest in our closest neighbour. Japan's first lunar probe (HITEN) was mainly dedicated to technology demonstration for future missions.

The successful CLEMENTINE mission was also not a lunar science probe but a technology validation of the US-American Ballistic Missile Defense Organization (BMDO), a test of sensors for defense applications originally driven by the Strategic Defense Initiative (SDI) of the 1980s. Due to a decision of the program management, lunar scientist were invited to take advantage of the remote sensing data making this small and short mission (two months in lunar orbit) a significant milestone in bringing back the Moon on top of the exploration agenda. With a laser ranging instrument as well as high resolution and UV/visual cameras a valuable new data set was obtained covering the complete lunar surface.

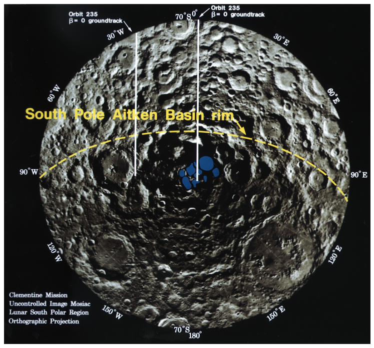

Figure 1.26: CLEMENTINE — Lunar south pole (blue spots indicates possible water in cold traps)[103]

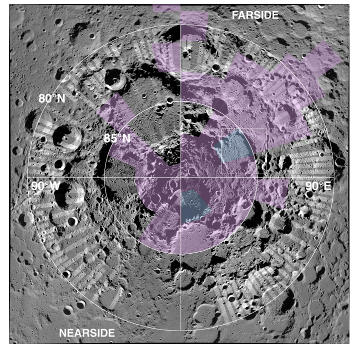

Figure 1.27: Lunar north pole mosaic (by MSSS from CLEMENTINE and LUNAR PROSPECTOR data, color indicates possible locations of ice)[103]

Especially evidence of (frozen) water at the lunar poles in permanent shadowed craters (so called "cold traps") of cometary origin initiated further activities (see figure 1.26). Based on the results of CLEMENTINE the LUNAR PROSPECTOR mission was launched to observe the Moon from a polar orbit to map the surface composition, create a detailed gravity map and search for polar water. The probe was equipped with non-imaging instruments to proof the lunar polar water hypothesis. Results are still under discussion (see figure 1.27) and it seems to be clear that only future remote sensing missions and finally in-situ measurements or better samples from these regions will clearify the status[28, 39].

	Total	Successful	Unsuccessful	Remarks
by Mission Type				
Flyby	8	8	0	
Impact	3	3	0	
Orbiter	3	2 (67%)	1 (33%)	HAGOROMO: contact lost
by Country				
USA	6	6	0	
Japan	2	2	0	Successful incl. partial failures

Table 1.7: Overview on Phase III Missions (1989 – 2001)[85]

Important first achievements from a mission design, engineering or scientific point of view during the new views phase were small due to the fact that proven technologies were used to perform cost-effective exploration and the Moon being not on top of the scientific agenda: multispectral imaging (GALILEO), small lunar mission (CLEMENTINE, LUNAR PROSPECTOR).

1.4.4 Phase IV: Return to the Moon (since 2003)

The first decade of the new millennium is characterized by a broad return to the Moon with an increasing number of dedicated missions. With the SMART-1 (Small Missions for Advanced Research in Technology 1) technology demonstration mission ESA sent its first probe to the Moon validating subsystems (electric propulsion system, broadband and laser communication, remote sensing instruments) for future planetary missions. The small spacecraft was launched as a secondary payload on top of a commercial Ariane 5 launch to GTO. After nearly 3,000 orbits the spacecraft performed an impact experiment (see figure 1.28). Besides the traditional lunar exploration nations new "players" entered the arena: India and China announced, built, launched and operated successfully their first remote sensing lunar orbiters (CHANDRAYAAN-1 and CHANG'E-1). Shortly afterwards Japan started its first scientific mission: SELENE consisting of three spacecrafts (KAGUYA, OKINA and OUNA) with a set of more than a dozen of instruments and two subsatellites for data relay and interferometry measurements. The US-American government announced their return to the Moon in 2004 with robotic missions preparing human missions before 2020. LUNAR RECONNAISSANCE ORBITER with its piggy-back satellite LCROSS was launched in 2009.

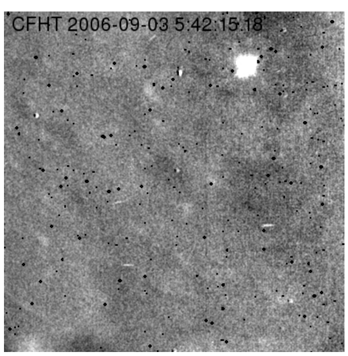

Figure 1.28: SMART-1 impact (September 3, 2006, Lake of Excellence, observed from CFHT, Hawaii)[103]

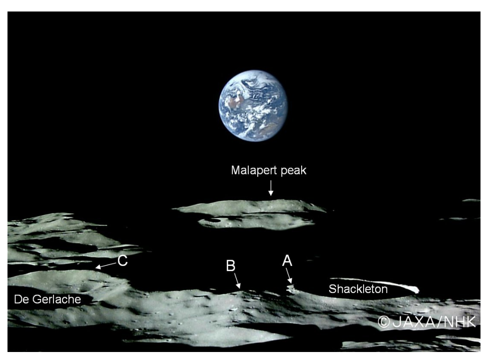

Figure 1.29: SELENE — South pole view with Earth (taken with the HDTV camera of Japan's national broadcast network NHK in cooperation with JAXA)[103]

Besides a long list of scientific objectives the search for water, detection and mapping of lunar resources and preparation of further robotic and later human exploration is on the top of the agenda of all programs — especially India and

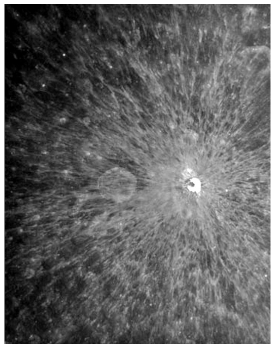

Figure 1.30: CHANG'E-1 far side image of a ray crater (9 km diameter, unnamed, at 260°E, 3.4°N, releases by CNSA)[103]

Figure 1.31: CHANDRAYAAN-1 — view from MIP during its ascent before impact (taken on November 14, 2008, released by ISRO)[103]

China emphasize their interest in lunar resources (e.g. He-3 as a potential but still unproven energy resource) but also their geopolitical position in being space exploring nations.

Important first achievements from a mission design, engineering or scientific point of view during the return to the Moon phase were: electric propulsion systems (SMART-1), multi-spacecraft mission (SELENE), lunar infrastructure (SELENE).

	Total	Successful	Unsuccessful	Remarks
by Mission Type				
Impact	2	2	0	
Orbiter	4	4	0	

Table 1.8: Overview on Phase IV Missions (since 2003)[85]

Many more missions are now on the roadmaps of space agencies and organizations (see appendix A) — the Moon is recognized as the important and necessary next step in exploration towards Mars. Also many countries consider a mission to Earth's natural satellite as a feasible ticket to enter the club of space exploring nations — usually because of (geo-)political and economical reasons. Typical participation (beyond provision of a payload) start with a Moon orbiting spacecraft. During the first half of the next decade (after 2010) we will still see some orbiters but mainly lander or combined lander/rover missions. The next step will be sample return missions until around 2020 before humans may return to the Moon hopefully. First for short APOLLO-type exploration missions to be extended to permanent stay and establishment of lunar bases.

1.5 Legal Issues

The principles of international space law are providing the rights of access to and freedom of scientific exploration as well as utilization of space and celestial bodies (stated in article 1 of the Outer Space Treaty) considering space as a common object prohibiting appropriation in any way[97, 53, 17, 36]. The Outer Space Treaty from 1967 provides these rights not only to signature states but also to any third non-signature state not offering specific advantage to states who signed and ratified the convention (in contrary to the Antarctic Treaty System). The number of ratifications of the Outer Space Treaty exceed 90 — considering the principles of the Outer Space Treaty common international law. Still there is potential conflict between the freedom of use and the non-appropriation (and possible exploitation) of celestial bodies[97, 36].

The Moon Agreement from 1984 is only ratified by a small number of states (currently: 17 signatures, 13 ratifications) being only a few space-faring (or even space exploring) nations. Major states like USA or Russia who landed on the Moon did not sign the Moon Agreement. Therefore its principles are not generally accepted[97, 36]. Especially in the field of exploitation and resource utilization the status has to be considered as controversial.

Open topics from current perspective are: (commercial) exploitation of the Moon, intellectual property rights at a stateless body, regulate limited resources like positions at Earth-Moon libration points, lunar orbits or frequency allocation in cislunar and lunar space for communication or navigation. The Moon Agreement states that an international regime should be established at the time resource exploitation will be possible (article 11, Moon Agreement)[17]. Currently the Outer Space Treaty prohibits any suppressing utilization and gives access to any area on celestial bodies as well as the necessary freedom to explore, take samples, install facilities and so on[97, 17].

From today's perspective there is no immediate necessity to discuss a new legal framework but following the return of humans to the Moon around 2020 issues like resource utilization and exploitation (e.g. He-3 for future energy production) might be raised again. Regarding limited resources (like orbit positions and frequencies) existing conventions might be adjusted. In the field of intellectual property rights a simple adjustment of existing frameworks like the ISS Intergovernmental Agreement seems to be not simple.

Former practise shows that discussions regarding an updated or new legal framework for the Moon will start at the United Nations Committee on the Peaceful Use of Outer Space (UNCOPUOS). Usually working groups are initiated and set up with member states with expertise in the related field (including experts from international bodies like COSPAR, e.g. to represent the scientific community).

Therefore expertise in lunare exploration proven by accomplished missions to the Moon provides an advanced status due to authority. The initial working groups or committees will propose the preliminary conventions or agreements transfering the discussions within the related ommunity into a soft law accepted outside of the related community. Beside of the possibility to contribute to (and maybe influence) the development of a legal framework also direct advantages for members are possible (like the privileged access of member states to Antarctica).

1.6 Open Questions and Modern Aspects

Even if the Moon was the target by the highest number of space missions in the field of planetary exploration (around 75 successful missions) a lot of questions remain unanswered. New instruments and sensor technologies open the potential to gain scientific knowledge being the base for any exploration especially to prepare a permanent human return to the Moon — more than 30 years after the very short APOLLO missions.

Figure 1.32: APOLLO 17 — Third EVA (S73-22871, EVA-3, December 13, 1972, mosaic from two pictures)[103]

The current knowledge about the Moon is considered as sufficient to prepare and design future missions. Open questions are raised in the areas of lunar environment, lunar surface processes and evolution, lunar minerals rocks and soils, lunar chemistry and physical properties and lunar data and mapping[31]. Within these areas specific questions and areas of interest are considered as important topics for future missions. Such topics of interest based on the knowledge of the scientific community[11, 39, 31] are:

- Origin of the Moon
- Origin of the internal structure of the Moon
- Origin of the global asymmetry of the Moon, structure of the lunar crust, mantle and core
- Origin of the differences between Moon and other planets
- Function of a magma ocean, early thermal evolution of the Moon, early volcanism, tectonism
- Relation between lunar surface material (regolith) and its internal structure, lunar paleomagnetism
- Effects of major basin-forming events, nature of the South Pole-Aitkin basin, flux of impacts and its variation
- Surface history and cratering rate, cratering mechanisms, crater and basin ejecta
- Global lunar properties
- Relation of the Moon's formation and evolution to Earth's history including the evolution of life
- Lunar poles
- Lunar atmosphere
- Transient lunar phenomena
- Lunar resources including the use of as a platform for research on, for and from the Moon

An important basis for further research is a detailed atlas of mapping data sets obtained in various parts of the electromagnetic spectrum of the lunar surface as well as the lunar environment and interior. This will be the starting point for selection of prospecting future landing and base sites but also for the utilization and development using lunar resources. Contributing to such data sets by accomplishing missions will offer participation not only in the programmatics of exploration and science but also in the decisions about the future status of the Moon.

Chapter 2

Mission Goals

"Your objective is ..."
M[1]

In this chapter:

- Stuttgart Small Satellite Program
- Mission Goals and Mission Statement
- Definition of Mission Objectives and Consequences
- Technological Objectives
- Scientific Objectives
- Heritage
- Additional Objectives

Every program, mission or spacecraft project has its goals and objectives. Usually goals and objectives are the origin but also the key for designing a space mission sucessfully[100]. In addition to scientific or technical objectives, programmatic issues are very important for the design process of such a project. Within an academic institution and at the responsible governmental and political institutions programmatics influence decisions about support and funding of specific programs and projects. Especially in an international environment like in the

[1]played by Robert Brown in: James Bond 007: The Living Daylights, 1987, in other movies played by Bernard Lee and Dame Judith 'Judi' Dench — based on: Ian Lancaster Fleming's novels and short stories, Jonathan Cape and Company, 1953-66[37]

field of space activities one has to analyze similar missions of comparable organizations as well as large space agencies carefully before deciding about one's own objectives.

2.1 Stuttgart Small Satellite Program

In 2002/03 the 'Stuttgart Small Satellite Program' was initiated at the Institute of Space Systems (IRS) of the Universitaet Stuttgart, Germany[69, 70]. The starting point was the institute's expertise and knowledge[34] in the areas of electric propulsion, aerothermaldynamics, atmospheric entry technologies and mission design and systems analysis as well as the experience of new staff members (H.-P. Roeser, M. von Schoenermark) gained from former successful micro-satellite projects: DLR-TUBSAT (launched in 1999)[74] and BIRD (launched in 2001)[74, 75, 76] — both projects initiated, designed and built at DLR Berlin-Adlershof.

The term 'small satellite' (sometimes also referred as 'miniature satellites' or 'light satellites') covers a wide range of systems divided into different subcategories depending on launch mass[100, 93, 8]. The most common type of small satellites are 'micro satellites' with launch masses of up to 100-150 kg (traditionally up to 100 kg, current piggyback launch opportunities provide up to 150 kg) like the first academic small satellite UoSAT-1 (1981, 52 kg) — from today's perspective the first satellite SPUTNIK 1 (1957, 84 kg) could be considered a micro satellite. Ongoing miniaturization enabled even smaller satellite systems like 'nano satellites' having launch masses of up to 10 kg. Systems with launch masses of up to 1 kg are considered as 'pico satellites' with cubesats being well-known standardized representatives of this category while more recently, the first 'femto satellite' projects with launch masses of 100 g (!) or less were announced. Systems larger than micro satellites are called 'mini satellites' with launch masses of up to 500 kg (sometimes referred to launch masses of up to 1.000 lbs or 453 kg). Commercial small satellites or spacecraft with main propulsions systems (like interplanetary probes) are typical examples of this class of small satellites.

The Stuttgart program consists of the design, development, launch and finally operation of several small satellites within a period of about 10-15 years with the following objectives[71, 49, 50]:

- An attractive academic program should enable students (undergraduate, graduate, PhD) to participate in real projects with hands-on experience. A successful thesis should enhance the students' career opportunities.

- The program not only focuses on the development of small satellites with respect to the engineering challenge but also on the operations using local and remote ground stations — in particular performing remote sensing experiments.

- Involvement in large agency space projects and missions is considered as a very important part of space activities. The development and operations of complete small satellite missions should enable an institution like a university to try a different approach in science, engineering, education and project management. Being fully responsible for a satellite allows a different approach other than the regulations and rules usually given by large space organizations.

- Many small satellites have been developed at different universities since the first launch in 1981. Analyzing past small satellites' capabilities defines the next logical step to be a fleet of spacecrafts with integrated propulsion systems useful for on-orbit inspection of other satellites or to change orbits and trajectories (like for lunar, planetary or deep space missions).

- The long-term goal is to demonstrate that academic institutions like a university — instead of a large space organization — are capable of accomplishing missions to the Moon from the development of the probe to the scientific operations in lunar orbit. A final end-of-life scenario of the mission should be an impact on the lunar surface. This should be the key to participation in future lunar activities as well as future political and programmatical decisions about the status of the Moon within the next decades.

Until the start of the program no complete small satellite mission was conducted in Stuttgart at the university. Therefore a step-by-step approach was chosen towards the long-term goal. Also infrastructure and a network of partners had to be established.

One main focus is incorporating the program intensely in teaching and research at the faculty of aerospace engineering and geodesy in close cooperation with partners from industry and academia. An important task is to offer a practice-oriented education. Participating students should gain valuable experience in working as student assistants or doing research papers, thesis or a PhD. In addition to the gain of knowledge the program provides a high potential of identification leading to motivated and interested students. Also useful soft-skills are developed while working in small interdisciplinary teams. Post-doc scientists, experienced staff members from different departments, lecturers and professors as well as experts from cooperating institutions and companies are embedded in all aspects of the program.

The network of regional partners is one example for academic-industrial cooperation. Companies like EADS Astrium in Friedrichshafen, Lampoldshausen and Ottobrunn, Germany make software and experts' knowledge available as well as new technologies for validation in space. This commitment is accompanied by providing lectures and seminars in Stuttgart but also workshops of several days' duration on site. Also PhD scholarships are funded and personal coaching of doctoral candidates and junior scientists is offered. In addition industrial and research partners provide software and hardware as well as access to their ground facilities during design and development as well as operations and the expertise of their staff on-site and as visiting experts. There are more industrial partners (ASP, Diehl and Eagle Pitcher, FIRST Fraunhofer-Institute, Litef, O.S.T., Rockwell Collins, RWE Space Power, SAFT, Tesat Spacecom, Theta Systems, TimeTech, TZ Raumfahrt, von Hoerner und Sulger, ZARM) who cover various areas of expertise but also academic and research institutions (DLR, Max-Planck-Institutes, universities in Germany and other countries).

There are different motivations for partners to participate in and support the Stuttgart Small Satellite Program:

- The most obvious reason is the recruitment of successful graduate students with hands-on experience gained from one of the small satellite projects. Especially partners who are involved with representatives in teaching are able to screen students directly due to their level and qualitiy of participation in courses, seminars or workshops. Communications between students and lecturers also lead to co-supervised thesis on-site of companies and institutions with excellent opportunities to evaluate students for future employment.

- Academic small satellite programs offers flight opportunities for technology demonstration and space qualification of subsystems and components. Due to lean management and low hierarchy approaches of small teams at university institutions partners have the opportunity to test and validate their product within a shorter time, at lower costs and with less restrictions than at a large space organization.

- Partners without access to space are interested in using data from the satellite or the spacecraft itself in a part-time rent-a-satellite mode without building and funding such a project completely by their own. Also the participation in such a program providing ground segment elements, satellite subsystems, scientific analysis, expertise can be a good starting point or motivation and justification for own future space activities.

- Knowledge and lessons learned from the different approach of academic small satellite projects are useful to transfer to own space projects. Such expertise can reduce costs and speed up projects — important in today's space activities.

- Small satellite development was and is creating new trends and tendencies in the field of space. The possibility to accept higher risks for different reasons offers the chance to demonstrate the value of new and sometimes unproven technologies for the use in space at very low costs.

- Partners are able to send representatives and staff members for further qualification as proven and recognized lecturers at an academic institution. This is a valuable possibility to establish a permanent link into the university environment with direct access to students but also to academic experts and their research.

- Due to the small size of their institution some partners are not able to accomplish such a challenging program or even a project on their own — the project's objectives might only cover partly the partner's interest. Participation in a program or project of high visibility like a lunar mission promise high recognition for partners inside and outside of their community as well as in the general public.

- Applying for funding from additional or new sources is another reason for partnership. Some institutions might not be able to submit proposals due to the lack of a necessary academic counterpart or the shortage of complete expertise in the field. For international partners without a similar project in their country participation can be very attractive to get support and funding.

The Stuttgart Small Satellite Program consists of multiple projects (see figure 2.1 and table 2.1) including four small spacecraft missions. In addition necessary ground segment elements and facilities are extended or established.

The *Flying Laptop* will be the first mission of the Stuttgart Small Satellite Program[23]. The micro satellite of approx. 120 kg launch mass is designed, built and will be operated in cooperation with the Steinbeis Transfer Center for Space (Steinbeis-Transferzentrum Raumfahrt). The *Flying Laptop* is planned to be launched by the indian space agency ISRO (Indian Space Research Organisation) as a piggy-back payload on top of a PSLV (Polar Satellite Launch Vehicle).

The small satellite will provide important opportunities to test subsystems and technologies for later use on and during the *Lunar Mission BW1*. In addition to technology demonstrations (e.g. FPGA on-board computer, Ka band high-speed broadband communication, rent-a-satellite mode) the satellite should perform Earth observation remote sensing experiments (e.g. BRDF measurements using target pointing observation, precipitation measurement demonstration, Ka-band atmospheric attenuation).

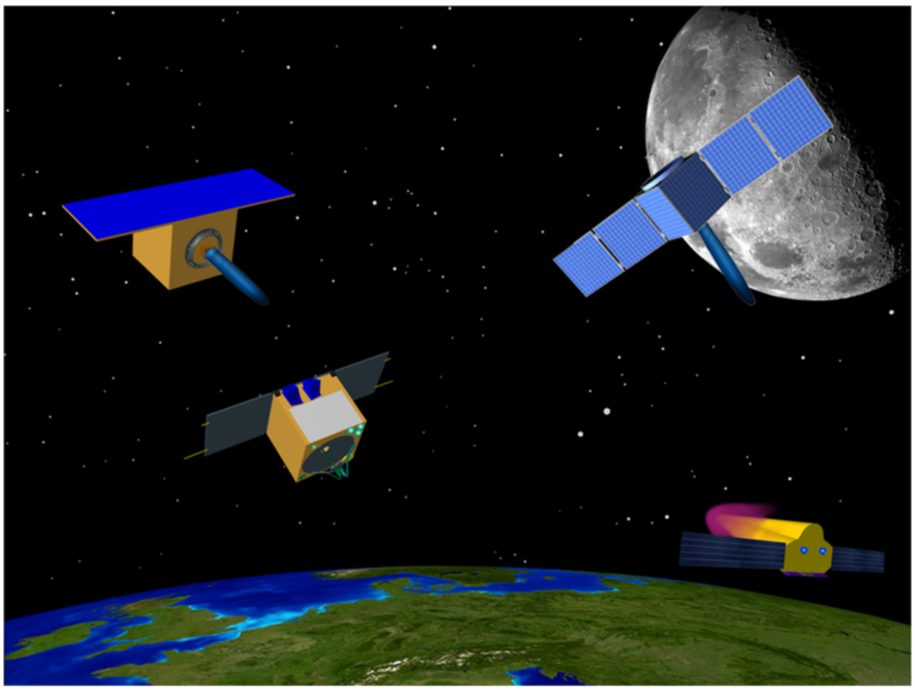

Figure 2.1: Spacecraft of the Stuttgart Small Satellite Program: *Flying Laptop* (bottom-left), *Perseus* (top-left), *CERMIT* (bottom-right), *Lunar Mission BW1* (top-right)

The small satellite *Perseus* of approx. 150 kg launch mass will be based on the *Flying Laptop* satellite bus. Two solar-electric propulsion systems (thermal arcjet, instationary magneto-plasma-dynamical thrusters) will be tested and qualified in space to be used for the *Lunar Mission BW1*. Due to the short electric propulsion test phase of only a few months a research phase operating an astronomical payload is planned. A UV spectrometer in cooperation with the Institute for Astronomy and Astrophysics (IAAT) of the Eberhard-Karls-Universität Tübingen is currently under analysis and design.

The return mission *CERMIT* (*Controlled Earth Reentry Mission to Improve Technology*) is the third small spacecraft project based on the institute's expertise in the field of return technologies[21, 22]. In the past the IRS participated in different unmanned atmospheric entry experiments. The test vehicle of around 200 kg launch mass will provide valuable own flight experience.

Project	Date
Laboratory Model ILSE (*IRS Laboratory Satellite Experiment*) electrical fully functional and telemetry test	2003
Ground Station (UHF, VHF & L band in operation) and Mission Control Center	
S band in operation	2007
Ka band in operation	2009/10
Software and Data Bases	
OLIMPIA (*Outline of Lunar exploration InstruMents and Payloads for Initial Analysis*)	since 2005
GOLEM (*General parametric Outline for Lunar Exploration Missions*)	since 2006
MDVE (*Model-based Development and Verification Environment*, rovided by EADS Astrium, Friedrichshafen), adaptation for small satellites in operation	since 2007
Satellite Integration Laboratory	2007
UAV carrying remote sensing instruments	2007
Flying Laptop	2012
Earth observation, technology demonstration, rent-a-satellite	
Perseus	2013+
Electric propulsion test, UV astronomy	
CERMIT	2014+
Atmospheric entry, autonomous GNC	
Lunar Mission BW1	2014+
Lunar remote sensing orbiter, technology demonstration	

Table 2.1: Projects of the Stuttgart Small Satellite Program

The project will be a platform for theoretical and practical research in the fields of mission and systems analysis, aerothermaldynamics, plasma research and development of diagnostics and sensor systems. Possible launch options are a sub-orbital launch with an upper stage for acceleration before re-entry or a piggy-back launch to low Earth orbit with a (chemical) de-orbit motor.

The *Lunar Mission BW1* is the fourth project of the Stuttgart Small Satellite Program to be launched at the beginning of the next decade — the first academic small satellite on an exploration mission to another celestial body, the Moon[47].

2.2 Mission Goals and Mission Statement

Based on the objectives and intention of the Stuttgart Small Satellite Program and the vision behind the idea of a lunar small satellite mission the following mission statement for the Lunar Mission BW1 was developed.

Lunar Mission BW1 Mission Statement

> To contribute significantly and visible to space exploration by its own an academic institution like the Universität Stuttgart should take the next logical step in academic small satellite development in performing a complete mission beyond Earth orbit. Because there is a new and increasing interest in our closest neighbour in space — the Moon — the Institute of Space Systems will design, build and operate a small low-cost lunar exploration probe.
>
> This mission will demonstrate an academic institution's ability as well as the capabilities and value of a small exploration satellite to validate and verify technologies, to perform experiments in cis-lunar and lunar space and to contribute to potential future infrastructure.
>
> The project will offer an attractive education program offering real hands-on training to students incorporating partners from industry and academia. The spacecraft development will make use of the institute's and its partner's knowledge and expertise in various fields and the experience gained from the previous missions of the Stuttgart Small Satellite Program.

The mission statement defines the major goals of the mission and initiates the iterative analysis and design process[100, 86, 36].

2.3 Definition of Mission Objectives and Consequences

The objectives are considered as the qualitative expression of a project based on the mission statement leading to requirements and constraints as quantitative expressions[100]. The Lunar Mission BW1 mission statement is turned into a set of primary and secondary objectives.

Lunar Mission BW1 Mission Objectives

Primary Objective:

To demonstrate the ability of an academic institution to perform a complete space exploration mission by sending a low-cost small satellite to the Moon.

Secondary Objectives:

To offer an attractive hands-on education program with participation of students, academic and industrial partners and users.

To demonstrate, validate and verify new technologies and subsystems for small satellite development and space exploration.

To perform remote sensing experiments and in-situ measurements in cis-lunar space as well as in lunar orbit.

To conduct an education and public outreach program to inspire the public and current and potential students about space exploration

To prove the capabilities of small satellites as a valuable tool in future space exploration for research, technology development and infrastructure.

Today small satellites are well-known as a cost-effective way for universities or even a single institute to perform research and engineering experiments in space — up to now in Earth orbit only[76, 73]. Since the very beginning of the space age universities and research institutes participated in lunar or even planetary exploration, processing and analyzing data, designing and providing instruments or performing further research. Usually academic institutions did not design, build and operate their own lunar probe.

The increase in cost of a lunar orbit mission compared to an Earth orbit mission of large space organizations leads to the assumption that a small lunar orbit mission will be much more expensive than a small Earth orbit mission. Reducing their costs dramatically by taking advantage of various conditions of an academic environment is important to make such a project feasible. Successful cost reduction within reasonable risks is a key to fulfilling the primary objective and accomplishing a task completed by large space organizations in the past. Total budget but also cash flow is a limitation of an academic project.

Incorporating student education in all levels of the project is common for academic institutions and part of any of their activities — teaching or research. Students interest and motivation and their fresh ideas are definitely to be considered a potential for such a project.

Quality assurance laid down on your own is a necessary element for a successful program but can be a challenge when working with inexperienced or untrained temporary team members like students or interns. Also the management of temporary knowledge is important for project success. Like new project and knowledge management approaches different risk management handling and quality assurance procedures and rules are key features of an academic program to provide hands-on experience with flight hardware as well as to enable a low cost approach compared to large agency missions. Within agency and space industry only certified engineers are permitted to work with real mission hardware; this prohibits students from gaining such valuable education and experience.

Selection of proven subsystems reduces the risks significantly. Proven subsystems do not provide possibilities for technology demonstration, validation and verification except of the fact that partners might be interested in demonstration experiments of existing hardware under the special environmental conditions beyond Earth orbit.

The potential research tasks have to be chosen carefully because of their possible fulfilment with respect to the limited on-board and ground capabilities and resources of an academic small satellite mission. Past and planned experiments, existing and expected results, gained knowledge in planetary science and open scientific questions as well as available technology are the starting points of the payload selection process.

Commitment for support from the political administration is another important element to successfully achieve the program's as well as the mission's objectives. The program itself and the lunar exploration mission is a possibility to gain political support because of the visibility of the project but also an opportunity to support further activities.

In addition to the visibility and the educational effect as well as the support of local industry (e.g. in research) especially the lunar exploration mission provides political opportunities due to the legal status of Moon (as described before) and possible resulting participation in future decision-making processes.

A mission like the first academic lunar orbiter offers a unique opportunity for outreach activities inspiring the general public but also the engineering and scientific community. The visibility of a successful project and useful results also leads to recognition of the value of small satellites in any field of future space exploratiuon activities.

2.4 Technological Objectives

The main focus of technological tasks of the *Lunar Mission BW1* is the demonstration, validation and verification of in-house subsystem development of the Institute of Space Systems. First priority is given to the electric propulsion systems which have a long tradition in research and engineering in Stuttgart. Also analysis and design of interplanetary missions and remote sensing technologies are a field of interest. Due to limited space segment (e.g. on-board memory, power storage, data transmission bandwith) and ground segment (available contact times, available team members) resource automation and autonomy during all mission phases are important topics.

Potential technology demonstration topics beyond low Earth orbit for the *Lunar Mission BW1* can be: solar-electric propulsion systems for complex attitude control and orbit transfer maneuvers using autonomous guidance and navigation; visible/near-infrared and thermal infrared imaging combined with target pointing observation; radio frequency and microwave technology for broadband communication, relay functions and radar sounding; advanced computer architectures for enhanced on-board processing capabilities; advanced sandwich structures; advanced miniaturized dust detectors; GPS usability beyond GEO; evaluation of degradation effects on satellite subsystems; controlled impact onto the lunar surface.

2.5 Scientific Objectives

Because of limited space and ground segment resources a small lunar probe is able to perform in-situ measurement and remote sensing experiments if operational aspects such as maintenance, communication and battery charging are taken into account. Different research topics were identified during the mission design process in cooperation with other academic and research institutes. Due to the listed limitations not all experiments and demonstrations can be performed during one single mission. Experiments which are flown on prior missions of the Stuttgart Small Satellite Program as well as in-house developments and research are prioritized.

Possible research targets of the *Lunar Mission BW1* in cislunar space for research of Earth environment and the Earth-Moon-System can be: space environment (gravitational and magnetic field, radiation environment); Earth influences and Earth-Moon interactions; observation of near Earth objects; the Kordylewski (dust) clouds at the Earth-Moon libration points L4 and L5, detection of dust and debris.

Possible research targets in lunar orbit can be: re-use of the *Flying Laptop* imaging system for high resolution multi-spectral imaging of selected areas of the lunar surface (e.g. for mineralogical observation); search for polar water and future landing site selection as well as remnant localisation of past missions; polarization and reflectance measurement and illumination observation of the lunar surface; surface roughness measurements; lunar environment (gravitational and magnetic field, radiation environment); dust detection; monitoring of transient lunar phenomena (TLPs) coordinated with ground-based observers; and detection of lunar impact flashes.

2.6 Heritage

The step-by-step approach of the Stuttgart Small Satellite Program is a key factor in reducing the risk of using a high number of non-qualified or new subsystems. Such an approach reduces also the complexity of each missions in design, development and operations by reducing their objectives. The necessary tests and operational experiences to be gained with the space and the ground segement are added and distributed to more than one small satellite project to be accomplished prior to the *Lunar Mission BW1* (see table 2.2).

Flying Laptop	**Perseus**	**CERMIT**
Integration	Complex mission operations	Real-time mission operations
Ground segment facilities	Solar-electric propulsion systems: thermal arcjet, magneto-plasma-dynamical thrusters	Complex attitude and orbit control
Basic Mission operations	Attitude and orbit control	Autonomous guidance navigation and control (GNC)
FPGA on-board computer		
S and Ka band communication		
VIS/NIR imaging systems		
Ka band radio science		
GaAs solar cells		
Li-Ion battery		

Table 2.2: Flight Heritage and Mission Experience in Preparation for the *Lunar Mission BW1*

The flight heritage and mission experience from these prior missions will enable and increase the probability of a successful *Lunar Mission BW1*.

2.7 Additional Objectives

The academic environment and its conditions results in the opportunity and demand to test and evaluate new approaches in project and team management. Especially due to limitations and special conditions of funding of such missions established project cycles and phase models have to be reconsidered with respect to their value and usage at a university institution. Especially the situation of dealing with temporary team and staff members is one of the issues.

Knowledge transfer, management and documentation is always of interest at academic projects. Apart of classical ways of knowledge transfer and storage like printed theses, upcoming knowledge management concepts and software-based tools offer new ways and solutions for such demands.

The successful achievement of a small satellite mission to the Moon is able to create and prove expertise in the field of lunar exploration. Such expertise could be an 'admission ticket' to participate in the preparation or eventually the realization of future decision-making processes regarding the legal status of the Moon and its exploration.

Chapter 3

Mission Concept

"That's a ridiculous concept. No one can do that."
Dagney[1]

In this chapter:

- Spacecraft
- Science
- Education and Public Outreach

Turning the programmatics towards a mission architecture many options have to be considered to find a concept which is able to meet the technical and non-technical objectives. Early in the project of a beyond Low Earth Orbit small (LEO) satellite mission many options were discussed[2]: lunar flyby or orbit mission, planetary flyby mission at Mars or Venus, flyby or rendezvous mission to a Near-Earth Object (NEO), deep space mission into a heliocentric orbit or to a Sun-Earth libration point. Main drivers investigating the feasibility of all the missions were the necessary delta-v demand, mission complexity, demand in communication bandwidth and time, subsystem lifetime issues, possible scientific and technology tasks, and visibility. Assuming a limit in launch mass and envelope as well as a piggyback or co-passenger launch the satellite must be designed to fly completely by itself independently from the initial delivery orbit.

Planetary or Near Earth Object flyby missions were taken out of further studies because of the communication demands. Even with a dedicated small ground

[1]played by Gabrielle Anwar in: Things to Do in Denver When You're Dead, 1995[37]

[2]Approx. 12 man-months were spent to study and analyze the differen mission options in 2003/04 at the beginning of the mission design

station the effective bandwidth, even using high frequencies in the GHz range, would be poor (a few bits per second or less). Also to satisfy the demand in precise navigation during critical mission phases (mid-course correction maneuvers, flyby) is quite difficult without additional ground support — and therefore extends costs.

In general, flyby missions have a very short science operations phase during the flyby. Combined with the risk of instrument failures during their critical part of the mission such a concept seems to be less favorable. Subsystem failures due to limited lifetimes of commercial off-the-shelf (COTS) hardware has to be taken into account especially if the mission will be performed employing electric propulsion systems. Flyby missions and deep space missions also have less visibility because of the short phase at the target or the lack of an impressive (planetary) target. Even if the cruise phase could be used intensively for education, research and technology demonstration a high and constant visibility is crucial for seeking support.

Taking into account that the complexity and delta-v demand of an orbiter mission is much higher than flyby mission the revenue in science return and visibility seems to be much more promising. Especially due to the limits in communication, a mission to the Moon was determined to be the most favorable. At the beginning of this project, the status of lunar exploration knowledge and interest was promising regarding scientific tasks, technology development and visibility.

3.1 Spacecraft

Starting from mission objectives the usual process of mission design is to characterize and evaluate the mission by defining options leading to one concept and finally to the following requirements.

- A mini satellite is necessary with a launch mass of around 200 kg and a spacecraft size of 1 m cubed: experience of the institute's staff from former missions (DLR-TUBSAT, BIRD), trends in the small satellite community and analysis of former lunar missions (SMART-1, LUNAR PROSPECTOR, CLEMENTINE, see table A.11) all suggest this selected spacecraft mass and size in order to acquire a piggyback or co-passenger launch opportunity (external).

- The spacecraft must be independent from the initial orbit after separation from the launch vehicle. and have a propulsion system for cruise, lunar orbit insertion and orbit station keeping (external).

- Taking into account the long-term development of electric propulsion systems at the Institute of Space Systems, two different thrusters should be used (thermal arcjet and magneto-plasma-dynamical thrusters) and demonstrated as main engines (internal).

- The communication capability should be set up for the Stuttgart Small Satellite Program, with K_a band communication for data transfer used in combination with S band communication and both available at the ground station (internal).

- As much as possible, proven systems from former missions should be used or adapted (e.g. FPGA on-board computer, ADCS/AOCS, PSS using Lithium-Ion batteries and high efficient Gallium-Arsenide solar cells, communication system, structures and materials, GPS) for use in the lunar satellite (internal).

- Payload instruments from former missions (panoramic camera, multi-channel imaging system) should be re-used if determined to be valuable to the science (internal).

- A payload mass of approx 15-20% or more of the dry mass should be the target to provide payload flight opportunities to external regional, national and foreign partners (internal).

- The satellite should be able to operate in a high inclined low lunar orbit for at least six months followed by impact on the lunar surface (internal).

Table 3.1: Internal project limits and defaults

Once the requirements are in place, mission and its elements must be designed and developed to meet these requirements (technical as well as non-technical like costs constraints)[100].

Within an academic small satellite project many limits and defaults are determined at the beginning of the project (see table 3.1) and must be turned into very strong requirements. Some are related to the fact that the mission should be accomplished as an academic small satellite project (external) but others are intrinsic (internal) to the specific institution (in this case, the Institute of Space Systems).

3.1.1 Satellite Bus

Resulting from the parameters given above, the spacecraft at this stage is a 1 m cube satellite of around 200 kg or more launch mass using solar-electric propulsion and providing approximately 20 kg for payload.

The bus necessary for such a satellite consists of the following subsystems: propulsion system, power supply system, structures and mechanisms, thermal control, communication, command and data handling, attitude determination and control.

3.1.2 Propulsion System

Because of the demands during different mission phases (as described in chapter 4) the *LUNAR MISSION BW1* is planned to be equipped with two electric propulsion systems: TALOS (Thermal Arcjet thruster for Lunar Orbiting Satellite, see figure 3.1) and SIMP-LEX (Stuttgart Impulsively Magnetoplasmadynamic Propulsion system for Lunar EXploration, see figure 3.2) within a cluster consisting of four instationary pulsed plasma thrusters. Both engines are in-house products of the Institute of Space Systems and have been developed and qualified completely at the institute in cooperation with industrial partners[3]. Using TALOS and SIMP-LEX as main engines is different from former operational concepts of such electric propulsion systems (e.g. for attitude control).

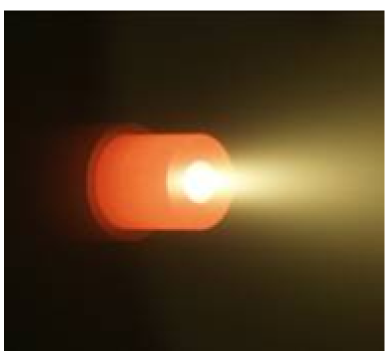

Figure 3.1: The TALOS thruster in operation[5, 48]

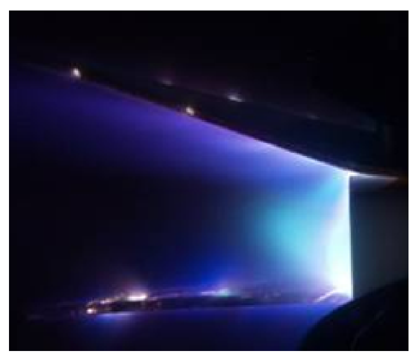

Figure 3.2: The SIMP-LEX thruster in operation[60, 48]

Based on former developments the thermal arcjet thruster TALOS (see figure 3.3) is a result of an optimization process to the requirements of the mission and provides a thrust of approx. 100 mN and a specific impulse of nearly 430 s with a mass flow between 20 and 30 mg/s while consuming a maximum electrical input power of 1 kW. Current investigations are focusing on lifetime tests using an operating cycle as foreseen during the mission of 1 hour operation and 1 hour

[3]Development and adaptation for the *LUNAR MISSION BW1* was done within two PhD theses[5, 60] based on past research incorporating diploma students and student assistants. A follow-Up PhD thesis has already been started which will continue and complete the propulsion systems and move toward final flight hardware

charging of the batteries due to constraints of the power supply system. Multi-hour test results enabling identification of lifetime limiting factors are required since the thermal arcjet is expected to operate for up to 1,000 hours. TALOS is an ammonia based propulsion system consisting of propellant storage, power supply, control unit and and propellant feed system. The feed system includes the following elements: a gas generator to vaporize and electrically heat the ammonia, a pressure reducer to compensate for variable input pressure, and filters to remove particles from the propellant[5].

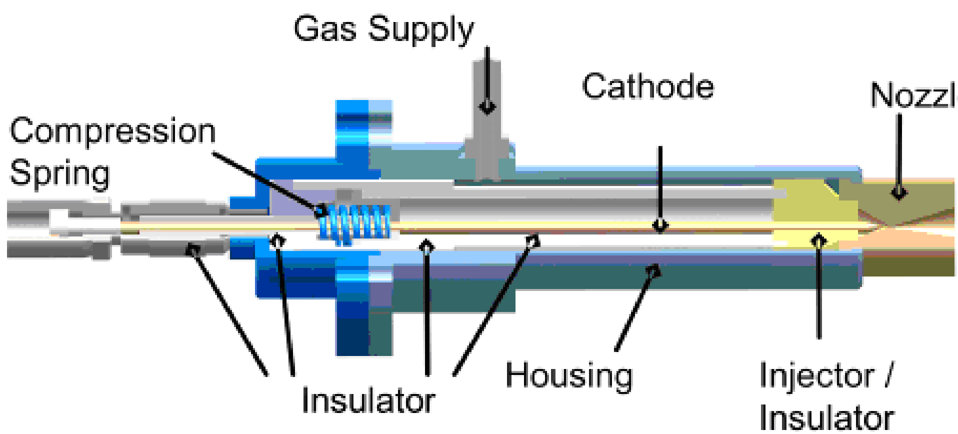

Figure 3.3: Sectional drawing of TALOS[5, 48]

SIMP-LEX is a low mass, robust and easy-to-integrated system consisting of a cluster of four pulsed MPD thrusters using solid propellant (PTFE, Polytetrafluorethylene, a.k.a. Teflon). A pulsed plasma thruster consists of four main parts in general: a capacitor bank, two electrodes, the propellant and a spark plug (see figure 3.4). After the capacitors are charged, the spark plug is triggered forming a short-time arc discharge. This discharge ionizes the solid propellant along its surface closing the main circuit through a plasma sheet formed by the ablated and ionized propellant. The circuit yields a current loop resulting in an induced magnetic field. The magnetic field component perpendicular to the plasma current leads to a Lorentz force and accelerates the plasma creating an impulse. The MPD thrusters provides an average thrust of approx. 1.5 mN each with a specific impulse of 1950 s pulsed at 0.5 Hz and consuming around 120 W per engine. Using a pulsed plasma thruster system as the main engine during the cruise phase demands lifetime tests and investigations especially of the solid propellant feed system (see figure 3.5) since an expected operational lifetime of up to 20,000 hours is required. For this case, the system is designed to feed the propellant from the side using a helical shape with up to two loops on each side for the *LUNAR MISSION BW1*[60].

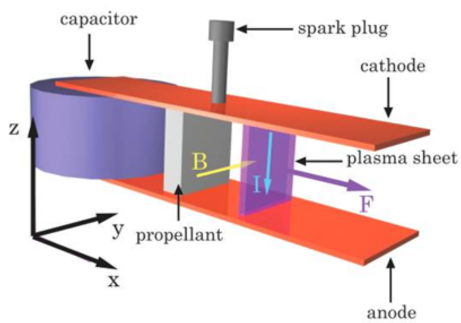

Figure 3.4: Working Principle of SIMP-LEX[60, 48]

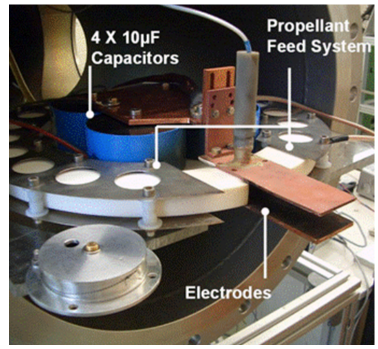

Figure 3.5: Test of SIMP-LEX propellant feed system[60, 48]

Due to the performance of the different systems, TALOS is planned to be used during the ascent, capture and the impact phase while SIMP-LEX will mainly operate during the cruise and descent phase. A combination of both engines may be necessary for orbital control during the science phase depending on the station keeping strategy[106]. TALOS can provide the thrust necessary to raise the orbit above the Van-Allen belt as quickly as possible or during critical mission phases when a high thrust level is demanded in a short time frame taking into account an increased propellant consumption compared to SIMP-LEX.

Both propulsion systems will be tested and qualified during the *PERSEUS* mission. *PERSEUS* is designed to perform multiple tests from a small amount of propellant (TALOS: 3 or more kg, SIMP-LEX: less than 1 kg) to raise a planned 700 km Earth orbit up to 950 km[105]. In addition to operational experience and real-time test data, possible contamination of surfaces (especially of solar cells or optical payloads) will be under investigation.

3.1.3 Power Supply System

The electric propulsion systems (especially the thermal arcjet TALOS) are the primary drivers of the design of the power supply system. To keep overall complexity low, the use of moving mechanisms for turning the solar arrays towards the sun is prohibited. Therefore, early studies were performed to evaluate different battery and solar panel options. A simulation environment (see figure 3.6) was established to investigate and analyze these options[16, 14][4].

The power supply system has to provide 1 kW of power to the propulsion system during all critical mission phases (also at the end of the mission) plus

[4]The simulation environment consists of a software tool to evaluate different power supply options during propelled cruise phase mission operations and electrical ground support hardware (e.g. computer controlled solar array simulation power supplies) to simulate operational cycles connected to potential engineering hardware (hardware-in-the-loop)

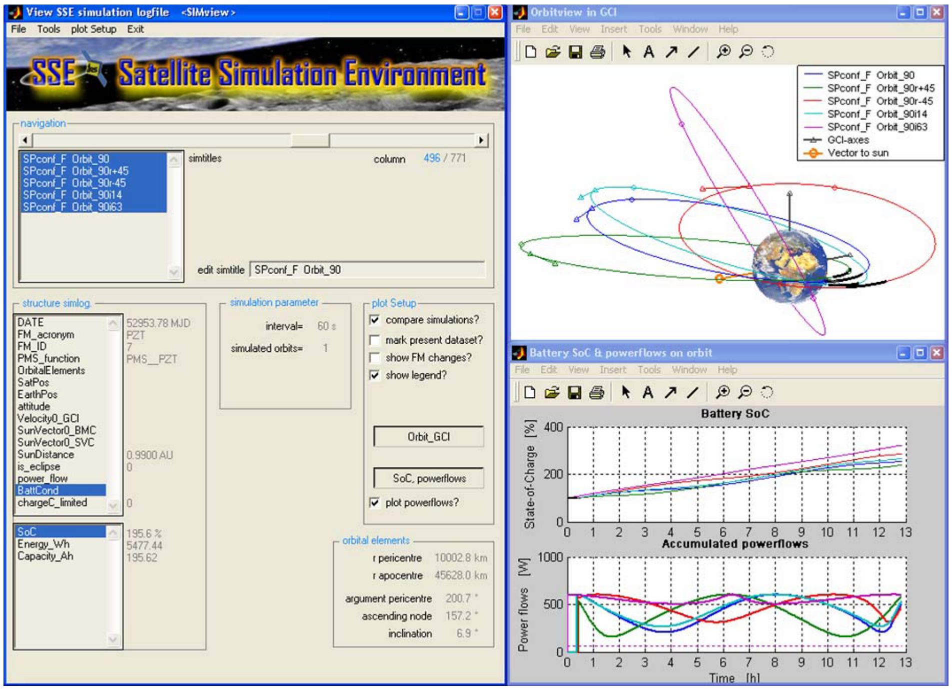

Figure 3.6: Simulation environment for PSS analysis[14]

any additional power necessary for on-board systems during propelled phases. Possible degradation effects during the flight through the Van-Allen belt as well as at the end of scheduled lifetime must also be taken into account.

Data from ESA's SMART-1 mission were analyzed to evaluate the influence of the Van-Allen belt on solar cells and estimated of up to 0.1% loss in available solar-electric power per day[14]. The scenario examined for the electric propulsion systems assumed multiple operations of 1 hour each for TALOS and nearly continous operation of SIMP-LEX outside of the eclipse.

Analyzing different battery technologies and their characteristics resulted in the selection of Lithium-Ion batteries due to good performance to mass ratio (reducing the mass for around 70%). Lithium-Ion batteries having a total capacity of 100 Ah (2800 Wh) combined with a solar panel area of approx. 6 m^2 (providing redundancy above the minimum of 4 m^2) using Gallium-Arsenide solar cells with high efficiency of 28% EOL are able to meet the power demand during all mission phases[14].

The simulation environment was extended with computer controlled power supply hardware in order to simulate charge and operation cycles with hardware-in-the-loop (e.g. dummy batteries) of the spacecraft prototype or for qualification and testing of flight hardware[16, 14]. Space qualification beyond low Earth orbit (and beyond the Van-Allen belt) is a promising field for cooperation with industrial partners who can provide hardware, expertise and integration support. Like the propulsion systems, the battery technology will be tested and space qualified during the *PERSEUS* mission and eventually the *FLYING LAPTOP* mission[105]. The calculations show the power available after reaching final operational lunar orbit should provide enough electrical energy for payloads without strong limitations (up to 1 kW).

3.1.4 Structures and Mechanisms

Initial investigations were performed in preparation for a full scale mock-up and to check the feasibility of the accomodation of all subsystems[66]. Early trade-off evaluations led to structural options to accommodate and position subsystems and components[25]. Further studies refined the selected structural options in preparation for the spacecraft prototype (see figures 3.7 and 3.8)[52][5].

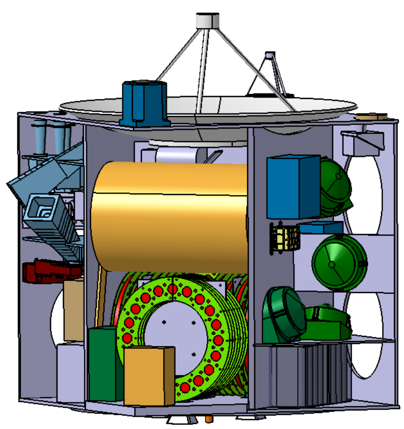

Figure 3.7: Structure option — View on propulsion module[52]

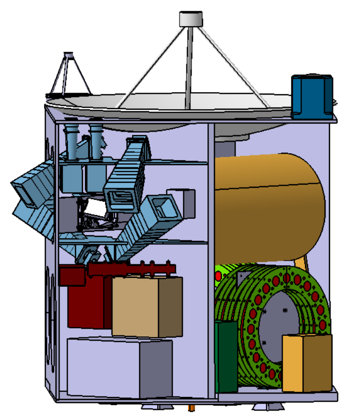

Figure 3.8: Structure option — View on star trackers and other subsystems[52]

Main drivers for the structure analysis are the structural loads during launch (based on information provided by the launch provider[38]), the mass of the overall structure and the number of necessary structures needed to accommodate all subsystems and components without reducing the handling and accessibility. FEM analysis was used to investigate structures with respect to launch loads (see figures 3.9 and 3.10).

[5]The structures and mechanisms work packages incorporated student theses of more than 2 man-years supervised by the responsible engineer. This position's responsibility consists also of the synchronization of all satellite's structures and mechanisms of the Stuttgart Small Satellite Program

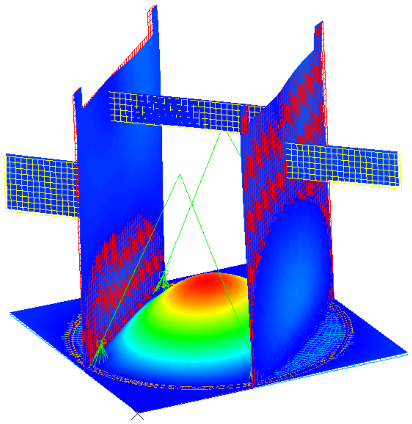

Figure 3.9: FEM analysis, longitudinal eigenfrequency[52]

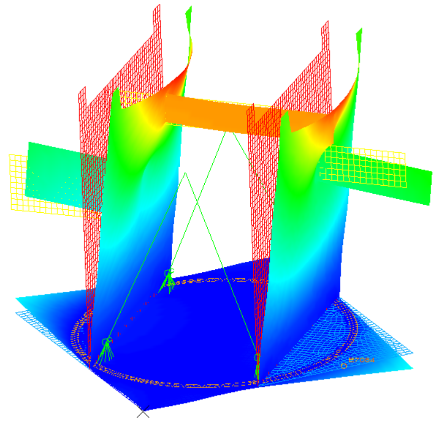

Figure 3.10: FEM analysis, lateral eigenfrequency[52]

Analysis of different materials were performed to reduce the structural mass. Initial options using carbon fibre fold core sandwich material was replaced by honeycomb sandwich structures due to less complex production and usage as well as availability[26, 52]. Further studies must still be performed in order to determine the final structural design of the satellite bus incorporating all mechanisms and solar panel structure.

3.1.5 Thermal Control System

A preliminary thermal analysis was performed to determine the required area for radiators resulting in the stipulation that at least two full sides of the spacecraft must be used for heat dissipation[25]. Further analysis showed that both the electric propulsion systems and the traveling wave tube of the K_a band communication system as well as the reaction wheels are main drivers for the thermal control system[55]. Further investigations have to be performed to determine necessary changes in accommodation and position of radiators and subsystems.

3.1.6 Attitude Determination and Control

The attitude determination and control system (ADCS) for 3-axis stabilization will be adapted from systems adapted for the *FLYING LAPTOP* and *PERSEUS*[105][6]. Due to the lack of a lunar magnetic field magnetometers and magnetic torquers will not be used. The value of GPS is also limited to early mission phases. The ADCS of the *LUNAR MISSION BW1* will consist of:

[6]The *LUNAR MISSION BW1* benefits from the related work package results of the design of *FLYING LAPTOP* and *PERSEUS* — design and development were covered by three PhD theses.

Four star tracking cameras (for redundancy)
Four fibre-optical gyros
Four reaction wheels
One GPS antenna and associated electronics
Earth-Sun or Moon-Sun sensors respectively

The final requirements for the precision of the ADSC will be established when the payload instruments are selected and their demands are finalized. Analysis of the reaction wheel operations show that the momentum storage capacity will be low during the propelled phases and dumping procedures will need to be performed every few days (i.e. between 2 and 10 days during ascent and cruise phase)[1]. Effective dumping strategies using the pulsed MPD thrusters and optimization of their position has yet to be investigated.

3.1.7 Command and Data Handling

The on-board computer (OBC) will be based on the FPGA on-board computer of the *FLYING LAPTOP* mission[15, 23][7]. The FPGA architecture provides both high performance and parallel processing due to the implementation of software directly into hardware.

The OBC with a cluster of FPGA-based boards is completely re-programmable and rebootable within a few milliseconds. Tolerance against radiation induced failure events is done by a decision making instance running on an additional computer. The FPGA offers OBC software adjusted to each mission phase providing high reliability on-board processing capabilities — e.g. for pre-processing of payload data.

Requirements for the amount of on-board memory necessary were determined through analysis of the memory demands of the strawmen payload. Results were on the order of 20 GBytes due to limitations in bandwidth and contact periods and demands in data storage between any two transmissions[106, 48].

3.1.8 Communication

Communication to and from the spacecraft once beyond low Earth orbit is an essential element to accomplish the mission successfully. To determine payload capability not only by available volume, mass and power have to be provided but

[7]The FPGA development is part of a collaboration lead by the Steinbeis Technology Tranfer Center for Space

also the available bandwidth and maximum data rate to transmit science data to the ground station[8].

During the early phase of the mission, an analysis to determine the data rates and bandwidth for different communications systems was performed[88]. Three options were evaluated: UHF using a dipole antenna with 5 W transmission power at the satellite (20 W from the ground), S band using a dipole (low gain) and patch (high gain) antenna with 20 W transmission power at the satellite (20 W from the ground using a 2.5 m parabolic dish) and K_a band using a 1 m parabolic antenna with less than 60 W transmission power at the satellite (5 W from the ground using a 3 m parabolic dish).

The results shown (see figure 3.11) represent the potential of K_a band communication to transfer high amounts of scientific payload data for varying atmospheric conditions and elevation angles. K_a band transmission is highly dependent on the amount of water and water vapor which can influence the data rate in the range from fifty to hundred kilobits per second up to some Megabits per second. S band transmission is not able to cover the full amount of scientific data transfer and will be mainly used for telemetry and telecommand. The K_a band data rate variations suggest the need for additional ground stations, especially in dry or high altitude regions of the Earth[88, 106].

Simulations show that compared to a low Earth orbit satellite having only several tens of minutes access time, a Moon orbiting satellite may be seen from one ground station many hours per day[88, 106]. The mean access time of the *LUNAR MISSION BW1* from Stuttgart during its six months phase in low lunar orbit will be 7 hours per day with approx. 1.5 hours per contact on average. With one ground station nearly 1,000 contacts are possible during the science operations. From an operational point of view, the access time will be reduced for periods of remote sensing, charging and maintenance. Establishing of a network of partner ground stations would increase the total access time and provide redundancy as well as backup communication with the spacecraft.

3.1.9 Additional Spacecraft

Studies in cooperation with one industrial partner (von Hoerner & Sulger, Schwetzingen) investigated the possibility of carrying a nano rover (within a lander) as a piggy-back payload to the Moon and releasing the vehicle during the controlled impact[9]. Different options for the Nanokhod rover (see figure 3.12) were considered with vehicle mass of 2.5-5.5 kg containing different payloads and providing

[8]Communication with the spacecraft is one of the driving elements of the design of this mission — therefore intensive studies and supervised analyzes were undertaken for this work package incorporating more than 12 student man-months accompanied by PhD student work.

[9]Feasibility study mainly covered by two diploma theses[59, 20] at IRS in 2005

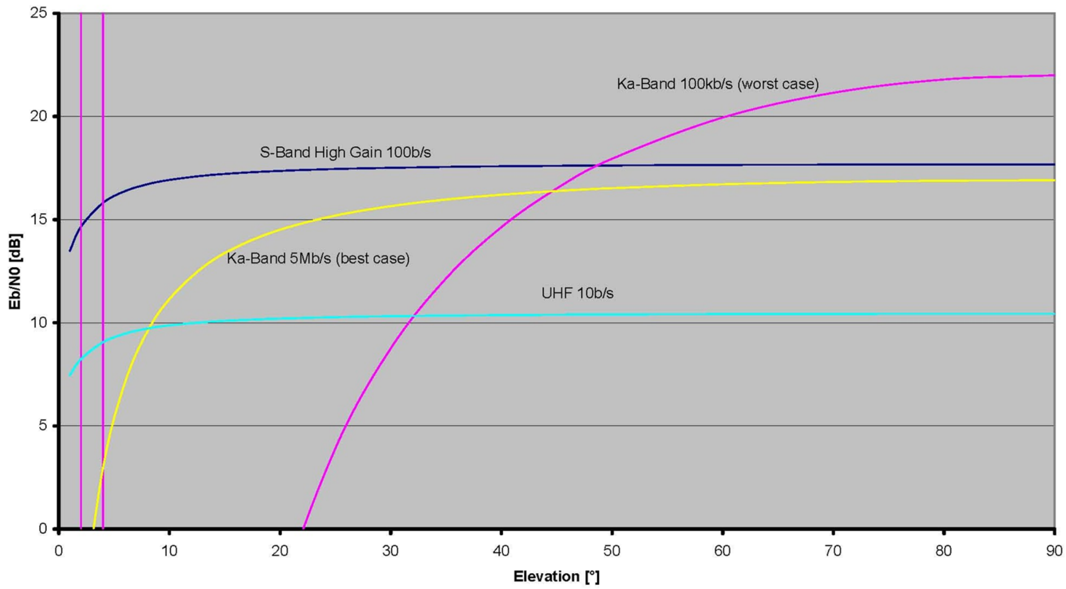

Figure 3.11: Data rates from the Moon; calculations are part of investigations of remote sensing observation scenarios at IRS[88]

increasing capabilities. Depending on the mission duration ranging from a very short time (transmitting an image) up to nearly a lunar day (traverse of tens of meters or more, mineralogical measurements) different power supplies, thermal control and communication options had to be analyzed.

The study results showed that a semi-hard landing delivery to the surface is feasible. A lander of approx. 15-25 kg (including the rover) with a combination of a solid propellant motor, an airbag system and a crushable structure is able to deaccelerate the complete system after separation from the descending *LUNAR MISSION BW1* directly before impact. The total mass seems to make it unfavorable to carry the Nanokhod (plus lander) to the Moon if the total payload mass of 30 kg is considered for the *LUNAR MISSION BW1* — additional system mass has to be taken into account to connect the lander to the satellite.

Also the transport of one or more cubesats or picosats were considered as an option for additional spacecraft. The release of such satellites having 10 kg mass or 1 kg respectively in cis-lunar space or in lunar orbit would provide valuable opportunities for interferometric experiments as well as infrastructure demonstrations (relay tasks). The cubesats or pico satellites would be provided by partner universities[89].

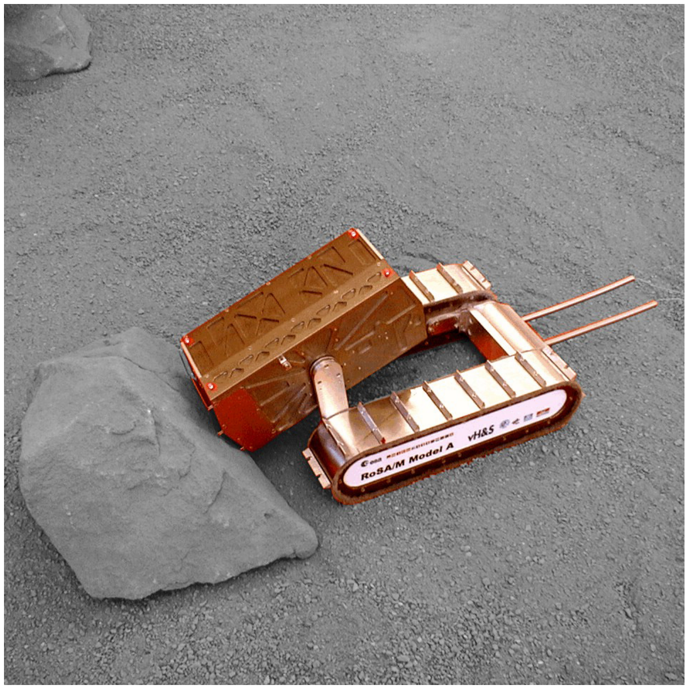

Figure 3.12: The Nanokhod rover with payload cabin (measuring at the rock), the two locomotion units and the tether unit (right) providing connection to a lander (Image: von Hoerner & Sulger)[59]

3.2 Science

The proposed design approach of the *LUNAR MISSION BW1* describes the project as an academic small satellite starting with mass and envelope constraints to use a piggy-back or secondary payload/co-passenger launch opportunity. The approach focuses on consideration of the satellite as a transportation platform to a selected target (here: the Moon) in a selected type of mission (here: an orbiter) to provide payload capacity. Initial analysis started in 2003 from the question of which instrument types had been flown to the Moon and which data sets were available[32]. The results of this study initiated the development and set up of the OLIMPIA (Outline of Lunar exploration InstruMents and Payloads for Initial Analysis) data base in 2004 at the Institute of Space Systems to provide information for payload selection processes[10].

More than 70 successful lunar missions carried a large number of instruments

[10]This database includes set up for lunar exploration but also targets design support for missions to Near-Earth Objects (NEO). The scientific objectives and the payload selection are major work packages of the design of this mission (as well as of this thesis) consisting of a large in-house work force of PhD thesis work incorporating student assistants and theses over a time frame of 4 years.

to the Moon between the mid-1960s and mid-1970s[85]. These instruments can be categorized by the observed part of the electromagnetic spectrum or the field of work. The results (see figure 3.13) show that most experiments were performed in the field of visual observations, cosmic ray detection and soil investigation to prepare for human lunar exploration by providing landing site maps and properties as well as medical information. Complete data sets for these instruments are not always available for different reasons: instruments did not work successfully, data were not transmitted due to mission failures, data sets were lost. The quality and the different types of resolution (spatial, spectral, radiometric, time) of the data sets must also be evaluated again with respect to current available sensor technologies (see figure 3.14). Data collected during this specific period did not use digital sensors (e.g. CCD detectors) or digital transmission.

The analysis showed areas which were covered small (e.g. gamma-ray, x-ray, ultraviolet, infrared, radiation) in lunar exploration but even areas which were covered widely could be of interest due to up-to-date sensors providing more performance in many ways (e.g. hyper channel spectrometers, multi spectral high resolution imaging, highly sensitive particle detectors). Current and future lunar exploration missions like SELENE, CHANG'E-1, CHANDRAYAAN-1 or LUNAR RECONNAISSANCE ORBITER focus especially on multi spectral high resolution mapping combined with altitude information in order to generate a complete three-dimensional topographic atlas of the Moon. This data set has been identified by the science community as a valuable information source for preparation of future lunar exploration missions.

Scenario	GSD	Data
Panchromatic imaging (VIS/NIR)	7 m	approx. 40 MBytes/min.
Spectral mapping (NIR, 4 channels)	10 m	approx. 150 MBytes/min.
Panchromatic 3D mapping (VIS/NIR)	4 m	approx. 300 MBytes/min.

Table 3.2: Examples of High Resolution Imaging as part of feasibility studies at IRS regarding imaging scenarios depending on scientific topics and detector systems[88]

Due to the amount of past or future photographic data (see figures 3.15 and 3.16) of the Moon additional imaging in the visual range would not seem to be useful but remains a favorable topic. Pictures provide context imagery which can be combined with data from other instruments as well as being valuable public relation tools to gain visibility. Analysis shows that imagery with resolutions down to 1 m is possible from low lunar orbit (see figure 3.17)[88]. Due to the revolution of the Moon, during one orbit around Earth, it is thus possible to image the complete surface from a frozen low polar orbit (assuming no limitations in propellant for maintaining orbital parameters) within half a month — the distance between two ground tracks of such a two hour orbit is around 30 km at the lunar equator. Maintenance (e.g. momentum dumping), charging of batteries and communication with ground stations will reduce the amount of observation time. Requirements on specific observational conditions (e.g. minimum Sun elevation angle) could also reduce the observation time.

Complete surface coverage on one hand or high resolution imagery on the other results in large amounts of data (see table 3.2). Therefore, complete surface coverage under high resolution seems not to be feasible for a small satellite mission due to limitations in communication bandwidth, on-board memory and orbital lifetime.

Parameter	SMART-1	LUNAR PROSPECTOR	CLEMENTINE
Launch Mass	367 kg	295 kg	458 kg
Dry Mass	287 kg	158 kg	235 kg
Payload Mass	19 kg	24 kg	8 kg
Payload/Dry mass Ratio	6.6%	15.2%	3.4%

Table 3.3: Lunar probe comparison — payload ratio, examples from data sets compiled at IRS (OLIMPIA, MoonSnap, MoonWiki) [85, 103, 94]

Examples from analyzed missions (see table A.11 and 3.3) show that miniaturized and low mass instruments can be combined into a low mass payload packages to accomplish a small lunar mission. Even so all instruments are cost-extensive, unique developments. For a low-cost mission approach considering commercial off-the-shelf hardware to be successful, the number of instruments has to be reduced. Additionally, the ratios are not absolutely comparable due to the fact that both the LUNAR PROSPECTOR and CLEMENTINE were launched with upper stages for the trans lunar trajectory boost. SMART-1 was also equipped with its own propulsion system to cover the complete travel from Earth orbit — like the *LUNAR MISSION BW1*.

Examination of to these numbers during in-house studies (using OLIMPIA and additional sources) the goal of 15-20% payload mass (including propulsion system monitor sensors) appears feasible.

3.2.1 Announcement of Opportunity

The proposed approach consists of the idea of offering available payload capacity to external national or foreign partners by releasing an "Announcement of Opportunity". The goal is to provide and communicate the following advantages to potential partners while also describing limitations:

- Partners will be able to participate in a project with a short schedule compared to large space organizations. For example, in 2007 ESA requested mission and instrument proposals for the Cosmic Vision 2015-2025 program to be launched in late 2018 and receiving around 60-70 proposals only in the area of science missions. Partners do not have to compete with a large number of competitors.
- Partners have direct access to project management during both mission development and operations. Due to the low number of instruments involved fewer compromises in operations and mission design must be made compared to traditional missions. Due to the small team size and lean management approach, the team is able to remain flexible during operations with respect to events and changes in the observation planning.
- Compared to a traditional mission approach, an academic institution can accept increased risk supporting technology demonstrations without the level and amount of qualification and documentation of a large space organization mission (e.g. as a result of securing complete success due to political expectations)
- Partners must accept the described limitations and constraints in mass, volume, amount of data return, observation time and more.
- Partners must also accept increased risk due to less space qualification of used hardware and the incorporation of students as non-certified engineers.
- Additionally partners must accept and deal with the uncertain funding situation in an academic environment.

To finalize the research topics and complete the payload an announcement of opportunity (AO) is planned for the near future. Initial discussions will incorporate both invited partners and collaborators of the Stuttgart Small Satellite Program network.

The process will be in close communication with the German Space Agency DLR as part of current activities within a national Moon initiative (e.g. consisting a proposal for a national lunar orbiter mission: LEO — Lunar Exploration Orbiter).

3.2.2 Strawman Payload

As an example to demonstrate the capabilities of a small lunar satellite mission and to enable the possibility of further studies a suite of instruments was selected for a strawman payload (see figure 3.18). The set of instruments is a result of the intense investigations and evaluations of lunar science objectives and payloads at IRS and studies analyzing the in-house capabalities as well as from collaborators. The payload consists of instruments qualified on former missions as well as provisions from partners of the program.

The strawman payload consists of seven instruments[45, 48] covering several different types of experiments.

The **MICS 2 (Multi-channel Imaging Camera System 2)** is based on the camera system used on the *FLYING LAPTOP* mission[15] adapted for remote sensing of the Moon. The MICS2 provides imaging in the visual to near-infrared range to map selected areas of the lunar surface in high-resolution.

Three independent systems with a CCD detector and associated optics (including filter) each and 12 bit radiometric resolution provides a ground sample distance of up to 10 meters and a Signal-to-noise ratio (SNR) better than 100. During operations the camera generates a data flow of 5500 kbit/s (uncompressed). Ongoing studies will evaluate if the camera system will be able toobserve with spectral filters for mineralogical mapping or with polarization filters to analyze physical properties of the lunar regolith.

The **TICS 2 (Thermal Imaging Camera System 2)** is based on a design originally planned for the *FLYING LAPTOP* and will use an uncooled microbolometer detector[15] in the spectral range of 7-14 μm for mineralogical observations of selected areas of the lunar surface. To increase the instrument aperture without significant increase in mass, the K_a band antenna will be of dual use as the primary mirror of the thermal imager due to a special coating. A ground sample distance of around 15 meters seems to be feasible and will improve the data quality in the infrared range.

The **SPOSH (Smart Panoramic Optical Sensor Head)** is a specialized wide angle camera system originally developed by DLR with ESA support for terrestrial all-sky meteor and fireball observations[62, 54]. To detect faint events like lunar impact flashes or transient lunar phenomena on the surface during night time magnitudes of +6 with a SNR better than 5 the camera consists of a highly sensitive CCD sensor. The field-of-view is 120 x 120 degrees and 1,000 meteoroid impact detections per year are assumed. The data are processed and analyzed on board so that only images containing an event are transmitted for data reduction purpose resulting in approx. 1 kbit/s.

LUDENA (Lunar Dust Environment Analyzer) is an in-situ measurement experiment developed by the Cosmic Dust Group of the Max-Planck Institute of Nuclear Physics[79, 2]. The instrument collects dust particles and space debris in the cis-lunar and lunar environment to measure velocity vector, mass, and composition to determine the spatial and temporal variations of the particle flux. Approximately 500,000 particle detections per year with a particle size ranging from 0.5 to 100 μm are assumed.

In addition to these payload instruments the following experiments are also planned: the PAMCAM2 (Panoramic Camera 2) adapted from the *FLYING LAPTOP*[44] and scheduled to be used primarily for education and public outreach activities and provide panchromatic overview images in the visual range, the PHOENIX GPS experiment from the *FLYING LAPTOP* and *PERSEUS*[15] and eventually a radio science experiment using the on-board K_a band communication system for investigations of lunar surface material.

Instrument	Mass	Power	Data Rate
MICS2	12 kg	15 W	5,500 kbit/s
TICS2	3 kg	10 W	450 kbit/s
SPOSH	2.5 kg	10 W	1 kbit/s
LUDENA	1.5	2 W	8 kbit/s
PAMCAM2	1	5 W	560 kbit/s
Total	20 kg	42 W	6,509 kbit/s

Table 3.4: *LUNAR MISSION BW1* Strawman payload parameters (instrument mass, power, data rate)[45, 48]

The strawman payload will be able to perform significant research themed "Dust, Debris and (very) Small Bodies" with intense support of academic as well as industrial partner institutions. The parameters (see table 3.4) are within provided limits of mass, power and data rate leaving spare mass for propulsion monitor sensors.

3.3 Education and Public Outreach

To gain visibility within the scientific and enginering community as well as in the general public an education and public outreach program will be an important element of the project. Up-to-date communications involves classical instruments like press releases for broadcasting and print media coverage but also online media like web-based home pages, blogs and wiki-based information systems. Initiating partnerships with telecommunication and web media providers should favorably establish such activities while enabling the mission team to concentrate on its project.

To link the scientific community and the general public amateur astronomy groups will also be involved in payload experiments and the organization and management of ground-based observations (e.g. space and ground based imaging of transient lunar phenomena). These groups will establish a network to education and public outreach institutions like public observatories, science museums, planetariums and others to support an successful outreach program.

The involvement of cooperating institutions in foreign countries also offers the opportunity to start education and public outreach activities with the partners. The partner institutions would establish adjusted activities in their country and then use the *LUNAR MISSION BW1* as a platform to foster space education in general while supporting and advertising their projects.

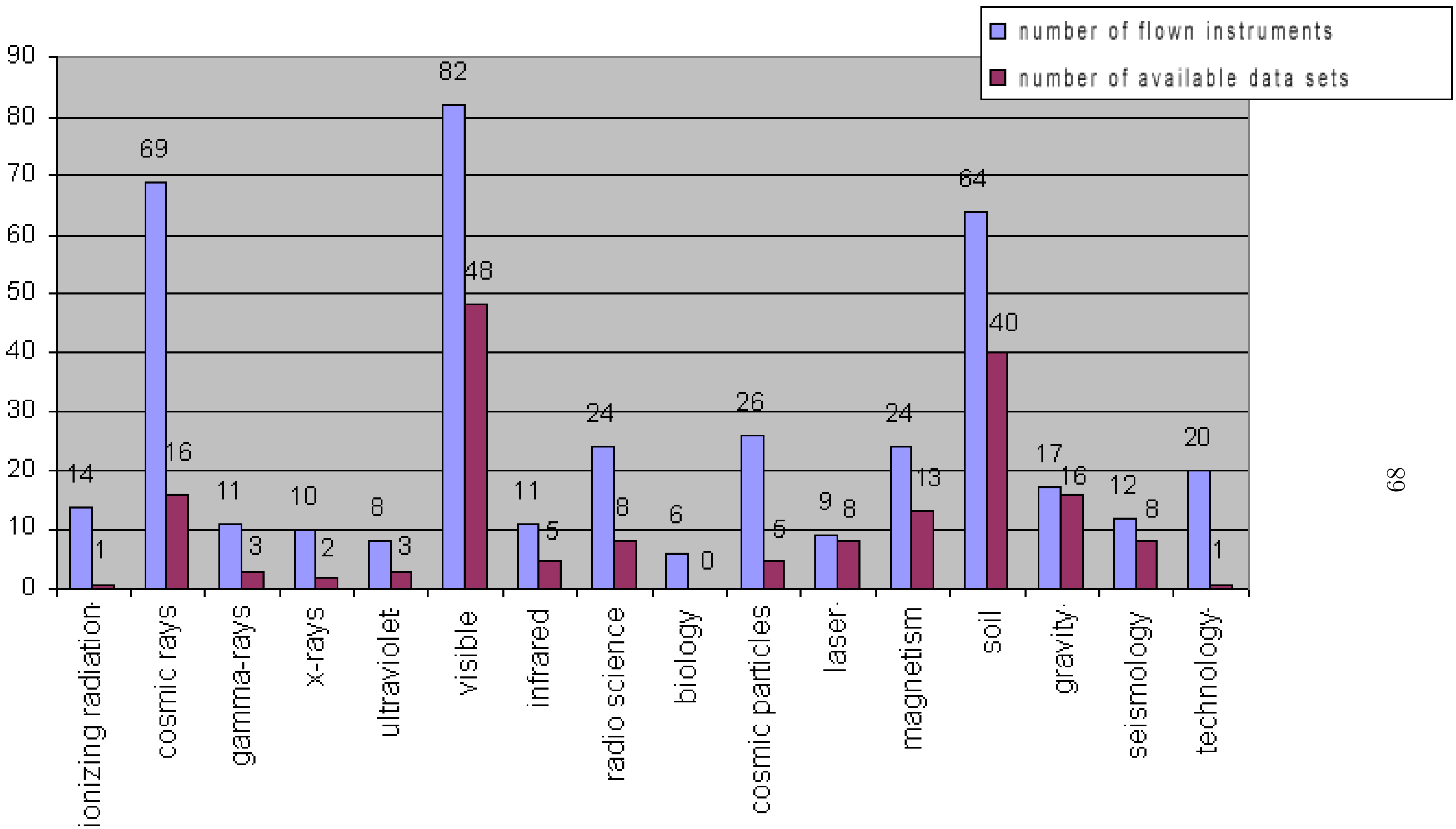

Figure 3.13: Scientific lunar payloads - number of flown instruments (blue) and available data sets (red)[32]

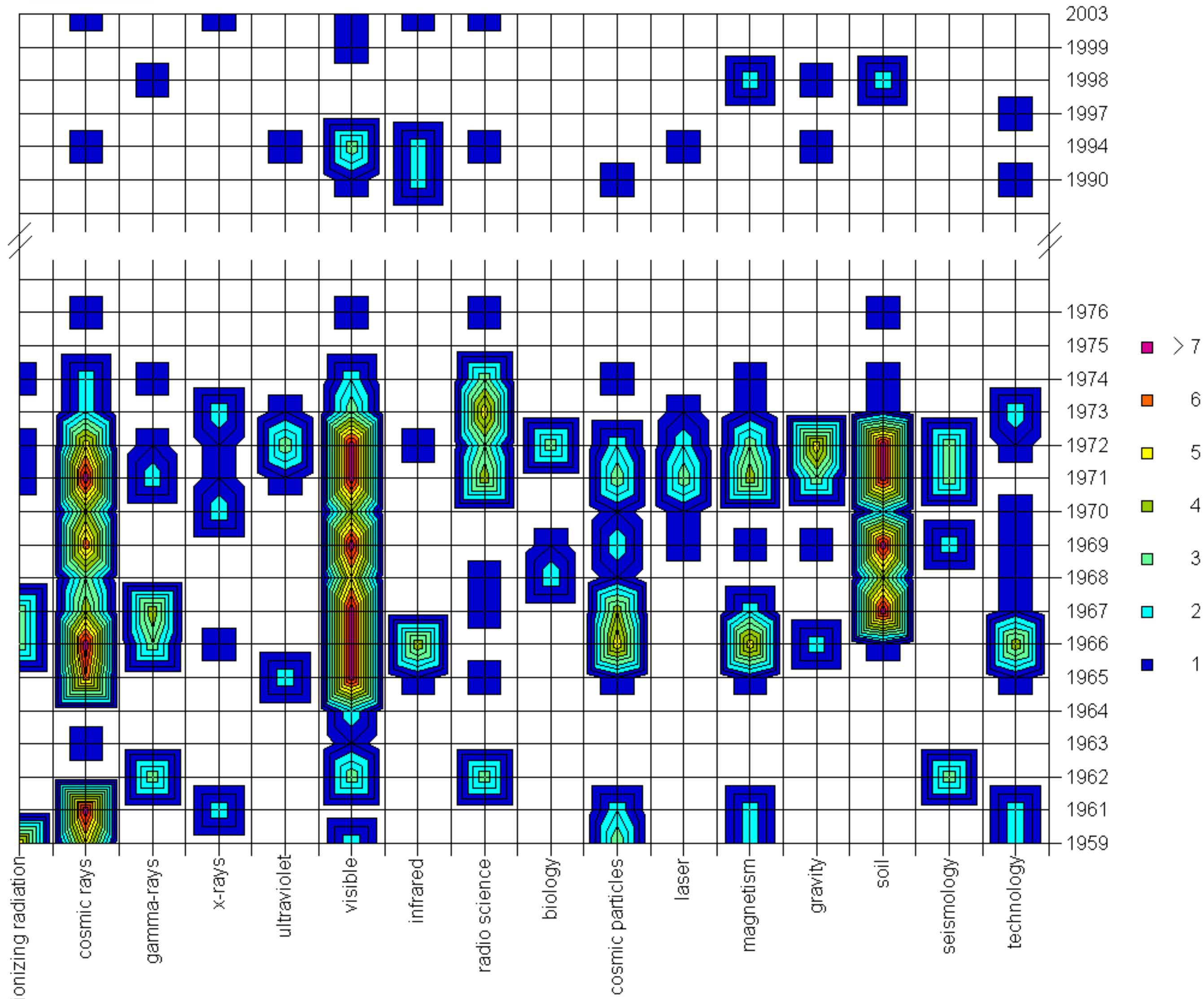

Figure 3.14: Scientific lunar payloads - instrument chronology[32]

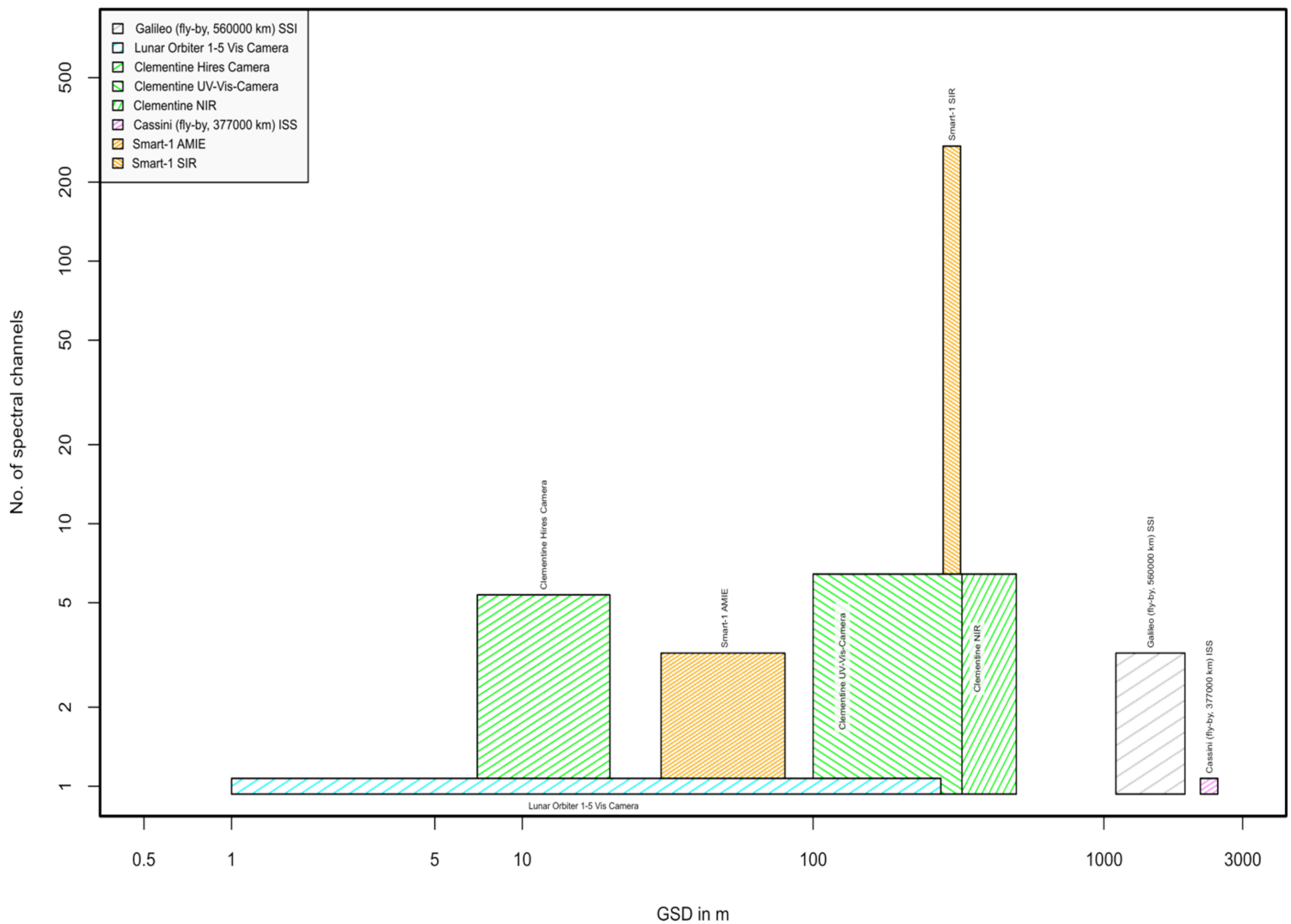

Figure 3.15: Past Imaging Systems[45]

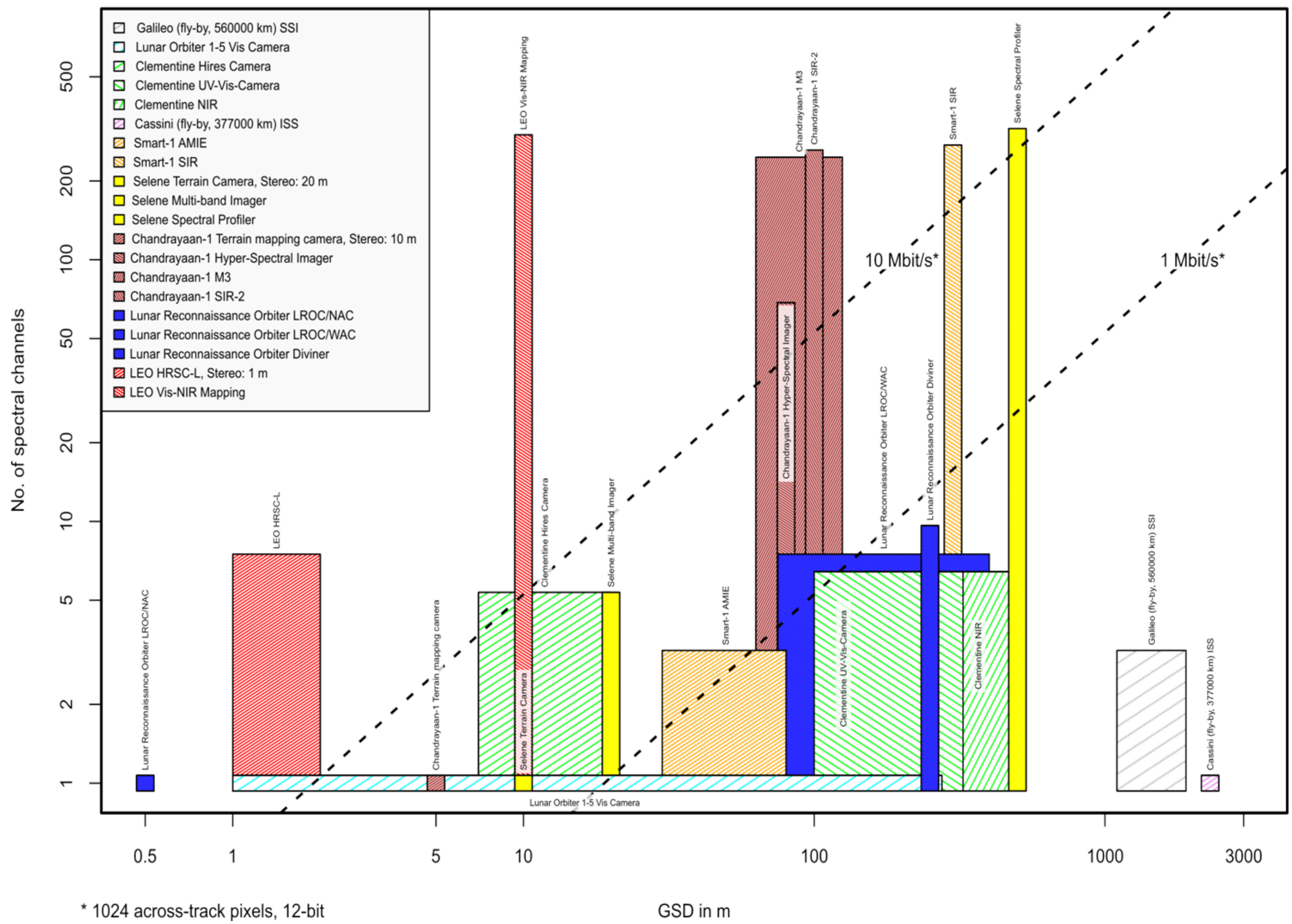

Figure 3.16: Past and future Imaging Systems[45]

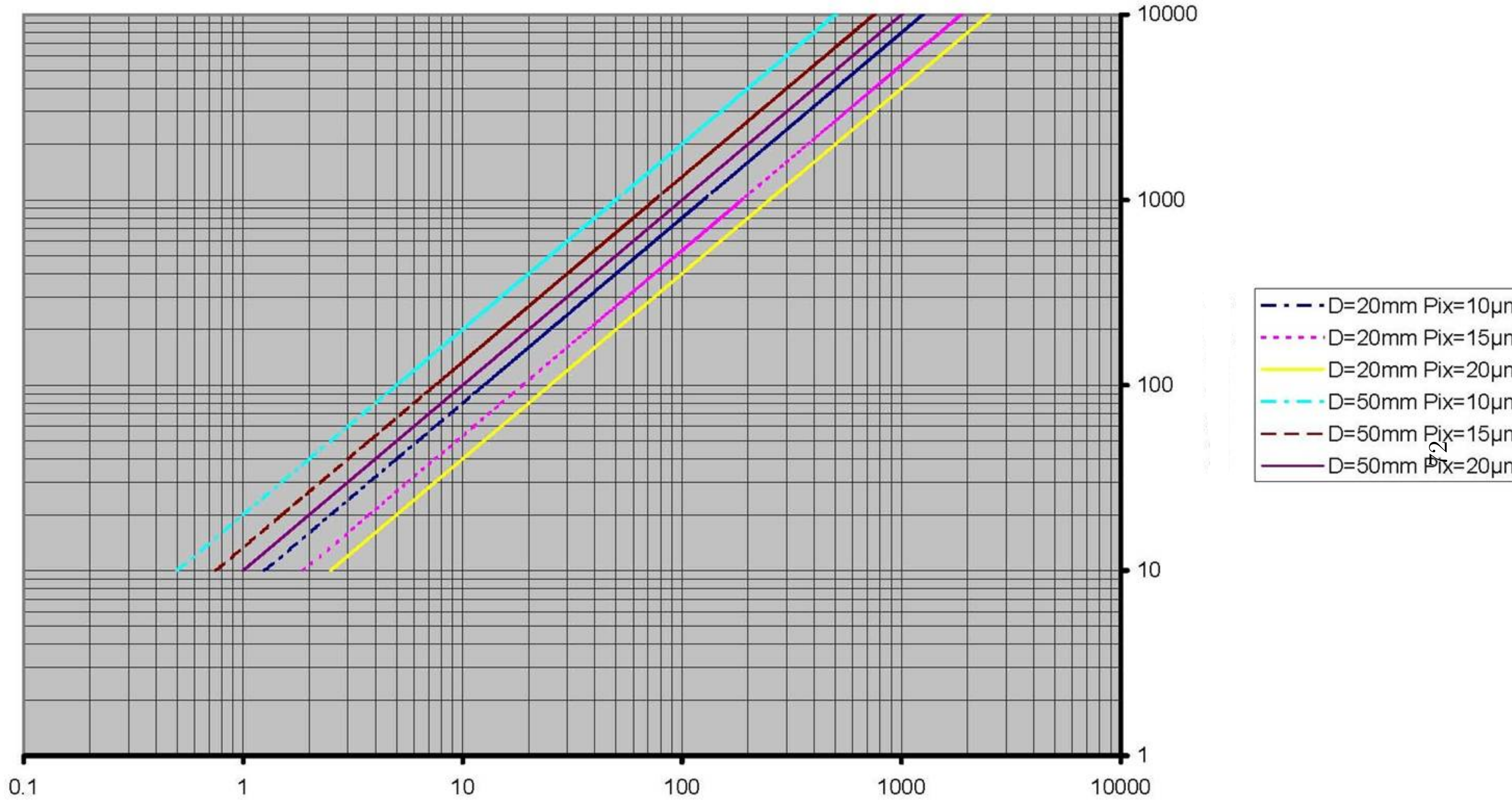

Figure 3.17: Possible Ground Sample Distance (GSD) depending on the optical System (x-axis: GDS in m, y-axis: altitude in km, F = 4)[88]

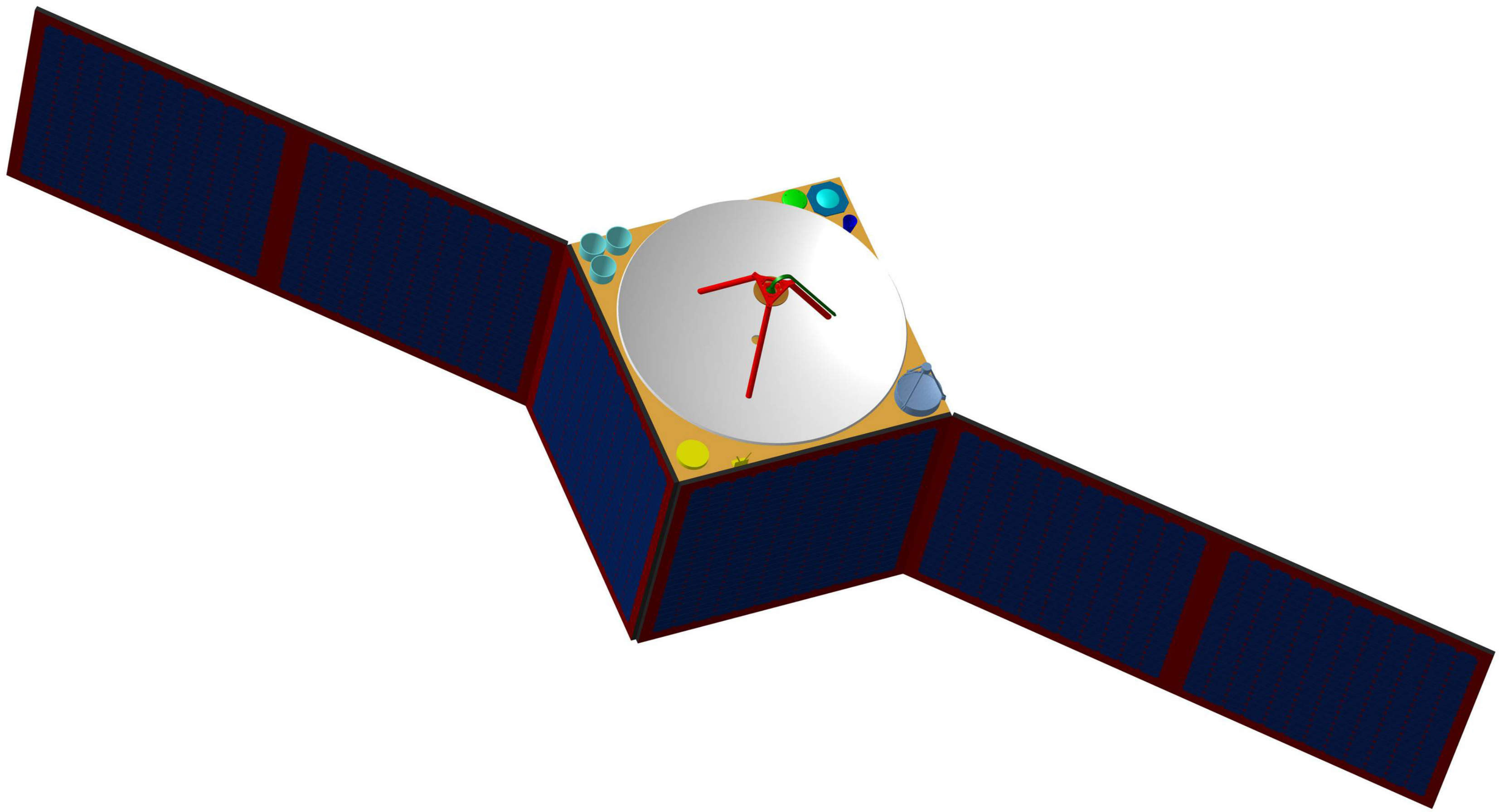

Figure 3.18: Accomodation of the strawman payload (left corner: MICS2, upper corner: SPOSH (blue), PAMCAM2 (dark blue), right corner: LUDENA, center: TICS2[45]

Chapter 4

Mission Scenario

"... it's just a scenario"
Dr. Jeremy Stone[1]

In this chapter:

- Launch System
- Ground Segment
- Mission Phases
- Post-Mission Phases

Every mission or spacecraft project has at least one scenario. Based on objectives leading and designed to a mission and spacecraft concept, the planned scenario shows the elements and their operational role during the mission.

4.1 Launch Segment

The launch is a service offered by an external provider. Traditionally launches are dedicated to one satellite and the related mission profile. Launch costs range from less than 10 million Euros for a dedicated launch of a few hundred kilograms into low Earth orbit (LEO) up to more than 125 million Euros for a dedicated launch to place a satellite of a few tons into a geostationary orbit (GEO). Such a cost level is usually not feasible for academic institutions.

[1] played by Arthur Hill in: The Andromeda Strain, 1971, nominated for two Academy Awards (Best Edit, Best Art Direction) — based on: Michael Crichton, *The Andromeda Strain*, Alfred A. Knopf, Inc., 1969[37]

Launch vehicles like the Delta or Ariane 5 providing additional transport capacity (secondary or piggy-back payloads) in the range of a few hundreds of kilograms opened up new capabilities for carrying small spacecraft into space. In 1981, the first academic small satellite UoSAT-1 was launched as a secondary payload. A piggy-back launch opportunity usually has the following characteristics:

- The orbit is established by the main passenger (e.g. sun synchronous orbit, geosynchronous transfer orbit).
- The piggy-back payload satellites are separated from the launcher after the main passenger is released.
- Time and orientation of the separation is uncertain - this translates into uncertainty in some of the orbital parameters.
- The piggy-back satellites have to be inactive before and during launch - telemetry and telecommanding is not possible since batteries are not completely charged.
- After release the piggy-back satellites have to de-tumble, charge the batteries and establish contact with a ground station.
- The launch costs are primarily covered by the main passenger; as a result piggy-back launch costs range from nothing to 20,000 US-Dollar per kilogram depending on the negotiations and the interest of the launch provider in the project.

Today many launch vehicles provide piggy-back launches of two, four, six or even more satellites in addition to the main passenger. Based on the successful launches of DLR-TUBSAT (1999) and BIRD (2001) the decision was made to search for piggy-back opportunities on top of Indian launch vehicles like PSLV (Polar Satellite Launch Vehicle) for the spacecraft of the Stuttgart Small Satellite Program. The PSLV can launch two piggy-back satellites ranging from 50 kg up to 150 kg (see figure 4.1) within a fixed envelope[38]. *FLYING LAPTOP* and *PERSEUS* are planned to be launched using this launch service.

Investigations of launch opportunities showed that for a mini satellite of around 200 kg or more a traditional piggy-back launch is not feasible due to size and mass restrictions. *LUNAR MISSION BW1* has to be transported as a secondary payload or co-passenger into a geosynchronous transfer orbit (GTO). One possible offer is to take a qualification flight of the next generation Indian launch vehicle GSLV-Mk III (Geostationary Launch Vehicle - Mark III). The

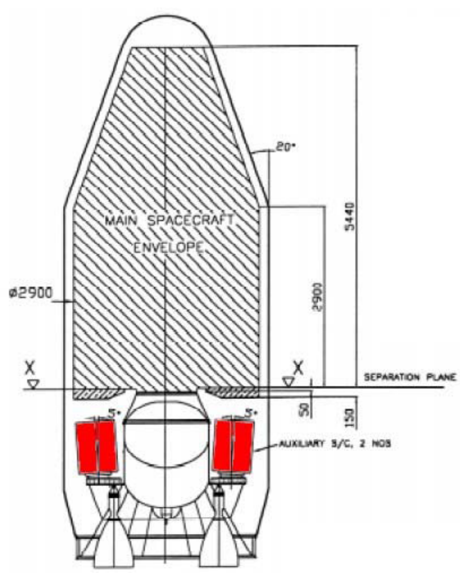

Figure 4.1: PSLV fairing with auxillary payloads (marked red)[38]

GSLV-Mk III will be able to transport two main passengers because of a dual-payload adapter structure (like Ariane 5). Usually a qualification flight before entering commercial operations is available at very low cost. Although final decision about the launch has not yet been made, a contract must be negotiated and signed three and two years respectively before launch.

4.2 Ground Segment

The three visible elements of the ground segment are the satellite integration laboratory, the mission control center and the ground station. After initiation of the Stuttgart Small Satellite Program theses facilities were built-up or existing facilities were extended (like the large vacuum chamber laboratory, see figure 4.4, or the Steinbeis Transfer Center ground station for UHF/VHF/L band communication with a research experiment at the ISS). The ground segment facilities established at IRS since 2003[2] consist of:

- A satellite integration laboratory with more than 200 m^2 area to provide the capability to integrate more than one spacecraft in parallel — an important capability to run an academic program with longer integration phases due to funding and management issues (see figure 4.2). The laboratory hosts an optical test and calibration area with a working places with computers

[2] Facilities were planned and set up with collaboration from local and regional partners and student involvement at IRS as well as at partner institutions.

for students who work with engineering or flight hardware or integrate such systems. Additionally an exchange area ("airlock") with working places for students who do not have to be in the integration laboratory all the time is available.

Due to investment and operational costs the laboratory is not a (certified) clean room but a "regularly cleaned room". Clean room conditions are available for subsystems using flow boxes or additional tents for a complete satellite.

- A ground station for UHF, VHF, L band extended to S band and K_u/K_a band. To operate a lunar mission two (or more) additional dishes of 2.5 m and 3 m respectively for S and K_u/K_a band must be established.

  To increase the contact number and duration of communication with the satellite a network of partner ground stations will be established taking advantage of cooperating institutions who can provide antenna capacities. Usually a barter agreement is arranged providing access to the satellites of the Stuttgart Small Satellite Program for access to ground station capacity.

- A mission control center to operate two small satellite missions in parallel (see figure 4.3). Parallel operations might be necessary since critical mission phases (e.g. trajectory maneuvers) may need to be prepared or take place during the same timeframe for different missions. Today such a mission control center only needs a few working places due to the easy availability of necessary computer power at low costs and small size.

Figure 4.2: Satellite Integration Laboratory, view from the "airlock" area (Image: IRS/Univ. Stuttgart)

Figure 4.3: Mission Control Center, view on one working place (Image: STW, IRS/Univ. Stuttgart)

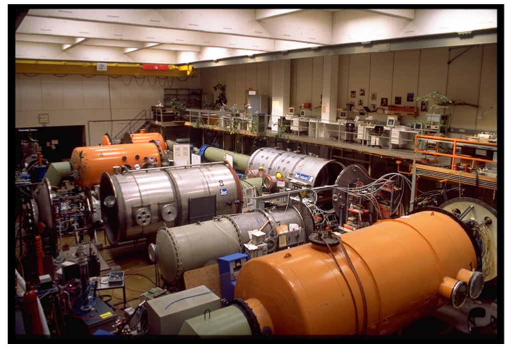

Figure 4.4: IRS vaccum chamber and plasma wind tunnel laboratory (Image: IRS/Univ. Stuttgart)

The ground segment consists also of software tools — some especially set up for the Stuttgart Small Satellite Program or one of its mission. Major elements are simulation tools to investigate and optimize orbital trajectories (e.g. ASTOS[3]) or to simulate satellite systems (e.g. MDVE[4]). To achieve the educational goals of the program the mission design software STK[5] is used to teach basic as well as complex concepts of orbital mechanics simulation.

Additionally data bases are an important and valuable part of the ground segment set up to support different steps of the mission design and store and provide information gained during the program: GOLEM[6], OLIMPIA[7] and the knowledge management system MoonWiki[8] as well as satellite related hardware databases are already in place.

4.3 Mission Phases

Due to different operational constraints and requirements at different times of the mission, a delineation into separate mission phases has been made. The phases itself and the separation between any two phases is primarily driven by

[3]ASTOS: Aerospace Trajectory Optimization Software by Astos Solutions GmbH

[4]MDVE: Model-based Development and Verification Environment, a satellite system simulation software provided by EADS Astrium, Friedirchshafen, adapted to small satellites at IRS

[5]STK: Satellite Tool Kit, integrated analysis software for land, sea, air and space assets by Analytcal Graphics, Inc. (AGI)

[6]GOLEM: General parametric Outline for Lunar Exploration Missions[107, 50]

[7]OLIMPIA: Outline of Lunar exploration InstruMents and Payloads for Initial Analysis[50]

[8]MoonWiki: a wiki-based information system for sharing knowledge and data within IRS and with internal partners

the usage of one of the propulsion systems because of specific demands. Based on architecture and concept the mission is divided in to the following phases which are described in detail below[9]:

- Launch Phase (Phase I)
- Ascent Phase (Phase II)
- Cruise Phase (Phase III)
- Capture Phase (Phase IV)
- Descent Phase (Phase V)
- Science Phase (Phase VI)
- Impact Phase (Phase VII)

The use of electric propulsion systems increase the necessary delta-v to nearly twice the amount of a chemically propelled mission with impulsive maneuvers[57]. Despite the increased delta-v demand, simulations show that electric propulsion systems are able to reduce overall propellant mass significantly when compared with chemical propulsion options for the same mission scenario (see table 4.1).

Propulsion System	Dry Mass	Propellant Mass	Flight Duration
Hydrazine	100 kg	320 kg	5 days
	150 kg	480 kg	5 days
	200 kg	640 kg	5 days
NTO/AZ50	100 kg	190 kg	5 days
	150 kg	270 kg	5 days
	200 kg	370 kg	5 days
TALOS	150 kg	190 kg	5.5 months
TALOS + 4 SIMP-LEX	150 kg	160 kg	27 months
TALOS + 6 SIMP-LEX	150 kg	160 kg	20 months

Table 4.1: Comparison of chemical and electric propulsion options (TALOS/SIMP-LEX mixed mode: TALOS until GEO, then SIMP-LEX) as a result of in-house simulations

[9]The investigations and simulations at IRS of the different mission phases are large work packages each. Since 2003 the work force for detailed analyses can be estimated with more than 3 student man-years and approx. the same amount of staff man-years.

In the above simulations calculated only the flight from a geostationary transfer orbit (GTO) to the orbit of the Moon around Earth in order to compare propulsion options without taking lunar resonance effects into account. The data shows the feasibility of an electrically propelled mission but suggests the need for optimization to reduce propellant as well as spacecraft dry mass.

Potentially one other phase might be carried out: a Surface Phase (Phase VIII), depending on the existence of an additional spacecraft delivered to and operated on the lunar surface. The complete operational phases will be followed by necessary post-mission phases. Parameters of the in-house simulations for different propulsion-driven mission phases are listed in appendix A.

4.3.1 Launch Phase (Phase I)

During launch the satellite will experience various loads which must be taken into consideration when designing the structure to meet the requirements of the launch provider. After being launched as a piggy-back payload or co-passenger into a GTO the *LUNAR MISSION BW1* will be separated from the launch vehicle. Assuming a launch on top of an indian GSLV (or PSLV respectively) the satellite will be injected into a 180 km $\times$ 36,000 km orbit with an inclination of 19.2° and an orbital period of 10.6 hours[10].

After separation, the satellite initiates a SafeHold Mode to perform initial attitude acquisition, de-tumbling, battery charging and establish communication[11]. The on-orbit checkout is planned to be similar to the *FLYING LAPTOP* satellite[12] or the *PERSUES* satellite. The checkout consists of the following tasks: housekepping telemetry transmission and check, solar array deployment, satellite subsystems tests (except K_a band communication, propulsion systems and payload instruments), high gain K_a band communication tests, propulsion systems tests (incl. maximum power consumption check), and payload instrumentation tests.

4.3.2 Ascent Phase (Phase II)

During the ascent phase the orbit should be raised above the Van-Allen belt mainly by increasing the perigee. The Van-Allen belt can cause degradation and failure effects to hardware and software, debris in low Earth orbits might also affect the spacecraft.

[10] To compare data results calculated with different software January 1, 2011 was chosen as launch date for all in-house simulations

[11] see *FLYING LAPTOP* PDR document, SafeHold Mode[15]

[12] see *FLYING LAPTOP* PDR document, On-Orbit Checkout[15]

Detailed investigations and simulations at IRS of the perigee raise analysed the effect of variations in the number of propelled phases during each orbit. A low number of arcjet burns is favored to extend the lifetime of the engine. The results show that with one operation of 3 hours during each orbit the perigee can be raised within nearly 6 months consuming less than 85 kg propellant to provide a delta-v of approx. 1,300 m/s. The flight duration can be reduced to less than 4 months by increasing the amount of propellant for another 5 kg but adding another two burns per orbit[108, 51].

The debris risk analysis for the *PERSEUS* mission shows a risk of collision with a 1 mm particle at 920 km of a few percent[13]. Most particles are expected to impact on the front side of this spacecraft in flight direction. Analysis suggests providing additional front plate structure as well as side accommodation for the payload[105]. The *LUNAR MISSION BW1* will spend only a limited time in this orbital altitude, therefore an increased risk of debris collisions is not expected. However it is important to note due to the fact that all payloads are accommodated on the front side.

4.3.3 Cruise Phase (Phase III)

The cruise phase will be divided into two parts: raising the apogee and using lunar resonance effects using the SIMP-LEX propulsion system. The apogee will be raised within 36 months consuming less than 20 kg of propellant to provide a delta-v of approx. 1,500 m/s until lunar gravity provides the opportunity to take advantage of lunar resonance effects. The SIMP-LEX thrusters are operated with increasing durations of 20-80 hours per orbit. Continuos operations do not provide significant advantages in reducing the flight duration but increase the total operation time of the thrusters.

Simulations showed that using lunar resonance effects can save approx. 200 m/s by using the SIMP-LEX thrusters for another 6 months consuming 10 kg propellant[108] until the lunar capture. The operations during the lunar resonance phase from a navigational point of view has to be considered as highly complex — especially with respect to positioning the spacecraft as precisely as possible in order to perform a successful lunar capture maneuver.

Analysis of the cruise phase (see figure 4.5) shows the advantage of using the SIMP-LEX propulsion system due to its very efficient use of propellant. Further trade-off studies still need evaluate mixed TALOS/SIMPLEX options in comparison to a TALOS only option, taking increased propellant mass into account but reducing the total system mass of the propulsion system. Special attention

[13] Results from in-house simulations using ESA's MASTER model[13] as a part of *PERSEUS* feasibility studies.

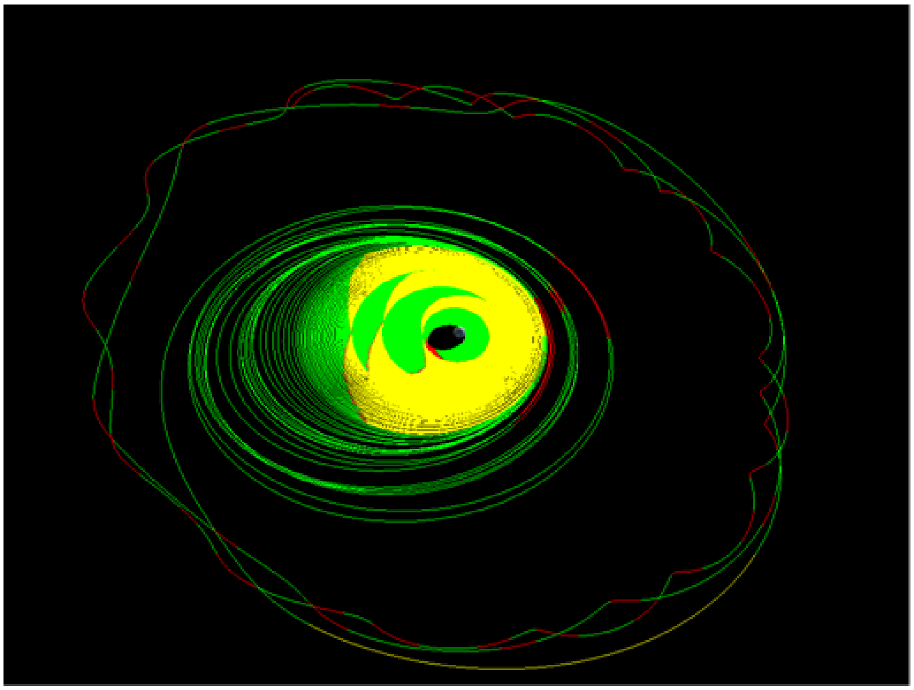

Figure 4.5: *LUNAR MISSION BW1* cruise phase simulation — displaying the initial perigee and apogee raise and the lunar injection trajectory using lunar resonance effects[108]

must be spent in any further analysis in order to develop momentum dumping strategies during ascent and cruise phase as a result of investigations of potential attitude control for the *LUNAR MISSION BW1*[1].

4.3.4 Capture Phase (Phase IV)

A successful lunar gravitational capture maneuver is able to reduce the overall delta-v demand by several hundreds of m/s. The maneuver using the TALOS thermal arcjet demands approx. 2-2.5 kg of propellant to provide the necessary delta-v of around 50 m/s but is quite sensitive in many ways[108]: for example precise navigation with a timing accuracy in the range of 10-15 minutes, precise attitude control and constant precise orbital tracking as well as a reliable propulsion system will all be required.

This definitely raises the need for additional ground stations to provide the 24 hour coverage and real time telecommand capabilities needed at a minimum during critical mission phases. The need for a powered maneuver depends on the chosen orbit and trajectory as well as the accepted risk of impacting on the lunar surface or thrown out of the planned orbit.

4.3.5 Descent Phase (Phase V)

Depending on the initial orbit after lunar capture, additional time and propellant will be necessary during the descent phase to circularize and lower the orbit while changing the inclination. The duration of such a possible necessary descent suggests early operations of the payload instruments even before reaching the final science orbit. Analysis shows that a descent can last from 18 months (SIMP-LEX) down to 1 month (TALOS) with a propellant consumption of less than 10 kg to nearly 40 kg respectively[108]. This demonstrates the advantage of a successful capture maneuver into a nearly final orbit — or changing the requirement of a highly inclined circular low lunar orbit to a less ambitious (e.g. elliptical) orbit.

Simulations of the overall transfer trajectory to the Moon without trajectory optimization consists of scenarios with mixed TALOS/SIMP-LEX operations as well as TALOS only operations in different modes. Results showed flight durations reaching from around 2 years (TALOS only) up to more than 5 years (complex TALOS/SIMP-LEX operations) with minimum propellant consumption of 150 kg taking advantage of lunar resonance effects[108] — much longer than expected. Trajectory optimization is ongoing to reduce propellant mass and flight duration below 2 years. Also further investigations of the accuracy requirement of propelled maneuvers and navigation have to be performed to analyse the sensitivity due to deviations in the thrust vector during the mission.

4.3.6 Science Phase (Phase VI)

Because of the inhomogeneous lunar gravitional field, any orbiter not capable of regular station keeping will impact the lunar surface within weeks or months depending primarily on the initial inclination of the chosen orbit[42, 106]. Analysis during early mission design phase showed that perturbating accelerations are on the same order of magnitude as the level of thrust delivered by the electric propulsion systems[92, 91, 43].

To plan for at least six months of operation in a low lunar orbit, detailed in-house simulations were performed to investigate the lifetime of different orbits and determine station keeping strategies for a small lunar satellite[3, 106]. The analysis used existing high grade and high order lunar gravity models for simulation[42]. Results proved previously published literature data showing that choosing specific inclinations can extend the orbital lifetime significantly. Starting with such stable areas, further studies investigated possible station keeping strategies to provide stable orbital conditions for payload instruments with low delta-v demand assuming that after the capture and descent phase no significant amount of propellant is left. Simulation data suggest that even simple regular orbital maintenance maneuvers demand high delta-v and therefore an optimized strategy is more favorable. Such a strategy takes advantage of regular harmonic effects of the chosen orbit radius to minimize propellant consumption resulting in a so called 'trade-off-orbit' with an inclination of 70 degrees which can minimize the delta-v to a few tens of m/s while still providing high inclination, high surface coverage capabilities for remote sensing payloads[106].

Investigations are still ongoing to refine these results and prepare the detailed data set necessary for further mission analysis and design — e.g. to finalize the orbit after payload and launch opportunity selection.

4.3.7 Impact Phase (Phase VII)

The decision was made to conclude the mission with a controlled impact on the lunar surface for scientific (impact research) but also programmatical (future participation in status discussions) reasons. If a piggy-back surface element should be delivered a controlled descent is also necessary. Impact must occur on the near side in order to provide a communication link to Earth during the descent as well as for any possible surface element. For observation of the impact lunar night conditions at the selected site is favored — for a surface element mission daylight for solar-electric power support is demanded.

The analyses showed that the low thrust level of the MPD engines would lead to descent duration of 12 days or more and is therefore not promising. Due to the very low angle of descent and the huge variations in height of the lunar surface (up to 20 km) the probability of an unpredicted crash is high. Fortunately the thermal arcjet system provides enough thrust to make an electric propelled descent feasible. During a descent duration of 18-24 hours, around 1 kg of propellant is necessary to provide a delta-v of 40-60 m/s is resulting in an impact velocity of approx. 1.6-1.7 m/s[92, 91]. Additional reboost maneuvers can be performed if needed to more pecisely determine the impact site.

From an operational point of view this scenario seems to be feasible as long as support from additional ground stations at partner institutions or access to large dishes for a very short time (just a few hours) are available to receive data from the spacecraft using low-gain omni-directional transmission.

4.3.8 Surface Phase (Phase VIII)

The nano rover/lander system decribed in chapter 3 would be operated independantly from the *LUNAR MISSION BW1* spacecraft — either from the institute's mission control center or from an external facility providing additional ground station antennas. The announcement of the Google Lunar X PRIZE[19] two years after the nano rover feasibility studies raised interest in such an option. However any additional piggy-back payload like the nano rover and lander would directly influence the complete mission resulting in a new mission design and redesigned spacecraft.

4.4 Post-Mission Phase

Independent from any possible surface phase, mission operations will conclude shortly after impact. The post-mission phase mainly consists of the following tasks:

- Archiving and providing science data to partner institutions (by perhaps transfer data to PDS/PSA if requested)
- Archiving and providing housekeeping and subsystem data to partner companies/institutions, and certifying space qualification of subsystems and components if requested
- Shutting down and transfering ground segment elements if dependent on this mission only
- Analyzing data and information to compile and provide any lessons learned from the mission
- Concluding documentation of the mission

Finally, at the end of the mission, future projects for the Stuttgart Small Satellite Program or subsequent activities have to be in preparation or implementation already building on the experience and results of the *LUNAR MISSION BW1*.

Chapter 5

Mission Management

"I'll manage it better next time."
Thomas Edward Lawrence[1]

In this chapter:

- Programmatics
- Proposed Phase Model and Schedule
- Team Structure
- Mission Costs

The approach in management of a project influences significantly the probability of success in many ways. Especially in an environment having limited resources in manpower and funding, an effective scheduling and innovative management approach is crucial to achieve given mission goals. The vision of accomplishing a space exploration mission performed up to now only by large space organizations both demands and offers the possibility of new approaches in management and programmatics.

[1]a.k.a. Lawrence of Arabia, played by Peter O'Toole in: Lawrence of Arabia, 1962, nominated for 10 Academy Awards (Best Actor, Best Supporting Actor, Best Picture, Best Director, Best Writing, Best Cinematography, Best Edit, Best Art Direction, Best Music, Best Sound), won seven Academy Awards (Best Picture, Best Director, Best Cinematography, Best Edit, Best Art Direction, Best Music, Best Sound) — based on: Thomas Edward Lawrence, *Seven Pillars of Wisdom*, private edition, 1922[37]

5.1 Programmatics

Analysing attributes of national or multi-national exploration mission management of large space organizations as described in chapter 0 the following characteristics were identified which should be handled different in an academic environment:

- Long project scheduling due to the large number of participants and increasing level of decision making processes,
- Compromises in mission design (e.g. orbit) due to the large number of payload instruments,
- Complex spacecraft and ground segments due to the large number of objectives and requirements,
- Increasing administrating efforts due to decision making, complexity, scheduling and number of participants,
- Low flexibility in replying on new scientific questions or using innovative technologies,
- High total mission cost due to schedule, complexity, low risk and high reliability resulting in high quality assurance and administration efforts,
- High political pressure (and often influence) to achieve mission success

A commong approach in mission design at ESA or NASA[100, 18] is to first define scientific objectives and identify payload instruments before than designing the orbit and spacecraft to carry and operate these instruments. For the *LUNAR MISSION BW1* the decision was made to propose a different approach adjusted to a program within an academic environment.

Statement 1: The mission target (e.g. Moon) and mission type (e.g. orbiter) is selected. The spacecraft is designed to meet the objectives, reach the target and fulfill the type of the mission without respect to a possible payload (while still providing payload capacity). At this point it is just a "flag-carrying" mission.

Statement 2: The spacecraft will use existing ground infrastructure. Specific ground segment components and adjusted satellite subsystems are only introduced if necessary to fulfill the basic mission (target and type).

Statement 3: The available payload capacity will be offered to internal and external scientists. The limits on mass, power, memory, data transmission bandwidth, orientation and observation time as well as risk must be accepted by partners planing to provide an instrument or technology experiment.

Statement 4: The number of instruments is kept low. Selection will be made with respect to the management structure of the partner, the provided instrument and the value of the expected scientific return.

Statement 5: Using commercial-off-the-shelf hardware or even innovative non-space qualified hardware reduces the total costs significantly but increases the risk. A useful risk strategy is to make sure that meeting only some of the objectives or fulfilling only part of the goal is still possible with some systems not working completely and considered as a basic mission success. Quality assurance is important and necessary but to decide on the level by your own enables an effective cost control tool. Defining one (or only a few) primary objectives and additional secondary objectives keep the mission design simple and low-cost.

Statement 6: Keeping documentation at an appropriate level lowers the cost and avoids additional administrative and management expenditures.

Usually the design of a small satellite is driven by the given mass and envelope of the available launch opportunity. After design of the satellite bus the resources are distributed to the main (often only) payload — remaining mass, volume and power is given to secondary or other payloads. For a small exploration satellite the approach instead focused on considering the spacecraft as a transportation platform to a given target providing payload capacity. With a low number of selected payloads partners will be incorporated directly into the team structure with direct access to the team management during all phases of the mission without intermediate evaluation committees or additional management entities. After payload selection adjustments of the mission design within the small range of available resources can be made.

The proposed approach reduces compromises due to widely varying types of instruments and experiments and their requirements. Due to a low number of partners the administration and management effort is kept small and stays flexible. Accepting an instrument or technology experiment from a partner who is working under large space organization conditions would establish these conditions within the program and influence costs, administration and schedule — this has to be avoided.

5.2 Proposed Phase Model and Schedule

Common space organization's models of development phases (Phase 0, A-F) are characterized by an important and valuable review at the end or after each phase, an increasing amount of manpower starting from phase 0 (study) to phase D (production) and an increasing amount of time. This is mostly possible due to dedicated and fixed teams (with assigned human resources) during each phase. An academic environment is instead characterized by a mix of temporary and permanent staff involved in teaching, administration as well as additional funded research and therefore only partly available for the project. In addition, temporary team members such as students, PhD students and post-docs can be involved over a period ranging from 6 months to 5 years. These parameters result in a proposed phase model called the ßhifted phase model" consisting of the following phases:

- Phase 0: a very extensive study phase performed by just one or two staff members dedicating up to 50% of their time with student support (thesis, research papers) for 6-18 months (depending on mission complexity). The study results can also be a feasibility study allowing the phase to often be merged with the next phase. Beside of ongoing internal discussions within the program no review takes place. A first mock-up is a possible visible product of this phase.
- Phase A&B: This extensive phase covers the feasibility, definition and design in as detailed manner as possible including preparation necessary for ordering selected hardware (due to the time until delivery). Not all areas are are under investigation at the same time due to limited cash-flow, available staff and PhD positions at any time. Therefore all studies have a shifted starting and end point raising the importance of knowledge management techniques and tools to maintain all important information and data. Also to keep all information updated regularly is crucial. The second half of the phase consists of the Preliminary Design review (PDR) prepared by all available team members with involvement of industrial and institutional partners. An electrically fully functioning prototype or engineering model is a possible visible product of this phase. Due to possible shifts this phase can last from 2 up to 5 years depending on the amount of manpower allocated to the project.
- Phase C&D: The production and development phase must be kept short in order to involve only one generation of team members in the critical integration process and avoid changes in staff positions resulting in loss of important knowledge and experience. Due to the preparation of subsystems and components provision during the final phase all necessary flight hardware is delivered in a very short time frame. This phase mainly focuses on integration of the flight model and therefore lasts only 9-18 months. A Critical Design Review (CDR) is performed at the beginning of the phase in order to make necessary design changes followed by an Acceptance Review (AR) before delivery to the launch site.
- Phase E: The operational phase of an academic small satellite has a typical design lifetime of only one or two years although they often last much longer.

Depending on the existing expertise and facilities an academic small exploration mission can be performed in 4-8 years as a second or third project within an educational program.

5.3 Team Structure

The conditions of an academic environment tends itself to a very small and lean project management team with a dedicated project manager directly negotiating and deciding in coordination with the program manager (usually the head of the institution). PhD students are assigned to specific subsystems (e.g. payload engineer) or areas of work (e.g. systems engineering). Additional staff members are assigned partly to the team to provide additional expertise and support.

The experience necessary to built an Earth orbiting small satellite designed and built by one to two generations of PhD students (depending on the size and complexity) requires a team of one part-time staff person (project manager) and 5-10 PhD students. A small exploration satellite mission covers approx. three generations of PhD students for 6-8 years due to overlap. The experience required for the *LUNAR MISSION BW1* suggests 2-3 permament staff members — one (project manager) involved 100% completely at the end and the others at least 50% of their time. Up to 6 PhD students at the same time should be involved in design or integration, so a number of 12-18 PhD positions in total is suggested. This team is supported by approx. 6-10 student assistants and thesis students per year.

The special situation within an academic environment, requires a mechanism to safeguard the knowledge gained by temporary team members as well as techniques and methods for providing and distributing the information to other and future team members. The usual thesis report is only one important method. New and innovative software tools can support significantly the project communication. Within the Stuttgart Small Satellite Program hardware information databases (hardware tree) were set up to store all available component and subsystem data for each mission. Wiki and PHP based web sites are used to store heterogeneous information of the missions as well as for administrative purposes (e.g. project management). Additional databases like GOLEM and OLIMPIA were initiated during the *LUNAR MISSION BW1* to provide information in support of decision making within the project but are now also being used for participation in future mission proposals.

5.4 Mission Costs

The analysis of former small satellite missions showed the feasibility of a low-cost academic small lunar exploration mission[74, 75, 76]. With respect to existing cost models and cost-reduction strategies[100, 99] the assumptions for the three stages of the *LUNAR MISSION BW1* are:

- Mock-Up: 10,000 - 25,000 Euros, depending on the level of detail (only exterior or including interior boxes symbolizing subsystems and components)
- Prototype: 250,000 - 500,000 Euros, depending on the level of functions (dummy systems with similar characteristics or engineering models of subsystems)
- Flight Model: less than 10 million Euros excluding launch costs

The listed costs do not cover payload costs. Scientific instruments or technology experiments (if not subsystems) are provided by the responsible partner institution. The variations in instrument costs would distort the mission costs significantly. The human resource costs are also not included because most PhD positions are not university funded but covered by scholarships, scientific foundations or industrial partners. Acquisition of funding is an important task of the program and project management. The human resources required are up to 2-3 permanent full staff members for 6-8 years, up to 18 PhD students for three years each and up to 8 student assistants for one year each.

The main constraint of an academic program is the annual cash flow. As such flight hardware orders have to be planned carefully in advance in order to prepare the acquisition of the budget demand of that year. The usage of university facilities for testing as well as having the authority to decide which tests can be simulated, replaced or avoided reduces the costs significantly making the most of the advantage provided by small documentation and higher risk acceptance. Innovative and high performance commercial-off-the-shelf technologies and systems are available at affordable costs but must be qualified to meet the mission requirements by the institution itself. Such systems as well as components provided by partners who are interested in low-cost space qualification reduces the necessary budget. Most information and database tools are available as open source for free or for very low cost if used in an academic environment.

Compared to exploration missions of large space organizations the small team size and short schedule is also cost-reducing. Such cost figures do not make such small exploration satellites a favorable product offered by the space industry; however the results and experience gained by such programs are very interesting for industrial partners.

Chapter 6

Products

"They expect results."
Dr. Raymond Stantz[1]

In this chapter:

- Mock-Up
- Prototype
- Flight Model

The spacecraft is one of the most visible implementations of a program, mission or project and is the result of the design process. The number of models necessary to validate the flight hardware is one identified cost drivers. Therefore, the necessary models have to be built while others must be simulated with respect to the approach in design, risk analysis and project management.

6.1 Mock-Up

A mock-up is often displayed within an educational program but it can also be used for analysis and studies as well as tests. One advantage it has over three dimensional CAD drawings is that a full scale mock-up provides hands-on experience of the size, mass, subsystem positions and integration, accessability and handling of the selected satellite design. The first *LUNAR MISSION BW1* mock-up was built after early configuration analysis[66, 67]. This study proved the feasibility to accomodate all necessary subsystems in the envelope of a 1 m cube based on rough assumptions of the subsystems (see figure 6.1). Structural

[1] played by Dan Aykroyd in: Ghost Busters, 1984, nominated for two Academy Awards (Best Music, Best Effects)[37]

and thermal aspects were not taken into consideration and not all necessary subsystem information were available at that time — early visualizations showed that more than 50% of the satellite's interior will still be available for additional structures, thermal control systems as well as redundancy of subsystems or larger components. The CAD design was the initial point for setting up a data base of component and subsystem information. The first mock-up was also used for important accessibility and handling tests of the mechanical ground support equipment (see figure 6.3) as well as for display at exhibitions (see figure 6.2).

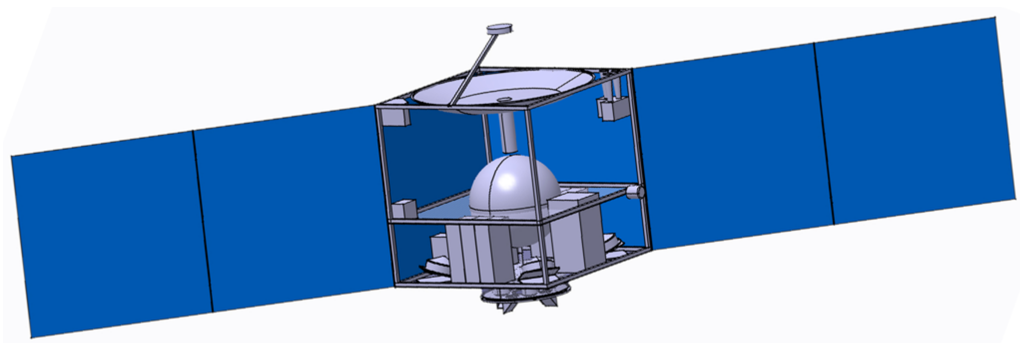

Figure 6.1: Early mock-up configuration[66, 67]

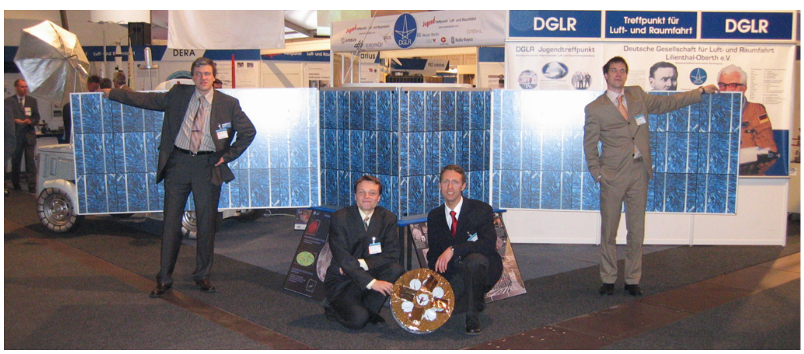

Figure 6.2: First Mock-Up on exhibition[66]

During later stages of subsystem and component configuration, real time accomodation tests were no longer valuable. Changes now took place at a detailed level of size, mass and shape — frequent adaptation of fake boxes were highly time-consuming. The next logical step is a kind of engineering model (Prototype). For public outreach activities as well as payload acoomodation tests a second mock-up was built (see figure 6.4). Due to the fact that only one side will be available for payload the arrangement of each instrument and its alignment and orientation could be demonstrated and discussed. The model does not contain any subsystems or components but gives a highly relistic view of the exterior based on the latest configuration.

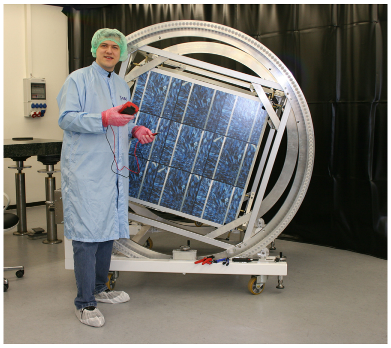

Figure 6.3: MGSE handling test with full scale Mock-Up

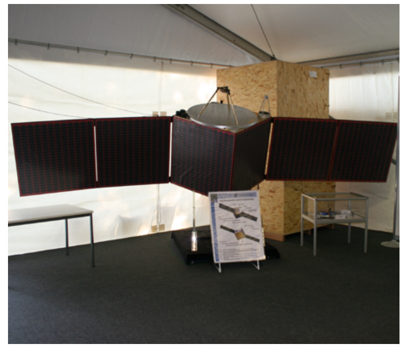

Figure 6.4: Second Mock-Up on exhibition

6.2 Prototype

The next step towards flight hardware is establishing an electrically correct fully functioning model: a prototype. Its main task is to test the integration and handling of subsystems and components, interfaces between subsystems, software and operation of the overall system.

The prototype has to be equipped with engineering models of subsystems or equivalent hardware (e.g. battery dummies with similar input and output parameters and characteristics). Payload instruments are represented by their electronics without detectors and fake boxes replacing optics. For iteration in arrangement of subsystems the prototype in its first stage is not euquipped with the planned sandwich structure. In the beginning an alumnium alloy based structure provides more cababilities for replacing boxes and components regularly for improving in terms of accessability and handling — issues which can not be evaluated easily based on CAD models only. Studies based on stuctural and components analyis[25, 26, 52] finally lead to a proposed design for the prototype model.

For payload tests instruments or engineering models of instruments will be delivered by external partners and tested at the instrument area which is part of the satellite integration laboratory. To protect sensitive electronical or optical components, integration on a separate optical bench is necessary. A similar approach will be used for the propulsion module of the prototype. The fully functional engineering models of the propulsion systems are tested both as a single system and later as a complete module. Due to the inherent danger posed by propellant a replacement with dummy components (e.g. mass dummy for propellant) for integration into the prototype is favorable.

The prototype is an iterative model with many stages due to regular replacement of system dummies by real engineering subsystem models or partly function-

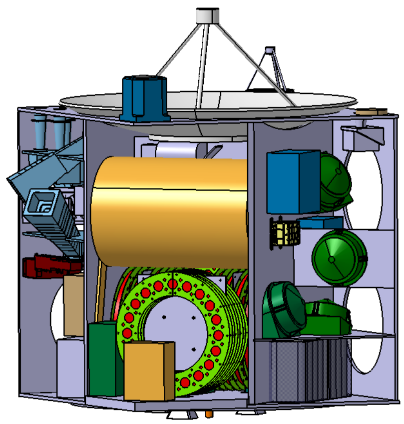

Figure 6.5: Prototype design — View on propulsion module[52]

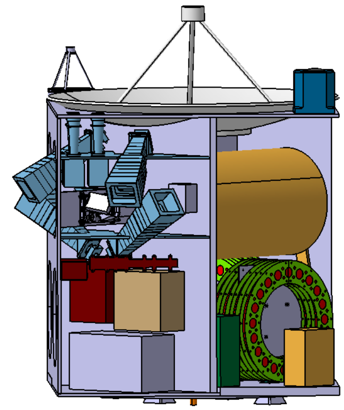

Figure 6.6: Prototype design — View on star trackers and other subsystems[52]

ing subsystem models by fully functioning subsystems — covering the iterative cycles of the V-model of systems design. Therefore it is a very valuable tool towards the final spacecraft accompanying computer-based CAD and simulation models. The prototype provides important and very valuable hands-on information and experience especially as part of an education program for students in the fields of integration planning and procedures, subsystem and component handling as well as in the area of transfer from design to reality.

6.3 Flight Model

The final flight hardware (or flight model, FM) is the visible implemetation of the mission design representing the space segment. Due to cost limitations the classical approach of progressing from engineering model (EM) to one or two flight models (FM1 and FM2 as a flight spare) does not fit the academic environment as discussed previously. Because of using the prototype also for design and implementation the prototype is not used like a traditional engineering model to perform operational and environmental tests in space simulation facilities. Coming from the prototype the decision was made to go with a proto-flight model (PFM) approach.

The proto-flight model is planned to be integrated at the satellite integration facility next to the prototype model. Some subsystems and components will be certified as flight hardware and moved from the late prototype to the proto-flight model (e.g. on-board computer, star trackers, some payload instruments) while others are stored and handled only under clean room conditions using flow boxes or temporary clean room tents. The support and expertise of industrial partners in the field of integration and flight hardware handling as well as the knowledge gained from the *FLYING LAPTOP* and *PERSEUS* missions will be crucial at this phase to work with students and provide hands-on experience.

Like other missions the proto-flight model will be used for environmental tests (loads during launch, space simulation). All subsystems and components will be tested at facilities on campus or at the institute while tests of the complete spacecraft have to be performed at external facilities of partner institutions. The transport to and from test facilities will again provide valuable experience in handling of a mini satellite sized spacecraft (compared to the two micro satellites) before the *LUNAR MISSION BW1* will be shipped to the launch site and finally launched to the Moon.

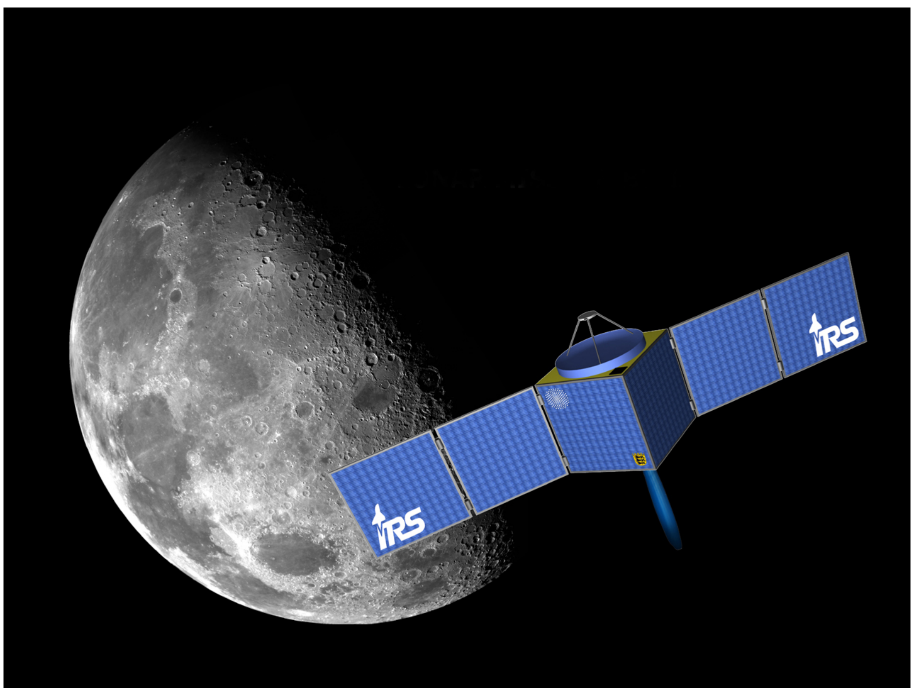

Figure 6.7: LUNAR MISSION BW1 at the Moon (Image: IRS/Univ. Stuttgart (Spacecraft), NASA/JPL/RPIF (Moon)[103])

Chapter 7

Summary

"We've come to the end of our journey"
Rose Sayer[1]

In this chapter:

- Lessons Learned
- Outlook

The *LUNAR MISSION BW1* project demonstrates that an academic institution is able to participate in and contribute to space exploration by designing, building and operating their own spacecraft. The concept of a probe of around 200 kg launch mass and 1 m cube size using in-house development (e.g. electric propulsion systems) and experience from former missions of the Stuttgart Small Satellite Program has been proven. The solar-electric propulsion systems (thermal arcjet, magneto-plasma-dynamical thrusters) are used as main engines on a 18-24 months or longer journey to the Moon. Operating for at least six months from a high inclined low lunar orbit to perform remote sensing and in-situ experiments the mission is concluded with a controlled impact on the lunar surface. The strawman payload focusing on "Dust, Debris and very Small Bodies" offers real scientific return within the limits of a small satellite mission in space and limited ground resources. The mission management approach and methods gained during the project will be valuable for other small satellite missions as well as for graduates and partners of the education program.

[1]played by Katharine Hepburn in: The African Queen, 1951, nominated for four Academy Awards (Best Actor, Best Actress, Best Director, Best Writing), won one Academy Award (Best Actor) — based on: Cecil Scott Forester, *The African Queen*, Little, Brown and Company, 1935[37]

7.1 Lessons Learned

Every project provides lessons learned as a result of experience gained during the process of design, development and implementation. The lessons can and should be incorporated directly into future missions to avoid failures as well as to enhance performance increasing the probabilty of mission success. Also lessons can result in enabling participation in other projects or establishing cooperation with additional institutions. Some lessons provide open unanswered questions which could lead to necessary further missions. A complex project such as the Lunar Mission BW1 within an academic environment provides specific lessons as a result of the program's and project's objectives and the conditions at a university institution.

- In the past, Earth orbiting academic small satellites demonstrated high value as research platforms, technology demonstration tools and educational instruments. On the basis of the increasing new and world wide interest in lunar exploration an academic lunar probe is a next logical step in small satellite development.

  Low-cost lunar small satellite missions offer potential additional flight opportunities to accomplish research experiments and technology demonstrations for validation and verification in spite of their limitations. An important future application can be the installation of lunar infrastructure for exploration (e.g. communication, navigation and monitoring). All these areas are significant contributions to space exploration creating new scientific knowledge and new innovative technology visible within the community and in the public as well as having an enduring effect in the space arena.

- The Lunar Mission BW1 like all projects of the Stuttgart Small Satellite Program is both an experimental and technological platform for demonstrating a different approach in design, engineering, development, management, operation and education with respect to limited human and financial resources as well as spacecraft volume and mass. Only a small satellite mission provides the opportunity to try such a different approach rather than working with or in a large space organization — with the attendant regulations, risks, quality assurance, documentation and more.

- The lunar small satellite project can also be used as an educational tool for the benefit of students to provide hands-on experience in design, integration and operation of a spacecraft while also offering interdisciplinary soft-skills training in team work and project management. The experience gained from previous projects of the Stuttgart Small Satellite Program indicates a direct link between a successful thesis within such a project and excellent career opportunities.

- A small exploration spacecraft mission can be conducted within 6-8 years covered by three generations of PhD students as a part of an educational program with precursor missions following a step-by-step mission approach.

- The mission costs of the flight model should be less than 10 million Euros excluding the launch and instrumentation provided by partners, not covering expenditures for a team of up to 2-3 permanent staff members, up to 12-18 PhD students (3 years each) and up to 8 student assistants (1 year each) for the project time frame described above. This provides one of the primary challenges which is the limited cash-flow of academic institutions and careful budget planning as well as acquisition of funding for human resources. During the first five years of the project four PhD theses directly related to the mission have been submitted, with four more ongoing. Additionally more than 40 diploma theses were completed covering different topics and work packages of the mission accompanied by four man-years of student assistants.

- An adapted project phase model supports cost-reduction as well as the challenge of temporary team members and subsequent knowledge management within an academic environment. Innovative techniques and software tools helps to face the challenge of information and knowledge storage and distribution — with most of these tools available at low costs. Also up-to-date technologies (most commercial-off-the-shelf) are available at affordable costs making a university's lunar orbiter mission feasible today.

- The mission is a starting point for expanding existing and building new networks of industrial and research partners for support and funding. The partners have various interests in such a cooperation: getting well-educated graduate engineers with interdisciplinary hand-on experience, taking flight opportunities for research and technology demonstration experiments, and verifying and validating technologies in space beyond low Earth orbit.

- The Stuttgart Small Satellite Program and the goal of accomplishing an academic lunar exploration mission is creating the visibility and political support needed to seek funding as well as kick-off additional large projects like the Space Center Baden-Wuerttemberg (RZBW). The RZBW is a complete new building providing office space and laboratories for both the institute and collaborators to house and present large projects like SOFIA (Stratospheric Observatory for Infrared Astronomy) or the Stuttgart Small Satellite Program including staff, technicians, PhD and diploma students. The educational and research potential but also the opportunities of political recognition due to possible participation in lunar legal status discussions as well as support for industry created interest of regional and national politics.

Also some partners are interested in such an endeavor because of the opportunity to apply for funding and other support at different sources due to the fact of their participation. Taking limitations in size, expertise or programmatics into account these institutions successfully use the lunar small satellite project as a platform to foster or expand own activities.

- Because of the institute's approach, the lunar small satellite project creates knowledge and expertise in the field of space exploration, small spacecraft development and mission design beyond low Earth orbit. New data bases, information collections and tools provides capabilities beyond subsystem development and mission element analysis.

Already during the process of the project the team has been offered the opportunity to participate in studies and proposals for lunar or planetary exploration missions. Major participations include the areas of small bodies exploration (asteroid sample return[58], NEO mission[7], dust research[84, 82, 83, 81], dust in-situ measurenments and sample return[24, 80], impact research[72]), fundamental physics in the solar system (Pioneer anomaly investigations[90], Heliopause research[82]), Moon and Mars missions (lunar payloads[40, 63, 35], Mars rover[101]). The work package responsibility usually consists of complete mission design as well as spacecraft, trajectory, orbit, communication, payload and cost analysis and design taking into account especially expertise in low-cost small satellite projects.

7.2 Outlook

The *LUNAR MISSION BW1* is not yet built or launched. The current stage of the missions is within phase A&B preparing the set up of the prototype. The focus is set to the integration of the *FLYING LAPTOP* and finalizing the design of *PERSEUS*. Both satellites will provide important experience in integration, testing, operation and validation of subsystems which are important for the Moon orbiter. Every result from both missions will influence the final design of the *LUNAR MISSION BW1*.

Due to the planned schedule for the *LUNAR MISSION BW1* and its educational, technological and research objectives the German Space Agency DLR and the Institute of Space Systems agreed upon intense communication in preparation of DLR's own plans for a national lunar orbiter mission. Even though currently not funded a national lunar orbiter is still at the top of the agenda of the German scientific community.

Finally the *LUNAR MISSION BW1* demonstrates that virtual exploration is not possible — hence it is not a feasible or useful option as an alternative for designing, building and operating an own exploration mission to offer and provide real hands-on experience and real research data as well as space qualified small satellite technology beyond low Earth orbit.

Epilogue

"The irrationality of a thing is not an argument against its existence, rather a condition of it"

FRIEDRICH W. NIETZSCHE[2]

"The exploration of space will go ahead, whether we join in it or not, and it is one of the great adventures of all time"

JOHN F. KENNEDY[3]

There is no final point yet of this project. At present the *LUNAR MISSION BW1* is not yet launched but the first satellite *FLYING LAPTOP* will be integrated and is planned to be launched in 2010. *PERSEUS* should follow 12-18 months later and both teams are working intensly towards the successful achievement of their missions.

This report arose mainly until end of 2008 — many students particpated in related courses, some graduates accomplished their thesis within this project, a few became team members during this period. A network of partners from industry, research and academia interested in the *LUNAR MISSION BW1* was established to support and foster the idea but also accompanied with criticism and advice. Many thanks to all for help and encouragement.

In the beginning a question was raised and the next years will see the next stages of realisation of the *LUNAR MISSION BW1*. This report just tried to give an answer from the intermediate state of work of this project: a small exploration satellite mission can be accomplished by an academic institution, such a mission would have high visibility and can contribute significantly to space exploration, virtual exploration is not an option — because space exploration is one of the great adventures of all time!

René Laufer
Stuttgart and Berlin, 2008/2009

[2]Aphorism 515, From Experience[61]
[3]Speech at Rice University, Houston, Texas, USA, September 12, 1962[41]

Bibliography

[1] Philipp Altenhöfer. *Applications of Magnetic Bearing Reaction Wheels for Attitute Control of Small Satellites during Orbital Maneuvers.* Diploma thesis, Institute of Space Systems (IRS), Univ. Stuttgart, Stuttgart, Germany, 2008. Supervised by O. Zeile, M. Gräßlin, R. Laufer, H.-P. Röser.

[2] Roland Bauernfeind. *Investigation of piezo dust sensors and their application on small satellite missions.* Student research paper, Institute of Space Systems (IRS), Univ. Stuttgart, Stuttgart, Germany, 2007. Supervised by R. Laufer, R. Srama, H.-P. Röser.

[3] Eduard Baumstark. *Prediction of the Orbital Elements and Maneuver Strategies of a Low Lunar Orbit Spacecraft in a Non-spherical Gravitational Field.* Student research paper, Institute of Space Systems (IRS), Univ. Stuttgart, Stuttgart, Germany, 2008. Supervised by M. Lachenmann, O. Zeile, R. Laufer, N. Sneeuw, H.-P. Röser.

[4] BIRA-IASB and ESA/ESTEC TEC-EES. *SPENVIS - Space Environment Information System.* BIRA-IASB Web site. http://www.spenvis.oma.be/spenvis/intro.html.

[5] Dagmar Bock. *Untersuchung eines thermischen Lichtbogentriebwerksystems für die Lunar Mission BW1 — Investigation of a thermal arcjet thruster for the Lunar Mission BW1.* PhD thesis, Institute of Space Systems (IRS), Univ. Stuttgart, 2008.

[6] Ernst E. Both. *A History of Lunar Studies.* Buffalo Museum of Science, Buffalo, NY, USA, 1961. Online available: http://www.lpod.org/?page_id=1593 (Text), http://www.lpod.org/?p=1597 (Picture).

[7] Juan L. Cano and the A-Track Mission Proposal Team. *A-Track Mission Proposal – Proposal in Response to The Planetary Society's Apophis Mission Design Competition*, August 2007.

[8] Surrey Space Center. *Small Satellites Home Page.* SSTL Web site. http://centaur.sstl.co.uk/SSHP/.

[9] Arthur C. Clarke. *Profiles of the Future - An Inquiry into the Limits of the Possible*. Harper & Row, New York, NY, USA, 1962 (revised 1973).

[10] Arthur C. Clarke. *2001: A Space Odyssey*. New American Library, New York, NY, USA, 1968.

[11] Space Studies Board Committee on the Scientific Context for Exploration of the Moon. The scientific context for exploration of the moon. Technical report, National Research Council of the National Academies, Washington, DC, USA, 2007.

[12] Peter Eckart et al. *The Lunar Base Handbook — An Introduction to Lunar Base Design, Development and Operations*. McGraw-Hill Companies, Inc., New York, St. Louis, San Francisco, Auckland, Bogota, Caracas, Lisbon, London, Madrid, Mexico, Milan, Montreal, New Delhi, Paris, San Juan, Singapore, Sydney, Tokyo, Toronto, 1999. Space Technology Series.

[13] ESA/ESOC and ILR/TU Braunschweig. *MASTER — Meteoroid and Space Debris Terrestrial Environment Reference*. ESA/ESOC, Darmstadt, Germany. `http://master-model.org/`.

[14] Albert Falke. *Design of a Power Supply System for a solar-electric Lunar Small Satellite*. Diploma thesis, Institute of Space Systems (IRS), Univ. Stuttgart, Stuttgart, Germany, 2004. Supervised by R. Laufer, M. Hartling, T. Wegmann, H.-P. Röser.

[15] Albert Falke, Markus Gauer, Georg Grillmayer, Manfred Hartling, Felix Huber, Gunter Künhardt, Michael Lengowski, Uwe Putze, Hans-Peter Röser, Maria von Schönermark, Marx Schwarzbach, and Sebastian Walz. *Flying Laptop — Technical Note*. Technical Report FLP-TN-1000-001-IRS, Institute of Space Systems (IRS), Univ. Stuttgart, Stuttgart, Germany, 2005. (May 3, 2005).

[16] Albert Falke, Manfred Hartling, René Laufer, and Hans-Peter Röser. *Implementation of a Simulation Environment for Software & Hardware Simulation of Power Management for a Lunar Small Satelite Mission*. In *55th International Astronautical Congress (IAC), Vancouver, 2004*. International Astronautical Federation (IAF), 2004.

[17] United Nations Office for Outer Space Affairs (UNOOSA). International space law. UNOOSA Web site. `http://www.oosa.unvienna.org/oosa/en/SpaceLaw/index.html`.

[18] European Cooperation for Space Standardization. *Collaboration Website of the European Cooperation for Space Standardization*. Online web data base. `http://www.ecss.nl/`, last visited: December 2008.

[19] X PRIZE Foundation. *Google Lunar X PRIZE*. Online Web page. `http://www.googlelunarxprize.org/, last visited: December 2008`.

[20] Tanya Graf. *Conceptional Design of a Lunar Microlander and corresponding Feasibility Study*. Student research paper, Institute of Space Systems (IRS), Univ. Stuttgart, Stuttgart, Germany, 2005. Supervised by S. Klinkner, R. Laufer, H.-P. Röser.

[21] Michael H. Gräßlin and Hans-Peter Röser. *CERMIT: Controlled Earth Reentry Mini-Vehicle to Improve Technology*. In *55th International Astronautical Congress (IAC), Vancouver, 2004*. International Astronautical Federation (IAF), 2004.

[22] Michael H. Gräßlin and Hans-Peter Röser. *CERMIT – Controlled Earth Re-entry Mini-Vehicle to Improve Technology*. *Space Technology*, 25:189–196, 2005. No. 3-4.

[23] Georg Grillmayer, Michael Lengowski, Sebastian Walz, Hans-Peter Röser, Felix Huber, Maria von Schönermark, and Thomas Wegmann. *Flying Laptop – Micro-Satellite of the University of Stuttgart for Earth Observation and Technology Demonstration*. In *55th International Astronautical Congress (IAC), Vancouver, 2004*. International Astronautical Federation (IAF), 2004.

[24] Eberhard Grün, Ralf Srama, and the DuneXpress Team. *DuneXpress – Mission Proposal in Response to ESA's Cosmic Vision 2015-2025 Call for Mission Ideas*, June 2007.

[25] Richard Haarmann. *Analysis of Different Structure Options for a Lunar Small Satellite*. Student research paper, Institute of Space Systems (IRS), Univ. Stuttgart, Stuttgart, Germany, 2005. Supervised by M. Lengowski, R. Laufer, H.-P. Röser.

[26] Richard Haarmann. *Development and Fabrication of a CFRP Fold Core for the Primary Structure of the Lunar Mission BW1*. Diploma thesis, Institute of Aircraft Design (IFB), Univ. Stuttgart, Stuttgart, Germany, 2007. Supervised by R. Kerle, M. Lengowski, R. Laufer, H.-P. Röser.

[27] Rex D. Hall and David J. Shayler. *Soyuz: A Universal Spacecraft*. Springer, Praxis Publishing Ltd., 2003.

[28] David M. Harland. *Exploring the Moon: The Apollo Expeditions*. Springer, Praxis Publishing Ltd., 1999.

[29] William K. Hartmann and Donald R. Davis. *Satellite-sized planetesimals and lunar origin*. *Icarus*, 24:504–515, April 1975.

[30] Brian Harvey. *Soviet and Russian Lunar Exploration*. Springer, Praxis Publishing Ltd., 2007.

[31] Grant H. Heiken, David T. Vaniman, and Bevan M. French, editors. *Lunar Sourcebook — A User's Guide to the Moon*. Cambridge University Press, Lunar and Planetary Institute (LPI), Houston, TX, USA, 1991.

[32] Olivier Helbig. *Analysis of Scientific Payloads of Lunar Missions*. Student research paper, Institute of Space Systems (IRS), Univ. Stuttgart, Stuttgart, Germany, 2004. Supervised by R. Laufer, H.-P. Röser.

[33] Albert Van Helden and Elizabeth Burr. *The Galileo Project*. Office of the Vice President of Computing of Rice University, TX, USA. `http://galileo.rice.edu/`, last visited: May 2008.

[34] Georg Herdrich, René Laufer, Michael H. Graesslin, and Hans-Peter Roeser. *Key Technologies for Interplanetary Return Missions*. In *DGLR International Symposium 'To Moon and Beyond', Bremen, 2007*. German Society for Aeronautics and Astronautics (DGLR), 2007.

[35] Harald Hiesinger and the SERTIS Team. *Selenial Radiometer and Thermal Infrared Spectrometer (SERTIS) – Instrument Proposal in Response to DLR's Announcement of Opportunity for the LEO Mission*, October 2007.

[36] Alice E. D. Houston and Michael J. Rycroft, editors. *Keys to Space — An interdisciplinary approach to space studies*. McGraw-Hill Companies, Inc., Boston, Burr Ridge, Dubuque, Madison, New York, St. Louis, Bangkok, Bogota, Caracas, Lisbon, London, Madrid, Mexico City, Milan, New Delhi, Seoul, Singapore, Sydney, Taipei, Toronto, 1999.

[37] IMDb.com Inc. *IMDb - Internet Movie Database*. Online Web project. `http://www.imdb.com/`, last visited: May 2008.

[38] Indian Space Research Organisation (ISRO). Polar satellite launch vehicle: Auxiliary satellite user's manual. Technical report, Indian Space Research Organisation (ISRO), Gov. of India (Department of Space), 1999. Doc No: VSSC:PSLV:PR:PM:176/99.

[39] Brad L. Joliff, Mark A. Wieczorek, Charles K. Shearer, and Clive R. Neal, editors. *New Views of the Moon*. The Mineralogical Society of America, Chantilly, VA, USA, 2006. Reviews in Mineralogy and Geochemistry Volume 60.

[40] Sascha Kempf and the LEOPARD Team. *Lunar Exploration Orbiter Particle Detector (LEOPARD) – Instrument Proposal in Response to DLR's Announcement of Opportunity for the LEO Mission*, October 2007.

[41] John F. Kennedy. *Address at Rice University on the Nation's Space Effort*. John. F. Kennedy Presidential Library and Museum, Boston, MA, USA, 1962. Online version of: Public Papers of the Presidents of the United States, Volume 1, 1962, pp. 669-670, Office of Federal Register, `http://www.jfklibrary.org/Historical+Resources/Archives/Reference+Desk/Speeches/JFK/003POF03SpaceEffort09121962.htm`.

[42] A. S. Konopliv, S. W. Asmar, E. Carranza, W. L. Sjogren, and D. N. Yuan. *Recent gravity models as a result of the Lunar Prospector mission*. *Icarus*, 150:1–18, March 2001. Issue 1.

[43] Nils Krafack. *Determination of gravitational and non-gravitational Influences on a Spacecraft in Lunar Orbit*. Diploma thesis, Institute of Space Systems (IRS), Univ. Stuttgart, Stuttgart, Germany, 2004. Supervised by R, Laufer, M. Gräßlin, K. Yazdi, H.-P. Röser.

[44] Michael Lachenmann. *Utilisation of Low-Cost-CMOS-/CCD-Cameras on a Small Satellite for Monitoring and Public Relations*. Diploma thesis, Institute of Space Systems (IRS), Univ. Stuttgart, Stuttgart, Germany, 2006. Supervised by ZZZZZZZZZZ.

[45] Michael Lachenmann, René Laufer, and Hans-Peter Roeser. *Experiments and Instruments of Lunar Mission BW1*. In *European Planetary Science Conference, Potsdam, 2007*. European Planetary Network (EuroPlaNet), 2007.

[46] Jacques Laskar, Frederic Joutel, and Philippe Robutel. *Stabilization of the Earth's obliquity by the Moon*. *Nature*, 361:615–617, February 1993.

[47] René Laufer, Monika Auweter-Kurtz, Michael Lengowski, Anuscheh Nawaz, Hans-Peter Röser, Maria von Schönermark, and Henri P. Wagner. *An All Electrical Small Satellite for a Technology Demonstration and Science Mission to the Moon*. In *55th International Astronautical Congress (IAC), Vancouver, 2004*. International Astronautical Federation (IAF), 2004.

[48] René Laufer, Dagmar Bock, Michael Lachenmann, Hans-Peter Röser, and the Lunar Mission BW1 Project Team. *Academic Small Lunar Satellite Mission Concept and Design*. In *59th International Astronautical Congress (IAC), Glasgow, 2008*. International Astronautical Federation (IAF), 2008.

[49] René Laufer and Hans-Peter Röser. *Die Stuttgarter Mondmission LUNAR MISSION BW1 — Ein Modell für universitäre-industrielle Public-Private-Partnership (The Stuttgart Moon Mission LUNAR MISSION BW1 — A Model of Academic-Industrial Public-Private-Partnership)*. In *Deutscher Luft- und Raumfahrtkongress (German Aerospace Congress), Friedrichshafen, 2005*. German Society for Aeronautics and Astronautics (DGLR), 2005.

[50] René Laufer and Hans-Peter Röser. *Reasons for University Interests in Accomplishing a Lunar Exploration Mission*. In *11th ISU Annual International Symposium, Strasbourg, 2007*. International Space University, Strasbourg, France, 2007.

[51] Federico Letterio. *Optimization of a Satellite Transfer Trajectory with Low Thrust Electric Propulsion From Earth Orbit to an Orbit over the Van Allen Radiation Belt*. Diploma thesis, Institute of Space Systems (IRS), Univ. Stuttgart, Stuttgart, Germany, 2005. Supervised by M. Gräßlin, S. Erb, H.-P. Röser.

[52] Vincent Mariathasan. *Detailed Design of the Primary Structure and Conception of the Engineering Model of the Lunar Mission BW1*. Student research paper, Institute of Space Systems (IRS), Univ. Stuttgart, Stuttgart, Germany, 2008. Supervised by M. Lengowski, M. Lachenmann, R. Laufer, H.-P. Röser.

[53] Nicolas Mateesco Matte. *Aerospace Law*. Sweet and Maxwell, 1969.

[54] Thorsten Maue. *Analysis and interpretation of All-Sky-Camera data*. Diploma thesis, Institute of Space Systems (IRS), Univ. Stuttgart, Stuttgart, Germany, 2006. Supervised by J. Oberst, J. Flohrer, R. Laufer, H.-P. Röser.

[55] Christian Messe. *Development of the Thermal Control Concept and Setup of Analytical Thermal Models of the Lunar Mission BW1*. Student research paper, Institute of Space Systems (IRS), Univ. Stuttgart, Stuttgart, Germany, 2009. To be submitted, Supervised by ZZZZZZZZZZ.

[56] Ernst Messerschmid and Reinhold Bertrand. *Space Stations — Systems and Utilization*. Springer, 1999.

[57] Ernst Messerschmid and Stefanos Fasoulas. *Raumfahrtsysteme (Space Systems)*. Springer, 2000.

[58] Michael Nagy. *Design of a Mission Concept for an Asteroid Sample Return Mission*. Diploma thesis, Institute of Space Systems (IRS), Univ.

Stuttgart, Stuttgart, Germany, 2005. Supervised by U. Johann, R. Förstner, R. Laufer, H.-P. Röser.

[59] Michael Nagy. *Mission Analysis for a Microrover as a Microsatellite Payload landing on the Moon*. Student research paper, Institute of Space Systems (IRS), Univ. Stuttgart, Stuttgart, Germany, 2005. Supervised by S. Klinkner, R. Laufer, H.-P. Röser.

[60] Anuscheh Nawaz. *Aufbau, Charakterisierung und Optimierung eines gepulsten instationären MPD Triebwerks — Design, Characterization and Optimization of a pulsed instationary MPD thruster*. PhD thesis, Institute of Space Systems (IRS), Univ. Stuttgart, 2008.

[61] Friedrich W. Nietzsche. *Menschliches, Allzumenschliches Ein Buch für freie Geister (engl.: Human, All Too Human - A Book for Free Spirits)*. Verlag Ernst Schmeitzner, Chemnitz, Germany, 1878. Online version: `http://www.davemckay.co.uk/philosophy/nietzsche/`.

[62] Jürgen Oberst, Harald Michaelis, R. Schroedter, M. Buhl, J. Ehrich, and M. Rößler. *Meteor Observations from Space with the Smart Panoramic Sensor Head (SPOSH)*. *Small Satellites for Earth Observation: Digest of the 5th International Symposium of the International Academy of Astronautics*, 2005. 5th IAA Symposium on Small Satellites for Earth Observation.

[63] Jürgen Oberst and the SPOSH Team. *Smart Panoramic Optical Sensor Head (SPOSH) – Instrument Proposal in Response to DLR's Announcement of Opportunity for the LEO Mission*, October 2007.

[64] Richard W. Orloff. *Apollo By The Numbers: A Statistical Reference*. NASA History Division, NASA History Division, Washington, DC, USA, 2000. NASA SP-2000-4029, Online available: `http://history.nasa.gov/SP-4029/SP-4029.htm`.

[65] Richard W. Orloff and David M. Harland. *Apollo: The Definitive Sourcebook*. Springer, Praxis Publishing Ltd., 2006.

[66] Sandra Podhajsky. *Modelling of the Subsystems of a Lunar Small Satellite for setting up a Configuration Model in full size scale*. Diploma thesis, Institute of Space Systems (IRS), Univ. Stuttgart, Stuttgart, Germany, 2004. Supervised by R. Laufer, H.-P. Röser.

[67] Sandra Podhajsky, René Laufer, and Hans-Peter Röser. *Modelling of the Subsystems of a Lunar Small Satellite for setting up a Configuration Model in full size scale*. In *55th International Astronautical Congress (IAC), Vancouver, 2004*. International Astronautical Federation (IAF), 2004.

[68] Ralph B. Roncoli. *Lunar Constants and Models Document.* Technical Report JPL D-32296, Jet Propulsion Laboratory (JPL), Pasadena, CA, USA, 2005. (September 23, 2005).

[69] Hans-Peter Röser, Monika Auweter-Kurtz, Henri P. Wagner, René Laufer, Sandra Podhajsky, Thomas Wegmann, and Felix Huber. *Challenges and Innovative Technologies for a Low Cost Lunar Mission.* In *5th IAA International Conference on Low-Cost Planetary Missions, Noordwijk, 2003.* International Academy of Astronautics, Paris, France, 2003. ESA SP-542.

[70] Hans-Peter Röser, Monika Auweter-Kurtz, Henri P. Wagner, René Laufer, Sandra Podhajsky, Thomas Wegmann, and Felix Huber. *Challenges and innovative technologies for a low cost lunar mission.* *Acta Astronautica*, 59:1048–1051, 2006. Issues 8-11.

[71] Hans-Peter Röser and René Laufer. *Das Stuttgarter Kleinsatellitenprogramm — Vom Flying Laptop zur Lunar Mission BW1 (The Stuttgart Small Satellite Program — From Flying Laptop to Lunar Mission BW1).* In *Spring Conference of the Deutsche Physikalischen Gesellschaft (DPG), Heidelberg, 2006.* Deutsche Physikalischen Gesellschaft (DPG), 2006.

[72] Hans-Peter Röser, Rene Laufer, Jürgen Oberst, Joachim Flohrer, Harald Michaelis, Wilfried Tost, and cooperating scientists. *Observations of Lunar Impact Flashes – Proposal for a German Science Foundation (DFG) Research Grant*, April 2007.

[73] Rainer Sandau, Larry Paxton, and Jaime Esper. *Trends and Visions for Small Satellite Missions.* *Small Satellites for Earth Observation — Selected Contributions of the 6th International Symposium of the International Academy of Astronautics*, 2008. 6th IAA Symposium on Small Satellites for Earth Observation.

[74] Rainer Sandau, Hans-Peter Röser, and Arnoldo Valenzuela, editors. *Small Satellites for Earth Observation: Digest of the 4th International Symposium of the International Academy of Astronautics.* Wissenschaft und Technik, 2003.

[75] Rainer Sandau, Hans-Peter Röser, and Arnoldo Valenzuela, editors. *Small Satellites for Earth Observation: Selected Proceedings of the 5th International Symposium of the International Academy of Astronautics.* Gruyter, 2005.

[76] Rainer Sandau, Hans-Peter Röser, and Arnoldo Valenzuela, editors. *Small Satellites for Earth Observation — Selected Contributions of the 6th International Symposium of the International Academy of Astronautics.* Springer, 2008.

[77] Klaus Scherer, Horst Fichtner, Bernd Heber, and Urs Mall, editors. *Space Weather — The Physics behind a Slogan*. Springer, Berlin, Heidelberg, New York, 2005.

[78] David J. Shayler. *Apollo: The Lost and Forgotten Missions*. Springer, Praxis Publishing Ltd., 2002.

[79] R. Srama, T. Stephan, E. Grün, N. Pailer, A. Kearsley, A. Graps, R. Laufer, P. Ehrenfreund, N. Altobelli, K. Altwegg, S. Auer, J. Baggaley, M. J. Burchell, J. Carpenter, L. Colangeli, F. Esposito, S. F. Green, H. Henkel, M. Horanyi, A. Jaeckel, S. Kempf, N. McBride, G. Moragas-Klostermeyer, H. Krüger, P. Palumbo, A. Srowig, M. Trieloff, P. Tsou, Z. Sternovsky, O. Zeile, and H.-P. Röser. *Sample Return of Interstellar Matter (SARIM)*. *Experimental Astronomy*, 2008. DOI 10.1007/s10686-008-9088-7.

[80] Ralf Srama, Eberhard Grün, and the SARIM Dust Team. *Sample Return of Interstellar Matter (SARIM) – Mission Proposal in Response to ESA's Cosmic Vision 2015-2025 Call for Mission Ideas*, June 2007.

[81] Ralf Srama, the Dust, and Debris Analyser Team. *Dust and Debris Analyser (DDA) – Proposal in Response to ESA's Call for Interest (CFI-08-SEP) for Mission Opportunities for Small Payloads on the Columbus Robotic Facility (SPERO)*, April 2008.

[82] Ralf Srama and the HDA Team. *Heliopause Dust Analyser (HDA) – Instrument Proposal in Response to ESA's Cosmic Vision 2015-2025 Call for Mission Ideas*, June 2007.

[83] Ralf Srama and the JEDI Team. *Jupiter Enhanced Dust Instrument (JEDI) – Instrument Proposal in Response to ESA's Cosmic Vision 2015-2025 Call for Mission Ideas*, June 2007.

[84] Ralf Srama and the SOLO Dust Telescope Team. *Solar Orbiter (SOLO) Dust Telescope – Instrument Proposal for the ESA Solar Orbiter Mission*, September 2006.

[85] IRS Scientific Staff. *MoonWiki*. Institute of Space Systems (IRS), Univ. Stuttgart, Stuttgart, Germany. MoonWiki URL.

[86] John P. Stark and Peter W. Fortescue, editors. *Spacecraft Systems Engineering*. John Wiley and Sons, Chichester, West Sussex, UK, second edition, 1995.

[87] Philip J. Stooke. *Neolithic Lunar Maps at Knowth and Baltinglass, Ireland*. *Journal for the History of Astronomy*, XXV:39–55, 1994. Updated online summary: `http://publish.uwo.ca/~pjstooke/knowth.htm`.

[88] Lars Tiedemann. *Observation and Communication Conditions of a Lunar Small Satellite*. Student research paper, Institute of Space Systems (IRS), Univ. Stuttgart, Stuttgart, Germany, 2005. Supervised by R. Laufer, M. von Schönermark, G. Kühnhardt, H.-P. Röser.

[89] Lars Tiedemann. *AdeSat - Structural Design of a Small Satellite*. Diploma thesis, Institute of Aircraft Design (IFB), Univ. Stuttgart, Stuttgart, Germany, 2006. Supervised by G. Schneider, K. Drechsler, H.-P. Röser.

[90] Sebastian Tivig. *Propulsion Concepts for Deep Space Missions with Special Consideration of the Fundamental Physics Mission ENIGMA*. Diploma thesis, Institute of Space Systems (IRS), Univ. Stuttgart, Stuttgart, Germany, 2005. Supervised by U. Johann, R. Förstner, R. Laufer, H.-P. Röser.

[91] Nikolas Trawny. *Mission Scenarios for a Controlled Lunar Impact of a Small Satellite*. Diploma thesis, Institute of Space Systems (IRS), Univ. Stuttgart, Stuttgart, Germany, 2004. Supervised by M. Gräßlin, R. Laufer, H.-P. Röser.

[92] Nikolas Trawny, Michael Gräßlin, René Laufer, and Hans-Peter Röser. *Mission Scenarios for a Controlled LunarImpact of a Small Satellite*. In *55th International Astronautical Congress (IAC), Vancouver, 2004*. International Astronautical Federation (IAF), 2004.

[93] Nikolaos Balteas Udo Renner, Joachim Nauck, editor. *Satellitentechnik: eine Einführung*. Springer, 1988.

[94] Paolo Ulivi and David M. Harland. *Lunar Exploration: Human Pioneers and Robotic Surveyors*. Springer, Praxis Publishing Ltd., 2004.

[95] Jules G. Verne. *De la Terre à la Lune (engl.: From the Earth to the Moon)*. Edition Hetzel, 1865.

[96] Claus Vester. *AstroLink.de - Projekte der Raumfahrt (engl. Space projects)*. Online web project. `http://www.astrolink.de/`, last visited: May 2008.

[97] Wulf von Kries, Bernhard Schmidt-Tedd, and Kai-Uwe Schrogl. *Grundzüge des Raumfahrtrechts — Rahmenbestimmungen und Anwendungsgebiete*. C. H. Beck, 2002.

[98] Mark Wade. *Encyclopedia Astronautica*. Online web project. `http://www.astronautix.com/`, last visited: May 2008.

[99] James R. Wertz and Wiley J. Larson, editors. *Reducing Space Mission Cost*. Microcosm Press, Hawthorne, CA, USA, 1996. Space Technology Library — Space Technology Series.

[100] James R. Wertz and Wiley J. Larson, editors. *Space Mission Analysis and Design*. Microcosm Press, Hawthorne, CA, USA, third edition, 1999. Space Technology Library — Space Technology Series.

[101] Frances Westall, Göstar Klingelhöfer, and the Mars Origins Mission Science Team. *Mars Origins Mission – Mission Proposal in Response to ESA's Cosmic Vision 2015-2025 Call for Mission Ideas*, June 2007.

[102] Don E. Wilhelms. *The Geologic History of the Moon*. United States Government Printing Office, Washington, DC, USA, 1987. U. S. Geological Survey Professional Paper 1348.

[103] David R. Williams. *Chronology of Lunar and Planetary Exploration*. National Space Science Data Center, NASA Goddard Space Flight Center, Greenbelt, MD, USA. `http://nssdc.gsfc.nasa.gov/planetary/chronology.html`, last visited: May 2008.

[104] Anthony Young. *Lunar and Planetary Rovers: The Wheels of Apollo and the Quest for Mars*. Springer, Praxis Publishing Ltd., 2007.

[105] Oliver Zeile. *Feasibility analysis for a small satellite for UV-astronomy*. Student research paper, Institute of Space Systems (IRS), Univ. Stuttgart, Stuttgart, Germany, 2006. Supervised by M. von Schönermark, K. Werner, N. Kappelmann, R. Laufer, H.-P. Röser.

[106] Oliver Zeile, Michael Lachenmann, Eduard Baumstark, Alexandra Mohr, Dagmar Bock, René Laufer, Nicolaas Sneeuw, and Hans-Peter Röser. *Analyses of orbital lifetime and observation conditions of small lunar satellites*. In *59th International Astronautical Congress (IAC), Glasgow, 2008*. International Astronautical Federation (IAF), 2008.

[107] Oliver Zeile, René Laufer, Florian Renk, and Hans-Peter Roeser. *Database and Identification of Design Parameters for the Preliminary Design of Lunar Orbiter and Lander Missions*. In *11th ISU Annual International Symposium, Strasbourg, 2007*. International Space University, Strasbourg, France, 2007.

[108] Andreas Zöllner. *Development of a Low-Thrust Earth-Moon-Trajectory with STK*. Student research paper, Institute of Space Systems (IRS), Univ. Stuttgart, Stuttgart, Germany, 2008. Supervised by M. Lachenmann, O. Zeile, R. Laufer, H.-P. Röser.

Appendix A

Additional Tables

"We need some information."
Vincent[1]

In this appendix:

- Tables

Tables

Information provided by the tables containing data about robotic and human missions of the different phases of lunar exploration are collected carefully. Various sources publish deviating information (e.g. spacecraft mass, orbital data). Data retrieved for the tables should appear consistently at least at two serious sources.

[1]played by Jean Reno in: Ronin, 1998[37]

List of Phase I Missions (1958 – 1968): Early Exploration

Name	Country	Launch Date	Launch Vehicle	Mass [kg]	Type & Date	Remarks
Pioneer 0 (Able 1)	USA	17.08.1958	Thor-Able	38 / 27 (dry) / 11 (pl)	O, —	launch failure
Luna 1958A (E-1/1)	USSR	23.09.1958	R72		I, —	launch failure
Pioneer 1 (Able 2)	USA	11.10.1958	Thor-Able	34 / 23 (dry) / 18 (pl)	O, —	launch failure
Luna 1958B (E-1/2)	USSR	11.10.1958	R72		I, —	launch failure
Pioneer 2 (Able 3)	USA	08.11.1958	Thor-Able	39 / 28 (dry) / 16 (pl)	O, —	launch failure
Luna 1958C (E-1/3)	USSR	04.12.1958	R72		I, —	launch failure
Pioneer 3	USA	06.12.1958	Juno II	6	F, —	launch failure, contact lost
Luna 1 (E-1/4)	USSR	02.01.1959	R72	361	I→F, 04.01.1959	**1st Flyby** 5,995 km
Pioneer 4	USA	03.03.1959	Juno II	6	F, 04.03.1959	60,000 km
Luna 1959A (E-1A/5)	USSR	18.06.1959	R72		I, —	launch failure
Luna 2 (E-1A/6)	USSR	12.09.1959	R72	390	I, 14.09.1959	**1st Impact** (29.1N, 0E)
Luna 3 (E-2A/1)	USSR	04.10.1959	R72	279	F, 06.10.1959	**1st Far Side Pics** 6,200 km, 29 pics
Pioneer P-3 (X, Able 4)	USA	26.11.1959	Atlas-Able	169 / 55 (pl)	O, —	launch failure
Luna 1960A (E-3/1)	USSR	15.04.1960	R72		F, —	launch failure
Luna 1960B (E-3/2)	USSR	19.04.1960	R72		F, —	launch failure
Pioneer P-30 (Y, Able 5A)	USA	25.09.1960	Atlas-Able	176 / 60 (pl)	O, —	launch failure
Pioneer P-31 (Z, Able 5B)	USA	15.12.1960	Atlas-Able	175 / 60 (pl)	O, —	launch failure
Ranger 3 (P-34)	USA	26.01.1962	Atlas-Agena B	330	I/L→F, 28.01.1962	36,800 km, partial failure
Ranger 4 (P-35)	USA	23.04.1962	Atlas-Agena B	331	I/L→I, 26.04.1962	(15.5S, 229.3E), partial failure
Ranger 5 (P-36)	USA	18.10.1962	Atlas-Agena B	342	I/L→F, 20.10.1962	725 km, partial failure
Sputnik 25 (E-6/1)	USSR	04.01.1963	R78		L, —	launch failure
Luna 1963B (E-6/2)	USSR	03.02.1963	R78		L, —	launch failure
Luna 4 (E-6/3)	USSR	02.04.1963	R78	1,422 / 100 (lander)	L→F, 05.04.1963	8,336 km, partial failure
Ranger 6 (A)	USA	30.01.1964	Atlas-Agena B	365	I, 02.02.1964	(9.3N, 21.5E), partial failure
Luna 1964A (E-6/4)	USSR	21.03.1964	R78M		L, —	launch failure
Luna 1964B (E-6/5)	USSR	20.04.1964	R78M		L, —	launch failure
Zond 1964A	USSR	04.06.1964	na			launch failure
Ranger 7 (B)	USA	28.07.1964	Atlas-Agena B	366	I, 31.07.1964	(10.7S, 339.3E), 4,308 pics

Table A.1: List of Phase I Missions (1958 – 1968)[68, 85, 103, 98, 96]

Launch Vehicles: R72 – R7 Luna 8K72, R78 – R-7 Molniya 8K78, R78M – R-7 Molniya 8K78M
Abbreviations: F – Flyby, I – Impact, L – Landing, O – Orbit, dry – dry mass, pl – payload mass, na – not available

Name	Country	Launch Date	Launch Vehicle	Mass [kg]	Type & Date	Remarks
Ranger 8 (C)	USA	17.02.1965	Atlas-Agena B	367	I, 20.02.1965	(2.7N, 24.8E), 7,137 pics
Cosmos 60 (E-6/9)	USSR	12.03.1965	R78	6,530 (?)	L, —	launch failure
Ranger 9 (D)	USA	21.03.1965	Atlas-Agena B	367	I, 24.03.1965	(12.9S, 357.6E), 5,814 pics
Luna 1965A (E-6/8)	USSR	10.04.1965	R78		L, —	launch failure
Luna 5 (E-6/10)	USSR	09.05.1965	R78M	1,474 / 100 (lander)	L→I, 12.05.1965	(31S, 352E), partial failure
Luna 6 (E-6/7)	USSR	08.06.1965	R78M	1,442 / 100 (lander)	L→F, 11.06.1965	159,613 km, partial failure
Zond 3 (3MV-4A/3)	USSR	18.07.1965	R78	960 / na	F, 20.07.1965	9,200 km, 25 pics
Luna 7 (E-6/11)	USSR	04.10.1965	R78	1,504 / 100 (lander)	L→I, 07.10.1965	(9N, 311E), partial failure
Luna 8 (E-6/12)	USSR	03.12.1965	R78	1,550 / 100 (lander)	L→I, 06.12.1965	(9.1N, 296.7E), partial failure
Luna 9 (E-6M/202)	USSR	31.01.1966	R78M	1,538 / 99 (lander)	L, 03.02.1966	**1st Lander** 4 pans, (7.1N, 295.6E)
Cosmos 111 (E-6S/204)	USSR	01.03.1966	R78M	6,540 (?)	O, —	launch failure
Luna 10 (E-6S/206)	USSR	31.03.1966	R78M	1,595 / 245 (orbiter)	O, 03.04.1966 30.05.1966→(I)	**1st Orbiter** 350x1,017 km, 72°
Luna 1966A	USSR	30.04.1966	na			launch failure
Surveyor 1 (A)	USA	30.05.1966	Atlas-Centaur	995 / 294 (dry)	L, 02.06.1966 →13.07.1966	(2.4S, 316.7E), 11,240 pics
Explorer 33 (IMP-D)	USA	01.07.1966	Delta-E	212 / 93 (dry)	O, —	partial failure
Lunar Orbiter 1 (A)	USA	10.08.1966	Atlas-Agena D	386 (?)	O, 14.08.1966 I, 29.10.1966	189x1,867 km, 12°, 229 pics (6.7N, 162E)
Luna 11 (E-6LF/101)	USSR	24.08.1966	R78M	1,638	O, 28.08.1966 01.10.1966→(I)	160x1,200 km, 27°
Surveyor 2 (B)	USA	20.09.1966	Atlas-Centaur	292 (dry)	L→I, 23.09.1966	(5.5N, 348E) landing failure
Luna 12 (E-6LF/102)	USSR	22.10.1966	R78M	1,620	O, 25.10.1966 19.01.1967→(I)	100x1,740 km, 4°
Lunar Orbiter 2 (B)	USA	06.11.1966	Atlas-Agena D	386 (?)	O, 10.11.1966 I, 11.10.1967	196x1,850 km, 12°, 817 pics (4S, 98E)
Luna 13 (E-6M/205)	USSR	21.12.1966	R78M	1,700	L, 24.12.1966	(18.9N, 298.0E)

Table A.2: List of Phase I Missions (1958 – 1968), contd.[68, 85, 103, 98, 96]

Launch Vehicles: R78 – R-7 Molniya 8K78, R78M – R-7 Molniya 8K78M
Abbreviations: F – Flyby, I – Impact, L – Landing, O – Orbit, dry – dry mass, pl – payload mass, na – not available

Name	Country	Launch Date	Launch Vehicle	Mass [kg]	Type & Date	Remarks
Lunar Orbiter 3 (C)	USA	04.02.67	Atlas-Agena D	386 / na	O, 08.02.67 I, 09.10.67	210x1,802 km, 21°, 626 pics (14.6N, 268.3E)
Surveyor 3 (C)	USA	17.04.67	Atlas-Centaur	1,026 / 296 (dry)	L, 20.04.67 →04.05.67	(3.0S, 336.6E), 6,326 pics
Lunar Orbiter 4 (D)	USA	08.05.67	Atlas-Agena D	386 / na	O, 08.05.67 I, 31.10.67	2,706x6,111 km, 86°, 546 pics (330-338E)
Surveyor 4 (D)	USA	14.07.67	Atlas-Centaur	283 (dry)	L→I, 17.07.67	(0.4N, 358.7E), landing failure
Explorer 35 (IMP-E)	USA	19.07.1967	Thor-Delta E1	230 / 104 (dry)	O, 21.07.1967 24.06.73→(I)	484x675 km, 32°
Lunar Orbiter 5 (E)	USA	01.08.67	Atlas-Agena D	386 / na	O, 05.08.67 I, 31.01.68	195x6,023 km, 85°, 844 pics (2.8S, 277E)
Surveyor 5 (E)	USA	08.09.67	Atlas-Centaur	1,006 / 303 (dry)	L, 11.09.67 →17.12.67	(1.5N, 23.2E), 19,118 pics
Zond 1967A (7K-L1/4L)	USSR	27.09.1967	P82	na / na	F, —	launch failure
Surveyor 6 (F)	USA	07.11.67	Atlas-Centaur	1,006 / 300 (dry)	L, 10.11.67 →14.12.67	(0.4N, 358.6E), 29,952 pics
Zond 1967B (7K-L1/5L)	USSR	22.11.1967	P82	na / na	F, —	launch failure
Surveyor 7	USA	07.01.68	Atlas-Centaur	1,039 / 306 (dry)	L, 10.01.68 →21.02.68	(41.0S, 348.6E), 21,038 pics
Luna 1968A (E-6LS/112)	USSR	07.02.1968	R78M		O, —	launch failure
Luna 14 (E-6LS/113)	USSR	07.04.1968	R78M	1,700	O, 10.04.1968 04.1968→(I)	140x870 km, 42°
Zond 1968A (7K-L1/7L)	USSR	22.04.1968	P82	5,390	F, —	launch failure

Table A.3: List of Phase I Missions (1958 – 1968), contd.[68, 85, 103, 98, 96]

Launch Vehicles: P82 – Proton 8K82K/11S824, R78 – R-7 Molniya 8K78, R78M – R-7 Molniya 8K78M
Abbreviations: F – Flyby, I – Impact, L – Landing, O – Orbit, dry – dry mass, pl – payload mass

List of Phase II Missions (1968 – 1976): Complex Missions

Name	Country	Launch Date	Launch Vehicle	Mass [kg]	Type & Date	Remarks
Zond 5 (7K-L1/9L)	USSR	14.09.1968	P82	5,375	F, 18.09.1968	**1st circumlunar flight & recovery**
						1,950 km, biological payload
					E, 21.09.1968	Indian Ocean (32.63S, 65.55E)
Zond 6 (7K-L1/12L)	USSR	10.11.1968	P82	5,375	F, 14.11.1968	2,420 km, biological payload, 1 pic
					E, 17.11.1968	partial failure
Apollo 8 (C')	USA	21.12.1968	Saturn V	28,817 (CSM)	O, 24.12.1968	**1st crewed Orbiter**
						110x112 km, 12°
					E, 27.12.1968	Pacific Ocean (8.13N, 165.02W)
Zond 1969A (7K-L1/13L)	USSR	20.01.1969	P82	6,900	F, —	launch failure
Luna 1969A (E-8/201)	USSR	19.02.1969	P82		L/R, —	launch failure
Zond L1S-1 (7K-L1A/N1-3L)	USSR	21.02.1969	N1	6,900	O, —	launch failure
Luna 1969B (?)	USSR	15.04.1969	P82		S, —	launch failure
Apollo 10 (F)	USA	18.05.1969	Saturn V	28,834 (CSM)	O, 21.05.1969	109x114 km
(Charlie Brown / Snoopy)				13,941 (LM)	23.05.1969→(I)	LM-Descent Stage
					E, 26.05.1969	Pacific Ocean (15.03S, 164.65W)
Luna 1969C (E-8-5/402)	USSR	14.06.1969	P82		S, —	launch failure
Zond L1S-2 (7K-L1A/N1-5L)	USSR	03.07.1969	N1	6,900	O, —	launch failure
Luna 15 (E-8-5/401)	USSR	13.07.1969	P82	2,718	O, 17.07.1969	140x295 km, 126°
					L→I, 21.07.1969	Mare Crisium (17N, 60E)
					S, —	
Apollo 11 (G)	USA	16.07.1969	Saturn V	28,801 (CSM)	O, 19.07.1969	101x122 km, 0°
(Columbia / Eagle)				15,065 (LM)	L, 20.07.1969	**1st crewed landing**
						Mare Tranquilitatis (0.6741N, 23.4730E)
					S, 21.07.1969	1 EVA (2.53 h, 250 m), 21.55 kg
					22.07.1969→(I)	LM-Ascent Stage
					E, 24.07.1969	Pacific Ocean (13.32N, 169.15W)
Zond 7	USSR	07.08.1969	P82	5,379	F, 11.08.1969	1,985 km, biological payload
					E, 14.08.1969	
Cosmos 300	USSR	23.09.1969	P82		S, —	launch failure
Cosmos 305	USSR	22.10.1969	P82		S, —	launch failure
Apollo 12 (H1)	USA	14.11.1969	Saturn V	28,790 (CSM)	O, 18.11.1969	101x123 km, 0°
(Yankee Clipper / Intrepid)				15,116 (LM)	L, 19.11.1969	Oceanus Procellarum (3.0124S, 336.5784E)
					S, 20.11.1969	2 EVA (7.75 h, 1.35 km), 34.35 kg
					I, 20.11.1969	LM-Ascent Stage, (3.94S, 338.80E)
					E, 24.11.1969	Pacific Ocean (15.78S, 165.15W)

Table A.4: List of Phase II Missions (1968 – 1976)[68, 85, 103, 98, 96]

Launch Vehicles: N1 – N1 11A52, P82 – Proton 8K82K/11S824
Abbreviations: E – Earth Re-Entry, F – Flyby, I – Impact, L – Landing, O – Orbit, R – Rover, S – Sample Return, dry – dry mass, pl – payload mass

Name	Country	Launch Date	Launch Vehicle	Mass [kg]	Type & Date	Remarks
Luna 1970A (E-8-5/405)	USSR	06.02.1970	P82		L/S, —	launch failure
Luna 1970B (?)	USSR	19.02.1970	P82		O, —	launch failure
Apollo 13 (H2)	USA	11.04.1970	Saturn V	28,945 (CSM)	O→F, 15.04.1970	115 km, partial failure
				15,196 (LM)	L, —	
					S, —	
					I, —	
(Odyssey / Aquarius)					E, 17.04.1970	Pacific Ocean (21.63S, 165.37W)
Luna 16 (E-8-5/406)	USSR	12.09.1970	P82	5,600	O, 17.09.1970	111x111 km, 70°
					L, 20.09.1970	Mare Fecunditatis (0.68S, 56.3E)
					S, 21.09.1970	101 g, 35 cm depth
					E, 24.09.1970	**1st robotic sample return**
Zond 8 (7k-L1/14)	USSR	20.10.1970	P82	5,375	F, 24.10.1970	1,110 km
					E, 27.10.1970	Indian Ocean
Luna 17 (E-8/203)	USSR	10.11.1970	P82	na / 756 (rover)	O, 15.11.1970	85x85 km, 141°
					L, 17.11.1970	Mare Imbrium (38.21N, 324.80E)
& Lunokhod 1				756 / na	R, 17.11.1970	**1st rover**
						10.54 km, >200 pans, >20,000 pics
					→14.09.1971	Mare Imbrium (38.29N, 324.81E)
Apollo 14 (H3)	USA	31.01.1971	Saturn V	29,229 (CSM)	O, 04.02.1971	
(Kitty Hawk / Antares)				15,277 (LM)	L, 05.02.1971	Fra Mauro (3.6453S, 342.5286E)
					S, 06.02.1971	2 EVA (9.38 h, 3.45 km), 42.28 kg
					I, 08.02.1971	LM-Ascent Stage, (3.42S, 340.33E)
					E, 09.02.1971	Pacific Ocean (27.02S, 172.65W)
Soyuz L3 (7K-LOK&LK/N1-6L)	USSR	26.06.1971	N1	9,850 (LOK)	O, —	launch failure
				5,560 (LK)		
Apollo 15 (J1)	USA	26.07.1971	Saturn V	30,371 (CSM)	O, 29.07.1971	
(Endeavour / Falcon)				16,434 (LM)	L/R, 30.07.1971	**1st crewed rover**
						Hadley Rille (26.1322N, 3.6339E)
					S, 02.08.1971	3 EVA (18.58 h, 27.9 km), 77.31 kg
					I, 03.08.1971	LM-Ascent Stage, (26.36N, 0.25E)
					E, 07.08.1971	Pacific Ocean (26.12N, 158.13W)
& A15 Subsatellite (PFS-1)				26.3 (?)	O, 04.08.1971	102x141 km, 28.5°
					22.01.1973→(I)	
Luna 18 (E-8-5/407)	USSR	02.09.1971	P82	5,600	O, 07.09.1971	100x100 km, 35°
					L→I, 11.09.1971	Mare Fecunditatis (3.57N, 56.5E)
					S, —	
Luna 19 (E-8LS/202)	USSR	28.09.1971	P82	5,810	O, 03.10.1971	140x973 km, 41°
					10.1972→(I)	

Table A.5: List of Phase II Missions (1968 – 1976), contd.[68, 85, 103, 98, 96]

Launch Vehicles: N1 – N1 11A52, P82 – Proton 8K82K/11S824
Abbreviations: E – Earth Re-Entry, F – Flyby, I – Impact, L – Landing, O – Orbit, R – Rover, S – Sample Return, dry – dry mass, pl – payload mass

Name	Country	Launch Date	Launch Vehicle	Mass [kg]	Type & Date	Remarks
Luna 20 (E-8-5/408)	USSR	14.02.1972	P82	5,600	O, 18.02.1972	100x100 km, 65°
					L, 21.02.1972	Mare Fecunditatis (3.53N, 56.55E)
					S, 22.02.1972	30 g
					E, 25.02.1972	
Apollo 16 (J2)	USA	16.04.1972	Saturn V	(CSM) / (LM)	O,	
(Casper / Orion)					L/R, 21.04.1972	Descartes (8.9730S, 15.5002E)
					S,	X EVA (xxx h, xxx km), xxx kg
					→I	LM-Ascent Stage
					E, 27.04.1972	Pacific Ocean (S, W)
& A16 Subsatellite (PFS-2)				36 (?)	O, 24.04.1972	96x122 km, xxx°
					I, 29.05.1972	(10.16N, 111.94E)
Soyuz L3 (7K-LOK&LK/N1-7L)	USSR	23.11.1972	N1	9,850 (LOK)	O, —	launch failure
				5,560 (LK)		
Apollo 17 (J3)	USA	07.12.1972	Saturn V	(CSM) / (LM)	O,	
(America / Challenger)					L/R, 11.12.1972	Taurus-Littrow (20.1908N, 30.7717E)
					S,	X EVA (xxx h, xxx km), xxx kg
					I, 15.12.1972	LM-Ascent Stage, (19.96N, 20.50E)
					E, 19.12.1972	Pacific Ocean (S, W)
Luna 21 (E-8/204)	USSR	08.01.73	P82	na / 840 (rover)	O, 12.01.73	90x100 km, 60°
					L, 15.01.73	(25.85N, 30.45E)
& Lunokhod 2				840 / na	R, 16.01.73	37 km, 86 pans
						>80,000 pics
					→03.06.73	(25.83N, 30.92E)
Explorer 49 (RAE-2)	USA	10.06.73	Delta 1913	328	O, 15.06.73	1,053x1,064 km, 56°
					08.77→(I)	
Luna 22 (E-8LS/220)	USSR	29.05.74	P82	5,835	O, 02.06.74	220x220 km, 20°
					11.74→(I)	
Luna 23 (E-8-5M/410)	USSR	28.10.74	P82	5,300	O, 02.11.74	95x105 km, 130°
					L, 06.11.74	(13N, 62E))
					S, —	partial failure
Luna 1975A (E-8-5M/412)	USSR	16.10.75	P82		S, —	launch failure
Luna 24 (E-8-5M/413)	USSR	09.08.76	P82	5,306	O, 14.08.76	115x115 km, 120°
					L, 18.08.76	(12.75N, 62.2E)
					S, 22.08.76	170 g

Table A.6: List of Phase II Missions (1968 – 1976), contd.[68, 85, 103, 98, 96]

Launch Vehicles: N1 – N1 11A52, P82 – Proton 8K82K/11S824
Abbreviations: E – Earth Re-Entry, I – Impact, L – Landing, O – Orbit, R – Rover, S – Sample Return, dry – dry mass, pl – payload mass

List of Phase III Missions (1989 – 2001): New Views

Name	Country	Launch Date	Launch Vehicle	Mass [kg]	Type & Date	Remarks
Galileo	USA	18.10.1989	STS-34/IUS	3, 881 / 2,380 120 (pl)	F, 08.12.1990 F, 08.12.1992	(EM1) (EM2)
Hiten (Muses-A)	Japan	24.01.1990	Mu-3S-II	185 kg	F, 18.03.1990 I, 10.04.1993	 (34.3S, 55.6E) or (34.0S, 55.3E)
& Hagoromo				12	O, 18.03.1990 →I	partial failure, contact lost
Clementine	USA	25.01.1994	Titan II SLV	458 / 235 (dry) 8 (pl)	O, 19.02.1994 →21.07.1994	400x8,300 km after leaving lunar orbit on 05.05.1994
Cassini AsiaSat 3 (HGS-1)	USA USA	15.10.1997 24.12.1997	Titan IV B Proton-K	5,655 / 2,523 (dry) 2,534	F, 18.08.1999 F, 13.05.1998	
Lunar Prospector (LP)	USA	07.01.1998	Athena-2	295 / 158 (dry) 24 (pl)	O, 11.01.1998 I, 31.07.1999	100x100 km (87.7S, 42.0E)
Nozomi (Planet-B)	Japan	03.07.1998	M-V	540 / 258 (dry) 33 (pl)	F, 24.09.1998 F, 18.12.1998	
MAP	USA	30.06.2001	Delta 7425-10	840 / 768 (dry)	F, 30.07.2001	5,200 km

Table A.7: List of Phase III Missions (1989 – 2001)[68, 85, 103, 98, 96]

Launch Vehicles: IUS – Inertial Upper Stage
Abbreviations: F – Flyby, I – Impact, O – Orbit, dry – dry mass, pl – payload mass

List of Phase IV Missions (since 2003): Return to the Moon

Name	Country	Launch Date	Launch Vehicle	Mass [kg]	Type & Date	Remarks
SMART-1	ESA	2003	Ariane 5	367 / 287 (dry)	O, 15.11.2004	300x3,000 km, 90°
				19 (pl)	I, 03.09.2006	(313.8E, 34.4S)
ARTEMIS	USA	17.02.2007	Delta II	126 / 77 (dry)	F	
(THEMIS B and C)					O	
Kaguya (SELENE)	Japan	14.09.2007	H-2A	2,885 / 1,984 (dry)	O, 03.10.2007	100x100 km, 90°
				300 kg (pl)	O, 01.02.2009	50x50 km, 90°
					I, 10.06.2009	(65.5S, 80.4E)
& Okina (RSAT)				53	O, 09.10.2007	115x2,399 km, 90°
					I, 12.02.2009	Mineur D crater
& Ouna (VSTA)				53	O, 12.10.2007	127x795 km, 90°
Chang'E-1	China	24.10.2007	Long March CZ-3A	2,350 / 130 (pl)	O, 05.11.2007	200x200 km, 64°
					I, 01.03.2009	(S, 52.36E)
Chandrayaan-1	India	22.10.2008	PSLV-XL	1,380 / 523 (dry)	O, 08.11.2008	100x100 km, 90°
				56 (pl)	→29.08.2009	contact lost
& MIP		2008		34 / 29 (dry)	I, 14.11.2008	
Lunar Reconnaissance Orbiter (LRO)	USA	18.06.2009	Atlas V	1,846 / 949 (dry)	O, 23.06.2009	
				92 (pl)	O, 15.09.2009	50x50 km, 90°
& LCROSS		18.06.2009		834 / 534 (dry)	I, 09.10.2009	Cabeus crater
				16 (pl)		
Chang'E-2	China	2010			O	
GRAIL	USA	2011			O	
LADEE	USA	2011		130 (dry) / 20 (pl)	O	

Table A.8: List of Phase IV Missions (since 2003)[68, 85, 103, 98, 96]

Abbreviations: I – Impact, L – Landing, O – Orbit, R – Rover, S – Sample Return, dry – dry mass, pl – payload mass

Name	Country	Launch Date	Launch Vehicle	Mass [kg]	Type & Date	Remarks
Chandrayaan-2	India	2011/12			O/L/R	under development
Lunar Mission BW1	Germany	2012			O/I	under development
Lunar Exploration Orbiter (LEO)	Germany	2012			O	proposed
Luna-Glob 1	Russia	2012			O/L/I	proposed
Luna-Glob 2	Russia	2012			L/R	proposed
Chang'E-3	China	2012/13			L/R	under development
SELENE-2	Japan	2012/2013			O/L/R	proposed
MoonLITE	UK	2013			O/I	proposed
Moonraker	UK	2013			L	proposed
International Lunar Network (ILN) 1	USA	2013			L	under development
International Lunar Network (ILN) 2	USA	2014			L	under development
Luna-Grunt 1	Russia	2014			O/L/R	proposed
Luna-Grunt 2	Russia	2015			L/S	proposed
GLXP teams	various	bef. 2015			L/R	Google Lunar X PRIZE
International Lunar Network (ILN) 3	USA	2016			L	under development
International Lunar Network (ILN) 4	USA	2017			L	under development
Chang'E-4	China	2017			L/S	proposed
Luniy-Poligon	Russia	2020			O/L/R	proposed
?	South Korea	2020			O	proposed
?	South Korea	2025			O	proposed

Table A.9: List of Phase IV Missions (since 2003) contd.[68, 85, 103, 98, 96]

Abbreviations: I – Impact, L – Landing, O – Orbit, R – Rover, S – Sample Return, dry – dry mass, pl – payload mass

Parameter		Value
Satellite Dry Mass		150 kg
Satellite Drag	Coefficient (Cd)	2.2
	Area	1 m^2
Satellite Solar Radiation Pressure (Spherical)	Coefficient (Cd)	1
	Area	5.4 m^2
Satellite Radiation Pressure (Albedo/Thermal)	Coefficient (Cd)	1
	Area	5.4 m^2
Satellite GPS Solar Radiation Pressure	K1	1
	K2	1
Satellite Ammonia Fuel Tank	Tank Pressure	1×10^6 Pa
	Tank Volume	0.01^3
	Tank Temperature	293.15 K
	Fuel Density	700 kg/m^3
	Max. Fuel Mass	166 kg
GTO epoch		Januar 1, 2011, 00:00:00.000 UTCG
GTO semimajor axis	$a_{GTO,GSLV}$	24,468.1 km
GTO eccentricity	$e_{GTO,GSLV}$	0.731972
GTO inclination	$i_{GTO,GSLV}$	19.2°
GTO right ascension of the ascending node (RAAN)	$\Omega_{GTO,GSLV}$	0°
GTO argument of perigee	$\omega_{GTO,GSLV}$	0°
GTO true anomaly	$\vartheta_{GTO,GSLV}$	0°
GTO orbital period	$P_{GTO,GSLV}$	10.5806 h

Table A.10: Lunar Mission BW1 Simulation Parameters[85, 108]

Parameter	SMART-1	LUNAR PROSPECTOR	CLEMENTINE
Launch Mass	367 kg	295 kg	458 kg
Dry Mass	287 kg	158 kg	235 kg
Payload Mass	19 kg	24 kg	8 kg
Size	1.6 m x 1.2 m x 1 m	1.28 m x 1.37 m x 1.37 m	1.88 m x 1.14 m x 1.14 m
Propulsion	Hall-Ion Thruster for Cruise, LOI, OSK	Monopropellant for LOI, OSK	Bipropellant for LOI, OSK
Power	1,850 W	200 W	360 W
Stabilization	3-axis	Spin	3-axis
Communication	S band (Ka/X band)	S band	S band
Orbit	300 km x 3,000 km	100 km x 100 km	400 km x 8,300 km
Costs	100-120 Mio EUR (2001)	63 Mio US$ (1998) 34 Mio US$ (Dev) 25 Mio US$ (Launch) 4 Mio US$ (Ops)	80 Mio US§(1996) 55 Mio US$ (Dev) 20 Mio US$ (Launch) 5 Mio US$ (Ops)
Remark		No OBC	

Table A.11: Lunar probe comparison: SMART-1, LUNAR PROSPECTOR, CLEMENTINE[85, 103, 94]

Appendix B

Mission Team

"I've still got the greatest enthusiasm and confidence in the mission."
HAL9000[1]

In this appendix:

- Lunar Mission BW1 Project Team
- Lunar Mission BW1 Science Team
- Lunar Mission BW1 Operations Team

As described, the team structure is designed to be small and efficient with a lean management approach in order to reduce costs and incorporate graduates and PhD students in many areas of the project.

Lunar Mission BW1 Project Team

The proposed team structure is linked to a work breakdown structure following the tasks of the different project phases.

Program Manager — Head of the Institute of Space Systems

Project Manager — Staff member of the Institute of Space Systems

Project Management — consisting of Administration, Finances, Controlling, Education and Public Outreach, Documentation Management, Frequency Allocation and Launch Campaign

[1]spoken by Douglas Rain in: 2001 - A Space Odyssey, 1968, nominated for four Academy Awards (Best Director, Best Writing, Best Effects, Best Art Direction), won one Academy Award (Best Effects) — based on: Arthur C. Clarke, *2001 - A Space Odyssey*, New American Library, 1968[37]

Mission Engineering — consisting of Mission Analysis, Orbit Analysis, Payload Analysis, Operations Analysis and Launcher Interface

Systems Engineering — consisting of Systems Analysis, Subsystems Interfaces, System Budgets and Payload Interfaces

Systems — consisting of Payload, Attitude COntrol System, On-Board Computer, Power System, Structures & Mechanisms, Thermal Control System, Telemetry & Tracking & Command, Harness and Propulsion (Thermal Arcjet, MPD Thruster)

Integration & Qualification — consisting of MDVE, Integration, Payload Calibration and Qualification & Verification

Mission Operations — consisting of Ground Station, Mission Control, Propulsion Operations and Payload Operations

Lunar Mission BW1 Science Team

The proposed science team structure should support the payload operations. The science team could consist of the following positions:

Program Manager, Project Manager, Mission Operations Manager, Systems Engineer, Payload Engineer, Science Coordinator/Mission Scientist, Payload Scientists and Instrument/Experiment Manager representing their instruments

Lunar Mission BW1 Operations Team

The proposed operations team structure should support the operations of the spacecraft with respect to the payload instruments and technology instruments as well as the spacecraft and ground resources.

Program Manager, Project Manager, Mission Operations Manager, Deputy Mission Operations Manager, Systems Engineer, Spacecraft Operations Engineer, Flight Dynamics Engineer, Attitude Control Engineer, Payload Engineer, Propulsion Engineer, Power Engineer, Thermal Control Engineer, Communications Engineer, Electrical Engineer (On-board Computer, Harness, Interfaces), Ground Station Engineer, Science Coordinator

Appendix C

Publications

"It is not a comedy I'm writing now"
Will Shakespeare[1]

In this appendix:

- Related Publications

Related Publications

R. Laufer, D. Bock, M. Lachenmann, H.-P. Roeser and the Lunar Mission BW1 Project Team (P. Altenhoefer, E. Baumstark, U. Beyermann, F. Boehringer, A. Falke, M. Graesslin, M. Hartling, G. Herdrich, S. Klinkner, M. Lau, M. Lengowski, V. Mariathasan, D. Mehlert, A. Mohr, D. Petkow, M. von Schoenermark, O. Zeile, A. Zoellner). *Academic Small Lunar Satellite Mission Concept and Design*. IAC-08-B4.8.5, 59th International Astronautical Congress (IAC), September 29 October 3, 2008, Glasgow, United Kingdom, 2008.

O. Zeile, M. Lachenmann, E. Baumstark, A. Mohr, D. Bock, R. Laufer, N. Sneeuw, H.-P. Roeser. *Analyses of Orbital Lifetime and Observation Conditions of Small Lunar Satellites*. IAC-08-B4.8.6, 59th International Astronautical Congress (IAC), September 29 October 3, 2008, Glasgow, United Kingdom, 2008.

[1] played by Joseph Fiennes in: Shakespeare in Love, 1998, nominated for 13 Academy Awards (Best Actress, Best Supporting Actor, Best Supporting Actress, Best Picture, Best Director, Best Writing, Best Cinematography, Best Edit, Best Art Direction, Best Costume, Best Makeup, Best Music, Best Sound), won seven Academy Awards (Best Actress, Best Supporting Actress, Best Picture, Best Writing, Best Art Direction, Best Costume, Best Music)

L. H. Surdal, S. Wan, J. S. Almeida, D. K.-W. Chen, M. Laine, O. Stelmakh, L. Fletcher, J. D. Burke, R. Laufer and the Team Noumenia. *The Lunar X Prize A Tool to Catalyze the First Generation of Private Enterprise as well as Governmental Lunar Exploration and Beyond*. IAC-08-B4.8.11, 59th International Astronautical Congress (IAC), September 29 October 3, 2008, Glasgow, United Kingdom, 2008.

J. D. Burke, R. Laufer. *Google Lunar X PRIZE to Stimulate Developing World Projects*. IAC-08-A3.2.A16, 59th International Astronautical Congress (IAC), September 29 October 3, 2008, Glasgow, United Kingdom, 2008.

ISU SSP08 TP Noumenia Team. *Noumenia Building on the Google Lunar X PRIZE: Recommendations for Future Activities on the Moon and Beyond*. Space Studies Program Team Project, June 30 August 29, 2008, Barcelona, Spain, International Space University, Strasbourg, France, 2008.

J. L. Cano, M. Sanchez, N. Sanchez, S. Cornara, F. Cacciatore, A. Rathke, U. Schaefer, R. Lang, R. Lemke, R. Laufer, O. Zeile. *A-TRACK: A Mission to Tag Asteroide Apophis*. New Trends in Astrodynamics and Applications V, Jun 30 July 2, 2007, Milan, Italy, 2007.

R. Laufer. *Indiens erste Reise zum Mond (Indias First Journey to the Moon)*. In: Raumfahrt Concret, 2/2008, Verlag Iniplu 2000, Neubrandenburg, Germany, 2008.

R. Srama, T. Stephan, E. Gruen, N. Pailer, A. Kearsley, A. Graps, R. Laufer, P. Ehrenfreund, N. Altobelli, K. Altwegg, S. Auer, J. Baggaley, M. J. Burchell, J. Carpenter, L. Colangeli, F. Esposito, S. F. Green, Ha. Henkel, M. Horanyi, A. Jaeckel, S. Kempf, N. McBride, G. Moragas-Klostermeyer, H. Krueger, P. Palumbo, A. Srowig, M. Trieloff, P. Tsou, Z. Sternovsky, O. Zeile, H.-P. Roeser. *Sample Return of Interstellar Matter (SARIM)*. Experimental Astronomy, DOI 10.1007/s10686-008-9088-7, Springer, 2008.

D. Bock, G. Herdrich, R. Laufer, A. Nawaz, H.-P. Roeser, O. Zeile. *Electric Propulsion Technology Applications for Future Space Missions*. 12th ISU Annual International Symposium, February 20 22, 2008, Strasbourg, France, 2008.

M. von Schoenermark, H.-P. Roeser, R. Laufer. *50 Jahre Raumfahrt — Vom Sputnik zum universitären Kleinsatelliten (50 Years of Space Flight — From Sputnik to Academic Small Satellites)*. In: Sitzungsberichte der Leibniz-Sozietät der Wissenschaften zu Berlin, Kolloquium '50 Jahre Weltraumforschung', Berlin, September 29, 2007 (submitted).

R. Laufer, H.-P. Roeser and the Lunar Mission BW1 Project Team (D. Bock, F. Boehringer, A. Falke, M. Graesslin, M. Hartling, G. Herdrich, F. Huber, S. Klinkner, H. Kurtz, M. Lachenmann, M. Lengowski, D. Mehlert, A. Nawaz, D. Petkow, M. von Schoenermark, O. Zeile). *Lunar Mission BW1 — An Academic Low-Cost Small Lunar Exploration Satellite.* IAC-07-A3.I.A.03, 58th International Astronautical Congress (IAC), September 24 - 28, 2007, Hyderabad, India, 2007.

R. Laufer, H.-P. Roeser and the Lunar Mission BW1 Project Team (D. Bock, F. Boehringer, A. Falke, M. Graesslin, M. Hartling, G. Herdrich, F. Huber, S. Klinkner, H. Kurtz, M. Lachenmann, M. Lengowski, D. Mehlert, A. Nawaz, D. Petkow, M. von Schoenermark, O. Zeile). *The Stuttgart Moon Orbiter LUNAR MISSION BW1.* 1st CEAS European Air and Space Conference / Deutscher Luft- und Raumfahrtkongress 2007 (German Aerospace Congress 2007), September 10 - 13, 2007, Berlin, Germany, 2007.

R. Laufer, H.-P. Roeser and the Lunar Mission BW1 Project Team (M. Auweter-Kurtz, D. Bock, A. Falke, M. Graesslin, M. Hartling, G. Herdrich, F. Huber, S. Klinkner, H. Kurtz, M. Lachenmann, M. Lengowski, A. Nawaz, M. von Schoenermark, T. Wegmann, O. Zeile). *Objectives and Tasks of Lunar Mission BW1.* EPSC2007-A-00400, 2nd European Planetary Science Congress (EPSC), August 20 - 24, 2007, Potsdam, Germany, 2007.

S. Kempf, R. Srama, G. Moragas-Klostermeyer, H. Henkel, R. Laufer, E. Gruen. *Dust camera for a Lunar orbiter.* EPSC2007-A-00346, 2nd European Planetary Science Congress (EPSC), August 20 - 24, 2007, Potsdam, Germany, 2007.

M. Lachenmann, R. Laufer, H.-P. Roeser. *Experiments and Instruments of Lunar Mission BW1.* EPSC2007-A-00225, 2nd European Planetary Science Congress (EPSC), August 20 - 24, 2007, Potsdam, Germany, 2007.

S. Kempf, R. Srama, G. Moragas-Klostermeyer, H. Henkel, R. Laufer, E. Gruen. *Dust Detector for a Lunar Orbiter.* EGU2007-A-06739P, European Geosciences Union (EGU) General Assembly, April 15 - 20, 2007, Vienna, Austria, 2007.

G. Herdrich, R. Laufer, M. H. Graesslin, H.-P. Roeser. *Key Technologies for Interplanetary Return Missions.* DGLR International Symposium 'To Moon and Beyond", March 14 - 16, 2007, Bremen, Germany, 2007.

R. Laufer, H.-P. Roeser. *Reasons for University Interests in Accomplishing a Lunar Exploration Mission.* 11th ISU Annual International Symposium, February 21 - 23, 2007, Strasbourg, France, 2007.

O. Zeile, R. Laufer, F. Renk, H.-P. Roeser. *Database and Identification of Design Parameters for the Preliminary Design of Lunar Orbiter and Lander Missions*. 11th ISU Annual International Symposium, February 21 - 23, 2007, Strasbourg, France, 2007.

R. Laufer, W. Tost, O. Zeile, H.-P. Roeser. *The Kordylewsky Clouds — An Example for a Lunar Mission BW1 Cruise Phase Observation*. 11th ISU Annual International Symposium, February 21 - 23, 2007, Strasbourg, France, 2007.

R. Haarmann, M. Lengowski, R. Laufer, H.-P. Roeser. *Analysis of Different Structure Options for a Lunar Small Satellite*. IAC-06-B5.6.05, 57th International Astronautical Congress (IAC), October 2 - 6, 2006, Valencia, Spain, 2006.

H.-P. Roeser, M. Auweter-Kurtz, H. P. Wagner, R. Laufer, S. Podhajsky, T. Wegmann and F. Huber. *Challenges and innovative technologies for a low cost lunar mission*. In: Acta Astronautica, Volume 59 (2006), Issues 8-11, pp. 1048-1051, Selected Proceedings of the 5th IAA International Conference on Low Cost Planetary Missions 2003, International Academy of Astronautics, Elsevier Ltd., United Kingdom, 2006.

S. Klinkner, C. G. Lee, R. Laufer. *Destination Moon for the Microrover Nanokhod*. EPSC2006-A-00671P, 1st European Planetary Science Congress (EPSC), September 18 - 20, 2006, Berlin, Germany, 2006.

W. Tost, J. Oberst, J. Flohrer, R. Laufer. *Lunar Impact Flashes: History of observations and recommendations for future campaigns*. EPSC2006-A-00546, 1st European Planetary Science Congress (EPSC), September 18 - 20, 2006, Berlin, Germany, 2006.

R. Laufer, H.-P. Roeser and the Lunar Mission BW1 Project Team (M. Auweter-Kurtz, D. Bock, A. Falke, M. Graesslin, M. Hartling, G. Herdrich, F. Huber, S. Klinkner, H. Kurtz, M. Lengowski, A. Nawaz, M. v. Schoenermark, T. Wegmann). *LUNAR MISSION BW1 — A Small Lunar Exploration and Technology Demonstration Satellite*. EPSC2006-A-00488P, 1st European Planetary Science Congress (EPSC), September 18 - 20, 2006, Berlin, Germany, 2006.

H.-P. Roeser, R. Laufer. *Das Stuttgarter Kleinsatellitenprogramm — Vom Flying Laptop zur Lunar Mission BW1 (The Stuttgart Small Satellite Program — From Flying Laptop to Lunar Mission BW1)*. EP 5.1, Spring Conference 2006 of the Deutsche Physikalischen Gesellschaft (DPG), March 13 - 16, 2006, Heidelberg, Germany, 2006.

S. Klinkner, R. Laufer, T. Graf, M. Nagy, H.-P. Roeser. *Lunar Exploration using Small Satellite with Micro Rover Technology*. 10th ISU Annual International Symposium, November 30 - December 2, 2005, Strasbourg, France, 2005.

R. Laufer, H.-P. Roeser and the Lunar Mission BW1 Project Team (M. Auweter-Kurtz, D. Bock, A. Falke, M. Graesslin, M. Hartling, G. Herdrich, F. Huber, S. Klinkner, H. Kurtz, M. Lengowski, A. Nawaz, M. v. Schoenermark, T. Wegmann). *LUNAR MISSION BW1 — Preliminary Design and Status of an All Electrical Small Satellite Mission to the Moon*. IAC-05-A3.2.B.02, 56th International Astronautical Congress (IAC), October 17 - 21, 2005, Fukuoka, Japan, 2005.

R. Laufer, H.-P. Roeser. *Die Stuttgarter Mondmission LUNAR MISSION BW1 — Ein Modell für universitäre-industrielle Public-Private-Partnership (The Stuttgart Moon Mission LUNAR MISSION BW1 — A Model of Academic-Industrial Public-Private-Partnership)*. Deutscher Luft- und Raumfahrtkongress 2005 (German Aerospace Congress 2005), September 26 - 29, 2005, Friedrichshafen, Germany, 2005.

R. Laufer. *Aufbruch zu einem alten Bekannten — Künftige Missionen zum Erdmond (Decampment to an Old Friend — Future Missions to the Moon)*. In: Raumfahrt Concret, 2/2005, Verlag Iniplu 2000, Neubrandenburg, Germany, 2005.

R. Laufer, H.-P. Roeser and the Lunar Mission BW1 Project Team (M. Auweter-Kurtz, D. Bock, A. Falke, M. Graesslin, M. Hartling, G. Herdrich, F. Huber, H. Kurtz, M. Lengowski, A. Nawaz, M. v. Schoenermark, T. Wegmann). *An Academic Small Satellite Mission beyond Low Earth Orbit — The LUNAR MISSION BW1 of the University of Stuttgart*. IAA-B5-0508P, 5th IAA Symposium on Small Satellites for Earth Observation, April 4 - 8, 2005, Berlin, Germany, 2005.

R. Laufer, H.-P. Roeser and the Lunar Mission BW1 Project Team (M. Auweter-Kurtz, D. Bock, A. Falke, M. Graesslin, M. Hartling, G. Herdrich, F. Huber, H. Kurtz, M. Lengowski, A. Nawaz, S. Podhajsky, M. v. Schoenermark, T. Wegmann). *Small Satellites for Future Cislunar and Lunar Infrastructure — Lunar Mission BW1 of the University of Stuttgart*. 9th ISU Annual International Symposium, November 30 - December 3, 2004, Strasbourg, France, 2004.

R. Laufer, H.-P. Roeser and the Lunar Mission BW1 Project Team (M. Auweter-Kurtz, D. Bock, A. Falke, M. Graesslin, M. Hartling, G. Herdrich, F. Huber, H. Kurtz, M. Lengowski, A. Nawaz, S. Podhajsky, M. v. Schoenermark, T. Wegmann). *Lunar Mission BW1 — A University Small Satellite Mission To The Moon*. 6th International Conference on Exploration and Utilization of the Moon (ICEUM), November 22 - 26, 2004, Udaipur, India, 2004.

R. Laufer, M. Auweter-Kurtz, M. Lengowski, A. Nawaz, H.-P. Roeser, M. v. Schoenermark, H. P. Wagner. *An All Electrical Small Satellite for a Technology Demonstration and Science Mission to the Moon*. IAC-04-IAF-Q.2.b.05, 55th International Astronautical Congress (IAC), October 4 - 8, 2004, Vancouver, Canada, 2004.

A. Falke, M. Hartling, R. Laufer, H.-P. Roeser. *Implementation of a Simulation Environment for Software & Hardware Simulation of Power Management for a Lunar Small Satelite Mission*. IAC-04-IAA.4.11.6.05, 55th International Astronautical Congress (IAC), October 4 - 8, 2004, Vancouver, Canada, 2004.

N. Trawny, M. H. Graesslin, R. Laufer, H.-P. Roeser. *Mission Scenarios for a Controlled Lunar Impact of a Small Satellite*. IAC-04-IAA.4.11.P.05, 55th International Astronautical Congress (IAC), October 4 - 8, 2004, Vancouver, Canada, 2004.

S. Podhajsky, R. Laufer, H.-P. Roeser. *Modelling of the Subsystems of a Lunar Small Satellite for Setting Up a Configuration Model in Full Scale*. IAC-04-IAA.4.11.P.06, 55th International Astronautical Congress (IAC), October 4 - 8, 2004, Vancouver, Canada, 2004.

H.-P. Roeser, M. Auweter-Kurtz, H. P. Wagner, R. Laufer, S. Podhajsky, T. Wegmann, F. Huber. *Challenges and Innovative Technologies for a Low Cost Lunar Mission*. ESA SP-542, 5th IAA International Conference on Low-Cost Planetary Missions, September 24 - 26, 2003, ESTEC, Noordwijk, The Netherlands, 2003.

ISU SSP03 TP Metztli Team. *METZTLI — An International Space Station Approach to Lunar Exploration*. Summer Session Program Team Project, July 5 - September 6, 2003, International Space University, Strasbourg, France, 2003.

R. Laufer. *Effects on Space Activities as a Result of Changes in Scientific Priorities in the Field of Planetary Exloration*. Space Systems Analysis and Design Symposium, August 19, 2003, Summer Session Program, International Space University, Strasbourg, France, 2003.

H. H. Koelle (Editor), D. G. Stephenson (Assistant Editor), S. Abitzsch, U. Apel, H. Benaroya, R. Cesarone, P. Eckart, F. Eilingsfeld, C. Gritzner, N. Jarvstrat, O. Liepack, R. Laufer, R. Lo, M. Mielke, G. Morgenthaler, M. Reichert, E. Repic, E. de Schrijver, W. H. Siegfried, G. Vulpetti. *Preparing for a 21st Century Programme of Integrated, Lunar and Martian Exploration and Development*. 5th Cosmic Study, The International Academy of Astronautics, Paris, France, 2000.

K. Kayal, R. Laufer, A. Lohstoeter. *Entwurf und Betrieb einer Mondstation (engl.: Design and Operations of a Lunar Base)*. ILR-Report 297, Institute of Aeronautics and Astronautics (ILR), Technische Universitaet Berlin, Berlin, Germany, 1995.

Lebenslauf / Curriculum Vitae

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(Personal Details)

Name:	René Laufer
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Staatsangehörigkeit:	Deutsch
Familienstand	Ledig

Ausbildung
(Education)

08/1975 – 07/1979	Besuch der Ernst-Habermann-Grundschule, Berlin-Wilmersdorf
09/1979 – 07/1981	Besuch der Birger-Forell-Grundschule, Berlin-Wilmersdorf
08/1981 – 07/1988	Besuch der Walther-Rathenau-Oberschule, Berlin-Wilmersdorf Abschluß: Allgemeine Hochschulreife (Abitur)
10/1988 – 10/2001	Studium der Luft- und Raumfahrttechnik an der TU Berlin Abschluß: Dipl.-Ing., Luft- und Raumfahrttechnik
07/2003 – 09/2003	International Space University (ISU), Strasbourg, Frankreich, ESA-Stipendiat, Summer Session Programme (SSP)

Berufserfahrung
(Professional Experience)

07/1987 – 08/1987	Praktikum am Fraunhofer-Institut für Betriebsfestigkeit, Darmstadt
07/1988 – 09/1988	Praktikum bei Schindler Aufzügefabrik GmbH, Berlin
01/1990 – 12/1993	Selbständige Tätigkeit im Bereich Veranstaltungsorganisation und -management

08/1993 – 01/2000	Studentischer Mitarbeiter am DLR-Institut für Planetenerkundung (ab 1999: DLR-Institut für Weltraumsensorik und Planetenerkundung), Berlin-Adlershof Missionen und Projekte: *Mars'96, Galileo, Mars Pathfinder, Deep Space 1, Mars Polar Lander Cassini, SOFIA*
02/2000 – 11/2001	Studentischer Mitarbeiter am Institut für Geologie, Geophysik und Geoinformatik der FU Berlin Missionen und Projekte: *Corot, Mars Express*
seit 05/2001	Gastdozent am Institut für Luft- und Raumfahrt der TU Dresden im Fachgebiet Raumfahrtsysteme und Raumfahrtnutzung
12/2001 – 06/2003	Wissenschaftlicher Mitarbeiter am DLR-Institut für Weltraumsensorik und Planetenerkundung, Berlin-Adlershof Missionen und Projekte: *Mars Express*
07/2003 – 05/2009	Wissenschaftlicher Mitarbeiter am Institut für Raumfahrtsysteme der Universität Stuttgart, Bereich: Kleinsatelliten und Bodenstation, Missionen und Projekte: *LUNAR MISSION BW1, PERSEUS, DUNE Staubteleskop, SOFIA*
seit 02/2005	Gastdozent an der International Space University (ISU), Strasbourg, Frankreich im Masters (MSc.) Program sowie im Space Studies Program (SSP)
seit 02/2009	Adjunct Faculty Member der International Space University (ISU)
seit 06/2009	Research Scientist und Leiter des Space Science Lab am Center for Astrophysics, Space Physics and Engineering Research (CASPER) der Baylor University
seit 02/2010	Faculty Member der International Space University