Institute of Space Systems

Status Report
2007 – 2016

Part I

DLR

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Cover Image Final assembly and integration of the microsatellite AISat in the integration clean room of the Institute of Space Systems. AISat is demonstrating technologies to receive the signals of the Automatic Identification System (AIS) of maritime vessels in space. The satellite's most prominent feature is the large helix antenna, which is shown in the image before stowing it in launch configuration.

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Preface

This status report describes DLR's Institute of Space Systems (Institut für Raumfahrtsysteme) and its work, results, and success stories since its foundation in 2007. Furthermore, its objectives and plans for the future five to ten years are outlined. This report serves as documentation for the review of the Institute in December 2016 and consists of two parts. Part I is also used to inform external partners, while Part II contains information for internal purposes. The report contains an overview of the Institute as a whole, describes results achieved with respect to both, the methods developed and contributions to the research programs, and documents the various activities performed.

The Institute of Space Systems was founded in 2007. Its role and mission is to serve as "system developer and integrator". Within the scope of the research and development (R&D) activities of the German Aerospace Center (DLR), the objective of the Institute of Space Systems is the realization of orbital and deep-space scientific missions as well as technology demonstrations in low-Earth orbit. Further key aspects are contributions to advanced developments of expendable and reusable launch vehicles and re-entry vehicles, as well as related propulsion systems. The management and control of the entire design process including the integrated system chain, ranging from the component level through to application-oriented products, is the ambition of the Institute.

The strategic goal of the Institute of Space Systems is to reflect the broad and diverse spectrum of the DLR R&D activities by concentrating on applied scientific and technological space experiments with a feasible economic perspective, having the potential to advance direct application and overall usability. By putting knowledge into practice, the Institute has a coordinating and integrating role within DLR. It is the catalyst for systematic growth and preservation of space system competencies, in particular the activities of system development — system management, system engineering as well as system design, integration, and testing of space assets.

The Institute participates in and coordinates many national and European research projects, and is interacting with industry in the fields of space engineering and technology development. It supports industry and society with expert knowledge concerning a sustainable development. Finally, the Institute contributes to education of young talents.

This report was written by a large team of engineers and scientists. The Institute's director thanks all staff of the Institute for their great dedication and their contributions to the results.

The Institute of Space Systems gratefully acknowledges the productive cooperation and great support received from many partners all over the world and the support by the funding organizations, and looks forward to a prosperous future.

Figure 1: The main (left) and laboratory (right) building of the DLR Institute of Space Systems in Bremen from a bird's eye view.

List of Abbreviations

AAUSAT	Aalborg University Satellite
ACS	attitude control system
ADR-S	Active Debris Removal Service
ADS-B	Automatic Dependent Surveillance – Broadcast
ADS-C	Automatic Dependent Surveillance – Contract
AHP	analytical hierarchy process
AI	assembly/integration
AIDA	Asteroid Impact and Deflection Assessment
AIM	Asteroid Impact Mission
Airbus DS	Airbus Defence and Space
AIS	Automatic Identification System
AISat	Automatic Identification System Satellite
AIT	assembly, integration, and test
AIV	assembly, integration, and verification
AMPI	adaptive multivariate pseudo-spectral interpolation
amu	atomic mass unit
ANGELA	A New Generation Launcher
ANGELA-II	A New Generation Launcher II
AOCS	attitude and orbit control system
AoS	ADS-B over Satellite
ARM	advanced RISC machines
ASIC	application-specific integrated circuit
ASTRA	Ausgewählte Systeme und Technologien für Raumtransport
ASTROD	Astrodynamical Space Test of Relativity using Optical Devices
ATILA	Atmospheric Impact of Launchers
ATLLAS	Aerodynamic and Thermal Load Interactions with Lightweight Advanced Materials for High-Speed Flight
ATON	Autonomous Terrain-Based Optical Navigation
ATV	Automated Transfer Vehicle
AWI	Alfred-Wegener-Institut
BERT	Bemannter Europäischer Raumtransport
BLSS	bio-regenerative life support systems
BOOST	Boost Symmetry Test
BSDU	boom and sail deployment unit
BSP	board support package
C&DH	command & data handling
CAD	computer-aided design
CAN	controller area network
CCC	Compact Control Center
CCSDS	Consultative Committee for Space Data Systems
CDR	Critical Design Review
CE	concurrent engineering
CEA	controlled-environment agriculture
CEF	Concurrent Engineering Facility
CER	cost estimating relationships
CFD	computational fluid dynamics
CFRP	carbon fiber reinforced plastic
CHATT	Cryogenic Hypersonic Advanced Tank Technologies
CMC	ceramic matrix composites
CNES	Centre national d'études spatiales
COBC	Compact On-Board Computer
CoG	center of gravity
CompSat	Compact Satellite
COTS	commercial off-the-shelf
CPS	cyber-physical system
CPU	central processing unit
CROP	Combined Regenerative Organic Food Production
Cryo Lab	Cryogenic Laboratory
CSCU	central spacecraft unit
CSP	CubeSat Space Protocol
CTD	Cryogenic Upper Stage Tank Demonstrator
CTE	coefficient of thermal expansion
DFKI	German Research Center for Artificial Intelligence
DIN	Deutsche Industrie-Norm
DLR	German Aerospace Center
DoF	degrees of freedom
DSL	DLR_School_Lab
E-Box	Electronics Box
EAGLE	Environment for Autonomous GNC Landing Experiments
ECC	error-correcting code
ECSS	European Cooperation for Space Standardization
EDEN	Evolution and Design of Environmentally-Closed Nutrition Sources
EDL	entry, descent, and landing
EEE	electrical and electronics engineering
EGSE	electrical ground support equipment
ELV	expendable launch vehicle
EM	engineering model
EMC	electro-magnetic compatibility
EN	European Norm

Envisat	Environmental Satellite
EPC	Étage Principal Cryotechnique
ESA	European Space Agency
ESTEC	European Space Technology Center
EU	European Union
Eu:CROPIS	Euglena and Combined Regenerative Organic-Food Production in Space
EUROCAE	European Organisation for Civil Aviation Electronics
EVA	extra-vehicular activity
Ex-Lab	explosion-protected laboratory
FAA	Federal Aviation Administration
FACE	Facility for Attitude Control Experiments
FAR	Final Acceptance Review
FAST20XX	Future High-Altitude High-Speed Transport 20XX
FDIR	failure detection, isolation, and recovery
FEM	finite element method
FM	flight model
FMS	flight management system
FPGA	field-programmable gate array
G&C	guidance and control
GEO	geostationary orbit
GNC	guidance, navigation and control
GNSS	global navigation satellite system
GoSolAr	Gossamer Solar Array
GRACE	Gravity Recovery and Climate Experiment
GRACE-FO	Gravity Recovery and Climate Experiment Follow-On
GSOC	German Space Operations Center
GTO	geostationary transfer orbit
HAL	hardware abstraction layer
HDA	hazard detection and avoidance
HEO	highly elliptical orbit
HI-SEAS	Hawaii Space Exploration Analog and Simulation
HIKARI	High-Speed Key Technologies for Future Air Transport
HNS	Hybrid Navigation System
HP3	Heat Flow and Physical Properties Package
HPS	High Performance Satellite Dynamics Simulator
HTHL	horizontal take-off, horizontal landing
HTWG	Hochschule für Technik, Wirtschaft und Gestaltung
HY2	Hayabusa2
HYPMOCES	Hypersonic Morphing for a Cabin Escape System
I4H	Incubator for Habitation
I^2C	inter-integrated circuit
IABG	Industrieanlagen-Betriebsgesellschaft mbH
IAS	Institute d'Astrophysique Spatiale
ICAO	International Civil Aviation Organization
ICD	interface control document
IEC	International Electrotechnical Commission
IGEP	Institute for Geophysics and Extraterrestrial Physics
IMU	inertial measurement unit
INS	inertial navigation system
InSight	Interior Exploration using Seismic Investigations, Geodesy, and Heat Transport
IOD	in-orbit demonstration
IP	intellectual property
ISO	International Organization for Standardization
ISRU	in-situ resource utilization
ISS	International Space Station
ITR	Integrated Technology Roadmap
ITT	Invitation to Tender
JAXA	Japanese Aerospace Exploration Agency
JPL	Jet Propulsion Laboratory
KT	Kennedy-Thorndike
L/D	lift-to-drag ratio
LAMA	Landing & Mobility Test Facility
LAPCAT	Long-Term Advanced Propulsion Concepts and Technologies
LCH_4	liquid methane
LED	light-emitting diode
LEO	low-Earth orbit
LEOP	launch and early orbit phase
LFBB	Liquid Fly-Back Booster
LH_2	liquid hydrogen
LIDAR	light detection and ranging
LISA	Laser Interferometer Space Antenna
LM	lander module
LN_2	liquid nitrogen
LOx	liquid oxygen
LRI	laser ranging instrument
LSS	life support system
M-VCM	Micro-Volatile Condensable Material
MAIT	manufacturing, assembly, integration, and test
MAM	MASCOT Autonomy Manager
MARA	MASCOT Radiometer
MASCAM	MASCOT Camera
MASCOT	Mobile Asteroid Surface Scout

MASMAG	MASCOT Magnetometer
MBSE	model-based systems engineering
MDRS	Mars Desert Research Station
MEO	medium-Earth orbit
MER	Mars Exploration Rover
MESS	mechanical-electrical support system
MLI	multi-layer insulation
MMX	Mars Moon Exploration
MRR	Mission Requirements Review
MSR	Mars Sample Return
MSS	Mars Soil Simulant
mSTAR	miniSpaceTime Asymmetry Research
MUSC	Microgravity User Support Center
NAND	not and
NASA	National Aeronautics and Space Administration
NEA	near-Earth asteroid
NEO	near-Earth object
NGGM	Next Generation Gravity Mission
NGL	Next Generation Launcher
NPL	National Physical Laboratory
NTT	neighbor-trajectory tracking
OBC	on-board computer
OGSE	optical ground support equipment
OOS	on-orbit servicing
OPS	optical proximity sensor
OS	operating system
PA	product assurance
PCB	printed circuit board
PCDU	power conditioning and distribution unit
PDR	Preliminary Design Review
PEC	photoelectrical cell sensor
PRISMA	Prototype Research Instruments and Space Mission Technology Advancement
PRM	preload release mechanism
Proba	Project for On-Board Autonomy
PSA	parametric sensitivity analysis
PSLV	Polar Satellite Launch Vehicle
PSR	primary surveillance radar
PUS	Package Utilization Standard
PWM	pulse width modulation
R&D	research and development
RCE	Remote Component Environment
ReFEx	Reusability Flight Experiment
RF	Radio Frequency
RLV	reusable launch vehicle
ROBEX	Robotic Exploration of Extreme Environments
RTCA	Radio Technical Commission for Aeronautics
RTL	register transfer level
RTOS	real-time operating system
RTU	remote terminal unit
S2TEP	Small Satellite Technology Experiment Platform
SART	search and rescue transponder
SAVOIR	Space AVionics Open Interface aRchitecture
SDR	software-defined radio
SES	Société Européenne des Satellites
SHEFEX	Sharp Edge Flight Experiment
SHEFEX II	Sharp Edge Flight Experiment II
SHEFEX III	Sharp Edge Flight Experiment III
SHPL	Space Habitation Plant Laboratory
SimMoLib	Simulation Model Library
SINPLEX	Small Integrated Navigator for Planetary Exploration
SLME	SpaceLiner main engine
SMPC	simple message passing channel
SoC	system on chip
SOLID	Solar-Generator-Based Impact Detector
SPI	serial peripheral interface
SRAM	static random-access memory
SRR	System Requirements Review
SSME	Space Shuttle main engine
SSO	Sun-synchronous orbit
SSR	secondary surveillance radar
STARS	Laboratory for Sensor Testing and Assessment on a Rotation Simulator
STATIL	Static Tilt Meter
STE-QUEST	Spacetime Explorer and Quantum Equivalence Space Test
STI	SpaceTech Immenstaad
SWOT	strengths, weaknesses, opportunities, threats
SWT	Single Wheel Test Facility
SyDe	System Design Joint Graduate School with Uni Bremen
TEAMS	Test Environment for Applications of Multiple Spacecraft
TEM-A	Thermal Excitation Measurement – Active
TEM-P	Thermal Excitation Measurement – Passive
TLM	Tether Length Measurement
TM/TC	telemetry/telecommand
TMA	triple mirror assembly
TPM	traction prediction model
TPS	thermal protection system
TRL	technology readiness level
TRON	Testbed for Robotic Optical Navigation
TSTO	two-stage-to-orbit

UFFS	ultra-low-cost flash file system
UHF	ultra-high frequency
ULE	ultra-low expansion
US	United States
UV	ultraviolet
UVM	Unified Verification Methodology
VEGA	Vettore Europeo di Generazione Avanzata
VELOX	Verification Experiments for Lunar Oxygen Production
VENUS	Vega New Upper Stage
VF	vertical farming
VGA	video graphics array
VHF	very high frequency
VTHL	vertical take-off, horizontal landing
VTVL	Vertical Take-Off Vertical Landing
X-TRAS	Expertise Raumtransportsysteme
ZARM	Center of Applied Space Technology and Microgravity

Executive Summary

Since its foundation in 2007, the Institute of Space Systems has grown to an institution with more than 150 employees distributed amongst eleven departments of dedicated space system expertise. Together with a broad infrastructure comprising a concurrent engineering facility, an integration hall, and various test laboratories, the Institute provides the perfect environment for developing space systems and system technologies.

Within the scope of the research and development (R&D) activities of the German Aerospace Center (DLR), the objective of the Institute of Space Systems is the realization of orbital and deep-space scientific missions as well as technology demonstrations in low-Earth orbit (LEO). Further key aspects are contributions to advanced developments of expendable, reusable and re-entry vehicles, as well as related propulsion systems.

In order to fulfill its goals and to contribute to DLR's strategy, the Institute of Space Systems has been based on three columns, maximizing transverse knowledge transfer and robust cooperation between the different entities. *System Analysis* provides an overview of space systems as a whole and is therefore one central column of the Institute. The analysis work encompasses both the space transportation field (i. e., launchers, space transportation systems) and the space segment comprising, among others, satellites, planetary landers, large orbital structures, and robotic and human bases on planetary bodies. One key role of *System Analysis* is the assessment and preparation of future missions, technologies and roadmaps for space activities. The implementation of space mission projects is anchored in the second column of the Institute, *System Development*, which executes the detailed design and development on system level. The third column is the *System Technology* focusing on technologies which improve performance, efficiency, and quality of subsystems as well as the overall system.

In order to fulfill its role as a space segment integrator and provide a key element of the system chain, the Institute of Space Systems researches and develops system critical technologies in three fields: satellites, exploration including human space flight, and space transportation. In the field of satellites, the critical subsystems are avionics, including the command & data handling (C&DH), the attitude and orbit control system (AOCS), communication, power, thermal, structure, and the ground segment. In this sector, the Institute of Space Systems focuses on avionics, AOCS and power distribution, while the expertise in the other subsystems is complemented by other institutes of DLR. Similarly, the Institute of Space Systems covers the field of exploration with a focus on landing technology for planetary landings, instrument carriers for on-surface operations as well as regenerative life support systems for human spaceflight. The third working field is space transportation with its critical technological areas: propulsion, propellant management, structures, guidance, navigation and control (GNC), and aerothermodynamics. While the Institute of Space Systems is researching and developing technologies for propellant management and GNC, the necessary expertise is completed by the other DLR institutes.

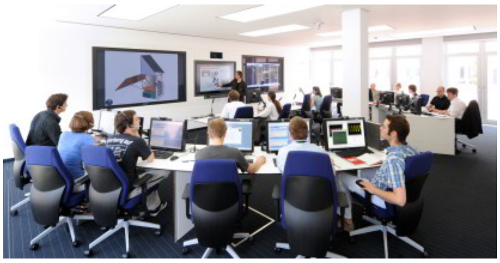


Figure 1: Engineers and scientists in the Concurrent Engineering Facility (CEF) during a feasibility study.

The development of space system technologies closely interacts with space system analysis and system implementation. The available labs and testing facilities create a representative operational environment for many technologies. In addition, a complete set of testing facilities is at hand to qualify components and equipment based on new technologies. Beyond that, most importantly, with its current missions and the upcoming Small Satellite Technology Experiment Platform (S2TEP), there are opportunities to verify new technologies in space. A similar validation of technologies in their relevant environment for space transportation systems is accomplished via future flight experiments such as the Reusability Flight Experiment (ReFEx).

Beside being maintained as stand-alone scientific disciplines aiming for excellence on international level, there are tight interconnections between the three columns.

Leveraging this fruitful collaboration, the Institute has demonstrated its capability to design, manufacture, and qualify space systems as well as conduct entire space missions by accomplishing a remarkable number of achievements over the past nine years. In addition to the establishment of the necessary system competence by combining required disciplines within the Institute, DLR and by collaborating with space industry, the Institute has achieved high-impact scientific results in space technologies.

In less than seven years, the Institute successfully managed to launch its first satellite in June 2014, the Automatic Identification System Satellite (AISat), to monitor high-density ship traffic. In addition, the Institute has expanded its system expertise in the field of interplanetary exploration, being prime developer of the Mobile Asteroid Surface Scout (MASCOT) lander for the near-Earth asteroid sample return mission Hayabusa2 of the Japanese Aerospace Exploration Agency (JAXA). For the Mars mission Interior Exploration using Seismic Investigations, Geodesy, and Heat Transport (InSight) of NASA's Discovery Program, the Institute, in partnership with several other DLR institutes, has built the Heat Flow and Physical Properties Package (HP3) surface science instrument. With Euglena and Combined Regenerative Organic-Food Production in Space (Eu:CROPIS), the Institute is currently preparing its first compact satellite mission to be launched in summer 2017. Also to be mentioned in this context is the "ADS-B over satellite" payload developed in close cooperation with SES Astra and launched in May 2013. It has marked the first step to a global, full-coverage air traffic monitoring system.

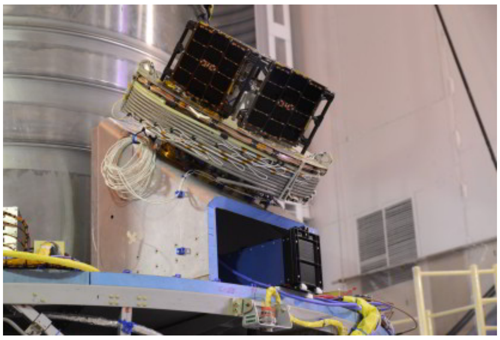


Figure 2: The Institute's first satellite AISat integrated on the launch vehicle.

Further achievements of the Institute were accomplished in the area of system analysis with groundbreaking results in the field of space transportation and the space segment. Besides the purpose of developing conceptual designs, evaluating feasibility, or estimating costs, these studies are also performed as direct consultancy and advice to the DLR executive board, the DLR program directorate as well as to political decision-makers. Study results are also prepared as input for the Ministerial Council of the European Space Agency (ESA).

Together with United States and European industry, human space flight operators, and scientists, DLR conducted a concept concurrent engineering (CE) study to elaborate a program for the time after the International Space Station (ISS) ("Post-ISS") focusing on future low-cost options by evaluating various LEO infrastructure concepts. Exhaustive analysis work was conducted in the frame of the Expertise Raumtransportsysteme (X-TRAS) project including the evaluation of the different concepts for the Ariane 6 proposal in preparation to the ESA Ministerial Council of 2014. Presently, the driving force behind the Institutes reusable launch vehicle (RLV) ambitions is the X-TRAS group with their concept studies on the corresponding European RLV roadmap.

The Institute was successful in acquiring third party funding by coordinating or participating in European Union (EU), ESA or similarly funded projects. On the basis of such projects, new cooperation across Europe was established, which was and is used for new research activities. As an example, the EU FP7 project Cryogenic Hypersonic Advanced Tank Technologies (CHATT), running from 2012 to 2016, based on the SpaceLiner concept, was led by the Institute and had the goal of developing cryotank technologies for hypersonic and RLV systems. Together with European partners, the Institute achieved a leading position in composite cryotank technologies in Europe. In 2011, the Institute launched its in-house research initiative called Evolution and Design of Environmentally-Closed Nutrition Sources (EDEN). A major achievement over the last years is the EU-funded EDEN-ISS project on controlled-environment agriculture technologies, comprising fourteen consortium partners of the leading European experts in the domain of human spaceflight.

The major achievements in space system design and development together with the extensive scientific research in the field of innovative space technologies allowed the Institute to attain a solid foundation and leave it well prepared for future challenges.

Figure 3: The investigation of bio-regenerative life support system technologies within the EDEN Laboratory.

1 The Institute of Space Systems

1.1 Our Mission

Within the scope of the research and development (R&D) activities of the German Aerospace Center (DLR), the objective of the Institute of Space Systems is the realization of orbital and deep-space scientific missions as well as technology demonstrations in low-Earth orbit (LEO). Further key aspects are contributions to advanced developments of expendable, reusable and re-entry vehicles, as well as related propulsion systems. The management and control of the entire design process including the integrated system chain, ranging from the component level through to application-oriented products, is the ambition of the Institute.

A strategy has been agreed upon that commits the Institute of Space Systems to a robust and competitive foundation in order to

- obtain an internationally recognized scientific excellence in space engineering,
- invent and develop innovative space technologies,
- perform space missions with high national and international visibility, as well as
- support and reinforce the German space industry to underpin Germany's ambitious role in space science and technology.

The Institute's strategy assures that information, lessons learned, and capabilities derived from its research benefit the scientific and space communities.

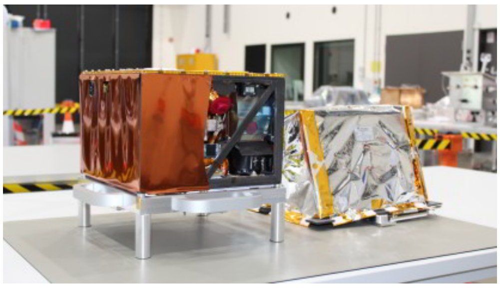


Figure 1.1: Asteroid landing package MASCOT before integration into the Hayabusa2 mother spacecraft.

1.2 Contributions to the Overall DLR Strategy

The German Federal Government strategy pursues the goal to use space activities to respond to global challenges and reach sustainable development, as laid down in the fifth German Space Program. DLR space activities follow this strategy as well as those of the European Commission and the European Space Agency (ESA) with its own developed expertise in climate research, environmental monitoring, communication, safety and security, and other areas. The relevant Helmholtz Association research objectives are supporting DLR's implementation efforts.

In response to this framework, the strategic goal of the Institute of Space Systems is to reflect the broad and diverse spectrum of the DLR R&D activities by concentrating on applied scientific and technological space experiments with a feasible economic perspective, having the potential to advance direct application and overall usability. By putting knowledge into practice, the Institute has a coordinating and integrating role within DLR. It is the catalyst for systematic growth and preservation of space system competencies, in particular the activities of system development — system management, systems engineering as well as system design, integration, and testing of space assets.

1.3 Research Areas

In order to fulfill its mission and to contribute to DLR's strategy, the Institute of Space Systems is based on three columns, maximizing transverse knowledge transfer and robust cooperation between the different entities:

- System Analysis
- System Development
- System Technologies

System Analysis: Encompasses the assessment of advanced space systems (launch vehicles and orbital systems) with respect to their technical performance and cost. It relies on modern methods of multidisciplinary engineering for systems design. Thus, system analysis serves both the design of the Institute's projects as well as providing consultancy and advice to government, industry, and society.

System Development: Underpinning the key core competencies of the Institute in project management and systems engineering (system design, system integration, system verification, and system qualification), innovative space missions are designed and implemented by taking advantage of small and affordable space missions. In the context of DLR R&D, this reflects the increasing interest in small satellites with their relatively low cost and short development times as well as the expressed will to put DLR research Institutes into the position to conduct their own science and/or technology experiments in space. They are considered crucial contributors to satisfying the DLR R&D research strategy. In addition, missions for the scientific exploration of space as well as R&D for future space transportation are implemented to support DLR's research agenda in these fields.

System Technologies: To enable future advanced space missions and/or to improve existing technologies in terms of performance and quality, the Institute of Space Systems conducts research into relevant system technologies with a wide range of highly innovative and emerging technologies, such as cryogenic propellant management, landing technologies, guidance, navigation and control systems, avionics systems, and high-precision optical measurement systems, adopting an agenda for sustainable development goals.

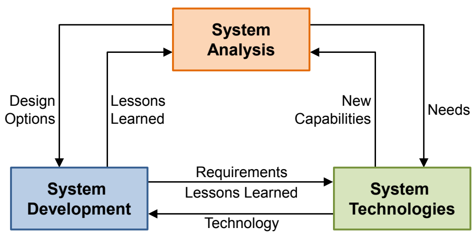


Figure 1.2: Interconnection between systems analysis, system development and system technologies.

Interconnections: As figure 1.2 indicates, space system analysis — especially of future missions — impacts the technology development by defining the needs for new capabilities and increased performance. The development and implementation of space systems and missions demands technological solutions to meet the mission requirements. System analysis also delivers exact requirements as a target for technology developments. Furthermore, the implementation and execution of space missions provides valuable lessons learned as well as the needs for improvements on system and subsystem level.

In turn, R&D on system technologies is returning new solutions and technologies to be considered in system analysis and to be integrated in space missions. They enable both fields — system analysis and system development — to generate new solutions on system level and to explore new areas. Moreover, R&D on system technologies is generating a deep insight and a profound background knowledge on subsystems and their technologies which is necessary to conduct system analysis as well as system development and implementation on a cutting-edge level.

The Institute supports developments from small equipment products to full space systems and transforms R&D investments into possible future products and services and, as such, is maintaining and improving its capabilities and competitiveness. It will continue to consolidate user needs, observe market trends and identify possible future space technology options to react and to contribute to the very dynamic and competitive global marketplace with appropriate space technologies and developments.

The Institute of Space Systems is conscious of its responsibility towards society in a high-level investments area as it is providing in return cutting-edge scientific research, technology developments, and consultancy services in a core area of national interest.

1.3.1 System Analysis

System analysis is a mandatory engineering activity to assess and prepare future missions, technologies, and roadmaps for space activities. Careful analysis, among other aspects, allows to identify new technologies, which allow new missions or better mission performance, to effectively plan mission scenarios and the interaction of mission elements, and to identify development needs for future space activities.

System analysis provides orientation and, therefore, is one central column of the Institute of Space Systems. The analysis work encompasses both the space transportation field, such as launchers, advanced (partially) reusable space transportation systems, but also the space segment, comprising satellites, planetary landers, large orbital structures, and robotic and human bases on planetary bodies (e. g. Moon or Mars).

The spectrum of activities ranges from stand-alone preliminary studies to critical analysis and assessment of new concepts and plausibility verification of published launcher data of launch providers worldwide. The respective results often serve as input for the DLR executive board and political panels. The consultancy is independent and covers all types of large-scale future space activities.

System analysis is a multidisciplinary activity, as all aspects of a study subject need to be addressed, among others, mission and trajectory analysis (or optimization), structural engineering, thermal control, preliminary aerodynamic design, and propulsion systems. The integration of vehicle and rocket engine analysis within a single team is a unique quality within the German space sector.

Computer-aided analysis, simulations, and optimization methods are a vital part of the system analysis. Especially the utilization of the Concurrent Engineering Facility (CEF) (see section 2.2.1) allows fast, efficient, and thorough design of systems and concepts. The concurrent engineering process allows cost reduction and time savings, and incorporates all relevant analysis domains, for example costs, technical subsystems, and orbit analysis. It allows analysis of feasibility and support of further development work.

Figure 1.3: Orbital-Hub Free Flyer as possible Post-ISS approach.

The long-term subjects under investigation in the system analysis column are:

- How will future space systems look like, what are new relevant technologies, how does the performance compare to current technological solutions?
- How can the future of human spaceflight be shaped in LEO, beyond, and as permanent outpost on other planetary bodies (e. g. Moon) with special emphasis on life support systems and an overall system view?
- How can the concurrent engineering (CE) process be further evolved to increase its performance and allow the continuous application in system design phases beyond Phase A?
- How to make access to space more affordable, more reliable, and accessible to a broader client base, what could be new applications for space transportation, and what are the necessary steps and technologies to develop such systems?

Answering these questions involves review of technology (concepts), missions, space politics, and methods to be enhanced and further developed.

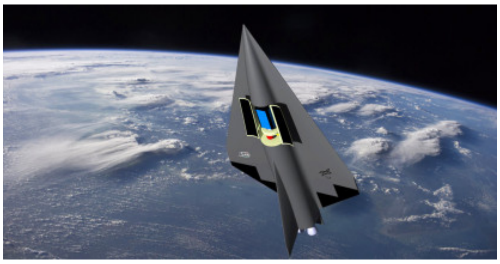


Figure 1.4: Artist's impression of satellite payload release from SpaceLiner 7 Orbiter's open payload bay in low-Earth orbit (LEO).

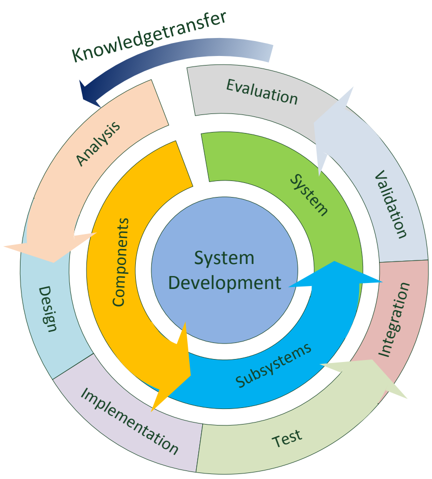


Figure 1.5: The life cycle of system development from analysis on component level to the final verification and evaluation of the integrated system. The lessons learned of each project should be transferred to the next one, thus closing the process loop to maintain knowledge within the Institute.

1.3.2 System Development

Space mission projects are key elements of the Institute to realize space systems which comprise satellites, landing systems, and reusable space transportation systems. The goal is to provide a proof of concept for innovative key technologies in response to increasingly demanding parameters of future space applications such as attitude control precision, electrical power provision for deep space missions, thermal regulation, and stability to support fundamental physics experiments in space and exploration of the Solar System. Within the Institute's main scientific and technological operating areas stands the system development as one of the three main columns. It is closely connected via core processes with the other columns "system analysis" and "technology development". Among these core processes, project development is the most prominent one. It is an end-to-end ("planning, building, testing") process that allows to identify, evaluate, and improve the impact of each subsystem and processes to optimize the overall satellite system performance.

In addition to the development of complete space systems, the Institute performs in-depth development of subsystems to advance the state of the art of selected fields (e. g. data management, power management, and high-precision thermal control subsystems) and to investigate ways to improve the level of system/subsystem/instrument interaction (e. g. to increase the failure robustness while decreasing the overall system complexity and cost). As a side effect, this approach allows to collect, evaluate, and maintain lessons learned on a complete mission scale. The subsystem and technology developments are performed on department level, whereas complete space systems are under the responsibility of the Institute as a whole.

The Institute has demonstrated its ability to design, develop, and build (end-to-end) a system with the successful launch of the Automatic Identification System Satellite (AISat) (section 3.3.4) and the Mobile Asteroid Surface Scout (MASCOT) lander (section 3.4.1) aboard the Hayabusa2 spacecraft of the Japanese Aerospace Exploration Agency (JAXA) in 2014. Both space systems are the in-flight proof of an innovative platform concept in the nanosize class (total mass approximately 10 kg) that is highly flexible to accommodate and operate several small scientific payloads.

The AISat project has realized its prime objective to find a cost-effective approach by using commercial off-the-shelf (COTS) available CubeSat components. The MASCOT project has demonstrated the possibility to realize a lander for deep-space exploration within a short time of only three years from Phase B to D by using a tailored systems engineering and assembly, integration, and verification (AIV) process via a parallel test track approach.

The goal is to implement the knowledge and the processes that were gained and validated in the AISat and MASCOT projects in the core disciplines of system development: systems engineering, AIV, and product assurance (PA) for the next projects of the Institute such as the Small Satellite Technology Experiment Platform (S2TEP) and the Reusability Flight Experiment (ReFEx) as described in sections 3.3.6 and 3.5, respectively. Challenges on the system development of future space systems are, among others:

1. How can we reduce the time and financial resources needed for development?
2. How can we improve system reliability?
3. How can we improve reactions on failures and non-nominal conditions, i. e., failure detection, isolation, and recovery (FDIR)?
4. How can we increase system autonomy for deep-space missions?

These system aspects are not only achieved by technology development of single subsystems, but need to be validated in an integrated in-space demonstration. Therefore, additional demand exists for different approaches and innovative technologies to be tested early concerning their use in space. To this end, the Institute focuses its satellite strategy on small satellites with a mass between ten and 250 kg. This strategy is regarded as a way to implement and test new technologies at acceptable costs and risks. This satellite strategy will be complemented by planetary landing systems and demonstrators for reusable launch systems.

Since the foundation of the Institute of Space Systems, a continuous optimization and improvement of the relevant infrastructure such as integration and test facilities (sections 3.2.1, 3.2.2, and 3.2.3) and core processes (figure 3.1 on page 38) for systems development took place. In addition, to cope with the aforementioned challenges of future space systems, the Institute will focus on respective research fields which are, among others, the development of robust thermal control systems for satellites and advanced production techniques to reduce the development time and costs of a project.

Figure 1.6: The Institute's large clean room for space system integration.

1.3.3 System Technologies

The research and development of system technologies is a mandatory activity when striving to improve space systems and their performance. In line with the Institute's goals, the development focuses on space systems by delivering technologies which are improving performance, efficiency, and quality of subsystems as well as the overall system.

Being able to implement and integrate space missions requires the capability to manage and control critical system and subsystem technologies. An overarching challenge across all technology domains is the space environment with its harsh conditions for structures on launchers, the unique environment of low gravity, vacuum, and high-energy radiation as well as vastly varying requirements depending on missions and payloads.

Within this setting, DLR is focusing on the capability to research, develop, and integrate the complete system chain of space systems from component level to the final demand-oriented information product (e. g. in Earth observation). In order to fulfill its role as a space segment integrator and provide one key element of the system chain, the Institute of Space Systems researches and develops system-critical technologies in three fields: satellites, exploration including human space flight, and space transportation.

In the field of satellites, the critical subsystems are avionics, including the command & data handling (C&DH), the attitude and orbit control system (AOCS), communication, power, thermal, structure, and the ground segment. In this sector, the Institute of Space System focuses on avionics, AOCS, and power distribution, while the expertise in the other subsystems is complemented by other institutes of DLR, for example the Institute of Communication and Navigation for communications and the German Space Operations Center (GSOC) for ground segment and operations.

Similarly, the Institute of Space Systems covers the field of exploration with a focus on landing technology for planetary landings, instrument carriers for on-surface operations as well as regenerative life support systems for human spaceflight. Again, the expertise is complemented by other institutes, such as the Microgravity User Support Center (MUSC) for operations and the Institute of Aerospace Medicine.

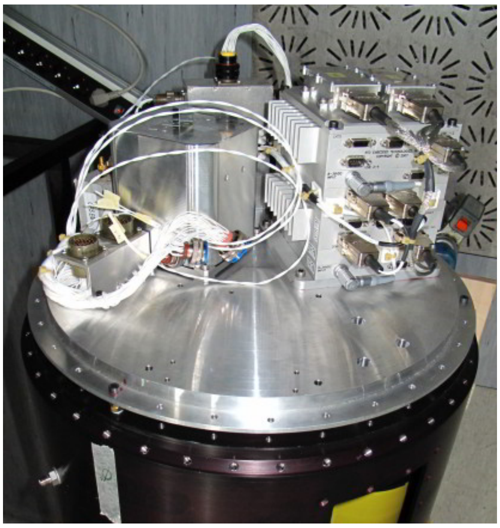


Figure 1.7: Flight model of the Hybrid Navigation System (HNS) during integration into the SHEFEX II vehicle. Hybrid navigation is one of the technologies for future space transportation systems, which has been demonstrated within the SHEFEX II mission.

The third working field is space transportation with its critical technology areas: propulsion, propellant management, structures, guidance, navigation and control (GNC), and aerothermodynamics. While the Institute of Space Systems is researching and developing technologies for propellant management and GNC, the expertise is completed by the Institute of Space Propulsion, the Institute of Structures and Design, and the Institute of Aerodynamics and Flow Technology.

For each of the three fields, general research questions for space system technologies exist which need to be addressed in the next five to ten years:

- Satellites: How can technologies for small satellites be improved to be more flexible and at the same time more efficient in cost and time? How can the performance of subsystems and payloads be increased?
- Exploration and Human Space Flight: How can landing probes be improved to be more precise and safe? How can the human exploration of space be supported with biological closed-loop life support systems? What is the system cost of this innovation?
- Space Transportation: How can cryogenic propellant management technologies be improved to enable future mission needs such as ballistic flight phases with multiple re-ignitions and long-duration missions? How can reusable space transportation systems be made more efficient and more flexible?

For all the new technologies which will be developed to answer these research questions, the same challenges remain as in the last six decades of spaceflight. First of all, the new technologies have to be engineered to survive and to be operated in the hostile space environment. Furthermore, in contrast to other areas like aeronautics or automotive, there is usually no series of prototypes which can be extensively tested in the operational environment to allow maturing of the technologies. So all space system technologies have to climb up step by step to the needed technology readiness level before being considered for a mission.

The Institute of Space Systems provides the perfect environment for developing space system technologies. The development closely interacts with space system analysis and system implementation. Labs and testing facilities are available to create a representative operational environment for many technologies. A complete set of testing facilities is at hand to qualify components and equipment based on new technologies. Beyond that, most importantly, with its past missions and the upcoming S2TEP there are opportunities to verify new technologies in space.

1.4 Major Achievements

Despite being a young Institute founded in 2007, a remarkable number of major achievements were accomplished over the past nine years. In addition to scientific results in space technologies, the Institute successfully established the necessary system competence to accomplish space missions by combining required disciplines within the Institute, DLR, and by collaborating with space industry. In less than seven years, the Institute successfully managed to launch its first satellite and contributed to an international science mission by providing an asteroid lander module, among many other activities.

But not only scientific work, space missions and projects are an indicator for the outstanding performance. Over the last nine years, the Institute grew to an institution with more than 150 employees capable of designing, manufacturing, and qualifying space systems as well as executing entire space missions. In addition, the infrastructure comprising a concurrent engineering facility, an integration hall, and various test laboratories was planned and put into operation, enabling the realization of orbital or even interplanetary missions.

The numerous achievements in system analysis as well as system and technology development are documented in detail in the following chapters. Nonetheless, developments that reveal the Institute's capabilities and that are cornerstones in representing the Institute and DLR in the scientific community and space business shall briefly be highlighted hereafter.

Missions and Payloads

On June 30, 2014, after less than four years of development, AISat, the first satellite of the Institute, was launched with the Polar Satellite Launch Vehicle (PSLV) C-23 from Sriharikota in India. Its aim was to receive Automatic Identification System (AIS) signals in areas of very dense ship traffic. Up to now, it has received over one million data sets as can be seen in figure 1.9. Although far beyond its design life, the satellite is still in operation.

In December 2014, the compact asteroid surface science lander MASCOT (figure 1.8) was launched aboard JAXA's near-Earth asteroid sample return

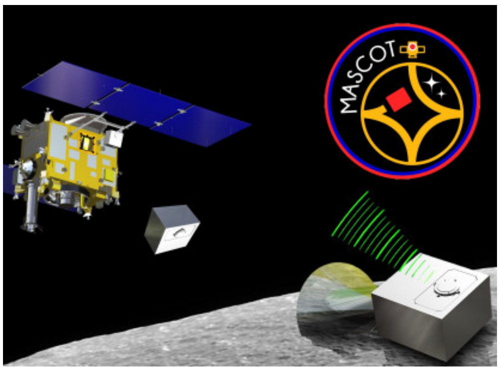


Figure 1.8: MASCOT asteroid lander with JAXA's main spacecraft Hayabusa2 (HY2).

mission Hayabusa2 heading towards the asteroid (162173) Ryugu. With the Institute of Space Systems being system and project lead, the lander is a joint development between several DLR institutes, the French Centre national d'études spatiales (CNES), and Institute d'Astrophysique Spatiale (IAS). In 2018, MASCOT will arrive at the asteroid and will perform scientific measurements on its surface. After Philae, MASCOT is the second DLR lander that will land on and investigate a small extraterrestrial body.

For the Mars mission Interior Exploration using Seismic Investigations, Geodesy, and Heat Transport (InSight) of NASA's Discovery Program, the Institute developed — in partnership with several other DLR Institutes — the Heat Flow and Physical Properties Package (HP3) surface science instrument. The experiment will determine the geothermal heat flux by penetrating down into the Martian surface up to a depth of five meters. The Institute contributed by developing the Mole, consisting of a ground penetrating element, and the support system, comprising the main structure which contains scientific and infrastructural elements. In August 2015, the fully qualified flight unit was handed over to Jet Propulsion Laboratory (JPL) for its launch in March 2016. Due to problems on mission level, the launch was postponed until the next Mars transfer window in May 2018.

With Euglena and Combined Regenerative Organic-Food Production in Space (Eu:CROPIS), the Institute is currently preparing its first compact satellite mission. After successfully passing qualification testing and the Critical Design Review (CDR), the flight unit integration was started on August 1, 2016. The aim of Eu:CROPIS is conducting long-term experiments with closed-loop, bio-regenerative life support systems under varying gravitational environments. By providing opportunities for experiments and technology demonstrations in space, it is an excellent platform for international cooperations such as NASA's "Power Cells" experiment. Eu:CROPIS will be the first of a line of compact satellites and will be launched in summer 2017.

The payload "ADS-B over satellite" was developed in close coopera-

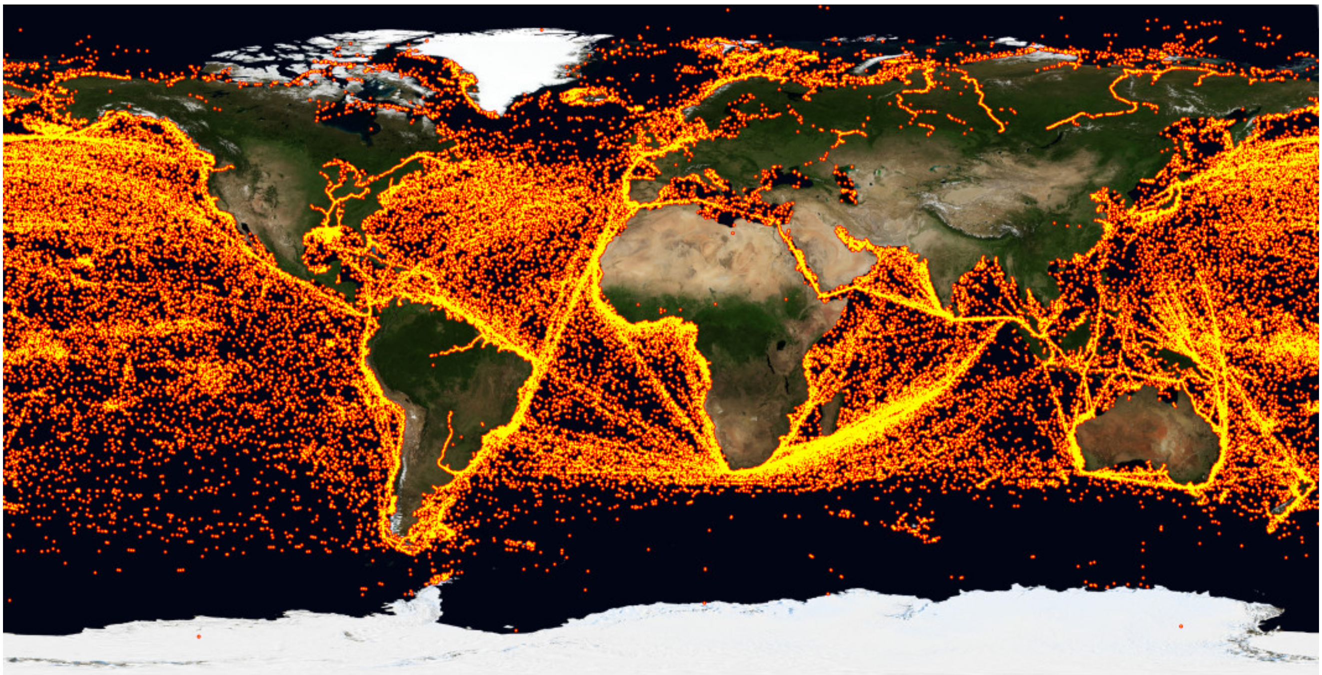


Figure 1.9: Received AIS signals during operational time of AISat (since 2014).

tion with Société Européenne des Satellites (SES) Astra and successfully launched on ESA's Earth observation satellite Proba-V (Project for On-Board Autonomy) in May 2013. This flight experiment is the first ever flown payload to prove the feasibility of satellite-based air traffic monitoring and marks the first step to a global, full-coverage air traffic monitoring system. Still in operation by August 2016, it is being successfully operated even after its design life time.

System Studies

The Institute also performed a number of groundbreaking system analyses in the field of space transportation and space segment. Besides the purpose of developing conceptual designs, evaluating feasibility, or estimating costs, these studies are also performed as direct consultancy and advice to the DLR executive board, the DLR program directorate as well as politics. Study results are also prepared as input for the Ministerial Council of ESA.

Together with United States (US) and European industry, National Aeronautics and Space Administration (NASA), and ESA astronauts, operation specialists, current International Space Station (ISS) users, and scientists, DLR conducted an extensive concept CE study to elaborate a program for the time after the ISS — called Post-ISS. Setting priority to affordability, the Institute investigated future low-cost options by evaluating various LEO infrastructure concepts. The result is a Phase A design called Orbital-Hub based on a small, low-cost, manned LEO platform including a man-tended free flyer.

Exhaustive analysis work was conducted for the benefit of the Expertise Raumtransportsysteme (X-TRAS) project, which consisted primarily of critical analysis and cross-checking work on launch systems which are in concept or exploitation phase. A notable highlight was the evaluation of the different concepts for the Ariane 6 proposal in preparation to the ESA Ministerial Council of 2014. Significant foreign competitors such as Falcon 9, including the return flights of its first stage, and concepts such as the Skylon concept were extensively studied and evaluated.

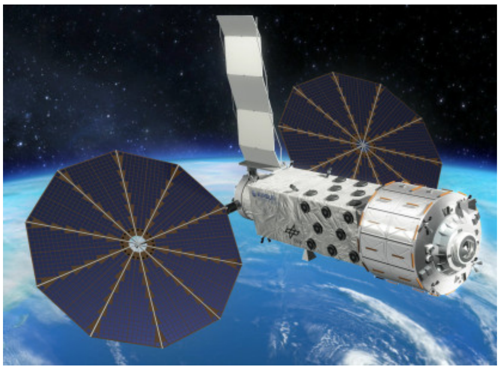


Figure 1.10: Orbital-Hub Free Flyer as possible Post-ISS approach.

Projects

The Institute was successful in acquiring third-party funding by coordinating or participating in European Union (EU), ESA, or similarly funded projects. On the basis of such projects, new cooperations across Europe were established which were and are used for new research activities. Some of the projects enjoyed significant public interest and have attained wide media coverage, including television, radio, newspapers, magazines, and the Internet such as activities on SpaceLiner and on Evolution and Design of Environmentally-Closed Nutrition Sources (EDEN).

The SpaceLiner concept successfully underwent a mission requirements review in 2016 with external reviewers, reaching Phase A status. In total four EU FP7 projects, Future High-Altitude High-Speed Transport 20XX (FAST20XX), Cryogenic Hypersonic Advanced Tank Technologies (CHATT), High-Speed Key Technologies for Future Air Transport (HIKARI), and Hypersonic Morphing for a Cabin Escape System (HYPMOCES), were based on the SpaceLiner concept. As an example, the EU FP7 project CHATT was led by the Institute and had the goal of developing cryotank technologies for hypersonic and reusable launch vehicle systems from 2012 to 2016. Together with European partners, the Institute achieved a pioneering position in composite cryotank technologies in Europe.

Figure 1.11: Panorama view of the EDEN laboratory to develop, test, and demonstrate technologies for bio-regenerative life support systems.

In 2011, the Institute launched its in-house research initiative called EDEN. A major achievement over the last years is the EU-funded EDEN-ISS project, comprising fourteen consortium partners of the leading European experts in the domain of human spaceflight. Until end of 2018, the EDEN-ISS consortium will design and test essential controlled environment agriculture technologies for potential testing aboard the ISS. The technologies will be tested in a laboratory environment and at the highly-isolated Antarctic Neumayer Station III.

With the presented major achievements, which are only a small selection of all accomplishments, and the progress made in fields like publications, participation in committees, and taking a leading role in space system design, the Institute has attained a solid foundation and is well prepared for its future challenges.

1.5 Organization of the Institute

In summer 2016 (2010), the Institute comprised about 150 (110) employees. The Institute is structured into eleven departments including a department for logistics and administration (see figure 1.12).

The Institute is organized in a matrix structure where the departments provide and maintain expertise in their research fields. The project teams are formed by members of the departments from which the expertise and work force is required for the specific project. The project managers of large projects, e. g. the satellite mission Eu:CROPIS, are reporting directly to the head of the Institute. In figure 1.12, the structure and the contribution of departments to different projects is visualized exemplarily for the three projects Eu:CROPIS, MASCOT, and ReFEx.

The following subsections summarize the tasks of the Institute's individual departments.

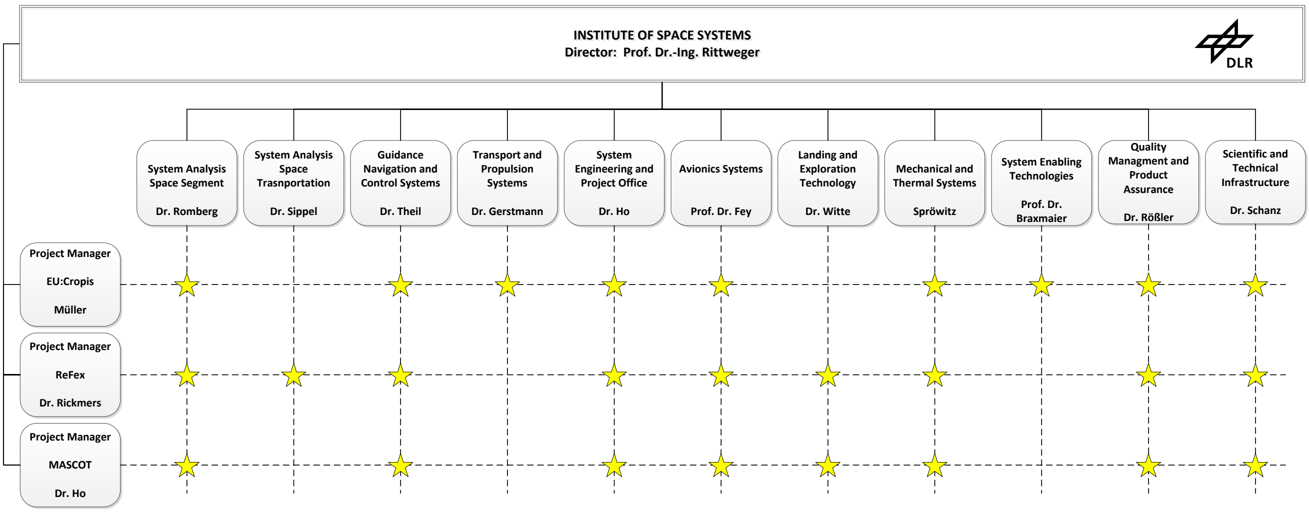


Figure 1.12: Organizational structure of the Institute of Space Systems: The Institute is organized in a matrix structure with department heads and project managers directly reporting to the director. The stars denote the involvement of the departments in the different projects. Eu:CROPIS, ReFEx and MASCOT are shown as an example.

1.5.1 System Analysis Space Transportation

The *Space Launcher Systems Analysis Department* of the Institute has the task of examining all types of future space launch systems and the required engines for it by means of modern, computer-aided methods. Activities range from stand-alone preliminary studies to critical analysis and assessment of foreign concepts. Another key aspect is the professional support provided in the definition of the German space development strategy playing a key-role in the DLR-wide project X-TRAS.

1.5.2 System Analysis Space Segment

The *Department of System Analysis Space Segment* researches and develops space systems (orbital and planetary) on a conceptual level taking into account technical, economic and socio-political aspects. Studies carried out within the department serve as preparatory measures for activities in the field of systems engineering and support the decision-making process for politics.

The department's key research objectives are set to mission analysis, concurrent engineering methods, human space flight including life support systems, and habitat technologies. The department runs the CEF, a simultaneous design laboratory, for conducting feasibility studies, technology evaluations, and maturation Phase-A concepts. Furthermore, the department built up the laboratory EDEN for the development and testing of life support systems (on breadboard level) for future habitats like on Moon and Mars.

Figure 1.13: The Concurrent Engineering Facility (CEF) — a simultaneous design laboratory.

1.5.3 Avionics Systems

The avionics of the Institute's space systems is typically designed in-house. This includes C&DH with hardware and software, the power subsystem, and the communications subsystem for ground contact.

On-board computers and on-board software constitute research priorities in the avionics field where innovative computer architectures and advanced design methodology including tool automation are a focus of the latest developments. An example of this is the development of a scalable on-board computer which is adaptable in terms of essential parameters to the differing requirements of each space vehicle.

1.5.4 Landing and Exploration Technology

The duty of the *Landing and Exploration Technology Department* is research and development of descend and landing technologies as well as instrument carriers for planetary exploration. This comprises their mechatronic elements, mechanisms, and energy-absorbing structures for descend and landing. This embraces the exploration mission-specific requirements engineering, the design, development and qualification of our subsystems, and the support during mission operation. Several analytical and numerical tools and experimental methods are maintained for these tasks. The department runs the Landing and Mobility Test Facility and associated labs for experimental research and qualification tests.

1.5.5 Guidance, Navigation and Control Systems

The mission of the *Department of Guidance, Navigation and Control Systems* is to research and develop sensors, actuators, algorithms, simulations, and on-board data processing systems for attitude and orbit control system (AOCS) as well as guidance, navigation and control (GNC) systems for space applications. This involves a range of disciplines, including requirements management, systems engineering, algorithm development, flight-software implementation, systems analysis/simulation/verification, and hardware-in-the-loop testing. Furthermore, the department is conducting research and development of promising and strategic technologies for AOCS and GNC systems. Strongly connected to the projects, the department develops and maintains own tools for design, development, and simulation of AOCS and GNC systems and operates hardware test laboratories which include dynamics simulators, configurable real-time test benches as well as sensor- and actuator-specific facilities.

1.5.6 Mechanics and Thermal Systems

Structures, mechanisms, thermal control system development, and radiation control are essential disciplines for a reliable space system design. The *Department of Mechanics and Thermal Systems* has its focus on the realization and qualification of such elements by using latest technologies or own customized developments. Software tools are applied during design, and environmental tests are conducted to validate and verify mathematical models as well as to qualify the developed hardware. Operated environmental testing facilities are for vibration, pyroshock, and thermal-vacuum testing complemented by radiation testing combined with thermo-optical properties and outgassing measurements.

A further research priority is the deployment system development. The Institute is leading the way towards deployable structures for large solar arrays and deorbiting devices. It is coordinating and bringing together expertise from across DLR for the implementation of hardware capable of flight.

Based on its expertise, the Institute was and is being consulted for assessing and reviewing the subsystems structures, mechanisms and thermal characteristics for DLR missions and external clients.

1.5.7 Transport and Propulsion Systems

The *Department of Transport and Propulsion Systems* is concerned with the research and development of technologies for transport and propulsion systems of space systems. Focus of research is the propellant management in tanks and lines of launcher systems, in particular for cryogenic upper stages. The intelligent and efficient propellant management and the successful mastery of the propellant handling of cryogenic upper stage systems is a key technology for achieving the development goals, like the realization of missions with multiple restart options paired with long-duration ballistic flight phases.

To support and enable the essential research activities, the Institute of Space Systems operates a Cryogenic Laboratory (Cryo Lab) equipped with special test facilities with unique selling points. In the Cryo Lab, experiments can be performed with cryogenic liquid gases down to liquid hydrogen at -253 °C. In addition, the department develops numerical simulation tools for the prediction and analysis of propellant behavior in launcher systems.

1.5.8 System Enabling Technologies

The *System Enabling Technologies Department* investigates key technologies for current and future space missions in science and Earth observation and examines and evaluates missions on system and subsystem level. One focus of the activities of the department is optical metrology. This specifically relates to specific assembly-integration technologies required for future operation of the optical instruments in space. This includes, for example, the design, implementation, and verification of highly stable optical clocks and laser sensors for measuring distance and angle variations between distant satellites. As part of the Gravity Recovery and Climate Experiment Follow-On (GRACE-FO) mission, due to be launched in 2017, the department is responsible for the optical ground support equipment (OGSE), which supports the integration of the laser ranging instrument and tests the performance in distance measurement. The department operates the Laser Ranging Test Facility.

In addition, thermal characterization of highly stable materials and experiments and simulations to study specific thrusters with extremely low propulsion are carried out. Systems engineering is used to evaluate future science missions, in particular with regard to feasibility and Phase A studies. Focus here is placed on missions that test fundamental physics, such as the special and general theory of relativity.

The projects are carried out in close collaboration with the Center of Applied Space Technology and Microgravity (ZARM) at the University of Bremen and Airbus Defence and Space (Airbus DS) (Friedrichshafen), and also in part with the University of Applied Sciences Konstanz (Hochschule für Technik, Wirtschaft und Gestaltung (HTWG)), Leibniz-University Hannover, and Humboldt-University Berlin.

1.5.9 System Engineering and Project Office

The *System Engineering and Project Office* develops and implements the complex space missions of the Institute of Space Systems by inheriting the technical responsibility of the projects. To cope with this endeavor, the department unifies the key core competencies in project management, systems engineering, and AIV. In addition, the projects are supported by processes such as budget controlling, payload management, and knowledge management maintained within the department.

The spacecraft are constructed in a central integration laboratory, supported by different test stands, equipment, and laboratories. This integration laboratory is coordinated by the department as well. Modern product and quality assurance processes are applied during the development and qualification. The concentration of the key competencies and processes of system development (i. e., from design to integration and qualification) within one department should enable short communication paths allowing effective and efficient project management and project implementation.

1.5.10 Research and Technical Infrastructure

To satisfy the Institute's technical and administrative requirements, the *Department of Scientific and Administrative Infrastructure* is responsible for the ongoing management of the administrative operations, the infrastructural processes, and the public relations of the Institute. One of the main aims is the service-oriented implementation of the department tasks to provide an adequate infrastructure for the scientific and technical work of the R&D departments. A significant part of the department's cross-sectional duties is the co-operation with DLR's central headquarters and their appropriate facilities.

The department's work focuses on:

- Controlling and Logistics
- Human Resources
- Facility Management
- Site Logistics
- IT Management
- Coordination of the Institute's Laboratories
- Institute Library
- Location Development
- Development and Implementation of Investment Strategy
- Public Relations

1.5.11 Quality and Product Assurance

The *Quality and Product Assurance Department* covers three areas of interest. First, quality management implements and maintains consistent core, steering, and supporting processes in the framework of EN ISO 9001. Second, product assurance identifies and controls spaceflight-typical technical risks like insufficient reliability or inadequate selection of materials and processes. The selection of electronic, electrical, and electromechanical parts is assessed and approved. For non-qualified parts, mission-specific qualification plans are developed. Quality control as part of product assurance includes inspections, test surveillance, and problem processing. A quality lab has been established to support the inspection tasks. Safety risk analysis, i. e., the avoidance or mitigation of threats to humans, is one further key element. Related to this, also occupational safety and health is the third column of the department.

Figure 1.14: Founding ceremony at Upper Hall of historic Bremen Town Hall, from left to right: Mayor of the Free Hanseatic City Bremen Jens Böhrnsen, DLR Program Director Space Hubert Reile, Founding Director Josef Kind, Chairman of the DLR Executive Board Sigmar Wittig, Astronaut Thomas Reiter, and Founding Director Berndt Feuerbacher. Weser Kurier Bremen, January 27, 2007.

1.6 History

Since the Institute of Space Systems is under review for the first time since its foundation, this section provides a short historical review of its evolution.

On initiative of Prof. Dr.-Ing. Hans Rath, the former director of the ZARM at the University of Bremen, the discussion about founding a new research institute of DLR in Bremen was started as early as 2005. After discussions and negotiations between institutions of the federal government, the government of the federal state Bremen and DLR, in mid 2006, it was agreed to found a new research institute of DLR in Bremen. On August 17, 2006, a project office to establish the Institute of Space Systems was founded and started operations on September 1 the same year. The project office organized the internal logistics for the new Institute and prepared the foundation of the Institute. The Institute of Space Systems started officially on January 1, 2007. The founding ceremony took place at the Upper Hall of historic Bremen Town Hall on January 27, 2007 (see figure 1.14).

The founding directors Prof. Dr. Feuerbacher and Mr. Kind started business in a small office hosted by ZARM. The first employees of the new Institute started work in rented office spaces in the "Technische Akademie Bremen" building opposite to the Bremen drop tower on March 1, 2007. In the first year, the Institute was growing fast. More office space had to be rented until all employees could move into the newly completed main building in August 2008 in Robert-Hooke-Straße 7. The inauguration ceremony took place on October 13, 2008 (see figure 1.15).

Figure 1.15: New office building, Robert-Hooke-Straße 7, inauguration October 13, 2008.

With the foundation of the Institute, the planning of facilities and laboratories started. It was clear from the start that the Institute required a lot of lab space for its research and development activities. Throughout the first years, the laboratory building was planned and construction started in 2009. The building was finished and inaugurated on August 25, 2011 (see figures 1.16 and 1.17). With more research facilities and new projects, the Institute grew such that more office and lab space was needed in the coming years. Thus, offices and labs were rented in Linzer Straße 1 (in 2013) as well as in Robert-Hooke-Straße 6 opposite the main building (in 2016).

Figure 1.16: Delivery of the space simulation chamber to new laboratory building, 2011.

In eight short years since its foundation, the Institute has grown to almost 150 employees, eleven departments, and necessitating four buildings at Bremen Technologiepark. The Institute has initiated and joined cooperations both with industry, universities, and research organizations worldwide in the fields of space transportation systems, orbital/exploration systems, and satellites. It has so far successfully launched two spacecraft (MASCOT and AISat), the next one is in preparation for launch in 2017 (Eu:CROPIS).

Figure 1.17: Inauguration ceremony of the laboratory building, August 25, 2011.

1.7 Cooperation with Universities

The Institute of Space Systems closely collaborates with the University of Bremen. This manifests itself in, for example, joint professorships, doctoral degrees taken at the university but supervised from the Institute, and — of course — numerous Bachelor as well as Master theses.

The Institute offers internships of varying lengths, including pre-study internships so that students can get a taste of the exciting everyday activities at DLR before they commence their studies. Within the study framework, supported by a team of four professors and several teaching assistants, members of the Institute hold lectures with aerospace-specific content at the University of Bremen.

The director of the Institute, Andreas Rittweger, holds the chair in "Space Technology" at the Department of Mechanical Engineering and Process Engineering at the University of Bremen.

Hansjörg Dittus, a member of the DLR Executive Board, has the chair in "Space Systems" in the same department.

Görschwin Fey, head of the Institute's Avionic Systems Department, leads the group of "Reliable Embedded Systems" in the Department of Mathematics and Computer Science at the University of Bremen.

Claus Braxmaier, head of the Institute's System Enabling Technologies Department, holds the Christa and Manfred Fuchs-Endowed Professorship for Space Technology/System Enabling Technologies at the Department of Mechanical Engineering and Process Engineering at the University of Bremen.

Particularly, the Institute is involved in activities at the University of Bremen resulting from the German Excellence Initiative. The joint graduate school System Design Joint Graduate School with Uni Bremen (SyDe)[1] focuses on the design of electronic hardware-software systems. These are a core component of not only spacecraft, but also in almost any modern appliance present in our daily life, ranging from cars to smartphones. Challenges are in the economic development of correct hardware-software systems with respect to a wide range of application domains. Besides DLR and University of Bremen, the German Research Center for Artificial Intelligence (DFKI) is the third partner in SyDe — joining three high-profile research partners.

With respect to promotion of young researchers, the cooperative junior research group "Parallel Computing for Embedded Sensor Systems"[2], also partially funded by the Excellence Initiative, started in 2012. The group focuses on fractionated systems as an attractive possibility for cost reduction in terrestrial as well as space applications. Research and development for navigation and interoperation of multiple participating vehicles are demonstrated using quadcopters.

1.8 Outreach

This section summarizes outreach activities of the Institute with respect to education of students. See chapter 6 for a list of scientific outreach activities, such as the organization of conferences, lectureships at University of Bremen, and guest lectureships at other universities.

1.8.1 DLR_School_Lab

The Institute hosts one of twelve DLR_School_Labs (DSL). The DSL in Bremen focuses on spaceflight — how are people and technology transported into space, and what conditions do they encounter there? How is Earth observed from space, and how are other planets, moons, and asteroids explored?

The Bremen-based DLR Institute of Space Systems primarily focuses on a comprehensive systematic approach as a key element of research. In line with this approach, young visitors at the DSL can perform a complete mission to Mars as part of a team — from the rocket launch to landing on the Red Planet, and from controlling a robot on the planet to sample analysis. They also experience, first hand, the importance of good teamwork for the success of a mission.

[1] http://www.informatik.uni-bremen.de/syde

[2] http://www.math.uni-bremen.de/~mhoelzel/

Overall, hands-on experiments are offered in three areas:

- Extreme conditions and dangers in space,
- Satellite technology and remote sensing, and
- Mission to Mars.

The students explore phenomena such as vacuum, microgravity, and space weather. They deal with infrared, radar, and attitude control systems, and carry out experiments on the topics of propulsion technology, landing navigation, robotics, and sensors. These tests can also be performed independently of one another.

Based on these exciting hands-on experiments, students can learn about current DLR research projects and gain fascinating insights into the world of science and technology.

1.8.2 Education and Training at the Institute of Space Systems

The DLR offers various programs for students and several training lectures. The DLR Institute of Space Systems in Bremen trains electronics technicians for devices and systems, as well as administration specialists.

PhD, Master, Diploma, Bachelor Thesis, Internships

Over the last eight years, scientists of the DLR Institute of Space Systems supervised an overall of

- 55 master and 22 diploma theses,
- 51 bachelor theses, and
- 191 internships.

A total number of 14 doctoral theses have been completed since 2007.

Electronics Technicians for Devices and Systems

The standard training time is 3.5 years, and is accompanied by vocational school classes. A big advantage of training at the Bremen site is the direct relation to practical applications. Circuits, systems, and other components built during training will find direct use in aerospace applications.

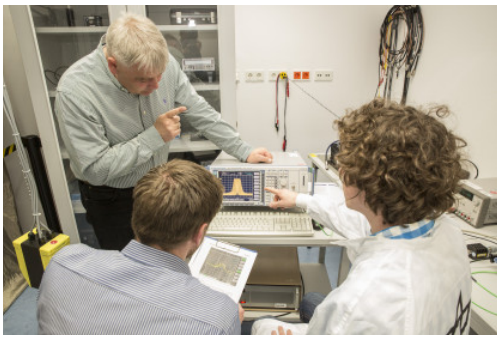


Figure 1.18: Electro-magnetic compatibility (EMC) measurements in electronics laboratory.

Administration Specialists

Administration specialists carry out organizational and commercial activities. The focus of the training is to teach business and operational relationships, together with the use of administration tools. The training period is usually three years, a period during which the trainees are introduced to various secretariats, project teams, and parts of the administration (personnel, accounting, and procurement) at the Bremen site and at the DLR offices in Braunschweig.

Students are not just equipped with the necessary practical skills, they are also supported with additional lessons and helped to prepare for examinations. They are gradually introduced to tasks requiring more and more responsibility. Everything possible is done to prepare the students for the professional world following their training at DLR.

2 System Analysis

2.1 Space Transportation

The launcher system analysis of the Institute has the task of examining all types of future space launch systems and the corresponding engines by means of modern, computer-aided methods, while also utilizing the Concurrent Engineering Facility (CEF). One of the fundamental aims is to reduce the cost of access to space through the identification of viable technologies. Activities range from stand-alone preliminary studies to critical analysis and assessment of foreign concepts. Thanks to integrated vehicle and engine analysis performed within a single group, the Institute's systems analysis fills a unique position within the German space sector. Together with its continuous strive to improve simulation techniques, it also participates in the analysis of new technologies. Another key aspect is the professional support provided in the definition of the German space development strategy, playing a key role in the DLR-wide project Expertise Raumtransportsysteme (X-TRAS).

The system analysis has been involved in several European Union (EU)-funded studies of hypersonic flight: Long-Term Advanced Propulsion Concepts and Technologies (LAPCAT), Aerodynamic and Thermal Load Interactions with Lightweight Advanced Materials for High-Speed Flight (ATLLAS), Future High-Altitude High-Speed Transport 20XX (FAST20XX), Cryogenic Hypersonic Advanced Tank Technologies (CHATT), High-Speed Key Technologies for Future Air Transport (HIKARI), and Hypersonic Morphing for a Cabin Escape System (HYPMOCES). The CHATT project on advanced cryogenic propellant tanks [226] was coordinated by the system analysis.

2.1.1 Interdisciplinary Launcher Design Process

The basic engineering disciplines of (any) launcher design are:

- Propulsion
- Mass Estimation
- Aerodynamics
- Ascent Trajectory & Performance

Designing an reusable launch vehicle (RLV) poses greater challenges then designing an expendable launch vehicle (ELV), because a functional RLV design requires at least the return to Earth (or to the launch site) of the RLV stage for all nominal missions. The functions of ascent and return are directly coupled and the inter-dependencies are highly non-linear. Therefore, an iterative process is the most promising approach. In addition, the design process of an RLV is inherently more complex than the design of an ELV because more key engineering disciplines need to be considered:

- Propulsion, subdivided into rocket and fly-back (air-breathing)
- Mass Estimation
- Aerodynamics
- Aerothermodynamics
- Ascent Trajectory & Performance

- Reentry & Return Trajectory
- Preliminary Analysis of Flight Dynamics

System analysis design for launchers is an early conceptual engineering trade-off comparable to Phase 0 and Phase A studies. Fast modeling and very fast computational performance are essential, while the obtained results should still be sufficiently reliable and accurate. This last requirement is not easy to be quantified and is obviously dependent on the technical field, but should at least deliver correct integral results and also the right tendencies for parameter variations. Based on the RLV design process, the simulation tools currently used for the key engineering disciplines are briefly explained.

The Institute maintains the following system tools for propulsion system analysis and design:

- Liquid rocket engine: several cycle analysis tools for one- or two-dimensional nozzle flow calculations including performance estimation, internal engine conditions, and engine mass estimation
- High-speed air-breathing propulsion: flexible cycle analysis tool for one-dimensional calculations, including performance estimation, internal engine conditions as well as separate tools for supersonic air-intake pre-sizing and engine mass estimation
- Propellant feed & tank pressurization system: pre-sizing of propellant tanks, feedlines, and pressurization system of liquid rocket stages and hypersonic transport systems along complete mission trajectories
- Solid rocket motors: performance assessment, thrust profile, and grain geometry generation according to system requirements

Mass management is of paramount importance for successful launcher system analysis and can usually be subdivided into two steps. A first mass estimation of the major components is performed based on empirical data. Then, in a second step, mass data is collected from the preliminary sizing of major components (e. g. mechanical architecture and structural sizing). Tools covering the following aspects are available:

- Center of gravity (CoG) and inertia calculation in all phases for flight dynamic assessment and trimming requirements
- Geometrical arrangement & mechanical architecture comprising the integration of all major components and the suitable introduction of structural loads. Usually, an iterative approach with mass management, aerodynamics, and flight dynamics is required. An automatically generated 3D-graphic output (VRML format) of design tools conveniently supports the process. Computer-aided design (CAD) tools like CATIA are implemented at increased maturity level of the design, which improves the precision and supports data exchange with partners.
- Mechanical architecture & structural design: preliminary structural sizing based on beam- and shell-theory as well as automatic generation of the structural architecture of winged RLVs for fast analyses using finite element method (FEM) programs. The main interest of the approach is to obtain reliable structural mass data and to improve the selection process for different design options.

Aerodynamics and aerothermodynamics are of limited importance in the preliminary sizing of ELVs, because the performance impact is small but gain an increased prominence in RLV sizing because of the high-speed atmospheric reentry of potentially winged stages. The basic requirement of launcher systems analysis is knowledge of the vehicle's aerodynamic coefficients for lift and drag. In case of aerodynamically controlled configurations, the trimmability needs to be assessed and for that at least the pitching moment coefficient is required. In order to perform these tasks, various very fast design tools are used, supported by fast mesh generation of the defined geometries:

- empirically (DATCOM) based methods which also allow early automatic assessment of trim capabilities,
- surface inclination method combined with supersonic flow expansion in the hypersonic flight regime,
- singularity method based on Boeing/NASA PANair-code preferably in lower-speed, low angle of attack regime.
- Atmospheric reentry of RLV at high speed is a major challenge to reusability due to the severe thermal loads. Usually, a thermal protection system (TPS) is applied on the outer surface of a reentry stage. A fast one-dimensional TPS-sizing tool is used for preliminary sizing along the full reentry trajectory, and thickness and mass data are obtained.

Trajectory and performance estimation is performed with different computational tools based on data generated in the previously mentioned disciplines:

- Ascent trajectory to orbit & payload performance of multiple-stage launch vehicles optimized in three-dimensional space for point-mass model
- Reentry & return trajectory optimized under constraints of mechanical and thermal loads for point-mass model
- Flight control and guidance assessment with mass and inertia models (up to six degrees of freedom (DoF)).

Environmental impact assessment of launchers could become increasingly more important in future system analysis. Rocket exhaust gases are known from equilibrium combustion calculations. The Institute contributed to this topic by leading the European Space Agency (ESA)-funded project Atmospheric Impact of Launchers (ATILA) [436]. In addition, sonic boom on ground estimation of returning RLV stages is under development and will support improved realism of reentry flight constraints.

Cost assessment is an integral part of launcher system analysis as the reduction in launch cost is a key objective and critical in a competitive environment. Cost estimation methods developed are based on parametric models with empirically derived cost estimating relationships (CER) and are applied to development, production, and operational costs [917]. Such CERs are only useful if an extensive validation process of actual European and international launchers is constantly performed and updated.

2.1.2 The SpaceLiner

The SpaceLiner (see figure 2.1) is an advanced, visionary concept for a sub-orbital, hypersonic, winged passenger transport, which is currently under investigation. The two-stage vehicle will be powered by rocket propulsion. The European Union's 7th Research Framework Programme has supported several important aspects of multidisciplinary and multinational cooperation in four different projects. The concept has now passed its Mission Requirements Review (MRR) and is ready for structured development.

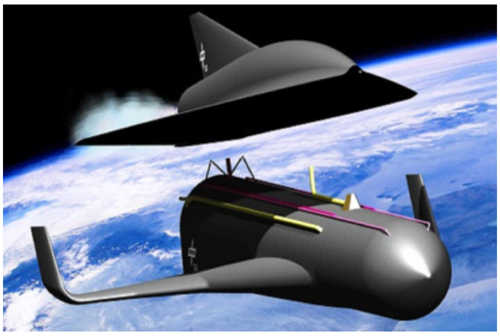


Figure 2.1: The SpaceLiner vision of a rocket-propelled intercontinental passenger transport could push spaceflight further than any other credible scenario.

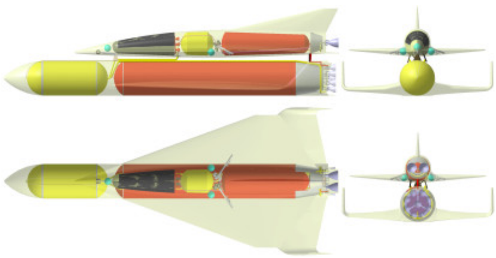


Figure 2.2: Sketch of SpaceLiner 7-3 launch configuration with passenger stage on top and booster stage positioned below. [227]

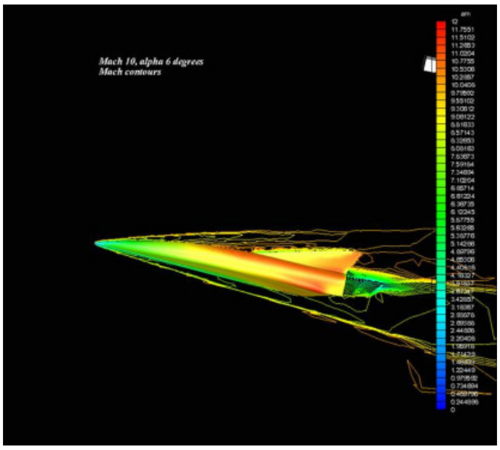


Figure 2.3: Mach contours of SpaceLiner 7-1 passenger stage at M = 10, angle of attack $\alpha = 6°$ from ESA ESTEC Euler computational fluid dynamics (CFD) calculation. [622]

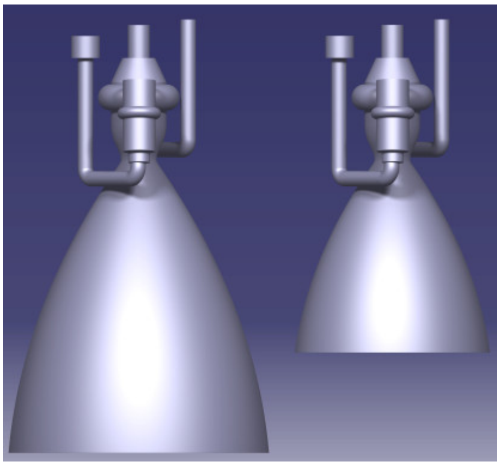


Figure 2.4: CAD model of SpaceLiner main engine (SLME) high-performance rocket engine for orbiter and booster stage.

The key challenge of space transportation is the reduction in launch cost. Production is one of the main cost drivers due to the very low manufacturing numbers of stages and engines. Without a new market application for space technology, no improvement is to be expected. The German Aerospace Center (DLR) has developed a vision which ultimately has the potential to enable sustainable, low-cost space transportation to orbit. The number of launches per year should be strongly raised and hence manufacturing and operating cost of launcher hardware should dramatically shrink [600, 111, 615]. The obvious challenge of the vision is to identify the actual application creating this new, large-size market. Intercontinental airline traffic is a huge and mature market. Since the termination of Concorde operation, intercontinental travel is restricted to low-speed, subsonic, elongated multi-hour flights. Launcher technologies could be very attractive for long distances (>9 000 km) by allowing significantly reduced flight times. At the end of 2012, with the conclusion of the EU project FAST20XX, the SpaceLiner reached a consolidated technical state (see figure 2.2).

The general baseline design concept consists of a fully-reusable booster and passenger stage arranged in parallel. The two-stage, vertical-takeoff configuration concept consists of a large unmanned booster and a manned stage designed for 50 passengers and two crew members. The fully-reusable vehicle is accelerated by a total of eleven liquid rocket engines (nine for the booster, two for the passenger stage), which are to be operated using cryogenic liquid oxygen (LOx) and liquid hydrogen (LH_2) [622].

The concept design also foresees the passenger cabin to function as an autonomous rescue capsule, which can be separated from the vehicle in case of an emergency, allowing the passengers to return safely to Earth.

After engine cut-off, the orbiter stage is to enter a high-speed gliding flight phase and be capable of traveling long intercontinental distances within a very short time. Altitudes of 80 kilometers and Mach numbers beyond 20 are projected, depending on the mission. Flight times of the SpaceLiner from Australia to Europe should take just 90 minutes or no more than 60 minutes on the Europe to California route. Acceleration loads for the passengers on these missions are designed to remain below those of the Space Shuttle astronauts, with a maximum of 2.5 g being experienced during the propelled section of the flight.

Several advanced technologies are required for the realization of the SpaceLiner which are currently under investigation at DLR and with international partners. A few examples:

The SpaceLiner 7 achieves an excellent hypersonic lift-to-drag ratio (L/D) of 3.5 up to Mach 14 without flap deflection, assuming a fully-turbulent boundary layer (see figure 2.3) [586].

Staged combustion cycle rocket engines with a moderate 16 MPa chamber pressure have been selected as the baseline propulsion system (see figure 2.4). The engine performance data are not overly ambitious and have already been surpassed by existing engines such as the Space Shuttle main engine (SSME) or RD-0120. However, the ambitious goal of a passenger rocket is to considerably enhance reliability and reusability of the engines beyond the current state of the art [621].

The SpaceLiner concept intends to use a single type of reusable liquid rocket engine, which operates in the full-flow staged combustion cycle mode. The nozzle expansion ratio is adapted to the different missions of the booster and passenger stages. Furthermore, liquid hydrogen and liquid oxygen will be used as the propellants, a combination which is both very powerful while remaining eco-friendly.

The maximum acceptable temperature of any passive TPS on the SpaceLiner is 1 850 K. In those areas (leading edge and nose areas) where the heat flux and temperatures exceed those values acceptable for ceramic matrix composites (CMC), transpiration cooling using liquid water is one potential technical option. This innovative method has been experimentally tested in DLR's arc-heated facility in Cologne using subscale probes of different porous ceramic materials [47, 223].

2.1.3 Reusable Launchers

Different return and landing modes were systematically analyzed. They include the well-known fly-back mode that reverts to the use of wings and air-breathing engines and the patented "in-air capturing" mode (see figure 2.7). The "in air-capturing" method by which a reusable booster stage is captured by a towing-aircraft and then returned to the launch site is a highly promising concept for the return of an RLV to the launch base because of its superior performance.

While the aforementioned return modes involve a horizontal landing, other examined configurations rely on a vertical landing of the stage, preceded by a toss-back maneuver of the booster stage with the purpose to direct the velocity vector towards the landing site. For an exhaustive comparative study, several engine cycles and potentially interesting fuel types are considered and evaluated on a system level. As an example, two micro-launch systems with either LOx/LH_2 or LOx/LCH_4 in a reusable first stage (fly-back mode) and LOx/LH_2 in an expendable upper stage were studied (see figure 2.6). Both were capable of transporting 250 kg to a Sun-synchronous orbit (SSO). Another important aspect is the separation Mach number. The Mach number is varied for the various designs and its effect on the overall RLV design is studied.

The DLR Department of Space Launcher Systems Analysis already existed before the Institute was founded. It was later integrated into the Institute of Space Systems. In the past, this department extensively studied the Liquid Fly-Back Booster (LFBB) concept (see figure 2.5). LFBB was based on an expendable Ariane 5 core stage and was investigated within the German future launcher technology research program Ausgewählte Systeme und Technologien für Raumtransport (ASTRA) from 1999 to 2004. The continuing efforts regarding RLVs build on the insights gained through this project.

An RLV designed at the Institute is the SpaceLiner (see section 2.1.2), which is not only an advanced intercontinental passenger transport concept, but also serves at the same time in a dedicated variant as heavy launch vehicle for satellites. The baseline design of the orbital launcher remains unchanged to the passenger version and the external shapes will be very similar. Trajectory optimizations show that the orbiter is able to deliver internally more than 26 000 kg of separable payload to a very low and unstable orbit. Subsequently, an orbital transfer is necessary from low-Earth orbit (LEO) to higher orbits of commercial use like geostationary transfer orbit (GTO). A convergent design solution with storable propellant transfer stage permits a separated satellite mass in GTO of 8 250 kg, which is compatible with super-heavy communication satellites of more than 8 m in length to fit inside the cargo bay together with its stage.

Figure 2.5: ASTRA Liquid Fly-Back Booster (LFBB) at staging from core stage in artist's impression.

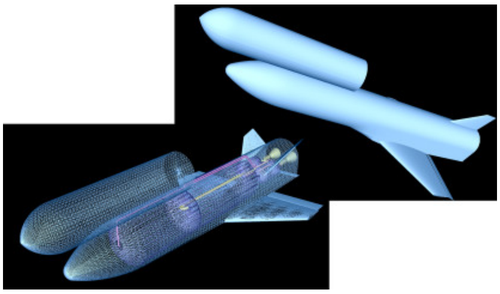


Figure 2.6: Micro-launch concept with reusable first stage for different propellant combinations.

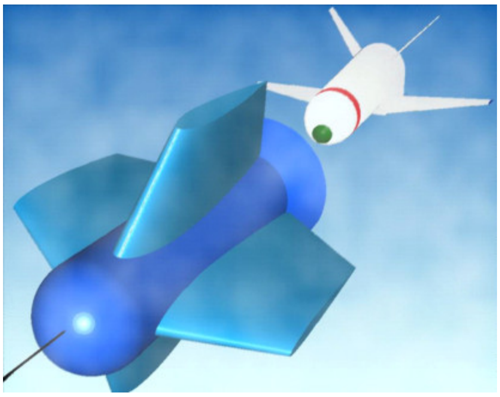


Figure 2.7: Rendering of the "in-air-capturing" with specialized capturing device and reusable winged stage approaching.

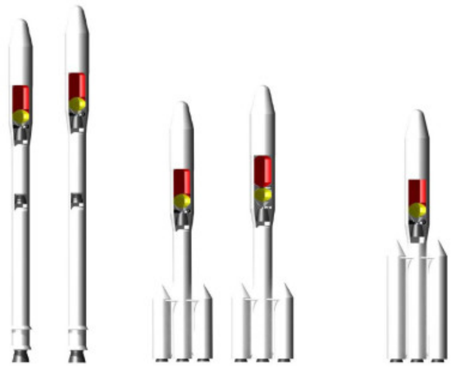


Figure 2.8: Sketches of different medium-size launcher options with solid rocket first stage and cryogenic upper stage. [603]

2.1.4 Expendable Launch Vehicle Concepts

In the past, the Institute proposed several ELVs concepts [604, 609, 610, 618]. While the Vega New Upper Stage (VENUS) project, which ended in June 2011, addressed small launchers with an evolution of the Vega launch vehicle [609, 674], the A New Generation Launcher (ANGELA) [362], the Next Generation Launcher (NGL) [364], and the Ariane 6 preparatory studies considered medium-class launch vehicles. In particular, technical and economic analyses were performed to propose launch vehicle concepts in the class of Soyuz while exploiting synergies with the rest of the European launcher fleet (see figure 2.8) [603]. An advanced two-stage-to-orbit (TSTO) launch vehicle considered as an evolution of the Vega launch vehicle has also been investigated [359, 362, 364, 609]. Over the years, the Institute has acquired a broad knowledge basis for the global assessment of ELVs, covering technical feasibility and optimization, performance, and costs. This capability is unique within Germany.

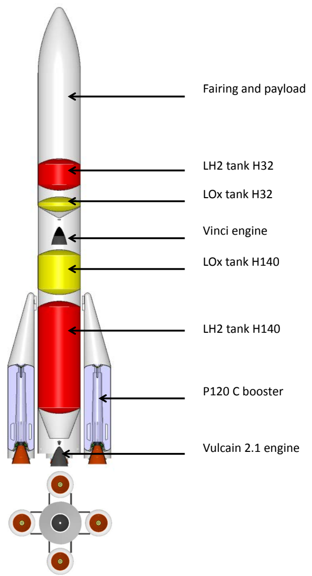


Figure 2.9: Overview of the Ariane 62/64 launcher as modeled in the X-TRAS study team.

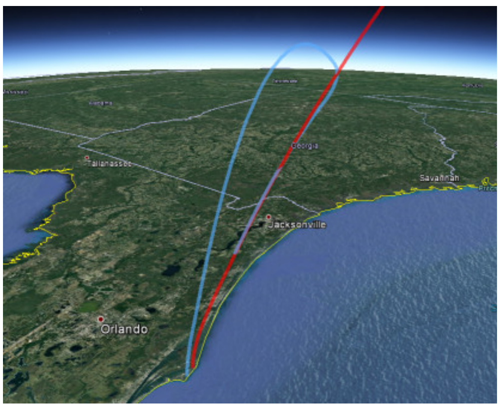


Figure 2.10: Falcon 9 ascent and booster return trajectory calculated at the Institute of Space Systems (Orbcomm 2 mission).

2.1.5 Expertise Raumtransportsysteme (X-TRAS)

The strong need for independent technical advice in all aspects of space transportation has been a key requirement of launcher system analysis at the Institute of Space Systems since its founding. Encouraged by the DLR executive board, this consulting role has been extended to those institutes of DLR involved in space transportation activities. In the wake of the discussions about a next generation of the Ariane rocket, such a group was planned under the leadership of the Institute since 2012 and formally established in 2013 under the name X-TRAS. The principal purpose of this group, formally organized as an executive board project, is to provide technically sound consultation to any decision of the German space policy by federating all DLR competencies relevant to an in-depth analysis of a launch system concept. As such, the group is composed of permanent members from different DLR institutes that provide the required analysis competencies. The project was managed by DLR Lampoldshausen from mid-2013 to early 2016. The project management has since been returned to the Institute. Past studies focused on critical analyses of the different proposed Ariane 6 concepts (see figure 2.9). First, the concepts were modeled, then the expected performance and cost were recalculated and estimated. Further, potentially critical issues were identified. Beyond these activities, the group proposed its own launcher concepts.

With the renewed interest in reusable launch systems, the focus will shift towards these systems, in particular in the face of the cooperation with the French Space Agency Centre national d'études spatiales (CNES). Key technologies necessary for reusability are to be identified and roadmaps to be developed. In parallel, foreign competitors on the launch market are analyzed such as the SpaceX Falcon 9 launch system (see figure 2.10) and its variants including an interesting approach for reentry and potential return of a reusable first stage.

2.1.6 Crewed Space Transportation — Bemannter Europäischer Raumtransport (BERT)

At the end of 2007, the former DLR executive board member and European astronaut, Thomas Reiter, asked the newly founded Institute of Space Systems to perform an extensive system study on the technical and programmatic options for independent European manned space transportation. This activity, led by the Institute, studied how the Ariane 5 could be transformed into a crew launch system, including the technical definition of a crewed capsule (see figure 2.11). Three concepts were analyzed with respect to requirements towards the launch system, the capsule design, reliability, operational aspects of the ground segment, and costs. Other DLR institutes and industry (ASTRIUM, Bremen) provided major contributions. This study was the first big system analysis study at the newly founded Institute and was successfully finished in summer 2008.

The study concluded that in principle an Ariane 5 rocket with a re-ignitable upper stage would be capable for crew transportation, but that some modification and qualification effort would be required. Major modifications included an increase in reliability of the core stage, Étage Principal Cryotechnique (EPC), the integration of a suitable health monitoring system and an appropriate adaptation of the ground infrastructure.

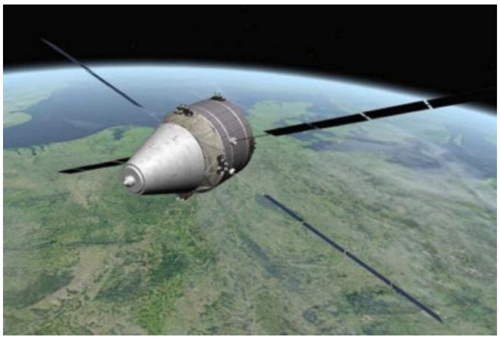


Figure 2.11: BERT capsule.

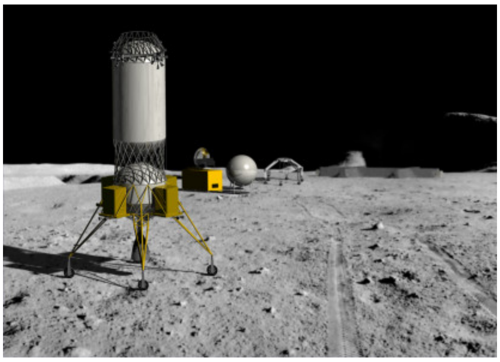


Figure 2.12: Concept of the reusable Lunar Lander.

2.1.7 Interplanetary Transportation Systems

The Institute also designs transportation systems for interplanetary missions. One of these projects has been the design of a large storable propellant transfer stage for ESA (see figure 2.12) [351]. Currently, an innovative transportation system for Moon missions is being developed for the project Robotic Exploration of Extreme Environments (ROBEX), which is funded by the Helmholtz Association. The transportation system is characterized by the implementation of cryogenic propulsion, in-situ propellant production, and reusability in order to reduce the costs of transportation for large infrastructure and ease the feasibility of a permanent presence on the Moon. In particular, the study addresses how reusability can allow large benefits for the transportation chain in terms of cost, sustainability, flexibility, and adaptability for different missions scenarios [351, 361]. Analyses rely mainly on structural design, trajectory computations, missions planning, and cost estimations. ROBEX is being performed in collaboration with numerous partners within Germany. For other work being performed by the Institute within ROBEX see section 4.3.2.

2.1.8 System Analysis of Launcher Technologies

A crucial research topic for future reusable launch vehicles as well as high-speed transport aircraft are extremely lightweight and reusable cryogenic propellant tanks made of carbon fiber reinforced plastic (CFRP). This technology and associated research topics were investigated within the CHATT project in the 2012–2015 time frame. CHATT was co-founded by the European Commission within the 7th Framework Programme, coordinated by the Institute, and included a total of eleven European partners. Within CHATT, four different CFRP tank structures were manufactured and tested, complemented by comprehensive material research on specimen level.

The achievements significantly contributed to the development progress of composite cryotanks and increased the technology readiness level (TRL) of several associated technologies [226]. In particular, the very promising potential of the novel thin-ply CFRP material technology for cryogenic tank applications was identified.

Another technological aspect under investigation is the sloshing of cryogenic liquid propellants and the pressurization of the corresponding tank systems. The complex fluid-dynamic and thermodynamic phenomena during the active-pressurization process were experimentally investigated in close collaboration with Center of Applied Space Technology and Microgravity (ZARM) at the University of Bremen. The results were then compared to numerical simulations and analytical considerations [866]. Also the temperature and pressure changes in a tank caused by sloshing were studied. The work resulted in the development of an engineering model that improves the design of the propellant feed system [824].

2.2 Space Segment

The Institute's system analyses of the space segment are focusing on analyzing and evaluating existing and future space concepts in terms of technical, economic, and social aspects. The system analysis studies and concepts prepare the Institute's activities in the field of system technology after a space concept has been assessed regarding applicability, feasibility, acceptance, costs, and benefit. Furthermore, the results are processed into decision guidance and recommendations for politics and policy objectives. Thus, the German position on space is strengthened in the international competition; national and European space flight is in the focus of research and development. The engineers and scientists engaged with system analysis develop and apply qualitative and quantitative computer-based evaluation, design methods, and tools, for example the DLR software package Virtual Satellite [548] developed by the DLR Institute for Simulation and Software Technology. The main tool of the system analysis activities is the CEF [330] located at the Institute of Space Systems in Bremen. The corresponding activities and disciplines such as mission analysis or cost estimation are subdivided in three sub-areas: concept development for satellites & human spaceflight, evaluation and cost as well as concurrent engineering (CE). In the following, the main content of recent and current activities is described in more detail.

Figure 2.13: Concurrent Engineering Facility (CEF) main room during non-moderated working time.

2.2.1 Concurrent Engineering Facility

The CEF is DLR's systems analysis laboratory, located in Bremen, where CE studies are conducted. It provides the necessary environment and tools to implement the CE process. The CEF, depicted in figure 2.13, facilitates simultaneous access to a common set of data, as well as direct verbal and digital information exchange among the different domains during the design process, through the intelligent use of modern tools and communication technologies. The DLR CE team is the focal point for ESA concerning Concurrent Engineering in Germany. The experts in Bremen are actively involved in the preparation and implementation of the regularly (two-year term) occurring ESA Systems & Concurrent Engineering Conference for Space Applications (SECESA) as a committee member.

The CEF in Bremen is divided into three design rooms with 21 work stations in total and built-in media capabilities. One of these rooms is the main design room, where studies are conducted and which allows for up to 12 domains to be included in a study. The other two rooms act as splinter rooms, which are typically used for small-group discussions during unmoderated time in a study, or to accommodate other parallel working groups or auditors.

The basic idea behind the CE process is the strong reliance on active communication within a selected study team, i. e., facilitated with model-based systems engineering (MBSE) and corresponding software tools. An iterative design process is applied during a study (see figure 2.14), where the design evolves witch each iteration and finally converges to a consistent design, which fulfills all desired requirements [517].

Working within a guided process [164], the concurrent access of all experts to a shared database, and the direct verbal and medial communication [163] between all subsystem experts are the defining characteristics of CE studies. Compared to traditional design approaches, the major advantages of the highly successful CE process are:

- very high efficiencies regarding cost and project outcome in early design phases,
- close-quarters collaboration which facilitates direct communication and quick data exchange,
- that team members can easily track the design progress, which also increases the project understanding and identification, and
- that ideas and issues can be discussed in groups, which bring new viewpoints and possible solutions, as well as it assists in the identification and avoidance of mistakes.

Up to now, the process is only applied in early design phases, but this very successfully. To transfer the above mentioned advantages into later phases, research at the Institute of Space Systems aims at further developing the process for application in these phases (see below).

Until mid-2016, almost 60 studies (see figure 2.18) have been conducted in the CEF, maturing the CE process in early phases (Phases 0 and A) and adapting it to combine the system and domain expertise of DLR and its specific conditions. Although mostly focused on satellite design, exploration missions and space transport systems, the CEF has enabled the study of life support systems, and space-based or terrestrial infrastructures. Overall, there have been thirteen exploration studies, including six lander vehicles, eight studies regarding human spaceflight, and eight studies about launchers of various kinds. Ten satellite studies, nine technology demonstration missions and eight studies concerning scientific experimentation or observation like space-bound telescopes, complete the list. Visual representations of some results can be seen in figures 2.15 to 2.19. International partners for studies have been the Max-Planck Institute of Solar System Research, OHB, Airbus, ESA, Japanese Aerospace Exploration Agency (JAXA), RKK Energia, Bigelow Aerospace, and many others.

Process Development

While initially derived from the concurrent design process as applied by the European Space Agency, the process was adapted to the needs of the Institute of Space Systems, reducing the overall length of typical studies, but retaining approximately the same number of sessions in between. This

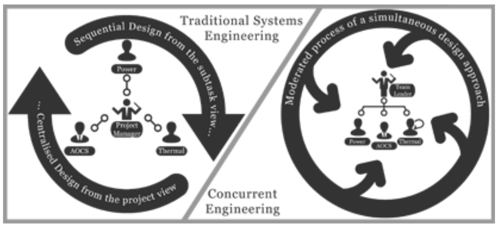


Figure 2.14: Conventional study approach compared to Concurrent Engineering.

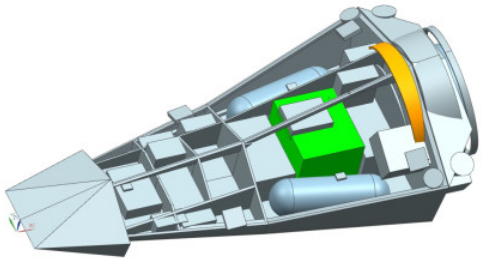


Figure 2.15: CE study result example: Sharp Edge Flight Experiment III (SHEFEX III).

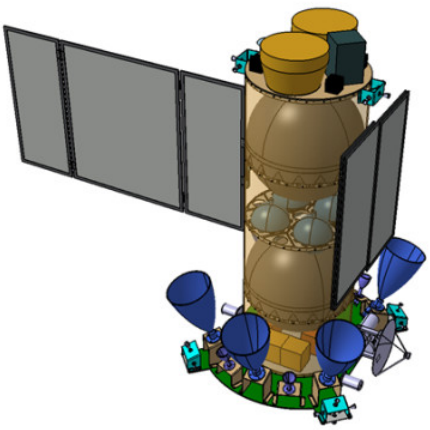


Figure 2.16: CE study result example: Active Debris Removal Service (ADR-S).

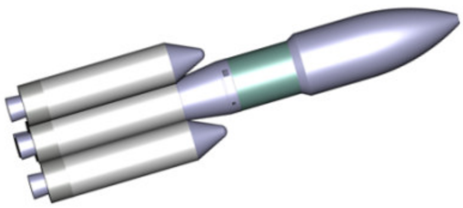


Figure 2.17: CE study result example: A New Generation Launcher II (ANGELA-II).

led to an effective and very fast method of creating an early design of a system [164], bolstered by experience of over 60 studies conducted at the CEF [328]. As an integral part of system analysis at the Institute, the development of the CE process is also in the scope of system analysis research. Currently, main players in the space industry have found different levels of success in integrating their design processes throughout the complete lifecycle of any development. This is especially true for those entities that apply the concurrent engineering process for their early-phase designs. Through internal collaboration in the area of software for space systems and interactive visualization, efforts are being made to study and test the implementation of CE in Phase B [324]. By the means of a combined approach that would use a model-based software that would be operational throughout all phases, and an optimized methodology for the use of the CEF and other collaborative strategies, the Institute aims to develop new processes that contribute to make the design and development of space systems more efficient, reliable, and economical. The CE process has been successfully used to evaluate and design overall mission architectures, which has an increased complexity than studies with only one system to be designed and results in a different dynamic within the study team [475]. As one major element in the preparation of a CE study is the definition of a mission, e. g. via requirements, a shortened process has been developed to be used for the same purpose directly in the CEF [672]. This has successfully been applied to several studies already. Furthermore, a modified process and modeling has been used for launcher design [327].

Figure 2.18: Chronological overview of conducted CE studies.

Mission Relevance

The CEF has proven to be an important tool for analysis activities and mission preparation of the Institute and DLR in general. All missions that have been implemented or are implemented at the Institute, for example Mobile Asteroid Surface Scout (MASCOT), AsteroidFinder/Euglena and Combined Regenerative Organic-Food Production in Space (Eu:CROPIS) (compact satellite), and Automatic Identification System Satellite (AISat) (using the CLAVIS bus) have been initially designed in the CEF. Other external missions that have been realized with the help of the CEF are, amongst others, the Compass II of the University of Applied Sciences Aachen (currently in testing phase) and the PELADIS robot of the Centre for Marine Environmental Sciences (already in operation) [773].

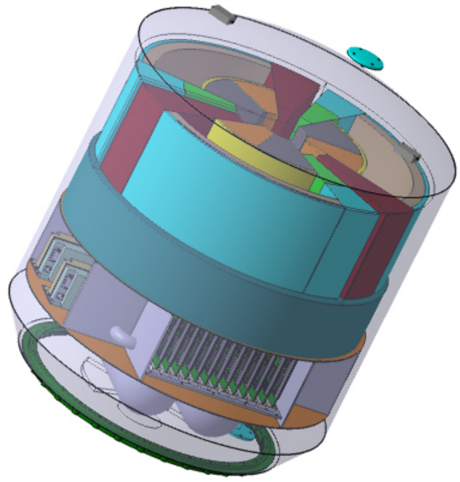


Figure 2.19: CE study result example: Euglena and Combined Regenerative Organic-Food Production in Space (Eu:CROPIS).

Outlook

Strategic goals for the CEF can be sorted in three areas:

- To update equipment and systems of the technical infrastructure, as well as supplementing it with additional elements that can contribute to the CE process or the diversification of activities carried out within the facility.
- Strengthen the Institute's role in systems engineering and the CEF as a reference center for feasibility and early design studies. This not only includes CE studies as the core activities, but also other undertakings such as specific workshops that could benefit from the use of the facility and a guided-thought approach.
- The development and evolution of CE and systems engineering processes, focusing primarily on developing the necessary process to perform activities within Phase B [324] and support projects as fully as possible within that phase, but also considering the potential adaptation of the current process to increasing demands and particular projects.

Collaboration with other institutions, both those with potential interest in the use of the CEF for their own studies or studies in cooperation with DLR, as well as prospective exchange of ideas, technologies, and personnel for studies with other CE centers, is also part of the CE development.

2.2.2 Mission Analysis

Mission analysis, regarding activities such as orbital mechanics and trajectories, is an essential part of the development and design work for any mission. Already in the earliest design stages, it is needed to assess the feasibility and to set framework conditions. The diversity of today's missions, its constraints, and the different propulsion systems (for example solar sail, electrical and chemical thrusters) and mission types (e. g. Sun-synchronous orbits, interplanetary missions, stationary orbit at Lagrangian points, gravity-assist missions) require an extensive portfolio of tools, which must be adapted to the specific mission if necessary, as well as properly applied know-how. At the Institute of Space Systems, mission analysis is an important core competency, required for the investigation of new mission proposals during CE studies and in support of projects (for example Eu:CROPIS). The rising demand for low-thrust trajectories and gravity-assist sequences is an area of special interest. Typical objectives of such missions are objects such as comets, near-Earth objects, trojan asteroids, but also missions to planets (Venus, Mercury, or Jupiter). The activities of the mission analysis are divided into the following three areas:

Mission analyses for concept phases, e. g.:

- Earth orbits (LEO, MEO, HEO, GEO): coverage, Sun angles, contact times, eclipse times
- lifetime analysis: orbit decay, orbit drift
- lunar and interplanetary analysis: trajectory design (see figure 2.20), maneuver planning, launch window, delta-v calculations
- small body missions (e. g. near-Earth objects (NEO), asteroids, comets, trojans)
- low-thrust scenarios/gravity assists

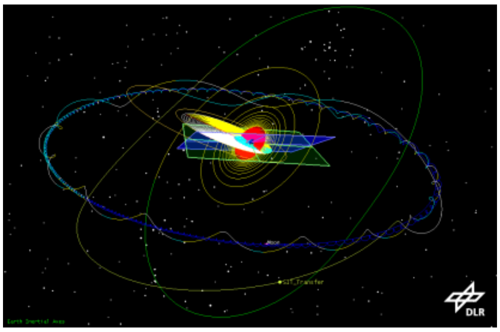


Figure 2.20: Low-thrust transfer from Earth orbit into a lunar orbit with the help of lunar gravity assists and back.

Mission analysis for selected missions in support of projects, for example:

- operational orbits
- payload behavior (sensor field of view, coverage)
- constellations
- supporting data (orbit and attitude) for other domains (e. g. thermal, power, payload)
- power generation on the basis of solar panel sizing, positioning, orientation, and obscuration
- thruster design and propellant budgets
- optimization of the communication system and ground network
- modeling of communication link and antenna pointing

Methods and tool adaptation or development for:

- trajectory optimization
- low-thrust
- gravity assist
- supporting data

One significant part of analyses run recently have been trajectories to asteroids, for example for usage for crewed missions to NEOs [511], or multi-rendezvous missions for low-thrust spacecraft to Jupiter's trojans [78]. At the same time, effective usage of gravity-assist maneuvers in combination with low-thrust propulsion has been investigated by the Institute mission analysis domain, a methodology for optimizing such missions is currently being developed [472]. Further successes have been the analysis of effective trajectories for low-cost missions to Mars or Moon by exploiting weak-stability-boundary transfers, enabled by gravitational peculiarities in the Earth-Moon system [92].

2.2.3 Models for Cost Estimation

The cost estimation domain is one of the most critical engineering domains with respect to early space mission concept design. At the Institute, a method is under development which allows to quantitatively evaluate a space mission concerning technical, economic, and social aspects. This assessment tool helps engineers to discover obstacles and upcoming difficulties in a project early on so that proper actions can be taken. Among others, the following assessment tools were used for economical evaluations of space missions:

- strengths, weaknesses, opportunities, threats (SWOT) analysis
- cost estimates

- morphological box analysis
- scenario analysis
- portfolio techniques
- system dynamics models

During the early stages of a project, cost engineers usually do not have sufficient technical and management information in order to estimate the total mission cost. For this reason, project teams use parametric cost estimate methods that were built up of so called CER. In addition to using commercial cost models, an in-house developed cost model, which takes into account the special DLR conditions was developed. Only with an accurate and sustainable cost estimate, project managers and decision makers can assess a space mission effectively.

The aggregation of the cost estimates is done with the manufacturing, assembly, integration, and test (MAIT) function. The basic principle behind this function can be seen in figure 2.21. Based on the cost for the Flight Model 1 (FM-1) or T-1, the costs for e. g. systems engineering, the hardware matrix, project office are calculated backwards by the usage of defined cost factors. These factors were derived from previous projects and best engineering practices.

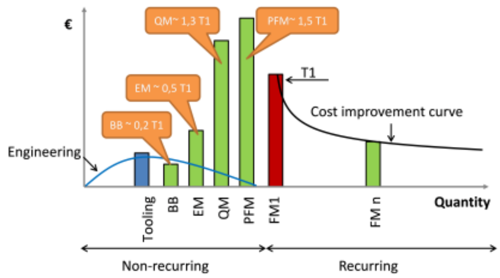


Figure 2.21: General cost distribution (including hardware matrix) for a space mission until finalization of the flight model; BB: Bread-Boarding, EM: Engineering Model; QM: Qualification Model; PFM: Proto-Flight Model; FM1: Flight Model 1.

2.2.4 Study Topics

A major source for study subjects are CE studies, which enabled system analysis for a large number of spacecraft in the broadest sense. In addition, there are a number of study fields which have been pursued in subsequent studies and are an established field of research, often under advisement of the DLR management or external partners (e. g. ESA, EU, industry).

Human Spaceflight and Post-ISS

Due to the significant financial effort associated with human spaceflight, careful analysis and evaluation of future concepts in that field has been one cornerstone of the Institute's system analysis activities. System analysis contributed to the evaluation of the Automated Return Vehicle, by assessment of the thermal control system and the ground segment required to successfully operate such a capsule [929]. Furthermore, a broad review of a possible human mission to an asteroid using exclusively European technology has been conducted, revealing the feasibility of such an undertaking as all relevant technologies could be developed from technology already existing in Europe, highlighting Europe's technological expertise. A mission architecture involving a four-person crew and relying on a heavy launcher, based on Ariane 5, a Columbus-derived habitation module, and a modified Automated Transfer Vehicle (ATV) capsule was established [774, 479].

The current major fields of research and evaluation in system analysis with regards to human spaceflight are activities in LEO as a follow-on to the International Space Station (ISS), called "Post-ISS". The DLR project Post-ISS (a system analysis study), led by the Institute of Space Systems in Bremen, can be understood as national preparatory work for the establishment of future programs in the field of human spaceflight and to secure European and German long-term research and astronautical activities in LEO [780]. The study is focused on the question how to continue with space research and space technology development after the ISS utilization period ends around 2024. Therefore, the following objectives were defined, whereas corresponding tasks have been worked out within the study:

- Analysis of the pros and cons of the ISS (DLR internal) and recommendations based on lessons learned,
- market research of existing technologies/techniques,
- analysis of additional user demand and utilization opportunities by including additional scientific disciplines and technological research,
- design of infrastructure concepts that conform to crew-system integration standards, and
- analysis of the reusability of the current architecture.

Several options (in total thirteen including sub-options) were identified as fitting to the project's concept framework conditions. Four of them were chosen for detailed evaluation using the analytical hierarchy process (AHP) [929] regarding political, social, technical, and economic criteria. A lean multi-purpose station with a dockable module/platform, dubbed "Orbital-Hub", was evaluated to be the most promising option from a European and German point of view. The Orbital-Hub is intended as basis or core element of a space village idea: On the hub, spacecraft can dock and be serviced, or goods (e. g. propellant or experiments) can be distributed (confer "hub" as distribution node of the Internet).

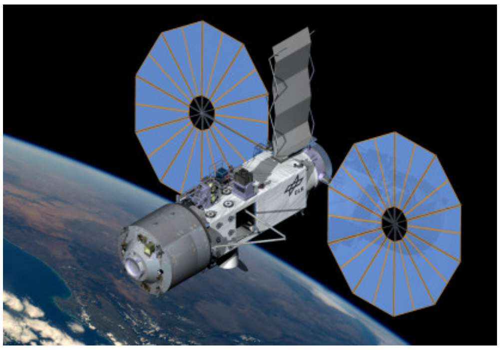


Figure 2.22: Orbital-Hub architecture: Dockable Free-Flyer to comply with specific science and user requirements.

Requirements regarding such a future mini-platform in LEO have been collected from German scientists and engineers. Stakeholders of several research disciplines, including ESA and National Aeronautics and Space Administration (NASA) astronauts, as well as space industry, like Airbus Defence and Space (Airbus DS) (EU) and Bigelow Aerospace (US) participated in Orbital-Hub dedicated CE studies. They further contributed recommendations for payload definitions for the preferred mini-platform option including a desired Free-Flyer, which most of the times operates independently of a human crew and the base station. Technical details can be found in [780]. In addition to traditional μg-research, an extended focus is placed on Earth observation, atmospheric physics, technology demonstration, commercial use as well as exploration preparation, i. e., Moon or Mars flight crew training based on human-rated platforms.

The concept, depicted in figure 2.23, as selected by experts from the scientific and human spaceflight community, aims to employ only the minimum functionality required for a scientific astronautical base station (three crew members continuously plus visitors) in LEO: At least one module is needed for science laboratories, the crew accommodation, and corresponding environmental control and life support systems (example design: expandable habitat). In addition, a service module is needed to ensure attitude and orbit control and to provide power and thermal control. A five-point docking node (one used by the cupola) allows for crew and cargo transfer, extension opportunities, and can comprise communication and data systems or backup subsystems. In contrast to the ISS, the Orbital-Hub concept is designed without any extra-vehicular activity (EVA) required for station assembly and maintenance by avoiding items placed externally to the station. However, an EVA contingency is foreseen on the base station. Also, a payload airlock is included between the pressurized and unpressurized parts of the Free-Flyer to service the external science platform with new payloads using a robotic arm. Since the critical requirements regarding attitude and disturbances are shifted towards the Free-Flyer, the base station is free to roll or yaw a certain amount. This reduces the system complexity significantly below ISS standards. Orbit maintenance can be achieved via docked crew or cargo vehicles, possibly using electrical thrusters.

The Free-Flyer is intended to fly uncrewed in a safe formation to the base station for about three months periods after which it can be maintained or reconfigured when docked to the station for short durations. Analogous to the base station, it also requires a service module for attitude and orbit control and also for formation flying and independent power and thermal control. Furthermore, it contains a pressurized module for microgravity research which can be accessed when docked to the base station (e. g. via the docking node or via the expandable habitat module) or to a crew vehicle. The external science platform is the center-piece of the Free-Flyer. It has a berthing structure for any external payload and provides power, data, and thermal conditioning. The Free-Flyer will most likely fly with the instruments pointed nadir. However, it is designed to freely change attitude for certain periods depending on scientific requirements. As one result of the Free-Flyer CE study, which has been conducted in close cooperation with Airbus DS, the external science platform has been designed as a rigid rectangular truss structure covered with multi-layer insulation (MLI), see figure 2.22. The main volume of the payload airlock is located inside this structure and can be reached through a cut-out by the robotic arm. This manipulator is moving along a rail around the structure to place different payloads onto the four sides of the platform with respect to their desired viewing direction. As the Free-Flyer's service module does not need to be pressurized, it utilizes the same truss approach as the external science platform for stiffness and launch load transfer through the overall structure. Robotic arm interfaces are foreseen to handle the payloads on the platform, which is based on the Orbital-Hub user CE study, described above.

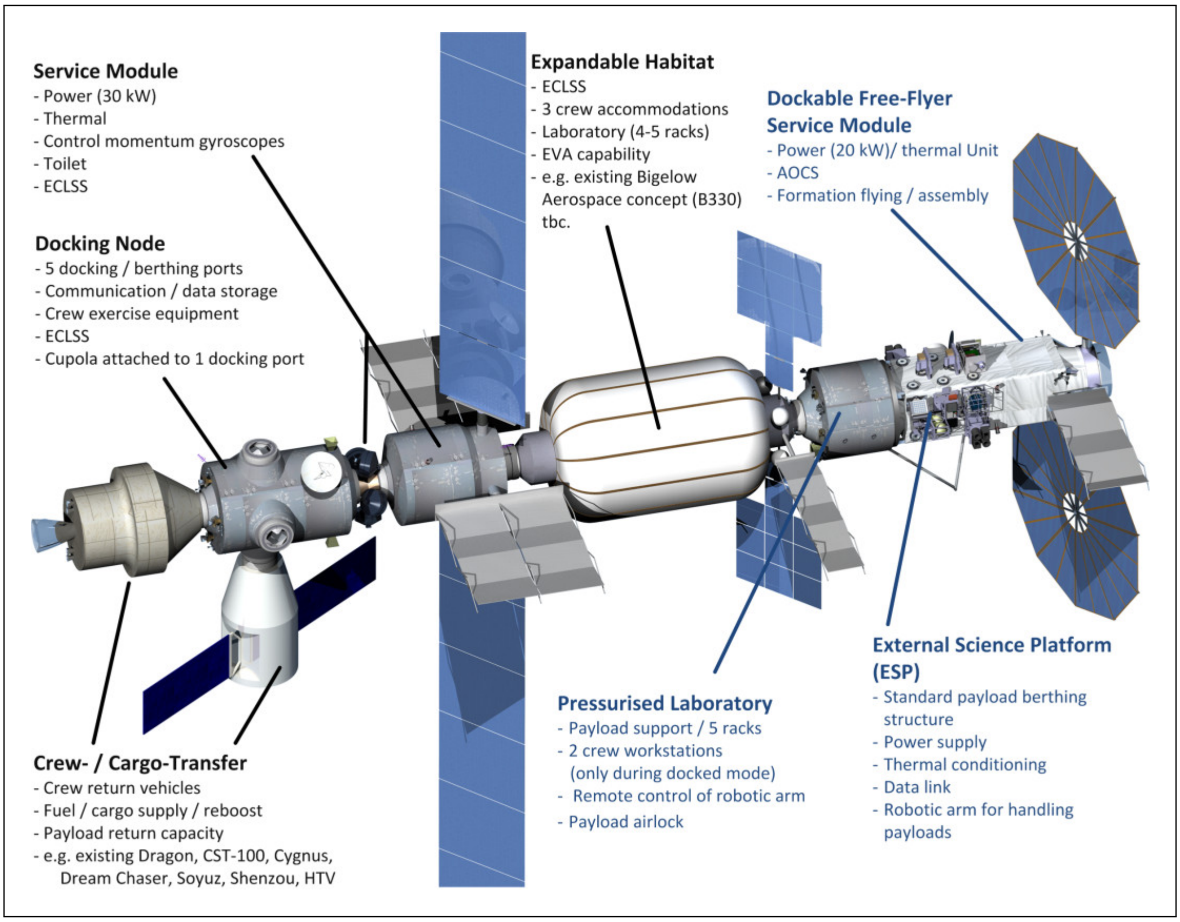


Figure 2.23: Modular Orbital-Hub architecture: multi-purpose station with dockable module/platform as a European initiative.

Furthermore, the Free-Flyer is intended to support the assembly of the base station by being the active part of automated docking since there is currently no similar vehicle like the United States (US) Space Shuttle available. The overall dimensions of the Free-Flyer in stowed configuration (retracted solar panels and radiator wings) have been optimized to be in line with the launch scenario using a single Ariane 64.

Habitation and Life Support Systems

Investigating the future of spaceflight in general and in particular of human spaceflight, space habitation is also a relevant subject of system analysis. Within the area of system analysis, this topic has been approached from three different directions:

1. Design (with external partners) of a laboratory complex, labeled Incubator for Habitation (I4H) for maturing habitation technology in a closed-loop environment,
2. design and development of life support systems for space application (especially in greenhouses, culminating in the EU project EDEN-ISS, see section 4.7), and
3. conducting analogue test site missions for bolstering the two previously mentioned topics.

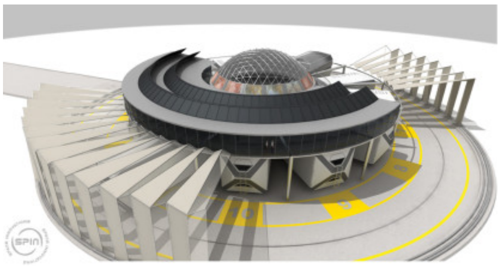


Figure 2.24: The current design of the Incubator for Habitation, artistic expression by Space Innovations (SPIN).

I4H has been a research subject in the system analysis branch for several years. Part of the design was the successful modeling and documentation of all material fluxes within a closed loop of such a laboratory simulating the habitation on Moon or another planet [91]. Currently, a proposal for the European Horizon 2020 program is in preparation for funding further development work of this idea. I4H has a modular design (see figure 2.24) to allow easy exchange of technology and system components. It is intended to be a complete research infrastructure, including accompanied public outreach areas, laboratories, and workshops. The incubator is intended to act as focal point of all related research. Benefits of I4H are not exclusive to space applications, but can help to reduce the environmental impact of humanity on Earth, by applying closed-loop technology in urban regions, areas with harsh living conditions such as deserts, and in general introducing them to society.

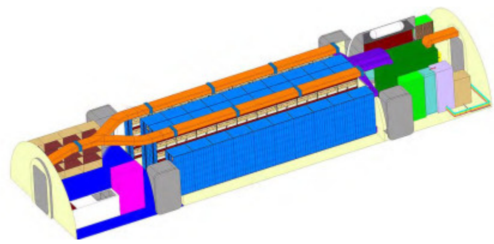


Figure 2.25: Example of a semi-deployable extra-terrestrial greenhouse module [236, 919].

Analogue test site missions have been used to improve the design work regarding habitats in general and green-houses in particular [478, 262], and to gain operational experience.

The analytical focus of the habitation and life support system domain is the implementation of higher plants into bio-regenerative life support systems (BLSS). Several basic studies on the implementation challenges were conducted. [59, 875, 90, 520, 219, 266, 928, 241, 244] Starting with general layout considerations of the greenhouse outer structure (e. g. spherical, dome-like, torsos shape) and environmental parameter analysis, the focus was the systems engineering regarding such planetary elements; see figure 2.25 as an design example. [829, 236, 919].

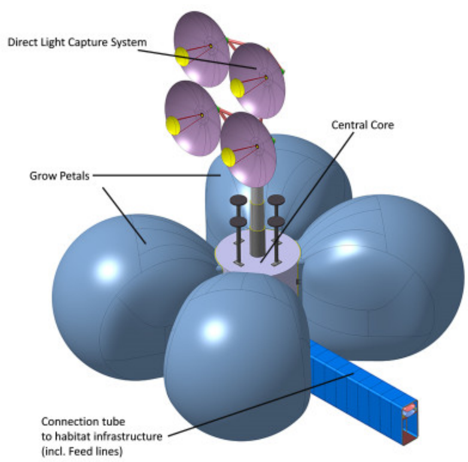


Figure 2.26: Example of a semi-deployable extra-terrestrial greenhouse module, designed by the EDEN Initiative within the ESA project "Greenhouse Module for Space" in collaboration of Airbus DS, HTWD, and Enginsoft. [365].

Here, the holistic evaluation of possible controlled-environment agriculture (CEA) technologies and their implementation in planetary surface greenhouses was a key element of the research objectives. [817, 852, 869, 905] Feasibility and Phase-A studies, technology evaluations, morphological boxes, and trade-offs were key instruments for this kind of investigation. Subsystem accommodation analyses as well as calculations of mass, power, and thermal budgets were performed within several CE studies.

Following the principles of the system analysis approach, a deep understanding of such complex systems and relationships was of high interest within this domain. This way, a solid understanding of the complex nature of biological systems and their technical (and organizational) support systems within closed-loop environments like in Moon or Mars outposts could be generated.

One example within this design work was the "Greenhouse Module for Space" project, which was under the lead of DLR Bremen. The design study was conducted for the MELiSSA group of ESA in 2014 [0, 365, 508, 236]. Key focus was set on a semi-inflatable greenhouse system for the lunar environment for a quasi-full nutritional food supply for a six-person crew. This and other studies were executed by the group over the course of the last four years in order to strengthen the knowledge capacity with respect to extraterrestrial BLSS (compare figures 2.26 and 2.27).

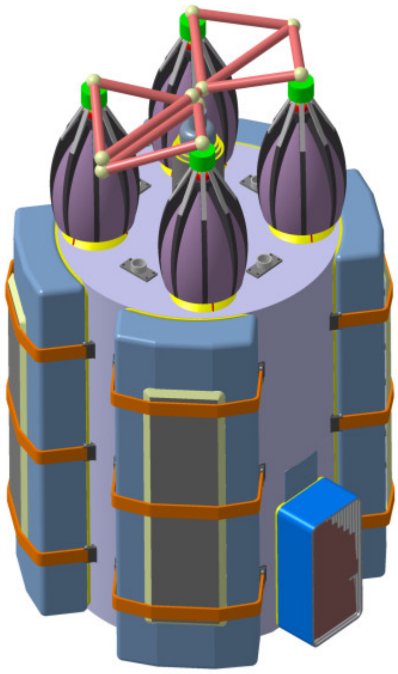


Figure 2.27: Example of a semi-deployable extraterrestrial greenhouse module, designed by the EDEN Initiative within the ESA project "Greenhouse Module for Space" in collaboration of Airbus DS, HTWD, and Enginsoft. [365].

Path-Breaking and Visionary Mission Studies

As part of the mission analysis of future mission concepts, several path-breaking mission designs have been investigated. Such missions involved, for example, a special satellite used for analyzing currently inaccessible atmospheric regions on Earth by "diving" down into them, before returning to a sustainable orbital altitude [769].

Another relevant topic has been the solar electrical mission to Jupiter's trojans — a group of asteroids in Jupiter's resonant orbits around the Sun. While it is very ambitious to supply a mission with power by a solar array at such a large solar distance, the concept proved feasible with current technology and subsequent mission analysis showed that a multi-rendezvous mission is possible, allowing visits at four different asteroids and thus opening up an opportunity to better understand the formation and development of the Solar System [78].

Missions regarding space debris removal have been a recurring subject of analysis. Several studies have been conducted, evaluating different spacecraft and capture options to remove large space debris, such as defunct satellites from orbit. Evaluation of business cases, service opportunities, and overall mission designs have subsequently been executed, painting a clear picture about space debris removal missions. These activities culminated in the "On-Orbit Servicing — Robotic Arm Verification" study conducted in cooperation with several DLR institutions [775].

2.2.5 Experimental System Analysis

The majority of system analysis work at the Institute involves analysis using computer models, evaluation based on existing data and theory, calculations, and simulations. But some ideas require an early experimental justification to further continue the system analysis effort. The following sections describe some corresponding experimental investigations.

Lunar Environment Research

Since the Apollo landings, returning to the lunar surface has been considered and evaluated several times. Usually, scenarios involve permanent bases in contrast to short-term landings of mere days. One approach to sustain a permanent lunar outpost is in-situ resource utilization (ISRU) for obtaining relevant resources like oxygen or helium-3.

An experimental set-up was built at the Institute that allows simulation of ISRU processes in a vacuum chamber. The Verification Experiments for Lunar Oxygen Production (VELOX) was used to model extraction of oxygen from lunar soil in a simulated lunar environment [323].

The set-up was further modified to include a cooling down to lunar surface conditions. This was first used to investigate the possibility of using sub-surface heat for power generation during lunar nights when solar power generators are not usable. A concept analogously to geothermal power generation, dubbed selenothermal power generation, was investigated, reviewed, and analyzed in its feasibility after it won the first place and thus funding in a DLR internal competition of ideas. To achieve this, experiments were conducted involving heating of a fluid (liquid nitrogen) which could be used as a fluid in a cycle-process for power generation similar to water on Earth. Results were negative, which supported numerical simulations and mathematical considerations ruling the usage of selenothermal energy out for long-term lunar outposts [480]. The testbed is depicted in figure 2.28.

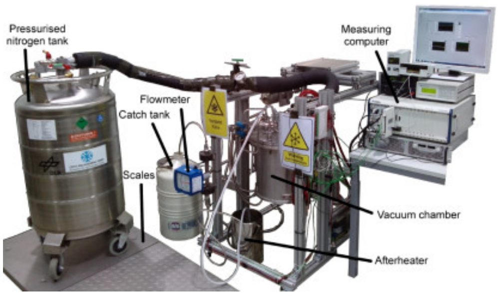


Figure 2.28: The VELOX testbed as used for measurement of heat transfer in lunar environment conditions.

Subsequently, the testbed was further modified and used to determine thermal properties of the artificial regolith JSC-1A, i. e., the thermal conductivity and the heat capacity. [820] In general, a profound knowledge about the lunar environment was established and is used for designing space-based habitats, especially on the lunar surface [469].

On-Orbit Debris Detection

Small orbital debris parts (from sizes of 100 µm and upwards) are abundant in LEO, but currently there is little knowledge about them and their orbital properties, because their size does not allow them to be tracked from Earth. To analyze the quantity of space debris and micrometeoroids in LEO and thus to enhance space debris and micrometeoroid population datasets and enable the validation of relevant models, an in-situ impact detection method has been fully developed at the Institute [801, 18]. The Solar-Generator-Based Impact Detector (SOLID) uses existing solar panels for impact detection. Since solar panels provide large detection areas, this method allows to gather large amounts of data. After an initial system analysis, design, and construction, the detector was successfully validated on the ground via Hypervelocity Impact (HVI) tests at the Fraunhofer Ernst-Mach-Institut (EMI) in Freiburg. The obtained test results have been in agreement with damage equations developed by ESA [16]. The corresponding German patent (DE 102012000260) and the US patent (US 8,593,165 B2) on this method have been granted recently. In 2016, the next step is to demonstrate the SOLID technology in orbit as technology payload for the TechnoSat mission of the Technische Universität Berlin [17]. Figure 2.29 shows an illustration of the spacecraft (left) as well as the already manufactured and tested SOLID panel for this mission.

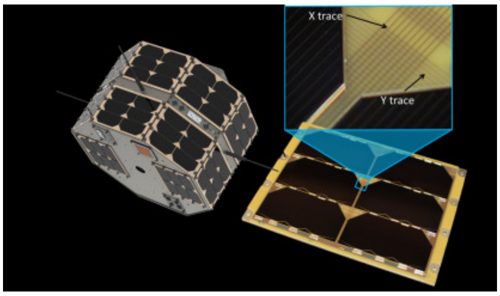


Figure 2.29: Debris detector SOLID on TechnoSat.

3 System Development

The development of a system is realized within the Institute as projects and performed as a consistent end-to-end process. The projects request the contribution of all columns of the Institute to fulfill the various work packages and is supported by in-house processes like controlling. If no in-house expertise is available, the project seeks for cooperation with other German Aerospace Center (DLR) Institutes or external partners. An overview on the typical project process and the involvement of the main columns of the Institute is provided in figure 3.1.

The projects follow a phase-oriented approach according to European Cooperation for Space Standardization (ECSS) standards. This process starts with projects ideas coming from within the Institute, DLR, or from external institutions such as European Space Agency (ESA) calls and Invitation to Tenders (ITT). The initial risk assessment is essential for the tailoring of the (mostly ECSS) standards and their transfer to project plans and design documents. Lessons learned from previous missions are taken into account as well as the availability of crucial technologies that are essential for mission success. The initial risk assessment is kept up-to-date throughout the complete mission life cycle.

Each of the major project phases is finalized by standard project reviews, e. g. System Requirements Review (SRR), Preliminary Design Review (PDR), or Critical Design Review (CDR). External experts are invited to evaluate the design maturity and the compliance of the design with the mission objectives.

After the initial evaluation phase focusing to examine various alternate possible design solutions, the formal project plan is agreed upon and signed. The concept evolved in the preliminary design definition phase is verified by in-house environmental tests to scrutinize the robustness of the design and thus qualifying the system. Subsequently, the pre-flight end-to-end tests that include not only the spacecraft itself, but also the mission control centers are also within the capabilities of the Institute.

Within the mission phase itself, not only expertise is provided to the ground segment but also ground reference models are maintained for failure analysis and validation of modified on-board software before upload.

The following core management and engineering components are addressed within the capabilities of the Institute. Wherever necessary to assure insight into system design options, various key engineering domains are covered within the Institute as well, especially mechanical/thermal design and electrical design including electro-magnetic compatibility (EMC) engineering. In order to provide a closed loop for system development, the Institute provides (environmental) test facilities in order to provide a short response path for potential design options.

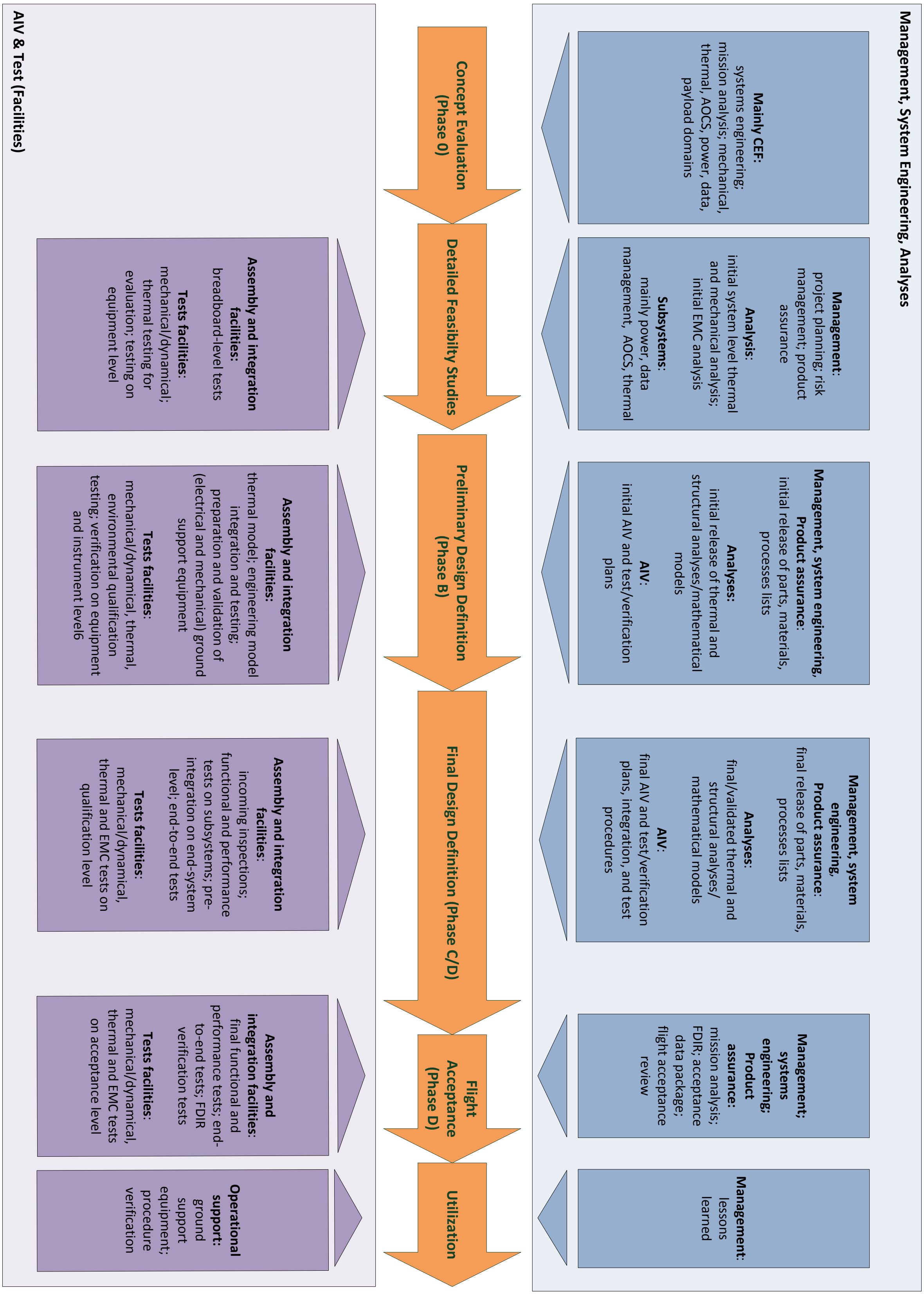


Figure 3.1: Contributions of the Institute to the phase-oriented project development flow. The upper part contains the management and analytical part, the lower part the main technical and test contributions.

3.1 System Development Activities

3.1.1 Management

The most important process is the **project management** process for coordinating and controlling the engineering sub-disciplines. It plans and monitors project budgets and schedule and is the final decision making instance on project risks like deviations from major mission requirements, schedule, or budget. The project manager directly reports to the director of the Institute.

3.1.2 Systems Engineering

Systems engineering is the core and highly interdisciplinary engineering process controlling the consistent translation of mission requirements into the design definition on system level. In the early design phase, emphasis is on the understanding of the mission respectively customer needs. It harmonizes the partly contradicting demands of the various engineering subdomains, for example thermal and electrical engineering into a consistent design description that can be converted into physical models (structural/thermal, engineering, and flight). One main objective is the maintenance of the interface control documents (ICD).

3.1.3 Product Assurance

Product assurance (PA) intends to reduce or eliminate space flight specific risks. Reliability analyses, especially failure modes analyses, intend to identify and mitigate failure modes. The philosophy is that failures can happen within the mission, however, suitable reaction measures need to be defined already in the early design stages. Failure reactions need to be suitable for the necessary response times. If these are long enough, also ground intervention becomes (the last) barrier against failures to impact the mission success.

The usage of parts, materials and processes as well as electronic, electrical, and electromechanical parts are assessed and approved within the frame of their application. Commercially available parts have been used successfully after mission-specific qualification on board level, e. g. ADS-B over Satellite (AoS). Some material key performance characteristics like outgassing are also evaluated within the test facilities of the Institute.

Safety risks (with potential threat to humans but also to ancillary equipment) are evaluated as well and appropriate control measures are defined.

Quality control assures that the as-built hardware complies with the agreed design definition. Key elements are incoming/outgoing inspections utilizing the quality lab of the Institute. It is understood that problems should not only be processed but shall be considered in the lessons learned/best practices database as well. The steering of the problem tracking process is under PA responsibility as well. Configuration management is also within the responsibility of product assurance.

Methods of software quality assurance are implemented after suitable tailoring not only in order to assure and improve the robustness of the final software but also to enforce the reusability of in-house produced software.

The Institute's product assurance supports external partners that have no internal PA capabilities in order to assure a consistent project quality standard (e. g. inspections expertise in materials/processes selection).

3.1.4 Assembly, Integration, and Verification

Figure 3.2: Flight harness fabrication for a satellite project.

The **assembly, integration, and verification (AIV)** management includes the definition of necessary tests to prove the requirements verification. In general, to reduce the risk of damage, these verification activities are not done on the flight model but on dedicated mechanical/thermal engineering models. Tests on the flight model focus on the verification that the model to be flown is free of manufacturing flaws. Accordingly, a series of qualification tests are performed to prove that the design is able to comply with all mission-related performance and functional requirements throughout the mission-induced environmental conditions (mainly mechanical vibrational loads during launch, shock loads, large temperature swing, extreme temperature conditions, and also electromagnetic compliance to externals loads).

The key control elements that govern the AIV process such as the overall AIV plan, verification control plan, test and inspection plans, and test procedures are developed and validated in-house.

The assembly and integration process can be done within integration facilities such as a clean room of ISO 8 and, if required, also according to planetary protection standards. The environmental tests facilities are close to the integration facility itself within the same building. This significantly reduces the transfer times within integration and test facilities. This close vicinity provides the advantages of the co-location principle (i. e. creating a closed loop of experts and laboratories enabling short communication and reaction paths).

Essential to the AIV process is the design and manufacturing of mission-specific mechanical and electrical ground support equipment. The AIV process is further supported by the in-house electronic department in the field of design, manufacture, and checkout of selected components (e. g. harness). The electric part of incoming inspections is also supported.

In general, the broad spectrum of design expertise combined with the in-house availability of integration and test facilities establishes a fast lane for design optimizations, and establishes ways to accelerate the design and AIV flow. Last but not least, this provides also the opportunity for cost saving.

Environmental tests are crucial for the development and flight acceptance of space systems. These can be performed within the premises of the Institute as well. The types of the environmental testing are roughly the same for the qualification tests to prove mission robustness and acceptance testing in order to demonstrate flight worthiness of the flight model.

3.2 System Qualification Facilities

Space systems have to undergo a qualification process before being launched for a mission. The same rule is applied on subsystem, component, and material level. The purpose is to verify the functionality of the system under all possible project phases and all possible environmental conditions to which the systems is exposed to during storage, transport, launch, and flight operation.

Tests are a crucial verification method in the development of a system. They demonstrate that the requirements which are defined in the conceptual phase of the system are met and thus the system is qualified.

The qualification in this sense, depending on the system, component, or material, will be acquired via electrical functional testing, electro-magnetic testing, or environmental testing. Also, software testing may be required depending on the subsystem and system level the test applies to.

The capabilities for system qualification at the Institute of Space Systems comprise:

- functional testing (see section 3.2.1),
- electrical testing (see section 3.2.2) focusing on electromagnetic compatibility,
- mechanical testing (see section 3.2.3) enabling vibration and pyroshock tests,
- thermal-vacuum testing (see section 3.2.4) enabling thermal balancing and thermal cycling tests,
- contamination testing on material and component level (see section 3.2.5) enabling Micro-Volatile Condensable Material (M-VCM) tests and ultra-high vacuum tests, and
- degradation testing on material level (see section 3.2.6) enabling irradiation tests and thermo-optical properties measurements.

Degradation and contamination qualification is usually performed in Phase A or Phase B of a space project since they are critical for the design. Mechanical and thermal-vacuum testing may also be performed early in projects but mostly on component level.

The system qualification is usually performed in Phase C or Phase D depending on the model approach to be pursuit. Hereby a test as you fly philosophy is applied.

3.2.1 Functional Qualification

The functionality and the related qualification procedures and tests are typically very specific to each system. During development, the typical measures are taken to ensure correctness, such as, unit testing and static checks for software, tests of interfaces, early integration tests on the lowest level possible. *Electrical ground support equipment (EGSE)* is always prepared jointly with a space system or subsystem itself for testing and debugging purposes. Specialized laboratories like Landing & Mobility Test Facility (LAMA) or Facility for Attitude Control Experiments (FACE) focus on certain system level functionality that requires interaction with an environment.

3.2.2 Electrical Qualification

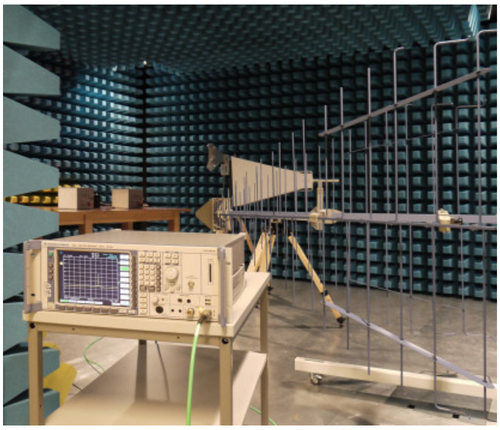


Figure 3.3: Electro-magnetic compatibility (EMC) laboratory.

Electro-magnetic compatibility (EMC) of electronic or electrical devices and components means to function properly in a given electromagnetic environment without emitting intolerable electromagnetic disturbances. To verify the compatibility of systems and components for space applications, the EMC testing laboratory shown in figure 3.3 can simulate various electromagnetic conditions and measure the radiated electromagnetic disturbances caused by the equipment. The tests are carried out according to the standards for space engineering ECSS-E-ST-20-07C and MIL-STD-461F. The following tests are performed in the EMC testing laboratory:

- conducted emission and susceptibility tests in the frequency range of 30 Hz to 100 MHz
- conducted susceptibility tests with different transient disturbances
- measurements of radiated electric field in the frequency range of 10 kHz to 18 GHz
- radiated susceptibility test against the electric field in the frequency range of 30 MHz to 80 MHz with a field strength between 1 V/m and 10 V/m
- radiated susceptibility test against the electric field in the frequency range of 80 MHz to 6 GHz with a field strength between 1 V/m and 20 V/m

Most tests are performed in a semi-anechoic chamber with usable dimensions of 4.4 m × 5.2 m × 2.7 m (L × W × H). The test chamber is designed according to the standards MIL-STD-461 and ECSS-E-ST-20-07C for frequency ranges up to 40 GHz. The basic measuring equipment (test receiver, signal generators, and power meters) is also designed for the frequency range up to 40 GHz, so it can be easily upgraded. In addition to performing the verification tests, the EMC laboratory is providing support to projects and missions in the following areas:

- development-related investigations of electromagnetic compatibility
- assistance in the development of EMC test procedures
- support in the analysis of electromagnetic incompatibilities and in locating the sources of interference

3.2.3 Mechanical Qualification

Especially during launch, space structures and mechanisms as well as other hardware components like sensors or electronic boards are exposed to high quasi-static and dynamic loads. In order to validate analysis results and to qualify components and systems, the Institute of Space Systems operates the Mechanical-Dynamical Test Laboratory containing a vibration shaker table as shown in figure 3.4 and a pyroshock test facility as shown in figure 3.5. To be compliant with cleanliness requirements, this laboratory is run as class 8 clean room according to ISO 14644-1. The laboratory is accredited according to DIN EN ISO/IEC 17025:2005 for mechanical-dynamical vibration and shock testing for the following testing standards: ECSS-E-ST-10-03C "Space Engineering — Testing", MIL-STD-810 G "Environmental Test Methods", DIN EN 61373 (IEC) "Schwingen und Schocken für Bahnanwendungen", NASA-STD-7003 "Pyroshock Test Criteria" and aviation standard EUROCAE RTCA DO-160C.

Vibration Testing

Vibration testing is performed using a vibration shaker. The force to accelerate the test specimen is generated by electro-magnetic excitation. The shaker table has a maximum force output of 11 kN hence allowing tests of systems of the Small Satellite Technology Experiment Platform (S2TEP) size (see section refsec:S2TEP). The following tests are performed with the vibration shaker:

- quasi-static loads testing at low-frequency sinusoidal excitation used to verify quasi-static design loads
- sinusoidal testing and resonance search testing 5 … 2 000 Hz used to verify frequency response behavior and to experimentally determine the eigenfrequencies
- random vibration testing 5 … 2 000 Hz often used to test equivalent acoustic loads
- half-sine shock pulse testing simulating certain shock events

Besides standard testing of space systems and components, special test cases allowing vibration tests combined with cryogenic temperatures can be performed. Typical applications are electrical components near cryogenic tanks on the Ariane upper stage. The test facility is also used for testing in the aeronautics, automotive, and railway sector.

In order to prepare for future test activities like for Euglena and Combined Regenerative Organic-Food Production in Space (Eu:CROPIS) with up to 250 kg test mass, a more powerful facility is needed. Therefore, the Institute received approval from the DLR executive board for the installation of a larger 89 kN vibration shaker. It shall be put into operation in March 2017 with Eu:CROPIS as its first large customer.

Figure 3.4: Vibration shaker in the Mechanical-Dynamical Test Laboratory.

Pyroshock Testing

Pyroshock testing is performed to verify the functionality of systems and components when exposed to events like stage separation, fairing separation, or any kind of release on the system. For this kind of separation or release events, actuators based on pyrotechnics or based on high-strain energy are used. They induce high shock loads into the system and may cause damage especially to electronic equipment.

Figure 3.5: Pyroshock Test Facility in the Mechanical-Dynamical Test Laboratory.

A pyroshock test facility is part of the Mechanical-Dynamical Test Laboratory. It allows the simulation of high-transient acceleration excitation as for above mentioned events. For that purpose, the ringing plate method is applied. An 1 m by 1 m and 20 mm thick plate is excited with pyrotechnical nail guns of different power on varying load introduction pads. As the plate is excited, the test object is also exposed to a transient vibrational load, known as the shock event.

This facility allows testing of objects up to 35 kg with shock levels up to 26 000 g in the shock response spectrum. It is well suited for the testing of systems like Mobile Asteroid Surface Scout (MASCOT) (see 3.4.1) or S2TEP (3.3.6). All structural responses are monitored according to customer request and the shock response spectra are derived.

3.2.4 Thermal Qualification

Thermal boundary conditions in a mission can have a great variety: storage, launch, orbit or transfer, decent phases onto celestial bodies, and seasons as well as day and night phases on such bodies. All those boundary conditions need to be accounted for and the system needs to be verified that it meets all the resulting requirements. In order to enable necessary test scenarios, the Institute of Space Systems operates the Solar-Thermal-Vacuum Test Laboratory consisting of:

1. Space Simulation Chamber
2. Sun Simulation Chamber
3. Calorimetric Test Stand
4. Climate Chamber

The facilities can be used for qualification testing of thermal models. Due to the large variety of different possible test scenarios, they offer excellent opportunities for thermal model validation purposes. This goes along with the capability to design, fabricate, and operate non-standard test setups for all kinds of mission scenarios.

The Solar-Thermal-Vacuum Test Laboratory is accredited according to DIN EN ISO/IEC 17025:2005 and is run as class 8 clean room according to ISO 14644-1 allowing to perform flight hardware acceptance tests or flight hardware qualification tests in case of a protoflight model approach.

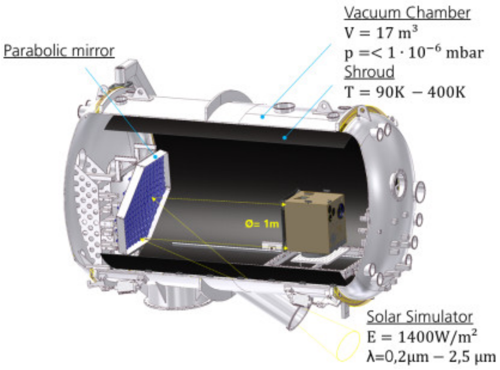


Figure 3.6: Principle design of the Space Simulation Chamber.

Space Simulation Chamber

The Space Simulation Chamber as shown in figure 3.6 is the largest thermal-vacuum facility operated at DLR. With a test diameter of more than 1.6 m and a length of 3 m, it is unique in DLR and is suitable for all kind of hardware developed at the Institute. Test items can be thermally conditioned within an envelope of 90 K to 400 K. Using external thermostats, test items can additionally be conditioned via tempering plates. Furthermore, the chamber features an artificial Sun which creates one solar constant of heat flux on a 1 m diameter area. All sources can be run independently from each other, allowing to create a great variety of different thermal states that may occur during a mission.

Thermal tests usually performed in thermal-vacuum chambers are:

- Thermal Balance Test: thermal balance and temperature distribution under certain conditions of interest
- Thermal Cycling Test: prove of functionality for a certain number of cycles at prior defined temperature levels

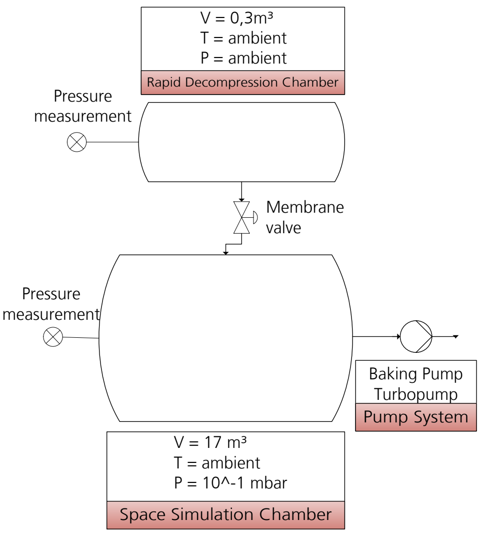


Figure 3.7: Principle of venting testing.

Combining the Space Simulation Chamber with a smaller vacuum chamber allows for testing of venting scenarios, simulating the pressure decrease during launcher ascent. In the research work of the Institute, this specific test is primarily applied to stowed deployable membranes (see 3.6.1) in order to verify no air is trapped in the stowed membrane causing damages to the membrane which can endager a save deployment.

At the beginning of the test, the small chamber has ambient pressure while the space simulation chamber is already evacuated. Both chambers are interconnected by a vacuum line with a valve. By opening the valve to a previous determined setting, the air quickly flows from the small chamber into the space simulation chamber. After the first significant pressure drop, the little remaining air is evacuated more slowly by the vacuum pumps. Figure 3.7 shows the principle test setup for venting testing.

Sun Simulation Chamber

The Sun Simulation Chamber as shown in figure 3.8 was developed to investigate the effect of solar pressure on material surface in front of a deep space background. With a size of 0.45 m diameter and a length of 0.8 m it is a mid-size chamber at the Institute and is suitable for testing of systems of size of MASCOT or S2TEP. It features a shroud which can be cooled down to -90 °C using liquid nitrogen, test items can be thermally conditioned using tempering plates with external thermostats and an artificial Sun of approximately 100 mm diameter can create one solar constant of heat flux onto the test specimen. Typically, thermal cycling and thermal balancing tests are performed in this facility.

Figure 3.8: Sun Simulation Chamber.

Calorimetric Test Chamber

The Calorimetric Test Chamber is a small facility with a diameter of 0.25 m and a length of 0.5 m. Test items are thermally conditioned using an external thermostat. It is well-suited for small components in tests where no special ambient environment needs to be considered. Typically it is good for thermal cycling tests and has been used for numerous tests of electronic and mechanical hardware like the separable umbilical connectors of MASCOT and Gossamer-1.

Climate Chamber

The Climate Chamber is used for simulating environmental temperature and moisture effects on systems, components, and materials at ambient pressure. It allows for accelerated life cycle testing if vacuum is not mandatory for the verification. Within the Interior Exploration using Seismic Investigations, Geodesy, and Heat Transport (InSight) support system development (see 3.4.2), it has successfully been used for cold and warm support system separation, tether deployment, and mole hammering tests besides numerous other tests. Furthermore, it is used for dry-heat microbial reduction for interplanetary missions or biological payloads.

3.2.5 Contamination Qualification

Most of available materials and components tend to outgas when exposed to vacuum conditions. The rate of outgassing is dependent on the materials itself, their treatment during manufacturing but also their exposure time and temperature in vacuum. For space applications, the outgassing can lead to severe quality problems especially if volatile materials condense onto neighboring surfaces. Especially for optical instruments or sensor surfaces, this can lead to a dramatic decrease in performance. Therefore, the qualification of all used materials with reference to their outgassing behavior is of great importance for the design of space hardware. The same applies to materials to be used in test facilities in order to avoid contamination prior to the mission itself. For the qualification of the outgassing behavior of materials and components, the Ultra-High Vacuum Laboratory runs a M-VCM test facility for material tests and a Ultra-High Vacuum Test Facility for component testing. Both facilities are accredited according to DIN EN ISO/IEC 17025:2005 for ultra-high vacuum testing.

Micro-Volatile Condensable Material Test Facility

Figure 3.9: Outgassing Test Facility.

The M-VCM test facility allows outgassing tests of materials according to the ESA standard ECSS-Q-ST-70-02C "Thermal vacuum outgassing test for the screening of space materials". Three outgassing parameters are determined, which are widely used for material selection for space applications:

- Total Mass Loss: percentage weight loss of a sample after 24 h in high vacuum at 125 °C. The sample is preconditioned for 24 h at 55 % relative humidity and 22 °C.
- Recovered Mass Loss: percentage weight loss of a sample after 24 h in high-vacuum at 125 °C. The sample is post-conditioned for 24 h at 55 % relative humidity and 22 °C.
- Collective Volatile Condensable Material: percentage weight of condensate on a collector plate (temperature 25 °C) above a material sample after 24 h in high vacuum.

Ultra-High Vacuum Test Facility

Figure 3.10: Ultra-High Vacuum Outgassing Test Facility.

The Ultra-High Vacuum Test Facility as shown in figure 3.10 is a supplement to the M-VCM testing. Materials or components will be irreversibly tested with regards to their outgassing behavior. Examples for components tested in this facility are motors, electronic boards, heaters, or camera lenses. Furthermore, cleaning procedures can be tested by testing materials or components after each cleaning step.

Tests are based on the comparison of measured outgassing rate in the test chamber before and after transfer of the test specimen. Depending on the shape of the test object, either an areic outgassing rate or the total outgassing rate can be determined. Test duration is usually between one to two weeks to determine time-dependent outgassing rates. A mass spectrometer in the range 1–512 atomic mass unit (amu) yields important results for causes of outgassing (entrapped air, remainders of detergents, or outgassing of specific materials).

3.2.6 Degradation Qualification

Due to the solar radiation and particles such as protons and electrons, thermo-optical properties of material surfaces (absorptivity, emissivity, and reflectivity) change over time. This surface degradation plays an important role for a robust spacecraft thermal control system design to ensure proper function under begin-of-life and end-of-life conditions. Considering solar sails as an alternative propulsion technique, the surface reflectivity is decisive for its effectiveness. Beyond this, degradation testing is also performed in order to determine the reduction of efficiency of thin-film photovoltaic cells for space applications (see section 3.6.1). Recently, degradation testing is also performed to test the longevity of membrane materials which shall be used for drag-sail applications to de-orbit satellites from a low-Earth orbit (LEO). This subject is mainly driven by ESA's Clean Space Initiative which resulted in the ESA projects "Deployable Membranes" and "Architectural Design of a De-orbiting System" where the Institute is one of the contributors. For degradation testing, the Institute runs the Complex Irradiation Facility and a spectrometer for solar absorptivity and infra-red emissivity measurements.

Complex Irradiation Facility

The Complex Irradiation Facility as shown in figure 3.11 is operated to perform material investigations in vacuum under radiation conditions as prevalent in space environment. Multiple radiation sources are combined to a vacuum irradiation chamber. Specimens can be exposed to a well-defined irradiation with protons, electrons, and electromagnetic radiation (infrared, visible light, ultraviolet and vacuum ultraviolet).

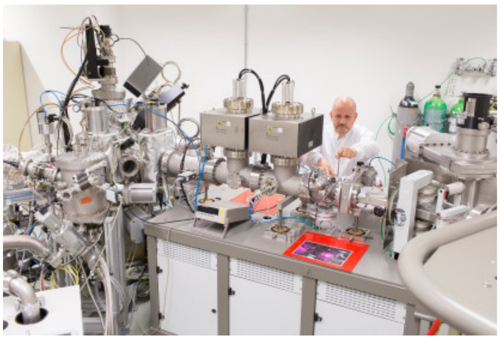


Figure 3.11: Complex Irradiation Facility.

Absorptance and Emissivity Measurement Facility

The term thermo-optical properties in space applications typically summarizes solar absorptivity α and emissivity ϵ. Their ratio determines the thermal behavior of a surface and hence can have a strong influence on the thermal balance of space systems. A Brucker VERTEX V80 spectrometer with a white and gold Ulbricht integrating sphere is used for measuring the spectral solar absorptivity and the hemispherical emissivity of thermo-optical surfaces.

3.3 Satellites

With respect to the decision of the space program directorate of DLR to establish its own satellite program, the Institute has developed a strategy to harmonize and systematize satellite design and development within DLR research and development (R&D). It has been created to provide a reliable planning tool to perform DLR R&D-financed science missions and technology demonstrations in outer space.

The DLR satellite roadmap focuses on the development and integration as well as the launch and operations of small satellites. The scientific and technical issues to be solved within the framework of future satellite missions are subject of the mission roadmap as part of this strategy. Also, their integration into DLR global and/or overall objectives are covered. The activities cover the entire development cycle of the definition, design, development, and validation of the required infrastructure elements. These include the satellite bus and payload as a whole system, the ground segment, and operations.

Thus, the build-up and maintenance of system capabilities based on an "end-to-end philosophy", is a major goal of the Institute's satellite development strategy. This covers as well the mastery of mission design tools, interface standardization, and service management tools.

The Institute's satellite strategy covers the following mission elements (see also figure 3.12):

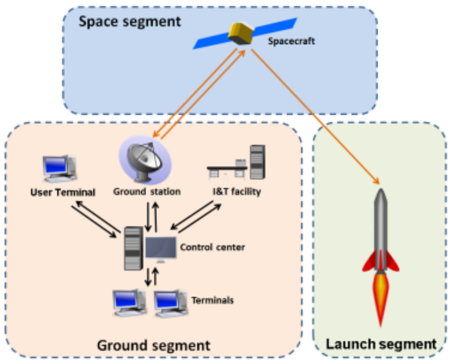


Figure 3.12: Mission elements of any satellite mission.

- space segment: satellite bus systems and payload (P/L) requirements
- launch segment: options for access to space

In the frame of a continuous development process, a cooperation between all DLR institutes and fusion of capabilities of same is aimed for to

- ensure, together with all DLR institutes, competitiveness in the area of satellite systems in the fields of fundamental research, technology development and -testing as well as innovation in an international context and
- to develop a modular platform for all DLR institutes (satellite bus) for experiments in space environments.

3.3.1 Mission Concepts

First of all, future missions opportunities shall be selected with regard to innovative services, applications, systems, and/or technologies. The main focus shall be the option for DLR institutes to develop, launch, and operate those missions. In addition, outstanding features with respect to technology, programmatics, and a possible later marketing of the results. In the detail, this means:

- mission goals
- context and added value
- market research
- demonstration of technologies and services
- performance factors
- mission architectures
- technological and economical risks
- evaluation of supply chain ("make or buy")
- synergies
- roadmap for future developments

3.3.2 Technologies for DLR Satellites

The R&D activities of the Institute of Space Systems focus on investigating technologies for small satellites, development as well as design and execution for completely in-house developed satellite missions. The higher-level, long-term purpose is the design and the continuous development of the overall system competency for which a reliable and long-term planning is essential.

The in-house manufacturing of critical elements is preferred, as long as no alternatives are available off-the-shelf. System competency in this sense also covers the capability to translate mission requirements in technical requirements as well as the capability to realize space missions from a perspective of project management, system design and integration, verification, and qualification.

In addition to complex, long-term satellite missions, small satellites allow new research options in space. Within a short amount of time, experimental missions with a dedicated focus can be realized in preparation for the above mentioned large and complex missions. Beside the flexibility in terms of mission architecture and programmatics (stability of schedule and costs), small satellites offer the chance to realize innovative design architectures (for example with respect to functional share between sensors and bus). Also, dedicated observational strategies (in particular for single-sensor platforms) as well as shorter times-to-science offer the chance to close gaps in long-term observations. Cluster and constellations of small satellites will provide increased spatial as well as temporal resolution for fundamental research, e. g. remote sensing.

For the realization and implementation of the above mentioned goals, corresponding satellite bus systems are to be provided, serving as platforms for own experiments in Earth's proximity. Two complementary, flexible and scalable satellite bus systems are to be developed, S2TEP and Compact Satellite (CompSat), see table 3.1. The DLR Institute of Space Systems is prime in the development of these two lines. However, synergies with other DLR institutes are essential as well.

The microsatellite (S2TEP) will mainly support a single experiment and is realized in a short time frame due to its reduced complexity and its simpler design. The focus of the missions of these satellites lies on technology demonstrations using innovative satellite technology (single-sensor satellite missions). For the development of the S2TEP platform, experience and expertise of the successfully completed projects Automatic Identification System Satellite (AISat) and MASCOT is essential.

The area of small satellites will be covered by the CompSat, already established in DLR. When it comes to size, functionality, and complexity, the CompSat is comparable to S-class missions (Small Mission Opportunities) in the ESA science program. It is understood as a multi-sensor platform or as a carrier of an elaborate instrumentation platform. Compared to micro satellite platforms, more challenging boundary conditions such as thermal, calibration, guidance, navigation and control as well as power are to be coped. Applications range from astronomy and Earth observation missions to biological research or interplanetary missions with different requirements, for example to the position control, energy consumption, data link, etc.

Due to the desired standardization, the modular design approach and the further use and reuse of developments in both satellite bus programs provides the option to share resources. The microsatellite platform S2TEP already has a close connection to DLR small satellite platform CompSat and their first mission Eu:CROPIS. Components that are developed as part of S2TEP to the required maturity for a flight mission (performance and reliability), are used in an adapted and scaled form in future compact satellite missions. A common roadmap, broken down to component and subsystem level for the two satellite buses and their technical dependencies is outlined below (see figure 3.14 and figure 3.27). In the following, differences, similarities, and synergies between S2TEP and CompSat will be further addressed.

The interlacing of the two different program lines — microsatellite (S2TEP) and small satellite (CompSat) — promises a great synergy and optimizes the re-use of technological developments. This leads to an improved vertical depth of development in order to make make-or-buy decisions and an overall reduction in development risk.

Due to the anticipated reduction of one-time development costs (nonrecurring costs), shorter project times and the reduction of the overall effort in follow-up projects will be realized in both the microsatellite and small satellite field.

The corresponding technology program focuses on the development of core competencies that will be available in all future DLR R&D satellite projects. This includes that both bus systems with their subsystems, components, parts, etc. are coordinated in order to guarantee a high degree

Category	Launch mass [kg]
Picosatellite	< 1
Nanosatellite	1 – 10
Microsatellite	10 – 100
Small Satellites	100 – 500
Medium Satellites	500 – 1 000
Large Satellites	1 000 – 5 000
Extra-Large Sat.	> 5 000

Table 3.1: General Satellite Classification

of mutual re-use and to achieve a visible, overall flight heritage (continuity and sustainability).

This includes development and implementation of complete satellite missions by application of system competency in management as well as system engineering as well as the organizational support of the experimenters in the engineering and management area, technical support for the development, and qualification of payloads. With respect to organizational aspects, all DLR R&D satellite developments are concentrated in Bremen, where contributions of the Institute of Space Systems can be found in the overall mission and the satellite bus. The close co-operation with other DLR institutes is essential. Typically, the experiments and/or payloads for the missions will be supplied by other DLR institutes.

Additionally, design, construction, and testing of key systems for satellite buses is part of the strategy. The ability to develop own satellite buses and their subsystems to a certain vertical depth of production is a prerequisite for an independent decision to use either own systems or components or to buy from outside suppliers ("make-or-buy").

Modular systems to be implemented in satellite buses, initially generate additional costs for standardization, engineering services, etc. However, the payback is noticeable in significant savings in the total cost, the duration of the project, and the reliability of the systems. Complex satellite systems can be constructed quickly and reliably by assembly of existing scalable building blocks using an open architecture with standard interfaces.

In the technical area, a flexible layout and subdivision of the satellite bus designs into subsystems such as on-board computers, software, communications, power supply, navigation, position and attitude control, structure, thermal control, and drive system is provided. This will lead to a high degree of reusability in different mission types. A much larger range of applications are possible than it would be the case with a fixed, predetermined configuration.

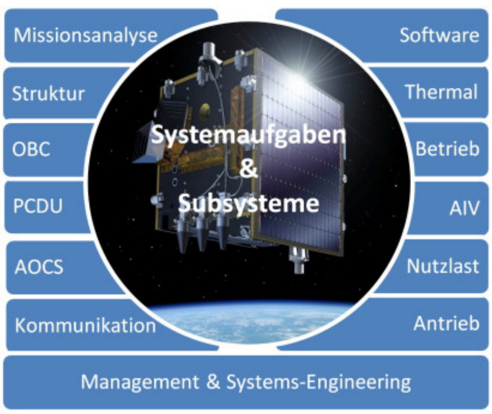


Figure 3.13: R&D activities in the domain of satellite technologies.

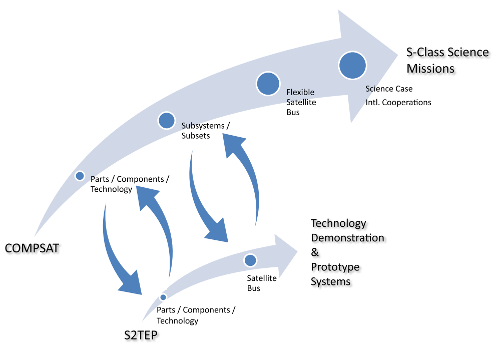


Figure 3.14: DLR roadmap for small and microsatellites, showing interconnections between both development lines.

3.3.3 Compact Satellite – First Mission Eu:CROPIS

In conjunction with the goal setting for the Institute of Space Systems the DLR CompSat shall provide a programmatic approach supporting the sustainable improvement of an end-to-end system competence for scientific Space missions within German institutions and industries.

In this context the program for compact satellites shall:

- cover all Space mission elements, incl. Space Segment (Satellite Bus and Payload), Ground Segment and Space Transportation
- provide an independent accessible platform for Space based research and development
- support the improvement of scientific excellence for DLR R&D projects
- invite DLR external institutions and industries for collaboration
- provide a platform for international collaboration in the field of aerospace R&D
- improve the end-to-end system competence for scientific Space missions

Following these basic requirements the compact satellite class was defined leading to a satellite with dimensions of 1 000 mm × 1 000 mm × 1 000 mm and a mass of approximately 200 kg. Standardized components shall be applied to the highest extend possible in order to allow a maximum adaptability of the satellite's configuration to the payload needs. The following figure gives an overview of the potential development line for the DLR compact satellite.

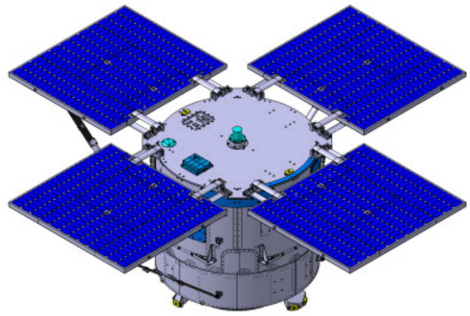


Figure 3.15: DLR Compact Satellite.

Goals of the Eu:CROPIS Mission

From programmatic point of view, the compact satellite shall establish the DLR owned platform for space-based R&D with flight heritage. For this reason the successful in orbit operation of the satellite bus and its components as such is a major target of the mission. Also the international cooperation shall be promoted, leading to the requirement for provisions for additional experiments. However, the major target is the proof of the applicability of the compact satellite for scientific applications. Therefore a concrete scientific experiment was proposed as anchor application for the design of the first DLR compact satellite mission.

The selected first mission "Eu:CROPIS " is allocated to the area of Human Space Exploration with respect to develop enabling technologies for long term missions. The availability of an efficient and reliable closed loop environmental control systems is to be seen as a key enabling element for long term missions with enclosed living spaces or with zero emission habitats - in Space (ISS or interplanetary missions) or on Earth (polar stations, safe air in mining, submersibles, etc.).

In this context bio regenerative life support systems are considered as highly effective with low energy consumption, promising long term stability. The functional principle is utilizing the production of biomass and oxygen by plants and the production of carbon dioxide by humans consuming oxygen and biomass.

The compact satellite mission Eu:CROPIS includes as primary payload an experiment to proof the long term stability and the restart ability of such a bio regenerative closed loop life support system including the production of atmosphere and food (tomatoes) based on the utilization of waste (urine). The feasibility of this approach shall be proofed for different gravity levels such as 1 g (Earth), 0.38 g (Mars), 0.16 g (Moon) and 0.1 g (ISS) and under radiative environmental conditions in space. In addition to this the molecular determination of adaptation processes on cell level shall be performed, considering the influence of variations of gravity level as only variable environmental factor.

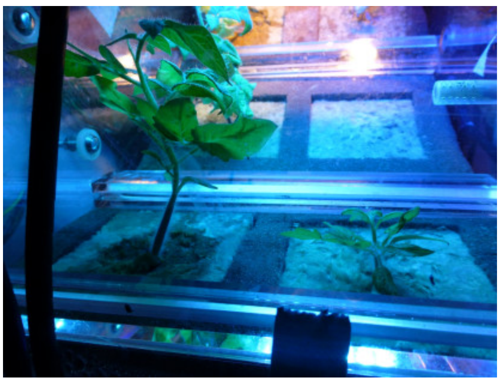


Figure 3.16: Eu:CROPIS greenhouse.

Fostering international co-operation, the Eu:CROPIS mission is hosting a biological experiment from the National Aeronautics and Space Administration (NASA), testing photosynthetic cyano bacteria for the production of food for non-photosynthetic microbes. The application of this experiment is to be seen in the provision of a biological source of energy for future Space colonies.

The third payload on-board is focused on the measurement of radiation inside and outside the spacecraft in order to improve radiation models for future Space missions and to investigate the variation of radiation exposition in dependence from mission duration and solar cycle.

Mission Duration (incl. LEOP & Commissioning)	Expected 15-18 months, max. 24 months
Orbit Type	Low Earth Orbit (LEO)
Orbit Altitude (TBR)	565 – 585 km (circular), 600 km under negotiation
Orbit Inclination (TBR)	~ 96.4° - 98.4°, sun synchronous (SSO)
Orbit (SSO) LTDN (TBR)	10:00 – 10:45
Spacecraft Attitude	spin stabilized, sun pointing spin axis (Z)
Primary Ground Station	Weilheim, Germany
Launch Vehicle	Falcon 9v1.1 (SpaceX, Spaceflight Inc.)
Spacecraft Launch Mounting	90° tilted, Spaceflight Secondary Payload System (SHERPA), directly mounted
Launch Date	Q3/2017, Mission "2017A SSO Express"
Launch Site	Vandenberg AFB, SLC-4E

Figure 3.17: Eu:CROPIS mission parameters.

Furthermore the compact satellite shall serve as technology demonstrator. The fourth payload will proof the applicability of the DLR-developed on-board computer (OBC) "SCORE" under real space conditions and the satellite bus as such will serve as an experiment on its own, providing for new-technology light weight mechanisms (solar array deployment mechanism) and structures (light weight carbon fiber pressure vessel).

Satellite Configuration

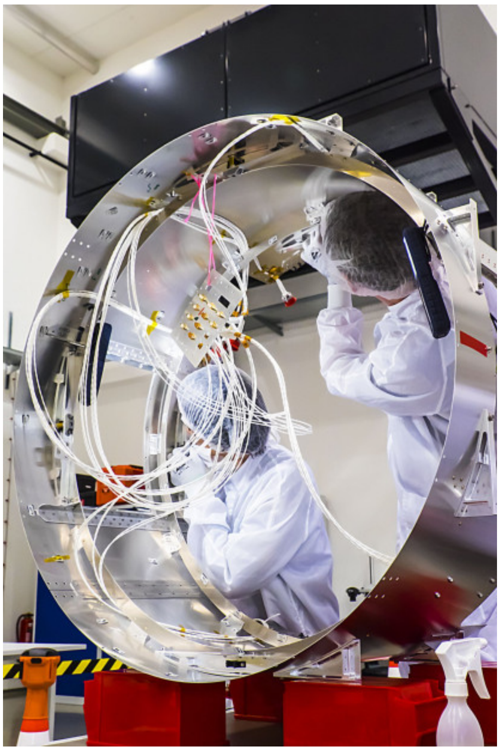


Figure 3.18: Eu:CROPIS strucutre model assembly.

In order to support the scientific goals the compact satellite will be launched into an orbit between 500 km and 650 km. The variation of gravity levels will be achieved by different rotation speeds. Therefore the compact satellite is configured as spin stabilized.

In principle the satellite is separated into two compartments from which the bottom part represents the satellite bus including all subsystems required for the satellite operation. The top part hosts the payload segment, which is also divided into the electronic section (bottom) and the biology section (top). The complete payload of the Eu:CROPIS experiment is accommodated inside a pressurized vessel at standard atmosphere conditions at sea level.

In order to allow the experiment execution at different gravity levels the experiment set up is duplicated and installed in two separated segments. Each segment includes tanks, organisms, experiment infrastructure and green house for plant growing on the shell wall.

The segments will be operated in sequence (each segment for the duration of six months) while the rotation of the satellite will be adjusted for the generation of 0.16 g at the outer wall for the operation of the first segment and 0.38 g for the operation of the second segment. In both cases the spin up phase will be used for experiments under 0.1 g conditions.

Eu:CROPIS Status

The first concept studies for Eu:CROPIS were started late 2012 and the

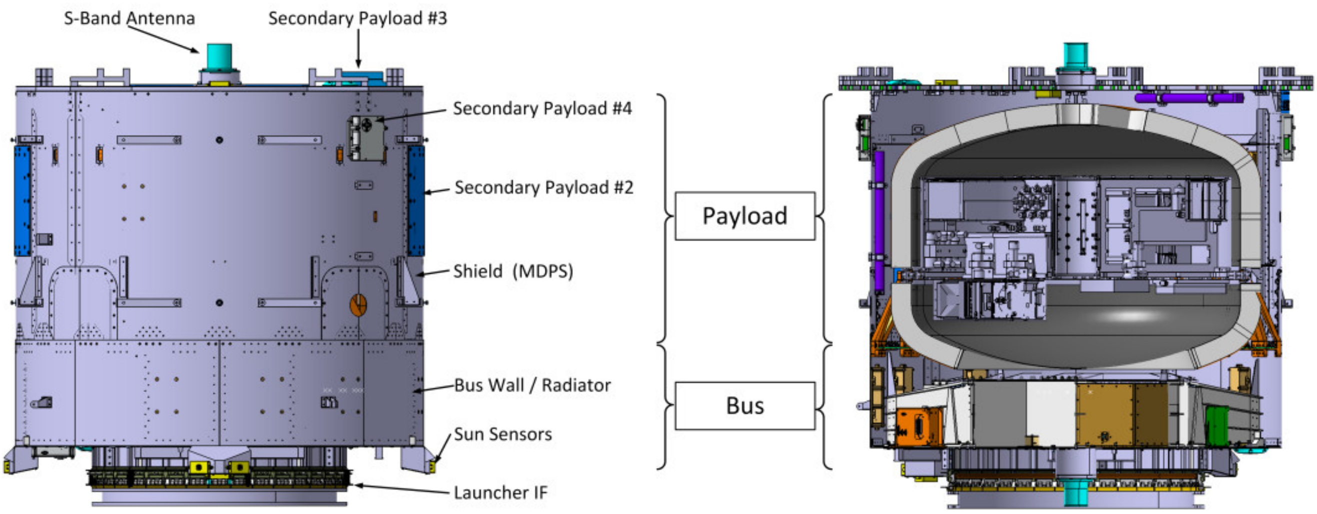


Figure 3.19: Compact Satellite configuration.

project was established in 2013. The launch is envisaged for Q3 2017 on Falcon 9.

Presently Eu:CROPIS is in Phase C/D having passed all required environmental tests for the structure model. Figure 3.20 shows the Eu:CROPIS structure model testing at Industrieanlagen-Betriebsgesellschaft mbH (IABG).

For the time being the assembly and test of the engineering model is ongoing and within summer 2016 the integration of the flight model will start. For January 2017 the begin of the functional testing of the flight model is schedule leading to the delivery for launch in May 2017.

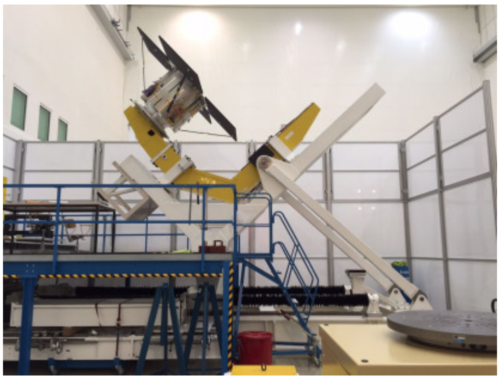


Figure 3.20: Eu:CROPIS structure model testing at IABG.

3.3.4 AISat

Globalization causes increasing traffic density on the oceans. The Automatic Identification System (AIS) was established to provide information about a ship to other ships and to coastal stations automatically. Since 2004 it is mandatory for international vessels over 300 gross-tonnages, cargo vessels over 500 gross-tonnages and passenger ships of all sizes to carry an AIS transponder. These devices receive and send signals by using a very high frequency (VHF) Radio Frequency (RF) transmitter for broadcasting important information to nearby receiver on other ships or land-based systems. AIS devices transmit for example their identity, position, speed, course and other travel related data. Marine authorities uses AIS data to improve their awareness of the current maritime situation. But the AIS technology has its limitations; namely signals can't reached beyond about 50 nautical miles (curvature of the Earth).

Satellite based AIS receiver extends the range since signals can be received from many kilometers above land and sea to monitor the maritime traffic far from coastal regions. The main challenge of satellite AIS is the possibility to get a much more complete picture of maritime activities especially in high ship density zones, like the German Bight or Strait of Gibraltar. But in these zones, multiple AIS messages are received from many different ship transmitters sending the signals at the same time. This can lead to signal overlapping and data corruptions. This is where AISat draws on. AISat is a technology demonstrator for global sea-traffic monitoring with focus on high density traffic zones, developed by the DLR in Bremen. The satellite is equipped with a directive antenna to decrease the field of view and with this the number of messages received at the same time. Beyond that, a filter and different attenuator stages allow a manipulation of the received signal.

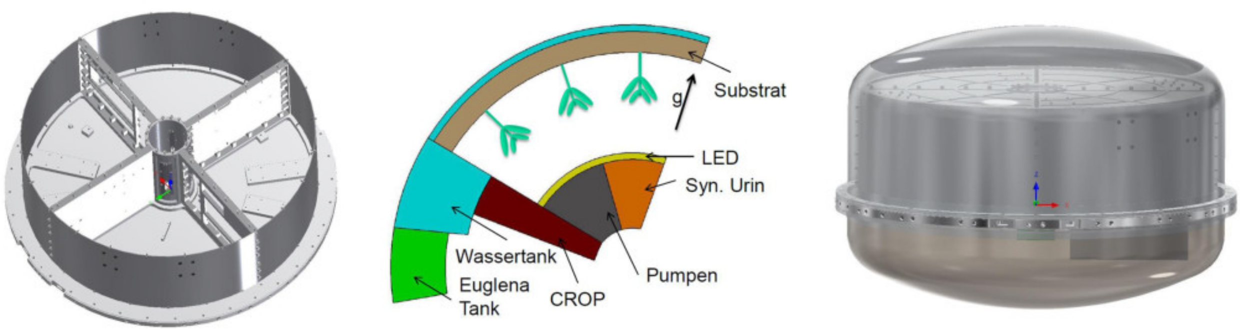


Figure 3.21: Eu:CROPIS payload configuration.

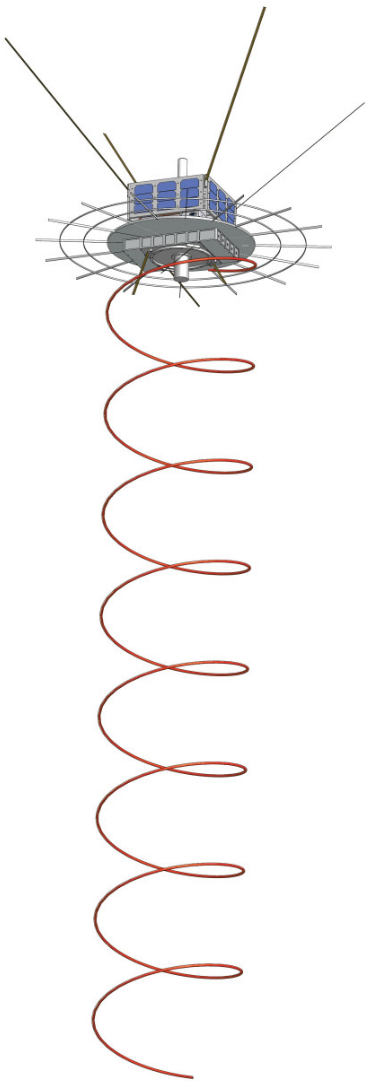


Figure 3.22: AISat in deployed antenna configuration.

AISat Mission Objectives

The mission objectives split into the fields of payload related satellite based AIS reception and the development of a flexible and cost-effective nanosatellite platform. Four primary mission objectives have been defined for AISat:

- Development of a cost effective Nano-satellite platform
- Receiving AIS class A and class B messages from LEO
- Receiving AIS messages from a high density zone (like the German Bight)
- Receiving messages from AIS search and rescue transponder (SART)

System Overview

The platform design is an outcome of a DLR working group which investigated the possibility of using commercial of-the-shelf available CubeSat components to build a highly flexible nanosatellite platform for small DLR-payloads. The most challenging issues of this approach are the limitations of the PC104 standard header, insufficient redundancy support of the components available at the CubeSat market, and missing Consultative Committee for Space Data Systems (CCSDS) compatibility [496]. On the other hand complete subsystems can be delivered off-the-shelf which reduces development time considerably.

Two interface modules for power and data line connections have been developed in house, beside parts of the power distribution unit. Additionally the application software has been developed by DLR. To manage conflicts in pin assignments, caused by the non-standardized pinout and the limitations of the PC104 header, a quad-stack design was established. That allows handling of PC104 boards with up to four competing pinouts. The boards within the stack are connected by an interface board. The required harness is mainly reduced to connect the payloads and external mechanisms to the bus compartment. The electrical power subsystem consists of separate units for power conditioning and distribution, redundant secondary batteries (20 Wh, Li-Ion) and five solar panels for power generation. The solar panels are mounted on a carbon fiber reinforced plastic (CFRP)-framework. In this manner the available panel area is independent from the size of the bus compartment. The CFRP-framework can be adapted to accommodate the required panel area. Each solar panel is capable to provide more than 10 W during the lighting time. The average depth of discharge of the batteries during eclipse is approximately 10 %. The power conditioning unit provides lines for 3.3 V, 5 V, 12 V and an unregulated battery voltage. In stand-by mode (all payloads are switched off) the spacecraft bus consumes a little more than 1.2 W.

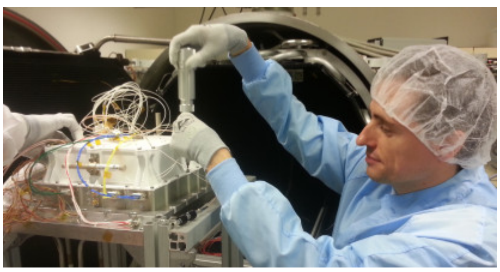


Figure 3.23: Thermal-vacuum test preparation of the AISat bus.

The on-board computer is based on an 32 bit ARM 7 CPU with 2 MB SRAM and 8 MB NAND flash memory. It provides controller area network (CAN), inter-integrated circuit (I^2C) and serial peripheral interface (SPI) interfaces for data transmission between the subsystems and payloads. Furthermore it supplies pulse width modulation (PWM) signals for magnetic torquer control. RS232 is provided to the payload by one of the interface modules. As operating system FreeRTOS is used, a scalable real time kernel specifically designed for small embedded systems. The non-volatile memory is managed by ultra-low-cost flash file system (UFFS), which provides wareleveling and bad block management.

The AISat attitude control system (ACS) utilizes a combination of passive gravity gradient torques and an active magnetic torquer control scheme. This scheme was selected because of its simplicity and cost effectiveness. The details of the ACS algorithms and preflight analysis can be found in [412]. As actuators three orthogonal arranged magnetic torquer rods are used and as sensors a three axis magnetometer and a nine degree-of-freedom inertial measurement unit are used.

Figure 3.24: The AISat team during integration campaign.

Thermal control is realized as a completely passive system mainly relying on special surficial coating and thermal buffer for high power consuming components with low duty cycle. The bus compartment additionally benefits from the shadowing, caused by the solar panels.

Spacecraft-to-ground communication uses amateur radio frequencies in ultra-high frequency (UHF) band. The transceiver is operated in half-duplex mode with an uplink data rate of either 1.2 kbps or 2.4 kbps and 4.8 kbps for downlink. Two antennas are mounted on the spacecraft orthogonal to each other to approximate an omnidirectional antenna pattern. 5W transmission power is split to the antennas. The data stream is coded by Reed-Solomon (223,255) forward error correction. For the space segment the CubeSat Space Protocol (CSP) is applied. On the ground segment CSP is translated to CCSDS for compatibility reasons. The spacecraft is operated by a DLR UHF ground station, located in Bremen. Especially during the launch and early orbit phase (LEOP) the TU-Berlin provided support with its ground station facilities and experiences in pico- and nanosatellite operations. The Spacecraft contains four AIS receivers; two commercial ship receivers and two CubeSat AIS receivers, developed by the Danish Aalborg University and already flown on Aalborg University Satellite (AAUSAT) series. The AIS signals can be received using either two VHF dipole antennas, or the directive helix antenna [313]. Additionally, the AIS signal can be routed through different attenuation stages as well as a bandpass filter. An amateur radio beacon provides amateur radio services and a commercial video graphics array (VGA) camera allows the validation of the helix antenna deployment.

The spacecraft's size and mass is dominated by the payload. Including launch adapter AISat weights 12 kg. In launch configuration the satellite has a diameter of approximately 60 cm and a height of 33 cm. In deployed configuration the reflector increases the diameter to 125 cm and the height to 430 cm.

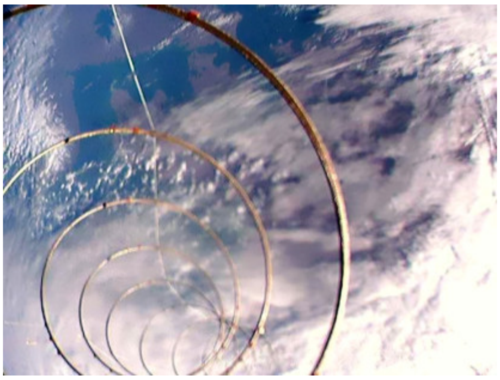


Figure 3.25: In-orbit deployed AISat helix antenna.

AISat Results

The satellite was launched on June 30, 2014 from Satish Dhawan Space Centre (SHAR), Sriharikota. After the LEOP was accomplished by deploying the antennas, all components operated well. The footprint of the helix antenna was a third of a normal di pol antenna. After two year more than 800 000 AIS messages have been received by AISat. These signals are from more than 34 400 different ships. Proportionally signals from 267 class B ships have been detected. A considerable proportion of all received messages are AIS position reports, which are more than 95 %. Approximately 3 % are signals from base stations. Compared to the distribution to received messages in the German Bight 87 % are position reports, 5 % are static data, 4 % are base station messages and 1 % are position reports from class B transmitter. In March 2015 a software update of the receiver provided the possibility to receive message type 27 from the new satellite AIS channels 3 and 4.

The satellite was completely operating more than two years, which is about two times as much as planned mission life time. After that time the main AIS receiver failed. Since then a limited operation is still performed by using the secondary AIS receivers.

3.3.5 ADS-B over Satellite

Air traffic surveillance as required in controlled airspaces nowadays predominantly uses ground stations equipped with primary surveillance radar (PSR) and secondary surveillance radar (SSR) including Mode-S. Seamless and continuous flight surveillance as necessary in airspace with high traffic density and separation minima of five respectively three nautical miles require an extensive ground infrastructure of radar stations, networks and surveillance data processing, as implemented in Central Europe, the U. S. or certain regions in Asia, thereby providing the necessary situation awareness to the controllers in the air traffic control centers.

In the recent years Automatic Dependent Surveillance – Broadcast (ADS-B) as a further surveillance technology has evolved. Modern Mode-S transponders on board of aircraft transmit the flight position and other information by so-called Extended Squitter messages (1090ES) on the 1090 MHz SSR-Mode-S downlink frequency (ADS-B Out). In the future, radar systems will be complemented or even replaced by less costly ADS-B ground stations, which will be integrated in the existing surveillance infrastructure. The European ADS-B Implementing Rule requires that new aircraft heavier than 5 700 kg or faster than 250 knots will be equipped with ADS-B-Out from 2015 onwards when flying Instrument Flight Rules, and for already operational aircraft a retrofit from end of 2017 on. In 2020 ADS-B surveillance shall become operational.

Anyway, most regions of the world are uncontrolled airspace. In areas without radar coverage (non-radar airspace), like oceanic airspaces, Polar or structurally lagging continental regions the installation of ground stations is either impossible or too expensive. Today, aircraft surveillance in these regions is applied procedurally, i. e. by voice radio position reports of the pilots when the aircraft reaches certain waypoints. Also Automatic Dependent Surveillance – Contract (ADS-C) is used, a point-to-point data link connection (FANS1/A/Satcom), which transmits positional and other flight information only every fifteen minutes due to limited bandwidth. In both cases no seamless and continuous flight surveillance is possible, with the consequence of relatively ample separation distances due to safety reasons. This becomes especially problematic for search and rescue activities in case of flight accidents: the location of the impact site of the crashed AF447 flight from Rio de Janeiro to Paris in 2009 took more than five days. However it must be stated with regard to a recent fatal accident, that either a technical failure of the transponder or the navigation system, from where the transponder gets the actual aircraft position, or a manual deactivation will prevent an aircraft from being tracked via its ADS-B signals.

In 2008, DLR started to investigate the option to receive the 1090ES ADS-B signals broadcasted by aircraft on board of low earth orbiting (LEO) satellites. The efforts resulted in the DLR project AoS, with the goal to develop an ADS-B payload for an in-orbit demonstration (IOD) and thereby demonstrate the feasibility of worldwide satellite based ADS-B surveillance.

This AoS IOD was conducted in the frame of ESA's Proba-V mission (Project for On-Board Autonomy Vegetation) and was successfully launched on top of Europe's newest launch vehicle Vettore Europeo di Generazione Avanzata (VEGA) on May 7, 2013 at 04:06:31 CEST from the European spaceport Centre Spatial Guyanese in French Guyana. ADS-B over Satellite was the first experiment of its kind and has already proofed the feasibility of space based ADS-B. The results from this IOD will pave the way for future developments towards global satellite based air traffic surveillance.

DLR has approached several national and international partners and companies in order to emphasize and promote the necessity of global air traffic surveillance, resulting in projects with Airbus Defence and Space (Airbus DS), Thales Alenia Space Germany and an ongoing close cooperation with Luxemburg based satellite operator Société Européenne des Satellites (SES). The U. S. based satellite operator Iridium has been contacted by DLR in order to investigate the possibility for an ADS-B payload on all of the satellites of the Iridium Next satellite constellation. As a result, the Iridium spin-off AIREON has been founded and will offer global seamless air traffic surveillance once the Iridium Next constellation has been deployed. The launch of the first ten satellites is scheduled for Q3 2016 with Harris as payload developer and NAV Canada as prime contractor. Following the different initiatives and the recent tragedy of Malaysian aircraft MH370 several regulatory initiatives by e. g. International Civil Aviation Organization (ICAO), Federal Aviation Administration (FAA) and EUROCONTROL have been started. One important milestone with participation of DLR was the allocation to the aeronautical mobile-satellite service (Earth-to-Space) for reception by space stations of ADS-B emissions from aircraft transmitters during the World Radio Conference (WRC-15).

AoS on Project for On-Board Autonomy (Proba)-V is still operational and has received a major firmware update in mid 2016. Furthermore, DLR is contributing to different studies in the frame of European Commissions H2020 program and will reply to the next ESA Artes Call end of 2016. Further cooperation with Airbus DS and SES Techcom are very likely in 2017.

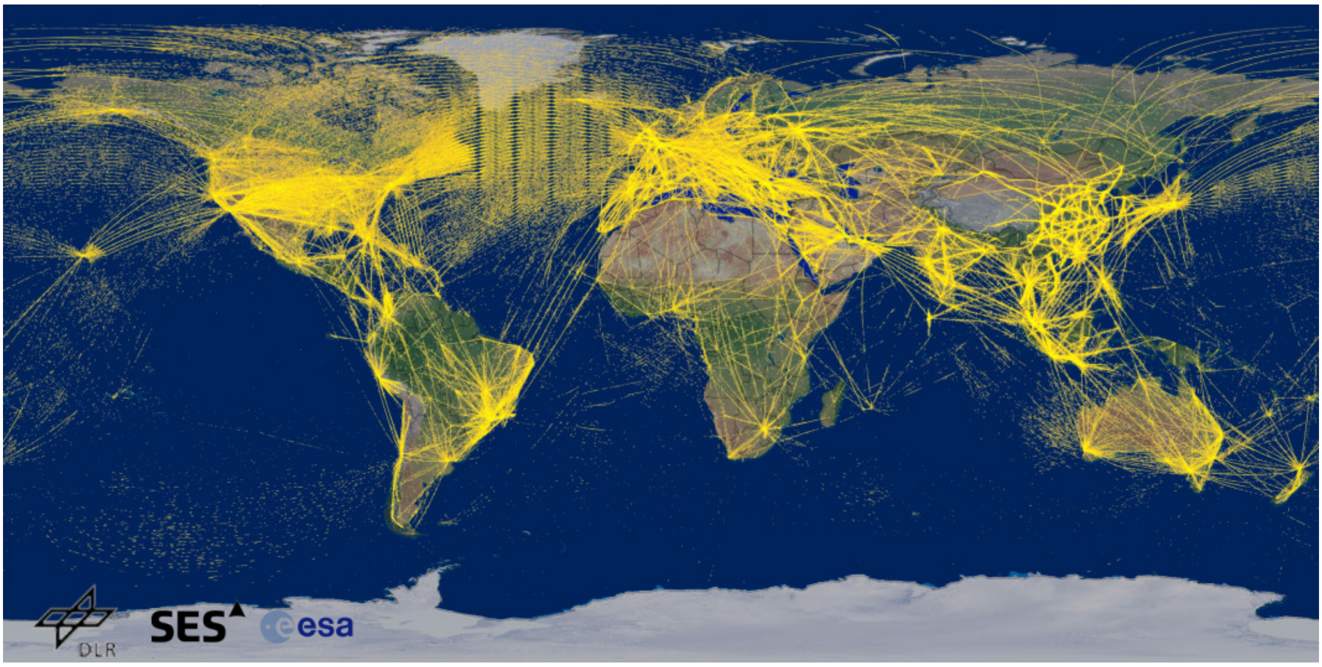


Figure 3.26: Global Air Routes captured by ADS-B over Satellite (AoS) on Proba-V within 2.5 years of operation.

3.3.6 S2TEP – Small Satellite Technology Experiment Platform

The DLR pursues the objective to develop a satellite platform for technology in-orbit demonstration and for serving small scientific payloads. It is called *Small Satellite Technology Experiment Platform* – in short S2TEP – and is located within the class of microsatellites as shown in Table 3.1.

The satellite design mainly focuses on the usage of DLR's own technologies, which is the reason why we call this approach technology driven. Emphasizing on in-house developed technologies shall accomplish the following long-term goals:

- shorten the development time and costs for each S2TEP-based satellite
- short-term design adaptions
- environment for own research and development activities
- allow for deep design understanding

The micro satellite platform S2TEP has a close connection to DLR's already existing small satellite program CompSat and its first mission Eu:CROPIS which is scheduled to be launched by the middle of 2017 [408] for further details). This connection is mainly driven by the fact, that the CompSat platform will make use of the maturation of system components onboard S2TEP: the in-house developed core avionics are scalable in both performance and component quality to satisfy the requirements from the microsatellite S2TEP up to the high reliable small satellite CompSat. Newly developed components are firstly utilized on S2TEP to gather in-orbit experiences, before a scaled-up version of the component is used for CompSat.

Taking the Compact On-Board Computer (COBC) [656] as an example, after demonstrating its suitability in space onboard the Eu:CROPIS mission as one of the secondary payloads, the COBC will be adapted and used as the on-board computer of the first S2TEP mission. Having heritage from these two DLR missions, the COBC is hereafter a mature system component and is most likely to be used as the on-board computer for the next CompSat mission as well as for future S2TEP missions (see figure 3.27).

In addition, also the S2TEP-platform as a whole has some kind of heritage, as its design benefits from the experiences gathered during the development of the AISat mission (based on the microsatellite bus CLAVIS [633]), as well as the development of the MASCOT asteroid lander [393].

Development Phases

The development of the S2TEP platform is based on the classical aerospace project approach, tailored from the ECSS recommendations. It mainly defers in the mission and system definition phases, due to the fact that bus design is not derived from a single mission. It is rather driven by the capabilities of the DLR in-house developed subsystems together with a mission envelope, formed by ten potential payloads. The subsystem capability analysis and the mission envelope, together with financial and programmatic constraints provide a reference mission which drives the design.

This approach shall satisfy the intended multi-mission compatibility where the focus is not on the optimal design for a specific mission but for the optimum of a series of satellites with different missions.

The platform development has been started with the reference mission definition phase, where the mission envelope, programmatic constraints and the in-house technology development have been surveyed. The findings resulted in a set of development goals, constraints, general requirements and recommendations as basis for the requirements engineering and concept development during the subsequent requirements and concept study.

During the feasibility study, the findings from the reference mission definitions are iterated, the system requirements are derived and basic system concepts are developed. After the feasibility of the reference mission will be proven, the payloads for the first mission will be selected from a pool of candidates.

After this phase the development follows in general the classical design approach. During the preliminary design phase the concepts will be elaborated, so that with the start of the final design phase the assembly integration and verification of the structural and engineering model can be started. During that phase the design is reviewed a last time. The flight model (FM) integration, qualification, and delivery phase finally focuses on the manufacturing and qualification of the flight model. The list of documents to be generated was reduced as well as the number of reviews in order to optimize development time. Each S2TEP project phase is completed by a review which is prepared in a dedicated workshop. Figure 3.28 summarizes the development process for the first mission.

For future missions, the development deviates in the long term from the process pointed out above. The Reference Mission Definition will be replaced by a payload application and assessment phase. After payload candidates are identified, the bus configuration and required payload adap-

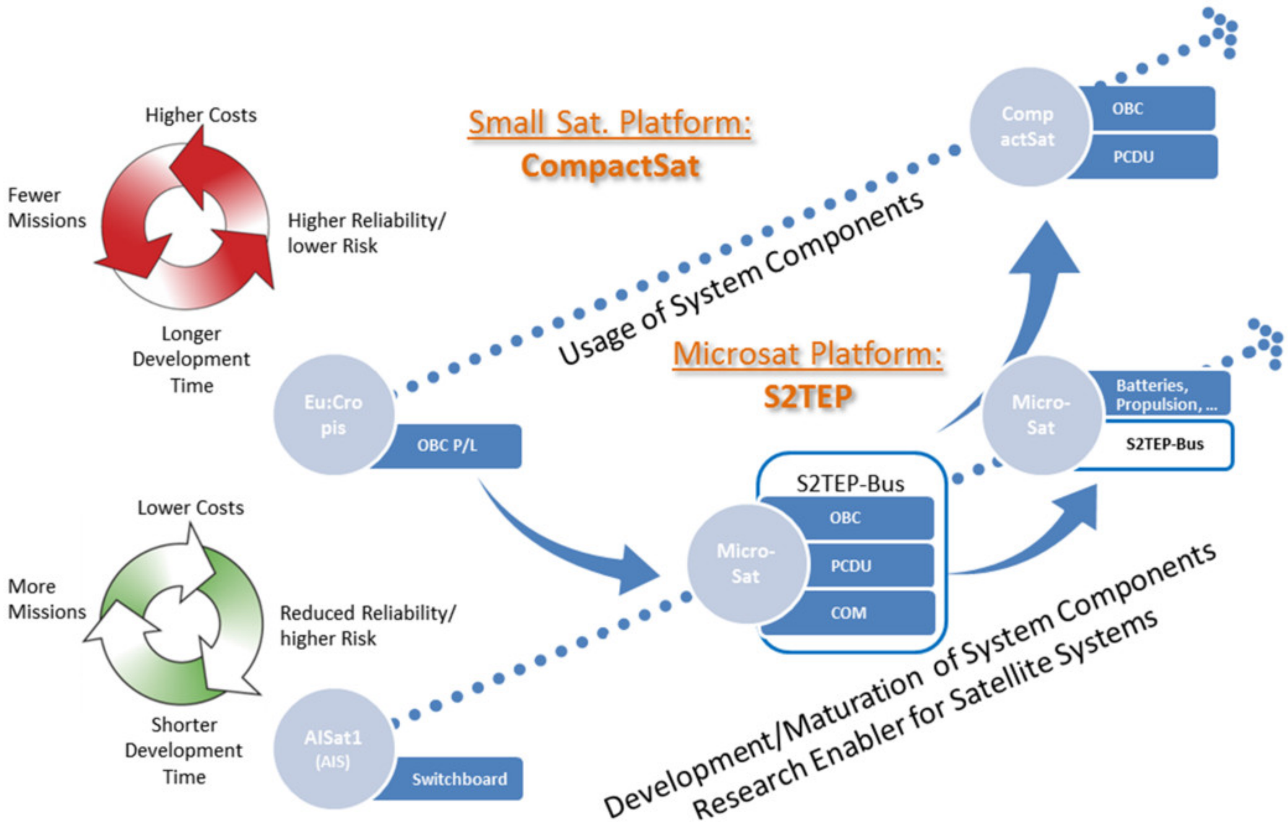


Figure 3.27: S2TEP roadmap and technology transfer.

tion are determined in a concurrent engineering study, and elaborated in a shortened preliminary design phase. The reviews are reduced to a delta PDR and a delta CDR.

MBSE Development Support The S2TEP development will be supported by model-based systems engineering (MBSE), for which tools and a suitable methodology are developed during the design and implementation of the first mission. S2TEP is a particularly interesting system for MBSE applications as it is being developed to have multi- mission compatibility. Here, the focus is not on the optimal design for a specific mission, but rather as one of a series of scalable and adaptable satellites with various missions, which provide benefits by relying on reuse on all levels of hardware and software as well as other design and systems engineering artifacts. In this sense, the S2TEP project is a good starting point for the exploration of MBSE within DLR and the implementation of model reuse and scalability. Within an initial dedicated project, a generic space system was modeled to explore the utility of creating a spacecraft template model for future space projects [447].

The template model was then populated to create a model of the S2TEP system as it was defined and designed at this point in time. The S2TEP model combined a descriptive and analytic model in order to elicit and analyze ways in which the practical application of MBSE will not only fasten the development time of each S2TEP-based satellite, but also allow for quick design adaption and significant reduction of costs during the project.

Integrated Technology Roadmap

The current status and further planning of DLR's own avionics technologies to be integrated in the S2TEP satellite bus is reflected within the S2TEP Integrated Technology Roadmap (ITR).

Using this kind of roadmap in order to define the technology development logic and combine it with the corresponding technology readiness

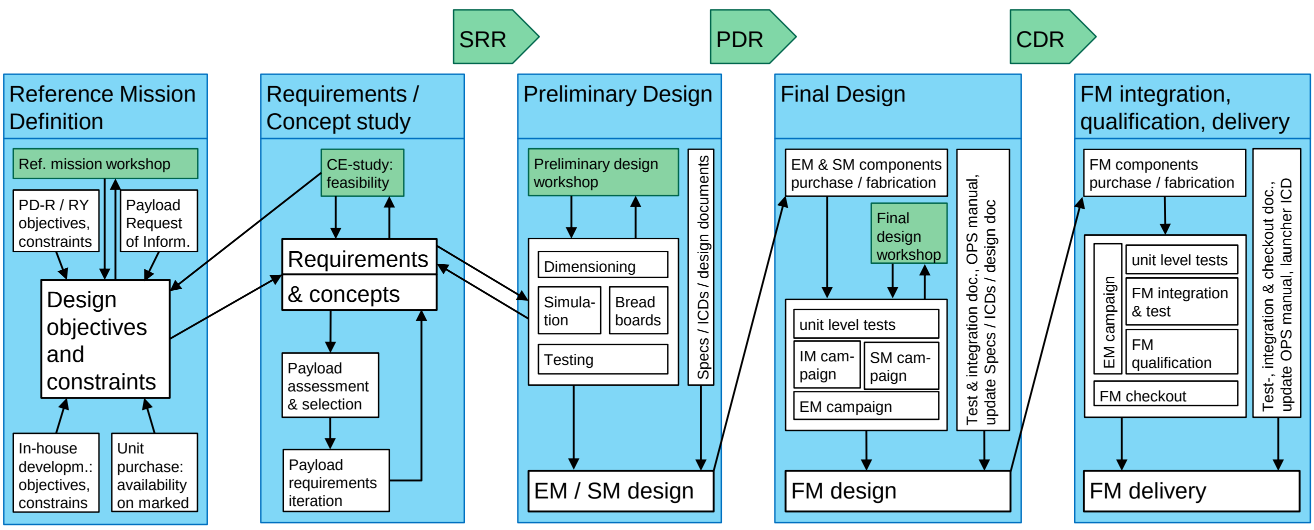


Figure 3.28: S2TEP development phases.

level (TRL) maturation as well as the use cases within missions is a technique used in space industry as well[1]. Within the S2TEP ITR, DLR's avionic technologies are mapped to their TRL and to their related projects in which these technologies will be further developed: as for some of them the main development activities will take place during S2TEP platform development, others have strong dependencies upon other DLR space projects. For the latter technologies, only adaptions to the S2TEP platform are foreseen. In detail, the core avionic technologies to be integrated over time are:

- the COBC
- the corresponding software platform libCOBC (see [343])
- the algorithms for the attitude and orbit control system (AOCS)
- the communication system based on software-defined radio (SDR)
- the power conditioning and distribution unit (PCDU)
- rechargeable batteries

In addition, a generic system model (see above) and the remotely-usable and highly autonomous ground station Compact Control Center (CCC) will support the design process as well as the operational scenario. The

[1] see e. g. http://iafastro.directory/iac/paper/id/25086/summary/

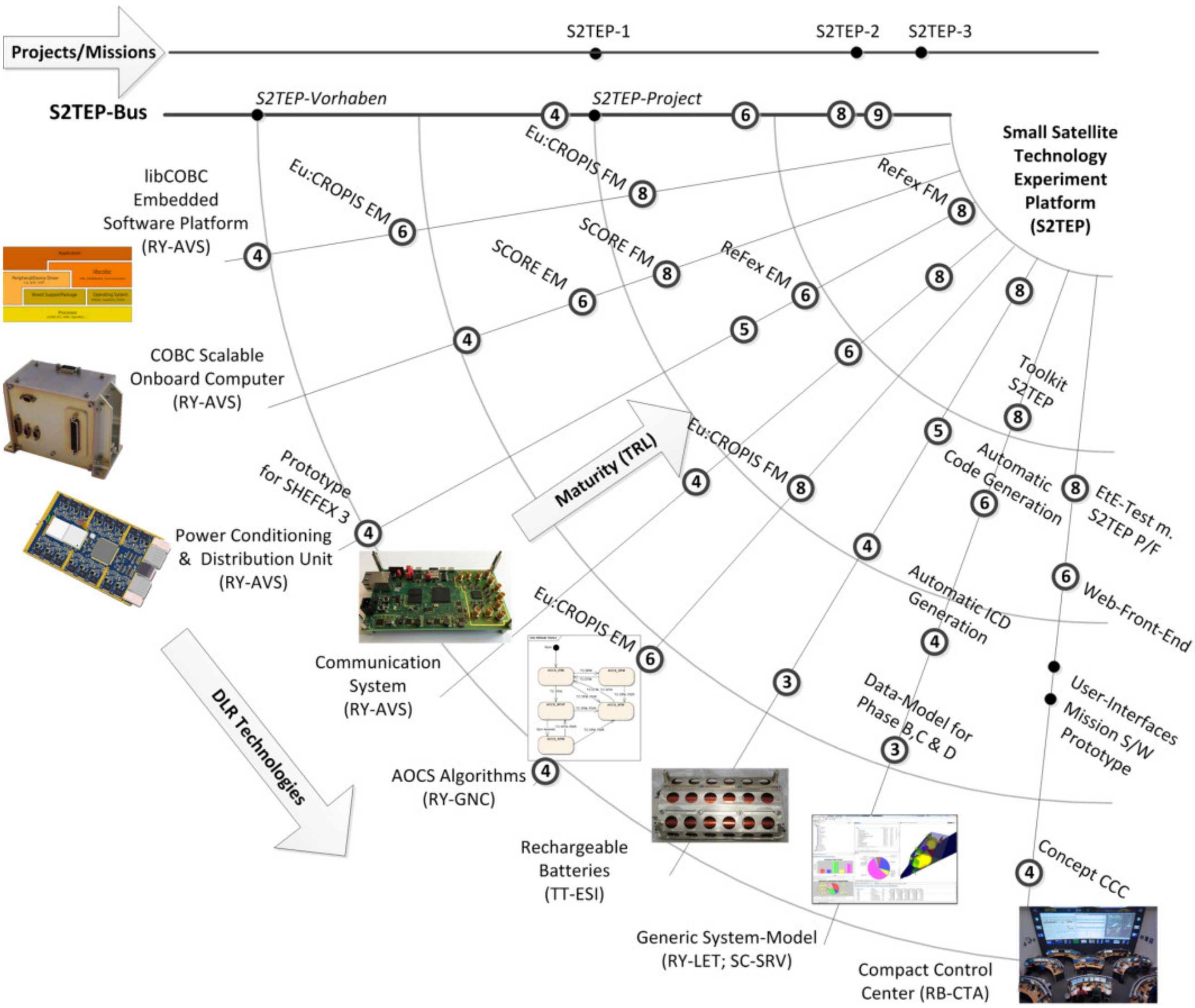


Figure 3.29: S2TEP integrated technology roadmap.

key point of all these technologies lies within the fact that all of them are scalable and adaptable on component level, thus enabling the scalability and adaptability of the whole S2TEP platform.

System Development Approach

Taking the high frequency of S2TEP-based satellites to be built, the development phases, and the platform design drivers into account, also the overall system development process for the current and future S2TEP missions is longing for a new approach. It is displayed in figure 3.30 and strongly oriented on the development approach created for the InnoSat platform[2] as well as the top-down product-driven design process presented by F. Alizon et. al. in "Frameworks for Product Family Design and Development".

In its center, there is the S2TEP baseline architecture which is driven by the core technologies to be used, the additional baseline equipment and a set of reference designs. As already explained, the most important design drivers are the core technologies and the reference payload. The core technologies are managed within the S2TEP ITR. Starting from this baseline architecture, the mission tuning can then take place using a concrete payload. Together with the corresponding ground segment tuning we are hereafter able to develop a complete S2TEP-based mission scenario.

[2] see http://www.snsb.se/Global/MATS_MDP_Report_Public_Summary.pdf

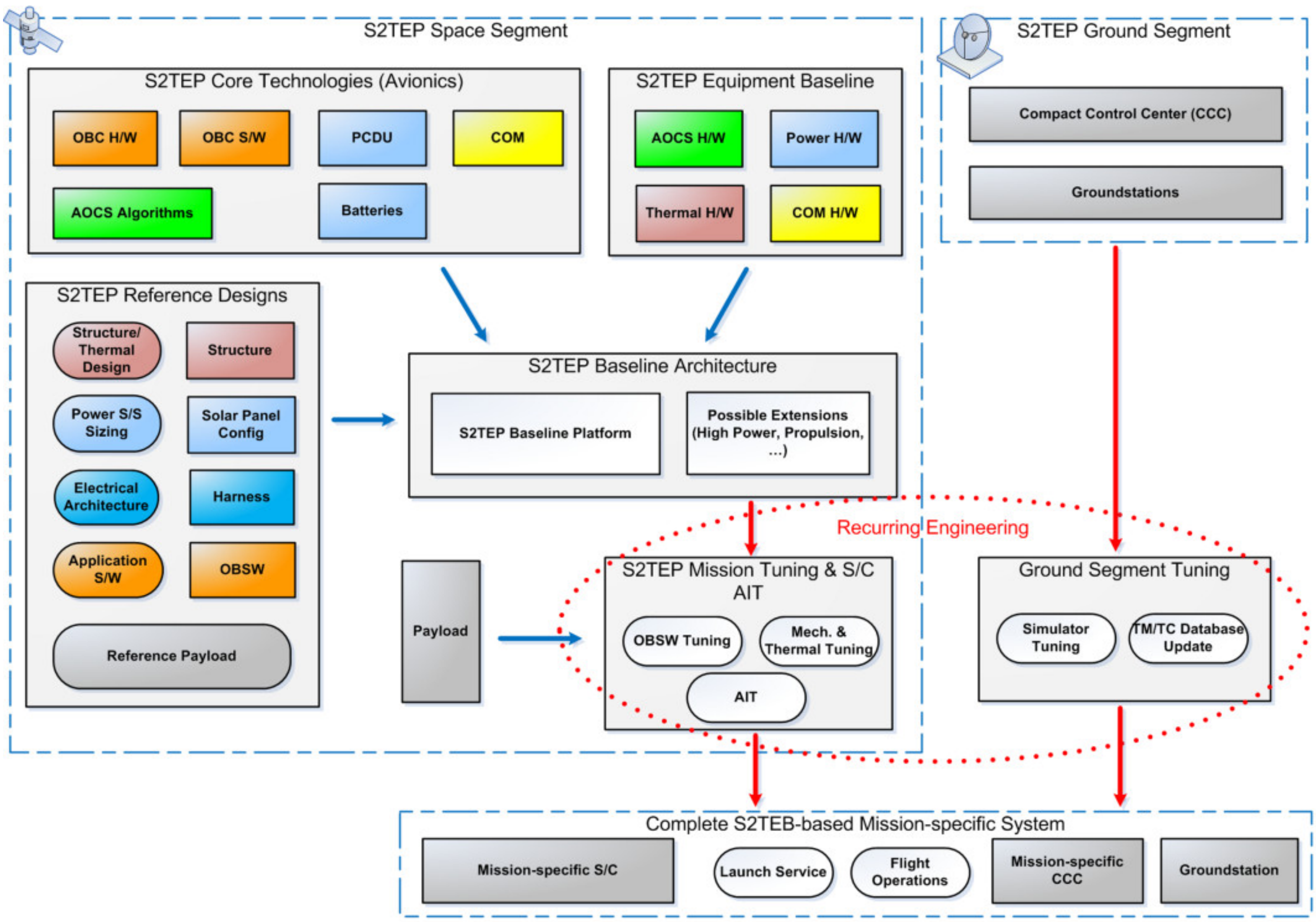


Figure 3.30: S2TEP system development approach.

Payloads for S2TEP-1

In distinction from the general satellite development strategy the selected payloads for the first S2TEP-based mission (S2TEP-1) have to be adapted by the payload supplier to satisfy the capabilities of the S2TEP payload interface standard. This is the expense on payload side for fast bus development and overall design cost reduction.

The roadmap for the S2TEP-series of satellite foresees a scalable concept: as S2TEP-1 will consist mainly of an electronic compartment and thus being rather small and lightweight, the next S2TEP mission will most likely contain a dedicated payload compartment. This compartment can then serve as the payload envelope for larger technology demonstrators as well as small scientific experiments, which can rely on an already flown and matured satellite platform.

The payloads selected for the first S2TEP mission will therefore consist of a number of smaller technology demonstrators, which will mostly fit into the satellite's electronic compartment. The topics addressed by these payloads range from on-board wireless technologies, space debris detection, software-defined radio, electrical and electronics engineering (EEE) in-orbit component verification, novel space batteries, scalable power systems up to a pure software experiment regarding a new space protocol.

3.4 Exploration and Interplanetary Missions

The long-lived desire of humanity to understand its place in the Cosmos might be the major motivation of the last approx. 60 years of continuous exploration of and beyond our Solar System. All missions from Voyager 1 to Rosetta pursued to give an answer on the questions of where we come from and where we go. Despite all the challenges on complexity, safety and/or cost interplanetary missions must meet, their implementation is doubtless important since in-depth knowledge of our Solar System cannot be gained by observations from Earth's ground or from orbit around the Earth, alone. Although discussions on the advantages and disadvantages of manned or robotic missions are ongoing in this context, to get a complete picture of the Solar System and its building blocks, we have to fly and if possible land there.

In general, orbiters (particularly extended with sample return capabilities) and landing probes return much more detailed and comprehensive information of their target (i. e. planet, moon, comet or asteroid) than fly-by missions. However, a trade-off between the science objectives versus cost and technological readiness would lead to the final decision on a fly-by, an orbiting (with or without landing probe) or a sample return mission.

Orbiting spacecraft would enable long-term global characterization of their targeted object via remote sensing instruments such as wide and narrow angle cameras in different colors, spectrometers covering various spectral ranges and/or ranging instruments. They would provide among others the geographical, geological, topographical and compositional information on a resolution of up to several meters of the target. Whereas, a landing probe would provide in-situ data on a higher resolution (in the μm scale).

Although DLR's programmatic does not foresee to realize a complete interplanetary mission and is mainly focused on experimental contributions, it has proven its expertise to develop and operate a landing system successfully with the Philae lander onboard ESA's Rosetta spacecraft to comet 67P/Tschurjumow-Gerasimenko [125]. To establish this heritage, the Institute of Space Systems has been involved in two major exploration systems of the last years by developing the MASCOT landing packet and providing system contributions to the Heat Flow and Physical Properties Package (HP3) instrument for the Hayabusa2 (HY2) of the Japanese Aerospace Exploration Agency (JAXA) and the InSight missions of the NASA, respectively.

3.4.1 MASCOT

Asteroids are belonging to the small bodies in our Solar System and are considered not only to be the remnants of the early planetary formation but might be the source of water on Earth. Heavy asteroidal bombardments approximately 3.8 billion years ago on our young Earth are supposed to be the key process that delivered water and higher molecules on this planet, therefore bringing those important elements for the formation of life. This makes the research field of minor bodies and their exploration so intriguing and leads to so many deep space missions such as NEAR Shoemaker of NASA and Hayabusa of the JAXA to Near-Earth asteroids (433) Eros and (25143) Itokawa, respectively.

Asteroids are distinguished by their orbits (i. e. Main Belt, Trojan, Near-Earth asteroids) and the features of their reflectance spectrum (*asteroid taxonomy*). Among them are of most interest for exploration missions near-Earth asteroids (NEA) of C-type (carbonaceous) since those should bear precious scientific data of the primitive solar nebula. In addition, hydrated (water-containing) minerals have been found on C-type asteroids. All these are important information to solve the missing link in the development of life.

The life matter and the origin and evolution of our Solar System are the main science objective of the second asteroid sample return mission of JAXA, HY2. For this purpose, the spacecraft carries onboard four remote sensing instruments (Optical Navigator Cameras, light detection and ranging (LIDAR), Near InfraRed Spectrometer, Thermal Infrared Imager), a sampling system, an impactor, three small rovers (Minervas-II-1A/1B/2), the reentry capsule and the MASCOT lander.

Figure 3.31: The launch of the Hayabusa2 spacecraft with MASCOT on December 3, 2014 from the Tanegashima Space Center.

MASCOT is an agile, lightweight, highly capable mobile science platform that has been developed by DLR in collaboration with the Centre national d'études spatiales (CNES). The Institute of Space Systems was responsible for the project's management, the systems engineering and the product assurance. In addition, several subsystems such as the multi-layer insulation (MLI), the umbilical, the preload release mechanism (PRM) have been manufactured and the lander has been assembled, integrated and tested in the laboratories of the Institute. The structure and the mobility were designed and developed by the DLR Institute of Composite Structures and Adaptive Systems and the DLR Robotics and Mechatronics Center, respectively. The power subsystem, the antenna and the mission analysis have been provided by CNES. The operation of the lander is coordinated at the Microgravity User Support Center (MUSC) belonging to DLR Space Operations and Astronaut Training. The MASCOT lander lifted-off with the HY2 spacecraft on December 3, 2014 from Tanegashima (see figure 3.31), towards C-type NEA (162173) Ryugu. Similar to its successful predecessor, Hayabusa, it should bring back samples from the asteroid's surface to Earth in 2020 after having completed between 2018 until 2019 detailed remote sensing and in-situ scientific investigations of the NEA.

Mission Concept

The MASCOT lander is belonging to the class of nanolanders with a total mass of approximately 10 kg [62]. It carries four scientific instruments: the MASCOT Camera (MASCAM) and MASCOT Radiometer (MARA) from the DLR Institute of Planetary Research, MicrOmega developed by the Institute d'Astrophysique Spatiale (IAS) and MASCOT Magnetometer (MASMAG) of the Institute for Geophysics and Extraterrestrial Physics (IGEP). The overall payload has a mass of approximately 3 kg.

MASCOT's development was from the very beginning a race against time. Passing the starting line in December 2011, when the interfaces with HY2 were frozen during its subsystem CDR, MASCOT was only at the beginning of phase B and since then constantly required to catch up with the mother spacecraft. A system PDR in July 2012, a CDR in April 2013, a Final Acceptance Review (FAR) in July 2014 followed by the launch on December 3, 2014.

HY2 is currently in its second year of a 3.5 year long cruise phase. Its overall mission concept is shown in figure 3.32. During this time MASCOT is stored on the -Y side panel and nominally off except for commissioning and periodic monitoring and calibration activities. Thermal control and power is provided by HY2 which allows MASCOT to save as much energy as possible for the on-surface operations as it is powered by primary batteries, only. MASCOT's telemetry will be relayed to ground via HY2.

Following the arrival at NEA (162173) Ryugu in July 2018, HY2 will perform global mapping. This phase is crucial for the characterization of this C-type asteroid and for the landing site selection process of MASCOT since knowledge of properties such as the asteroid spin state, the asteroid's surface geology and thermal conditions are essential information for a safe landing and a successful on-surface science operation.

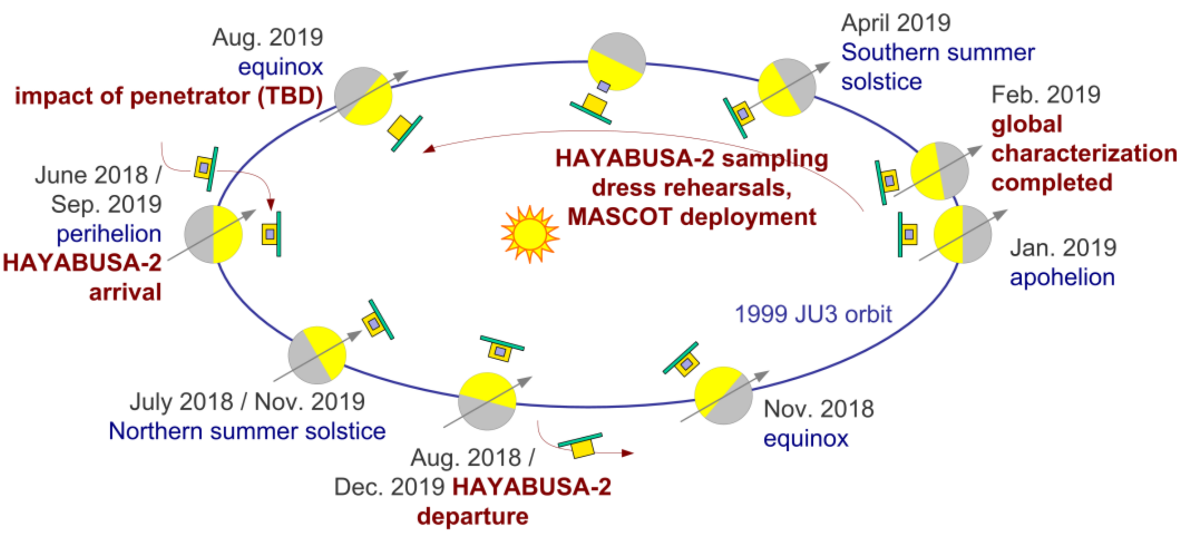


Figure 3.32: Baseline of the mission concept upon arrival at near-Earth asteroid (NEA) Ryugu of the approximately six years long Hayabusa2 (HY2) mission. The HY2 spacecraft will mainly hover at 20 km distance above the asteroid surface through out its near-asteroid operation phase unless its descents during several Touch and Go maneuvers.

The current baseline date of MASCOT's separation and landing is between October 1 - 4, 2018 with two further back up separation windows in late January or End of May 2019. The decision on the final separation time in the mission will be a careful trade-off considering:

1. The time needed for global mapping, landing site selection and preparation of telecommand sequences.
2. A landing before or after the first sampling attempt of HY2.
3. The desire to land at a cold landing site in order to avoid overheating of the experiments.
4. The need to land at a warm site to optimize battery performance.

Once the separation time is decided, HY2 will leave its Home Position at 20 km altitude and descent to 100 m at which MASCOT will be released from the mother spacecraft. MASCOT's free fall onto NEA (162173) Ryugu will take about 30 min due to the weak gravity field followed by a longer bouncing phase before the lander comes finally to rest on the asteroid. As soon as the lander reaches its final settlement point, its attitude control system will determine if the bottom plate of MASCOT is facing the asteroid's surface. The lander will initiate its scientific investigation if this condition is met or will be able to self-right itself into the correct orientation to allow the four instruments performing their in-situ investigations. After the first science cycle of the lander is accomplished, the same mechanism which gives MASCOT the ability to self-right will enable it to hop across the asteroid and start the second science cycle on a different site.

System Overview

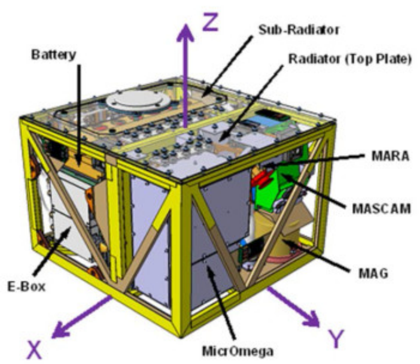


Figure 3.33: The accomodation of the subsystem and scientific payload within the lander' structure.

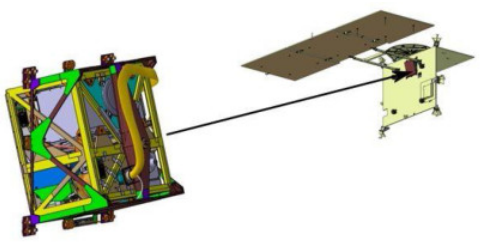


Figure 3.34: MASCOT and MESS (left). MASCOT attached on the -Y panel of the HY2 spacecraft (right).

The strict mass requirement of 11 kg total mass (i. e. landing platform including all interfaces with the mother spacecraft) and the available stowed volume (i. e. HY2 panel cut-out for the MASCOT lander is approx. 340 m × 300 m) given by the HY2 project made the design of the MASCOT lander as challenging as its tight development time.

Finally, the MASCOT lander module (LM) has a total size of 28 cm × 29 cm × 21 cm (see figure 3.33) and a total mass of 9.8 kg. The interface between MASCOT and HY2 is a mechanical-electrical support system (MESS) that weights 1.2 kg and is attached to the HY2 spacecraft on its -Y panel as shown in figure 3.34. The LM is stowed during cruise and until release via the MESS inside HY2. Next to the four scientific instruments, the lander structure accommodates all support elements (i. e. data handling, power, communication, attitude determination, mobility mechanism, and passive thermal control) for the on-asteroid operations. In order to meet the mass requirement the MASCOT LM structure is made of an ultra-lightweight CFRP foam sandwich framework structure, whereas the MESS is built of 3 mm thick solid CFRP struts. The structure of MASCOT is mainly driven by the required stiffness, with a minimal first system eigenfrequency of 120 Hz. The LM configuration is divided into two segments: a warm compartment containing the Electronics Box (E-Box) with the majority of the electronics, the battery package, and the mobility mechanism, and a cold compartment housing the scientific instruments. The four lateral external walls are covered with single layer insulator, with the top surface being used as the main radiator.

The E-Box is made of six separate aluminum plates providing thermal and radiation protection to all printed circuit boards (PCB) included. In addition, it serves as the structural interface for the battery package, the communication transceivers, and the mobility mechanism.

The mobility mechanism and a suite of attitude determination sensors enables MASCOT to self-right itself into the correct instrument orientation (i. e. MicrOmega's optical window requires to face the asteroid's surface) and to perform relocation via hopping on the asteroid's surface.

The mobility mechanism consists of mechanics, electronics, and an offline generator for optimized trajectories. The concept uses a small brushless DC motor to accelerate and decelerate an eccentric arm, which is able to rotate up to several revolutions. The resulting reactive force applies torque to MASCOT. Depending on the movement parameters of the motor controller the eccentric arm generates torque in different directions and enables MASCOT to hop or to self-right to its nominal position.

The motion state and the orientation on the asteroid surface of the MASCOT lander is determined mainly by two sensor systems to guarantee redundancy. The first sensor system consists of five optical proximity sensor (OPS) mounted on five different sides of the lander. Each OPS consist of an infrared light-emitting diode (LED) and an appropriate photo-diode. The light emitted by the LED is reflected by any object within the field of view of the sensor. With this the asteroid's surface can be detected and thus the lander's ground facing side identified. The second system comprise six PCB-mounted photoelectrical cell sensors (PEC) that are mounted on each side of the lander to detect the solar direction. Due to Lambert's cosine law the output voltage is proportional to the cosine of the angle between Sun vector and the normal vector of the cell. This information is then passed through a histogram filter for multi sensor data fusion to determine which side of MASCOT is pointing to the surface. In addition, decision logic is used to detect the motion status of MASCOT [551].

Control, housekeeping, autonomy, data handling, and local processing power are provided by the OBC. The OBC is designed to be dual redundant and consists of four boards. The two cold redundant "CPU-boards" (i. e. digital) are cross-strapped by internal Spacewire data links with two hot redundant "I/O boards" (i. e. analog). The OBC interfaces to all MASCOT subsystems and payloads via point-to-point serial data links (RS422 UARTs and SpaceWire) and dedicated, discrete analog/digital I/O interfaces.

Power is supplied during cruise by HY2 and during the surface operation by primary batteries consisting of nine SAFT LSH20 D-size non-rechargeable Li-SOCl2 primary cells via a power condition and distribution unit (PCDU). The design goal of the power system was to operate up to two asteroid days on the surface. The PCDU manages power-up activation of the command chain subsystems during cruise check-outs and during the separation process. It converts power from the 50 V power bus of the mothership to the battery unregulated power bus of MASCOT.

During flight, the communication is established wireless via a planar antenna and via two patch antennae once separated and landed on the asteroid. The main principle of the communication between the MASCOT lander and the HY2 mothership is a shared system with the three Minerva rovers also on-board and part of the HY2 mission to save mass. The MASCOT lander is equipped with redundant transceivers ("Child-COM") which were provided by JAXA to communicate with the transceiver ("Parent-COM") on HY2 side together with JAXA's three rovers based on half-duplex communications and time division multiple access methods. Communication is established via relay by the HY2 spacecraft. Due to the short duration of surface operations, the amount of direct telemetry to and control commands from Earth is extremely limited, requiring almost complete autonomy of the lander. Autonomous operation is performed by the MASCOT Autonomy Manager (MAM), a decision making algorithms as part of the software of the OBC. In its baseline design the MAM is programmed as a nominal state machine with internal state and transition logic.

Science & Scientific Payload

The science instruments, as illustrated in figure 3.33, onboard the MASCOT lander are a hyperspectral microscope (MicrOmega), a multi-spectral wide angle camera (MASCAM), a multi-spectral Radiometer (MARA) and a Magnetometer (MASMAG).

This combination of experiments should investigate at least at one position: (1) the geological context of the surface by descent imaging and far field imaging in-situ; (2) the global magnetization by magnetic field measurements during descent and any local magnetization at the landing positions; (3) the mineralogical composition and physical properties of the surface and near-surface material including minerals, organics and detection of possible, near-surface ices; (4) the surface thermal environment by measuring the asteroid's surface temperature over the entire expected temperature range for a full day-night cycle; (5) the regolith thermophysical properties by determining the surface emissivity and surface thermal inertia; (6) the local morphology and in-situ structure and texture of the regolith including the rock size distribution and small-scale particle size distribution; (7) the context of the observations performed by the instruments onboard the main spacecraft and the in situ measurements performed by MASCOT ('*cooperative observations*') and provide documentation and context for the samples and correlate the local context of the in situ analysis into the remotely sensed global context; (8) the body constitution on local and/or global scales and to constrain surface and possibly sub-surface physical properties; (9) the context of the sample collected and returned by the main spacecraft by qualifying its generic value and processed/pristine state and thus support the laboratory analysis by indicating potential alteration during cruise, atmospheric entry and impact phases.

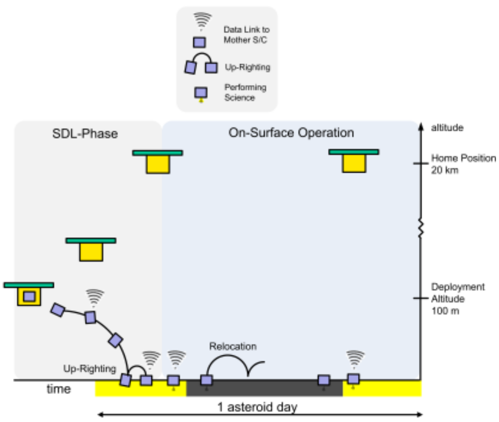


Figure 3.35: Baseline of the MASCOT operation concept during descent and on the asteroid's surface.

Cruise and On-Surface Operation

MASCOT, see figure 3.36, will be switched on about twice a year for health checks, calibration and maintenance activities via the umbilical line from HY2 and will communicate via RF-link to the HY2 spacecraft. Upon arrival in early 2018 at the asteroid, MASCOT will be released from HY2 between the end 2018 and early beginning 2019. After the separation, the HY2 spacecraft will ascent to an altitude of 20 km and act as the communication relay between MASCOT and the Earth.

The communications to HY2 should be maintained throughout the whole descent phase. MASCOT will attempt to take camera images of the asteroid already during descent. The magnetometer will perform one of its major science measurements during the MASCOT approach towards the asteroid surface. MARA will perform measurements while looking into deep space as additional calibration of the instrument.

During surface operations MARA and MASMAG will measure continuously. The camera will take several pictures at different Sun angles. During the asteroid night MicrOmega will perform its major scientific measurement, analyzing the grain composition.

MASCOT Status

Since launch in 2014 several health checks and the first calibration campaign of the scientific payloads during cruise phase were conducted successfully. In addition, the launch locks (PRM) have been activated. MASCOT, its subsystems and scientific payloads, are in a good health state.

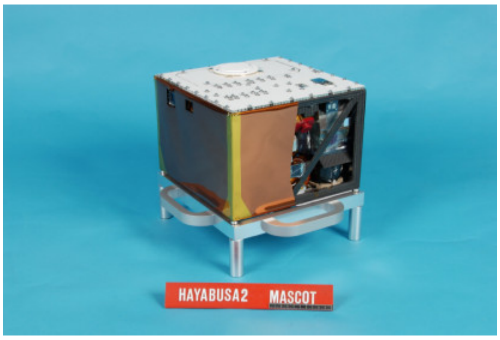


Figure 3.36: The MASCOT flight model before integration into the HY2 spacecraft.

Outlook

The MASCOT project has proven the feasibility of developing a lightweight landing platform for interplanetary exploration under micro-G condition. Because of its low mass (approximately 10 kg), small volume, and high payload to system mass ratio (7:3), the MASCOT design can be adapted with various suites of instruments (with a maximum total mass of approximately 3 kg) to the requirements of future landing missions on small bodies (asteroid or planetary moons). Further small lander concepts based on the MASCOT idea are currently under study by the Institute of Space Systems for the Asteroid Impact Mission (AIM) of ESA and Mars Moon Exploration (MMX) of JAXA.

3.4.2 InSight

InSight is a NASA Discovery Program mission that will place a single geophysical lander on Mars to study its deep interior. NASA's Marshall Space Flight Center in Huntsville, Alabama, manages the Discovery Program for the agency's Science Mission Directorate in Washington. NASA's Jet Propulsion Laboratory, a division of the California Institute of Technology, Pasadena, manages InSight for the NASA Science Mission Directorate. The mission has been scheduled to launch in March 2016 but has been postponed in December 2015 to the next launch window in May 2018 due to continuing problems in the vacuum sealing of the primary InSight payload SEIS.

The InSight mission will investigate the interior structure and processes of Mars, relating these to the evolution of other terrestrial planets, and will determine the present level of tectonic activity and meteorite impact flux on Mars. The following scientific questions are to be answered by InSight:

- The thickness and structure of the crust
- The composition and structure of the mantle
- The size, composition, and physical state of the core
- The thermal state of the interior
- The rate and distribution of internal seismic activity
- The rate of meteorite impacts on the surface

The HP3 instrument is built by DLR. The project team comprises DLR Berlin (science management, Thermal Excitation Measurement – Active (TEM-A)/ Thermal Excitation Measurement – Passive (TEM-P) subsystem and project management), DLR Bremen (AIV/assembly, integration, and test (AIT), mole and support system), DLR Cologne (Static Tilt Meter (STATIL) subsystem) and DLR Oberpfaffenhofen (dynamic simulation).

HP3 will determine the geothermal heat flux by penetrating down into the surface of Mars to at least three meters, five meters being the mission goal. HP3 measures thermal conductivity as a function of depth while penetrating into the regolith, then measures the subsurface thermal profile for the remainder of a Mars year.

The HP3 instrument, consists of the following functional hardware subunits:

- Back End Electronics (BEE), located in the lander warm electronics box
- Engineering Tethers, connecting the lander deck to the Support System
- Support System (including TLM), which will be deployed onto the surface
- Science Tether (TEM-P), which will be emplaced into the ground by the mole
- Mole (including TEM-A and STATIL)
- Radiometer, located under the lander deck

DLR Bremen owns responsibility for the following work packages:

- Support system design, systems engineering and manufacturing of components
- Mole design, systems engineering and manufacturing and components

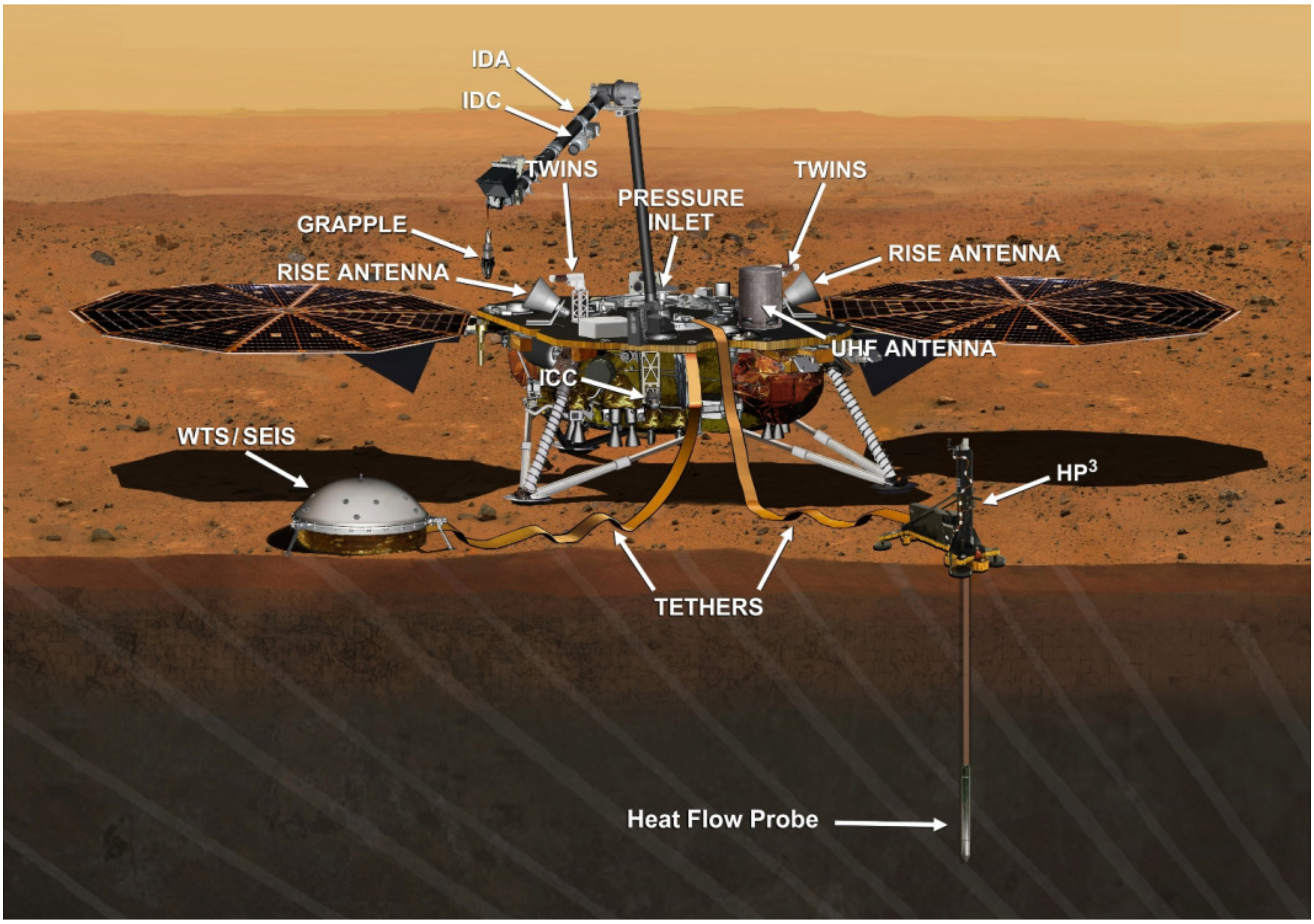


Figure 3.37: The InSight lander, taking heritage from the Phoenix mission. Primary P/L is SEIS, the HP3 instrument is a secondary payload. Image credit: NASA/JPL-Caltech

- AIV/AIT of support system, mole and HP3 instrument (support system assembly)

Integration of the mole (flight, flight spare and life test unit) as well as the support system (flight and flight spare) has been done in the Bremen clean room facility.

Support System

Main purpose of the HP3 Support System is to house the Mole, Tether Length Monitor, Science Tether and Engineering Tether until reaching the Martian surface as well as to position the Mole perpendicular and stable on the surface. Together with the so called cradles, as mechanical interfaces to the lander deck, and the tether storage box, which houses all tethers, it forms the Support System Assembly. The overall shape, which can be seen in figure 3.39, is driven by the available volume on the lander deck and by the need to gain stability against wind loads. As it will merely be placed onto the surface by a robotic arm it has to ensure a safe operation mechanically unsupported from the lander and without any active stabilization on the surface. An extensive qualification campaign, became necessary to verify the resulting set of requirements. Besides the vibration tests, special tests were developed to show compliance of the instrument design to the requirements. These tests are: Separation Tests from the lander deck in cold environment and under various tilting angles, Tether Deployment Tests under various temperatures, foldings and routings as well as Feet Sliding Resistance Tests to determine the motion of the instrument in sand under inclined conditions on the Martian surface. All the development test were performed using the environmental test infrastructure of the Institute itself. The responsibilities of DLR Bremen were the overall HP3 Support System design, systems engineering, manufacturing, assembly, integration and testing.

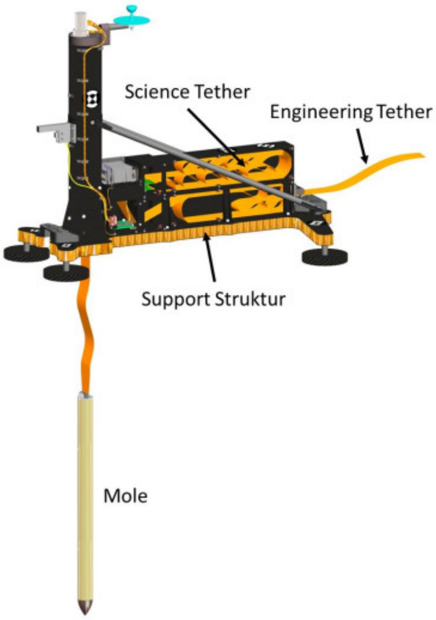


Figure 3.38: The HP3 instrument assembly, designated as "Support System Assembly". The mole is the tractor device, delivering access to the TEM-A/TEM-P instrument suite to the sub-surface.

Mole

The HP3-Mole is divided in two main parts: The hammering mechanism for locomotion purpose and the payload compartment containing the scientific payload STATIL (work-package DLR Cologne). As obstacles like stones will deflect the mole's trajectory, STATIL is used to determine the mole's inclination during the penetration phase. Thus together with the Tether Length Measurement (TLM), the absolute depth of the Mole can be determined. As the impact driven locomotion principle causes a high shock environment, STATIL (Static Tilt measurement unit) needs to be suspended by two galaxy shaped shock isolation springs. Additionally the outer hull is equipped with the payload TEM-A (DLR Berlin) to measure the heat flux below the Martian surface. On the mole's back, the science tether, equipped with the TEM-P (DLR Berlin) temperature sensors, is mounted in order measure the annular temperature wave of Mars and to supply the mole with electric energy. The hammering mechanism driving the mole has been developed and manufactured by company CBK in Warsaw, Poland.

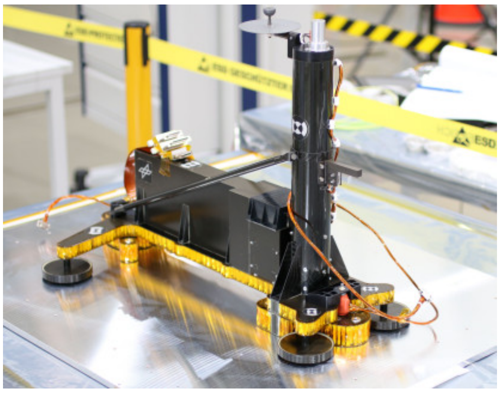


Figure 3.39: FM integration of support system assembly, i. e. the support system including the mole under planetary protection conditions.

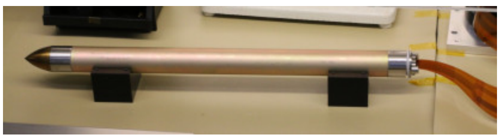


Figure 3.40: The flight model mole shortly after integration at DLR Bremen.

Deep penetration tests under ambient conditions have been carried out at DLR Bremen as part of the verification of the system requirements. Also, hammering tests under cold (-70 °C) and close-to-vacuum (8 mbar) conditions have been carried out in the DLR Bremen climate chamber. During

Figure 3.41: Deep penetration test bed used for mole development as well as for qualification tests (e. g. life test).

flight AIT/AIV, vibrational tests have been carried out at DLR Bremen. Thermal vacuum tests have been carried out under DLR Bremen's responsibility at DLR Berlin.

Calibration tests of the STATIL inclinometer have been done at DLR Bremen. DLR Cologne took responsibility for those tests, Bremen provided technical support as well as the test facility.

3.5 Reusable Launch Vehicles and Re-Entry

Reusable launch vehicles are considered the key technology to drastically reduce launch costs and in turn to enable a whole new group of users and applications to reach space. Currently expendable launch vehicles are used, meaning the launcher cannot be inspected post-flight and the real state of the hardware after a flight remains mostly unknown. Such a system optimization might possibly cut into the system margin, endangering the launcher. However, since launchers are extremely mass sensitive, every kilogram of mass saved equals a gain in payload. In essence minimum mass is desired, while too low margins are to be shunned. Without post flight analysis this conundrum is almost impossible to solve. This issue is compounded by the high value payloads that fly on such missions, making an error very costly. As such the design relies heavily on numerical models, stringent process and quality control and is in general characterized by a cautious approach. These techniques have produced remarkable launchers, with extremely high success rates but at literally a very high price.

If the same vehicle could be reused several times, the high development and construction costs could be averaged over its lifetime, thus vastly reducing per-launch costs and in addition providing invaluable information, through the product lifetime and post-flight analysis, facilitating much faster improvement of future systems. However, this is all contingent on low maintenance between flights. The Space Shuttle, while partially reusable, was a perfect example of the crippling effect on cost of low launch rates, high refurbishment and system complexity. A reusable system has to be rapidly and fully reusable, minimizing the maintenance between flights. The ultimate goal should be air-travel like operations: several flight with hardly any inspection and maintenance, interspersed with major overhauls dependent on the vehicle flight heritage.

Currently, there is a renewed push for reusable launch vehicles, mostly through the efforts of SpaceX and BlueOrigin. Both these companies are developing Vertical Take-Off Vertical Landing (VTVL) vehicles. This has the advantage of a system which is fairly similar to current rocket designs, even allowing testing of the re-usability systems step-by-step on missions with a customer. The systems needed here do not impact the primary mission and the return to the landing site happens after the payload is safely on its way. As such a loss of the booster is non-critical. The VTVL approach however carries a high propellant penalty, reducing either the available payload or making systems for larger payloads fairly large and expensive to develop.

On the other end of the spectrum are horizontal take-off, horizontal landing (HTHL) vehicles, these are also studied on a systems level, but current engine technology still mostly prohibits this approach.

Another intermediate approach would be a vertical take-off, horizontal landing (VTHL) system. In terms of propellant efficiency it would be helpful to utilize the Earth's atmosphere through aerodynamic means, such as wings and in turn relax the delta-v requirement on the propulsion system. This must be done in such a way that the mass penalty for the wing structure, additional thermal protection and cryogenic tank-wing interface is significantly smaller than the propellant needed for a boost-back maneuver in a VTVL configuration. The key technologies for this approach are studied in the Reusability Flight Experiment (ReFEx) project.

The ReFEx is meant to provide technological and scientific inputs by the DLR to the development of future reusable launch vehicle (RLV) space transportation systems. This will enable the DLR to provide guidance on technologies with a high degree of readiness and expert advice for future national and international programs. The following list contains an abstract of the project goals for the flight experiment. The list includes systems-technological as well as subject-specific research topics:

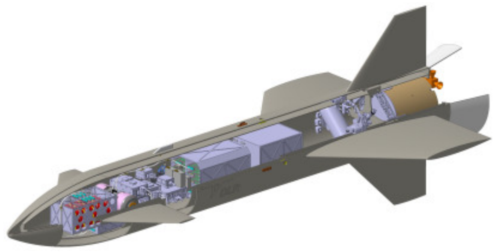


Figure 3.42: One possible (not final) configuration of ReFEx.

- Structures and materials for high thermal loads
- Guidance and maneuverability
- Aerothermodynamic experiments
- Flight navigation and control
- In-flight health monitoring of components

The mission of the experiment is to return safely to a predefined target area after traversing an initial boost-phase/stage separation and/or a re-entry interface. Hence it is imperative on the system component level to reach certain altitude and Mach number envelops in order for the experimental data to be relevant to determine applicability for future re-usability.

Maintaining flight stability and maneuverability throughout all flight regimes is a basic requirement for the altitude and range management necessary to reach the target area.

Mastering the altitude and range management and trajectory planning are key elements in reaching the targeted area precisely and safely. As such the flight management system (FMS) contains the flight guidance, navigation and event triggers and allows for autonomous trajectory adaptation.

The necessary control authority (aerodynamic and otherwise) must be maintained over a wide range of altitudes and Mach numbers between the entry interface and the end of the experiment. This means that the effectiveness of the control elements will vary dynamically throughout the flight and must be included in a closed-loop control system. Aerodynamic control surfaces such as fins, spoilers and flaps are under investigation, with the final configuration being determined during the design process. The design, construction and testing of these critical control elements is a key capability and requires the combination of all disciplines.

Future operational reusable launch vehicles must be able to traverse the transonic flight regime in a controlled manner. The challenge here is the unsteady aerodynamics. The design of the flight experiment for these flight regimes is especially rewarding for the design-aerodynamicists and flight control.

Handling integrated thermal protection systems under extreme thermal loads while at the same time avoiding degradation of these components is a critical capability for reusable space transportation systems. To address further reusability aspects, challenging interfaces such as for example a gap in the hinge region of control surfaces, shall be equipped with specially tailored materials. The hot structure of the vehicle as well as the thermal protection system however, shall not be limited to carbon based ceramics. Apart from these C/SiC materials, oxide based ceramics also exhibit high specific stiffness and hence are promising materials for reusable stage structures. Especially their low thermal expansion and ability to withstand thermal loads beyond the usual margin set these materials apart from metallic components. The combination of metallic and/or polymer materials will also be promising candidates for parts of the RLV structure with lower thermal loads. Here the metallic components offer advantages in reducing hot-spot build-up, while the polymer materials offer high specific stiffness and strength.

The acquisition of basic measurement data in different velocity regimes while using advanced newly developed sensors is a significant part of the project. As such the entire set of information of the flight including the status of all aerodynamic control surfaces, thrusters as well as inertial and aerodynamic data will be recorded throughout the flight. This will allow a detailed subsequent analysis of the flight using post-processing techniques. The data collected during the flight hence serve to validate and optimize the models used by the different disciplines during the design process. As such the data is invaluable for the development of future reusable systems. Applications of health monitoring systems during the flight complete the picture, to enable future rapid turnaround.

Transmitting the flight- and housekeeping data via a telemetry link as well as a comprehensive on board data storage system ensure that the insight gained from the experiment will be preserved. Certain unforeseen events recorded in this data might become explicable if the shape and size of the structural elements could be analyzed after the flight. Existing knowledge and databases should then be appended accordingly. The evaluation in terms of reusability hence requires quantified answers about possible damage and/or erosion of the structure in order to evaluate the possible lifespan of the concerned component. The post flight inspection thus is another building block for the test and proof of concept logic in the ReFEx flight experiment.

3.6 Future Missions

The following section presents future mission of the Institute of Space Systems to be realized on a mid-term time scale.

3.6.1 GoSolAr

Gossamer-1 as shown in figure 3.43 is a solar sailing technology demonstrator that was part of a three step technology development between DLR and ESA/European Space Technology Center (ESTEC), covering membranes, booms, photovoltaics and their corresponding mechanisms. Scalability of the technologies is one of the main contents of Gossamer-1, a 5 m × 5 m deployment technology demonstrator. It shall enable the development of Gossamer-2 with a 25 m × 25 m sail, demonstrating attitude control abilities, and Gossamer-3 with a 50 m × 50 m sail for a dedicated scientific application. The mission objective of Gossamer-1 is the demonstration and observation of a successful and reliable deployment, not yet its use as a solar sail or full scale solar power generator.

The demonstrator uses sail and boom technologies, which have already been partially developed within precursor projects on subsystem level at low TRL, but up to this project excluding system level consistency and functionality. It is mainly a demonstrator for solar sail technology, where the ratio of total mass to sail area is the driving factor for the performance of a solar sailcraft. For that reason, the deployment mechanisms will be jettisoned as they do not serve the solar sail purpose. Jettisoning of those mechanisms is therefore a mission critical element. Compliance with the space debris regulations will be ensured by jettisoning in very low orbits.

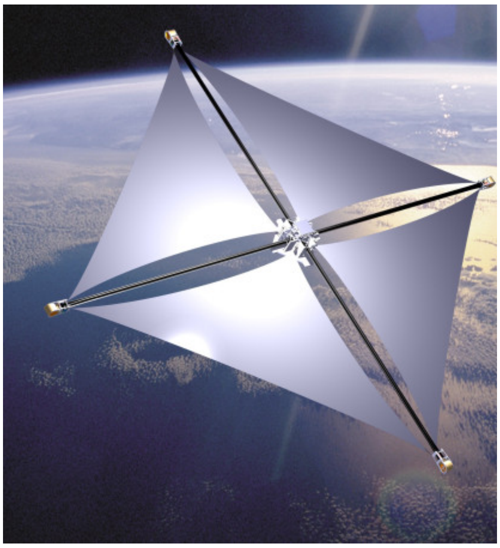
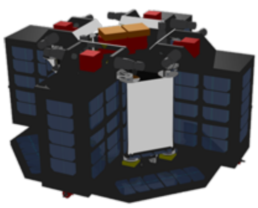


Figure 3.43: Artist's impression of the Gossamer-1 spacecraft.

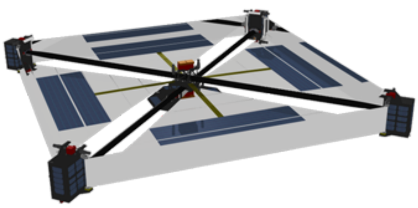
Gossamer-1 is based on a crossed boom configuration with four sail segments. At the geometrical center of the spacecraft, the boom crossing point, the central spacecraft unit (CSCU) carries the satellites main bus system including all electronics covering command and data handling, power system as well as ground communications system. The satellite was expected to have a mass of about 30 kg and a compact launch configuration shown in figure 3.44(a) with a maximum width of approximately 790 mm and a height of 500 mm. No scientific payloads were considered to avoid prematurely introduced higher complexity and thereby introducing additional risk to a mission, which is solely focused on the development of deployment technology. Such aspects were the cause for previous failures of solar sail projects. However, the sail system of Gossamer-1 includes flexible thin film photovoltaic technology, but the demonstrator will not necessarily have a sufficient amount of those photovoltaics for the satellite's operations.

Four boom and sail deployment unit (BSDU) s are mounted on the booms, one on each boom. In stowed configuration they are mechanically locked and electrically connected to the central unit. For deployment, the BSDUs are unlocked and disconnected from the central unit and move outward, thereby deploying the booms and the sail segments simultaneously (see figure 3.44 (b) and (c)). During deployment communication with the central unit is achieved with a wireless on- board communications system and will each have its own power system and board computer, as there are no wired connections foreseen in the booms.

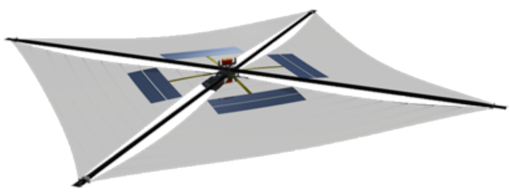
In contrast to other projects like JAXA's IKAROS and NASA's NanoSail-D, one of the main requirements and advantages is that the deployment is fully controlled. That means the deployment process is monitored by analyzing various characteristics and it can be stopped and resumed at any time, if required. This requirement refers to the fact that the whole deployment process must enable failure detection, isolation, and recovery (FDIR).



(a) Stowed Configuration



(b) During deployment



(c) Deployed Configuration

Figure 3.44: Gossamer-1 spacecraft in launch and deployed configuration.

It requires the possibility to obtain system status information as well as possibilities for reacting to certain system states, which in fact is the definition for controlled deployment.

The Gossamer-1 project is concluded with qualification testing of a ground demonstrator consisting of one deployment unit with one CFRP-boom and two sail segments. Linear drive units are used to simulate additional booms on the other sail edges to achieve representative deployment forces. The qualification testing includes venting testing, vibration testing and thermal-vacuum testing followed by a ground deployment. By means of the demonstrator testing the validation of all aspects of the deployment and the deployment monitoring is enabled. This is with respect to mechanical and deployment aspects, command and data handling, sensors data acquiring and processing as well as algorithms. The test rig with engineering models of the sail segments and the deployment unit is described in subsection 4.6. The solar sail specific technology development was concluded with the qualification on TRL 5.

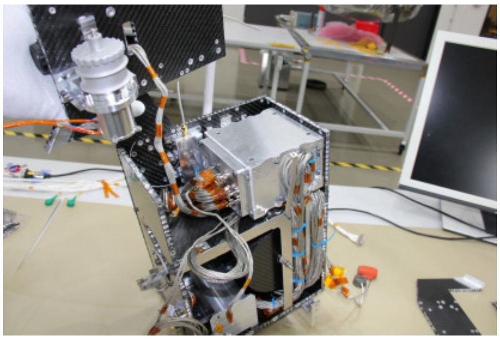


Figure 3.45: Gossamer-1 Boom and Sail Deployment Unit prior to final integration.

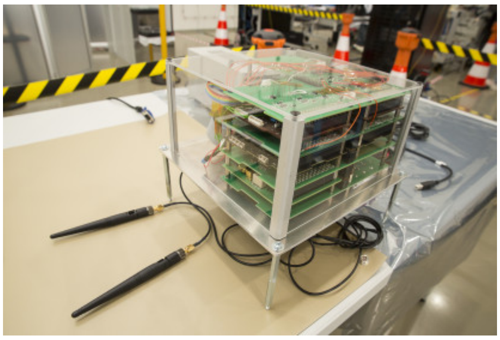


Figure 3.46: Gossamer-1 Central Spacecraft Unit in test configuration.

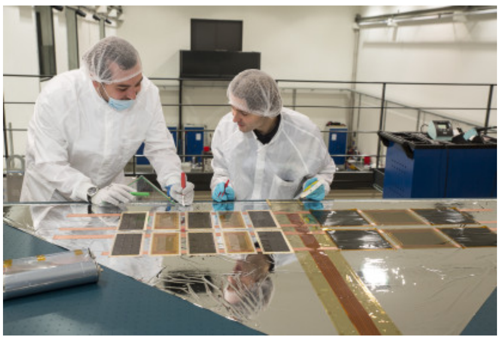


Figure 3.47: Gossamer-1 Sail segment with integrated photovoltaic modules and harness.

Developments accomplished within Gossamer-1:

- Worldwide first overall concept and design of a controlled deployment of a system consisting of ultra-lightweight CFRP booms [228] and polyimide membranes suitable for even larger structures [594, 597].
- A mission concept which defines all necessary operational and deployment modes [504] serving as basis for the definition of a realizable and cost-efficient operation concept together with the ground segment of German Space Operations Center (GSOC). Considering the low-cost approach the concept allows the application of professional methods, strategies and technologies of GSOC together with hardware components from university or cube-sat community developments including the implementation of the coding standards CCSDS and Package Utilization Standard (PUS) as well as a full duplex capability.
- Failure mitigation strategies to account for the typically reduces reliability of above mentioned hardware components were defined.
- Developed infrastructure like rigs for testing Gossamer structures under Earth gravity and EGSE to prove the system concept with development and functional tests or even qualification tests in certain development areas (see section 4.6).
- Using of the prior developed CLAVIS satellite bus concept. In case functional requirements exceeded the CLAVIS parameters (S-Band, power system, camera system, On-Board wireless communication, dedicated sensors) low-cost CubeSat components or commercially available hardware was implemented (see figure 3.46).

- Fully functional Boom and Sail Deployment Unit with wireless communication to the Central Spacecraft Unit (see figure 3.45).
- Integration of commercially available thin-film photovoltaic modules on membranes including harnessing and contacting by taking into account the whole deployment process.

Mission Concept

In many studies future satellite operation is based on exchangeable elements on the satellite which will be serviced by Space Tugs. For most of these Space Tug concepts electrical propulsion is the preferred technology. For that reason high power generation abilities are important. Large, deployable and very light-weight Gossamer systems together with thin-film photovoltaic may have a better mass to power ratio compared to conventional solar arrays even though the efficiency of thin-film photovoltaic with around 12 % is decisively lower. Therefore, the application of deployable Gossamer structures as part of the power subsystem is investigated on conceptional level in a so called Huge Solar Array development project.

The hardware project Gossamer Solar Array (GoSolAr) shall yield a 5 m × 5 m solar power deployment system which serves as one of the first S2TEP (see section 3.3.6) reference payloads. It will be partially integrated with thin-film photovoltaic and shall demonstrate the application of such a technology. Strong focus is put on the scalability since the application for a Space Tug would require power consumptions up to 100 kW leading to arrays sizes of 20 m × 20 m on each side of the Space Tug when using thin-film photovoltaics.

Within the project GoSolAr development results from Gossamer-1 need to be adapted for a photovoltaic application. Besides the reevaluation of packing and deployment techniques as well as the selection of critical components for the deployment strong focus is put on the membrane technology supporting the photovoltaic and the corresponding harnessing which is referred to as the experimental power subsystem.

3.6.2 Boost Symmetry Test (BOOST)

Boost Symmetry Test (BOOST) is a proposed small satellite mission that aims for testing the foundations of Special Relativity by comparing two high-performance optical frequency references in low-Earth orbit. By this, BOOST is also an important technology demonstration mission, verifying space operation of key technologies which are of high interest for a multitude of space missions related to science, Earth observation and navigation & ranging. A Phase 0 study was carried out at the Institute of Space Systems showing the feasibility of this mission using the DLR compact satellite bus. BOOST is therefore one candidate for an Eu:CROPIS successor mission.

Space-Based Test of Special Relativity

By comparing a length reference (i. e. a highly stable optical resonator) with a molecular frequency reference, BOOST will carry out a Kennedy-Thorndike (KT) experiment, measuring a potential boost dependence of the velocity of light. Employing frequency references with 10^{-15} frequency instability at orbit time (around 90 min) and by integration over 5 000 orbits (assuming a 2 years mission lifetime with a 50 % duty cycle as baseline) an at least 100-fold improvement in measuring the Kennedy-Thorndike coefficient is targeted, compared to the current best terrestrial test.

BOOST will address the following questions:

- What is the symmetry of space-time? Up to which accuracy is Special Relativity valid?
- Is there a deviation of the constancy of the light speed at a minuscule scale?
- What is the nature of space-time and which theories can (cannot) describe it?

- How do matter and energy, space and time behave under the extreme conditions, e. g. short after the big bang?

Although at a speculative level, measurements at the edge of the known theories certainly open the window to new exciting physics and will have impact on many different areas of physics.

Performing the experiment in space offers many advantages over ground experiments and ensures the improvement in KT coefficient determination by the BOOST mission. The main advantages of a dedicated space mission are:

- Higher orbital velocity: The spacecraft moves 25 times faster than a ground laboratory, directly improving the sensitivity in KT coefficient measurement by this factor.
- Faster orbital period: The typical LEO orbital periods of about 90 minutes are a definitive advantage in comparison with the 1 440 minutes (1 day) for the Earth's spin as this is the time scale the frequency references need to be optimized in frequency stability. Moreover, it implies much longer integration times as the number of orbits increases considerably in equal time periods. Due to long-term effects (drifts, ageing, etc.) the clock frequency stability is higher at shorter integration times.
- Quiet environment: For example, no acoustic and seismic vibrations could alter the experiment, e. g. by affecting the laser coupling to the optical cavity. With a well-designed spacecraft the vibration environment can be extremely quiet.
- Reduction of mechanical distortions due to gravity: Due to the altitude, tidal effects on the cavity due to an inhomogeneous gravitational field are suppressed.

In summary, a factor of 100 improvement over the current best KT experiment on Earth is possible, taking into account the 25 times gain in the velocity experiment multiplied with a factor of 4 gained in the integration of the modulation period. A further factor of 10 can be achieved if the clocks' frequency instabilities are further improved down to the 10^{-16} level at orbit time.

Technology Demonstration Mission

BOOST is a technology demonstration mission in which key technologies applicable to a variety of future space missions will be validated for the first time in space. Optical frequency references with highest frequency stability are e. g. needed for the gravitational wave observatory missions Laser Interferometer Space Antenna (LISA) and Astrodynamical Space Test of Relativity using Optical Devices (ASTROD) [12], Earth gravity missions such as Next Generation Gravity Mission (NGGM), and missions to test fundamental physics such as Spacetime Explorer and Quantum Equivalence Space Test (STE-QUEST) [7]. They are also needed in navigation and ranging, laser communication and in spectroscopy applications such as space-based LIDAR systems. Compared to microwave clock technology, optical frequency references offer the possibility of higher achievable frequency stabilities e. g. being the basis for an enhanced global navigation satellite system.

BOOST Payload

The BOOST payload is mainly based on technologies currently already realized at least on laboratory level. Cavity- and iodine-based frequency references for space — as payload foreseen for BOOST — are currently developed for space at the Institute of Space Systems in cooperation with University Bremen, Humboldt-University Berlin, Leibniz-University Hannover, University of Applied Sciences Konstanz and Airbus DS in Friedrichshafen.

A photograph of the compact and ruggedized iodine spectroscopy setup on engineering model level is shown in figure 4.61. A cavity-based frequency reference is currently realized using a cubic cavity with corresponding thermal shielding for highest long-term stability (see figure 3.48).

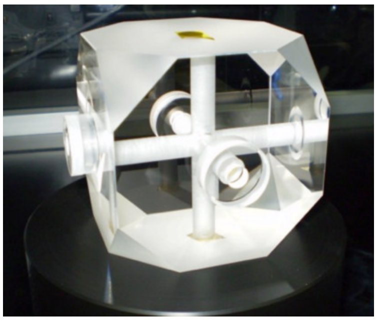


Figure 3.48: High-finesse optical cavity as proposed for the BOOST mission. The cavity design is developed by National Physical Laboratory (NPL), Great Britain, also for space applications.

Mission Concept

The feasibility of the payload and the mission was investigated in a concurrent engineering (CE) study with subsequent workshop involving all system relevant departments of the Institute of Space Systems. The proposed mission carrying a Kennedy-Thorndike experiment has been designed to operate in a LEO. One possibility for the orbit is to be circular and Sun-synchronous in order to minimize temperature variations at the optical cavity as well as reducing the needs for radiation and thermal shielding, although other possibilities may be considered as well. Meeting the science goals requires rather stringent temperature variations of the bus spacecraft interfaces at the orbit period (in the order of ±1 °C to ±5 °C) and the selection of the orbit will be driven in particular by this thermal requirement. For AOCS, spin stabilization as well as 3-axes control of the spacecraft are compatible with the payload and the science measurement.

The proposed mission is compatible with the DLR compact satellite bus with total payload budgets of approximately 65 kg and an average power consumption of 100 W. A possible satellite configuration is shown in figures 3.49 and 3.50.

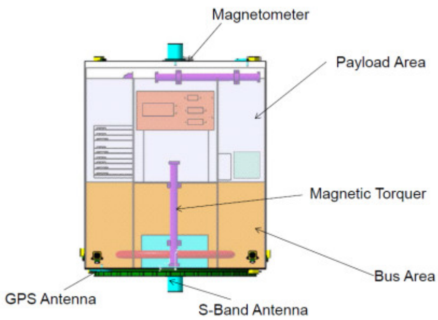


Figure 3.49: Possible spacecraft configuration with 3-axis stabilization.

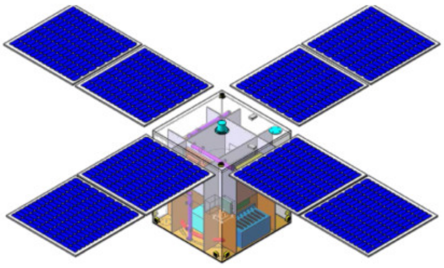


Figure 3.50: Flight configuration of the BOOST satellite.

4 System Technologies

4.1 Guidance, Navigation and Control

Determining and actively controlling the flight state of spacecraft is essential to successfully execute and complete space missions. Therefore, guidance, navigation and control (GNC) systems are an inherent part of all space vehicles. In the context of satellite applications, they are more specifically referred to as attitude and orbit control systems (AOCS). Space missions usually have very heterogeneous objectives, e. g., to launch space systems into a certain orbit, to observe specific regions of the Earth with satellites, or to land probes on asteroids, which is why they impose disparate requirements on the GNC subsystems and, in consequence, GNC subsystems are usually purpose-built for that reason.

However, for all the possible different applications, similar fundamental methods are applied to design and create a GNC subsystem which meets the requirements of the mission. The fundamental methods and tools applied to all missions include, e. g., techniques for state estimation, trajectory optimization, control design, and the design and development process of this type of systems. Especially the design and development process comprising modelling, design, implementation, and verification is common to the GNC systems of all missions. The research in this field is focusing on developing new technologies and techniques in order to improve performance, autonomy, reliability, and robustness of GNC systems. This includes applying them in missions and demonstrators. Furthermore, the implementation of DLR's own space missions requires the development of corresponding custom-designed GNC subsystems.

Since the field of work in GNC systems and technologies for space vehicles is vast, the research activities need to be concentrated on a selected branch that is in line with the objectives of DLR and of the Institute of Space Systems. Therefore, the main working areas of the Institute in the guidance, navigation and control domain are

- attitude, orbit control, and formation flying of satellites,
- guidance, navigation and control for exploration landing vehicles, and
- guidance, navigation and control for reusable space transportation systems.

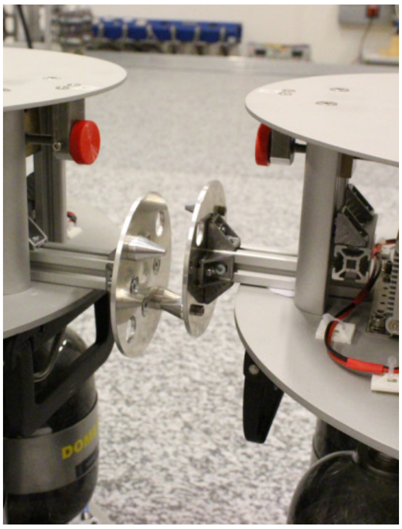


Figure 4.1: Two TEAMS vehicles are about to make a docking. Demonstration of model predictive control for rendezvous and docking with an uncooperative rotating target.

4.1.1 Satellite Attitude and Orbit Control Systems and Formation Flying

Since the founding of the Institute, the implementation of DLR's compact satellite program (see section 3.3.3) has been one of the key tasks for the AOCS development. Together with the emerging Small Satellite Technology Experiment Platform (S2TEP) micro satellite platform (see section 3.3.6), two satellite bus systems have to be equipped with the required AOCS. Although they differ in requirements on reliability, stability, and cost, the challenges remain similar. Since small satellites with a high performance have been identified as key elements in meeting the ambitious Earth observation and space science goals of the future, more ambitious requirements are imposed on the control systems. Imaging missions require high precision stability to prevent blurring while the platform has low moments of inertia. A high spacecraft agility is required to allow for more science time and to reduce re-pointing periods. A reduction of operating expenses shall be achieved by increasing on-board autonomy. This requires improved attitude control systems.

The implementation process for AOCS for a mission of DLR's compact satellite program and the S2TEP micro satellite platform provides a specialized solution tailored to the needs of the payload (e. g., AsteroidFinder, Euglena and Combined Regenerative Organic-Food Production in Space (Eu:CROPIS)) as it is the case for almost all satellites. The development process follows a pre-defined scheme mainly based on the European Cooperation for Space Standardization (ECSS) standards as in industry. However, with the objective to research in this field, the combination of delivering reliable AOCS with the motivation to create innovation, the development does not remain a standard repeated for every mission, but becomes a challenging trade-off between reliability and risk due to innovation.

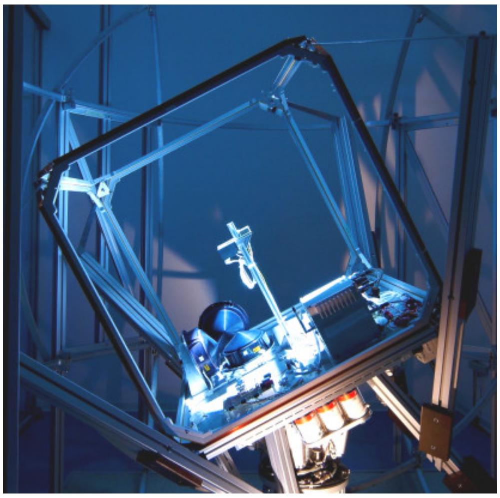


Figure 4.2: FACE — a ground-based dynamics simulator used for AOCS verification.

The AsteroidFinder mission was the first to be designed and developed within the compact satellite program. The payload — a telescope to detect asteroids between Earth and Sun — imposed challenging requirements on pointing stability and agility. First, the telescope needed to be stabilized to prevent blurring of images. Secondly, a region of the sky needed to be repeatedly imaged to detect asteroids and to determine their orbits. In the GNC domain, this included the development and implementation of an AOCS with a flexible adaptable design and high performance. The solution developed for this mission included a three-axis stabilized attitude control system which used also the optical payload as attitude sensor for fine pointing [840, 411, 257].

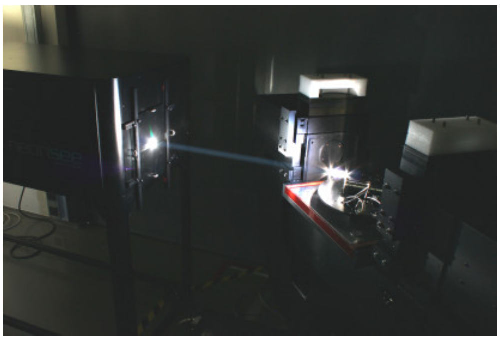


Figure 4.3: Sun sensor verification in the laboratory STARS using a Sun-equivalent light source and a rotation table to verify sensor accuracy and behaviour at high spin rates.

In the successor project Eu:CROPIS, the payload has different needs as it requires a constant spin rate at different speeds while complicating the control due to sloshing liquids within the experiments. The implementation of the AOCS for this mission is in its final stage [410, 468]. The whole AOCS development and implementation process is based on tailored ECSS standards and has undergone so far all reviews as well as the engineering model and flight model implementation phases. Throughout the project, several components and test set-ups have been designed and implemented to enable a cost efficient design as well as thorough testing and verification. One of them is Facility for Attitude Control Experiments (FACE), which is a dynamics simulator for the attitude motion of a satellite [66] (see figure 4.2). Another set-up is the Laboratory for Sensor Testing and Assessment on a Rotation Simulator (STARS), which allows calibration of inertial and optical sensors including the time response (see figure 4.3). With the delivery of Eu:CROPIS, the capability to complete an end-to-end-development of an AOCS for a scientific compact satellite mission will be finally demonstrated.

In parallel to the compact satellite program, AOCS developments for micro satellite missions have been conducted. For the Automatic Identification System Satellite (AISat) mission (see section 3.3.4), a magnetic attitude control system was developed which is modular and can be extended with further sensors and actuators. This will be continued with the S2TEP platform, where the modular design shall allow an reconfiguration of the AOCS to the needs of the payloads.

Along with the development of the AOCS for Earth-orbiting satellites, other missions have been equipped with systems and components. One is the mission Mobile Asteroid Surface Scout (MASCOT), a small asteroid landing package flying on the Japanese mission Hayabusa II. For its autonomous operation on the asteroid surface, MASCOT needs to know its attitude with respect to the ground. A histogram filter is used for attitude determination and multi-sensor data fusion. It is a Bayesian filter used to estimate states which can be divided in a finite number of possible values [551]. The filter software as well as the hardware have been implemented, extensively tested (see figure 4.4) and qualified for deep space environment before integration of MASCOT into the mother ship.

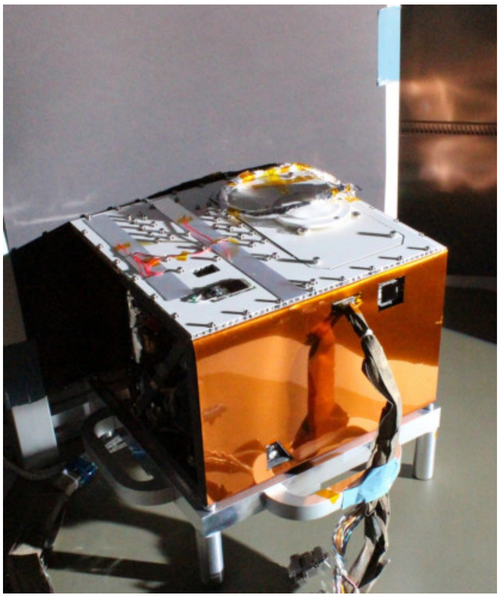


Figure 4.4: MASCOT's autonomous attitude determination system (EM) is tested with a dark surface resembling the asteroid surface and a special light source simulating the Sun.

Closely related to the AOCS development is the control of multiple satellites. A current trend in the satellite business is to move away from large monolithic spacecraft like the Environmental Satellite (Envisat) towards distributed sensors on multiple spacecraft. They shall allow a higher spatial and temporal resolution of measurements (e. g., for Earth observation). So far, satellite formations included only small numbers of satellites which were operated individually from ground. In case the number of satellites in a formation or cluster increases to several tens or hundreds, new autonomous methods for guidance and control must be found. This includes the autonomous cooperative pointing as well as position control which avoids having neighbor spacecraft in the field of view of sensors.

In the area of formations and clusters of satellites, a model-based predictive control algorithm for formation maintenance and reconfiguration of a two-satellite formation based on relative orbital elements was developed. A side-by-side comparison of the method together with an orbit control method from the mission Prototype Research Instruments and Space Mission Technology Advancement (PRISMA) were analyzed in a realistic simulation scenario including sensor and actuator errors. The results were published in [26].

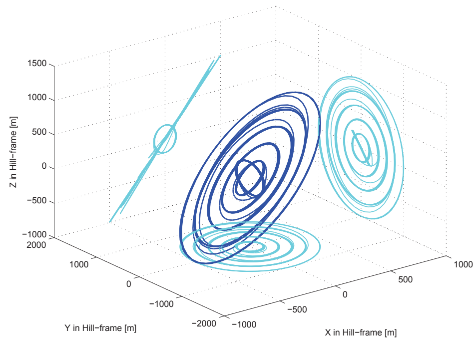


Figure 4.5: This figure shows the relative trajectories of a follower satellite around a leader satellite for several subsequent formation reconfigurations.

For establishing and maintaining along-track formations of satellites in a propellant-optimal way, a new method was developed. The method is called "delayed target-tracking" as it generates a guidance signal by delaying the target state, which is then tracked by a chaser satellite. The method was patented and presented in [27].

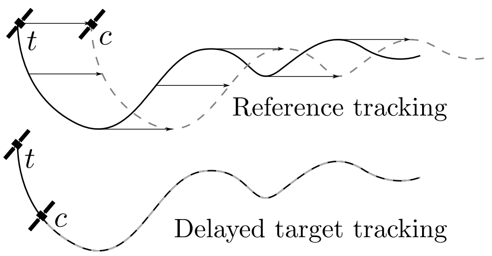


Figure 4.6: This figure shows basic principle of delayed target tracking compared to tracking a fixed reference.

In the field of guidance and control for rendezvous and docking of two spacecraft, a new technique has been developed and tested. The method uses a model predictive control algorithm to plan orbit and attitude maneuvers. The algorithm was successfully tested in the Test Environment for Applications of Multiple Spacecraft (TEAMS) and the results were presented in [920, 238].

The TEAMS facility has been recently extended with a robotic arm mounted on one of the TEAMS vehicles. First experiments have been carried out in order to simulate capturing of an object in space as it is envisaged for on-orbit servicing (OOS) and Active Debris Removal Service (ADR-S) operations. The goal is to increase the understanding of coupled vehicle and arm dynamics and to develop new GNC methods for these applications.

The station keeping of geostationary satellites can be seen as a kind of formation control. In that field, a new approach to modelling the dynamics of a geostationary satellite has been developed and an application of the

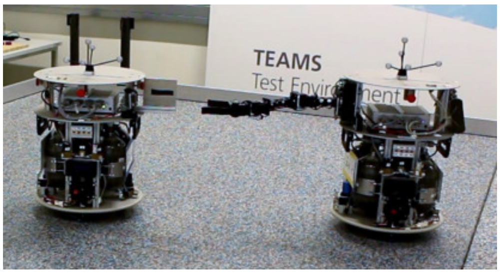


Figure 4.7: Two TEAMS vehicles simulating client and servicer spacecraft. Demonstration of GNC algorithms for capturing an uncooperative rotating target.

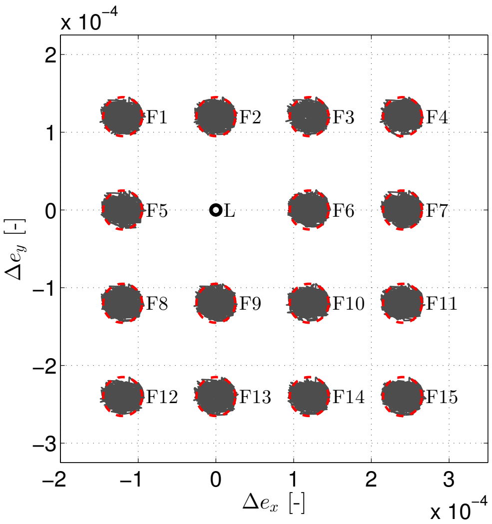


Figure 4.8: The relative eccentricity of a fleet of sixteen satellites is controlled within the assigned control window over the course of one year.

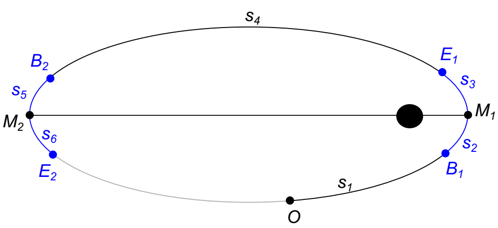


Figure 4.9: This figure shows, for a spacecraft located in O, how the impulsive control actions required in M_1 and M_2 can be transformed in quasi-impulsive actions from B_1 until E_1 and from B_2 until E_2.

new dynamics in a convex-optimization-based method for calculating regular station-keeping methods for geostationary satellites has been implemented. The method was shown to have excellent performance in terms of propellant consumption and thruster firings while being extremely versatile; it can be applied to satellites with a high thrust-to-mass chemical propulsion system as well as to satellites with low-thrust-to-mass electrical propulsion systems with vastly different thruster configurations. The method easily incorporates various types of (convex) constraints on state and controls and can be applied in open-loop and as a receding horizon controller. The results were published in [28].

In continuation of the research on control of geostationary satellites, an analysis of the minimum distance constraint and sensor cone avoidance constraints on fleets of collocated geostationary satellites in terms of relative orbital elements was performed. The outcome was used to develop a convex-optimization-based method for the calculation of orbit control maneuvers for maintaining a fleet of satellites in a geostationary slot subject to these constraints. The results were presented on conferences on formation flying and published in [165, 166].

In addition to developing solutions for formation flying and co-location with constraints, guidance and control algorithms for clusters with a large number of spacecraft were researched. For the control part — the execution of individual maneuvers for each spacecraft in the cluster — a new autonomous approach has been developed to compute orbital maneuvers to steer the orbital elements of a spacecraft to a desired value. In that research, it was considered that the small corrective maneuvers that are usually treated as impulsive are spread over a burning arc (see figure 4.9) and therefore are considered as quasi-impulsive. According to the characteristics of the foreseen propulsion system, the duration of the burning arc is also evaluated. The results were presented in [182].

For the guidance part, a new autonomous scalable approach for cluster keeping based on semi-major axis corrections was developed. The relative-motion constraints that characterize a cluster-keeping problem are less strict than the ones typically used in formation flying and this permits the relative distances to vary over a wide range of values. Through proper corrections of the semi-major axis of the spacecraft, it is possible to control the long term behavior of their relative distances since a desired slowly increasing or decreasing trend can be obtained (see figure 4.10).

For the development and verification of GNC/AOCS systems, models of the system dynamics of space vehicles, the expected environmental conditions and disturbances during flight, as well as sensor and actuator models are indispensable tools.

For this purpose, the Institute developed the High Performance Satellite Dynamics Simulator (HPS) in cooperation with the Center of Applied Space Technology and Microgravity (ZARM) at the University of Bremen [727]. The HPS is a simulation library and a collection of tools for the simulation of space GNC/AOCS systems. At the moment, the HPS comprises approximately 80 interconnected functions and simulation models for MATLAB/Simulink, which are continuously being enhanced and extended.

The HPS implements highly accurate simulation models applicable to science missions with a high demand for measurement accuracy. These models can be used, for example, to investigate the satellite-instrument interaction and the effect of external disturbances on the measurement signal, to generate data to evaluate post-processing algorithms or to test mission-specific control algorithms. Testing with Hardware-in-the-Loop simulations is currently possible with some of the modules, and will be made possible with all modules in the future. The HPS library is subject to a quality assurance process in which all module functionalities are tested thoroughly. The validation procedure is based on automated testing and provides extensive test reports. The high-precision multi-body dynamics module is validated with flight data. Single HPS modules and components have also been contributed to the Simulation Model Library (SimMoLib), a project to establish a DLR-wide platform for the exchange of simulation models [2].

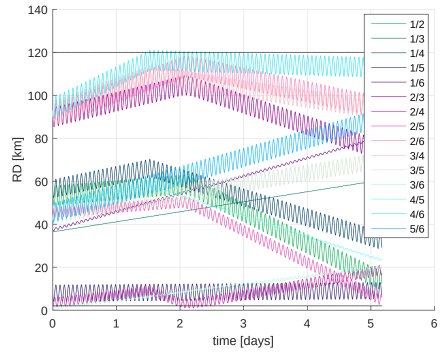


Figure 4.10: This figure shows the relative distances in a six-spacecraft cluster and how they can remain bounded through proper corrections of the semi-major axes of the spacecraft.

4.1.2 Space Transportation Vehicles

Space transportation systems, allowing the transport of people and cargo into orbit and back to Earth, are the key for any space mission. Improving their performance as well as enabling them to be re-used is a key factor for their further development. In the field of GNC, the main challenges can be separated as: accurate fault-tolerant navigation, on-board optimal control of flight trajectories, and control including the influence of flexible structures and sloshing fuel.

As in all GNC applications, navigation certainly plays a crucial role also for the autonomy of space transportation systems. Until recently, all European launchers rely for their ascent into orbit on inertial navigation only, i. e. the navigation was almost exclusively done using dead reckoning of inertial measurements. Although reliable, this approach has poor long-term accuracy, as the propagated states inevitably drift, and the sensor units that can still maintain acceptable accuracy are large, heavy, and extremely costly. global navigation satellite systems (GNSS) or combinations of them with inertial systems are not yet used. Since the business of launchers is very conservative, the main challenge is to develop accurate navigations systems which supersede today's navigation performance and are highly reliable and fault tolerant. The advent of low(er)-cost inertial measurement units together with the ever increasing maturation of GNSS technology provide a solution to this problem. The combination of these two technologies is commonly known as GNSS/inertial navigation system (INS) hybridization or, simply, *hybrid navigation*. One of the first activities of the Institute was to start research in this field. The first product, the Hybrid Navigation System (HNS), was developed precisely as an alternative to the classical purely inertial systems, providing improved long-term accuracy while greatly reducing system mass and cost [546, 641, 272, 643, 652] (see figure 4.12). Its capabilities were successfully demonstrated aboard the Sharp Edge Flight Experiment II (SHEFEX II) experimental vehicle, which was launched on June 22, 2012 from Andøya rocket range in northern Norway [114, 639, 908].

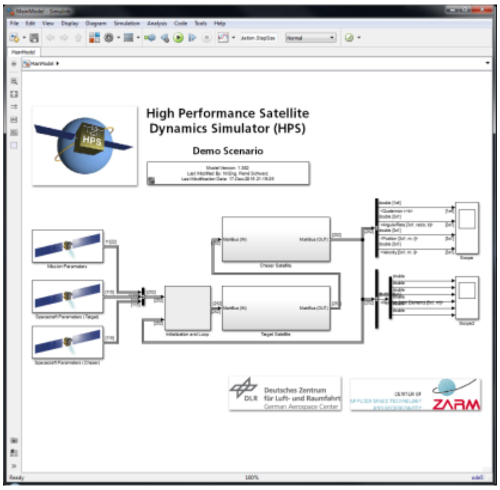


Figure 4.11: Utilization of HPS modules within a simulation campaign for satellite formation flight.

The promising results encouraged further development, which currently proceeds in several directions. One of these is an extended, more robust and reliable second version of the HNS, to be flown on the Reusability Flight Experiment (ReFEx) DLR mission (see section 3.5). The concept includes improved fusion algorithms and redundant inertial and GNSS units as well as additional reference sensors. This HNS features a fault-tolerant on-board computing and data handling architecture [900, 591], which also incorporates a concept for failure detection, isolation, and recovery for all system elements [796, 847, 857, 858, 888]. In parallel, a similar system is being designed to support several demonstrators and testing platforms. This navigation unit aims to support the robust feedback control of

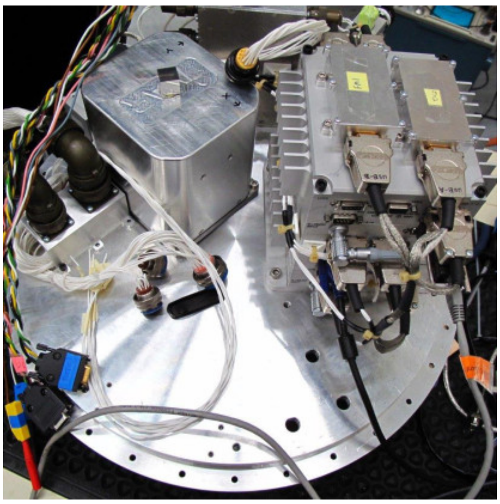


Figure 4.12: SHEFEX II Hybrid Navigation System (HNS) flight model before integration into the vehicle.

the demonstrators and to provide an accurate trajectory reference for any payloads under testing [366, 449]. Another promising application of such an GNSS/INS combination is for the localization and safety monitoring of launch vehicles. Exactly with this in mind, the project "Augmented GNSS" was started. This envisages to equip a GPS receiver with a low-cost inertial measurement unit, yielding a robust and reliable localization source. An experimental set-up will launch on a sounding rocket in spring 2017. Finally, all activities on hybrid GNSS/INS navigation are in-line with the aim of European Space Agency (ESA) to develop a robust and fault-tolerant hybrid navigation system for the European launcher family. This is reflected by an on-going ESA-DLR networking partnering initiative partnership project.

Figure 4.13: Laboratory prototype for the inertial measurement unit in redundant (tetraaxial) configuration developed for the ReFEx Hybrid Navigation System (HNS).

Trajectories for space transportation have always been optimized. However, so far the optimization is done on-ground before flight, as the reliability and performance of the guidance and control (G&C) system is mission critical for any type of space mission. During flight, the system tracks this pre-defined flight path. The challenge is to take the next step and to introduce the on-board generation of optimal trajectories. This will make the system more adaptable and more robust to changed conditions. This would also allow to increase the flexibility shortly before and during the mission. G&C for entry, descent, and landing (EDL) is especially challenging because crucial environmental properties cannot always be determined beforehand and the G&C algorithms must be able to adapt to different environmental conditions at flight time, while still respecting vehicle control constraints and safety-critical path constraints. Depending on the environment (e. g. Earth re-entry, Mars entry) and the mission scenario, different algorithms must be employed to achieve the accuracy and safety demands for today's missions.

Over the years, in virtue of the Sharp Edge Flight Experiment (SHEFEX) series of missions [213], the capability to analyze, develop, and verify classic and modern EDL G&C algorithms has been created. Expert knowledge on pseudo-spectral methods [189, 104, 5], non-linear control [896], convex optimization, and other cutting-edge technologies allows the development of EDL solutions for a wide range of mission scenarios and vehicles. A special focus is placed on methods to generate sub-optimal trajectories in real-time, such as adaptive multivariate pseudo-spectral interpolation (AMPI) [175, 896, 212, 900] and parametric sensitivity analysis (PSA) [224].

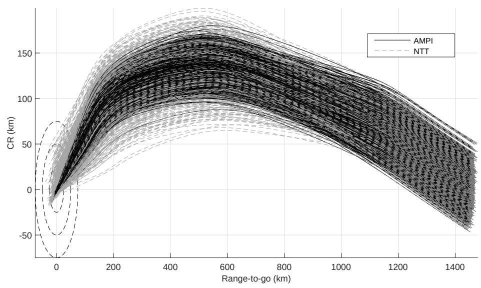


Figure 4.14: AMPI: Comparison of 1 000 groundtracks controlled with AMPI and with conventional NTT.

The core of AMPI is to fuse a pre-computed database of online trajectories to obtain an in-flight solution, which is able to cope with large entry-initial uncertainties. An example is depicted in figure 4.14, where the approach is compared with a more traditional neighbor-trajectory tracking (NTT) approach. One can observe how the AMPI method is able to strongly reduce the final dispersion (a key requirement for the recovery of the vehicle) despite large initial uncertainties.

The idea of the PSA is to reveal information on how the solution of an optimal control problem changes with respect to chosen perturbation parameters. This knowledge is used at flight time to compute a new near-optimal control sequence and state trajectory for the actually encountered flight conditions. The PSA method has been combined with non-linear trajectory tracking to form a G&C system for a small capsule entering the Martian atmosphere.

The development of entry G&C systems will continue in the frame of ReFEx mission, the new entry vehicle developed by DLR, which is foreseen to be launched in 2019. The aforementioned techniques will be crucial to enhance the concept of re-usability, which represents the paradigm shift for the next generation of space missions.

Controlling a rocket during ascent has always been a challenging task since it is a highly unstable system. With the need to improve performance, lightweight structures have been introduced which save mass but make the system more flexible and therefore more complex to control. Recent developments have included several orbit maneuvers of the upper stage, which is using cryogenic fuel for performance reasons. Having sloshing fuels aboard also is a fact which makes the design of a control system challenging.

As part of the Research Cooperation on Upper Stage Technologies (see section 4.4.2) control methods have been developed which maintain the attitude of a cryogenic upper stage during long ballistic phases in presence of fuel sloshing. This research has been extended to control methods for executing large angle slew maneuvers of cryogenic upper stages where the position and the motion of the fuel is controlled [149, 433].

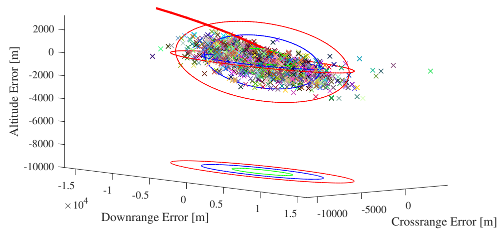


Figure 4.15: Control accuracy of guidance based on PSA: Dispersion of position at parachute opening for 1 000 cases with different initial errors and disturbances.

4.1.3 Space Exploration Systems

Upcoming exploration missions require landing at specific locations such as a site of a container with pre-collected samples, a riverbed on Mars, or a lunar base. Since locating the spacecraft from Earth is not sufficient for reaching specific landing sites, the spacecraft has to rely on the target body as reference for navigation.

Usually the terrain is known well enough for stating a sufficient probability for the abundance of a safe landing site. However, in many cases the exact location of a safe site will have to be determined during the final stage of the landing, when it becomes visible for the on-board sensors.

Precise landing also requires adaptation of the spacecraft's flight path to unforeseeable changes of the expected Martian atmospheric conditions in real-time.

Furthermore, such missions will be performed at various distances from Earth, reaching from the vicinity of Earth and Moon out to several astronomical units for targets like Mars, asteroids, or the icy moons of Jupiter and Saturn, imposing high delays for any communication with Earth. Therefore the spacecraft has to operate autonomously during the landing.

Therefore, upcoming missions impose the challenges of implementing spacecraft autonomous operation, utilizing the target body as a navigation reference, evaluating the landing area and optimizing the trajectory to the current conditions. This brings a novel requirement for the incorporation of a higher-than-before grade of knowledge about the target, based on a-priori data and on measurements collected during the mission. Examples are globally geo-referenced features originating from mapping missions, reconstruction of atmospheric conditions, and measurement of the 3D structure of the landing area.

From the beginning, one of the priorities of the Institute is developing navigation technology for enabling autonomous, precise and safe landing on planetary bodies.

Early on, the need for an absolute navigation method, i. e., to be capable of locating a spacecraft with respect to the mission's target body, has been identified. Since craters represent a widely abundant and distinctive feature, focus was set on developing a technology using craters as a navigation reference [467]. In parallel, work began on the design and implementation of the Testbed for Robotic Optical Navigation (TRON) for optical navigation technologies up to technology readiness level (TRL) 6 [254, 449, 463]. TRON offers the possibility to perform hardware-in-the-Loop tests within scenes representative for the ones encountered by optical sensors during exploration missions (see figures 4.17). Typical sensor hardware which can be tested in TRON are active and passive optical sensors like light detection and ranging (LIDAR) systems and cameras. The major components of the lab are a robot on a rail for dynamic positioning of the sensor under testing, a dynamic lighting system for illumination of the targets (3D terrain models), laser metrology equipment for high precision ground truth and a dSPACE real-time system for test observation and control, and synchronization of ground truth and sensor data. The laboratory can be customized with user defined hardware.

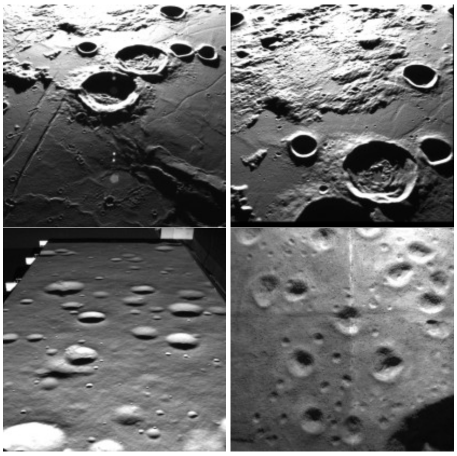


Figure 4.16: Lunar landing images created in TRON.

The Institute leads the DLR overarching project Autonomous Terrain-Based Optical Navigation (ATON). In this project, a hybrid navigation system is developed integrating the results of the crater navigation sensor and other optical sensors with inertial sensors.

The crater navigation method has been successfully demonstrated with a camera-in-the-loop test within a mock-up lunar environment in TRON. It showed the capability of locating itself with respect to the Moon by processing images of the mock-up lunar surface with an on-board crater map. The method works lost-in-space, i. e., it is capable of determining the pose with no further knowledge than a single image and an a-priori generated crater map. Moreover it was successfully integrated into the ATON navigation software [148] and tested with a camera-in-the-loop simulation in TRON. A helicopter flight campaign was performed over a field prepared as a lunar mock-up. In this way, real data for all sensors in the ATON system could be acquired. The ATON navigation software successfully demonstrated real-time capability by processing this flight data in real-time and achieving the expected navigation accuracy, showing also that

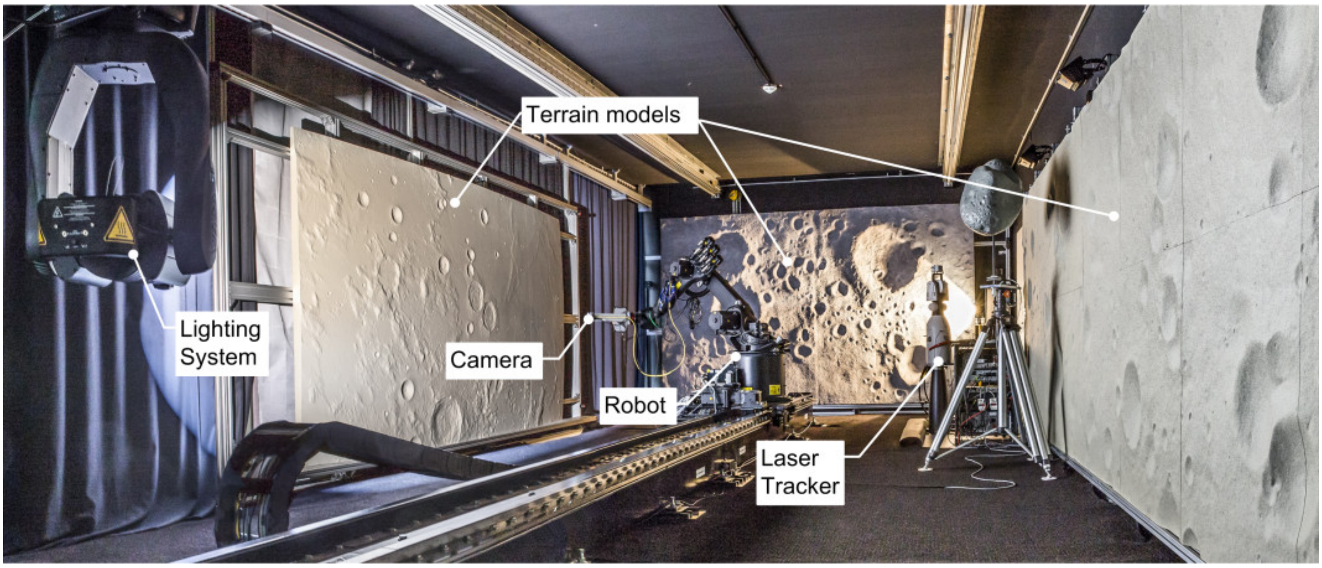


Figure 4.17: Simulation of the descent orbit phase of a Moon landing trajectory in TRON. The robot positions the optical sensor (in this case a camera) with respect to the illuminated terrain model, with the sensor recording data. Simultaneously the laser tracker measures precisely the true pose of the sensor with respect to the simulated Moon.

the crater navigation can be integrated well into a data fusion architecture. It is planned to perform a real-time in-flight demonstration of the ATON navigation system this year.

Within the EU project Small Integrated Navigator for Planetary Exploration (SINPLEX), a miniaturized navigation system for space exploration missions was developed. The main goal was to significantly reduce the mass of the navigation subsystem for exploration missions compared to conventional systems. The approach was to integrate multiple sensors into a hybrid navigation system. Within the project, a breadboard system was produced, which includes an inertial measurement unit, a star tracker, a navigation camera, a laser altimeter, a navigation computer, and a power distribution unit. Hardware-in-the-loop testing was done in TRON [743] to measure its navigation performance and demonstrate its applicability for relative autonomous navigation in space applications.

EDL for exploration of extra-terrestrial bodies has a key role for realizing exploration landing missions. The most important objective of those missions is to maximize the payload mass landed on a body. For that purpose the necessary tools have been developed to compute fuel-optimal trajectories for lunar landers using non-throttable engines [1]. Corresponding tracking controllers have also been designed to attenuate disturbances and steer the lander to the desired point with minimum thrust modulation.

Due to limited on-board computation resources, the trajectory cannot be optimized onboard yet and lander follows a pre-computed optimal trajectory. To overcome this gap a real-time capable trajectory generation algorithms was created which approximates sub-optimal solutions based on the attitude and position of the lander [74]. The method relies on a multivariate polynomial interpolation together with an off-line computed trajectory library.

Finally, the terminal landing is the most critical phase for the EDL due to the unknown surface properties and limited safety margins. The hazard detection and avoidance (HDA) system uses feature maps to evaluate the landing area with optical sensors. However, there is a need for another map which incorporates the physical limits of the actuators, available on-board fuel, and uncertainties due to measurements and system parameters. Our research interest includes the determination of safe and attainable landing areas using reachability analyses. The fuel cost, time cost, or success rate of the candidate landing region is evaluated for different scenarios with the in-house developed reachability computation tools [288]. The results provide additional information for the HDA system and could be used as an analysis tool during the mission design.

4.1.4 Outlook and Future Directions

Although many steps have been completed, the main challenges in the field of spacecraft GNC as described in the previous sections remain. With the launch of Eu:CROPIS in 2017, the maturity of the AOCS for the DLR´s compact satellites will be demonstrated. A follow-on mission to be selected and developed in the coming years will allow to further enhance the system and to utilize the modular design. The AOCS for the micro satellite platform S2TEP with its more frequent launches will require research and development for a flexible design and — more important — for processes and methods of automated verification. The opportunity to design, develop and implement an AOCS will enable research and development on

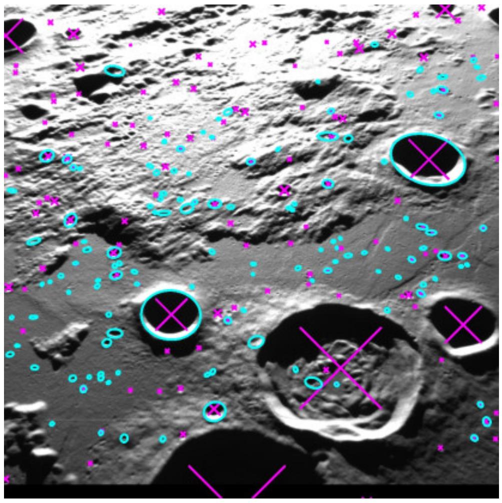


Figure 4.18: Crater navigation during lunar landing simulation in TRON. Turquoise ellipses: detected craters, Pink crosses: craters in database. Overlapping symbols indicate match between detected craters and database used for navigation.

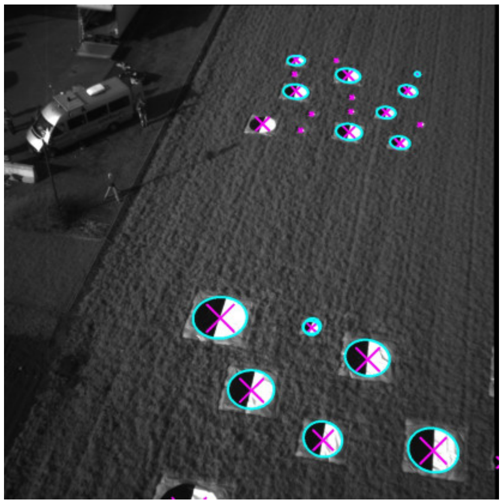


Figure 4.19: Crater navigation during helicopter test. Turquoise ellipses: detected craters, Pink crosses: craters in database. Overlapping symbols indicate match between detected craters and database used for navigation.

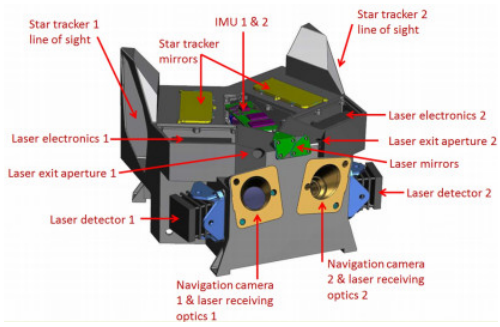


Figure 4.20: Design of the miniaturized, autonomous navigation system SINPLEX

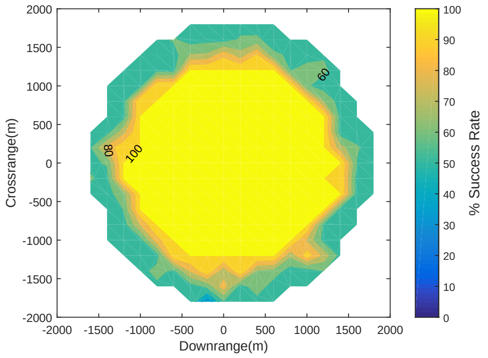


Figure 4.21: Reachable area for terminal landing phase: Success rate of landing considering uncertainties in the initial conditions.

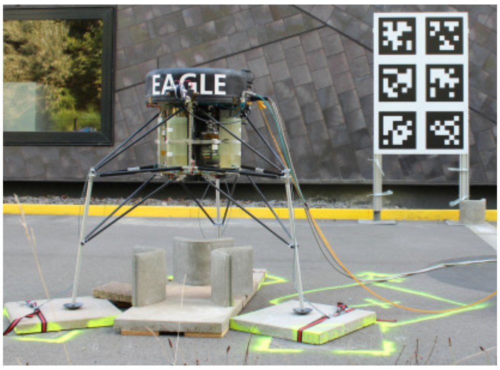


Figure 4.22: EAGLE during a strap-down firing test

new technologies such as novel filtering techniques to be applied for on-board state estimation, optimal-control-based trajectories for constrained, optimal re-orientation maneuvers as well as new control design techniques for mitigation of structural oscillations. The results from the experiments aboard the S2TEP series of micro satellites would be a basis for a further evolution of the compact satellites. Similarly, the platform can be used for the demonstration of GNC systems for multi-satellite applications which will be further developed and verified with the existing ground test beds.

In the space transportation sector, the trend is clearly going towards re-usability. In order to transfer re-usability in a day-to-day business, GNC technologies have to be further enhanced to provide higher flexibility and robustness. The next milestone is the demonstration mission ReFEx, which will provide an in-flight demonstration of accurate, robust navigation and robust, flexible, optimal trajectory control. Objectives for the further evolution of GNC systems are navigation and control system with improved accuracy and extended feasible flight envelope, which shall allow more precise return flights compared to the existing concepts of parachute landings. Horizontal or powered vertical landings like Space X's Falcon 9 first stage are potential solutions for operations of reusable space transportation for which the GNC systems must be adapted for. A development of European technologies for those applications remains a goal for the future.

Exploration missions impose on GNC systems the most diverse and challenging needs since in many cases the spacecraft enters new terrain with many uncertainties. Due to large distances relative to Earth autonomous operation is required without human interaction in very critical mission phases. Autonomous Earth-independent navigation and robust, flexible G&C are the key technologies. With the projects ATON and SINPLEX already a high TRL has been achieved which shall be further increased to find the application of this technology in a future exploration mission. G&C developments – especially for EDL– have shown new ways to make the G&C systems more adaptive and robust by using new mathematical methods for computing optimal control solutions on-board. One accelerator for this research is the demonstrator Environment for Autonomous GNC Landing Experiments (EAGLE). It allows practical implementation and verification of all GNC technologies for landing planetary exploration vehicles.

4.2 Avionics

Electronics and software are the key-enabler and a prerequisite for almost any aspect in today's space flight. In a subsystem's perspective the avionics domains covered by the Institute are the following:

- Communications
  All on-board aspects of communications engineering and infrastructure are covered. In rare cases like AISat even the ground segment has been created.
- Power subsystem
  Power engineering including generation, storage, and distribution is considered and technically implemented.
- Command-and-Data-Handling
  Data transfer and processing architectures are engineered and implemented. This comprises on-board software as well as computing hardware and procurement of peripheral devices.

Maturing any of these subsystems from concepts in Phase 0/A to a flight in Phase E requires a number of core capabilities:

- Subsystems engineering
  In early phases neither the overall space system nor the subsystems are precisely known. Requirements on all levels are developed through an interactive concurrent engineering process discussed in section 2.2.1. Here, the engineer for a subsystem must be able to anticipate how the detailed design of a subsystem will fit into the overall space system. Early models, simulation, and expert knowledge are the base for these discussions. Of course, this includes the tight interaction with the systems engineering team and other subsystem engineers.
- Hardware design, production and procurement
  For the detailed design phases hardware design and production from the architectural level, board level, register transfer level (RTL), down to the circuit level is required. This includes various aspects such as analog as well as digital circuits, component selection and concepts for thermal or power requirements to be fulfilled by processing hardware. Here, a detailed understanding of the subsystems is mandatory even in cases where specifications for components or subsystems are defined for external procurement.
- Software design and implementation
  Software engineering for spacecraft can only be done in tight cooperation with subsystems and systems engineers. Again, multiple levels from the architectural design, application implementation down to driver software for individual peripheral hardware devices are covered.
- Testing and Verification
  In all these activities testing aspects must be anticipated and test concepts as well as infrastructure are developed concurrently to the actual systems. This comprises functional testing and verification to ensure proper operation of individual components and their interaction as well as non-functional aspects like electro-magnetic compatibility (EMC) testing in an anechoic chamber, power consumption, or thermal aspects.

The competencies of the Institute in implementing avionics have actively been demonstrated with AISat [633] including a low-cost ground segment (see section 3.3.4) and MASCOT [393] (see section MASCOT 3.4.1) and is currently being performed for, e. g., CompactSat II/ Eu:CROPIS 3.3.3 and the micro-satellite S2TEP 3.3.6. Depending on the type of mission certain aspects are sub-contracted or implemented in-house. Only by having deep insight into all the capabilities and the subsystems, cost and time efficient realization of a space mission can be guaranteed. Particularly, a tight vertical integration of various steps from hardware manufacturing to application level software is an essential asset.

Typical space missions have a strict timeline driven by launch dates and strong quality demands with respect to functional aspects and dependability, i. e., reliability, availability, maintainability, and safety/security. In practice these demands can only be met by using iterative development based on well-understood previous designs and heritage that is usually implemented by following a strict development process according to best practices fixed in standards like the ones of the ECSS. In principle from the conceptual Phase 0/A all technical aspects of the subsystems including potential adjustment to a mission, testing, and qualification must be clearly known to smoothly progress with the development to meet the launch in time. However, research on the most advanced aspects of avionics technology typically requires to explore new concepts without heritage where timely convergence to well-defined requirements cannot always be guaranteed. Advanced research must be able to explore tracks with dead ends or solve unexpected technical issues. On the other hand both domains — mission driven development with the resulting experience and research — have mutual benefits cross-fertilizing each other within the Institute.

Instead of considering all the skills and the related avionics subsystems in detail, the following presentation of activities and of results picks development and research for command & data handling (C&DH) as an example.

The key challenges in the C&DH area are the continuous demand for increased processing power from the mission side while keeping strong constraints in reliability and development time.

We explain in section 4.2.1 how deep technical know-how in C&DH with a focus on on-board-computing and software enables research for future technologies. Besides technology advancements, design methodology is a central aspect in the implementation of a reliable system as discussed in section 4.2.2. These qualifications enable the outreach beyond DLR's missions briefly discussed in section 4.2.3.

4.2.1 Command and Data Handling

For research missions the requirements drastically change from one mission to the next, e. g., from a deep-space system like MASCOT to a low earth orbiting system like Eu:CROPIS. These mission level changes have a direct impact on the C&DH subsystem on an architectural, physical, and technological level. This is due to the fact, that in most space systems C&DH by definition communicates with all other subsystems. In addition, reliability and lifetime of the mission directly drive the selection of components with certain qualification grades to be used within the C&DH subsystem. Processing demands from the payload determine, e. g., the architecture to be used as well as the physical and logical interfaces needed. Availability requirements guide the selection of redundancy concepts to be applied. In turn these are drivers for power consumption and physical parameters like size and weight. All these decisions have a direct impact on costs.

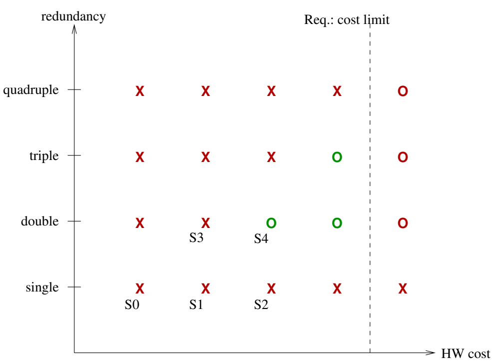


Figure 4.23: Simplified visualization of design-space-exploration [656]: Y-axis denotes hardware cost, X-axis counts the number of redundant components; circles denote technically feasible systems; ×-es denote infeasible systems.

In practice, that means to explore the design-space, i. e., exploring the technically feasible solutions under given constraints for a highly complex system to identify the solution that fits best with the mission under consideration. Figure 4.23 gives a drastically simplified view onto interdependencies considering only the redundancy concept and the hardware cost. Assume that availability and processing demands are only satisfiable by a system that is at least double redundant, i. e., there are at least two processing nodes. Moreover, each component has a fixed cost causing redundancy to proportionally — again in a simplified view — increase the hardware cost. As a result, only systems marked by circles are technically feasible to serve the mission. The cost constraint rules out expensive systems, leaving only those configurations marked by green circles as valid solutions for the mission under consideration.

While this simplistic example shows a structured approach to design-space-exploration, in practice the required data to formulate the search space is not explicitly available in almost all practical cases. Even the enumeration of all parameters and design options which have to be considered as dimensions in the search space is difficult. The full search space is defined by

- system level parameters, e. g., reliability, energy consumption,
- architectural decisions, e. g., interfaces and redundancy concept,
- functional aspects, e. g., computing performance, memory sizes,
- component parameters, e. g., total ionizing dose, device performance, and
- development aspects, e. g., engineering cost, hardware cost, risk.

Highly trained experts solve the problem by iteratively developing a feasible solution based on their knowledge. Thus, a practical approach can rely on building blocks feasible for covering a large part of the design space for C&DH systems in spacecraft. The coverage of the design space increases by allowing for scalability on various levels.

This concept of scalability is followed at the Institute of Space Systems with respect to hardware and software design. The aspect of scaling infers which levels in the system stack of figure 4.24 are to be considered. At the same time redesigning a hardware system depending on design choices at any of those levels may incur a large effort if scalability is not considered upfront. Here, the tight coupling between hardware development and software development is a unique advantage streamlining the overall design process. We follow an architectural concept allowing for scalability in various dimensions while reusing large parts of the design.

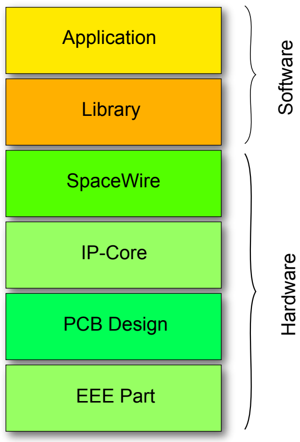


Figure 4.24: Scaling levels. Depending on the parameter under consideration, different levels in the system stack of a C&DH subsystem must be considered.

Hardware

For hardware the architectural concept builds on a base level design [656] shown in figure 4.25. This base level design consists of a CPU, memory, peripherals, multiple communication links and programmable logic. The unit is capable of executing software, storing the software and data, and communicating with outside systems. The programmable logic is connected to the CPU and allows additional peripherals to be implemented. The periphery is presented to the application software through a hardware abstraction layer (HAL), which hides most details about the type and configuration of the hardware as further discussed in section 4.2.1. Internal power conditioning, analog monitoring, and a watchdog allow for autonomous operation and, consequently, fault isolation properties in many configurations.

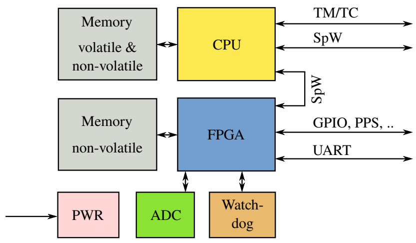


Figure 4.25: Base level design for processing hardware.

The base level design provides a functional unit that can be used for further composition at the architectural level. The instantiation of individual components depends on the application requirements and directly impacts dimensions like cost or reliability. The form-factor is also undefined at this stage as it depends on accommodation requirements and choice of components.

In the following, we will show two implementations of this design. Both implementations provide mostly the same functionality, but for vastly different environmental conditions and are designed for different purposes, but still share the same properties of the base level design. These two implementations are illustrated because they show the flexibility of the design and bridge the gap between commercial off-the-shelf (COTS) and space-qualified systems. Table 4.1 gives a coarse overview of some properties of

	GR712RC + ProASIC3	FPGA Boards
Cost	high	low
Reliability	high	not quantified
Functionality	flight model equivalent	emulation

Table 4.1: Properties of the implementations of the base level design. The two implementation focus on a highly reliable radiation hardened system and at a low-cost system supporting software development.

the implementations. After discussing these implementations in more detail, we provide a view how to use the base level design in a networked avionics system.

Implementation for High Reliability This implementation is intended to be used in a spacecraft. High reliability requirements and the radiation environment are addressed by selecting appropriate electrical and electronics engineering (EEE) parts as well as local mitigation techniques.

This implementation takes the base level design, shown in figure 4.25, and implements it with the following components:

- A GR712RC as CPU
- SDRAM is used as volatile memory
- Non-volatile memory connected to CPU is MRAM
- Non-volatile memory connected to the field-programmable gate array (FPGA) is a bank of NAND-Flash devices
- A single flash-based ProASIC3 FPGA as programmable logic

The GR712RC from Cobham Gaisler is a system on chip (SoC) that is specially designed and built for space applications and their radiation environment. This SoC offers a wide variety of interfaces, ranging from general purpose IOs and UARTs to Consultative Committee for Space Data Systems (CCSDS) telemetry/telecommand (TM/TC) interfaces and multiple high-speed SpaceWire ports. The chip also provides decoder/encoder for error-correcting code (ECC) on the SDRAM and the non-volatile MRAM. Two Leon3FT central processing units (CPU) provide sufficient computing performance for a wide variety of applications.

Using different memories is a consequence of the requirement for high capacity in volatile and non-volatile form.

A single Microsemi ProASIC3 flash-based FPGA is used as programmable-logic. In contrast to anti-fuse based FPGAs, a flash-based FPGA allows the unit to be reconfigured after assembly. Peripheral interfaces are typically implemented as intellectual property (IP) cores on the FPGA. Inside the FPGA, IP cores are connected to an internal bus which in turn is accessed over SpaceWire from the software. In the smallest possible configuration this FPGA only hosts the IP core controlling the NAND-flash.

The design decision about the interface between the SoC and the FPGA was between SpaceWire and a direct connection to the external memory interface of the GR712RC. SpaceWire was chosen being the more generic solution that allows for easier expansion. This choice also converts the FPGA effectively into an embedded remote terminal unit (RTU) and eliminates the dependency to the more specialized external memory interface of the GR712RC.

Implementation for Cost Efficiency This implementation is based on two commercial and readily available FPGA-development boards. This implementation is used for rapid prototyping intended for early software and IP-core development. The underlying hardware is easily accessible while behaving functionally very close to the targeted system. The required toolchains for software development and debugging are almost identical to the GR712RC based implementation.

The structure is shown in figure 4.26. The main building blocks are:

- The first FPGA-board emulates the SoC with CPU, memory controller and basic periphery.
- The second FPGA-board runs components that are placed in the programmable logic device in the base level design.
- Both boards are connected by a SpaceWire connection.
- Additional hardware like NAND-flash memory can be connected via standard pin headers to the second FPGA-board.

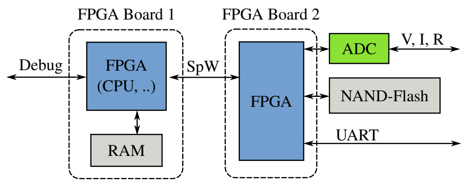


Figure 4.26: Implementation of the base level design on two commercial FPGA Boards.

SpaceWire-based Avionics All requirements on accommodation, reliability, environmental conditions etc. depend on the application, i. e., the specific mission and computing task to be performed. The choice between different implementations of the base level design as well as architectural considerations allow for adaptation to very different requirements.

While a non-redundant or a dual redundant use of the base level design serve standard missions, networking based on SpaceWire allows for more distributed and flexible configurations like the one shown in figure 4.27.

One unit derived from the base level design can basically be put in the position of the on-board data handling system of the satellite bus if the required interfaces are provided by additional RTUs also derived from the base level design. SpaceWire routers may be implemented in the programmable logic of the units or separately to allow for simplified reliability analysis.

Connections to the power system and communication to the ground station are separated from the SpaceWire network. This simplifies failure detection, isolation, and recovery (FDIR). Using dedicated connections guarantees that no other systems can interfere with fault-isolation and safe-mode operations, thereby removing some possible faults that are hard to analyze and address in the design.

The router-based design isolates external interfaces into separate RTUs. This simplifies the development process, in particular for complex specialized interfaces or new interface requirements. The new hardware can be functionally and — to a certain extent — electrically isolated from the core

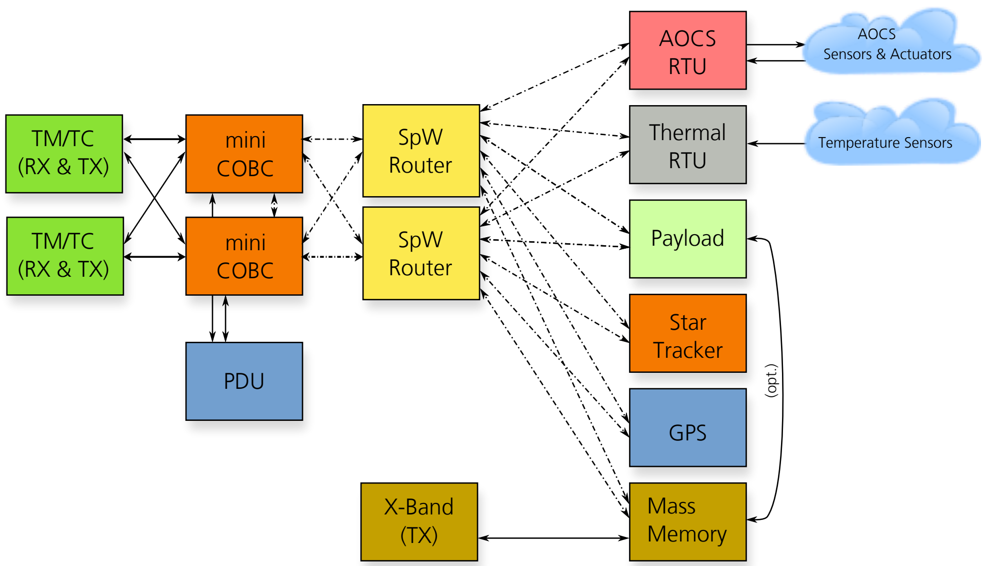


Figure 4.27: SpaceWire based satellite avionics. Units for miniCOBC and RTUs are derived from the base level design. A SpaceWire network allows to easily extend the C&DH system and implement various strategies for redundancy.

computing system. Besides fault isolation this also provides the opportunity to handle the new aspects in an independent development team or in a different organization which is a common scenario for scientific missions.

Software

On the software level appropriate infrastructure serves multiple missions, hardware implementations, and various applications at the same time. This software platform and an extended concept for unified on-board monitoring of spacecraft are discussed in the following.

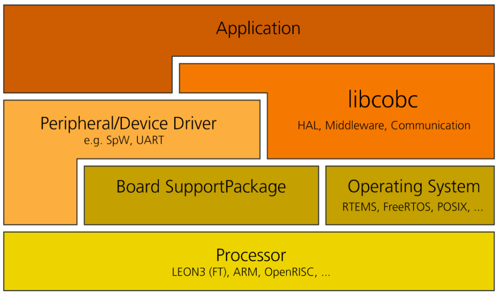


Figure 4.28: Layered software architecture [656]. The dedicated library libcobc provides hardware independent and application independent infrastructure required for space systems.

Software Library On the software level a reusable and portable library allows for lean software development [343]. The *libCOBC*-library provides a flexible, robust and reusable software platform based on the CCSDS/ECSS recommendations. As shown in figure 4.28, the library is located between the underlying operating system (OS) and the board support package (BSP) on the one hand and the applications on the other hand.

The core elements of this platform are composed of a hardware abstraction layer, an operating system layer, a middleware layer, and essential services like a CCSDS/PUS software stack.

The abstraction layers are separated as follows:

Operating System Layer
: To keep the software applications independent from the embedded real-time operating system (RTOS) used and facilitate later re-use, the software does not access the RTOS directly, but through a thin abstraction layer. This RTOS layer provides C++-style access to e. g. the synchronization mechanisms like mutexes and semaphores. Currently, the RTOS layer is ported upon the following systems:

  - RTEMS
  - FreeRTOS
  - POSIX compatible (e. g. Linux)

  The implementation is selected at link/compile time. The setup, initialization and resource management of the corresponding OS are beyond the scope of this library and have to be done by the user during the system initialization. For example, RTEMS requires the user to provide a maximum number of used resources like mutexes or threads.

Hardware Abstraction Layer
: Included in the RTOS layer is a HAL encapsulating access to the processor peripherals, e. g., registers. This allows building the components independent from the actual driver provided for a specific hardware platform. This also makes testing of the components possible in an easy way by exchanging the hardware drivers with mock-up versions. The HAL only includes drivers directly depending on the processor. To give an example, this includes all the built-in periphery of the GR712RC. Built on-top of the interfaces provided by these periphery drivers sits the *driver* module.

Middleware Layer

The simple message passing channel (SMPC) module provides simple middleware for communication between loosely coupled objects living in the same address space. The communication is based on the publish-subscribe paradigm. Topics are the main information source. Components can subscribe to topics or publish data under a topic to distribute it to all connected subscribers. Components can communicate with each other, without directly knowing each other. This generates a loosely coupled system with the possibility of replacing components during testing with mock-ups, allowing to test each component in isolation with full control of the environment.

Additional modules provide further functionality:

CCSDS/PUS Module

The CCSDS and PUS module provides for a spacecraft-to-ground communication according to the applicable CCSDS standards. The module consists of set of classes with the means to send and receive CCSDS TM/TC frames and serialize and de-serialize their contents. Frames can be sent and received in two ways: (1) fully encoded as a bit-stream with attached synchronization markers and Reed-Solomon encoded data using the CCSDS back-end of the processor, and (2) as a data stream for testing over a *Universal Asynchronous Receiver Transmitter* (UART). The PUS module provides a framework to develop applications and services according to ECSS-E-70-41A (PUS). Furthermore it implements some of the PUS standard services.

Time Module

The *time* module provides a time base for all other application handling all aspects related to time and has functions to convert between the local satellite time (relative to the mission start) and *Coordinated Universal Time* (UTC). The offset between the local time and UTC is changeable through telecommands. The time management implements PUS service 9 so that the ground segment can perform a correlation between satellite time and earth time.

Driver Module

The *driver* module contains driver interfaces and implementations for devices often used. This library includes drivers for external devices like the different UART's interfaces which are not directly connected to the OBC. The device drivers only depend on the interface provided by the HAL module and not on the underlying hardware. Therefore the device driver can easily be ported to another processor with similar capabilities by exchanging the HAL.

Monitoring On-Board Unified monitoring is a concept that helps during all stages of the development process [342]. Monitoring of spacecraft is typically done by collecting information on-board and sending this information to the ground station as *Telemetry* (TM). The information is divided into two data types: housekeeping and (science) data. Housekeeping data contains information about the spacecraft's health- and safety-state.

On-board housekeeping data is collected from all spacecraft devices and applications (e. g. for Thermal Control, AOCS, or *Electrical Power System* (EPS)) upon request by a software application called Housekeeper. The information is needed (1) by the on-board surveillance application to trigger FDIR activities, and (2) by the groundstation for real-time-analysis in order to check that everything works correctly.

Gathering housekeeping information on ground is most important to ensure a successful mission. Because of the criticality, the information is frequently sent using the spacecraft's real-time TM. Special emphasis is being put on optimization techniques for the transfer of housekeeping data, because typically the downlink capacity has to be shared among the spacecraft platform (e. g., satellite bus) and payload telemetry.

The telemetry data has to be provided by the applications in a frequent manner to the corresponding TM application; the downlink is done via historical and/or extended TM. Mission engineers and science staff use the data for additional analysis, like proving the quality of science data, instrument and device performance. The monitoring data, which is not already transferred to ground stations, is stored within the mass memory of the OBC until the next contact – typically in a ring-buffer structure where the oldest TM is overwritten after some time.

Beneath the TM capability, extensive debug information is needed in order to do a thorough monitoring of the spacecraft. But at the moment, this kind of information is only used for *Assembly, Integration & Verification/Test* (assembly, integration, and verification (AIV)/AIT) purposes for in-depth debugging of the internal state and control flow of the spacecraft's boot image. Currently there is no technology available, which would provide this information on ground. Debug statements within the software source code are not used during operation and often removed before the launch. Consequently, the observability into the data handling system is extremely reduced during the mission.

A powerful monitoring framework enhances the traditional housekeeping capabilities and offers extensive filtering and debugging techniques for monitoring and FDIR needs.

The monitoring framework offers the following functionality:

- store and forward debug information coming from other applications
- debugging in the development phase and during operation to evaluate software related issues and analyze the overall system
- fixed quota of the number of bytes sent to ground to avoid overflow of debug messages
- data storage in a dedicated buffer, discarded if the buffer is full
- designed by 'separation of concerns' principle
- fully configurable by telecommands in terms of the monitoring target and the level of detail
- very low resource consumption

4.2.2 Designing Reliable Systems

Designing systems and supporting missions requires in-depth technical know-how. Along with this expert knowledge, design methodology and computer-aided design automation are mandatory aspects. Space systems can be seen as an instance of cyber-physical system (CPS), i. e., the coherent view on a technical (cyber) system in the physical environment. Designing reliable CPS is considered as a hot research topic not only for space systems but for CPS in general where reliability aspects include, e. g., aging as well as fault tolerance by design [147]. The inherent difficulty of such design and verification tasks is visualized in figure 4.29 where fault management is done across various levels in the system stack.

The following discussion focuses on some aspects in the design process of CPS, hardware and software, namely functional verification in section 4.2.2, automation for reliability analysis in section 4.2.2, and new techniques to support an engineer in understanding unknown designs in section 4.2.2.

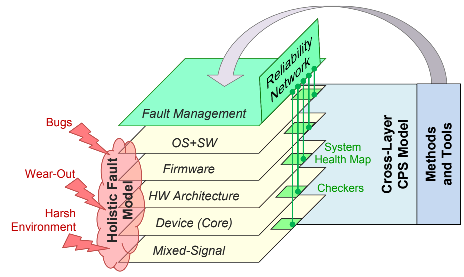


Figure 4.29: Fault tolerance of complex CPS is typically not implemented at a single place in the system. Here, the transition to a holistic fault model proposed in the IMMORTAL Horizon 2020 project funded by the European Commission can improve design and verification efficiency.

Verification

Following the latest methodology for functional validation and verification of software and hardware is a must according to quality requirements and standards. For example, static code checking tools and comprehensive unit testing methodology are used for software, verifying RTL descriptions for digital circuits is done using the Unified Verification Methodology (UVM) at the Institute [318]. Advancing verification methodology for hardware, software, and CPS are research challenges themselves.

One aspect is the functional comparison of digital circuit designs at different levels of abstraction. This is needed because hardware is usually developed iteratively. Starting at very abstract software-like models, the design is iteratively refined by adding structural information, timing information, etc., to a hardware description language that can be used as a starting point for circuit production. Here, comparing very abstract models is still an open research question. The algorithm proposed in [232] makes use of designer's knowledge and automated generalization techniques to compare two abstract descriptions. The efficiency is improved by combining reasoning engines and simulation [233]. Figure 4.30 shows results for the two algorithms.

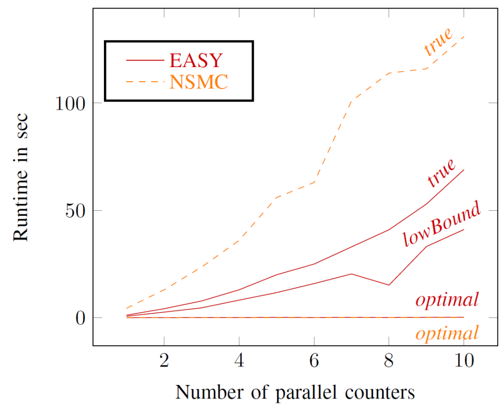


Figure 4.30: Functional comparison of abstract circuit descriptions: NSMC [232] has been improved by EASY [233]: "true" uses no designer's knowledge, "lowBound" uses imprecise knowledge, "optimal" uses perfectly described valid states.

The underlying verification techniques are applicable to software and have even been shown to be useful for CPS [195]. Here, the software-implemented controller is formally proven to keep the physical system in a safe state. As illustrated in figure 4.31 the approach starts from the software program given in machine code for the target processor. This machine code is instrumented to take hardware timing through a platform model $\mathcal{T}$ and the environment through a model $\mathcal{E}$ into account for the analysis using reasoning engines.

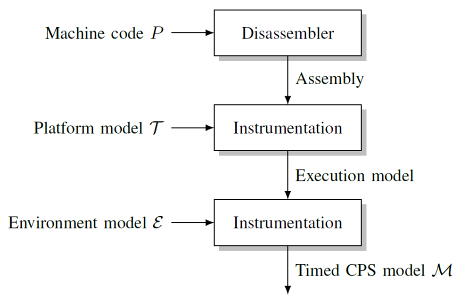


Figure 4.31: Proving correctness of a software controller with respect to the physical environment [195].

Underlying the formal verification techniques are reasoning engines that guarantee (a) to consider the full search space of all possible stimuli, and all possible system states that may be reached and (b) to carry out a mathematical proof of correctness on the system model. Whether this problem is theoretically decidable or not is determined by the logic chosen and the abstraction taken for the system under consideration. Choosing between the large range of reasoning engines is a technical problem itself. The framework metaSMT [93] provides a single front end to very different types of reasoning engines that can then be chosen even at run time of the verification procedure with very low overhead.

Reliability Assessment

As discussed in the beginning reliability features are typically spread across several levels. On the digital hardware level a typical approach is to triplicate memory elements (flip-flops) and vote over the state to harden the system against bit-flips caused by radiation-induced *Single Event Upsets* (SEU). This overhead can be reduced by a holistic approach reducing the hardware task to the detection of a SEU while using software to compensate for the error.Further optimization improve the performance of the resulting digital hardware [153]. Software hardening and hardware hardening can be traded one against the other. For small pieces of software this design space exploration can be formulated as an optimization problem [209].

However, at the end a design must be verified to fulfill requirements for reliability and fault tolerance [683]. One approach are simulation-based approaches applied at different levels during the design, either when only software is available [151] or after the hardware is known [151]. This is then done by applying stimuli to a model of the design and injecting faults to analyze the system's behavior under those faults. However, this provides only rough and – depending on the type of system model used – even misleading results as well as being inherently incomplete as only a few stimuli and a few faults can be considered during simulation.

Again reasoning engines can be employed to formally verify whether the system operates correctly under all faults, all stimuli and in all system states. Besides the system model this also requires a fault model. The analysis of SEUs at the level of digital circuits can be automated and yields precise results [180]. To consider further effects due to intermittent faults that must be modeled below the digital level, the circuit model must be extended to contain timing behavior [231]. Here, further algorithmic improvements are required to handle relevant circuits in acceptable run times [229].

Understanding Designs

While all these techniques directly and smoothly integrate with today's development and verification flow as well as tool automation, the task of understanding a design that is provided by some third party, through legacy blocks, or by other team members is hard and typically not automated at all. While in the software area this problem has been addressed under the terms reverse engineering, software maintenance and even software understanding, the problem has largely been ignored for descriptions of digital hardware. Nonetheless certain support is possible.

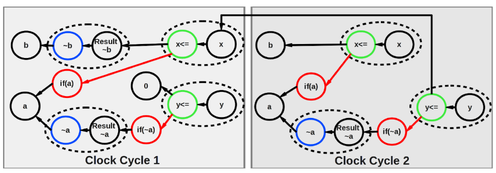


Figure 4.32: Recording the simulation of a use case. The dynamic dependency graph shows the interrelation between executions of statements, their effects and their causes.

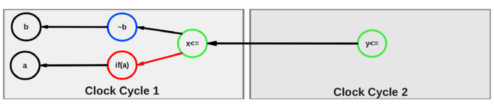


Figure 4.33: Reducing the recorded dynamic dependency graph. Given that the designer is only interested in certain outcomes and their causes as well as certain driving control stimuli, the graph can be drastically reduced.

Feature localization is one example. Given some use cases that execute certain functionality on the design under consideration, the goal is to identify which parts of the design description implement this functionality. Using dynamic analysis methods, very good hints can be automatically determined and provided to the designer [80]. Technically, the use case is simulated and recorded as shown in figure 4.32. By reducing the recorded information automatically the amount of relevant information is reduced as illustrated by Figure 4.33. The designer views the highlighted source code to identify which statements implement a feature. This approach is much more efficient than asking the designer to browse through the code manually or stepping through the code using a debugging tool.

Other tasks that have been automated are the analysis of the latency between providing data and receiving an answer [43] or creating the automated connection between various IP-cores of a single circuit [201]. Particularly, the localization of bugs has been studied quite extensively [34, 170, 36].

4.2.3 Outreach Beyond DLR Missions

To further drive the research in technology and methodology, the Institute of Space System does not only engage in implementing missions, but also in research projects like the projects MaMMoTH-Up and IMMORTAL funded within Horizon 2020 by the European Commission. While MaMMoTH-Up considers improvements in the telemetry subsystem for a launcher by online adaptivity, the IMMORTAL project seeks to improve the verification and design methodology with a particular focus on reliability.

The know-how is returned to the community by engaging in standardization bodies like the Space AVionics Open Interface aRchitecture (SAVOIR) focusing on the avionics architecture as well as CCSDS working groups on communication aspects.

Continuously ongoing research topics are the use of COTS for reduced costs and improved processing power, as well as improvements in the power subsystems using advanced battery technology or wireless communication technology during integration, test, and qualification as well as on-board the space system. Along with the S2TEP platform a model based development flow will be created that includes also C&DH rooted in the foundations provided by Eu:CROPIS. A highly scalable networked on-board computer architecture will serve as underlying hardware platform. Most of these aspects must be aligned with appropriate methodology for design and verification in the avionics design as well as the overall system design, interfacing to other domains, like guidance, navigation, and control or structure, quality assurance and testing.

4.3 Planetary Exploration

The Institute's main focus in the area of planetary exploration is research and development for landing and return systems as well as instrument and payload carriers (refer also to sections 3.4.2 and 3.4.1) for on-surface operations. This comprises the development and qualification of the respective components and subsystems and its operations support. These main areas and their associated tools, methods and test facilities are described in this section.

4.3.1 Landing Technology

Future exploration missions impose demanding requirements towards the access by vehicles to scientifically interesting sites on planetary surfaces. These stem particularly from the need of more flexibility in site selection, improved payload to vehicle mass ratios and higher mission success probabilities. The used landing technology interacts strongly with the planetary environment given by its atmosphere (if applicable) and ultimately its surface. To anticipate this environment during the design, development and verification is the particular challenge in this field. This is enabled with a combination ground- or laboratory based tests, flight tests with (terrestrial) demonstrators and high-fidelity and validated simulation tools as well as careful post-flight analysis of actually flown missions. In the area of planetary landings, the Institute of Space Systems is focusing on the design, development and verification of landing (gear) subsystems of landing vehicles. This work is based on experimental, numerical and analytical methods

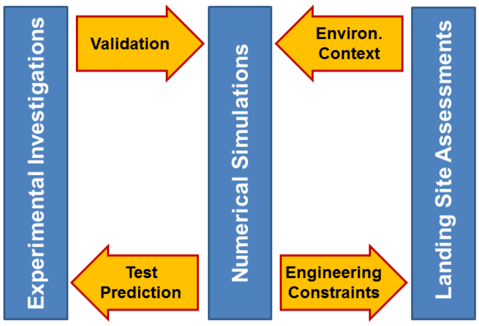


Figure 4.34: Touchdown dynamics, performance and safety: relations between experimental, numerical and analytical investigations.

Figure 4.35: Rosetta lander Philae suspended in the LAMA facility in a active weight-offloading test mode.

for the investigation of the touchdown dynamics of these landing systems. The interrelation between the three domains experimental investigation, numerical simulation and landing site assessment is outlined in figure 4.34 below. Experimental investigations and numerical touchdown simulation form a test prediction / validation cycle. The interaction between the validated simulation and the landing site assessment represents the vehicle-terrain-interaction in the mission planning and operations stage [675].

Experimental investigations: The core element for experimental investigation is the Landing & Mobility Test Facility (LAMA) facility, which supports lander drop tests or touchdown testing and rover locomotion testing under an apparently reduced gravitational environment using an active off-loading device. A more detailed description of LAMA is given in section 4.3.4 below or in [715].

The facility has been used for system level tests of legged landing systems represented by a modular lander engineering model [333] for mission scenarios to the Moon and Mars such as the ESA Lunar Lander or the Mars Precision Lander. Another landing system retested is the Rosetta lander Philae (figure 4.35, [130]). Experimental and numerical investigations informed the landing site selection process of that mission. Philae also represents a touch down system concept developed for small body landings.

Numerical simulations: usually not all relevant environmental properties of the target landing site can be provided in one single and complete test, any verification approach has to be supported by adequate numerical analyses. Thus, another key topic for the verification of the touchdown performance of a landing system is the accurate analytical and numerical representation of the flight system, its touchdown conditions and the landing site. In this area the research focuses on the development of high fidelity engineering simulations of the vehicle-to-terrain/soil interaction. Such high-fidelity engineering simulators, based on multi-body dynamics software tools, are available for multiple configurations. These configurations include three and four leg variants and comprising cantilever or inverted tripod gear kinematics. The models are parametrized and scalable. Own simulation model libraries are set-up to provide model elements unique for the lander-terrain interaction dynamics. A numerical model for the Rosetta lander Philae (figure 4.36) was developed in conjunction with the experimental investigations.

The landing site assessment and characterization focuses on the development of landing site assessment methods and tools to provide terrain models for engineering simulations. In return landing system performance limits and landing gear constraints are mapped onto cartographic landing site representations to support the landing safety assessment. Algorithms have been developed to integrate topographic data from geographical information systems and landing performance data from the landing dynamics analysis into joint map products [925].

The analysis scheme was applied on system level to mission studies such as the ESA Lunar Lander (Phase B1) and the Rosetta lander Philae (figure 4.37, for the landing site selection process).

The near and mid-tern goals for the landing technology portfolio aim at the development of energy absorbing structures (other than landing legs) and shells for small probes and pods. Developments regarding these elements follow the same test, simulation and assessment scheme as described above. Improved and/or complementing technologies for small body landers in the succession of Philae and MASCOT will be addressed and infused into related mission acquisition. Assessments of deployable drag devices as a means to lower the ballistic factor of entry, descent and landing systems are underway. This domain – pending final assessment and decision – would close a gap between the implemented landing technology in the Institute of Space Systems and the "Entry" domain covered by other German Aerospace Center (DLR) institutes.

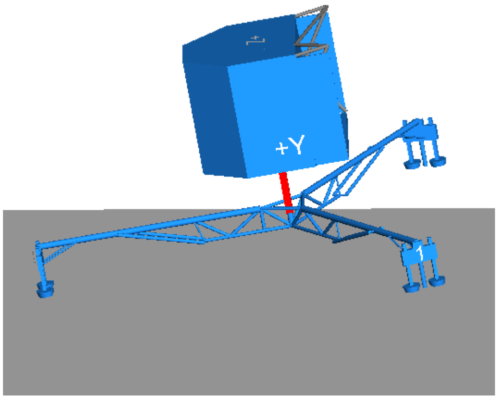


Figure 4.36: High-fidelity touchdown simulator of the Rosetta lander Philae used for landing performance and touchdown safety assessments [129].

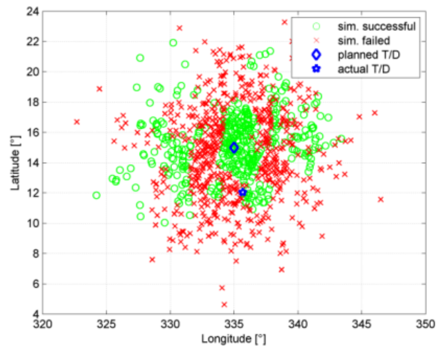


Figure 4.37: Rosetta lander Philae: dispersed landing positions failed/successful attribute obtained from touchdown dynamics simulation [129].

4.3.2 Robotic Exploration of Extreme Environments

The Institute is a major partner in the Helmholtz Alliance Robotic Exploration of Extreme Environments (ROBEX) funded by the Helmholtz Association.

ROBEX brings together space and deep-sea research from sixteen institutions distributed from all over Germany. The institutes are jointly developing technologies to improve the exploration of environments with extreme conditions such as deep sea, polar regions, our Earth's moon and other celestial bodies. The different scientific questions regarding the Moon and in the deep sea are addressed both by a similar scientific methods as well as with a similar or joint technological solutions. The development of similar core architecture from a combination of a stationary system with one or more mobile elements and deployable long-term stations or observatories ("remote units") was defined in the initial project phase. The stationary system as a central part shall supply energy to the other elements and act as data exchange node. The mobile systems perform the actual scientific exploration in the deep sea or on the Moon and deliver the remote units [682]. The collaboration between both communities manifested also differences which provide potential for cross-fertilization.

- Deep sea exploration: conducts regularly and frequently excursions and missions. This leads to a very broad actual experience and knowledge base how to operate exploration assets and to implement technical developments. The space community lacks of such regular and frequent experience and profits from infusion from the deep sea community especially in the area of operating procedures.
- Space exploration: the use of systems engineering and mission analysis tools are more widespread in the space community due to the necessity to simulate and optimize vehicle performance, mass and energy consumption for its launch, cruise and deployment in the planetary environment. As this aspect becomes more important as well in the ocean environment for autonomous and long-range vehicles or stations these tools, methods and standards become increasingly important within that domain.

The research of the alliance is organized in four main areas: (i) the first addresses the central research questions that are specific for the two environments considered in this alliance, (ii) the second – named ˝system infrastructure" – is headed by the Institute of Space Systems and focuses on landing systems and their role in a post-landing phase to deploy, support and sustain surface assets. Furthermore, development work is done on modular and autonomous surface stations in line with MASCOT-type small landers/stations. The third area (iii) addresses the development of mobile robots and manipulation systems while (iv) the fourth area addresses payloads and scientific instrumentation. Overarching activities of all partners are the "demonstration missions and technology transfer" and "training and education".

Thereby, the area "system infrastructure" is the supporting element between a multitude of instruments and the user/scientist and is also realizing a connection between the user and the harsh operating environment. Every scientific in-situ experiment and also probe sampler need such supply infrastructure in addition to the actual front-end instrument, which delivers the instrument to its dedicated target and provides support functions such as realizing power supply, data exchange, commanding as well as mechanical and thermal support. Three dedicated work packages investigate and develop solutions in this area which are based on commonalities identified in a preparatory phase.

- Re-configurability, modularity and standardization: A common goal in both communities is to gain a higher operational flexibility at lowered cost for system development, implementation and operation. A means to do so is to aim for higher equipment communality and to set-up product platforms or families. This enables to share and exchange equipment such as sensors, effectors or vehicle subsystems. New technologies can be implemented part-wise without the necessity to retire a complete existing asset. The vehicle or system is thereby adapted to a different task or mission.
- Navigation and communication infrastructure: Several smaller robots and/or surface units instead of single, large and complex systems are deployed for exploration tasks in the same sense to reduce costs and increase flexibility. However they require in return a precise relative location to each other. Additionally, scientific discoveries and exploration takes place with ever higher spatial resolution of the used sensors or tools. The geo-referencing of such in-situ gathered data requires precise and accurate navigation data of the carrying vehicle. This work package focuses mainly on providing navigation infrastructure for that purpose.
- Power infrastructure: Exploration assets – both in a space and deep sea environment – are typically deployed in remote sites and have to bring their own power source which is limited by the overall vehicle volume and mass budgets. This demands efficient energy management and transfer to the deployed sub-units. The robotic units operate in a contaminated environment – salt water / floating particles or dust particles from the lunar surface. Such an environment self-suggest contact less transfer of energy (and data).

The developed technology will be deployed and implemented in a real mission context (deep sea) and an Earth analogue moon mission (space) [703] respectively in the final year of ROBEX in 2017.

With regard to the Earth analogue mission, the first task was to translate and downscale the ROBEX Lunar Mission concept into an analogue mission scenario, which includes the demonstration of the main scientific and technical challenges, which are faced on the Moon. The chosen scenario features the deployment of a seismic network as an example for multi robotic asset operations and network science (figure 4.39).

During the "analogue mission space", all key elements of the mission shall be demonstrated, both from the science side and the technological side, i. e., mobility and navigation, communication, deployment, positioning and manipulation of the seismic packages, and drive-by-geology. The major objective of the test will be to demonstrate that the intended science objectives can be met with the developed technology, and that the level of implemented autonomy, together with limited human intervention for science decisions, is suitable and flexible enough for high-quality science results. Furthermore some key elements of the robotic main equipment, such as the rover's locomotion sub system, payload deployment and lander-rover-interaction, autonomy and long-term measurements shall also be tested against defined technological requirements, since the analogue mission is a field test and shall be used to increase the TRL level of such components.

The project is currently in the stage of hardware assembly, integration and test. The selected Earth analogue test site is the volcano Mt. Etna in Sicily/Italy. Preparations for the deployment of the field test and its supporting logistics are underway.

Figure 4.38: Remote unit (seismic station) after deployment by rover during pre-test at Mt. Etna.

4.3.3 Planetary Mobility

Mobility on planetary surfaces is crucial to fulfill scientific requirementrs with respect to spatial coverage (sampling along certain traverses driven by rovers), functionality (setup of seismic networks) or mitigation of landing inaccuracies (measurements of spots missed by the landing ellipse). Thus, the Institute of Space Systems maintains both analytical, numerical as well

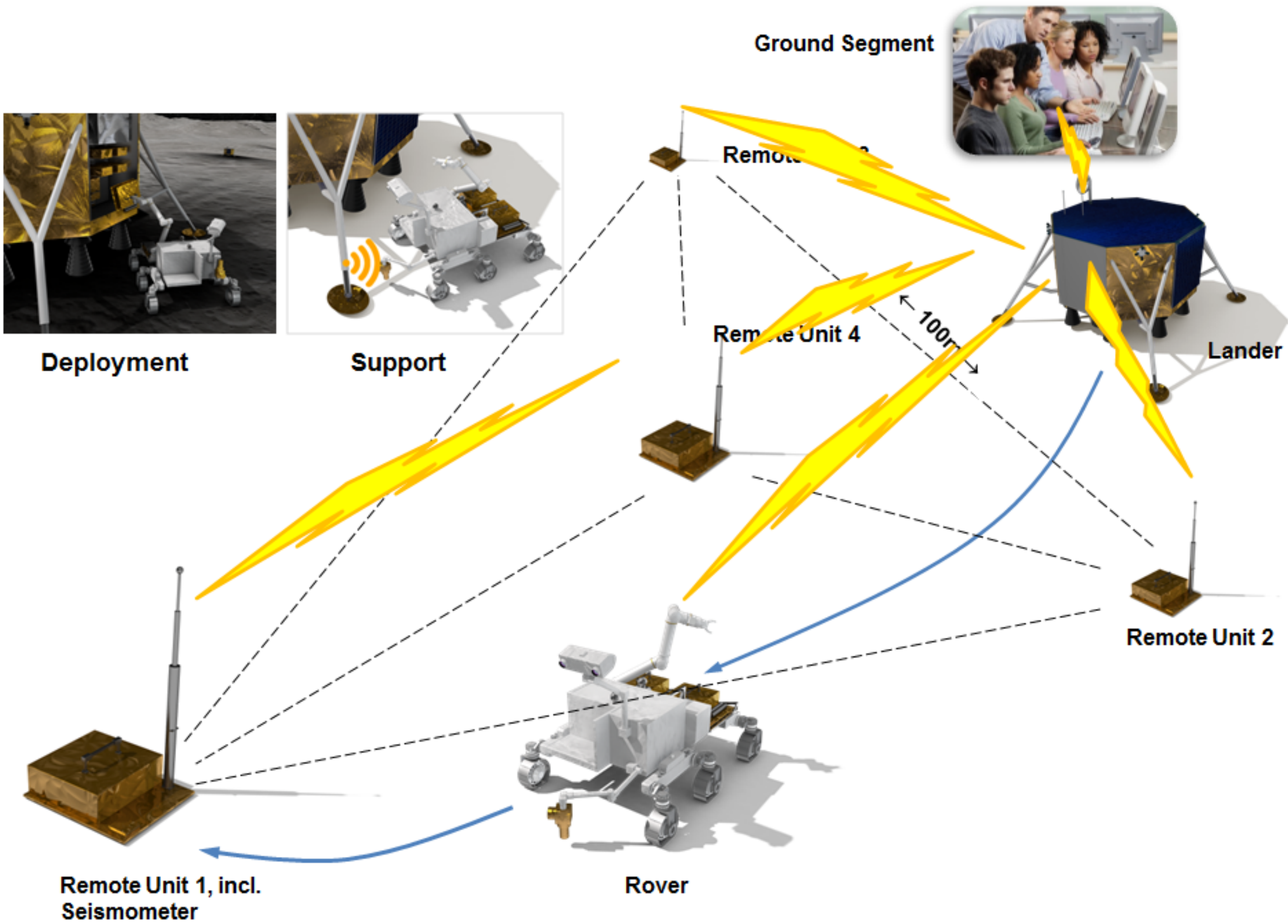


Figure 4.39: Architecture view of ROBEX lunar seismic network; lander element and remote units provided by the Institute of Space Systems.

as experimental capabilities to cover this field of research and technology development.

The Institute has carried out a number of studies with respect to planetary mobility and soil mechanics, mostly with focus on wheeled locomotion. Here, the ESA ExoMars mission was the main driver for scientific and engineering questions.

The ExoMars project was the first flagship mission of the AURORA program. As of 2007, the mission included a rover carrying the Pasteur payload, and a Mars orbiter for remote sensing and relaying the rover data to the Earth, and for performing an automatic rendezvous demonstration with a dummy orbiting sample. This mission was not only to search for life on Mars and return valuable scientific data but demonstrate Europe's ability to land large masses on the surface of Mars and master technologies required for automatic rendezvous (applicable to Mars Sample Return (MSR)). The ExoMars scientific objectives were (as of 2007):

- To search for signs of past and present life on Mars by deploying a mobile exobiology instrumentation package on the Martian surface and performing in-situ soil sample analyses
- To identify and characterize possible hazards to human exploration
- To enhance the knowledge of the Mars environment

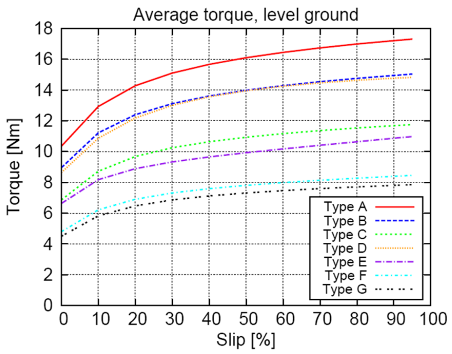


Figure 4.40: Exemplary output of traction prediction wheel model TPM. Different types of soils have been investigated, designated by "type A – G".

The phase A study of the ExoMars mission was kicked-off in September 2003, DLR was participating since then. DLR Bremen joined the locomotion subsystem work package in 2007 and contributed to the project up to Phase B2X2 in 2011. The locomotion system consists of six flexible wheels, all independently driven, connected by a passive double-rocker bogie suspension system to attachment points either side of the center of the rover body.

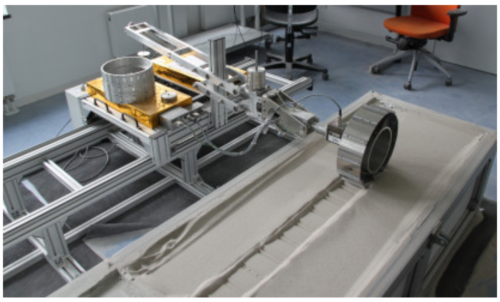


Figure 4.41: Single wheel test facility at DLR Bremen.

The Institute has been involved in the ExoMars project as subcontractor of RUAG Space (formerly Oerlikon Space), Switzerland. It developed a traction prediction model (TPM) to provide estimates of wheel performance both for rover design purposes as well as for strategic and tactical mission planning (see figure 4.40). In the first case, the model is used stand-alone application (Fortran source code), in the latter case, the model is used as subroutine for RUAG's MATLAB code comprising a full rover simulation. A number of quantities are be calculated by the wheel model, for example:

- Wheel sinkage (single wheel and multiple pass, i. e. rover)
- Wheel torque (single wheel)
- Drawbar pull (single wheel and rover)
- Lateral forces (single wheel, angle of attack not zero)

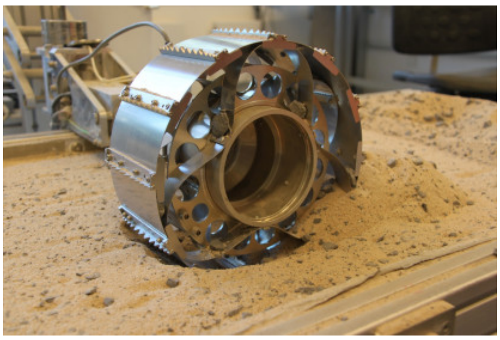


Figure 4.42: ExoMars phase B2X2 wheel in single wheel test bed at DLR Bremen.

The uncertainties of the TPM predictions can be estimated to be 10 – 15 % and 20 – 25 % for rigid and flexible wheels, respectively, on Martian soil simulant type Mars Soil Simulant (MSS)-D (this has been the major reference soil type in phases A – B2). This value has been derived from phase B1 measurements on the single wheel test facility.

Single wheel as well as rover tests have been performed between 2007 and 2011 to validate and improve the soil-wheel interaction model. For this purpose, a Single Wheel Test Facility (SWT) has been utilized, see figure (4.41). The facility allowed tests of planetary or terrestrial rover wheels on different types of soil. Different types of soil have been used, including terrestrial quartz sand as well as two different fine-grained Martian soil simulants. These three soils differed significantly in behavior and composition. This single wheel test bed has been developed in the course of a DLR

Cologne diploma thesis and was situated in Bremen for four years. After this time, the facility returned to ESA and has been disassembled.

The wheel was driven by a sled through the soil bin. The soil bin itself was 300 × 60 × 50 cm. It was possible to divide the bin into two parts filled with two different types of soil to allow efficient testing of different types of soil. All relevant locomotion parameters were recorded with 10 Hz frequency during a test run:

- Drawbar pull (0 – 100 N)
- Torque (0 – 30 N)
- Sinkage
- Wheel load (0 – 200 N)
- Wheel and sled velocity (0 – 100 mm/s)
- Slippage (-100 – 100 %)

The slippage is commanded by differential speeds of the sled and the wheel. Tests with an unpowered wheel have been possible as well.

For acquisition of reproducible test results, DLR Bremen developed handling procedures to refurbish the soil after a test run has been completed. This included loosening (e. g. by raking) of the soil as well as well-defined compaction (e. g. by loaded drum) to provide a well-known soil state to the next test run.

Impacts of wheel stiffness have been investigated independently from the ExoMars project and published on conference proceedings [380]. For any future planetary rover mission featuring wheeled rover vehicles, it is recommended to do a careful trade-off between the gain in performance and the potentially higher mass and complexity of flexible wheels in comparison to rigid ones. Also, the feasibility of inverse traction prediction modelling, i. e. inferring the soil parameters from wheel performances has been studied and published [375, 48].

In 2009, the Institute of Space Systems has supported the “Free Spirit” campaign of National Aeronautics and Space Administration (NASA) and Jet Propulsion Laboratory (JPL) to make effort to free the Mars Exploration Rover (MER)-A rover (“Spirit”) from sandy terrain. One of her six wheels has been almost buried in soft sand since end of April 2009. It has supported the analysis and mission planning by single wheel tests with the goal to mimic the situation on Mars as close as possible. For this purpose, a engineering model type rover wheel of MER has been buried in soft sand and loaded with a realistic wheel load. Different angles of attack and driving velocities have been evaluated and analyzed. A promising driving approach (large angle of attack, low angular velocity) has been proposed to JPL for their mission planning. Unfortunately, the rover could not be retrieved from the sandy terrain in the end.

Figure 4.43: Mars Exploration Rover (MER) wheel in single wheel test bed, representing the situation of MER-A during 2009. Despite extended studies and laboratory test campaigns to optimize the driving and locomotion strategy, the rover could not be retrieved from the sandy terrain.

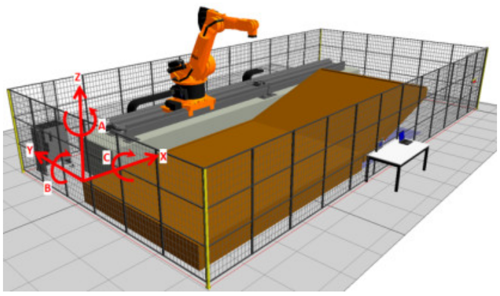


Figure 4.44: Overview of the Landing & Mobility Test Facility: a robotic arm supports handling and weight-offloading for vehicle-terrain-interaction tests in a soil bin.

4.3.4 Landing and Mobility Laboratory

The Institute has deployed the LAMA facility to test of landing vehicles and exploration rovers [715]. Objectives are to determine and investigate experimentally on system level the dynamic behavior of planetary vehicle, being either roving vehicle or lander in their very final landing at touchdown when ground contact occurs. Test objects and models used to represent such planetary vehicle shall have a similar dynamical behavior, identical stress level on load or shock absorbers and landing gears or wheel suspension and roving vehicles locomotion.

Figure 4.45: Lander engineering model after drop test into the soil bin.

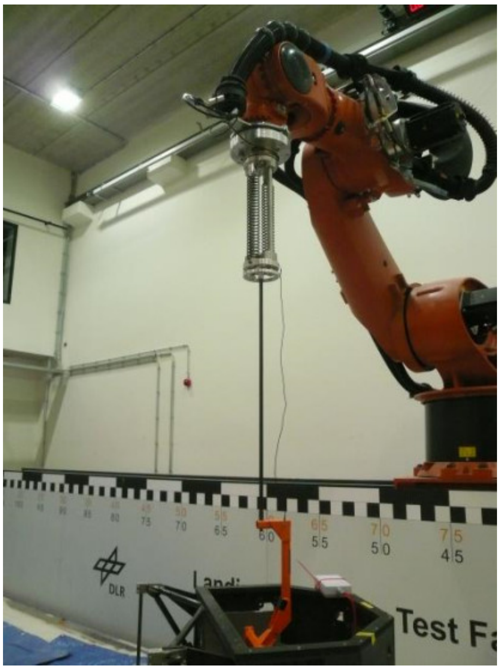


Figure 4.46: Weight off-loading suspension coupling the Rosetta lander Philae to the robotic arm.

Figure 4.47: Single leg test stand with full-scale ESA Lunar Lander leg engineering model.

The key elements of the facility (figure 4.44) are a robotic arm for the test object handling and a soil bin to contain a planetary surface set-up. The main reason for using an industrial robot is to provide a fully active, self-supporting and in the use cases highly flexible device for setup and maintaining load scenarios and test object handling. A large variety of additional off the shelf hardware and support such as software and sensor systems are available from service suppliers from the industrial automation branch. The nominal static load bearing capacity of this robot is 500 kg. It sits atop a rail track system allowing a lateral travel distance of 10 m. The soil bin contains the planetary soil simulant and, if needed, other terrain features. It has overall dimensions of 10 m × 4 m. A section of 4 m × 4 m is tiltable to provide slopes between zero and 30° in steps of five degrees. The soil depth is 0.25 m in the ramp area and 0.5 m in the non-tiltable area.

The facility offers two major test modes: These are (a) the drop test mode and (b) the weight off-loading mode. Both modes require a dedicated element which provides the link between robot hand flange and test object. This is a suspension device especially developed and patented for the weight offloading mode and a commercial off the shelf gripper to release an object in the drop test mode.

- Drop Test: The release mechanism for model drop tests uses an off the shelf pneumatic gripper mounted to the robots hand flange. The work pressure to operate the gripper is directed by a manifold valve which receives its lock/release signals from the robots real-time controller. The gripper's jaws engage into a dedicated form fit interface mounted on the test object. An example of a drop test with a lander engineering model is shown in figure 4.45.
- Weight-offloading: The test object suspension has to fulfil three functions: (i) transmit a (quasi-)static reduction or weight offloading force, (ii) provide sufficient degree of freedom to the test object and (iii) decouple the dynamics of the robot and the test object from each other. The build-up consists of the elements visible in figure 4.46: the upper flange plate connects the suspension to the force-torque sensor in the robot hand and linear guide pillars are limiting the degree of freedom to the vertical or "gravity axis". A set of tension springs has to be selected dependent to the test object mass. A carbon fiber beam provides the lateral degrees of freedom and is attached to the lower attachment plate.

LAMA is complemented by component level test rigs such as the single leg drop test stand (figure 4.47).

4.4 Cryogenic Fuel Handling

The knowledge and understanding, as well as the application of intelligent propellant management technologies is one of the key competencies for the successful design and the realization of future advanced cryogenic upper stage systems. The aim is to meet future market demands concerning more mission flexibility such as multiple restart options paired with long duration ballistic flight phases.

Main functions of the propellant system are: to guarantee the bubble free supply of propellants at the specified thermodynamic conditions during the complete mission; to minimize the boil-off losses due to evaporation particularly during the ballistic phases; to ensure no loss of propellants during venting; to avoid critical sloshing phenomena and to avoid critical pressure variations generated by heat- and mass transfer processes at the gas/liquid interface. Therefore, the availability of a cryogenic laboratory is of fundamental importance to develop, test and consolidate various propellant management technologies. In order to support the European launcher industry and to secure and to enhance the upper stage competence in Germany, the DLR decided to establish a Cryogenic Laboratory (Cryo Lab) at the Institute of Space Systems in Bremen and initiated a German research cooperation, to coordinate and perform research on advanced cryogenic upper-stage technologies. The Cryo Lab and selected research activities of the German research cooperation are described in the following

4.4.1 Cryo Lab

The mission of the Cryo Lab is to provide conditions that enable scientific research and technical development of propellant management technologies by using the real cryogenic propellants liquid hydrogen (LH_2), liquid oxygen (LOx), and liquid methane (LCH_4). Additional testing is feasible with storable liquids and with liquid Nitrogen. The handling of flammable and oxygen-displacing gases requires a certified safety concept and enforces strict safety rules. The Cryo Lab is designed to provide a maximum of flexibility and offer a wide range of possibilities for experimentation [378].

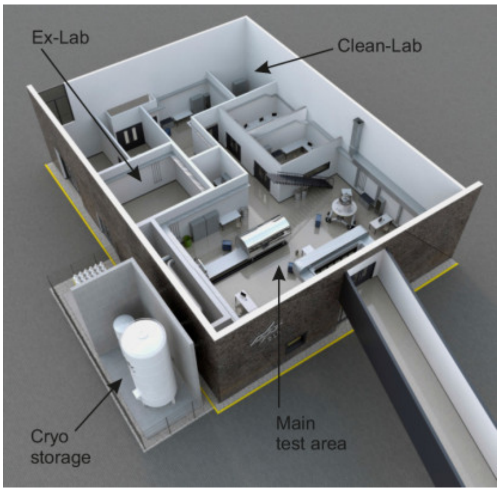


Figure 4.48: Sketch of the Cryo Lab.

Concept

The Cryo Lab is separated into different functional areas: the cryogenic supply system, the main test area, an explosion protected laboratory, a pre-integration room, a cleaning laboratory, a measurement laboratory, a workshop and a control room. The following technical gases are available: nitrogen (N_2), hydrogen (H_2), oxygen (O_2), methane (CH_4) and helium (He). The gases are stored in high pressure bundles. In addition methane can be liquefied on site. As a special feature the Cryo Lab provides as a separate room an explosion-protected laboratory (Ex-Lab). The Ex-Lab can be completely flooded with inert gas in order to run experiments with LH_2, LOx, or LCH_4. By external supply of nitrogen, the oxygen content in the Ex-Lab can be reduced below ignitable concentrations. By a slight pressurization of the Ex-Lab, the inflow of Oxygen can be prevented. In addition, the electrical system of this room is of an explosion protected design. The experiments are controlled outside from a control room. As further option the Hexapod can be operated in the Ex-Lab to perform sloshing tests with critical cryogenics.

Test Facilities

The Cryo Lab and the test equipment are designed specifically for the research and development of cryogenic propellant management technologies. As test equipment, among various cryostats, a vacuum chamber and a movable platform with six degrees of freedom (Hexapod), useable for the investigation of sloshing phenomena, are available. The test facilities are equipped with various measurement systems and sensors, to be able to measure forces, pressure, temperature, free surface position, flow rate, fill level and to control the experiment by video. An appropriate test environment close to the upper stage application is given by the cryogenic tank demonstrator provided by Airbus Defence & Space Bremen serving the needs for future upper stage developments.

Two cryostats for liquid nitrogen (120 l) and liquid hydrogen/oxygen (60 l) are available. The cryostats can be operated up to 5 bar tank pressure. One cryostat of each type has an outlet flange at the bottom, thus two cryostats can be connected to realize flow through experiments. The LH_2 cryostats are equipped with an additional liquid nitrogen (LN_2)-shield and multi-layer insulation (MLI)-insulation to minimize undesired heat flux. In the context of an ESA technology development program for advanced cryogenic upper stage technologies (CUST) we successfully determined screen characteristics for the use in propellant management devices. The bubble point behavior of various metallic screens material and screen elements are tested and physical correlations were verified. In a further project the flow resistance of metallic screens as a function of the Reynolds number was successful investigated [694].

A vacuum chamber will be used to perform experiments and tests with cryogenic media under defined and reproducible thermal boundary conditions and to simulate the orbital environment. The vacuum chamber is equipped with a shroud system which can be cooled down to liquid Nitrogen temperature to minimize undesired radiation effects. In the vacuum chamber, a vacuum pressure of 10^{-5} mbar can be realized. The vacuum chamber is connected to an exhaust system, so that in case of a leakage inside the chamber the forming flammable gases can be safely disposed.

The hexapod system is a particular test facility to generate defined movements with six degrees of freedom and is equipped with an experiment platform for mounting the payloads. The platform is connected via six struts with integrated force sensors. Thus, the acting forces on the payload can directly be measured during the test runs. In addition to the load cells, the experiment platform is equipped with acceleration sensors. With the measured quantities of forces and accelerations, it is possible to perform meaningful analyzes and further supplementary studies. The hexapod can be additionally equipped with a rotatable experiment platform. The combination of hexapod and rotatable platform provides the possibility to superimpose a lateral motion with a rotational motion.

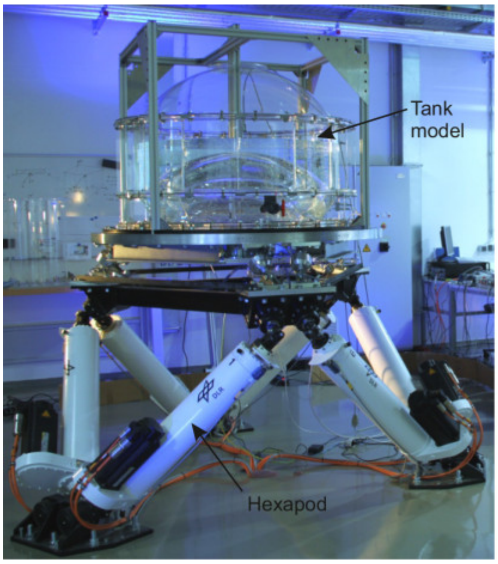


Figure 4.49: Hexapod equipped with tank model provided by EuroCryospace.

With the hexapod system, the Institute carried out successfully sloshing experiments with tank models of launcher systems. In the frame of the development of the Ariane 5 Midlife Evolution (A5 ME) development tests with scaled tanks made of acrylic glass has been successful performed. In isothermal sloshing experiments with water the damping and frequency behavior in dependence on the fill level and tank shape with common bulk head could be determined with high accuracy.Non isothermal sloshing behavior has been investigated by using a cryogenic tank demonstrator, partly filled with liquid nitrogen. Coupled phenomena under the influence of the acting heat and mass flows have been successfully tested in the ESA future launcher preparatory program (FLPP3). Next step and challenge will be the investigation of sloshing phenomena with liquid hydrogen.

In addition to the hexapod, the Cryo Lab provides a separate tilt table on which the rotatable platform can be operated in a similar fashion. The tilt table can be tilted up to 20° while providing rotation rates of the rotatable experiment platform up to 60°/s. The experiment platform is equipped with a power supply and a data acquisition system located on the platform. Using this technical solution, the experiment and the sensors can be supplied with the necessary energy during the operational mode of the rotatable platform. The recorded measurement data and control data are wireless transmitted to the control computer in the Cryo Lab during the experiment.

The Institute successfully performed draining tests with scaled tank models of the Ariane 5 Midlife Evolution (A5 ME) for different mission profiles (spin/no-spin). The remaining non-usable amount of propellant in the tank is determined in dependence of inclination, spinning rate and flow rate. The results enable a better exploitation of the loaded fuel quantity and thus offer the possibility of increasing the payload capacity [367].

The mission of the Cryo Lab is to provide the required opportunity for large-scale cryogenic cold tests on propellant management technologies supplemented with the necessary scientific know-how. General research objective is to develop the necessary enabling technologies for future space missions, including zero boil off systems (ZBO) and long term storage of cryogenic media.

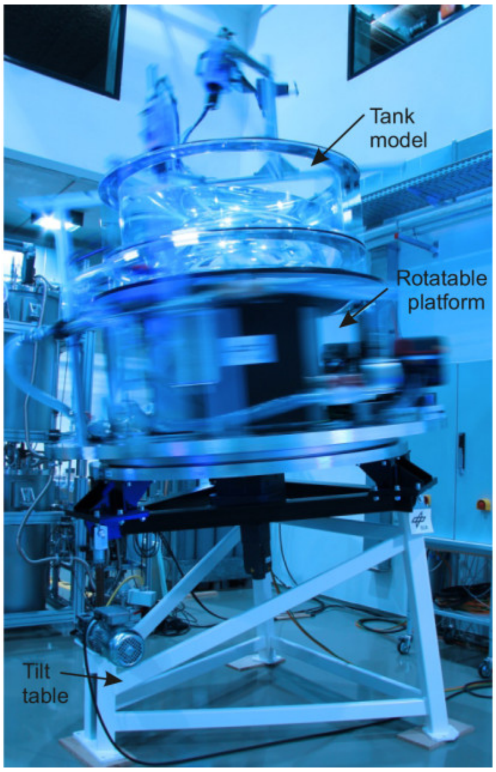


Figure 4.50: Tilt table equipped with tank model provided by EuroCryospace.

4.4.2 Research Cooperation on Upper Stage Technologies

Advanced technologies for upper stages are one of the primary German investigation areas. In preparation of the development of new European advanced cryogenic upper stages, the need to investigate related advanced technologies has been identified. A German research cooperation was initiated, to coordinate and perform research on advanced cryogenic upper-stage technologies, with potential application to programs such as ESA's Future Launcher Preparatory Programme (FLPP), stage system studies and national activities. The partners, involved in selected research areas, are Airbus Defence and Space (Airbus DS), MT-Aerospace, various DLR institutes: Institute of Aerodynamics and Flow Technology, Institute of Composite Structures and Adaptive Systems, Institute of Space Propulsion and the ZARM at the University of Bremen. All research work is coordinated by DLR Institute of Space Systems in Bremen. The propellant behavior in cryogenic upper stages tanks imposes challenging requirements on the design, especially for future upper stages designed for multiple restarts and intermediate long ballistic flight phases. The Cryo Lab with the described test equipment provides extensive opportunities for scientific research and technical development related to cryogenic propellant management issues. These include the following topics:

- Tank operations
- Critical fluid phenomena
- Tank systems and tank components
- Functional propulsion system
- Tool development and validation
- Sensor technology

Cryogenic Upper Stage Tank Demonstrator (CTD)

For the investigation of issues related to propellant management technologies and storage technologies in complex tank geometries with respect to real applications, i. e. cryogenic upper stage tanks, a Cryogenic Upper

Stage Tank Demonstrator (CTD) is available as shown in figure 4.51, provided by Airbus DS Bremen. The geometry of the Cryogenic Upper Stage Tank Demonstrator (CTD) is deliberately chosen as the scaled form of the Ariane 6 hydrogen tank compartment. The CTD is designed as a cryo container made of stainless steel and provides vacuum insulation between the outer and inner tank wall at the top and bottom. In addition, the CTD is insulated with an Airbus DS spray-on foam insulation. The tank has a concave bottom and a convex upper dome. The central part of the tank consists of a cylindrical removable single walled ring.

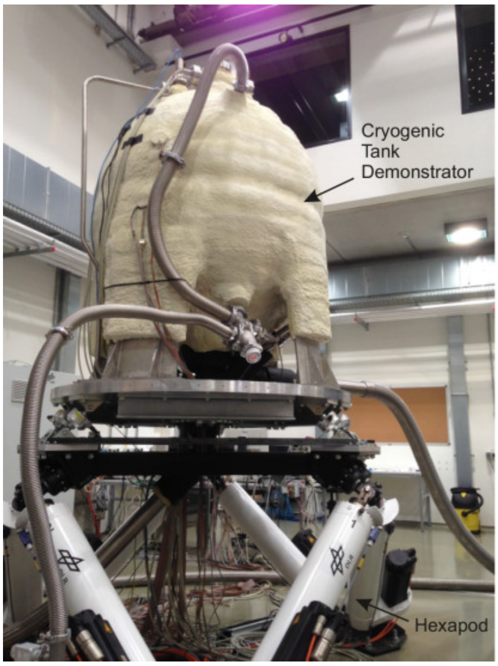


Figure 4.51: Hexapod equipped with Cryogenic Upper Stage Tank Demonstrator (CTD) provided by Airbus DS.

The CTD is basically equipped with temperature sensors. The temperature sensors are located on the inner and outer tank wall and along two special designed movable sensor rods. The sensor rods can be used to determine the temperature profiles in the liquid and the gaseous phase. The degree of filling of the tank is determined by a fill level measurement system. For observation purposes a camera system is available that can provide pictures or videos from the inside of the tank. Furthermore, the gas composition of the ullage is supposed to be measured at different locations to be able to determine concentration gradients of helium and/or vapor. The experimental data achieved with liquid nitrogen successfully used to verify models for the description of the sloshing, thermal stratification, the evaporation, condensation and pressure evolution due to sloshing of the propellant. Next challenging step will be to perform similar selected tests with liquid hydrogen to prove the evolved correlations.

The main tank operations are filling, draining, venting and pressurization during operation. All operations are significantly affected by the thermal behavior of the tank and the propellant behavior. For the design of a cryogenic tank system, the knowledge of the chill down behavior during the filling process, the heat input via the tank walls, as well as the behavior of propellant and pressurization gas has to be known a priori. The heat input into the tank walls determines the boil-off and therefore the loss of propellant over the mission duration. Therefore, the aim is to keep the boil-off as small as possible. A heating of the propellant cannot be avoided without active elements, like cryocoolers for example. Heated propellant must be cooled down to ensure an effective combustion. The corresponding required energy demand has to be taken into account and must be known. During draining the pressure loss, the thermodynamic condition of the propellant, the onset of gas ingestion and the related non-usable residual propellant mass in the tank are of interest. The onset of gas ingestion at the tank outlet is clearly visible in the measurement signal of the turbine in the flow path. Additionally, with an optical access at the tank outlet, the onset of gas bubbles can be observed in the cryogenic draining feedline by using a high-speed camera. The detection of gas bubbles are shown in figure 4.52 at different time steps.

Figure 4.52: Detection of gas ingestion at the tank outlet during draining. The photos show a window in the draining line at different times during tank draining. At time t_1, no bubbles are in the line. If the fill level drops below a critical value, gas is sucked in(t_2), until finally the gas content predominates t_3.

In the draining tests with liquid nitrogen the non-usable residual propellant mass was determined successfully in dependence on the flow rate. Next challenging task will be to perform similar selected tests with liquid hydrogen to prove the evolved correlations.

The design of the pressurization system represents a major challenge. Due to the low density of liquid hydrogen large tank structures have to be used and require a corresponding large amount of pressurization gas. The incoming pressurization gas undergoes a strong temperature change. The temperature drops as a result of cooling and correspondingly the density of the gas increases and additional pressurization gas is needed. Additional transient and coupled thermodynamic and flow phenomena such as evaporation, condensation, diffusion, stratification, sloshing, thermal convection and history effects have an influence on the final resulting pressure and impedes the correct prediction of the required amount of pressurization gas. Experiments are carried out to investigate the influence of the different involved parameter and to determine a validated mathematical model.

The knowledge of the propellant behavior in the tank systems is for the design and successful mission performance of fundamental importance. Design objective is to store the propellant at ideal thermodynamic conditions with respect to an optimal combustion in the engine, as well as to prevent and damp unwanted movements of the propellants to preclude changes in center of gravity (CoG). External influences (heat input, forces) during mission cause independent or coupled flow phenomena which have a non-negligible critical impact under certain conditions and are therefore referred to as critical flow phenomena.

One of the most critical fluid behaviors is the sloshing and its coupled phenomena (figure 4.53). The forces acting on the rocket due to sloshing forces can reach a critical magnitude and jeopardize the mission. The Hexapod of the Cryo Lab is equipped with a force measurement system, which allows measuring the forces due to fluid movement. In this manner, the characteristic values like sloshing forces, sloshing frequency and damping factor can be determined and used for analysis and to derive needed correlations for the design. In addition to the fluid-dynamic effects, coupled thermodynamic effects can arise, which affect the pressure in the ullage decisively. Due to the sloshing motion thermal stratified liquid boundary layers are mixed coupled with the transport of colder propellant in direction of the gas/liquid interface which leads to an increase of vapor condensation. In consequence the pressure in the ullage drops which has to be compensated by the pressurization system.

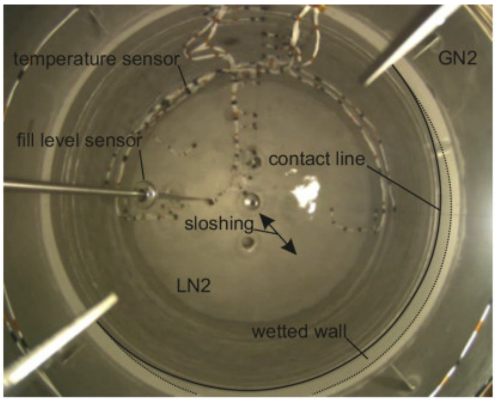


Figure 4.53: Lateral sloshing with the cryogenic tank demonstrator provided by Airbus DS, inside camera top view. The Tank is partly filled with liquid nitrogen (LN_2) and exited to lateral movement. The position and amplitude of the free surface is marked by a solid black line. In addition the temperature sensors and the fill level sensor are visible.

The tests have shown that the pressure drop during sloshing depends on the initial conditions, such as the level sub cooling, the stratification, the pressurization time and the temperature and composition of the pressurization gas. Next step will be the performance of similar tests with liquid hydrogen to prove the physical models. External heat input causes a thermal stratification in the gaseous and liquid phase. In the ullage a large temperature variation is present from almost saturation temperature at the liquid/gas interface up to the inlet temperature of the pressurization gas at the top of the tank. In the bulk the liquid temperature is approximately uniform, whereas warmer thermal boundary layers at the wall emerge and promote a warm increasing liquid layer at the gas/liquid interface. The heating of the interface leads to evaporation and associated with this an undesirable pressure rise in the tank. Due to the presence of a two-species system, consisting of pressurization gas and vapor, diffusion processes driven by concentration differences also affect the heat and mass transport in the ullage and has to be considered. In the performed experiments with liquid nitrogen temperature gradients in the liquid and gaseous phase could be measured precisely and successful used for model validation. The next task will be to perform experiments with liquid hydrogen to prove the determined correlations.

Tank Systems and Tank Components

In addition to the physical and fluid dynamic issues, the Cryo Lab is used for functional tests of tank systems and tank components. Future mission requirements such as the re-ignition of the engine and the performance of long ballistic flight phases require an efficient and intelligent propellant management supported by corresponding technologies and tank components. For the propellant management different technologies and systems are used. Various tank internals are successful tested to control and manage the propellant behavior. The damping of unwanted fluid movements or shift of the slosh frequency can be achieved with baffles. Liquid Acquisition Devices (LAD's) are used to provide at the tank outlet on demand a certain amount of propellant for re-ignition of the engine, independent of the gravity level. On the opposite side of the tank at the venting port a phase separation system is required which ensures that only gas and no valuable propellant leaves the tank during venting maneuvers. Studies of Airbus DS have revealed that the temperature conditioning of the propellant at missions with several re-ignitions can be further optimized by the use of a heat exchanger for the hydrogen tank. In the heat exchanger only the amount of propellant currently required is cooled down and not, as during the venting maneuver, the entire tank volume. The concept and the performance of the heat exchanger was successfully tested and demonstrated in the Cryo Lab. The test set up is shown in figure 4.54. In the experiments the performance of the heat exchanger could be measured very accurately and the specified design target has been confirmed.

Figure 4.54: Test facility for heat exchanger. Foreground: controller unit. Background: Water test bench consisting of a water circle circuit with heater, switch cabinet, water tank, centrifugal pump and to be tested evaporation cooler in the upper part of set up.

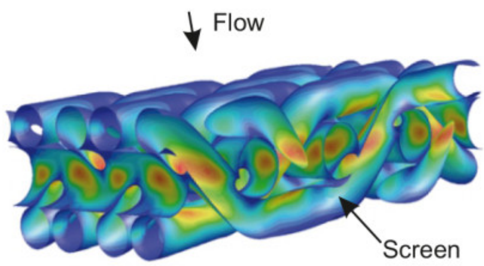


Figure 4.55: Calculated flow through metallic screen, colored by screen Reynolds number.

Tool Development and Validation

For a reliable and optimal design of launcher systems appropriate validated tools are an indispensable basis. The Cryo Lab offers the possibility to perform experiments in the range from small basic experiments to larger scale experiments. The aim is finally to enable a reliable prediction of the fluid behavior in the real application.

The calculation of the flow behavior in the tank systems is still today a major challenge for computational fluid dynamics (CFD) tools. To calculate the real behavior, the CFD tools must be able to describe a three dimensional two phase/two species system, taking into account phase changes, bubble formation, boiling, heat and mass transfer, diffusion, convection and wall effects. In addition to the variety of required physical models there are large geometric scale differences between the real tank dimensions, in the order of meters and the phenomena locally occurring such as small thermal boundary layers in the order of sub millimeter. Furthermore the scale differences together with high gradients have to be spatially resolved and represent an additional particular challenge [379]. The Cryo Lab provides the required sensor diversity and extensive test facilities to serve as a provider of the needed experimental data for tool validation and development with respect to propellant management issues. For calculation commercial (FLOW-3D) and open source codes (OpenFOAM) are used. Needed physical models are developed and implemented in the code.

An intelligent position control system of the upper stage responds to an imposed sloshing motion of the propellant with minimal effort while maintaining and ensuring the mission objectives. The Hexapod equipped with a tank demonstrator will be used to a first on ground validation of the closed loop tool develop by Airbus DS. In this tool the attitude control system and the rigid body dynamics are coupled with the forces resulting from the sloshing behavior of the propellants in the tank. During an initiated sloshing case, the slosh forces caused by the fluid movement are measured by the force measurement system and provided as an input variable to the implemented controller. The controller controls the movement of the Hexapod in a closed loop with the aim to dampen actively the movement of the sloshing liquid.

The closed loop demonstrator is used to demonstrate and optimize the controller capabilities as well as to investigate and deepen the understanding with respect to the coupling of fluid dynamics and rigid body dynamics.

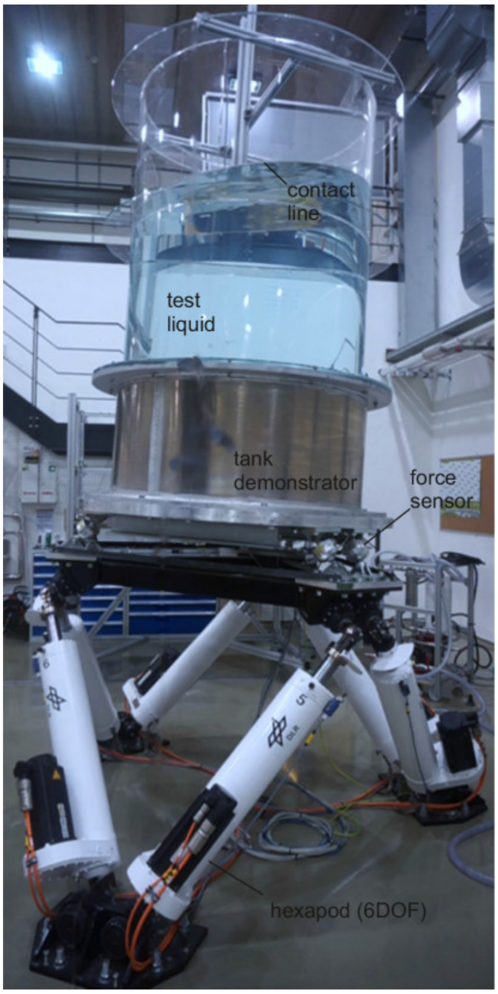


Figure 4.56: Closed loop tank demonstrator provided by Airbus DS on hexapod. Partly filled tank demonstrator with water exited to sloshing motion. The measured sloshing forces are used as input to active control and dampen undesired fluid motions.

Sensor Development

The experimental determination of flow parameters in cryogenic experiments is a further particular challenge. Experiments are typically conducted in isolated optically opaque containments and are therefore difficult to observe with optical systems. In addition sensors within the cryogenic containment have to withstand the extreme temperatures and must ensure that they submit themselves only a small amount of heat energy into the system. The precision of the experiment determines the achievable quality of the derived correlations or physical interpretation and decides on the suitability for tool validation. The accuracy of the experiment depends on the accuracy of the measurement of the flow phenomenon itself and to the same extent on the exact measurement of the prevailing experimental boundary conditions. The particular challenge is that the experiment should not be affected and influenced by the necessary sensors.

As part of the ESA project "CryoSense", the Institute searched together with their project partners Airbus DS, Coburg University of Applied Sciences and Arts and University of Bayreuth for novel sensors and measurement technologies which can be applied for measuring fluid phenomena under cryogenic conditions. By comparison with conventional sensors in the Cryo Lab application potentials could be demonstrated with various sensors, like ultra sound, electrical capacitance tomography and fiber optic sensors.

It is known that optical fibers can be applied for the measurement of temperature, pressure, strain, chemical composition, or can be used as a light guide for optical observation at normal or ambient temperature conditions. In the Cryo Lab Rayleigh Backscatter (RB) fiber optic sensors and Fiber Bragg Grating (FBG) sensors have been used successfully in an experiment under cryogenic conditions and have demonstrated their potential for application. In addition, the use of glass fiber bundles for the optical observation in an experiment could be tested successfully with liquid nitrogen [598].

The aim is to further develop novel advanced cryogenic sensor towards their application up to liquid hydrogen.

4.5 Optical Systems

DLR Bremen – in close collaboration with ZARM of the University of Bremen and Airbus DS Friedrichshafen, incorporating further Universities and Institutes – develops and experimentally investigates key technologies needed

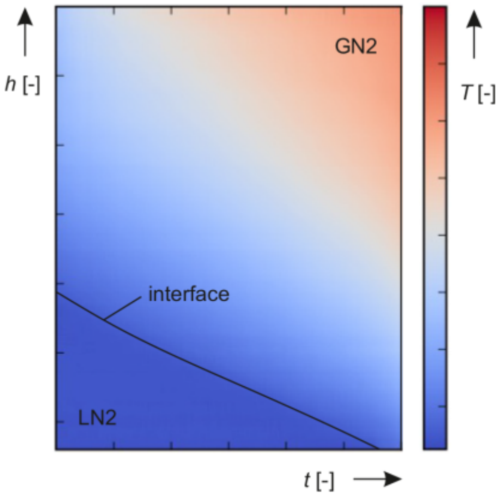


Figure 4.57: Temperature field measured with fiber optic sensor using Rayleigh-Backscatter method in a partly filled cryostat. The picture shows the decreasing fill level (*h*) of liquid nitrogen (LN_2) by evaporation as a function of time (*t*). The measured temperature distribution in the liquid (LN2) and gaseous phase (GN2) is distinguished by temperature dependent color variation.

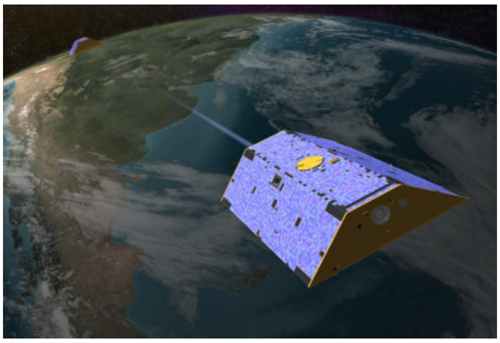


Figure 4.58: Artists view of the two GRACE satellites with the microwave link for distance metrology (source: NASA). The Gravity Recovery and Climate Experiment Follow-On (GRACE-FO) mission will employ an additional laser ranging instrument.

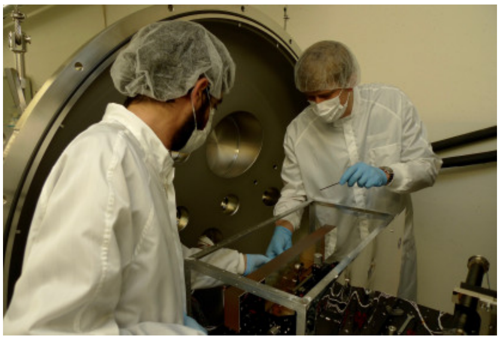


Figure 4.59: Scientists aligning the reference plate as part of the OGSE for verification of the GRACE-FO laser ranging instrument.

for future applications in space. This includes specific assembly-integration technologies for realizing compact and ruggedized optical setups such as compact optical frequency references based on molecular iodine and optical resonators and high-sensitivity interferometers for intra- and inter-spacecraft distance and tilt metrology. For thermal characterization of ultra-stable materials such as carbon fiber reinforced plastic (CFRP) and Zerodur, needed e. g. as structural material for high-precision optical systems, a continuously upgraded metrology test-bed is available.

The technologies are developed with respect to future applications in space missions related to fundamental physics, Earth observation and navigation and ranging. Examples are the gravitational wave detectors Laser Interferometer Space Antenna (LISA) and Astrodynamical Space Test of Relativity using Optical Devices (ASTROD) [24], missions to test Special and General Relativity such as miniSpaceTime Asymmetry Research (mSTAR) [402, 580], Boost Symmetry Test (BOOST) [283, 492] and Spacetime Explorer and Quantum Equivalence Space Test (STE-QUEST) [7, 110, 234], the quantum theory test mission MAQRO (Macroscopic Quantum Resonators) and Next Generation Gravity Mission (NGGM) measuring Earth's gravity field. As DLR in-kind contribution, the optical ground support equipment (OGSE) for verification and test of the laser ranging instrument aboard the Gravity Recovery and Climate Experiment (GRACE) follow-on mission is realized and the corresponding tests are carried out at the industrial partner sites.

4.5.1 Optical Ground Support Equipment for the Earth Observation Mission GRACE Follow-On

The main objectives of the Gravity Recovery and Climate Experiment Follow-On (GRACE-FO) mission are: (i) the continuation of data collection to accurately determine the Earth's gravity field and its changes, as follow-on mission to the successfully operating GRACE mission (primary target), and (ii) the first test of an laser ranging instrument (LRI) for laser-based distance measurement between two satellites in space (secondary target).

GRACE-FO consists of two satellites in a 500 km attitude low-Earth orbit (LEO), cf. figure 4.58. Their nominal distance of 200 km varies minimally due to different mass distributions on Earth e. g. caused by mountains, groundwater or glaciers. By measuring changes in these mass distributions over a longer period, statements on climate change can be made. In the current GRACE mission the distance changes are measured by a microwave link with obtained resolutions in the micrometer range. The successor mission GRACE-FO with launch in 2017 will additionally employ a nanometer-sensitivity laser interferometer. The two satellites of the US-German mission are built at Airbus DS in Friedrichshafen, the Laser Ranging Instrument is provided by the space company SpaceTech Immenstaad (STI). While the NASA JPL provides laser, optical frequency reference and processing computer of the LRI, the German contribution includes optical bench, retro reflector (triple mirror assembly (TMA)), optical bench electronics and the OGSE for verification of the LRI on component, subsystem and system level [145, 889].

DLR Bremen is responsible for providing the OGSE and carrying out LRI performance tests. Amongst others, this includes verification test beds for the TMA (cf. figure 4.61) and an inter-spacecraft link simulator for performance verification of the overall laser ranging instrument [107].

4.5.2 Optical Frequency References

High-performance optical frequency references are a key technology for a variety of future space missions dedicated to fundamental physics, Earth observation and navigation and ranging. Frequency stabilized lasers are needed as light source for high-sensitivity distance metrology between distant spacecraft (e. g. for missions such as LISA, ASTROD, GRACE-FO and NGGM). Proposed missions such as mSTAR and BOOST will test special relativity by performing clock comparison experiments using optical frequency references. Furthermore, optical clocks are a promising candidate for future GNSS with enhanced performance.

At DLR, two different technologies using laser sources at a wavelength of 1064 nm are investigated. Two absolute frequency references based on Doppler-free spectroscopy of molecular iodine were realized on elegant breadboard [578] and engineering model level [577], respectively, and the technology is currently evaluated for use on sounding rocket and a small satellite missions. A setup using an optical resonator as frequency reference is currently developed with focus on high thermal and mechanical stability [108].

A photograph of the iodine spectroscopy setup on engineering model level is shown in figure 4.61 using a specifically designed compact multi-pass gas cell. The optical components are integrated on a 380 mm × 180 mm × 40 mm fused silica baseplate using adhesive bonding technology. Assuming typical parameters and a location of the optical bench inside the spacecraft (similar to the optical bench on LISA Pathfinder), the spectroscopy unit was subjected to thermal cycling from -20 °C to +60 °C and vibrational loads with sine vibration up to 30 g and random vibration up to 25.1 g_{rms} [576, 581]. A frequency instability of better than 5×10^{-15} for integration times larger than 100 s was evaluated in a beat measurement with a ultra-low expansion (ULE) cavity setup, fulfilling both, LISA and NGGM requirements. The frequency stability is close to the one of the active hydrogen maser.

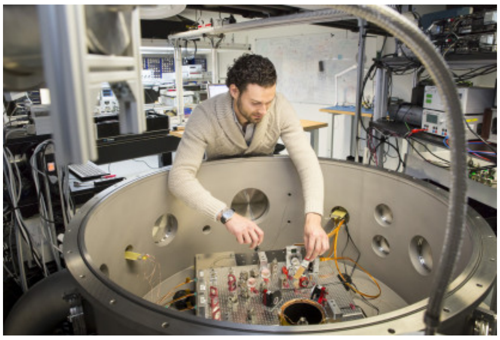


Figure 4.60: Aligning the heterodyne interferometer setup used for high resolution dilatometry of ultra-stable materials.

4.5.3 Technologies for Realizing Highly Stable Space Optical Instruments

Future operation in space includes specific design aspects for the optical instruments such as compactness, rigidity and modularity. The components as well as the system must fulfill mission specific requirements on vibration, shock, thermal cycling and radiation hardness. The assembly/integration (AI) technology for realizing the optical setup must offer high thermal and mechanical stability, high long-term stability, alignment feasibility of the optical components and the possibility of space-qualification. During the last years, an AI-technology based on a two-component space qualified epoxy was investigated in collaboration with Airbus DS (Friedrichshafen) and successfully applied to high-sensitivity interferometer setups and optical frequency references, cf. the iodine-based frequency reference shown in figure 4.61 [183].

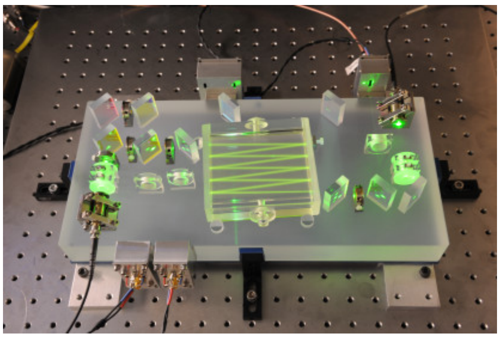


Figure 4.61: Photograph of the iodine spectroscopy setup on engineering model level using a compact gas cell in nine-pass configuration.

In order to characterize ultra-stable materials needed for space optical systems, such as CFRP or glass ceramics such as Zerodur or ULE, an optical dilatometer was developed (cf. figure 4.60) [805, 836, 872, 628, 629].

With this test bed, an accuracy below 10^{-7}/K in determination of the coefficient of thermal expansion (CTE) over a temperature range of 100 K to 300 K was demonstrated.

4.6 Deployment Systems

Deployment systems cover spacecrafts that are capable of changing their shape from a compact launch configuration to an expanded operational configuration. Such systems have a history nearly as long as space flight itself. Their applications range from simple booms for gravity stabilization and payloads to more complex structures for antennas, solar arrays and more recently membrane structures for solar sails and drag sails [592, 710]. The development of deployable membrane structures in Europe and for instance at DLR goes back to the 1990s when a first comprehensive solar sail breadboard of 20 m × 20 m was tested in a joint DLR, NASA/JPL and ESA project. Several following studies [394] and development projects focused on deployable structures and their mission application.

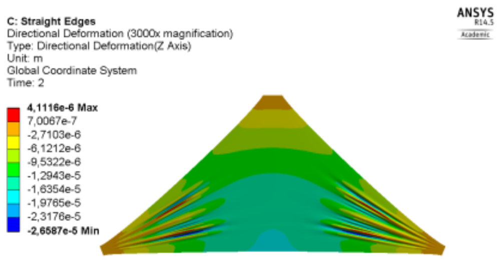


Figure 4.62: Deformation plot of membrane wrinkling analysis while membrane tensioning during deployment.

With the project Gossamer-1 a complete development cycle was established and is now being applied to the successor project Gossamer Solar Array (GoSolAr) aiming at a flight demonstrator on one of the first S2TEP missions. The development cycle includes a sound mission definition and derivation of requirements, taking specific characteristics like the deployment process into account. On this basis the hardware development, involving mechanisms, electronics, software and the structure itself, were pursued. Those developments led to a broad basis for future projects. Furthermore, verification strategies were established in order to qualify the hardware components and the complete system for its application in space. A summary of the main developments within the project Gossamer-1 is given in section 3.6.1.

The know-how described is employed in projects like the Heat Flow and Physical Properties Package (HP3) experiment on the NASA/JPL Mars mission Interior Exploration using Seismic Investigations, Geodesy, and Heat Transport (InSight). In addition, it is transferred to our industrial partners within the ESA drag sail projects "Deployable Membrane" and "Architectural Design and Testing of a De-orbiting Subsystem".

4.6.1 Membranes from Design to Manufacturing and Integration

Considering requirements ranging from the environmental conditions (e. g. radiation, atomic oxygen) to system specific aspects (e. g. a controlled deployment) suitable membrane designs can be realized. The designs are investigated from thermal, mechanical and degradation point of view. Figure 4.62 shows analysis results of a mechanical wrinkling analysis of the deployed membrane. Selected designs are being manufactured in the integration lab under clean room conditions as can be seen in figure 3.47 of section 3.6.1. The manufacturing employs a vacuum table of size 5 m × 3 m.

For the integration of deployable elements, especially for large membranes, a dedicated stowing strategy for the intended function is required. With respect to the technology development for solar sails and drag sails this included studies about possible folding and coiling techniques as well as development tests for verification purposes.

4.6.2 Mechanisms

Deployable systems usually require several mechanisms to enable the desired deployment process. Hold down and release mechanisms, which can withstand high mechanical loads, are required in order to secure the system in launch configuration. After launch those mechanisms must allow a release in order to initiate the deployment for which active or passive mechanisms can be applied. The comparably high number of different kinds of mechanisms together with the required high reliability of the function even after long term storage on ground and in space is a big challenge in the development of deployment systems.

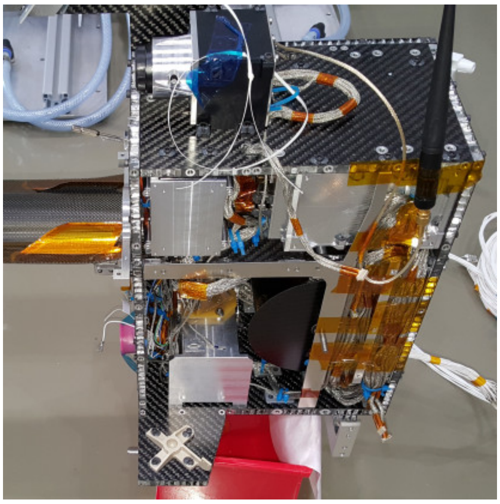
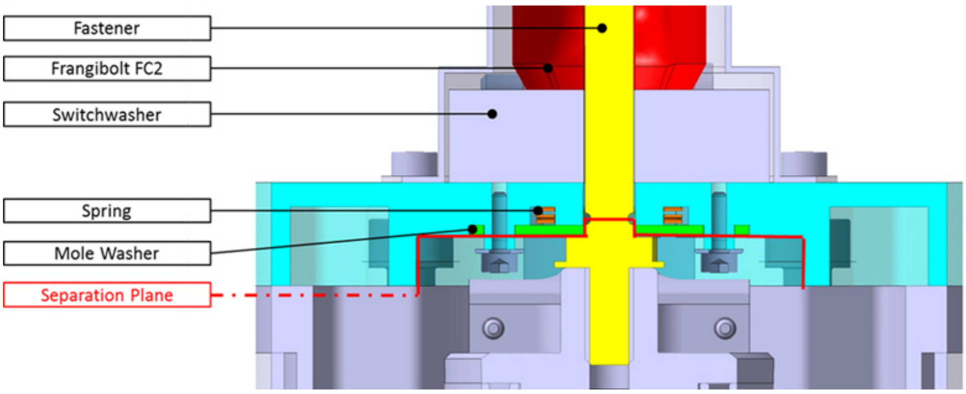


Figure 4.63: Engineering qualification model of Gossamer-1 boom and sail deployment unit (BSDU) with Motor, belt winding mechanism and camera.

Within the project Gossamer-1 several mechanisms were realized. On the one hand, already qualified actuators and sensors were employed, and on the other hand commercial off-the-shelf components were qualified according to project requirements by employing the test facilities of the Institute. Examples for such actuators are pinpullers, frangibolts, ejection and release mechanisms as well as electrical motors. Cameras, optical sensors, switches and switch washers were employed as sensors. Combining different actuators, sensors and working principles, customized solutions were implemented for projects like InSight (figure 4.64), Gossamer-1 (figure 4.63) or AlSat.

4.6.3 Verification of Deployment Systems

For the verification of deployment systems a test cycle according to a test-as-you-fly approach was established. Particular attention was payed to the venting behavior, which is especially for stowed membranes of utmost importance. In addition, a partial thermal-vacuum deployment was realized. The limiting factor for the deployment in vacuum is the size of the available thermal-vacuum chamber. The complete test cycle includes vibration testing (see section 3.2.3), venting testing (see section 3.2.4), thermal-vacuum cycling and deployment (see section 3.2.4) as well as full laboratory deployment (see figure 4.66 of this section), in this particular sequence. In some cases the mechanical testing is complemented by shock tests and external centrifuge tests.



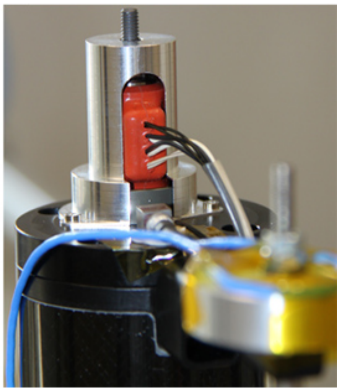


Figure 4.64: InSight HP3 mole release mechanism principle and qualified flight unit hardware.

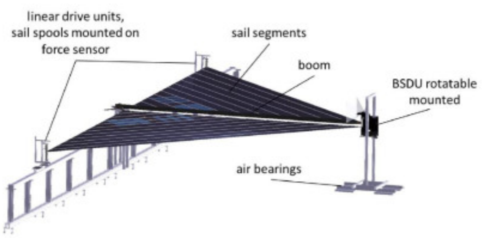


Figure 4.65: Test rig for the deployment of two sail segments together with one boom by employing the Gossamer-1 deployment mechanisms.

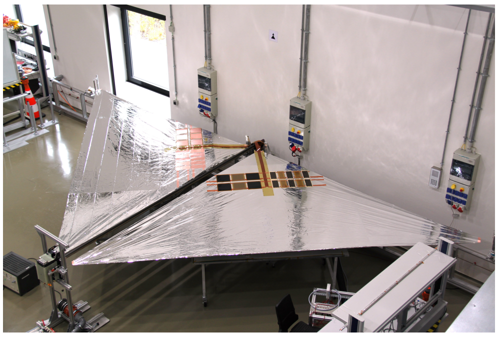


Figure 4.66: Gossamer-1 deployment test in progress.

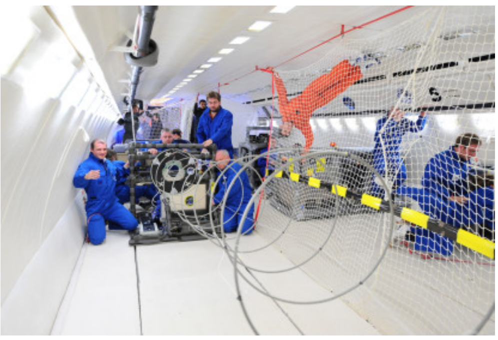


Figure 4.67: Deployment testing of the AISat helical Antenna on the 15. Parabolic Flight Campaign of DLR 2010 in Bourdeaux.

Deployment Test Rig

The deployment tests for membranes under gravity and in ambient conditions require a special test rig consisting of linear drive units, force sensors and a mounting carriage with air bearings. The test rig is illustrated in figure 4.65. Note that the test rig can be assembled in different configurations in order to meet requirements of different projects.

The linear drives are used in order to replace elements of the supporting structure, e. g. some booms. They are equipped with force sensors on the drive units. Thereby interface forces can be determined that are necessary for the sizing of structures and mechanisms. In case gravity compensation is required during deployment processes the mechanisms can be mounted on a carriage that is sliding on air bearings. Thereby the influence of friction between the test structure and the floor is reduced during the deployment process.

The test can be realized either on component level or on system level. A system level test would include the complete avionics as well as communication aspects in order to follow the expected mission scenario. Figure 4.66 shows the deployment test of the Gossamer-1 deployment unit with one boom and two sail segments. The deployment unit equipped with its own avionics, power and communication subsystems was commanded via a wireless communication link from a central base station.

Zero-Gravity Deployment

Another way of verifying deployment systems is their deployment in a zero-gravity environment. Within two parabolic flight campaigns the Institute already successfully organized this specific way of testing.

The first application was the deployment of the 4 m long helical antenna of the AISat (section 3.3.4) with a stowed length of merely 100 mm as shown in figure 4.67. The second application was testing the release of MASCOT (section 3.4.1) out of its support system to qualify the release scenario from the mother spacecraft Hayabusa-2.

4.7 Life Support Systems: The EDEN Domain

Sustained human presence in space requires the development of new technologies to maintain environment control, to provide water, oxygen, food and to keep astronauts healthy and psychologically fit. Furthermore, the logistics of mission resupply limits human exploration in space. Bio-regenerative life support systems (BLSS) in conjunction with in-situ resources will initially reduce and ultimately eliminate consumables from the logistics chain. Minimizing this need for resupply while ensuring human safety will allow astronauts to travel further and stay longer in space than ever before. While physical/chemical life support systems will likely form the back-bone as a fallback strategy, BLSS will expand to eventually become the primary system to ensure sustainable life support for long-duration missions.

In 2011 the Institute launched its research initiative called Evolution and Design of Environmentally-Closed Nutrition Sources (EDEN). The research initiative focuses on BLSS, especially greenhouse modules, and how these technologies can be integrated in future human-made space habitats. EDEN was established within the DLR internal project Combined Regenerative Organic Food Production (CROP)— a joint research endeavor between the Institute of Aerospace Medicine and the Institute of Space Systems [684, 253, 519, 520, 932, 564, 708, 219, 266].

The cultivation of higher plants can contribute to all major aspects within BLSS and represents an all-in-one-approach, not accomplished by any single physical/chemical system. [241].

The most apparent advantage of BLSS is the provision of food. Considering the symbiotic relationship between humans (carbon dioxide emitters) and plants (carbon dioxide absorbers), plant growth modules will also provide valuable oxygen to the crew. Through the exploitation of plant evapotranspiration, the deployment of plants can furthermore contribute to wastewater recycling. Astronaut physical and psychological well-being is vital, especially during long duration missions with constant isolation in a highly integrated machinery environment, including the dependency on these machines. From a long-term perspective, bio-plastic, latex, or other high value compounds that can be generated from plants, will also help reduce consumables and increase mission autonomy. Transforming bioplastics into granulates and using them with the latest 3D printing techniques opens a wide variety of in-situ production capabilities.

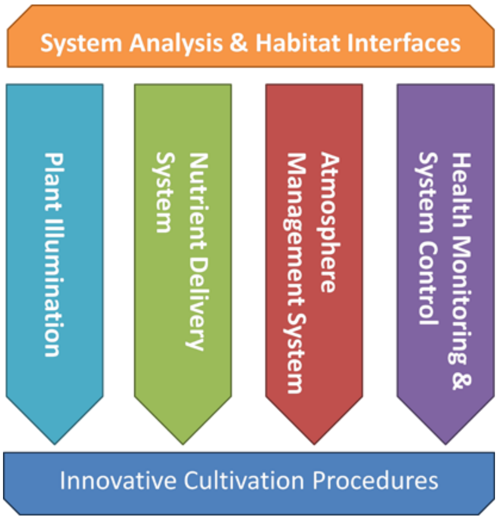


Figure 4.68: The six research domains of the Evolution and Design of Environmentally-Closed Nutrition Sources (EDEN) Initiative.

A key development focus of EDEN is controlled-environment agriculture (CEA), which is a combination of engineering, horticultural science and information technology to design highly efficient plant growth systems, see figure 4.68 [817, 852, 869, 905]. Through the implementation of CEA technologies regarding careful control of water conditions and nutrient provision (e. g. pH values, electrical conductivity, as well as soilless cultivation), the control of environmental conditions (e. g. temperature, relative humidity, ambient pressure, CO2- and O2-concentrations), and the provision of selective spectral light (e. g. red, blue, ultraviolet (UV)), it will be possible to achieve higher yields and shorter plant growth cycles than ever before. Through CEA, even the exact control of food quality (e. g. appearance, taste, enrichment of useful substances) is possible.

Figure 4.69: View towards the Closed-loop Test Facility within the Space Habitation Plant Laboratory (SHPL).

In 2014 the Space Habitation Plant Laboratory (EDEN Lab.) was opened (see figures 4.69 and 4.70). The main driver for the establishment of this research laboratory was the necessity to gather hands-on experience with the cultivation of higher plants in (semi) closed-loop environments. The laboratory offers a unique set of cultivation chambers for the conduct of plant growth studies and the development of the necessary supporting technologies. In particular, numerous CEA technologies were developed and tested within the EDEN Laboratory.

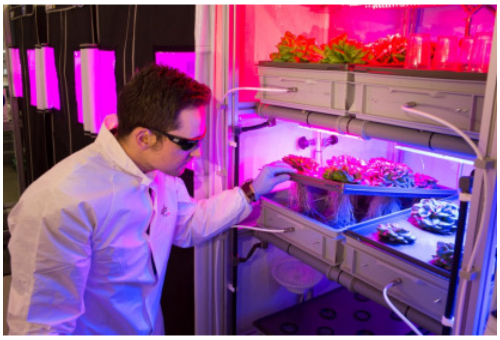


Figure 4.70: Multilevel plant growth systems within the EDEN laboratory employing aeroponics and water-cooled LED lighting.

In close collaboration with industry (Airbus D&S, OSRAM, Sierra Nevada Corporation/ORBITEC), universities (e. g. HTWD, Wageningen) and research institutes (e. g. NASA, ESA, Alfred-Wegener-Institut (AWI)), the EDEN team developed a unique set of plant cultivation systems in order to improve the performance and reliability. As mentioned above, major focus was set on soilless irrigation methods (e. g. aeroponics), high-performance water cooled LED-systems, closed-loop air management systems, and plant health monitoring.

It is essential to test and validate plant cultivation technologies in an environment similar to space and with relevant mass flows to increase their TRL. Testing individual subsystems to investigate performance requirements in clean rooms are typically insufficient to address the complex system interactions.

Furthermore, integrated system tests in realistic operational environments are difficult, often not planned nor budgeted, resulting in on-orbit surprises. Given the risks, costs, and complexities associated with human missions to Moon and Mars, space-analog research on Earth can be a powerful tool to explore the challenges associated with working and living upon another planet [262]. The EDEN team participated in several analog test campaigns:

- International Lunar Exploration Working Group's EuroMoonMars B mission (Crew 125) at the Mars Desert Research Station (MDRS) in 2013 [478]
- Reliability and Redundancy of Extreme Environment Habitat Structures and Power Systems mission (RAR Mission) within Crew 135 [505]
- Hawaii Space Exploration Analog and Simulation Mission II in Hawaii, USA [507]

In 2014 the team conducted several plant cultivation experiments during the Hawaii Space Exploration Analog and Simulation (HI-SEAS) Mission II in Hawaii, USA (see figure 4.71). HI-SEAS missions are managed by the University of Hawaii and are funded by the NASA Human Research Program. During four months, L. Poulet (EDEN member) lived together with five other crew members without direct communication with the outside world, in a dome-shaped habitat on the slopes of the volcano Mauna Loa on the Big Island of Hawaii. The area has Mars-like features and is in a remote area at an elevation of approximately 8200 feet above sea level. For this mission, the EDEN group was supported by NASA's Kennedy Space Center, Heliospectra and ORBITEC (Sierra Nevada Corporation). The prime focus of these experiments was to investigate the effect of different lighting wavelengths on plant growth and to assess the effects of having plants in the habitat on the crew during long duration isolation periods. These initial analog missions have already shown how analog test site utilization can enhance EDEN's research expertise in the field of habitat and life support system (LSS) design and in general the preparation of human missions to the Moon and Mars.

Figure 4.71: HI-SEAS habitat on the Mauna Loa volcano in Hawaii (USA), credits: Ross Lockwood

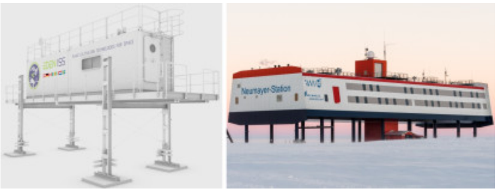


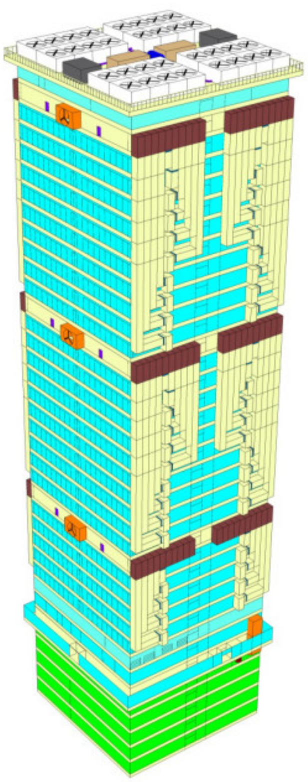
Figure 4.72: Left: Graphical representation of the EDEN-ISS Mobile Test Facility. Right: The Neumayer III Antarctic station, credits: DLR, AWI

Following the analog testing approach, a major focus of the group is set on the Horizon 2020 funded project EDEN-ISS (COMPET 7 - 2014: Space exploration - Life support/€ 5 million project), which is under the lead of the EDEN team of the Institute. The project foresees the development and demonstration of higher plant cultivation technologies, suitable for future deployment on the International Space Station (ISS), and from a long-term perspective, within Moon and Mars habitats. The EDEN-ISS consortium is comprised of fourteen consortium partners of the leading European experts in the domain of human spaceflight (e. g. Airbus D&S, TASI) and CEA. As a highlight of the project, a Mobile Test Facility comprising a closed-loop greenhouse system will be deployed at the highly-isolated Antarctic Neumayer Station III, operated by the AWI. This space analog mission will produce fresh food for the crew of the station for fifteen months. Compare figure 4.72. [154, 155, 677, 242].

EDEN's research results extend the knowledge of plant cultivation procedures in closed or semi-closed environments, an area with increasing terrestrial market potential. Closed or nearly closed-loop plant cultivation systems can enable terrestrial agriculture to be conducted in areas currently unsuitable for agriculture. A detailed market analysis was conducted in collaboration with the DLR Technology Marketing department [876, 793].

Besides the market analysis, the EDEN team is focusing its spin-off investigations on vertical farming (VF). VF is a proposed agricultural technique involving large-scale agriculture in urban high-rises or "farmscrapers", see figure 4.73. Using cutting-edge greenhouse methods and CEA technologies, these buildings would be able to produce fruits, vegetables, and other consumables (e. g. herbs and pharmaceutical plants) throughout the entire year. The concept foresees the growing and harvesting of a wide range of plants in high density urban areas (mega cities) and the sale of these crops directly within the city, reducing the required transportation efforts as opposed to the standard rural farming [697, 562, 717, 268, 718].

In conclusion, the EDEN research area leads to new resource-efficient systems and sustainable living and also strengthens the global food, energy and resource recovery industries. The imperatives for this research endeavor are high and challenging, and the requirement to adapt CEA technologies for the space sector adds even further challenges. Nevertheless, by investing in this research, new cultivation approaches in producing food and other useful elements can be achieved in a resource-efficient manner. Within only five years (2011-2016), the EDEN team was able to output



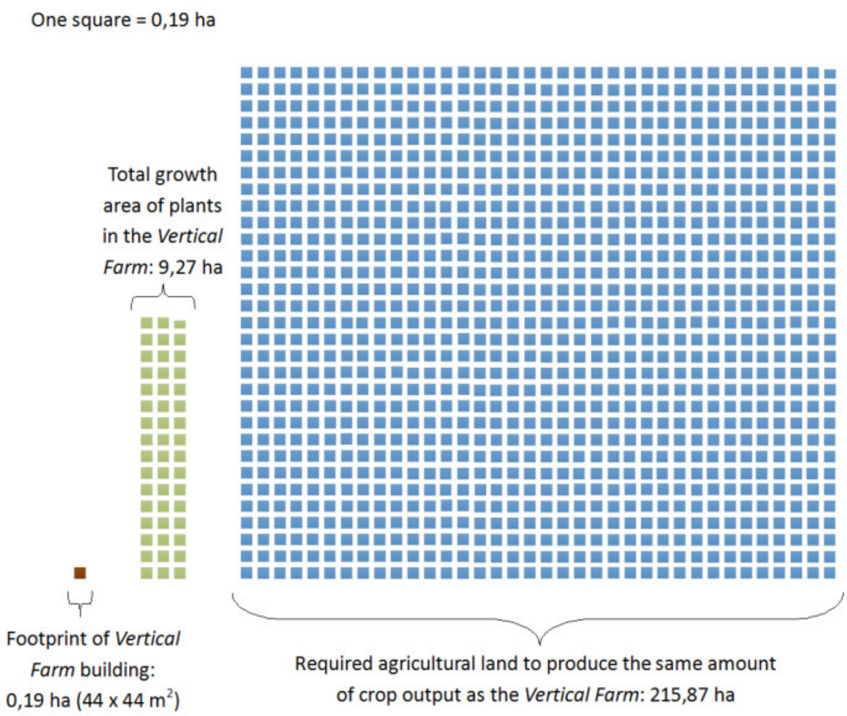


Figure 4.73: Left: Vertical Farm design which was elaborated during a concurrent engineering (CE) study at the DLR Institute of Space Systems. Right: Comparison of production footprint of the Vertical Farm to traditional agriculture. [268]

a total of over 100 key figures (e. g. journal contributions, peer-reviewed proceedings, invited talks, patents, and diploma, master's, and bachelor's theses). Also, with a third-party money ratio of over 56%, the research group displays a solid funding situation among DLR research entities. Furthermore, the EDEN group established a research network of 29 partners ranging from academia to industry. The public awareness of the EDEN initiative can be proven by its over 160 contributions in print, TV, radio and internet in 2013-2014 alone. For details, refer to the yearly reports [781, 783] and EDEN's strategy document [782].

5 Outlook

5.1 Future Directions

The following section describes the strategic goals and objectives of the Institute, outlining the Institute's vision on how to further strengthen knowledge and skills to strive for sustainable cutting-edge space science and technology development. The major initiatives for the upcoming next decade are reflected according to the three columns of the Institute, namely *system analysis*, *system development* and *system technologies*. This will be outlined and detailed in the following sections.

The Institute is committed to perform excellent science, supporting a strong and high-tech oriented German Aerospace Center (DLR) organization. In this context, the Institute will concentrate on the development of modular and flexible small satellite missions to support the DLR key scientific topics of

- dynamic Earth climate and environment monitoring,
- next generation communication & navigation systems by innovative time and frequency standards,
- safety and security issues with reference to optical and radar applications and reliable product delivery,
- space robotics to support demanding on-orbit servicing activities, and
- space propulsion with future need in propellant management and electric propulsion.

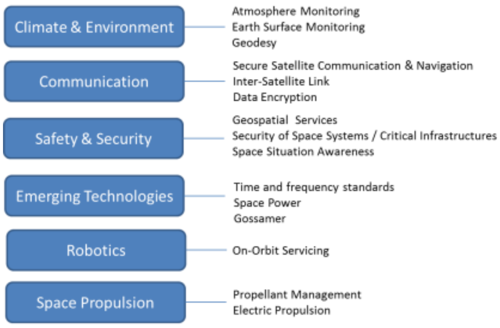


Figure 5.1: Future key scientific topics.

5.2 System Analysis

Continuously improving the concurrent engineering (CE) environment (facility, processes, and methods) is one of the major future research efforts in the area of system analysis. A primary goal is the establishment of the CE process in later mission phases, beginning with Phase B, but eventually extending it to the overall mission life cycle. In essence, using CE methods to encounter and handle failures occurring during a mission in Phase E. The project Small Satellite Technology Experiment Platform (S2TEP) will serve as a breadboard to adapt and enhance the process to later phases. This will include extending the focus of CE studies from the overall satellite system to a subsystem perspective as well, for example, by conducting studies on the thermal control system. Furthermore, the timescale of studies will be adapted, as calculations, simulations, and verification of design takes more time in later phases than in Phase 0/A. This way, a CE study for Phase B could stretch over several weeks (around four to five sessions). This envisioned development pathway will further cut down early Phase B design phases and cost respectively. Furthermore, analysis of group dynamics, introduction of more creative problem solving techniques and their ability to improve the process will be part of the research in order to enhance the CE process. Extending the CE process into later phases will also aid the CE team members in acquiring experience with these later design phases.

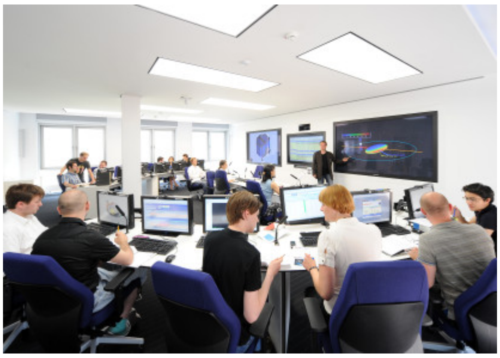


Figure 5.2: System analysis design lab: Concurrent Engineering Facility (CEF).

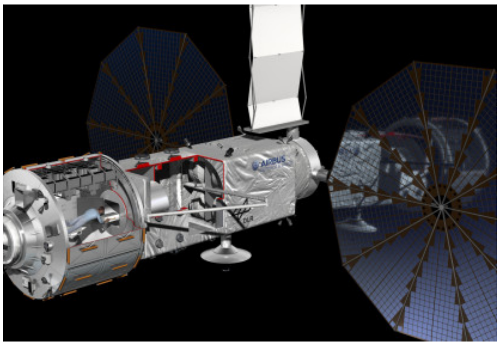


Figure 5.3: The Orbital-Hub man-tended (while docked) Free-Flyer as part of an ISS follow-on option.

This will be achieved by actively supporting mission development and operations of the Institute's missions. This way, lessons learned from actual missions can and will be fed back into the process and early designs, further improving design and process quality. The process development will be undertaken in close partnership with European Space Agency (ESA) and other CE stakeholders for increased effectivity.

At the same time, in accordance with the Institute's strategy regarding participation in an increased number of satellite missions, it is to be expected that even more CE studies will be conducted. Also a more efficient CE study execution, by adopting process changes, designed for later phases into the early-phase studies, will improve the CE process further. In addition, new technologies and equipment such as interactive screens and wireless control devices will keep the facility up to the state-of-the-art for the moderator team. Another aspect is the creation of a community-wide CE model standard under the leadership of ESA to allow for more efficient sharing of data within the mission design community, where the Concurrent Engineering Facility (CEF) team of the Institute plays a key role. A common standard will also increase cooperation of various CE stakeholders (institutional or industrial). Overall, the improved CE capabilities will also improve the continuous work on the topic of visionary mission concepts.

Figure 5.4: Artist's impression of SpaceLiner 7 passenger stage in gliding atmospheric flight.

The highly dynamic developments in first stage launcher re-usability currently ongoing in the United States (US) with successful return and landing of the Falcon 9R and the booster stage of New Shepard once again push worldwide interest in the direction of launcher reusability. The Institute is well prepared to even stronger focus its system analysis research activities on future space transportation systems in the direction of reusable launch vehicle (RLV). Configurations of semi and fully reusable launchers with different return concepts of the RLV stages (including vertical propulsive or aerodynamic landing) with different propellant combinations like liquid oxygen (LOx)/liquid hydrogen (LH_2), LOx/RP or LOx/Methane propulsion systems will be systematically investigated. The most attractive approach in terms of development as well as launch cost and technical risks shall be investigated and it is to be assessed how it fits into a future European launcher exploitation roadmap.

The highly efficient pre-design methods and tools for launcher system analysis could be further refined with focus on the interaction between:

- aerothermodynamic analysis and thermal protection system (TPS) pre-sizing
- flight controllability and guidance, navigation and control (GNC) pre-design
- mechanical architecture (automated pre-dimensioning) delivering reliable component mass estimation
- propulsion system pre-sizing with reliable component mass estimation
- validated cost estimation and environmental impact assessment

Research will be further intensified on how to extend the application of reusable launcher technologies beyond conventional satellite transport in order to surge the available market and hence to reduce production cost as well as increase investment funding. International cooperation in this field with public and private partners is key to the success.

Further, the Institute intends to develop a Virtual Launcher software for the CEF in collaboration with the DLR facility Simulation and Software Technology. It will be based on the already existing Virtual Satellite software, currently in use in the CEF. The goal is to enhance the capabilities of the CEF to cater to the specific needs of launcher studies. The main difference between launcher and satellite studies are twofold. First, the standard disciplines that are involved differ. Secondly, launcher design is a more sequential process than satellite design, where many analyses can be performed in parallel. A crucial aspect of launcher design is the trajectory analysis and with that the calculation of the payload mass that a specific launcher can deliver into a given orbit. The trajectory analysis also provides the loads that act on the structure of the launcher. Often other disciplines require this kind of data for their own calculations. A good example is the interaction between trajectory and structural analysis. The structural analysis requires knowledge of the loads, while the structural masses are an essential input to the trajectory analysis. A way to facilitate this more sequential approach is the introduction of the software Remote Component Environment (RCE), which is a workflow-driven integration environment. RCE has been developed by the DLR facility Simulation and Software Technology. First modifications that address specific needs of the Expertise Raumtransportsysteme (X-TRAS) group and its launcher studies are already on their way. Moreover, the basic requirement for the Virtual Launcher is a data model that hierarchical structures the design parameters of a launch vehicle. The definition of such a data model has already begun in cooperation with other DLR institutes within the X-TRAS group.

5.3 System Development

The Institute has, with its three major missions Automatic Identification System Satellite (AISat), Mobile Asteroid Surface Scout (MASCOT), and Euglena and Combined Regenerative Organic-Food Production in Space (Eu:CROPIS), proven its system competency and also successfully set the foundation for building space platforms. These concepts can be applied to numerous mission architectures because of their flexible design, allowing the accommodation of various scientific experiments.

In the field of small satellites, the DLR sets itself the objective to develop and operate a standard satellite bus within the ESA S-class missions. This satellite bus for technical demonstrations and science missions can be adapted to various missions and applications. The technical basis for all future DLR research and development missions consists of two efficient satellite bus systems, which cover a wide operational area: S2TEP and the Compact Satellite bus. Synergy effects of both satellite busses shall be developed in concepts, which are based on flexible, adaptable, and scalable architectures, miniaturization, autonomy and process automation (for example in testing and verification). Furthermore, the ability to handle the whole system shall be increased by accompanying research for the whole process, from the preliminary draft up to the operation of the space vehicle by employing progressive methods. The target is to create a variable and flexible structure which enables a quick and cost-effective development of a small satellite. This shall be achieved by utilizing innovative technologies in core avionics as well as innovative design, verification, and operation methods. Mid-term flexibility has to be improved to expand the envelope of tolerable disturbances and to compensate for failures and malfunctions. This will increase the reliability and safety of the missions.

One of the future ambitious S2TEP missions shall perform global and dynamic monitoring of the atmosphere (for example determine the sources and sinks of CO_2); thus requiring a constellation of small satellites and swarm flight of satellites. Therefore, modern concepts of communication (i. e., data transfer) and navigation with autonomy are required and will be reflected in the main research field of the Institute.

In addition to flexibility, continuous system optimization will be investigated to increase robustness either on system or subsystem level. On system level, a sophisticated modular mechanical design is currently under investigation. It shall provide a high level of adaptability to changing accommodation needs. This is an important aspect for satellites and landing systems.

A further research focus is put on the design and development of a robust thermal control system to cope with the wide temperature ranges within a space mission's lifetime. Based on an extensive survey and the characterization of thermal control elements, new subsystem designs will be developed. This also includes the development of customized solutions for specific components. Analysis tools, taking into account all gained data, shall allow for an accurate analysis and a fast adaption to changing mission scenarios and boundary conditions. The main goals are the development of a thermal control system which is robust against or which can easily be adapted to changing boundary conditions for space applications like S2TEP or future MASCOT concepts.

Figure 5.5: Asteroid landing package MASCOT integrated into the Hayabusa2 mother spacecraft.

DLR has achieved a historical milestone with the worldwide recognized Philae lander within the Rosetta Mission and has expanded its expertise in small body exploration with the MASCOT lander onboard Hayabusa2 (HY2). Within the next five to ten years new international flight missions lead by ESA, National Aeronautics and Space Administration (NASA), or Japanese Aerospace Exploration Agency (JAXA) with destinations such as asteroids, Mars, and Moon will be realized. Examples of these are NASA/ESA's Asteroid Impact and Deflection Assessment (AIDA) or JAXA's Mars Moon Exploration (MMX) mission. The target of the Institute is to participate in cooperation with other institutions in at least one of these missions with a landing element from the MASCOT development line, hence approximately a 10 to 30 kg MASCOT derivative. However, the Institute is well equipped to also develop landers in the Philae class (approx. 100 kg) or new micro landing systems for missions to Mars. It will thereby contribute its expertise in system development and technologies such as landing technologies, attitude and orbit control/guidance, navigation and control systems, and thermal control systems. In this context, lessons learned with MASCOT and Philae shall be applied to develop more robust concepts being able to cope with the unknown and/or harsh environment on the surface of a planet or small body. Improvements of the system ability such as long survivability (i. e., several months) under wide temperature variation, high-precision landing, and relocation capability (such as mobility with a higher degree of freedom) are, among others, foreseen for the next lander concepts.

Flight tests within the Reusability Flight Experiment (ReFEx) program with the focus on reusability provide technical and scientific contributions to the development of complete, reusable space systems. The technical and scientific goals comprise contributions such as thermally high-stressed structures and materials, controllability and maneuverability, aerodynamic experiments, flight instrumentation and sensors, navigation, and control. DLR's aim is to provide technologies of high maturity in further national and international programs. In this regard, the Institute's strategy and a next step in the RLV technology is a liquid propelled flight demonstrator, ReFEx II. The concept foresees an enlarged aeroshell and will enable verification of reusability of TPS and operational aspects. The focus of the Institute will be the systems engineering and the GNC of the vehicle.

5.4 System Technologies

Next generation launchers demand for advanced technologies to meet future mission requirements and to survive in the global launcher market by reducing launch costs. Reusability is a major challenge for the future. Fundamental key technologies are the intelligent and efficient propellant management, accurate and precise navigation, and effective and fault tolerant avionic systems.

The knowledge and understanding, as well as the application of intelligent propellant management technologies is one of the essential challenges for the successful design and realization of future advanced cryogenic upper stage systems. The aim is to meet future needs concerning more mission flexibility such as multiple restart options paired with long-duration ballistic flight phases (see section 4.4). In cryogenic tank systems, multifaceted complex flow and thermal effects arise (3D, two phase/two species, phase change, sloshing, boiling, stratification, wall effects, convection, varying g-level). The knowledge and deep understanding of the propellant behavior is of fundamental importance for the design of required propellant management technologies. External influences (heat input, forces) during the mission cause independent or coupled flow phenomena which have a non-negligible critical impact under certain conditions and are therefore referred to as critical flow phenomena. For a reliable and optimal design of launcher systems appropriate, validated tools are an indispensable basis. The calculation, prediction, and analysis of the fluid behavior in tank systems are a major challenge for the computational fluid dynamics (CFD) tools, even today.

The next goal is to develop and validate propellant management technologies to meet future mission needs such as multiple re-ignitions, ballistic flight phases, and long-duration missions. A current focus of development in Europe is propulsion using LOx/methane. Our aim is to solve the research questions regarding the fuel handling of methane in tank systems.

Future mission scenarios will require an increase in cryogenic propulsion technologies for orbital applications (refilling of cryogenic orbital upper stages, cryogenic landing vehicles, cryogenic transfer stages). The cryogenic propellant management of long ballistic phases, long-term storage, zero-boil-off techniques and refilling in orbit are essential topics of future research activities. Therefore, the ultimate goal is to prepare a flight experiment demonstrating these cryo technologies. In addition, the payload shall provide data of cryogenic fluid experiments under microgravity to enhance simulation tools.

As a first step, the existing cryo lab shall be extended by a large thermal-vacuum chamber, enabling tests on cryo-components. The chamber allows experiments within a well-defined space-equivalent environment, which permits tests with highly scaled launch vehicle tanks and explosion-prone liquids like hydrogen and methane. Furthermore, parts of the launchers functional propulsion system, like piping and valves, can be investigated in a safe environment.

Figure 5.6: Tank demonstrator provided by Airbus DS on the hexapod for investigation of coupled flow phenomena.

The avionics domain provides a library for on-board-software simplifying telemetry/telecommand (TM/TC) handling including holistic monitoring from debugging, through integration to operations. Besides core software components, a scalable base-level design for an on-board computer will gain heritage as a secondary payload with the launch of the mission Eu:CROPIS in 2017. High-profile research results in design automation for hardware systems and cyber-physical systems with a focus on reliability complement the practical technical solutions. This includes tools for automating diagnosis and techniques supporting designers in understanding their hardware design. Based on these experiences and results, the Institute actively engages in standardization groups of ESA like the initiative for the Space AVionics Open Interface aRchitecture (SAVOIR) standardization or Consultative Committee for Space Data Systems (CCSDS) in wireless technology.

Future research in the avionics domain continues to focus on automation and scalability. Particularly, a model-based development will be enabled along with S2TEP including software aspects for on-board and ground data handling and is firmly rooted in the existing developments for Eu:CROPIS. The underlying technology will be based on a networked computer architecture allowing for high-performance, high-availability, and high-reliability. Wireless technology for use on board, targeting an International Space Station (ISS) experiment in 2018 as well as an experiment on S2TEP, and during assembly, integration, and test (AIT) campaigns for simplification of the test setup, is actively researched.

In the domain of GNC the technologies for entry, descent, and landing (EDL), as well as for rendezvous and docking (including on-board servicing), and swarm flight of satellites shall be matured.

The GNC subsystem for EDL is influenced by the environment properties of the targeted celestial body (Earth, Moon, asteroid, planet), but there is a common denominator of similar principle that can be exploited in most EDL applications.

Earth-bound vehicles and space transportation systems — especially RLVs — can rely on terrestrial infrastructure (such as global navigation satellite system (GNSS)). The Hybrid Navigation System (HNS) capitalizes on this advantage and will be further matured to a fully one-failure tolerant, highly reliable navigation system for future RLVs. Its first operational use on the mission ReFEx will flight-qualify this technology for future use in European space transportation systems.

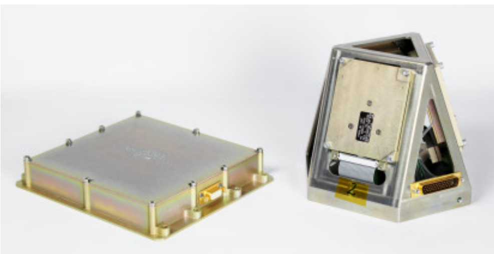


Figure 5.7: Engineering model (EM) of the Eu:CROPIS inertial measurement unit (IMU) (right) with the supporting electronics box (left).

The mission ReFEx and its follow-on missions will also demonstrate and verify new guidance and control methods for re-entry, aerodynamic flight, and landing. The central goal is to develop more flexible guidance and control systems that are able to dynamically adapt to environmental changes, system parameter changes, strong state perturbations, and emergency situations. A first step in that direction is the on-board adaption of optimal reference trajectories, which will be demonstrated with ReFEx. The next crucial step is to obtain the capability to perform on-board optimization. This will enable a new generation of guidance and control systems that will vastly expand the robustness, flexibility, and accuracy of the current state-of-the-art, and open new possibilities for in-flight load and relief management.

A perfect environment to test GNC technologies for powered descent and landing — as well as ascent — is the vehicle Environment for Autonomous

GNC Landing Experiments (EAGLE). It completes the experimental spectrum for EDL technologies of RLVs. Similarly, guidance and control techniques for EDL on asteroids, moons, and planets will be developed and tested with EAGLE using the same underlying principles, like optimal control. In order to increase the flight envelope and payload capacity of EAGLE, the development of a larger version with a take-off weight in the order of 150 kg is planned. A safe pin-point landing outside Earth's orbit can only be achieved by using the target body as a navigation reference, requiring a navigation architecture fusing data of inertial and optical sensors. The navigation system developed in the project Autonomous Terrain-Based Optical Navigation (ATON) is a realization of such an architecture and will be matured via real-time closed-loop testing on a helicopter flying over a mock-up of lunar terrain in 2017.

This is followed by activities to increase the technology readiness level (TRL) of all it's subsystems to six. The crater navigation will be ported to a radiation-hardened system comprising multi-core application-specific integrated circuit (ASIC) processors and field-programmable gate arrays (FPGA) in the timeframe until 2018. The result will be integrated to a full-scale stand-alone sensor product, providing the spacecraft position and attitude with respect to the target body.

The results of these activities enable the Institute to provide navigation systems for exploration missions. For achieving the ability to land on any solid body in the Solar System, the logical next steps are contributions to missions with increasing difficulty. Consequently, the Institute wants to contribute the navigation system to small body landing missions, such as the MMX mission of JAXA, the mission AIDA of ESA and NASA, and for upcoming lunar landers.

Clusters of small satellites in low-Earth orbits (LEO) are one vision for future communication and Earth observation systems. The future research will focus on scalable GNC algorithms which maintain satellites in a formation or cluster with limited information and independently of the number of spacecraft in the cluster. The verification and demonstration of these methods will be carried out in Test Environment for Applications of Multiple Spacecraft (TEAMS). In-orbit demonstration and verification of these technologies is planned with future S2TEP missions forming a satellite formation. Similarly, GNC techniques for rendezvous and docking, as well as proximity operations needed for on-orbit servicing missions will be researched. With TEAMS, the perfect ground-based environment is ready for lab demonstration of new developments in this area. In-orbit demonstration will be achieved with same formation-flying mission based on S2TEP.

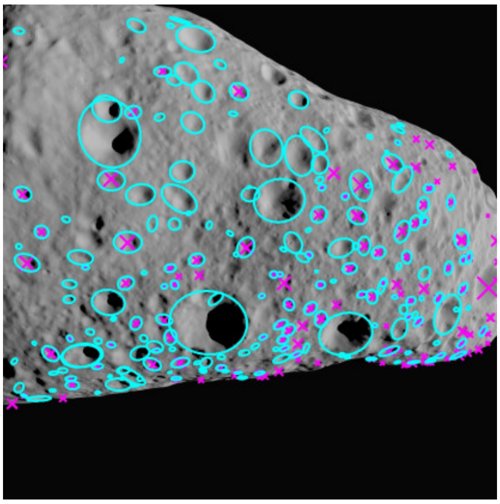


Figure 5.8: Crater navigation during approach to Eros. Turquoise ellipses: detected craters, pink crosses: craters in database. Overlapping symbols indicate a match between detected craters and the database used for navigation.

The capability to reliably land a spacecraft on a planetary surface or return it to Earth becomes an integral part of an increasing number of upcoming missions. The increased demand for this technology is driven by the desire to do in-situ science on planetary surfaces, return samples or experiments to Earth, or return launcher components to Earth for their re-use. The Institute extends its existing knowledge in the design, development, and verification of landing gear subsystems for planetary landers to reusable launch vehicles. A demonstration flight experiment for this application is foreseen as part of the project ReFEx.

The Institute will furthermore develop its knowledge about planetary habitat technologies and life support systems. One flagship mission is the upcoming EDEN-ISS mission in 2018. The EDEN-ISS greenhouse will be operated at Neumayer Station III in Antarctica to establish the groundwork for greenhouse usage on the ISS or on planetary missions. Based on this foundation, further life support projects are planned in order to investigate the usage of these systems in planetary surface infrastructures. In accordance with the goal of supporting long-term planetary crewed missions, the design of the Incubator for Habitation (I4H) will be further detailed with the aim of establishing a centralized research facility for coordinated development of habitat technologies. This approach goes along with the present Moon Village plans of ESA. This will allow progress in the field of space exploration, but also in the field of terrestrial application of closed-loop technologies to achieve a reduction of the human environmental foot print and to improve the living conditions in adverse environments (e. g. deserts) and highly populated urban regions (e. g. by application of urban or vertical farming).

The already successfully flying first small body landing system concept MASCOT— asteroid diameter around 0.9 km, landing velocity approximately 0.15 m/s — is complemented by a crushable shell. Such an energy-absorbing hull enables MASCOT successors to land with larger velocities on larger minor bodies — trojan asteroids, Martian moons with landing velocities of about 4 m/s.

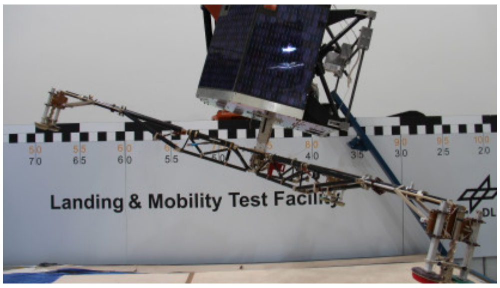


Figure 5.9: Landing tests of the comet landing vehicle Philae in the Landing & Mobility Test Facility (LAMA).

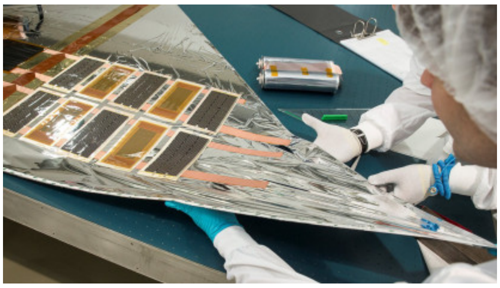


Figure 5.10: Application of thin-film solar cells on a deployable membrane.

These landing legs and energy-absorbing shells address the touchdown part of landing sequence. A new development line for advanced deployable aerodynamic decelerator devices is established to fill the portfolio gap of DLR between the touchdown phase and the preceding atmospheric entry phase. This technology will be contributed as enabling element particularly to micro probes for atmospheric planetary landings. An application example under investigation is the Mars Micro Lander concept in the mass range of 25 to 50 kg.

Landing system hardware components and/or engineering and qualification expertise is contributed also to large international missions such as the MMX mission of JAXA. These contributions are in addition to DLR-lead missions with a system mass in the range of 10 to 100 kg.

Future missions such as space-tug applications with high-power electrical propulsion systems in the class of 50 to 100 kW are foreseen. For in-space power generation, large photovoltaic arrays are an essential need. Using conventional solar arrays would inevitably lead to very high overall masses affecting launch masses and operational constraints. Therefore, a lightweight energy supply is mandatory.

Ultra-lightweight gossamer structures with thin-film photovoltaic or flexible, conventional photovoltaic offer the chance of deploying large, membrane arrays with a low-mass-to-power ratio. In order to generate 50 kW per array, sizes of 20 m × 20 m assuming low-efficient photovoltaic cells are realistic. A mass-to-power-ratio of 6 kg/kW and lower seems feasible according to first investigations of this technology compared to 8 kg/kW and higher for conventional technologies.

An in-orbit demonstration of a scaled deployable gossamer structure with photovoltaic surfaces, named Gossamer Solar Array (GoSolAr) is envisaged as part of one of the first S2TEP missions. It will have a size of 5 m × 5 m leading to 25 m² array size and will experimentally provide power to the satellite bus for technology demonstration purposes. The demonstrator design is scalable and will allow to achieve array sizes of up to 400 m² producing approximately 50 kW electrical power. For that purposes, intensive investigations on deployment system and photovoltaic membrane design are to be performed.

For future space missions in navigation, communication, Earth observation and science, new optical technologies and quantum technologies are of great interest, promising higher performances in space, time, and acceleration measurement sensitivity. Possible applications are multifunctional satellites that simultaneously measure space, time, and acceleration via optical clocks and inertial sensors and communicate with each other via optical links. One demanding application is the third generation of Galileo.

The Institute of Space Systems develops optical frequency references such as high-performance optical clocks (see section 4.5.2) and laser ranging technologies for distance and tilt metrology based on laser interferometry between satellites (e. g. for Gravity Recovery and Climate Experiment Follow-On (GRACE-FO), see section 4.5.1). Inertial sensors using microscopic (atom interferometry technology), mesoscopic (opto-mechanical cantilever technology) and macroscopic (cubic and spherical) test masses are developed, built, and tested up to engineering models.

For on-orbit verification of these quantum sensors, technology demonstration missions are planned for the upcoming years.

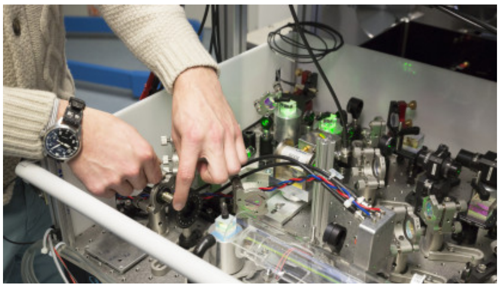


Figure 5.11: Fine adjustment of an optical setup for laser frequency stabilization, which serves as a stable laser source for the high-resolution thermal characterization of new materials.

5.5 Concluding Remarks

In the last decade, the Institute of Space Systems, with its many research activities, has created a sound basis to respond adequately to the different needs and aspects of future spaceflight. As such, it was acting in a field of global challenges while maintaining its competitiveness and performing excellent science.

Capabilities have been established to analyze, develop, launch, and operate flight hardware in any orbit, supported by newly installed research infrastructures as well as utilizing any available means to test emerging technologies for instance with sounding rockets, high-altitude balloon, and/or zero-g-flights. This has put the Institute into the position to acquire high-quality knowledge, well recognized by the scientific community.

Based on this expertise, the next decade will see the Institute focusing on further improving skills and capabilities for both, system and technology development in the next decade. This covers the project management and systems engineering, integration, verification, and qualification of space assets as well as developing small satellites for scientific applications in accordance with the newly established DLR Satellite Roadmap. In addition, increased cooperation with the other DLR research fields "Aeronautics", "Energy", and "Transportation" will generate unique synergies.

Based on the three identified columns, *system analysis*, *system development*, and *system technologies*, the Institute is in the position to further enhance its capabilities of innovative space research, ranging from basic principles to product development in cooperation with space industry in an international context.

6 Key Figures

6.1 Awards

Person	Award	Year
Arslantas, Yunus Emre	IAF-Emerging Space Leaders Grant	2014
Hartkopf, Stephan	ZARM Förderpreis 3. Preis	2014
Heise, Christian David	ZARM Förderpreis 2. Preis	2012
Schwanekamp, Tobias	Best Paper Award von AIAA / Thema: Active Cooling	2014
Schwarz, René	Student Research Award of the Merseburg University of Applied Sciences	2009
Steinbach, Jan Phlipp	ZARM Förderpreis 1. Preis	2010
Weiß, André; Romberg, Oliver	DLR-Wettbewerb der Visionen 2011 (1. Platz)	2011
van Foreest, Arnold	Best Paper Award von AIAA / Thema: Active Cooling	2008

6.2 Patents

6.2.1 Granted Patents

Patent No.	Patent	Inventors	Granted
AU002012228397 (A1)	Satellite communication network	Behrens, Jörg; Delovski, Toni; Hauer, Lars-Christian; Werner, Klaus	2013
AU002012228398 (A1)	Satellite having a plurality of directional antennas for transmitting and/or receiving air-traffic control radio signals	Behrens, Jörg; Delovski, Toni; Hauer, Lars-Christian; Werner, Klaus	2013
CA000002829817 (A1)	SATELLITE COMMUNICATION NETWORK	Behrens, Jörg; Delovski, Toni; Hauer, Lars-Christian; Werner, Klaus	2012
CA000002829821 (A1)	SATELLITE HAVING A PLURALITY OF DIRECTIONAL ANTENNAS FOR TRANSMITTING AND/OR RECEIVING AIR-TRAFFIC CONTROL RADIO SIGNALS	Behrens, Jörg; Delovski, Toni; Hauer, Lars-Christian; Werner, Klaus	2012
CA2848467 (A1)	Support System	Behrens, Jörg; Hauer, Lars; Suhr, Birgit	2013
DE102008004496 (A1&B4)	Seezeichen	Behrens, Jörg	2011
DE102008026415 (A1)	System zur Überwachung von Bewegungen von Flugkörpern im Luftraum	Behrens, Jörg; Schnell, Michael; Werner, Klaus	2009
DE102011013717 (A1)	Satelliten-Kommunikationsnetzwerk	Behrens, Jörg; Delovski, Toni; Hauer, Lars-Christian; Werner, Klaus	2012
DE102011013737 (A1)	Satellit	Behrens, Jörg; Delovski, Toni; Hauer, Lars-Christian; Werner, Klaus	2011
DE102011113153 (A1)	Unterstützungssystem	Behrens, Jörg; Hauer, Lars; Suhr, Birgit	2013
DE102012110540 (A1)	AIS-Schiffstransceiver	Behrens, Jörg; Dembovskis, Andis	2014
DE102012110541 (A1&B4)	AIS marine transceiver detects a rogue base station	Behrens, Jörg; Dembovskis, Andis	2016
DE102013101730 (A1)	Method and devices for unambiguously identifying an object	Behrens, Jörg; von Kopylow, Christoph; Dankwart, Collin; Falldorf, Claas	2014
EP000002684299 (A1)	SATELLITEN-KOMMUNIKATIONSNETZWERK	Behrens, Jörg; Delovski, Toni; Hauer, Lars-Christian; Werner, Klaus	2012
EP000002684300 (A1)	SATELLIT MIT EINER MEHRZAHL VON RICHTANTENNEN ZUM SENDEN UND/ODER EMPFANGEN VON FLUGSICHERUNGS-FUNKSIGNALEN.	Behrens, Jörg; Delovski, Toni; Hauer, Lars-Christian; Werner, Klaus	2014

EP000002728564 (B1&A3&A2)	AIS-Schiffstransceiver	Behrens, Jörg; Dembovskis, Andis	2016
EP000002728920 (A1)	AIS-Schiffstransceiver erkennt eine gefälschte Basisstation	Behrens, Jörg; Dembovskis, Andis	2014
EP000002756492 (A1)	Unterstützungssystem	Behrens, Jörg; Hauer, Lars; Suhr, Birgit	2014
EP2980771 (A1)	AIS MARINE TRANSCEIVER	Behrens, Jörg; Dembovskis, Andis	2016
US000008730124 (B2)	Self-deploying helical antenna	Behrens, Jörg; Block; Joachim; Hauer, Lars-Christian; Schütze, Martin; Schütze, Rainer; Spröwitz, Tom	2014
US000009252871 (B2)	AIS-Schiffstransceiver	Behrens, Jörg; Dembovskis, Andis	2016
US000009258795 (B2)	AIS ship's transceiver	Behrens, Jörg; Dembovskis, Andis	2016
US020140128098 (A1)	AIS ship's transceiver	Behrens, Jörg; Dembovskis, Andis	2014
US020140232599 (A1)	Method and devices for unambiguously identifying an object	Behrens, Jörg; Dankwart, Collin; Falldorf, Claas; von Kopylow, Christoph	2014
US2012146880 (A1)	Self-Deploying Helical Antenna	Behrens, Jörg; Block, Joachim; Hauer, Lars-Christian; Spröwitz, Tom; Schütze, Rainer; Schütze, Martin	2012
US2014002293 (A1)	SATELLITE COMMUNICATION NETWORK	Behrens, Jörg; Werner, Klaus; Hauer, Lars; Delovski, Toni	2016
US2014004791 (A1)	SATELLITE HAVING A PLURALITY OF DIRECTIONAL ANTENNAS FOR TRANSMITTING AND/OR RECEIVING AIR-TRAFFIC CONTROL RADIO SIGNALS	Behrens, Jörg; Werner, Klaus; Hauer, Lars; Delovski, Toni	2014
US20140218232 (A1)	Support System	Suhr, Birgit; Behrens, Jörg; Hauer, Lars	2014
US2014127990 (A1)	AIS-Schiffstransceiver	Dembovskis, Andis; Behrens, Jörg	2014
WO002012123360 (A1)	SATELLITEN-KOMMUNIKATIONSNETZWERK	Behrens, Jörg; Delovski, Toni; Hauer, Lars-Christian; Werner, Klaus	2012
WO002012123361 (A1)	SATELLIT MIT EINER MEHRZAHL VON RICHTANTENNEN ZUM SENDEN UND/ODER EMPFANGEN VON FLUGSICHERUNGS - FUNKSIGNALEN	Behrens, Jörg; Delovski, Toni; Hauer, Lars-Christian; Werner, Klaus	2012
WO002013037954 (A1)	Unterstützungssystem	Behrens, Jörg; Hauer, Lars; Suhr, Birgit	2012
DE10138250	Tragendes Bauteil in Sandwichbauweise	Romberg, Oliver	2008
DE102008048965	Mikroturbinengeneratoren für den Einsatz in Energieversorgungssystemen von Satelliten	Schubert, Daniel	2009
DE102011050545	Transportable Pflanzenanbaueinrichtung für abgelegene Orte	Schubert, Daniel	2011
DE102012000260	Solargenerator	Bauer, Waldemar; Romberg, Oliver	2012
US8593165 B2	Solar Generator	Bauer, Waldemar; Romberg, Oliver	2013
DE102012112080	Solargenerator	Bauer, Waldemar	2014
DE102012112081	Vorrichtung zur Ausrichtung eines mit einem Raumfahrzeug verbunden Solarpaneels relativ zu einer Strahlenquelle	Bauer, Waldemar; Kopp, Alexander	2014
DE102012110450	Objekt für eine Mission in den Weltraum	Bauer, Waldemar; Dumont, Etienne	2014
DE102010024329 B4	Scramjet Triebwerk mit einem dem Triebwerkseinlauf vorgeschalteten Treibstoffzufuhrmittel	Kopp, Alexander	2014
DE102012112081 B3	Vorrichtung zur Ausrichtung eines mit einem Raumfahrzeug verbundenen Solarpaneels relativ zu einer Strahlenquelle	Kopp, Alexander; Bauer, Waldemar	2014
DE102009036518 B4	Raumfahrt-Flugkörper und Verfahren zur Durchführung eines Landevorgangs desselben	Dietlein, Ingrid	2014
DE102008039981	Vorrichtung zur anteiligen Kompensation der Schwerkraft auf ein Testobjekt	Witte, Lars	2010
DE102013218427	„Phönixbox“ (thermal-electric power generation)	Rosta, Roland	2016
DE102010018756	Fortbewegungsmechanismus zum Erkunden von Himmelskörpern mit geringer Gravitation	Lange, Caroline	2010
DE202011000463	Adaptives Rad mit elastisch verformbarer Lauffläche	Lange, Caroline	2011

NL2009635C	A method for controlling a formation of spacecraft, and a system for formation flying of spacecraft	de Bruijn, Frederik; Gill, Eberhard	2014

6.2.2 Pending Patents

Patent No.	Patent	Inventors	Registration
DE102010001112	Raumfahrt-Nutzlastmodul	Romberg, Oliver; Wagenbach, Susanne	2010
DE102011054400	Stickstoff-basierter Kreisprozeß zur Energiegewinnung während einer lunaren Nacht	Weiß, André	2011
FR1360527	Objekt für eine Mission in den Weltraum	Bauer, Waldemar; Dumont, Etienne	2013
DE102010018756	Erkunden von Himmelskörpern mit geringer Gravitation	Quantius, Dominik; Krömer, Olaf; Schader, Nils	2010
DE102012217485	Vorrichtung und Verfahren zur Kompensation der Schwerkraft	Reershemius, Siebo; Spröwitz, Tom; Spietz, Peter	2012

6.3 Contributions to the Scientific Community

6.3.1 (Co-)Organized Conferences & Workshops

Conference/Workshop	Date	Location	Role
Agrospace Conference 2014 and White Paper Workshop	May 22–23, 2014	Sperlonga, Italy	Organizer
Agrospace Conference 2016	May 24–26, 2016	Sperlonga, Italy	Organizer
DEMOCRITOS Conference	January 26–27, 2016	Turin, Italy	Co-Organizer
ESA Systems Engineering and Concurrent Engineering (SECESA) 2010	October 13–15, 2010	Lausanne, Switzerland	Co-Organizer
ESA Systems Engineering and Concurrent Engineering (SECESA) 2012	October 17–19, 2012	Lissabon, Portugal	Co-Organizer
ESA Systems Engineering and Concurrent Engineering (SECESA) 2014	October 8–10, 2014	Stuttgart, Germany	Co-Organizer
International Society of Terrain-Vehicle Systems, 11th European Conference	2009	Bremen	Organizer
SpaceLiner Design Workshop	2010 – 2016	Bremen	Organizer
Systems Engineering Mini Symposium – Exploration	December 2011	Bremen	Organizer
Systems Engineering Mini-Symposium – Launcher	2009	Bremen	Organizer
Systems Engineering Mini-Symposium – Satellites	2010	Bremen	Organizer
Systems Engineering Mini-Symposium – System Analysis	2008	Bremen	Organizer

6.3.2 Review Activities

Person	Journal/Project	Date	Role
Bamsey, Matthew	Biotechnology and Applied Biochemistry	2014	Reviewer
	Open Agriculture - Guest Editor - Topical Issue: Space Agriculture	2016	Reviewer
Bauer, Waldemar	Acta Astronautica	since 2014	Reviewer
Braukhane, Andy	Journal of Space Science and Engineering	2011	Reviewer
Braxmaier, Claus	FSM Proceedings	2015	Reviewer
de Bruijn, Frederik	Acta Astronautica	since 2014	Reviewer
	IEEE Transactions on Aerospace and Electronic Systems	since 2014	Reviewer
	Advances in Space Research	2014 – 2015	Reviewer
Heidecker, Ansgar	CEAS Space Journal	2013	Reviewer

Maiwald, Volker	CEAS	2016	Reviewer
	Advances in Space Research	2015	Reviewer
Philpot, Claudia	ISS R&D Conference	2014	Reviewer
	IEEE Transactions on Aerospace and Electronic Systems	2014, 2016	Reviewer
Sagliano, Marco	AIAA Scitech Conference	since 2015	Reviewer
Scharringhausen, Marco	Advances in Space Research	2015	Reviewer
Schuldt, Thilo	Measurement Science & Technology	2013, 2015	Reviewer
	Review of Scientific Instruments	2015	Reviewer
	Optics Express	2015	Reviewer
	Optics Letters	2013 – 2015	Reviewer
	Int. Journal of Optomechatronics	2013	Reviewer
Sippel, Martin	Acta Astronautica	since 2008	Reviewer
	CEAS Space Journal	since 2011	Reviewer
	EUCASS book Progress in Propulsion Physics	since 2015	Reviewer
Theil, Stephan	Journal of Guidance, Control and Dynamics	2012 – 2013	Reviewer
	Acta Astronautica	since 2010	Reviewer
	Advances in Space Research	since 2010	Reviewer
	CEAS Space Journal	since 2012	Field Editor
Witte, Lars	Acta Astronautica	since 2012	Reviewer

6.3.3 Scientific Exchange

Person	Sending Organization	Receiving Organization	Period	Funding
Benvenuto, Riccardo	Politecnico di Milano	DLR	2016/01 – 2016/06	Politecnico di Milano
David, Emmanuelle	DLR	ESA Launcher Direktorat, Paris	2014/03 – 2016/12	Vorstand Raumfahrt und ESA
de Castro Leite Filho, Waldemar	IAE/CTA Brasilien	DLR	2014/09 – 2014/12	DAAD
di Mauro, Giuseppe	Politecnico di Milano	DLR	2012/06 – 2012/09	Politecnico di Milano
Dietlein, Ingrid	DLR	United Nations Office for Outer Space Affairs (UNOOSA), Vienna	2011/06 – 2012/06	Vorstand Raumfahrt
Dong, Chen	Beihnag University	DLR	2015/08 – 2016/09	China Scholarship Council
Nebelecky, Chris	University at Buffalo	DLR	2009/10 – 2010/07	DAAD
Yamashiro, Ryoma	JAXA	DLR	2011/11 – 2012/10	JAXA
Zabel, Paul	TU Dresden	DLR	2014/03 – 2016/03	NPI, Esa

6.3.4 Committees

Person	Organization	Role	Period	Appointed by
Bamsey, Matthew	AIAA - Life Sciences and Systems Technical Committee	Committee Member	since 2014	AIAA
David, Emmanuelle	D2 Space Transportation Comitée IAC	Deputy Chair Woman	since 2013	Election
Romberg, Oliver	ESA Systems and Concurrent Engineering Committee (SECESA)	Committee Member	since 2008	ESA
Schubert, Daniel	Agrospace Conference Review Board	Head of Technical Commitee	2014–2016	Aerosekur, Italy
	German Bioeconomy Council	Member	2015	German Federal Government
Sippel, Martin	D2 Space Transportation Comitée IAC	Committee Member	since 2008	Election
	EUCASS Paper Selection	Committee Member	since 2011	EUCASS
	ESA Aero-Thermodynamic Conference	Committee Member	since 2013	ESA

Theil, Stephan	IAF Astrodynamics Committee	Committee Member	since 2016	IAF
	CEAS Technical Comittee Guidance, Navigation and Control	Committee Member	since 2011	CEAS
	CEAS Technical Comittee Guidance, Navigation and Control	Co-Chair	since 2015	CEAS
	ESA GNC Conference Program Committee	Committee Member	since 2008	ESA

6.4 Teaching and Education

6.4.1 University Courses

Lecturer	University	Subject	07/08	08/09	09/10	10/11	11/12	12/13	13/14	14/15	15/16
Braukhane, Andy	Strassburg, Frankreich (ISU)	MBSE in Concurrent Engineering						■			
Braxmaier, Claus	Univ. Bremen	Raumfahrttechnologie 1							■	■	■
Fey, Görschwin	Univ. Bremen	Informatik für den Satellitenbau und On-board Data Handling						■	■	■	■
	Univ. Bremen	Rechnerarchitektur und Eingebettete Systeme						■	■	■	
	Univ. Bremen	Qualitätsorientierter Systementwurf						■	■	■	■
Hallmann, Marcus	Univ. Bremen	Raumflugmechanik	■	■	■	■					
	Univ. Bremen	Missionsanalyse					■	■	■	■	■
Maiwald, Volker	Univ. Bremen	Raumflugmechanik				■	■	■	■	■	■
Quantius, Dominik	Univ. Bremen	Raumflugmechanik				■	■	■	■	■	■
Rittweger, Andreas	Univ. Bremen	Strukturentwurf und -analyse von Raumfahrzeugen								■	■
Romberg, Oliver	Univ. Bremen	Lehrprojekt "Very Large Orbital Structures"								■	■
	Univ. Bremen	EDV-Projekt "Trajectory Optimisation"								■	
Scharringhausen, Marco	Univ. Bremen	Klassische Himmelsmechanik									■
	Univ. Bremen	Physik des Sonnensystems									■
	Univ. Bremen	Abriss der Astrophysik								■	
	Univ. Bremen	Klassische Himmelsmechanik								■	
	Univ. Bremen	Physik des Sonnensystems							■		
	Univ. Bremen	Klassische Himmelsmechanik							■		
	Univ. Bremen	Physik des Sonnensystems						■			
	Univ. Bremen	Abriss der Astrophysik						■			
	Univ. Bremen	Wissenschaftsmissionen					■				
	Univ. Bremen	Physik des Sonnensystems					■				
Sippel, Martin	Univ. Bremen	Raumfahrtantriebe 1				■	■	■	■	■	■
	Univ. Bremen	Raumfahrtantriebe 2					■	■	■	■	■
	RWTH Aachen	Raumfahrtantriebe			■	■					
Theil, Stephan	Univ. Bremen	Lage- und Bahnregelung		■	■	■	■	■			
	Univ. Bremen	Navigation und Regelung von Raumfahrzeugen							■	■	■
	Univ. Bremen	Raumflugmechanik/Flugmechanik	■								
	Univ. Bremen	Raumflugmechanik II	■								
	Univ. Bremen	Navigation und Regelung I	■								
	Univ. Bremen	Navigation und Regelung II	■								

6.4.2 Summer Schools

Person	Location	Subject	Date
Braukhane, Andy	Strassburg, Frankreich (ISU)	MBSE in Concurrent Engineering	July 7, 2013
Hallmann, Marcus	Alpbach Summerschool	Missionsanalyse	July 2011
	Alpbach Summerschool	Missionsanalyse	July 2012
	Alpbach Summerschool	Missionsanalyse	July 2013
	Alpbach Summerschool	Missionsanalyse	July 2014
	Alpbach Summerschool	Missionsanalyse	July 2015
	Alpbach Summerschool	Missionsanalyse	July 2016
Romberg, Oliver	Varel, deutschland	Spacecraft Development at DLR	September 23–25, 2014
Sanjuan, Josep	Alpbach, Österreich	Quantum Physics & Fundamental Physics in Space	July 2015
Sippel, Martin	DLR Campus, Lampoldshausen	Antriebe und Träger	July 29, 2014

6.4.3 Academic Degrees

Habilitations and Professorial Appointments

Name	Title	Institution	Year
Braxmaier, Claus	Christa und Manfred Fuchs-Stiftungsprofessur für Raumfahrttechnologie	Universität Bremen	2012
Dittus, Hansjörg	Professur für Raumfahrtsysteme	Universität Bremen	2008
Fey, Görschwin	Professur für zuverlässige eingebettete Systeme	Universität Bremen	2012
Geppert, Ulrich	Habilitation "Magneto-thermische- und Rotations-Entwicklung von isolierten Neutronensternen"	Jagiellonian University, Krakau	2011
	Associate Professor	University of Zielona Góra, Poland	2011
	Professur für Physik und Astronomie	University of Zielona Góra, Poland	2016
Hölzel, Matthew	Junior Professor for Parallel Computing for Embedded Sensor Systems	Universität Bremen	2014
Montenegro, Sergio	Professur für Informationstechnik für Luft- und Raumfahrt	Universität Würzburg	2010
Rittweger, Andreas	Professur für Raumfahrttechnik	Universität Bremen	2014

Doctoral Theses

Name	Title	Institution	Year	elib ID
Bauer, Waldemar	Space-Debris-Detektion zur Validierung von Simulations-Modellen	Technischen Universität Carolo-Wilhelmina zu Braunschweig	2015	106604
Dannemann, Frank	Unified Monitoring of Spacecrafts	Universität Würzburg	2015	97728
Dehbashi, Mehdi	Debug Automation from Pre-Silicon to Post-Silicon	Universität Bremen	2013	89523
Dembovskis, Andis	AIS message extraction from overlapped AIS signals for SAT-AIS applications	Universität Bremen	2015	106485
Ludwig, Carina	Analysis of Cryogenic Propellant Tank Pressurization based upon Experiments and Numerical Simulations	University of Bremen	2014	105611
Malburg, Jan	Feature Localization and Design Understanding for Hardware Designs	Universtität Bremen	2015	101515
Sagliano, Marco	Development of a Novel Algorithm for High Performance Reentry Guidance	University of Bremen	2016	103819
Schlotterer, Markus	Robuste Schätzung und Sensorfusion zur Navigation von wiederverwendbaren Raumtransportern	Universität Bremen	2008	57213

Steffes, Stephen R.	Development and Analysis of SHEFEX-2 Hybrid Navigation System Experiment	University of Bremen	2013	82946
Sznajder, Maciej	Degradation of Materials under Space Conditions - Extrapolation of Short Term Laboratory Results on Long Term Space Mission Effects	Universität Bremen	2016	106558
Sznajder, Maciej	Degradation studies of materials under space conditions; under special emphasize of recombination processes.	University of Zielona Góra	2013	102596
Trivailo, Olga	Innovative Cost Engineering Approaches, Analyses and Methods Applied to SpaceLiner – an Advanced, Hypersonic, Suborbital Spaceplane Case-Study	Monash University, Melbourne, Australia	2015	98434
Witte, Lars	Touchdown Dynamics and the Probability of Terrain Related Failure of Planetary Landing Systems - A Contribution to the Landing Safety Assessment Process	University of Bremen	2015	102482
van Foreest, Arnold	Modeling of cryogenic sloshing including heat and mass transfer	Deutsches Zentrum für Luft- und Raumfahrt	2014	105613

Master Theses

Name	Title	Institution	Year	elib ID
Ayoub, Samy	Development of a Power Distribution Unit Controller for the SHEFEX III Navigation System	Cologne University of Applied Sciences	2015	102330
Banerjee, Chirantan	Market analysis for terrestrial application of advanced bio-regenerative modules: Prospects for vertical farming	University of Bonn	2012	105068
Bernabeu Peña, Marc	Study of the European Research Opportunity for the Facility of Laboratories for Sustainable Habitation (FLaSH)	Técnico Lisboa	2015	102372
Bora, Leonardo	Ground Beacons to Enhance Lunar Landing Autonomous Navigation Architectures	Politecnico di Milano	2015	100498
Burow, Rick	Identification of liquid sloshing dynamics by CFD analysis on board of a spin stabilized satellite	Universität Bremen	2016	105893
Chakradhara, Sunayana	Implementing and developing a phasemeter on LabVIEW		2014	103643
Daitx, Henrique	Development of a combined attitude and position controller for a satellite simulator	Cranfield University, UK	2015	100548
Daria, Brysiak	Entwurf eines modularen Roboterarms		2015	102839
Doekhie, Sandra	A computer-based tool for preliminary design and performance assessment of Continuous Detonation Wave Engines	TU Delft	2013	84192
D´Onofrio, Vincenzo	Implementation of Advanced Differentiation Methods for Optimal Trajectrory Computation	University of Naples Federico II	2015	97511
Elsen, Michael	Messung der thermischen Eigenschaften in Mondregolith-Simulat	Institut for Space Systems	2014	103063
Evers, Robin	Modellbildung, Simulation und Verifikation der Aktorik und Sensorik eines Lander-Demonstrators	Universität Bremen	2012	103245
Flenker, Tino	Wörterbuchintegrierung für die Lokalisierung von Verzögerungsfehlern in Logikschaltungen	Universität Bremen	2014	89522
Friese, Peter	Experimentelle Untersuchungen zur Permeation kryogenen Heliums und Wasserstoffs durch Kohlenstofffaserverbundwerkstoffe	DLR Bremen	2014	102449
Gao, Xiao	Charakterisierung der Fehler von Eingebetteten Systemen	Universität Bremen	2014	89521
Geisler, Steffen	Development and design of a level-adjustable seismometer carrier for the alignment of the scientific payload in the Remote-unit of the ROBEX-system	University of Applied Sciences Bremen	2016	103711

Giannoulas, Dimitrios	Assessing the Disruptive Potential of Space Technology Concepts: Development and Application of an Evaluation Method	Technical University of Berlin	2012	78124
Glasgow, Leigh	Phase A Design of an innovative Greenhouse Chamber for Utilization in a Planetary Research Base	Cranfield University	2011	74986
Grimm, Christian	Concept Development and Design of a Flexible Metallic Wheel with an Adaptive Mechanism for Soft Planetary Soils	Luleå University of Technology	2011	94208
Göksu, Murat	Entwurf und Implementierung einer zur Laufzeit konfigurierbaren Logging-Komponente für Satelliten	Universität Bremen	2014	91005
Hamann, Ines	Charakterisierung und Entwicklung von Teilsystemen für ein Dilatometer zur Messung von CTEs dimensional stabiler Materialien	Hochschule Konstanz	2015	103641
Hempel, Johann	Untersuchungen zu Wurzelstützstrukturen in aeroponischen Systemen am Beispiel von Lactuca sativa	Hochschule für Technik und Wirtschaft Dresden	2014	94137
Händel, Tobias	Recovery of Gravitational Fields of Small Bodies from Trajectory Data	University Bremen	2016	106562
Johannsson, Magni	Optimization of Solid Rocket Grain Geometries	Kungliga Tekniska Högskolan/DLR-SART	2012	77294
Kahila, Heikki	Engine exhaust plume interactions with a planetary surface	Aalto University	2014	102814
Kolvenbach, Hendrik	Development of an Atmosphere Management System for Bio-regenerative Life Support Systems	RWTH Aachen	2014	93870
Kudari, Vishwas	Development and Implementation of Methods for Mapping Lunar Impact Craters by Optical Means	Hochschule Darmstadt	2015	103034
Kwiatkowski, Norbert	Entwicklung von Test- und Verifikationsprozeduren für eine hochverfügbare Leistungsversorgungseinheit auf Basis einer Fehlermöglichkeits- und -einflussanalyse	Hochschule Wilhelmshaven	2015	102331
Lange, Alexander-Thomas	Konzeptentwurf einer ereignisbasierten Steuerung für Raumfahrzeuge	Universität Bremen	2015	106555
Lehnert, Christopher	The drivers for the creation of European Adminstrative Bodies in the European Space Sector - Advantages and Disadvantages for Space Situational Awareness		2013	88051
Loui, Stefan	Fehlermodellierung optischer Sensoren mit Anwendung auf die Hinderniserkennung und -vermeidung von autonom agierenden Flugkörpern	Universität Rostock	2014	106324
Malik, Muhammad Shoaib	Design & Analysis of Power and Illumination Subsystems for Greenhouse Module of a Planetary Habitat	Cranfield University	2012	74989
Meyer, Frank	Korrelation und Bewertung eines FE-Modells zum virtuellen Testen des Crashverhaltens von Aluminium-Honigwaben-Sandwichstrukturen innerhalb des Marslander-Projekts	TU Braunschweig	2014	103157
Mikulz, Eugen	Konstruktion und Entwicklung der Thermaleinheit eines Dilatometers zur Charakterisierung von dimensional stabilen Werkstoffen im Temperaturbereich von 80K bis 340K im Vakuum	Uni Bremen	2013	103639
Nagendra, Narayan Prasad	System Analysis & Evaluation of Greenhouse Modules within Moon/Mars Habitats	Institut for Space Systems	2012	103060
Nana Ngongang, Martial	Konstruktion, Auswahl und Analyse einer Crashstruktur für einen planetaren Lander mit hoher Aufsetzgeschwindigkeit	Hochschule Bremen	2015	105092
Nasrullah, Madeeha	Market Analysis of DLR Greenhouse Module for Terrestrial Applications	Institut for Space Systems	2012	103057
Nordmann, Chris	Thermal Analysis of Deployable Membranes for Space Applications	Universität Bremen	2015	102728

Olsen, Morten	Development of Embedded Electronics for Space Debris Detector SOLID	Institut für Raumfahrtsysteme	2013	87916
Opfermann, Thorben	Entwicklung und Implementierung einer Methodik für die Erfassung von Sensor- und Referenzdaten sowie deren Anwendung zur Latenzmessung	Universität Bremen	2015	98569
Otte, Christian	Entwicklung und Implementierung eines AIS-Transceiver-Systems basierend auf einer Xilinx Zynq7000-Plattform	Hochschule Bremen	2015	106472
Rasch, Stefan	Modelling and Validation of a control System for a magnetic Levitation system	Universität Bremen	2015	103557
Schneider, Anton	Numerische Untersuchung der Abstiegs- und Landetrajektorie eines Mars-Mikrolandesystems	Universität Bremen	2016	106323
Schneider, Matthias Martin	Development of a Real-Time Capable Ethernet Gateway for the SHEFEX III Navigation System	Eindhoven University of Technology (TU/e), The Netherlands	2015	97977
Schomakers, Carina	Nichtlineare modellprädiktive Regelung für die Bahnplanung eines Wiedereintrittsproblems	Universität Bremen	2014	101941
Schwarz, René	Development of an illumination simulation software for the Moon's surface: An approach to illumination direction estimation on pictures of solid planetary surfaces with a significant number of craters	Merseburg University of Applied Sciences, German Aerospace Center (DLR)	2012	106532
Schwilling, Benjamin	Konzeptionierung und Auslegung einer induktiven Energieübertragung für robotische Infrastrukturen	Fachhochschule Bingen	2014	104905
Shirran, Colin	Conceptual Layout of an Advanced Nutrient Delivery System (NDS) for Greenhouse Modules on Moon and Mars	School of Engineering; Cranfield University	2013	86825
Singh, Taranjitsingh B.	Feedback Control Design for Weight Offloading of a Planetary Lander by Means of an Industrial Robot	Technical University of Hamburg-Harburg	2016	105091
Stappert, Sven	Reusability of launcher vehicles by the method of SpaceX	DLR	2016	104992
Thielman, Katrin	Hardware-in-the-loop-Testen von Satelliten-on-Board-Komponenten: Design und Implementierung eines Testframeworks		2015	101511
Vrakking, Vincent	Design of a Deployable Structure for a Lunar Greenhouse Module	TU-Delft	2013	86827
Vromen, S.	Design of Convex Guidance for the Final Phase of Satellite Rendezvous	Delft University of Technology	2015	102661
Wartmann, Sebastian	Hard- und Softwareentwicklung für den Space Debris Impaktdetektor SOLID	Institut für Raumfahrtsysteme	2012	87914
van der Veen, Egbert Jan	FORECASTING METHOD FOR DISRUPTIVE SPACE TECHNOLOGIES	University of Groningen	2010	64476

Diploma Theses

Name	Title	Institution	Year	elib ID
Ballatré, Thomas	Heat Conductivity Measurements in Artificial Lunar Soil Samples	Universität Stuttgart	2013	85680
Bartels, Christoph	Software Demonstrator für das NetworkCentric Core Avionics Konzept	Hochschule Bremen	2009	102332
Boden, Ralf	Development, Simulation and Testing of Temperature Sensors for the Attitude Determination of the MASCOT Asteroid Lander	Technische Universität München	2013	102621
Dietze, Claudia	Analyse der Landestrategien eines kleinen Asteroiden-Landers	Technische Universität Braunschweig	2009	106330
Dumke, Michael	Satellite attitude control system for demonstration purposes	TU Braunschweig	2011	101899
Fiebig, Christopher	Modellierung eines Aktor- Sensormodells für die Simulation eines Mondlanderdemonstrators	RWTH AACHEN	2014	103246

Grosse, Jens	Simulation and parameter studies for the conceptual design of a combined thermal and mechanical penetration mechanism for icy planetary bodies	Universität Bremen	2010	103784
Hartkopf, Stephan	Entwurf und Implementierung eines hybriden Navigationssystems für Experimentalanwendungen	Technische Universität Darmstadt	2013	103247
Heidecker, Ansgar	Development of algorithms for attitude determination and control of the AsteroidFinder satellite	Technische Universität Braunschweig	2009	63446
Heise, Christian	Entwurf eines robusten Reglers für ein LPV-System unter Verwendung einer parameterreduzierten Streckenbeschreibung	Technische Universität Kaiserslautern	2011	103248
Jetzschmann, Michael	Entwurf des Kommunikationssystems für den Gossamer-1 Satelliten	Technische Universität Berlin	2013	106471
Klemich, Kai-Sören	Missionsanalyse für den Nanosatelliten CLAVIS	Technische Universität Braunschweig	2011	102374
Löscher, Martin	Untersuchung und Entwurf bemannter Missionen zu Asteroiden	Technische Universität Bremen	2012	78798
Lüpken, Alexander	Machbarkeitsstudie zum Einsatz von Linear Shaped Charges anWiedereintrittsobjekten		2013	102941
Müller, Sven	Entwicklung eines Rahmenwerks zur Nachrichtenprotokollierung für das eingebettete Echtzeitbetriebssystem RODOS	Universität Oldenburg	2012	88788
Novoschilov, Sergej	Pfadplanung und Kollisionsvermeidung für Satellitenformationen und -schwärme	RWTH Aachen	2012	97737
Rumpf, Clemens	Development and Investigation of a Hybrid Navigation Solution for a Lander Demonstrator	Technische Universität Braunschweig	2012	103252
Stämmler, Michael	Auslegung und Inbetriebnahme der Sensorik, Aktorik und Avionik eines terrestrischen Landefahrzeugs	Technische Universität Darmstadt	2010	103253
Wippermann, Torben	Optimization of the InSight HP³-Mole	Technische Universität Braunschweig	2013	103342
Wolf, Andreas	Development of a well-defined monitoring-system to ensure optimized plant production in the DLR Greenhouse Module	Humboldt Universität Berlin	2012	105067
Zabel, Paul	System Analysis & Evaluation of Greenhouse Modules within Moon/Mars Habitats	Technische Universität Dresden	2012	88076
Zeidler, Conrad	Systemanalytische Betrachtung des europäischen ARV Bodensegments unter Berücksichtigung der Life-Cycle-Kosten	Technische Universität Carolo-Wilhelmina zu Braunschweig	2011	74995

Bachelor Theses

Name	Title	Institution	Year	elib ID
Auenmüller, Christoph	Thermal Analysis of Wrinkled Solar Sail Membranes	FH Aachen University of Applied Sciences	2014	102735
Baader, Matthias	Detailed Design and Prototype Construction of the Gassamer-1 Sail Spool Mechanism	University of Applied Sciences FH-Aachen	2013	102733
Bach, Malte	Inbetriebnahme eines Teststandes für ein Turbinentriebwerk und Identizierung der Parameter des Triebwerks	Hochschule Bremen	2012	103244
Birkenmaier, Clemens	Devolopment and Validation of an Electro Magnetic Levitation System for a Spherical Inertial Reference Sensor with Optical Readout	UAS Konstanz	2013	103555
Burow, Rick	Design und Aufbau eines hochsymetrischen Heterodyn-Interferometers	Uni Bremen	2014	103640
Carolin, Hennenberg	Technology Evolution Analysis of Spacecraft's Attitude determination and Control System (ADCS)	Hochschule Bremen	2010	66651
Dmitrij, Justus	Entwicklung einer multifunktionellen und modularen Leichtbau-Satelliten-Struktur		2010	102937

Dorn, Marcus	Analyse von Nutzpflanzen und Anbauverfahren für den Gewächshauseinsatz in extraterrestrischen Habitaten	Hochschule für Wirtschaft und Technik Dresden	2011	74987
Elsen, Michael	Modellierung und Simulation des Hazard-Avoidance-Manövers eines planetaren Landesystems	Hochschule Aachen	2011	106331
Freukes, Christoph	Thermal and Mechanical Investigation of a Preload Release Mechanism for a Space Probe under Laboratory Conditions	Hochschule Niederrhein	2013	104843
Gronow, Sabrina	Temporal evolution of the surface temperature distributions on isolated strongly magnetized neutron stars	University of Bremen	2014	102587
Grässer, Moritz	Entwicklung eines Hypervelocity-Impact-Versuchsaufbaus für den in-situ Detektor SOLID		2012	102936
Hans, Florian	Entwurf eines groben Sonnensensors für Raumfahrtanwendungen	Fachhochschule Kaiserslautern	2013	101426
Hass, Artur	Evaluation of the separation mechanism of the asteroid landing module MASCOT by analyzing test data of a microgravity experiment	Hochschule Bremen	2014	104842
Herrmann, Marius	Recherche zu und Bewertung von formbasierenden Verfahren im Bereich Niedrigschubbahnoptimierung	Universität Bremen	2011	79058
Herzig, Johanna	Ermittlung der Einflussparameter von Mondregolith auf die Induktive Energieübertragung	Technische Hochschule für angewandte Wissenschaften Deggendorf	2014	104913
Ivanytskyy, Volodymyr	Konzeptionierung der Sensorik fu r einen kryogenen Oberstufen-Tankdemonstrator	DLR Bremen	2014	102351
Johannsen, Lars	Erarbeitung eines Konzeptes zur aktiven Steuerung einer hochzuverlässigen Leistungsversorgungseinheit für ein hybrides Navigationssystem	Hochschule Bremen	2015	97701
Juhrs, Dominik	Entwurf, Analyse und Aufbau eines Versuchsstandes für einen gefesselten Flugtest eines Mondlandedemonstrators	Jade Hochschule Wilhelmshaven	2012	103249
Kleinermann, Patrick	Zeitsynchrone Erfassung seismischer Sensordaten	Universität Bremen	2015	103360
Korbjun, Fabian	Entwurf eines Terrestrischen Demonstrators für Mondlandungen	Hochschule Bremen	2010	103250
Kretzenbacher, Michael	Model Based Systems Engineering Applied through a SysML Model to the MASCOT Asteroid Lander	Monash University	2013	103710
Kwiatkowski, Norbert	Entwicklung eines Referenzdesigns einer hochverfügbaren Leistungsversorgungseinheit für das Shefex III- Navigationssystem	Hochschule Wilhelmshaven	2014	101419
Kühn, Jakob	Konzeption und Konstruktion einer standardisierbaren mechanischen Schnittstelle für modulare Systeme auf dem Mond	Fachhochschule Aachen	2013	103708
Lange, Alexander-Thomas	Entwurf und Implementierung von Softwarekomponenten für ein multi-missionsfähiges, verteiltes Bodensegment zur Datenvermittlung zwischen Boden- und Raumsegment und zur Kontrolle und Überwachung des Raumsegmentes	Universität Bremen	2012	106554
Laugwitz, Daniel	Konzeption und Konstruktion eines Deployment-Mechanismus für modulare Nutzlasten auf einem Lunaren Lander	Universität Bremen	2015	103041
Lipp, Sarah	Innovationsbewertung bei komplexen Raumtransportprojekten	Universität Bremen	2015	103552
Lis, Patrizia	Ermittlung des Einflusses von Salzwasser auf die induktive Energieübertragung		2015	103058
Meyer, Lars	Realisierung einer Steuerung für eine Mikroturbine	Hochschule Bremen	2014	101901
Opfermann, Thorben	Programming of an interface between a Laser tracker and a dSPACE system	Hochschule Bremen	2012	101518

Peters, Hauke	Plattformunabhängige Entwicklung von Funktionen zur Ansteuerung einer Satellitendynamiktestanlage	Fachhochschule Kiel	2010	97743
Pfeiffer, Christoph	Entwicklung eines Testmodells zur Beschleunigungsmessung für das Projekt SHEFEX III	Hochschule Karlsruhe	2013	101428
Pieper, Pascal	Umgebung für automatisierte Tests von Dateisystemen auf NAND-Flash	Universität Bremen	2016	104590
Proppe, Myrthe	Prototyp-Entwicklung einer Auswerteelektronik für Beschleunigungssensoren einer Inertialmesseinheit	Hochschule Bremen	2014	89999
Rasch, Stefan	Characerisation and set-up of a FPGA-based laserbeam control as a preexamination for the GRACE-FO mission	Universität Bremen	2014	103538
Reinking, Janosch	Design und Entwicklung einer Kameraschnittstelle nach dem Packet Utilization Standard	Universtität Bremen	2015	101514
Rinaldo, Rhea	Entwicklung und Auswertung der Telemetrie/Telekommando-Schnittstelle einer Logging-Komponente für Satelliten	Universität Bremen	2015	97702
Ruhhammer, Florian	Untersuchung des Parameterraums einer Concurrent-Engineering-Studie	FH Aachen	2011	102378
Rühenbeck, Tim	Automatische Analyse und Verifikation von AIS-Daten	Universität Bremen	2014	89513
Schiefelbein, Carsten	Entwicklung redundanter MOSFET-Relais zur An- und Abschaltung einzelner Komponenten eines Avioniksystems	Universität Bremen	2014	89519
Schlömer, Jöran	Automatische Generierung formaler Eigenschaften aus Hardwarebeschreibungssprachen	Universtität Bremen	2015	101512
Schulze, Michael	The development of an autonomous data-capture system for use in the service module of the XCOR Lynx suborbital space-plane, in the drop tower, and in other microgravity platforms	Universtität Bremen	2015	101510
Schwarz, René	Simulationsmodell eines Reaktionsrades für den Satelliten AsteroidFinder/SSB	Hochschule Merseburg (FH)	2009	106533
Steen, Frerk	Fehlertolerante drahtlose Kommunikation an Bord der Gossamer I-Satelliten	Universität Bremen	2014	89520
Steindorf, Lukas	Design Parameter Evaluation of the Gossamer Solar Sail	FH Aachen University of Applied Sciences	2014	102734
Stellmann, Svenja	HISTORICAL TECHNOLOGY EVOLUTION OF SPACE SYSTEMS WITH SPECIAL REGARD TOWARDS SUBSYSTEMS	UNIVERSITY OF APPLIED SCIENCES BREMEN	2009	62504
Strenge, Joachim	Development of the Mission Operations Plan of the Nanosatellite 'AISat' (CLAVIS-1)	University of Applied Sciences, Bremen	2012	106556
Strowik, Christian	Erstellen eines Energieverteilungskonzepts für einen autonomen Mondlandedemonstrator	Hochschule Wilhelmshaven	2013	101450
Temmen, Kai	Konzeptionelle Entwicklung eines Schwerkraftkompensationssystems für die Anbindung an eine Bodenentfaltungstestanlage	Institut für Raumfahrtsysteme	2015	102460
Wilsch, Cedric	Entwicklung und Detailkonstruktion einer standardisierten Andockstation für modulare Systeme auf dem Mond	Hochschule Niederrhein	2014	103709
Wohlers, Christoph	Entwurf und Konstruktion der Struktur für einen terrestrischen Landedemonstrator	Hochschule Bremen	2012	103255

6.5 Publications

6.5.1 Refereed Publications in ISI- or Scopus-Indexed Titles

Books & Book Contributions

[1] Oehlschlägel, Thimo; Theil, Stephan; Krüger, Hans; Knauer, M.; Tietjen, J.; Büskens, C.: *"Optimal Guidance and Control of Lunar Landers with Non-throttable Main Engine"*. In: ed. by F. Holzapfel; S. Theil. **Selected Papers of the 1st CEAS Specialist Conference on Guidance, Navigation and Control**. Advances in Aerospace Guidance, Navigation and Control. Springer Verlag, 2011, pp. 451–463. **(elib: 74978)**

Conference Publications

[2] Deshmukh, Meenakshi; Schwarz, René; Braukhane, Andy; Lopez, Rosa Paris; Gerndt, Andreas: *"Model Linking to Improve Visibility and Reusability of Models during Space System Development"*. In: *IEEE Aerospace Conference, 2014*. Aerospace Conference, 2014 IEEE, 2014, pp. 1–11. **(elib: 90086)**

[3] Lüdtke, Daniel; Westerdorff, Karsten; Stohlmann, Kai; Börner, Anko; Maibaum, Olaf; Peng, Ting; Weps, Benjamin; Fey, Görschwin; Gerndt, Andreas: *"OBC-NG: Towards a reconfigurable on-board computing architecture for spacecraft"*. In: *Aerospace Conference, 2014 IEEE*. 2014, pp. 1–13. **(elib: 89683)**

[4] Montenegro, Sergio; Dannemann, Frank; Dittrich, Lutz; Vogel, Benjamin; Noyer, Ulf; Gacnik, Jan; Hannibal, Marco; Richter, Andreas; Köster, Frank: *"(SpacecraftBusController+AutomotiveECU)/2=UltimateController"*. In: *Software Engineering 2010 / ENVISION2020*. Ed. by Gregor Engels; Markus Luckey; Alexander Pretschner; Ralf Reussner. **160**. Lecture Notes in Informatics. Gesellschaft für Informatik, 2010, pp. 103–114. **(elib: 64842)**

[5] Sagliano, Marco; Theil, Stephan: *"Hybrid Jacobian Computation for Fast Optimal Trajectories Generation"*. In: *AIAA Guidance, Navigation, and Control Conference*. AIAA, Aug. 2013. DOI: 10.2514/6.2013-4554. **(elib: 85394)**

Invited Conference Contributions

[6] Andraka, Charles; Moss, Timothy; Baturkin, Volodymyr; Zaripov, Vladlen; Nishchyk, Oleksandr: *"High Performance Felt-Metal-Wick Heat Pipe for Solar Receivers"*. In: *SolarPACES 2015. Concentrating Solar Power and Chemical Energy Systems*. 2016. DOI: 10.1063/1.4949054. **(elib: 102651)**

Journal Articles

[7] Aguilera, Deborah; Ahlers, H.; Battelier, B.; Bawamia, A.; Bertoldi, A.; Braxmaier, Claus; Schuldt, Thilo: *"STE-QUEST - Test of the Universality of Free Fall Using Cold Atom Interferometry"*. In: *Classical and Quantum Gravity* **31** (15). 2014. DOI: 10.1088/0264-9381/31/11/115010. **(elib: 87947)**

[8] Ales, Filippo; Gath, Peter; Johann, Ulrich; Braxmaier, Claus: *"Modeling and Simulation of a Laser Ranging Interferometer Acquisition and Guidance Algorithm"*. In: *Journal of Spacecraft and Rockets* **51** (1): 226–238. Jan. 2014. DOI: 10.2514/1.A32567. **(elib: 88180)**

[9] Ales, Filippo; Mandel, Oliver; Gath, Peter; Johann, Ulrich; Braxmaier, Claus: *"A phasemeter concept for space applications that integrates an autonomous signal acquisition stage based on the discrete wavelet transform"*. In: *Review of Scientific Instruments* **86** (8). 2015. DOI: 10.1063/1.4928489. **(elib: 103551)**

[10] Amelino-Camelia, G.; Aplin, K.; Arndt, M.; Barrow, J.D.; Bingham, R.J.; Bordé, C.; Bouyer, P.; Caldwell, M.; Cruise, A.M.; Damour, T.; D?Arrigo, P.; Dittus, H.; Ertmer, W.; Foulon, B.; Gill, P.; Hammond, G.D.; Hough, J.; Jentsch, C.; Johann, U.; Jetzer, P.; Klein, H.; Lambrecht, A.; Lamine, B.; Lämmerzahl, C.; Lockerbie, N.; Löffler, F.; Mendonca, J.T.; Mester, J.; Ni, W.-T.; Pegrum, C.; Peters, A.; Rasel, E.; Reynaud, S.; Shaul, D.; Sumner, T.J.; Theil, S.; Torrie, C.; Touboul, P.; Trenkel, C.; Vitale, S.; Vodel, W.; Wang, C.; Ward, H.; Woodgate, A.: *"GAUGE: The GrAnd Unification Gravity Explorer"*. In: *Experimental Astronomy* **23** (2): 549–572. Mar. 2009. Ed. by Peter von Ballmoos. DOI: 10.1007/s10686-008-9086-9. **(elib: 63368)**

[11] Anand, M.; Crawford, I.A.; Balat-Pichelin, M.; Abanades, S.; Westrenen, W. van; Péraudeau, G.; Jaumann, R.; Seboldt, W.: *"A brief review of chemical and mineralogical resources on the Moon and likely initial in situ resource utilization (ISRU) applications"*. In: *Planetary and Space Science* **74** (1): 42–48. 2012. DOI: 10.1016/j.pss.2012.08.012. **(elib: 80185)**

[12] Appourchaux, T.; Burston, R.; Chen, Y.; Cruise, M.; Dittus, H.; Foulon, B.; Gill, P.; Gizon, L.; Klein, H.; Klioner, S.; Kopeikin, S.; Krüger, Hans; Lämmerzahl, C.; Lobo, A.; Luo, X.-L.; Margolis, H.; Ni, W.-T.; Patón, A. Pulido; Peng, Q.; Peters, A.; Rasel, E.; Rüdiger, A.; Samain, E.; Selig, H.; Shaul, D.; Sumner, T.; Theil, S.; Touboul, P.; Turyshev, S.G.; Wang, H.; Wang, L.; Wen, L.; Wicht, A.; Wu, J.; Zhang, W.; Zhao, C.: *"Astrodynamical Space Test of Relativity Using Optical Devices I (ASTRO I)- A class-M fundamental physics mission proposal for Cosmic Vision 2015-2025"*. In: *Experimental Astronomy* **23** (2): 491–527. Mar. 2009. Ed. by Peter von Ballmoos. DOI: 10.1007/s10686-008-9131-8. **(elib: 63584)**

[13] Arantes, Gilberto; Rocco, Evandro Marconi; Fonseca, Ijar da; Theil, Stephan: *"Far and proximity maneuvers of a constellation of service satellites and autonomous pose estimation of customer satellite using machine vision"*. In: *Acta Astronautica* **66** (9-10): 1493–1505. May 2010. DOI: 10.1016/j.actaastro.2009.11.022. **(elib: 64295)**

[14] Arslantas, Yunus; Oehlschlägel, Thimo; Sagliano, Marco: *"Safe landing area determination for a Moon lander by reachability analysis"*. In: *Acta Astronautica* **128**: 607–615. Nov. 2016. DOI: 10.1016/j.actaastro.2016.08.013. **(elib: 106519)**

[15] Atkinson, David H.; Kazeminejad, Bobby; Lebreton, Jean-Pierre; Witasse, Olivier; Pèrez-Ayúcar, Miguel; Matson, Dennis L.: *"The Huygens Probe Descent Trajectory Working Group: Organizational framework, goals, and implementation"*. In: *Planetary and Space Science* **55** (13): 1877–1885. 2007. DOI: 10.1016/j.pss.2007.04.004. **(elib: 48465)**

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