Lander Engineering and Operations for Space Exploration

DLR

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The operation of landers on planetary surfaces is a special aspect of space exploration. The Microgravity User Support Center, MUSC, has a unique experience in this field: The first comet lander, Philae and the first asteroid nano-lander, MASCOT, were operated from the respective Lander Control Center at MUSC, in Cologne. Also, HP³, an instrument including a ground penetrating mole, which is part of the NASA/JPL InSight mission, was operated from MUSC. Currently, MUSC is involved in a mission to Phobos, with the Rover IDEFIX as part of the Japanese Mars Moon eXplorer (MMX) mission. It is being prepared to be launched in 2026. The rover IDEFIX will likewise be operated by MUSC.

These activities have opened the door for further opportunities, by continuing the investigation of the small bodies in the Solar System, asteroids and comets, as well as in-situ exploration and lander technology for missions on moons and planets.

Lander Operations have to cope with additional challenges, if compared to interplanetary flyby or orbiter missions. Obviously, there are the challenges of the landing itself. A lander shall not crash on the surface nor rebound to space. Therefore, the selection process of an optimal landing site is not trivial. Once on the surface, the reception of data and the possibilities for commanding are not only dependent on the availability of ground stations on Earth but also restrictions in visibility due to the rotation of the celestial body as well the geometry between landing site and a possible relay orbiter need to be taken into account.

Close collaboration with lander engineering enhances the successful operations of the landers, especially on system level. Apart from general system engineering, MUSC contributed in the areas of thermal control and software engineering for both Philae and MASCOT.

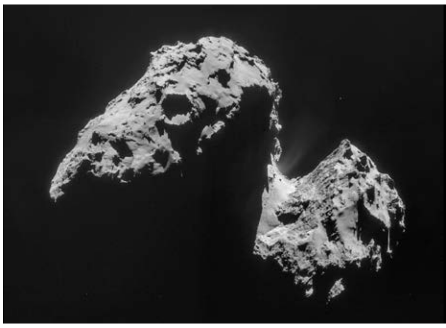

Fig. 1-1 Comet 67P/Churyumov-Gerasimenko, as imaged with the Rosetta Navigation Camera. Credit: ESA

Fig. 1-2 Asteroid Ryugu, a imaged by the JAXA spacecraft Hayabusa2. The asteroid is a C-type rubble pile with a clear top-shape.

Comets and asteroids are of particular interest for four main reasons:

1. For scientific research, as they contain relic material from the early phases of the Solar System and allow conclusions on the evolution of the Solar System as well as the origins of life;
2. As possible threats, as they occasionally collide with the Earth and mitigation strategies are to be developed;
3. As possible targets for a next step of human exploration, and
4. As possible targets for future resource utilization or "asteroid mining".

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Table of Contents

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2. Development of Lander Control Centers

Lander missions, especially to comets or asteroids, are rare and usually unique in their mission design. Consequently, it is currently not common to develop a generic Lander Control Center, coping with all types of missions, to all possible target bodies and in partnership with various space agencies. Nevertheless, the experience in MUSC in developing and operating the – so far – only comet or small asteroid landers, is an essential strength in preparing similar missions, also to moons and planets. The different Lander Control Center are built up on the strong heritage of knowledge, tools and software packages, which were developed with the experience of various successful space missions.

Philae was part of the ESA Rosetta mission, MASCOT an element of the JAXA Hayabusa2 mission and in case of InSight, MUSC is cooperating with NASA. IDEFIX is part of the JAXA MMX mission. Future lander missions may also involve India, S-Korea or Taiwan. Philae was a complex spacecraft with ten instruments (and many more sub-systems) designed for long term operations on comet 67P/Churyumov-Gerasimenko while MASCOT was small, lightweight and designed to survive only about 17 hours on the surface of asteroid Ryugu. IDEFIX is a rover that will operate and drive for about 100 days on the surface of Phobos. There is a wide span of missions, but many elements, like the landing site selection process, operations planning, relay management with a carrier spacecraft, lander delivery, science planning or data distribution and archiving, stay similar and the available experience is essential to avoid completely new developments or duplication of competences. The tools used or developed at MUSC enable the center to run multi mission operations. Specifics for the dedicated missions will be taken into account in the configuration of the ground systems.

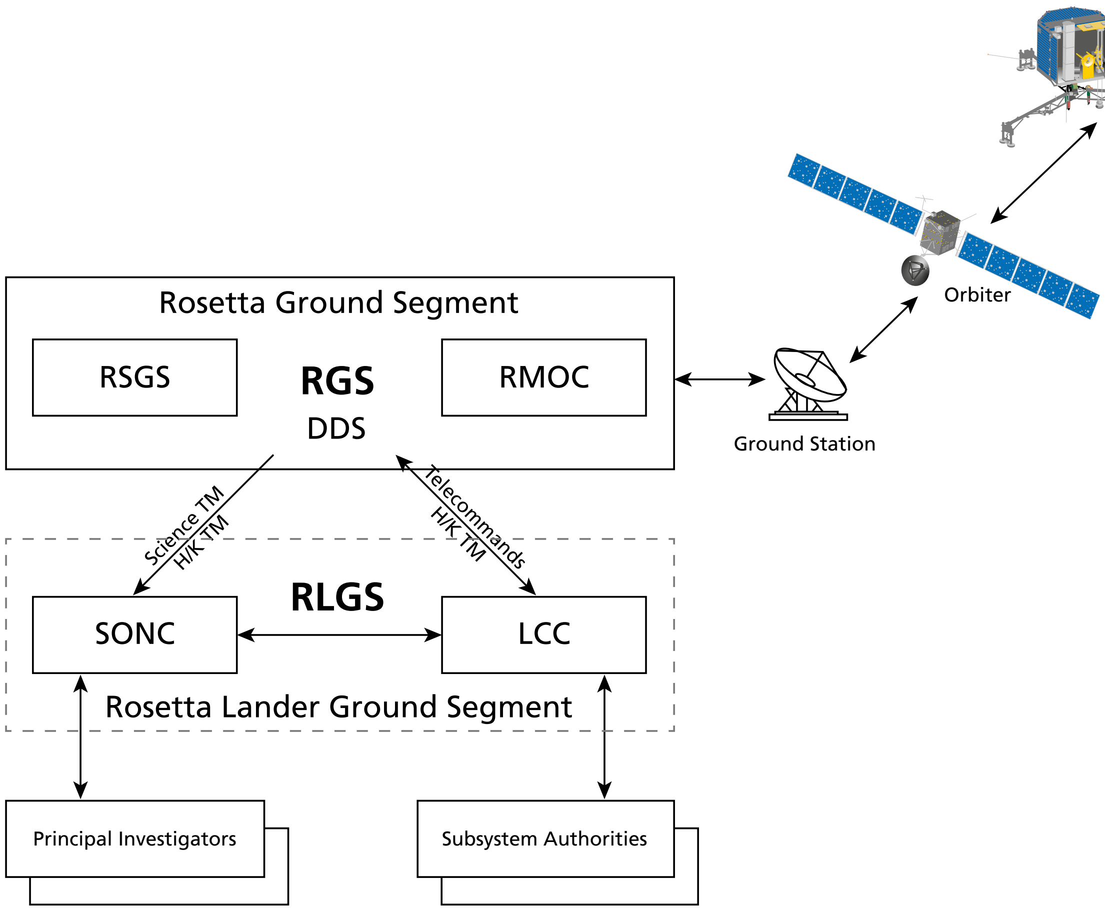

Fig. 2-1 Rosetta Lander Philae as example for the setup of control centers of planetary landers with a relay spacecraft and separated mission- and science control centers for each flight segment.

3. The Philae Lander for the Rosetta Mission

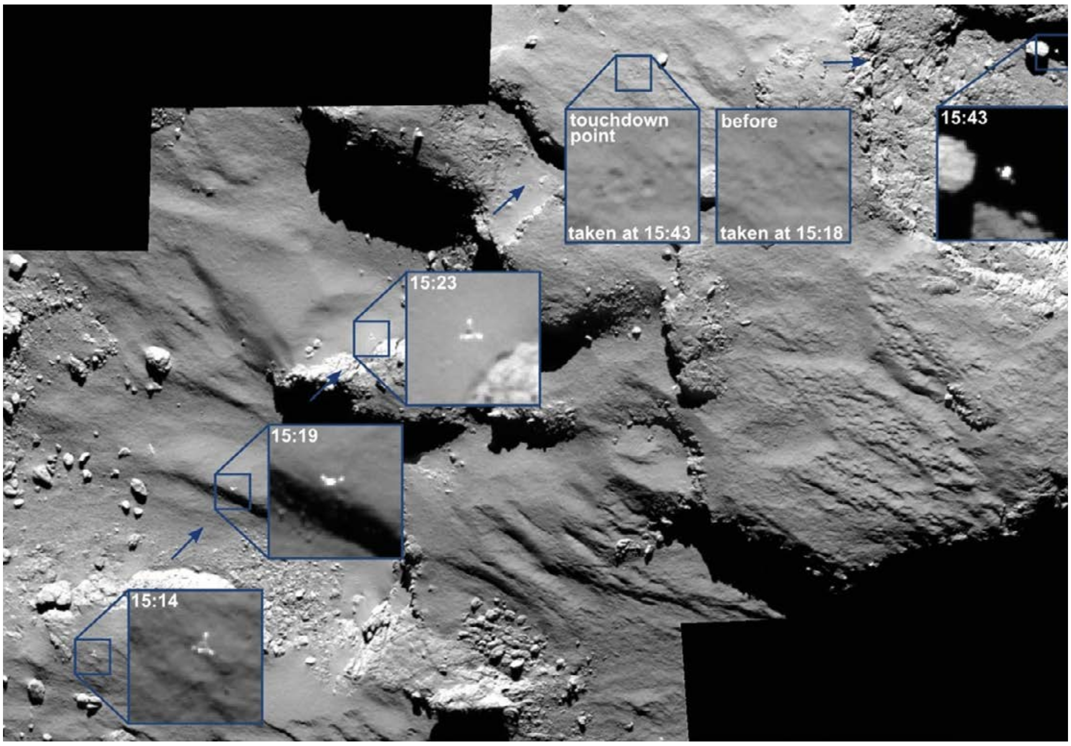

Fig. 3-1 Philae approach to the comet's surface as seen from the orbiter camera OSIRIS. Credit: ESA/Rosetta/Philae/CIVA

Rosetta was a Cornerstone Mission in the ESA Science Program. Its goal was to rendezvous with comet 67P/Churyumov-Gerasimenko and to study its nucleus and coma using an orbiting spacecraft and a landed platform, called Philae.

Rosetta was launched in 2004 and reached the target comet after a ten years cruise in August 2014. About three months later, November 12th, Philae was successfully deployed and became the first lander ever on the surface of a comet. Unfortunately, due to a malfunction of the anchoring harpoons, the lander bounced and only came to rest after a around two hours "jump" in a poorly illuminated area (called "Abydos"), about one kilometer away from the originally targeted landing site.

Nevertheless, all ten scientific instruments aboard Philae could be operated at least once and unprecedented scientific data were sent from the surface of the comet for about 64 hours after separation from the main spacecraft. The science results include high resolution images of the area near the landing place, mass spectra of the surface material, radar data from the sub-surface, measurements of the magnetization and estimations of the surface strength.

Due to the unfavorable illumination conditions at "Abydos", the secondary batteries could not immediately be re-charged and Philae went into an un-planned hibernation until lander and comet were closer to the sun. When sufficient power was available, the lander got active again and eventually signals were received in June 2015. Although several contacts with the lander were established and useful housekeeping data could be obtained, all efforts to command further science measurements were not successful. The Rosetta main spacecraft, however, continued to observe 67P until the end of mission in September 2016.

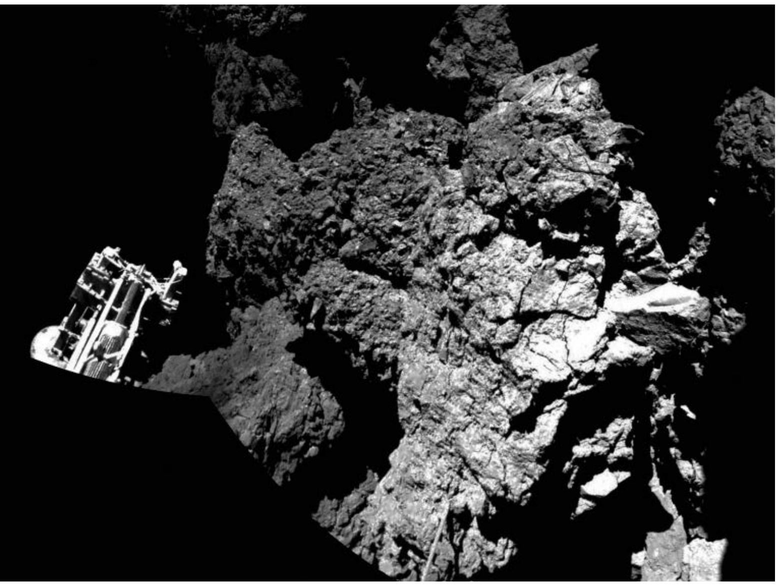

Fig. 3-2 Cometary surface as imaged by the CIVA cameras aboard Philae, at Abydos in 2014. Credit: ESA/Rosetta/MPS for OSIRIS Team MPS/UPD

Fig. 3-3 Philae as mounted on Rosetta spacectraft in cruise configuration

Philae was operated from the LCC (Lander Control Center) at DLR MUSC in Cologne, during its cruise as well as at the comet. A second operations center, SONC (Science Operations and Navigation Centre), was located at CNES (Toulouse) and supporting the science operations, data distribution to the PIs (Principal Investigators) and mission analysis aspects.

The LCC was directly connected via the ground segment to the Rosetta Mission Operations Center (RMOC) at ESOC, Darmstadt. Rosetta science operations planning was performed at the SGS (Science Ground Segment) at ESAC, near Madrid. At the LCC a Lander Ground Reference Model (GRM) as well as a software simulator has been available for reference tests, optimization of procedures and trouble-shooting tasks.

The philosophy of the set-up of LCC was to combine system competence (project management, system engineering and the responsibility for several subsystems of Philae were also at MUSC) and close relationship with the involved science institutes and the science community with the experience in interacting with control centers at ESA and CNES. The concept was very successful and served as a blue-print for the MASCOT control center, at the same physical location, but with different mission constraints, roles and different partners (as JAXA is responsible for the Hayabusa2 mission).

The Rosetta Lander Philae has been provided by an international consortium with the participation of Germany (DLR and Max Planck Institutes), France, Italy, United Kingdom, Finland, Ireland, Hungary and Austria. Project lead, payload management, subsystem provision and system responsibility as well as the Lander Control Center, LCC, were at DLR in Cologne.

4. The Nano-Lander MASCOT of the Hayabusa2 Mission

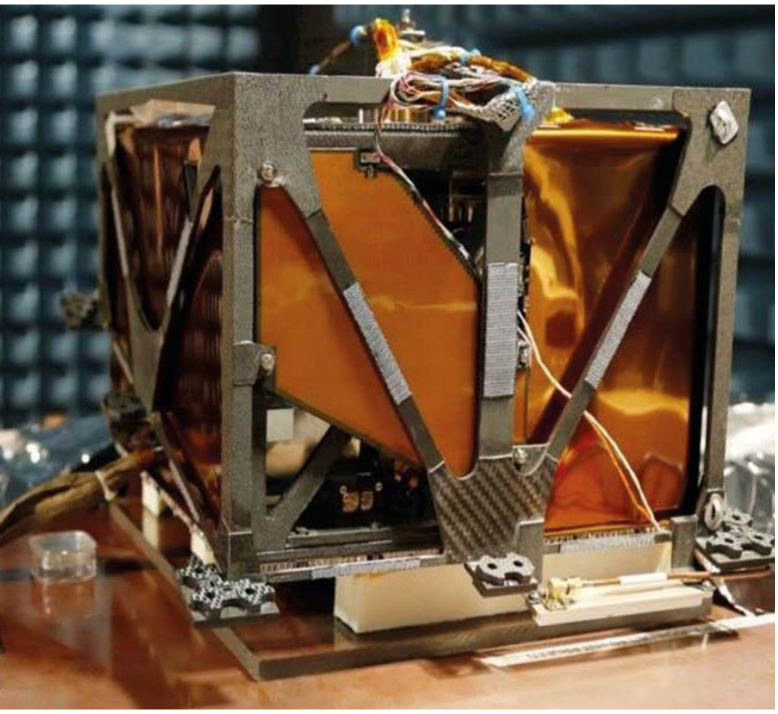

Fig. 4-1 MASCOT nano Lander during integration in clean-room

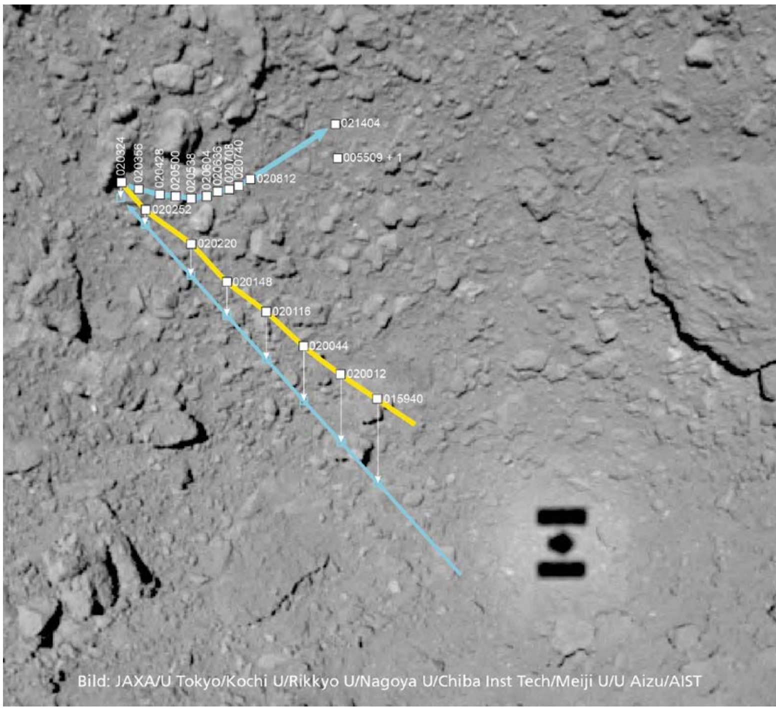

Fig. 4-2 Overview of the determined descent and bounce pass of MASCOT. The shadow of the Hayabusa2 main spacecraft is additionally visible.

MASCOT ('Mobile Asteroid Surface Scout') is a 10 kg mobile surface science package which was part of JAXA's Hayabusa2 sample return mission, investigating the asteroid (162173) Ryugu. The mission was launched in December 2014 from Tanegashima Space Center, Japan and the Hayabusa2 spacecraft reached the target asteroid in summer 2018. Hayabusa2 was very successfull and has returned its samples to Earth in December 2020. After arrival at the target asteroid 'Ryugu' a detailed mapping phase was performed and the landing site of MASCOT selected. The deployment of MASCOT to the asteroids surface took place on the 3rd October 2018.

MASCOT was operated on the surface of the asteroid for about 17 hours (as planned). All four instruments aboard have produced measurements multiple times. Using a hopping mechanism (an internal torque) the lander could even be relocated, to study another landing spot. MASCOT provided valuable context information to be compared with the analyses expected to be performed with the returned samples.

MASCOT is a concept with a considerable potential for spin-off for future small body's missions. It has been considered, e.g. as long-lived version with a radar instrument as MASCOT-2 for the ESA AIM mission. But there is also the potential to adapt the lander, for example to fly aboard a NASA Discovery or New Frontiers missions.

Studies are performed to adapt MASCOT for slightly larger bodies (e.g. Phobos or Jupiter Trojans) to cope with higher gravity and impact velocities in the 1 to 5 m/s range. Studies performed with JAXA include landers, based on the MASCOT concept, which for example could become part of a mission to Jupiter Trojan asteroid or a comet sample return mission (NGSR – New Generation Sample Return).

MASCOT was operated from MUSC, in the same physical location as the Philae lander, but of course with updated technologies, in cooperation with different DLR Institutes and with CNES. The MASCOT GRM was located at MUSC for commands checks and validation of the InFlight activities. The control room was at that time used in parallel for InSight mission integration test and cruise activities (see next chapter).

5. HP³ Experiment on Mars Mission InSight

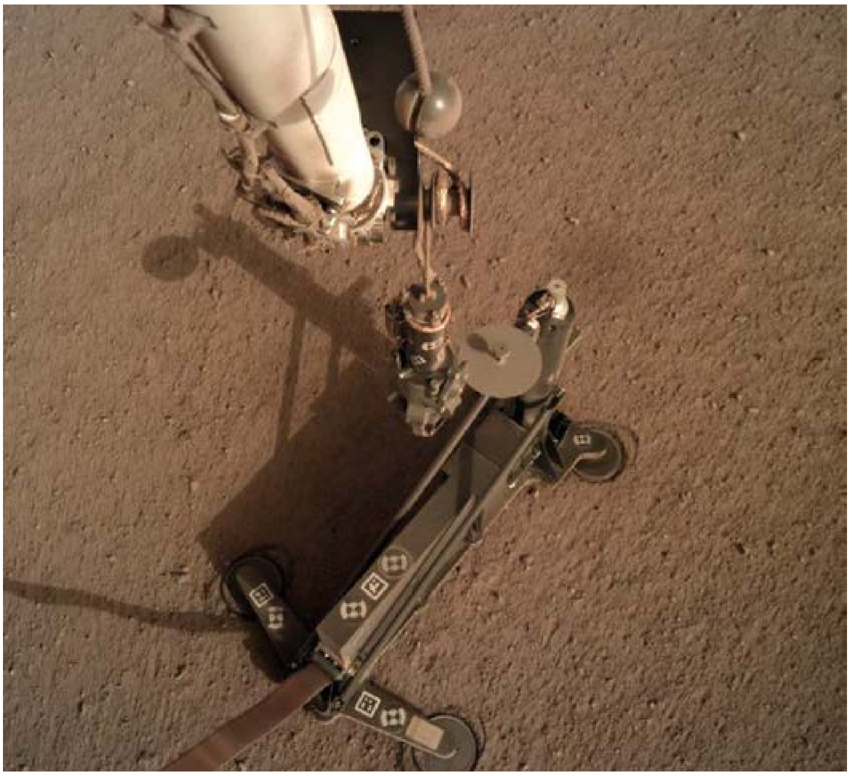

Fig. 5-1 HP³ after deployment to the Martian surface. InSight deployment arm has released HP³. Picture of arm camera IDC. Credit: NASA/JPL-CalTech/DLR

InSight is a Discovery class mission to Mars launched in May 2018. The mission is composed of a lander, based on NASA Phoenix heritage, and carries a seismometer and a Heat Flow and Physical Properties Package (HP³) to the Martian surface. The main scientific goal of the InSight (Interior exploration using Seismic Investigations, Geodesy and Heat Transport) mission was the investigation of the interior of Mars. InSight landed successfully on 26th November 2018 in Elysium Planitia region of Mars. Equipped with solar cells it successfully delivered data from the Martian surface until December 2022, much longer than originally anticipated. HP³ was the DLR contribution to the InSight mission, the lander was provided by NASA and the seismometer by the Centre National d'Etudes Spatiales (CNES). HP³ development has been led by DLR Institute of Planetary Sciences including the main mechanical contribution from DLR Institute for Space Systems at Bremen.

HP³ consists of a self-hammering device (mole) trailing a scientific tether behind down to a target depth of five meters. The scientific tether is equipped with thermal sensors for the determination of the heat flow and the thermal conductivity of the Martian upper surface. It is the first time that instruments are deployed on the Martian surface, outside the lander. The HP³ experiment is further composed of a radiometer mounted underneath the lander deck for monitoring the brightness temperature of the Martian surface.

Since the landing end of November 2018 until end of the mission, the HP³ experiment was successfully operated by MUSC. The radiometer operated since right after the landing. In February 2019 the HP³ Support Structure containing the mole was deployed to the surface by the robotic arm of the lander. The penetration of the mole turned out to be more difficult than expected, as the surface material on Mars consists of "duricrust" leading to a very low friction. But despite the fact that the mole did not reach the anticipated depth, valuable and unique information on the thermal properties of Mars' surface could be collected.

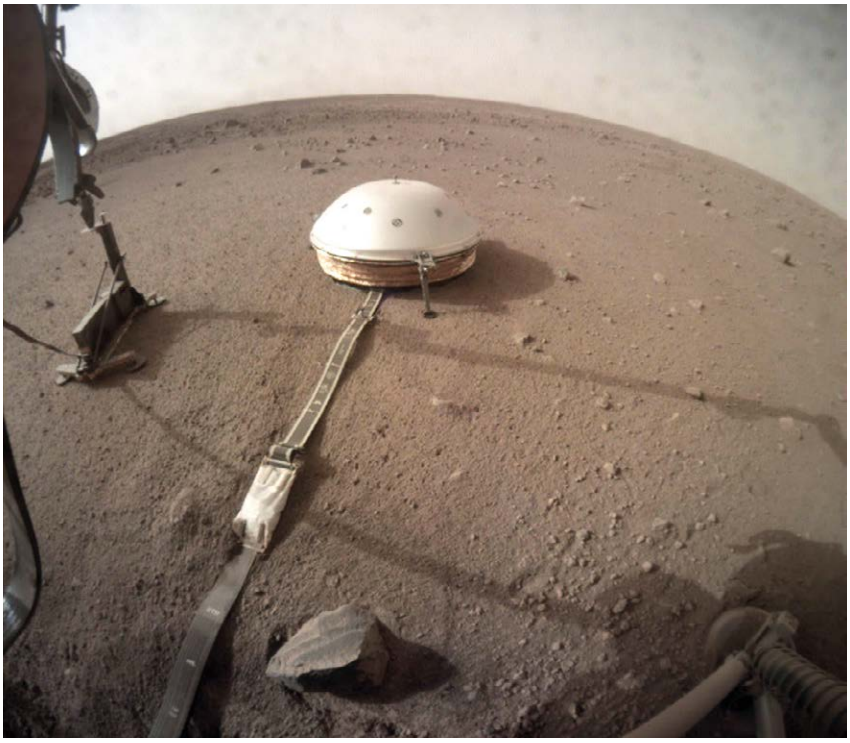

Fig. 5-2 View of InSight camera ICC, deployment of HP³ on sol 76 (left). SEIS instrument middle.
Credit: NASA/JPL-Caltech

MUSC was in charge of the HP³ operations and of the development and operation of the STAtic TILtmeter measurement suit (STATIL). The InSight mission was operated from JPL mission control in Pasadena. The HP³ telecommands and telemetry were routed through the InSight lander. MUSC retrieved the HP³ TM packets via a DDS. Afterwards the packets were stored, extracted and calibrated with the SpaceMaster software. The raw and calibrated data was distributed via web access to the HP³ community. The HP³ functional representative ground reference model (GRM) was located in the control center in Cologne for command testing and potential failure investigation. Together with its IOT (instrument operaion team) members in Berlin, MUSC monitored the HP³ operations and was in charge for building, testing, operations and verifying the telecommands before provision to JPL.

During the instrument deployment phase the HP³ operational team was co-located at JPL mission control equipped with a mobile SpaceMaster instance. During the monitoring phase HP³ was operated from the Control Center in Cologne. The interfaces used for data retrieval and telecommand provision are the same for the deployment phase as well as for the following monitoring phase.

MUSC also performed the HP³ spacecraft tests during the integration phase of the lander remotely from the Control Center in Cologne and on site at Lockheed Martin in Denver.

6. The IDEFIX Rover for the Martian Moons eXploration – MMX Mission

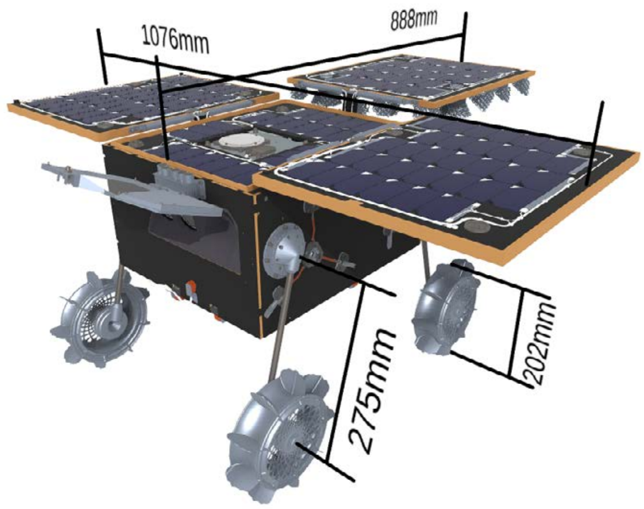

Fig. 6-1 Drawing of IDEFIX, with fully deployed wheels and solar generator, in on-Phobos configuration

Fig. 6-2 Flight Model of IDEFIX, in stored configuration, as attached to the mothership, during cruise, before separation

The Martian Moons eXploration (MMX) is a mission by the Japan Aerospace Exploration Agency, JAXA, to the Martian moons Phobos and Deimos. It will primarily investigate the origin of these moons by bringing samples back from Phobos to Earth and by delivering a small (about 25 kg) rover, IDEFIX, to its surface.

This rover is a collaborative contribution by the Centre National d'Etudes Spatiales (CNES) and DLR. Its scientific payload consists of a thermal mapper (miniRAD), a Raman spectrometer (RAX), a stereo pair of cameras looking forward (NavCam) and two cameras looking at the wheel-surface interface (WheelCam) to learn about Phobos' regolith mechanical properties. The cameras will serve for both, technological and scientific needs.

The MMX rover will be delivered to the surface of Phobos from an altitude of about 40 meters. Uprighting and wheel and solar panel deployment will start autonomously after the rover comes to rest on the surface. By applying a special sequence of deploying the legs, the rover will upright itself, irrespective of the orientation it came to rest after delivery and bouncing. Following the "universal upright" the solar generator will be deployed and the rover can send telemetry, re-charge its batteries and is ready to be commanded from ground. It is planned to operate for at least 100 days on Phobos and provide unprecedented science data covering a total distance of several meters to hundreds of meters. It will be the first time ever that a human-made instrument is driving on a low gravity body.

IDEFIX will be operated from two dedicated operations centers, one at CNES in Toulouse, the other one at MUSC in Cologne, making maximum use of the heritage with Philae, MASCOT and InSight. The responsibility for operations will alternate between the twto operations centers, also allowing to swap execution and planning phases and providing redundancy. The two rover control centers in Europe will work closely together with the JAXA Control Center in Sagamihara, Japan. JAXA will operate the MMX spacecraft itself. The communication to and from the rover will be relayed via the main spacecraft.

The MMX Rover operations require a close international collaboration to achieve the maximum scientific and technological output from this fascinating extraterrestrial mission.

MMX will be launched in October 2026 and inserted into Mars orbit in 2027, the Rover delivery and operations are planned for early 2029.

7. Collaborated Lander Engineering and Operations

Operations of small spacecraft like landers and rovers profit from a close collaboration with its engineering already during design, manufacturing, integration and testing. These types of spacecraft generally have very strict limits on mass, volume and power. This affects the availability for continuous science operations and causes thermal constraints to be considered during operation planning. Up-to-date technology usually hardly causes limitations on data storage, but a high level of autonomy due to the limited link possibilities to ground control requires a sophisticated design of the on-board software, e.g. for fault detection, isolation, and recovery (FDIR) functionalities.

MUSC has provided the thermal control system for Philae and kept this responsibility throughout operations until end of mission. The detailed knowledge of its design and performances and the experiences gained during the post-launch operational phase allowed a valuable contribution to the failure analysis and recovery after the unexpected landing, the follow-on hibernation and the predictions for possible operations restart.

After launch, MUSC had the responsibility for the thermal control system of MASCOT and the center performed the operations planning and supported the landing site selection for this one-shot (primary battery driven) mission.

Extraterrestrial missions are characterised by a long development phase, especially in international cooperation, and typically also by an extended cruise prior to reaching the target body, whose properties and characteristics are usually unknown before arrival. Therefore, these missions are often launched with baseline on-board software only, suitable for cruise, but requiring updates and adaptations prior starting the in-situ science phase.

Based on the development and validation of control sequences and timelines for lander operations, MUSC has established a profound experience in design, development and validation of software based autonomy concepts. A detailed analysis and validation of the on-board software of Philae accompanied by the continuous application throughout the cruise phase resulted e.g. in a dedicated adaptation of the FDIR functionalities triggered by MUSC for the separation and on-surface operations.

For MASCOT, the limited power resources of the lander required the development of the so-called MASCOT Autonomy Manager (MAM), a software package which would allow to autonomously starting control sequences and preprogrammed timelines based on external events when operating on the surface of asteroid Ryugu, thus providing the maximum science return. In cooperation with the on-board software provider MUSC refined and extended the necessary functionalities of MAM and again supported the FDIR preparations, which proved to be necessary to recover from the incorrect interpretation of MASCOT's attitude after landing.

Having low level flight software knowledge proved to be particularly valuable when HP^3 suffered from bit-flip errors while being operated on Mars. Based on a source code analysis the problem could be identified and operational mitigations were put in place.

The gained experience in these missions will be applied in future missions for system support (MMX rover, NGSR other other cooperations with international partners).

8. Facilities

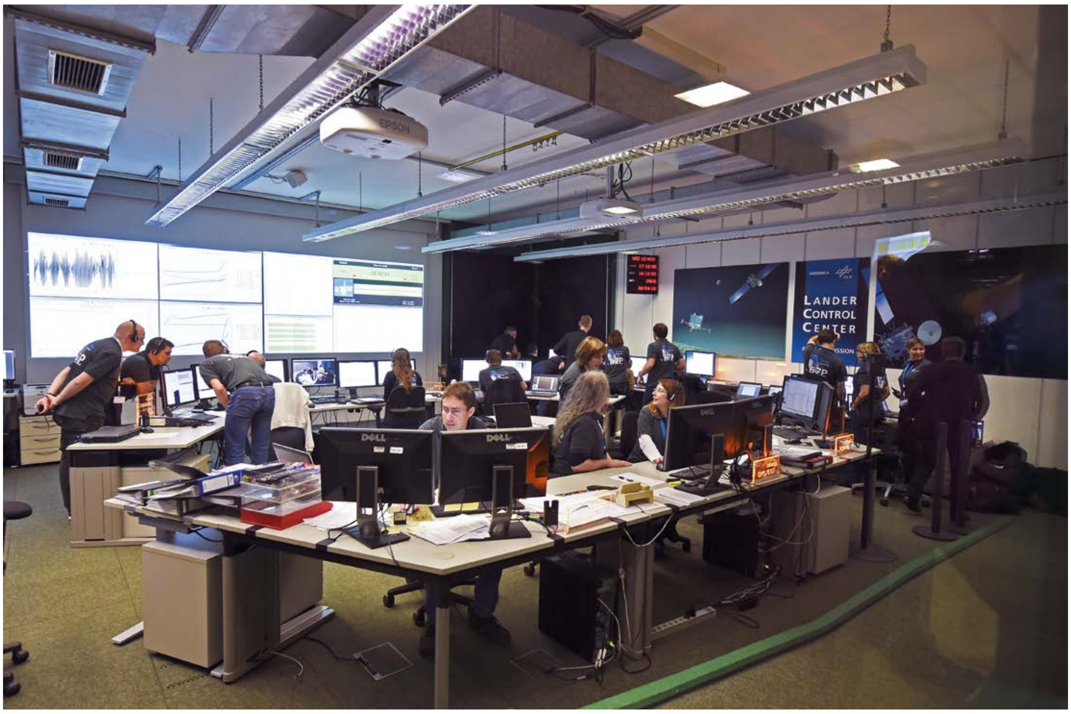

Fig. 8-1 Lander Control Center, LCC at DLR MUSC, during Philae operations

At the Microgravity User Support Center, there are several control rooms, including those, that have been used for Philae, MASCOT and HP³ operations, which can be well adapted for future lander missions with updated hard- and software.

Specialized software packages enable the MUSC team to run different missions in parallel from the same control room. Nevertheless, the databases used in the lander control and monitoring system as well the operations planning models and tools need to be adapted to the unique needs of every individual mission. A detailed simulation of the intended operations focusing on power, data, RF and thermal constraints will always be part of the performed activities and thus provides the confidence for a successful execution, especially for longterm missions.

In addition to the control rooms, there is a laboratory for accommodating, operating and testing ground reference models (GRMs) in a controlled environment. The use of such models has proven to be of crucial importance for the preparation of science sequences, verification of procedures and failure investigation for the flight segments. They also proved to be a useful tool for operations team training.

Finally, the interfaces with many international agencies like CNES, ESA, JAXA and NASA, not only for the lander missions, but also in the frame of ISS payload operations are well established and represent a valuable experience to set up future international cooperation with distributed operations centers.