Lander Engineering and Operations for Space Exploration

Lander Engineering and Operations for Space Exploration

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, is operated from MUSC. Currently a mission to Phobos, with a Rover as part of the Japanese Mars Moon eXplorer (MMX) mission, is being prepared.

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 has 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 is the selection process of an optimal landing site 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.

Point of Contact

German Aerospace Center (DLR)
Space Operations and Astronaut Training
Stephan Ulamec
Linder Höhe, 51147 Köln

Phone: +49 2203 601 4567
E-Mail: Stephan.Ulamec@dlr.de

DLR.de/RB

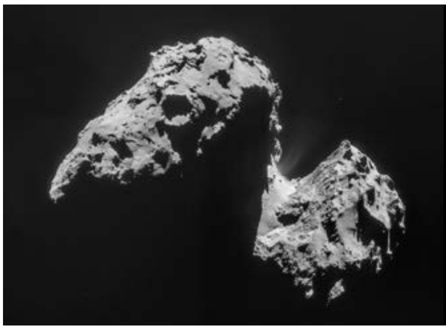

Fig. 1-1 Comet 67P/Churyumov-Gerasimenko, as imaged with the Rosetta Navigation Camera. Credit: ESA

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 targets for a next step of human exploration,
3. As possible threats, as they occasionally collide with the Earth and mitigation strategies are to be developed, and
4. As possible targets for future resource utilisation or "asteroid mining".

Table of Contents

Publisher
German Aerospace Center (DLR)
Spacecraft Operations and Astronaut Training
Münchener Straße 20, 82234 Weßling

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 meaningful 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 different 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. Future lander missions may involve also Russia, China, S-Korea or India. Philae was a complex spacecraft with 10 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 17h on the surface of asteroid Ryugu. 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.

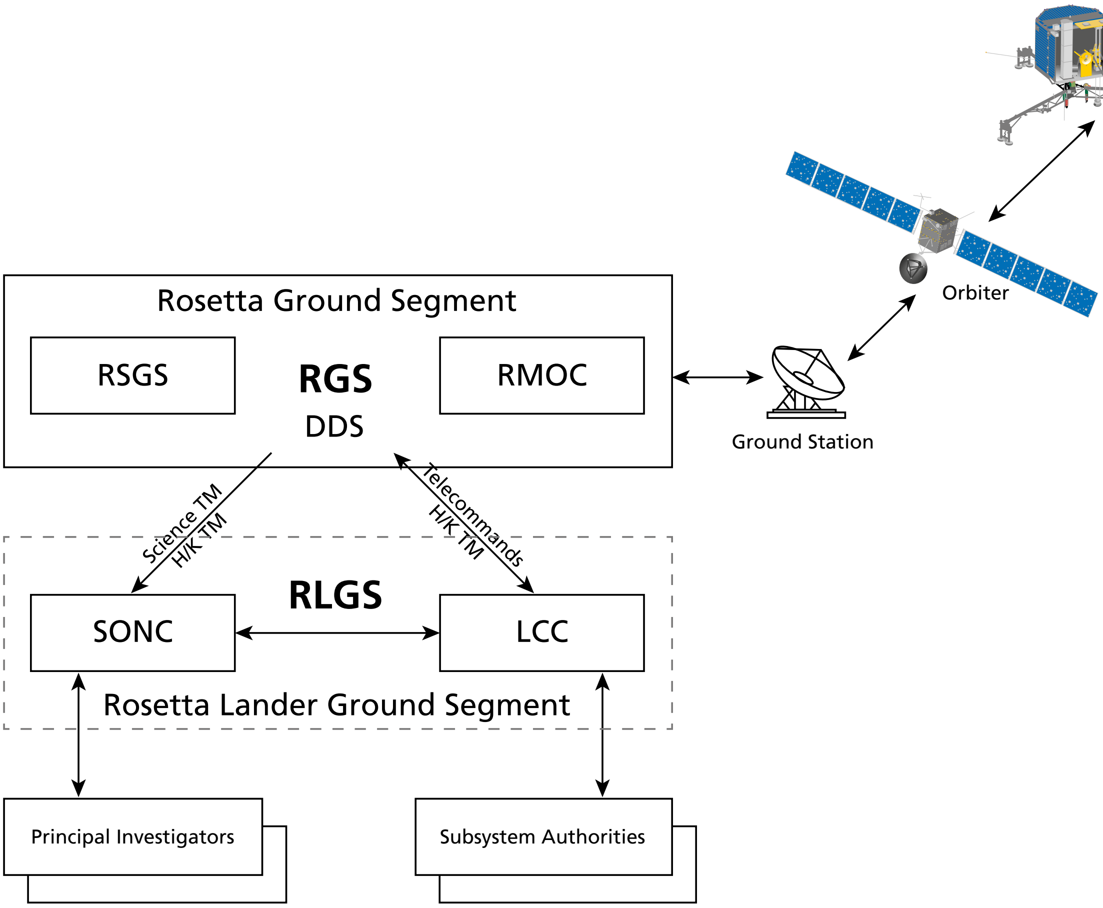

Fig. 2-1 Rosetta Lander Philae as example for the setup of control centers of planetary landers with a relay spacecraft and separated mission- and science control centers for each flight segment.

3. The Philae Lander for the Rosetta Mission

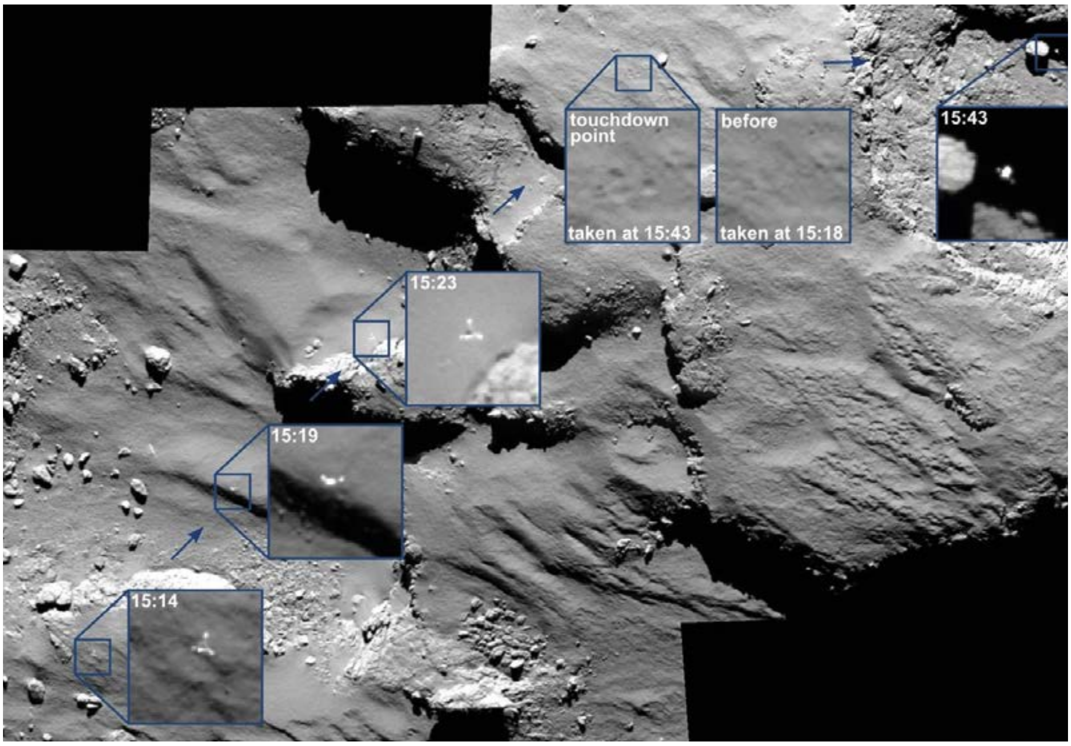

Fig. 3-1 Philae approach to the comet's surface as seen from the orbiter camera OSIRIS. Credit: ESA/Rosetta/Philae/CIVA

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 10 years cruise in August 2014. About three months later, November 12, Philae was successfully deployed and became the first ever lander 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 ca. 2 hours "jump" in a poorly illuminated area (called "Abydos"), about 1km 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.

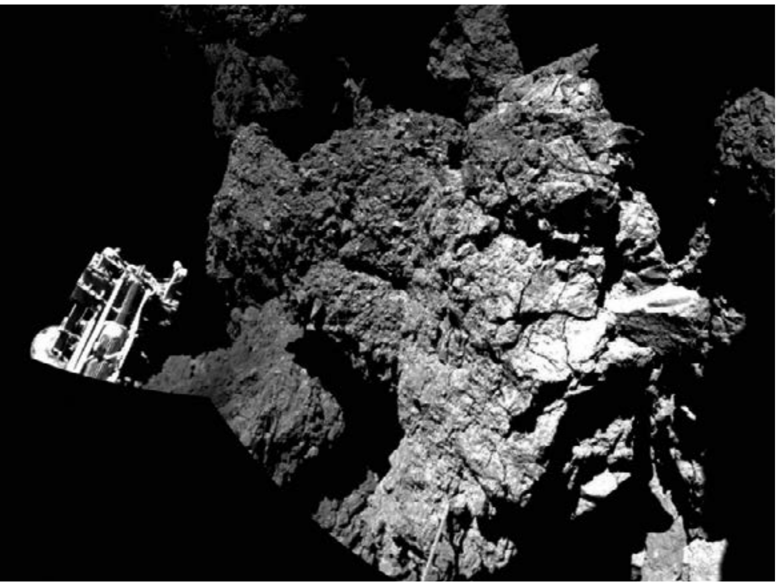

Fig. 3-2 Cometary surface as imaged by the CIVA cameras aboard Philae, at Abydos in 2014. Credit: ESA/Rosetta/MPS for OSIRIS Team MPS/UPD

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

Philae was operated from the LCC (Lander Control Centre) 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 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

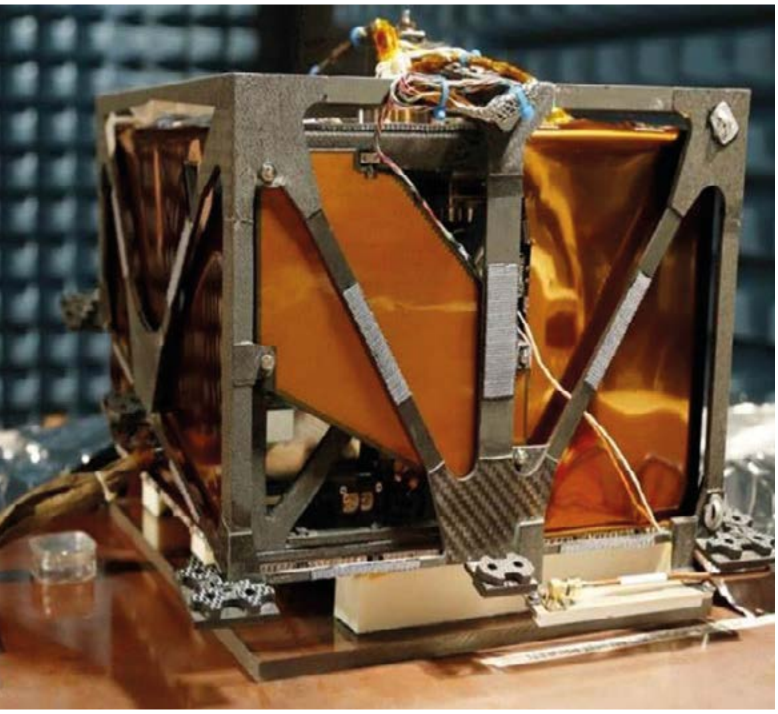

Fig. 4-1 MASCOT nano Lander during integration in clean-room

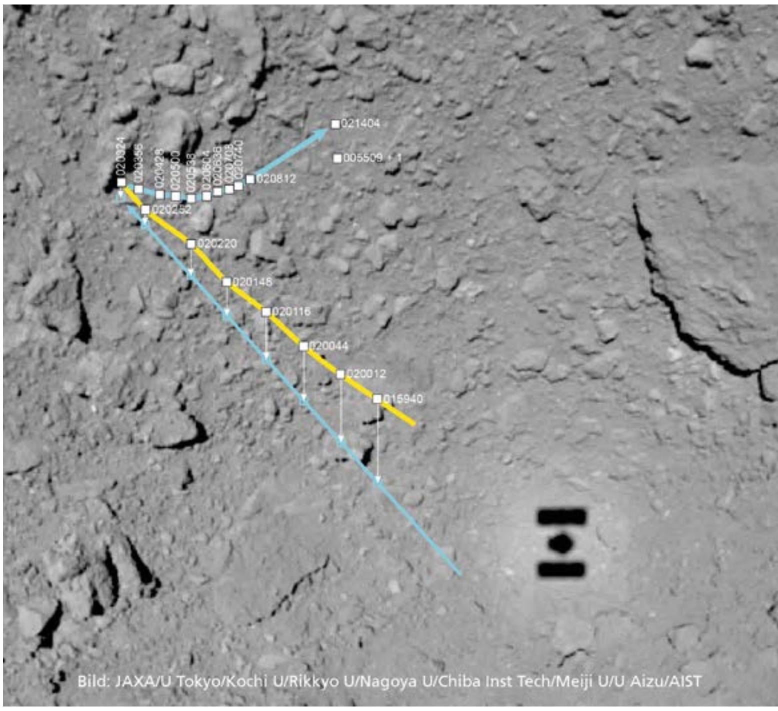

Bild: JAXA/U Tokyo/Kochi U/Rikkyo U/Nagoya U/Chiba Inst Tech/Meiji U/U Aizu/AIST

Fig. 4-2 MASCOT PM Overview

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 will return 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 been measuring for several times, by help of 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 e.g. to fly aboard a CAS led asteroid mission or on 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.
A study performed with JAXA, OKEANOS, includes a more sophisticated lander to be delivered to a Jupiter Trojan asteroid. OKEANOS is currently considered to be launched in the 2030 timeframe.

5. HP³ Experiment on Mars Mission InSight

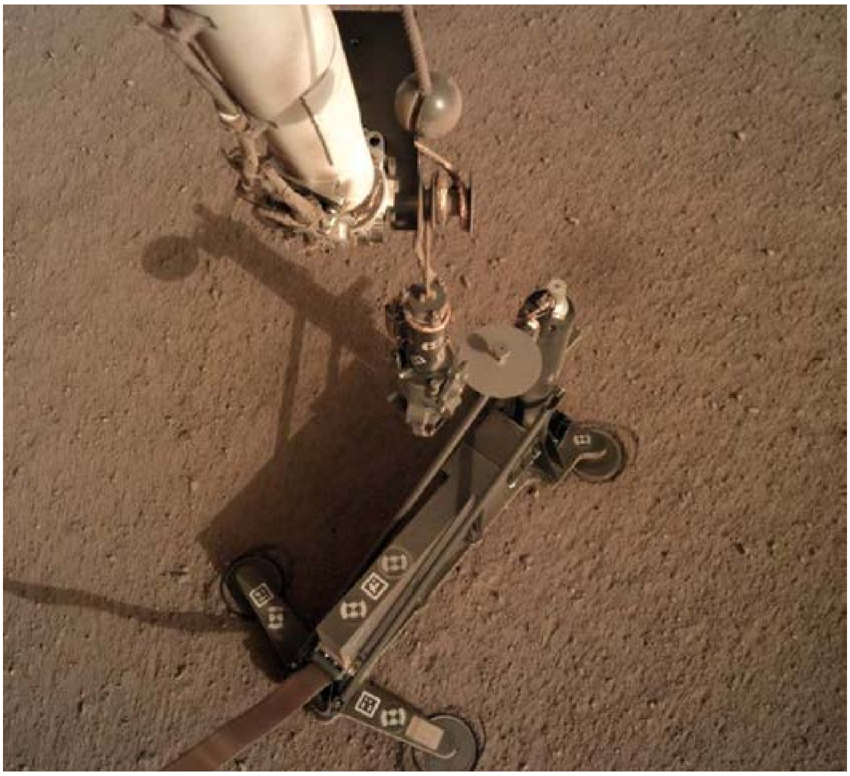

Fig. 5-1 HP³ after deployment to the Martian surface. InSight deployment arm has released HP³. Picture of arm camera IDC. Credit: NASA/JPL-CalTech/DLR

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 is 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 will monitor its measurement for at least one Martian year. HP³ is the DLR contribution to the InSight mission, the lander is provided by NASA and the seismometer by 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 5 m. 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 the HP³ experiment is operated successfully by MUSC. The radiometer is operating 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. Although 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, attempts are continuing to achieve the original goal to reach a depth of several meters below the surface. The activities are still ongoing.

MUSC is in charge of the HP³ operations and of the development and operation of the STAtic TILtmeter measurement suit (STATIL). The InSight mission is operated from JPL mission control in Pasadena. The HP³ telecommands and telemetry are routed through the InSight lander. MUSC retrieves the HP³ TM packets via a DDS afterwards the packets are stored, extracted and calibrated with the SpaceMaster software. The raw

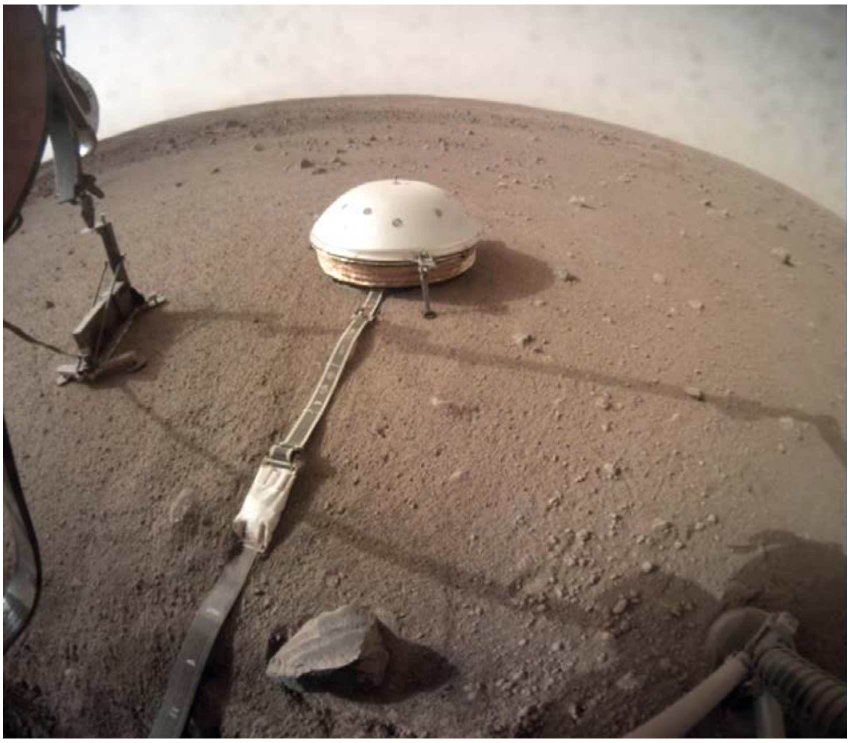

Fig. 5-2 View of InSight camera ICC, deployment of HP³ on sol 76 (left). SEIS instrument middle.
Credit: NASA/JPL-Caltech

and calibrated data are distributed via web access to the HP³ community. The HP³ functional representative ground reference model (GRM) is located in the control center in Cologne for command testing and potential failure investigation. MUSC monitors the HP³ operations and is in charge for building, testing 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 is 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 performed also 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. 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 causes hardly 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 characterized 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 HP³ 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).

7. Facilities

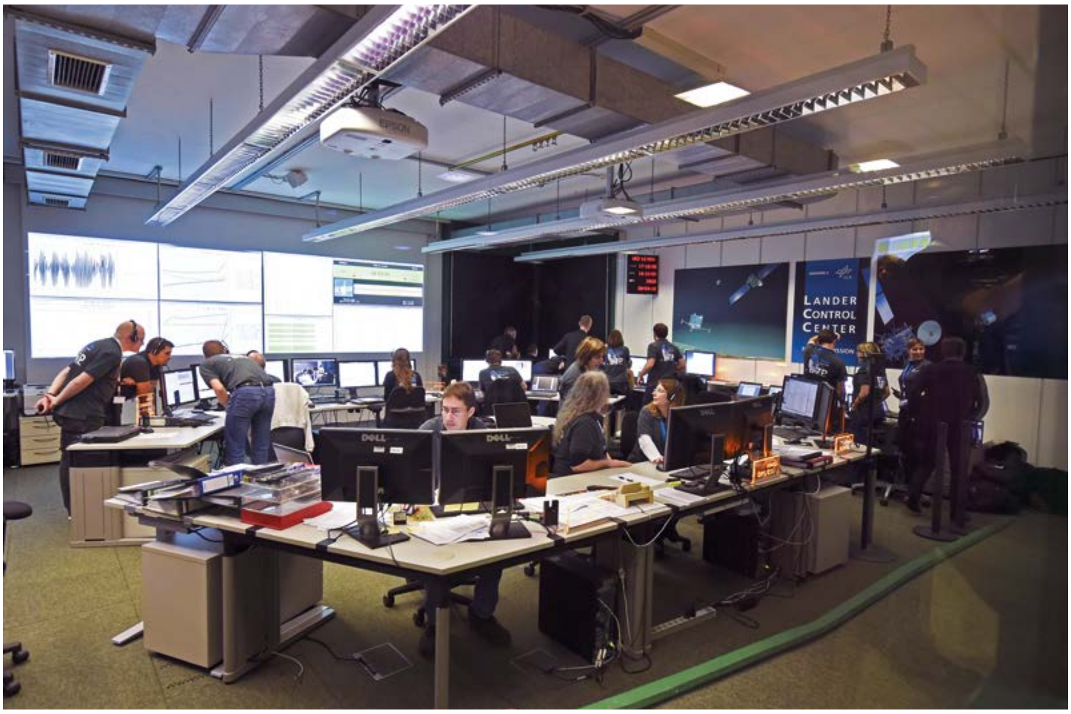

Fig. 7-1 Lander Control Center, LCC at DLR MUSC, during Philae operations

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 long-term missions.

In addition to the control rooms, there is a laboratory for accommodating, operating and testing ground reference models 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.