OPERATING SESAME: LESSONS LEARNED

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1. Document Change Record

Issue	Revision	Date	Affected pages or paragraphs	Description
1	0	10.08.2016	all	document set up
1	1	17.08.2016	4.2, 4.3	contributions by HK, WA, and HHF added
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1	3	30.08.2016	3, 4.1, 4.2, 4.4, 4.6, 5	contributions by WS, KT, HK added
1	4	05.09.2016	4.2, 4.6	contributions by KS added
1	5	13.09.2016	4.2, 4.3, 4.5	first 3 paragraphs of subsection on touchdown moved into new subsection "measurement principle". Some minor changes on wording. Final remark in 4.5 on representation of CASSE modified.
1	6	14.09.2016	4.2	paragraph on ADC resolution rewritten

2. Applicable Documents

R1	The instrument link-up of Rosetta. Some SESAME lessons learned	RO-LSE-TN-3101

3. Scope

This technical note summarized lessons learned during the operations of SESAME in cruise and especially during the comet phase of the Rosetta mission. The document deals with more generic aspects of project and experiment design as well as lessons learned about the development of the hardware. General lessons about interlinking different scientific instruments on a spacecraft are discussed in a separate document (RO-LSE-TN-3101).

4. Lessons Learned from SESAME

This section deals with lessons learned by the SESAME team concerning the own instruments and experiments, but also concerning overall mission aspects. Its subsections are organized such that aspects concerning the instrument and experiment design are separated from overarching considerations. We also refer the reader to reference document R1 for general considerations concerning collaborations between different instruments, e.g. like SESAME and MUPUS.

4.1 SESAME

Both CASSE and DIM suffer from insufficient ground testing of electronics. It is common knowledge (and it was in the 1990s), that electronics cannot be sufficiently characterized once it is in space. A possible reason for the low level of hardware ground testing of DIM is the extremely low manpower in the DIM team at the time (which might be the result of under-funding).

Regarding CASSE, it seems that hardware development did not comply with generally accepted rules and ESA standards. There is/was not even a hardware requirements document and no specification against which the hardware could be tested.

PP suffered from the very late completion of the landing gear design and its manufacturing after the original PP flight hardware was already built. Lack of time prevented a careful end-to-end re-calibration of the sensors integrated into the flight structure while incomplete hardware documentation made the manufacturing of an electrically equivalent laboratory model for ground calibration after launch difficult and uncertain.

With a carefully planned series of interference tests between instruments in flight configuration before launch, many problems should have been detected in time to develop a work-around. Additionally sufficient time should have been allocated in the assembly-, integration- and verification schedule of the completed spacecraft to allow calibration of instrument aspects which might be influenced by the proximity of an operating spacecraft or other instruments.

4.2 CASSE

When discussing the CASSE instrument, it must be taken into account that two measurement modes, which became the most significant ones during SDL and FSS, were not foreseen in the original planning. The MUPUS listening operation was designed at a time when only adaptations in flight software were possible, but not hardware modifications. The touchdown listening was put on the agenda only in 2009, five years after launch. Thus it is not surprising that CASSE has some shortcomings with respect to the execution of these two measurements.

Measurement principle

The original purpose of the CASSE instrument was to measure the time-of-flight of elastic wave signals from foot-sole to foot-sole in order to determine from these data the elastic constants of the surface material of comet 67P [1, 2]. As emitter of the signals a piezoelectric transducer was used which was developed by Fraunhofer-IZFP [3]. This emitter was designed such that it deformed the foot sole, acting like a loudspeaker. For reception a commercial Bruel&Kjaer accelerometer was used. Such a combination is not optimal if one considers SNR issues and frequency transfer functions.

In order to perform time-flight measurements of elastic waves between the feet of a landing gear, one uses usually in nondestructive testing piezoelectric transducers as transmitters *and* receivers either separately for sending and receiving (so-called double-ended technique in ultrasonics or seismology or bi-static in radar technology) or with a single transducer which can both transmit and receive (single-ended or mono-static) [4]. Piezoelectric transducers detect strain [5], i.e. the first derivative of the amplitude unlike an accelerometer which detects the second derivative of the elastic wave amplitude.

Which kind of modes, i.e. longitudinal, shear or surface waves can be employed depend (i) on the scientific problem to be studied and (ii) on the design of the foot soles. The vast experience in seismic instruments and ultrasonic technology for non-destructive testing should be exploited when designing such an instrument. The overall SNR and bandwidth of the system should be measured beforehand, in particular anisotropies in the directivity pattern of the transmitters and receivers [6].

ADC

The Apollo seismic experiments, designed in the 1960, used a 10 bit digitization for the passive seismometers at only 8 Hz sampling rate, while the Apollo 17 seismic profiling experiment used 200 Hz sampling with a linear 8-bit digitization. For CASSE the sampling rate was further increased up to 5 kHz. In order to keep the amount of generated data at a sufficiently low level with still a high resolution and large dynamic range, a complicated compromise was implemented. Using an 8-bit digitization approach with semi-logarithmic scaling and adjustable gain, both small-scale signals and large signals were supposed to be measurable on the comet. With a best-guess intermediate setting for the initial touch-down event, the recording system should have been adjusted later to the actual conditions found on the comet. This unfortunately was not possible, as the planned long-term-science phase could never be activated. The theoretical alternative of e.g. a 12-bit commercial ADC with higher resolution or larger dynamic range would have made the data analysis much simpler, but the amount of produced data would have increased, the needed power would have been much larger and the achievable combination of resolution and dynamic range would not have been sufficient. ADCs with even higher resolution were not available in space quality at the time the instrument was built.

A missing hardware reset function, circumvented by dedicated flight software functionality, made the identification of output channels challenging. The ADC unit itself tends to confuse which output channel corresponds to which sensor channel, and only by carefully analyzing channel-specific DC offsets in the output during payload checkouts, it was possible to correct for this.

Touchdown

CASSE was eventually used to measure the landing shock with the accelerometers built in the soles [7]. Accelerometers are in principle well suited to measure forces caused by ground motions and to measure the landing shock of a landing instrument platform, like Philae on comet 67P. The forces acting on the soles of the landing feet are determined by the seismic mass of the whole lander, here Philae, the landing speed and the springs with which this mass is coupled to the landing gear and eventually to the foot soles [8]. If the landing gear is more compliant than the appropriate elastic constant E^* or the compression strength σ of the comet material times the contact radius a of the landing sole, all deformation takes place in the spring system of the landing gear and no information on the surface stiffness of the comet is obtained [9]. In that case, one measures only the overall spring constant of the landing gear which of course is known beforehand. To circumvent this problem, the fixture of the accelerometer should be designed in such a way that it is decoupled from the forces acting in the landing gear and the lander, whereas it should be fully exposed to the contact forces of the comet soil. This would greatly simplify the force analysis and allow one to measure both elastic forces, i.e. elastic moduli and plastic deformation parameters like soil compression strengths etc. [8].

Listening to MUPUS

The following is taken verbatim from Knapmeyer et al., *The SESAME/CASSE Instrument listening to the MUPUS PEN insertion phase on comet 67P/Churyumov-Gerasimenko*, Acta Astronautica, vol. 125, 234-249, 2016:

> *More accurate clocks, both on spacecraft system level and instrument level would be beneficial. Timekeeping on spacecraft level should be designed in a way that considers the expected signal travel times. In our case, millisecond travel times require microsecond clock resolution. Also, a clock drift in the range of 15 to 20 seconds per day is uncomfortably large and would be considered inacceptable for seismic experiments of any kind on earth. Dealing with several independently drifting clocks is an additional source of uncertainty for the posterior synchronization of data from the involved instruments. A time stamping system that allows determining the drift rates and offsets of all involved clocks is necessary.*
>
> *Another timing issue arises from the lack of a trigger line between MUPUS and SESAME, by which that hammer mechanism itself could start the recording, as is standard in active seismics. Without having this possibility, and with the additional uncertainty of posterior stroke identification, we are forced to evaluate arrival time differences rather than travel times. This means that the travel time information of one foot is no longer available for the interpretation of ground properties.*
>
> *A recording of the source time function, possibly by an additional sensor within or nearby the source would be highly useful for the interpretation of recorded waveforms as well as for the identification of weak arrivals, or later arrivals within the signal coda. In addition, one might want to think about aperiodic stroke sequences, if using a hammer. A recognizable pattern, similar to a Barker code, would also support the posterior synchronization of source and receiver. For the same reason, housekeeping information about the activity of the source is highly useful. Even changes in hammering speed can be a useful source of information that increases the robustness of the experiment.*
>
> *Assumed that future penetrators or moles will also be instruments separated from any seismic recording system, an additional sensor of the seismic system that is placed in close proximity to the source of vibrations could help solving these limitations in one go: such a sensor could serve as a trigger, thus provide a direct (acoustic) connection between instrument clocks, and also record the source time function.*
>
> *Recording more hammer strokes, and at higher sampling rates, would of course be highly useful. The necessity to give up recording on nine channels, in order to be able to produce the only recording which contained more than one stroke, shows how severe a limitation of memory size can influence the quality of the data. With three channels per foot available, the arrival on the –Y foot would probably have been visible. Also, some*

recordings show that signal band width most likely exceeded the Nyquist frequency, while it is favorable to keep signal content of a recording clearly below that.

A good a priori knowledge of the spacecraft's elastic behavior is useful to clearly distinguish signal from crosstalk. In the case of Philae, this would involve the deployment boom, the spacecraft bus, and eigenmodes of the landing gear. It should also be made sure that electric crosstalk does not occur.

The triangular configuration of Philae's feet, as the likely symmetry of spacecraft landing gears in general, can be useful for the application of array methods. For the evaluation of travel times it is nevertheless useful to break this symmetry via the location of the source, in order to obtain as many different path lengths as possible. This of course may interfere with the measurement goals of involved instruments and depends on deployment possibilities in the given environment.

In order to gain the maximum benefit of instrument collaborations, possible synergies should be identified as early as possible, even if the hardware cannot be modified. Even the simple communication between MUPUS and SESAME, which works more like a bill-board rather than a messaging system, requires first to understand what instruments need or can provide, and subsequently the definition of software interfaces and data structures. Definition, implementation, and testing can take a significant amount of time even for a simple system.

Photographic documentation of the actual deployment is highly desirable. This concerns not only the locations and orientations of source and receivers and their coupling to the ground, but also the pathways between them.

4.3 DIM

Sensors and technical aspects

In the DIM instrument PZT plates are used to detect impacting dust particles. The equation for the output signal is given by

$$U_m \approx \frac{1}{C}(3.03 \times d_{33} \times E_r^{0.4} \times \rho^{0.6} \times R^2 \times v_Z^{1.2}) \quad (1)$$

where $d_{33} = \varepsilon_r \varepsilon_0 g_{33}$ (ε_r: relative permittivity, ε_0: absolute permittivity, and g_{33} is the piezoelectric voltage coefficient). Furthermore, E_r is the combined reduced modulus of the PZT sensor and the impinging particle, C is the capacitance of the sensor and v_z is the impact speed of the particle. The rise-time of the signal is approximately sinusoidal and equal to the contact time $T_c/2$ [10]. After the first maximum a ring-down signal appears which stems from the generation of an elastic reverberation field[11] through the force exerted by the particle and by piezoelectric action.

In order to improve the SNR, one should make the capacitance C as small as possible by sectioning the detector, i.e. by producing an array where each element should be read out separately. This would reduce the dead capacitance. Instead of using PZT which is a poled polycrystalline material with spatially inhomogeneous piezoelectric properties, one should explore to employ single crystalline materials like lithium tantalate $LiTaO_3$ or $Bi_{12}GeO_{20}$ as detector material. Their piezoelectric coupling factor is smaller than PZT, yet can be compensated with a smaller capacitance. These materials are stable which exhibit no microstructure and hence are homogeneous in their piezoelectric properties.

To suppress the reverberation signal which led to a dead time of the order of 1 *ms* after an impact, one should paste on the backside of the piezoelectric-plates a polymeric resin mixed with fine tungsten powder. The high scattering power for ultrasonic waves (tungsten particles) in conjunction with the high attenuation of the polymer resin shortens the dead time from *ms* to μs. This procedure is standard in commercial piezoelectric transducers for non-destructive testing. Finally, if possible, the complete signal should be captured and not only certain parameters of the signal form facilitating the analysis of the data considerably. This should render the calibration of the instrument much easier [11, 12, 13].

The level of electronics noise increased significantly after integration of the DIM PCB into the SESAME board stack, and again after integration into Philae. During cruise and SDL, additional quality reductions were found. The underlying problems can hardly be identified when the hardware is already in space. These problems should have been identified and fixed on ground.

For DIM only two parameters are measured on board and transmitted, the contact time and the signal amplitude. It must be kept in mind, however, that particle impacts are events short compared to e.g. the sampling rate of CASSE, thus a significantly faster electronics and a sufficiently large mass memory would be necessary. Progress since the 1990s probably makes this possible.

Since even a thin dust cover on the PZT sensor surface leads to a strong reduction of signal amplitudes, an option for photographic inspection of the sensor would have been advantageous.

We could only operate one of the three sensor sides at a time. Next time, one should be able to operate all sensor sides in parallel on separate channels in a way that we can distinguish which sensor was hit by a particle.

Operations

The interpretation of DIM data suffers from the still unknown (at the time of writing, August 2016) lander attitude during descent. Without knowing the orientation of the sensor plates in space, an interpretation of the direction of origin of the detected dust particle is not possible.

4.4 PP

The late Landing Gear completion, according to different design parameters than originally foreseen, made severe last-minute modifications to PP flight electronics and harness design necessary without the time to perform a careful end-to-end re-calibration of the sensors. Without up-to-date design documentation of some of the landing gear aspects the manufacturing of an electrically equivalent laboratory model for ground calibration after launch had partly to rely on pictures taken from the integrated flight hardware, manual entries in integration logbooks and interviews of project team members involved in the manufacturing and integration.

With the details of the sensor calibration and especially the effect of capacitive coupling between the harnesses and the flight version of the Landing Gear structure unknown at the time of launch, a sophisticated program for in-flight calibration was developed, to be executed once the Landing Gear was in its final configuration for PP-measurements. As this happened only after Lander separation, several calibration slots were included in the descent phase of Philae. From inter-instrument interference tests during flight it was known that the CONSERT radar pulses would distort any PP measurement severely, making precise calibration impossible. Therefore PP's calibration measurements were phased such that they were running safely in between CONSERT pulses, which was successfully verified after spacecraft hibernation.

But during the descent of Philae it turned out that not only the effect of the unfolded CONSERT antennas onto the PP receivers at the unfolded Landing Gear feet was much stronger than estimated, but also that the power transmitted by CONSERT was significantly higher than during the tests, both effects together causing the PP pre-amplifiers to saturate for most of the CONSERT inter-pulse time.

The following is taken verbatim from Lethullier et al., *Electrical properties and porosity of the first meter of the nucleus of 67P/Churyumov-Gerasimenko As constrained by the Permittivity Probe SESAME-PP/Philae/Rosetta,* Astronomy & Astrophysics, vol. 591, A32, 2016, doi: 10.1051/0004-6361/201628304:

> *Unfortunately, all potential measurements performed during the third and fourth block of the SDL phase were saturated (...) The observed disturbances are undoubtedly due to interferences generated by CONSERT sounding operations that stopped only three minutes after SESAME-PP’s last measurement block during the SDL phase. As a consequence, we do not have an in-flight calibration data from the instrument and, in particular, we are working under the assumption that the receiving electrodes and, specifically, the embedded preamplifiers have evolved similarly during Rosetta’s ten-year journey to the comet.*

With a carefully planned series of interference tests between instruments in flight configuration before launch, these problems should have been detected in time to develop a work-around. Additionally sufficient time should have been allocated in the assembly-, integration- and verification schedule of the completed satellite to allow calibration of instrument aspects which might be influenced by the proximity of an operating spacecraft or other instruments.

4.5 GROUND REFERENCE MODEL

The GRM facility hosted by DLR in Cologne and its staff were crucial for the development and testing of operational procedures. The competence and thoroughness of the colleagues there cannot be valued high enough, ultimately allowing the FSS being successful despite of the circumstances of the landing(s).

The GRM allows executing telecommands before relaying them to the spacecraft and shows the *electrical* feasibility of these commands, i.e. if the commands can be executed at all, what the power consumption is, and how much data is generated. Spare instruments integrated into the GRM can execute the commands as good as this is possible with the respective spare (e.g. the harpoons should not be fired, obviously).

For CASSE, however, a mechanical representative would be desirable. The GRM does not have a landing gear, and the soles containing the CASSE sensors and actuators were stored in a drawer of some cabinet within the GRM laboratory. Philae’s flywheel was also placed outside of the GRM body. Thus it was not possible to characterize the oscillational behaviour of the landing gear, the quality of sound transmission through the legs, or the amount of vibration caused by the flywheel.

For a full mechanical representativeness, conduction of tests in thermal vacuum would be necessary – this will probably be out of scope for any future mission as well. Nevertheless, the GRM was not optimal to represent the operations of CASSE, as these do not rely on the sensorheads alone, but on the entire structure of the spacecraft.

4.6 PROJECT MANAGEMENT

Knowledge management and manpower

A major challenge when running any kind of project over several decades (from the initial ideas for the mission, already using the name “Rosetta”, until the finalization of the last publications) is knowledge management. This concerns design decisions during the development of the experiment and instrument as well as tactical decisions made during operations, which should at least be documented in a way accessible to future colleagues.

In this respect, one of the most important mission phases of Rosetta was in fact the hibernation phase: three years during which no contact with the spacecraft was possible. Some people inside and outside of the mission appeared to think that this phase implies that work force is released and other tasks can be appointed to the personnel. This is a difficult situation especially for scientists with contracts ending prior to the end of the hibernation, who may find themselves in a situation where starting with new projects appears to be the safest option to obtain an extension of their contract. A loss of knowledge may result when theses scientists leave Rosetta, and the new projects demand workforce after hibernation, thus reducing the focus devoted to Rosetta. Also, the hibernation phase could have been used to prepare and test operational procedures, data reduction and inversion tools, and data archival.

When the responsibility for DIM was taken over by the current PI (and shifted to MPS, which was not involved with DIM before) in 2009, the DIM documentation was found confusing and sometimes contradictory, probably because of limited manpower during the design and development phase of DIM.

Limitations of manpower, translating into under-funding, appear to be at the heart of several problems that arose during the mission.

In 2007, SESAME, and especially CASSE, was short to being abandoned by DLR due to an accumulation of several problems. Besides other restructurings within DLR, the main point was that the team consisted of only two people and was overwhelmed by the tactical business of payload checkouts and their evaluation. CASSE could thus not make any progress concerning scientific data reduction and interpretation methods. These problems were predictable and could have been avoided entirely.

Data management

It was welcomed that the development of interfaces and formatting of data for the ESA Planetary Science Archive was, to a great extent, undertaken by SONC as a central agency for all of the lander. Although the colleagues from SONC obviously need the support of the instrument teams for the description of the necessary interfaces, the work load for the team was reduced considerably. This kind of centralized archiving agency within the mission should thus be adopted for future missions.

It was nevertheless unfortunate that much of the necessary support by the instrument teams was requested at a time when the scientific evaluation was – predictably – the main point on the agenda of the scientists, while little progress was made during the hibernation phase.

To support data archival and document exchange on team level, a SESAME ftp server was set up, maintained by DLR and the PI, but accessible to all team members. This server became a valuable resource during the mission.

5. Summary

Hindsight is easier than foresight, and in a document concerning lessons learned one is inclined to identify apparently predictable shortcomings that could have been mitigated beforehand.

It nevertheless turns out after compiling all the lessons we learned about our instruments, that many shortcomings boil down to three points:

1. develop and end-to-end experiment including cross-experiment interactions and data reduction and inversion
2. test before launch
3. have sufficient personnel (and funding) to do so

A fourth point arises from the evaluation of hardware limitations:

4. A next-generation SESAME experiment requires the re-development of almost the entire hardware. The sensor heads themselves were essentially sufficient, but DPU speed, ADC speed and resolution, and memory volume must all be increased significantly.

The current (as of August 2016) PI of SESAME as well as the current DIM PI joined the team only after launch (in 2005 and 2008, respectively. This alone underlines the challenges of knowledge management) and is thus hardly in a position to complain about what his predecessors should have accomplished. He does not want to blame anyone: After all, SESAME was a successful experiment.

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7. Appendix

7.1 LIST OF ACRONYMS

Table 1 List of Acronyms

Acronym	Expansion
ADC	Analog-Digital Converter
CASSE	Comet Acoustic Surface Sounding Experiment
DIM	Dust Impact Monitor
DLR	Deutsches Zentrum für Luft- und Raumfahrt
DPU	Data Processing Unit
ESA	European Space Agency
FSS	First Science Sequence
GRM	Ground Reference Model
IZFP	Institut für zerstörungsfreie Materialprüfung (Institute for nondestructive testing)
MPS	Max Planck Institute for Solar System Research, Göttingen
MUPUS	Multi-Purpose Sensors for Surface and Sub-Surface Science
PP	Permittivity Probe
PZT	Lead Zirconium Titanate (from Pb, Zr, Ti)
SESAME	Surface Electric Sounding and Acoustic Monitoring Experiment
SNR	Signal-to-Noise Ratio
SONC	Scientific Operations and Navigation Centre