OSIRIS4CUBESAT – SYSTEM ENGINEERING WITH NEW SPACE APPROACH FROM THE DEVELOPMENT OF A HIGH DATA-RATE OPTICAL COMMUNICATION PAYLOAD TO THE DEMONSTRATOR IN A QUASI-OPERATIONAL MISSION

Benjamin Rödiger (1), Marie-Theres Hahn (1), Christian Fuchs (1) , Christopher Schmidt (1)

(1) German Aerospace Center – Institute of Communications and Navigation, Muenchener Strasse 20, 82234 Wessling, GERMANY, Benjamin.roediger@dlr.de

ABSTRACT

Modern satellite missions are characterized by compact designs, low costs and extremely short development times. To reach these goals traditional processes have to be adapted to agile and efficient proceedings especially in the Systems Engineering.

The Optical Communications Group (OCS) of German Aerospace Center (DLR) follows this New Space approach in their developments of Optical Communication Payloads for small satellites like CubeSats.

This paper gives an overview of the development processes in the OSIRIS4CubeSat (Optical Space Infrared Downlink System for CubeSats) project, as an example of the tailored Systems Engineering processes in the OCS.

1. OSIRIS4CUBESAT

The OSIRIS4CubeSat (Optical Space Infrared Downlink System for CubeSats) project has the ambitious goal to develop a laser communication payload starting from scratch to a quasi-operational space mission within a very short time, using only Commercial Out Off The Shelf (COTS) components. The outcome of this project is a highly compact laser communication terminal. With its size of 0.3Unit (U), power consumption of less than 8.5W and a weight of less than 400g it can achieve a data-rate of 100 Mbit/s from Low Earth Orbit (LEO) to the ground. Figure 1 shows the final payload [1].

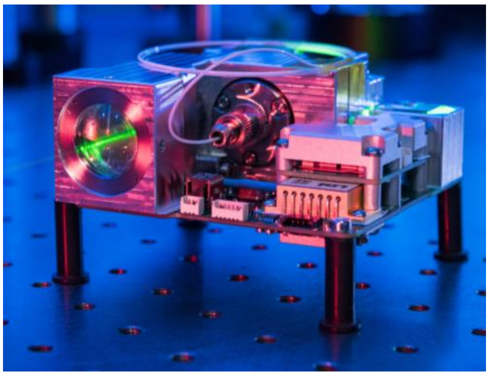

Figure 1. Flight Model (FM) of OSIRIS4CubeSat

1.1. Stakeholders

Beside German Aerospace Center (DLR) there are a couple of partners which are involved in the project. The contractee of the development is Tesat-Spacecom. They act like a costumer who will include the OSIRIS4CubeSat payload as the product "CubeLCT" into their portfolio.

The project does not only consist of the pure development, it includes a demonstrator mission in a realistic scenario. Therefore the first OSIRIS4CubeSat payload will be demonstrated on a 3U CubeSat from "GomSpace", a Danish CubeSat manufacturer.

The operation of the satellite itself will be done by the German Space Operation Center (GSOC) within DLR. This is the first time that a CubeSat will be commanded by an operational ground segment.

1.2. Requirements Definition

Before the official kick-off of the project, the requirements have to be defined. As the project includes the development as well as the operation and the handover to the costumer, several different requirements have to be distinguished.

First the high level requirements are stated in the project contract like Size Weight and Power (SWaP) or data-rate. These are more or less given by the contractee. To fulfil all functionalities of the payload the technical requirements have to be defined by the Systems Engineering. These *System Requirements* are extended with requirements based on the operational environment to guarantee that the payload survives the rough conditions in space and during launch.

For a successful link demonstration and meaningful experiments several requirements have to be given to the operation itself. These *Mission Requirements* are given to the satellite manufacturer GomSpace as well as to the launcher. The orbit parameters have a big influence on the success of the mission. Furthermore the Mission Requirements have to be aligned with GSOC to guarantee a frictionless commanding of the satellite in space.

OSIRIS4CubeSat is a technology demonstrator on a prototype level. In addition to that, the payload is offered by Tesat-Spacecom as a commercial product. In an industry company the assembling processes differ much from prototype integration like it is done in DLR. Thus further requirements to allow a smooth handover to the industry have to be defined. These *Costumer Requirements* are developed together with the costumer in a strong collaboration.

1.3. Model Philosophy

To achieve the goal of low costs and short developments DLR decided to build two models, one Engineering Qualification Model (EQM) and one Flight Model (FM). The use of components of the exact same batch for both models ensures that the qualification results can be directly transferred to the FM. Building both models in parallel allows to reduce the project duration a lot.

2. Project Phases

To achieve the goal of low costs and short development times, the project phases had to be tailored to the needs of the project. The projects structure still orientates on the NASA Systems Engineering project life cycles [2] but reduces the phases and reviews to the absolute necessity.

Phase	Review
1. Concept	Preliminary Design Review (PDR)
2. Design	Critical Design Review (CDR)
3. Development	Technical Readiness Review (TRR)
4. Qualification	Launch Readiness Review (LRR)
5. Operation	System Functionality Review (SFR)

Table 1. Project Phases in OSIRIS4CubeSat

During the whole project the Systems Engineering has to observe and coordinate that the development is compliant to all requirements mentioned in subchapter 1.2. The subsystems of OSIRIS4CubeSat can be mainly distinguished between

- Mechanics
- Electronics
- Optics
- Software

The Systems Engineering has to coordinate the work between the different development teams and to manage the interfaces between the different subsystems. For examples the change of an optical filter, with a different wavelength and size leads to a change in the mechanical design and has an impact on the opto-electrical converter, which leads to a compensation by the software. This is relevant for all phases of the project.

Furthermore the Systems Engineering follows a close alignment with Tesat-Spacecom, GomSpace and GSOC during all phases to also coordinate, align and (if necessary) adapt requirements.

2.1. Concept

Phase 1 starts with a Computer Aided Design (CAD). All subsystems of the payload are conceptual designed separately. For each subsystem specific tools are used:

Mechanics	Autodesk Inventor
Electronics	Altium Designer
Optics	ZEMAX
Software	Development kits

After finishing the single concepts all subsystems are digitally brought together into one payload.

2.2. Design

After finishing the concept the next step is to design the final payload. The goal is that after the CDR every component can be ordered and the payload can be assembled straight away. To assure that the design fulfils all requirements and to avoid recognizing obstacles at a late state in the project several simulations are performed. This prevents redesigns of an already built system in case an issue occurs.

To prepare the development for the harsh environment in space DLR uses ANSYS which takes the Finite Element Method (FEM) to simulate the conditions the satellite will face during the mission. The simulations are focused on the launch loads, the temperature loads according to the expected orbit and the quality of the optical system (this was done with ZEMAX).

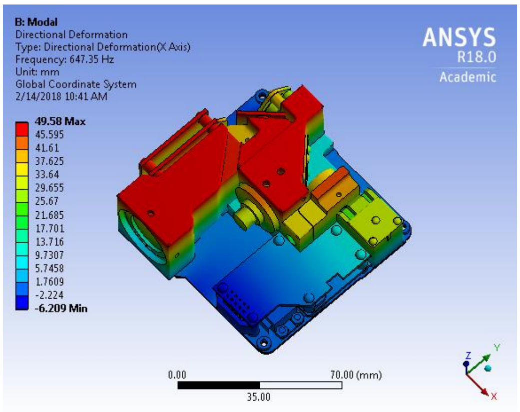

Figure 2. Modal Analysis of OSIRIS4CubeSat

Figure 1 shows an example of the result of the modal analysis for OSIRIS4CubeSat payload done with ANSYS 18.0.

2.3. Development

After a successful CDR the assembly of the payload can start. To reduce costs and lead times only COTS components are used.

Especially during the assembly processes some irritations occurred which were not able to be simulated in advance. For example some screws were not accessible with the tool. For a prototype these issues could easily be solved by special tools. To fulfil the Costumer Requirements a redesign had to be done.

During prototype development some integration processes itself have to be developed as well. This leads to flexible and agile changes in the work at DLR. For an industry manufacturing defined and reproducible processes are mandatory. That means that the processes during the development have to be adjusted and improved so that they can also be taken over by the customer.

2.4. Qualification

DLR orientates on the European Cooperation for Space Standardization (ECSS) [3] but tailors it down to the needs of the project. The suggestions made in the standard can be overpowered for a CubeSat mission. By strict following the ECSS it is likely that additional costs and time are created for qualification tests which are not necessary.

The qualification process is tailored to three necessary tests:

1. Vibration
2. Thermal-Vacuum
3. Radiation

For the vibration qualification process DLR follows pretty close the ECSS. As suggested three tests are done modal analysis, sine vibration and random vibration with modal analysis before and after every other test. Performing these in all three axes leads to 15 vibration tests in total.

CubeSats usually qualify for loads defined in the General Environmental Verification Standard (GEVS) by NASA [4]. Figure 3 compares the loads of random vibrations with the loads of different launchers.

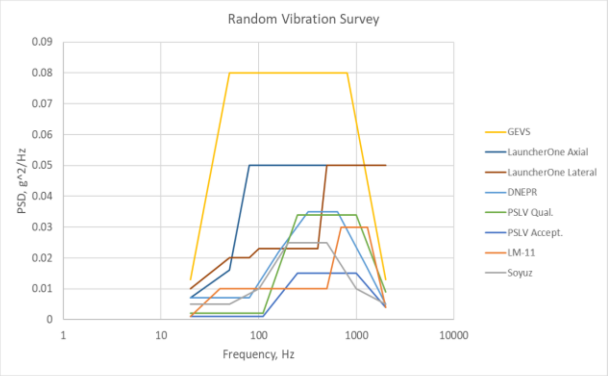

Figure 3. Overview of random vibration loads

The GEVS loads are much higher than every launcher DLR expects for their mission. The sensitive subsystems in OSIRIS4CubeSat lead to a risk that the payload could possibly fail the GEVS qualification but would survive the loads produced by an expected launcher. Thus DLR decided to qualify with loads which represent the highest loads of all possible launchers including some Margin of Safety. This ensures that the payload can survive the launch and prevents the system from over-qualifying.

In the final mission the satellite will face harsh environmental conditions like high and low temperatures and vacuum. The qualification of the payload was done in a thermal vacuum chamber (TVAC) to recreate these conditions. For the TVAC test DLR stick pretty close to the ECSS. As there are no values given in the standard the expected orbit conditions were simulated in advance. Figure 4 shows the qualification cycles.

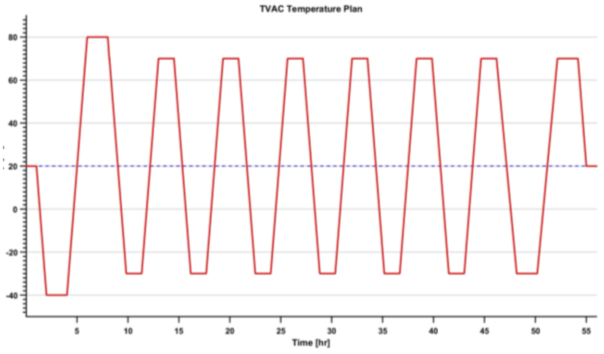

Figure 4. TVAC qualification test cycles

The survival temperature is defined with one cycle between -40°C and +80°C while the operational temperature is defined with seven cycles between -20°C and +60°C. These temperature ranges are much higher than what a CubeSat mission expects in orbit.

To reduce the complexity, time and costs of the TVAC tests some changes according to the ECSS are made. Both survival and operational test are done in one test. That reduces the complexity of the whole qualification and allows performing it in one process. There is no leaking test, corona or arcing test done. In the final mission there will be no operation in medium vacuum so that these cases do not have to be considered. Furthermore the ECSS recommends a dwell of several ours at the extreme temperatures. The missions orbit will be Sun Synchronous (SSO) so that a dwell time of several hours does not represent the final conditions. Thus DLR reduced the dwell time to a few minutes.

Besides thermal and vacuum effects radiation effects face the payload in space. As OSIRIS4CubeSat will be operated in the LEO a Total Ionization Dose (TID) is the only test which has to be considered. Corpuscular radiation is negligible in this orbit.

ECSS suggests performing the TID for every part separately. DLR follows a more pragmatic solution. The TID is performed with the whole EQM. The functionality is tested before, during and after the TID to measure irritations in the behaviour of the subsystems. This reduces the effort extremely.

2.5. Operation

With passing all the in subchapter 2.4 described tests the payload is ready to launch and the FM ready to be integrated into the satellite.

In the CubeSat market several bus standards exist. GomSpace uses the PC/104 standard. This standard is defined by its 104 pin connector and a defined mechanical design of the payloads [5]. OSIRIS4CubeSat directly follows this mechanical standard. With the goal of developing a highly integrated and compact payload a bulky connector like the PC/104 was not considerable. In coordination with GomSpace another solution could be found where all electrical interfaces are realised with small MOLEX connectors to reduce the necessary space for the connectors. As this realization differs from the standard a detailed Interface Control Document (ICD) has to be developed. Furthermore this leads to additional testing effort to verify the interfaces. Therefore GomSpace provides a so called “FlatSat”. This FlatSat includes the main components like the final satellite has. Together with the FlatSat the interfaces of OSIRIS4CubeSat could be tested and verified already during the development. The successful result of this procedure was that the delivery of the FM and the integration into the satellite went straight forward without any interface issues. Figure 5 shows the finally integrated satellite “CubeL” with the aperture of OSIRIS4CubeSat marked in green.

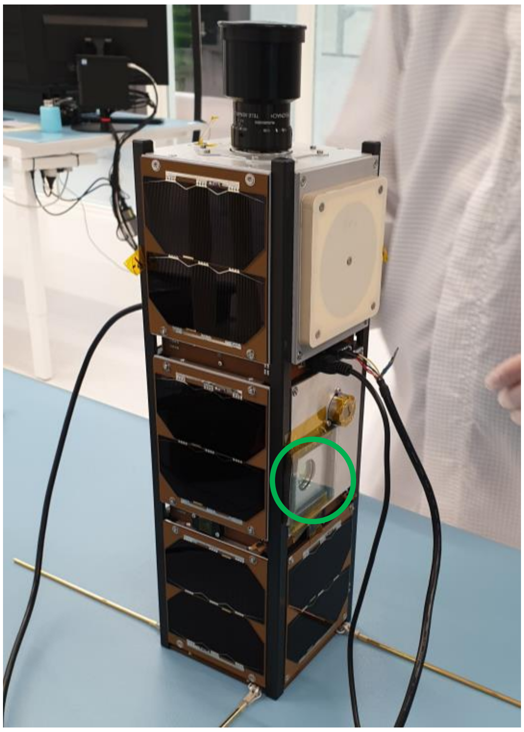

Figure 5. Fully integrated “CubeL” satellite with OSIRIS4CubeSat (green)

One further advantage of the FlatSat is that the operation of the satellite can be tested in advance. The satellite will be operated by GSOC. Via remote GSOC can access the FlatSat and test the entire software interfaces and data transfer of telemetry and telecommand (TM/TC). The Launch and Early Orbit Phase (LEOP) will be done by GomSpace. Afterwards the satellite will be handed over to GSOC. They start with an Ultra High Frequency (UHF) link to command the satellite. Afterwards the satellite will be commanded via s-band.

Due to the narrow laser divergence, especially the pointing accuracy of the satellite is very important. From the beginning of the project it was mandatory to align with GomSpace as well with GSOC if the high requirements in the pointing, which are mission critical can be fulfilled by the satellite and the operation.

3. RISK MITIGATION

Tailoring the Systems Engineering processes like described in the chapters above always increases the risk for the project. It is very important to weigh the benefit of less time and cost against the increasing risk a deviation from the standards leads to. Therefore the Systems Engineering has to work in very close collaboration with the project management. Together a risk mitigation was defined which was taken into account of the projects overall risk assessment.

To reduce the risk of failure additional processes where added. One procedure of reducing the risk is already mentioned in subchapter 2.2. Simulating the payload with FEM allows getting a feeling if the current design will fulfil the requirements or not. These simulations can already be done in a very early stage of the project. If the results of a simulation are negative it is easier to recognize this in the concept phase and change the digital design than failing the qualification.

Even if the entire EQM is qualified on payload level it is useful to test critical subsystems in advance. Some parts or subsystems are vulnerable for different conditions and their behaviour is hard to simulate (e.g. behaviour of Micro-Electro-Mechanical Systems in vacuum). These subsystems were tested separately in parallel to the development of the rest of the payload. With this pre-qualification of subsystems the iterative redesigns process could already start while other subsystems are still in the development.

As OSIRIS4CubeSat was built completely with COTS components DLR had to be prepared how to react on nonconformances. If a test is not passed or parts of the payload failed during a test there are processes defined how to react on this and which additional tasks and tests have to be started. For example if an electronic part fails the radiation test it has to be exchanged by another one which survives the assumed TID. To evaluate which part comes into account the same test is done with multiple parts from different vendors. The failed part is

afterwards replaced by one of the parts where all survived the second TID test.
By tailoring the standards to the mission needs, the tests only qualify the payload for the specific mission. To fully characterize OSIRIS4CubeSat delta-qualifications have to be performed. Performing tests with higher loads gives an indication of how much margin can be assumed for this and for future missions. A delta-qualification with GEVS loads for example would prove that OSIRIS4CubeSat can be flown on every launcher which transports CubeSats. Additionally this leads to a broader market for DLR's industrialization partner Tesat-Spacecom. As the FM is at that time already in the satellite the delta-qualification can be done with the EQM

4. CONCLUSIONS

From the first idea in 2016 to the expected launch in 2020 it took round about 4 years from scratch to a quasi-operational space mission. This fast development approach with the given resources was only possible with a highly pragmatic approach following the New Space idea. The advantages in lowering costs, time and effort will be taken into account for the upcoming projects in OCS.

4.1. Lessons Learned

Customizing the NASA Systems Engineering life cycle allows decreasing the administration effort in the project. By tailoring the project phases to the needs of the OSIRIS4CubeSat project, the number of meetings and the time for writing reports can be reduced significantly, so that the engineers have more time for the development and the tests itself.

Detailed simulations and analysis in the first two phases prevent the project from many non-conformances in later phases. Irritations are recognized already in early project phases. Iterative processes are initiated agile whenever they are necessary.

Using COTS components reduces the costs and the time extremely. Space qualified components are very expensive and often have a very special design and a long lead time. The focus in the evaluation is on COTS components which already have a big heritage in harsh environments like in the aerospace or automotive sector.

Assembling EQM and FM in parallel reduces the development, testing and qualification time even more. Precondition for this is a detailed analysis in phases one and two, to avoid unexpected obstacles or changes in the design when the model is already built.

To perform only the test which are absolutely necessary, reduces the time and the costs of the payload as well. Characterizing the payload by sticking to the standard is not necessary if scenarios are tested which will never happen in the final operation.

Testing critical subsystems in advance is absolutely necessary. This has to be considered including some buffer and possible alternative solutions already in the project plan. In these cases a plan B or even C or D have to be considered in advance, to be able to react if the outcome of a test or qualification is not as expected. Therefore a modular design approach like in O4C, where the payload consists of distinguishable subsystems is very helpful.

Using COTS components with standard designs allows uncomplicated changes when a non-conformance occurs. If a part fails a test it can easily be replaced by an identical one from a different vendor and be re-tested.

Changing the processes according to the New Space approach is always a balance between time, cost and effort and the risk the reduced processes bring along. The risks have to be analysed in detail in advanced, weighed against the benefit and communicated with the stakeholders

4.1. Outlook

The satellite is already fully integrated and the launch is expected in 2020. Equipped with a high resolution camera it will demonstrate the whole chain from taking a picture over the transmission via an optical link to the reception of the picture on an optical ground station.

OSIRIS4CubeSat is the basis for future developments. The fully qualified payload, the modular design and the defined interfaces allow extensions for future missions like inter-satellite links, lager apertures or Quantum Key Distribution (QKD). The developed processes and benefits of the qualification process are adapted to all other projects in the OSIRIS program.

5. REFERENCES

1. Schmidt, Christopher, et. al. (2018). *OSIRIS Optical Communication Demonstration on CubeSat*, The 4S Symposium, Sorrento, Italy, 3.

2. Hirshorn, Steven R. (2007). Fundamentals of Systems Engineering. *NASA Systems Engineering Handbook*, NASA SP-2016-6105 Rev2, pp8-9.

3. ECSS Secretariat (2012), *ECSS-E-ST-10-03C*, ESA Publications Division, European Space Agency, Noordwijk, The Netherlands.

4. NASA (2013), *General Environmental Verification Standard (GEVS) For GSFC Flight Programs and Projects*, NASA Goddard Space Flight Center, Greenbelt, Maryland, USA, pp2.4-14–2.4-19.

5. PC/104 Embedded Consortium (2008), *PC/104 Specification Version 2.6*.