PRELIMINARY MISSION RESULTS AND PROJECT EVALUATION OF THE DELFI-C^3 NANO-SATELLITE

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ABSTRACT

This paper discusses preliminary mission results of Delfi-C^3 up till the early operations phase. The first section will discuss the design philosophy of Delfi-C^3. To reduce operational risks, Delfi-C^3 followed the KISS principle and is designed to be Single-Point-of-Failure-free. A balance is made between adoption of professional space engineering customs and standards on one hand and the limitations of small satellites, financial budgets and limited human resources on the other hand. The second section of the paper discusses the project planning and management of Delfi-C^3. Addressed are reasonable timelines for the development of a nano-satellite, how to deal with a launch slip and the occasional conflicts between the interest of the students and the interest of the project. The third section of the paper will present the results of the early operations of Delfi-C^3. Discussed are the performance of the payloads, the bus and the ground network of the satellite. Finally, an early statement of the mission success will be given.

Figure 1 – PSLV-C9 launch (source: ISRO)

1. DELFI-C^3 MISSION

At Delft University of Technology, students and staff have worked for three years on the nano-satellite Delfi-C^3 [1]. On 28 of April 2008 3:53h UTC, Delfi-C^3 was launched from Sriharikota in India (Fig.1) as piggyback launch [2]. The Delfi-C^3 project started in October of 2004 an evolved from the heritage of satellite case studies, the enthusiasm of students and staff to develop a real spacecraft, the availability of payloads from Dutch Space and the MicroNed program [3] and the CubeSat standard (Fig. 2).

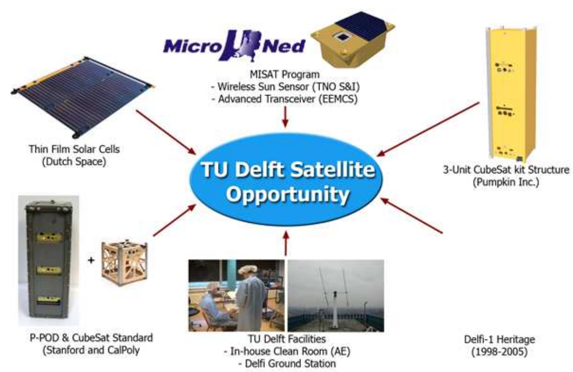

Figure 2: Delfi-C^3 Satellite Opportunity

Several objectives have been defined for the mission:

1.1. Educational objectives

The educational objective is to provide the best possible education in space engineering through team work, hands-on experience, designing and testing of a real spacecraft. The performance on this objective can be expressed in the number of students, the quality of their work and in finding a balance between the interests of the students and the project needs. The idea is to prepare students in an optimal way for a successful career in space engineering, showing all aspects of a real satellite project in a professional manner.

1.2. Technical objectives

The three main technical goals for Delfi-C^3 are:

1. in-orbit testing of the Thin Film Solar Cells (TFSC) payload from Dutch Space
2. in-orbit testing of the Autonomous Wireless Sun Sensor (AWSS) payload from TNO
3. operation of onboard radio-amateur platform with linear transponder

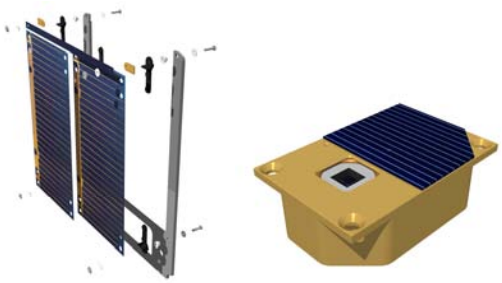

Fig 3: The TFSC (left) and AWSS (right) payloads

The first technical goal of Delfi-C^3 is to test the TFSC performance, a new type of photovoltaic cells with a higher power-to-mass ratio and lower cost than conventional solar arrays (Fig. 3). A Copper-Indium-Galium-diSelenide is deposited on a titanium base layer to form these thin film solar cells. The expectations are a power output of over 100 Watts per kilogram, with a cost lower than 350 Euro per Watt. The efficiency is estimated around 12% under full illumination in space. The measurements performed onboard include IV-curves and temperature of the TFSC and current and voltage of reference diodes.

The second technical goal is to prove that the AWSS (Fig. 3) performs as expected in space. Delfi-C^3 is equipped with two AWSSs which send their measurements through wireless one-way communication. Because the AWSS is equipped with its own power supply (solar cell) and transmits its data at all times when illuminated, it is fully autonomous and independent from the rest of the satellite. The advantage is that it is very flexible in placement, does not require any wiring harness and has very little interfaces, therefore reducing complexity of the whole satellite design.

The redundant radio amateur platform doubles as the communication subsystem of Delfi-C^3 and a linear transponder. Initially it was the intention to equip one transceiver with a high-efficient switching mode amplifier. This was later discovered to be unfeasible in the project timeline of Delfi-C^3. Nonetheless, the development of a communication system complying with radio amateur standards and including a linear transponder on a nano-satellite is a significant technical achievement. The linear transponder will be turned on after the scientific mission, during which the TFSC and AWSS payloads are tested. This will occur approximately three months after the launch.

1.3. Development objectives

When practical, most of the development, manufacturing and testing of Delfi-C^3 should be done by the project team itself. Since Delfi-C^3 is the first of a series of nano-satellites within the Delfi Program, achieving all project milestones is a great leap forward and can be regarded as the main development goal. Passing the major system and environmental tests would be a key indicator that the TU Delft has gained expertise and experience in the field of small satellite engineering.

2. DESIGN PHILOSPHY

Delfi-C^3 has been developed with a professional space engineering attitude. But because the project is constrained in time, money and resources a few adaptations had to be made to the usual way space engineering is done by major space organizations.

2.1. KISS principle

The “Keep It Simple, Stupid” principle is used to avoid unnecessary complexity in the design or the process. This is done in order to keep the costs down, development time acceptable and to reduce operational risks. For Delfi-C^3, there are a few examples of simple but effective solutions.

The VHF and UHF antennas needed to be stowed inside the CubeSat structure. During tests with several materials, measuring tape had the right characteristics for this purpose: good electric conductivity and enough resilience to force itself out of an enclosed box (Fig. 5). Even the finishing of the measuring tape, bought at a standard home improvement store, was left on, since there was no need for removal. The antenna is kept in place with a lid which is attached to Dyneema wire. The deployment sequence of the satellite controls thermal knives to melt the wire and hence deploy the antenna (Fig. 4). As a thermal knife, two redundant 1/8 W resistors are used and driven to produce 2 W of heat. Although it goes against the nature of engineers to use components far outside their specifications, more than 200 tests in thermal vacuum showed no failure of the resistor itself within the conditions which they are used. Thermal knifes in industry were not available at these low power ranges, so this was the simplest solution one could think of.

Figure 4: Antenna box deployment mechanism

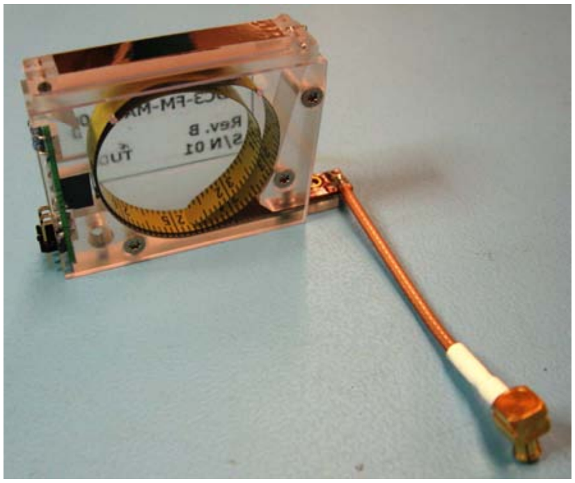

Figure 5: Antenna box side view

Another example of the KISS principle applied on Delfi-C^3 is the lack of onboard energy storage (battery). The wireless sun sensor and thin film solar cells payloads only require sunlight to work, so there is no need to operate the satellite in eclipse. The additional risk of a more complex electrical power subsystem with onboard energy storage does not add significant functionality to the satellite and has therefore been omitted.

2.2. Proto-flight approach

To reduce the development time of the satellite, a proto-flight approach was chosen. This means that there are as few steps as possible from design on paper to flight hardware. The potential flight hardware is tested and based on the results it is decided whether the hardware is designated as flight hardware, continues its proto-flight status because it needs some minor modifications or will be used as proto-type because the modifications required are too significant. Although bread-boarding was done for some sub-circuits and the communications platform, most subsystems followed the proto-flight approach directly from design on paper. It is debatable if this approach is justified. Almost all first proto-flight hardware degraded to proto-types or worse. This has been a risk to the project planning, since it was anticipated that many subsystems would qualify directly for flight hardware. It also limits the amount of testing performed on representative hardware, since for potential flight hardware the amount of strain due to testing should be limited for certain aspects. An example of this is the onboard database; flash memory has a limited amount of cycles of which a significant number is used for certain tests. Each of these tests reduces the operational life-time in-orbit. Other arguments against this approach is the fact that many design flaws could be avoided by having more hardware design iterations and from the educational objective of the project it would be good if also the first generation of students on the project would come in contact with hardware. For the successors of Delfi-C^3, this is not a major issue since there is hardware and experience available. But for universities starting a first satellite project, it is recommended to allocate some extra time for bread-boarding and prototyping or constructing an engineering model.

2.3. Single-Point-of-Failure-free Design

In the preliminary design of Delfi-C^3, Fault Tree Analysis (FTA) was used for the primary technical objective of the satellite [4]. The goal was to identify and remove all Single-Point-of-Failures (SPoFs) for the TFSC experiment. Although this method proved to be successful in the preliminary phase of the project, it was later abandoned because a more detailed design requires the FTA to become more quantitative instead of qualitative, producing a significant workload for a reliability engineer. Especially reliability figures of small components cannot be properly estimated without intensive testing, which is almost impossible to do in a space project with very short development time. It was therefore chosen to apply redundancy to every component and operation which lies in the path to the TFSC experiment. This yields redundancy in two deployment mechanisms per deployable, four solar arrays with their own conversion circuit, two different command and data handling systems, etc. Reliability engineering has shifted to subsystem level where the responsible people on each subsystem needed to identify possible SPoFs themselves and estimate whether a SPoF is a threat to the mission. In case of uncertainty, the fail-safe approach of duplicating components is chosen. This has lead to a design which is not optimized for volume and mass, but did not lead to budgetary problems. Delfi-C^3 is also not SPoF-free in a literal sense. For instance all system-bus wires, including redundant power and data lines, are connected through a single multi-pole connector (Fig. 6). Although some of those connectors can be regarded as SPoFs and no quantitative reliability figures are available, the chance that a whole connector would break off is considered to be negligible. There is also a problem on the definition of SPoFs on aggregation levels. Physically, there are two communication platforms (two PCBs in the stack), but there is only one central Electrical Power Subsystem PCB (Fig. 6). Looking closer at this board, there are redundant power conversion circuits, but they are not fully independent because they are all attached to the same power bus, which does have minor influence on those circuits. To conclude, Delfi-C^3 is considered to be SPoF-free for all components involved and leading to the TFSC-experiment, following a relaxed definition where only SPoFs are taking into account that threaten the mission with a probability that is not negligible.

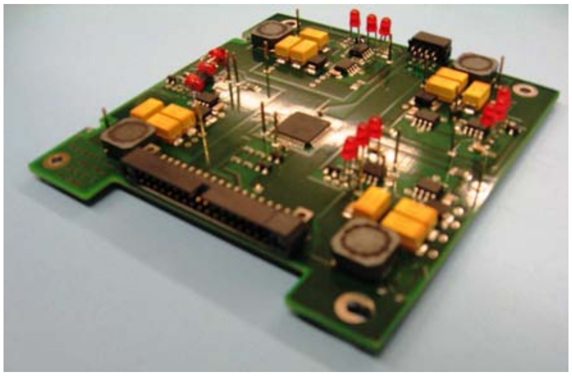

Figure 6: Electrical Power Subsystem PCB

2.4. Professional space engineering

Although some of the stated design philosophies are rather uncommon in professional space projects, the Delfi-C^3 project adopted many space engineering standards, disciplines and methods. As Delfi-C^3 is mainly an educational project, it is considered very important to implement all aspects of a space project. This also includes environmental testing with a thermal vacuum chamber (Fig. 7) and a shaker table (Fig. 8).

Figure 7: Vibration test on shaker table

Cleanliness and proper handling of flight hardware and equipment is considered very important and has to become routine for everyone on the project. The in-house class 100,000 cleanroom (Fig. 9) is used throughout the project to assemble and test components of Delfi-C^3.

One of the major disciplines in space engineering is systems engineering. Functional descriptions, task flows, interface control and documentation management are just a few examples of tools to improve the systematic approach which is needed to come to a final design where all characteristics of the satellite are known and controlled. This is in contrast to the trial-and-error approach which is often applied in other engineering fields but sometimes also in university satellite projects elsewhere. For Delfi-C^3, the process is more important than the technical product. Nonetheless, a professional attitude and working environment will increase the reliability of the product.

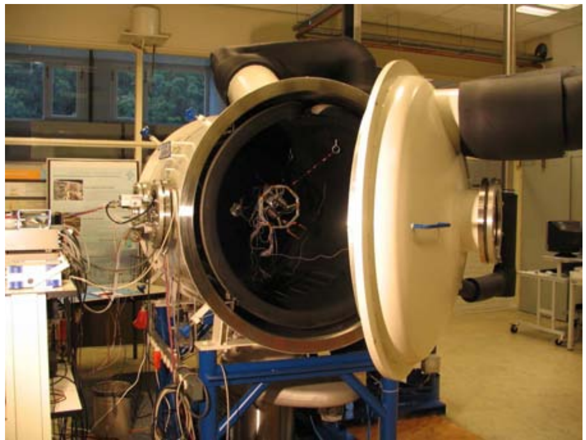

Figure 8: Delfi-C^3 in thermal vacuum chamber

2.5. Radio Amateur Network

Delfi-C^3 uses a distributed ground system network where radio amateurs all around the globe participate voluntarily in collecting telemetry and send the received data to a redundant database server. The reasons for this approach are:

- Delfi-C^3 has a low data-rate communications link because of limited power and lack of onboard data storage. The amount of payload data requires that the satellite sends out the measured data continuously. Combined with the fact that Delfi-C^3 is in a low Earth orbit and therefore spends limited time in range of a single ground-station, a distributed ground system would yield the most received telemetry.
- Professional frequencies are very expensive. A radio amateur frequency license is free of charge but requires the satellite to operate within the amateur satellite service as defined by the International Amateur Radio Union (IARU). Delfi-C3 includes a linear transponder as a return favour to radio amateurs and hence complies with the requirements to operate in the amateur satellite service.

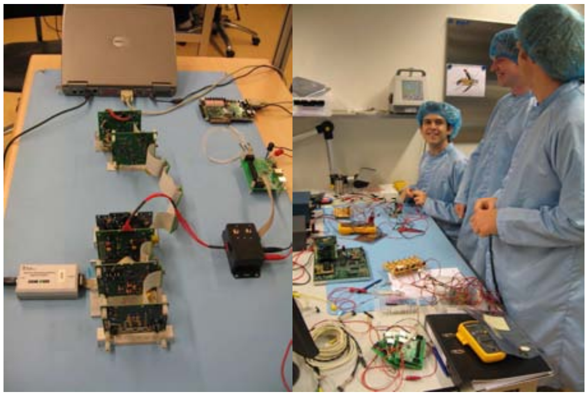

Figure 9: Delfi-C^3 subsystem tests in clean room

3. PROJECT PLANNING AND MANAGEMENT

It was decided that the project tasks would be exercised by MSc. and BEng. students as a thesis work. This would not only yield a more professional attitude towards the project from the students, but the amount of work was considered to be too much to be done part-time. One of the major problems encountered is the thesis-worthiness of the project work. Although a lot of work shows interesting results which have scientific value, a lot of time is spent on daily project work which does not have direct reflectance in the scientific outcome. Especially in the last phase of the project where production, assembly and testing asks a lot of effort and time, this becomes a problem. The examination committees did realize that extensive literature research or a perfect thesis report is difficult to combine with the laborious project work. On the other hand, care must be taken that the project work does not degrade the academic level which a university is supposed to maintain. Part of this has been compensated by many students by writing a conference paper as a compacted form of scientific reporting, but this was not always sufficient. For the Delfi-C^3 project it can be concluded that the practical workload was too high for the last generation of students. In the future it is recommended that students should be allowed for some time to do proper reporting and/or writing a paper. The best way to do this is to attract more students to distribute the workload. The cooperation of space systems engineers, computer engineers and electrical engineers from both the TU Delft as well as universities of applied sciences was very successful. Although there are some differences in mindset, people from all disciplines worked closely together and there was a form of self-management between individuals throughout the project.

The launch of Delfi-C^3 has been postponed several times. A first flight model of Delfi-C^3 was delivered to the launch broker in Canada in July of 2007. It became evident that the performance of this model was degraded due to a few remaining problems with the flight software and the communications platform. The time which was made available due to the several launch postponements was used to fix these problems. This raises the question though, whether part of the operational success is based on a longer development time and if the original planning was too ambiguous. The answer to this question is not a simple one. First of all, the team-size was decreased significantly because no new students were taken on the project after delivery of the original flight model in July of 2007. Secondly, a shifting deadline and a small team are not good motivators to finish the work earlier than necessary. Also the early operations phase of Delfi-C^3 was a little understaffed. A learned lesson is that the team-size should not decrease significantly before the missions operations are in a nominal phase. Once the launch is known, a deadline for delivery of the satellite must be set and should not be shifted every time the launch date shifts. It should be mentioned however that the launch preparations in India prior to the launch and mission control for the launch and early operations phase, were very well organized and went smoothly.

The development time for a CubeSat project depends on the objectives and design approach, but for Delfi-C^3 a three year development time from the start of the project until launch has been sufficient to do all the work properly, assuming a convenient team-size for every phase. For future projects, the aim is to develop nano-satellites in 2.5 years because a 0.5 year advantage related to the experience of Delfi-C^3 is taken into account.

4. EARLY OPERATIONS RESULTS

Delfi-C^3 was successfully launched on 28 of April at 3:53h UTC onboard the PSLV-C9 launch vehicle (Fig. 1). At 4:10h UTC, Delfi-C^3 was injected in to a sun-synchronous orbit at 630 km. At 6:45h UTC, signals from Delfi-C^3 where picked up by the radio amateur Rick Mann in California, USA. He made a recording of this event and the Delft Ground Stations operators where able to verify that this was indeed Delfi-C^3 by the typical sound which was heard. At 11:55h UTC, Delft Ground Station was able to receive and decode the first telemetry. This was at the third predicted pass over Delft, the Netherlands. Operations can in general terms be regarded as a great success. The telemetry shows nominal behavior of all satellite subsystems and all four solar panels and eight antennas where deployed. The onboard software autonomously switched from a 5-minute idle mode to the deployment mode and finally into the science mode. No tele-commands where required for Delfi-C^3 to become fully operational. The distributed ground system of a network of radio amateurs around the globe has already shown to be very successful (Fig. 10). Radio amateurs have not only contributed to a significant amount of all received telemetry, they have also proven to be very helpful in analysis and problem solving. The key to this success can be found in the close involvement of radio amateurs throughout the whole project and this should be continued for future projects.

Orbit determination of Delfi-C^3 has been difficult in the first weeks. Because PSLV-C9 launched a total of ten satellites in approximately the same orbit, it is very difficult to find out which observed object corresponds to which satellite. Finally, two weeks into the mission, Delfi-C^3 was associated with NORAD object #32789.

There are a few problems with the stability of the available electrical power, and hence some subsystems sometimes turn off during the orbit. In some cases this leads to a decrease of payload data, but in the worst case the communications platform turns off and a recovery tele-command or a reboot is required. Fortunately, there is a reboot of the satellite every orbit due to the lack of power in eclipse. It is however a major lesson learnt for future satellites like Delfi-n3Xt, which is designed to have an onboard battery in the sense that better watchdog-circuitry or autonomous recovery options are required for a reliable system.

Despite a few small problems, most of the operations succeed very well and the received data-volume is already enormous. The TFSC measurements show smooth IV-curves, with an estimated accuracy of 1%. An example of the measured IV-curves can be found in figure 10, which is just one of the thousands of TFSC measurements which have already been received. Also AWSS data is received through the intra-satellite wireless communication link. Currently, analysis is performed on the validity of this data.

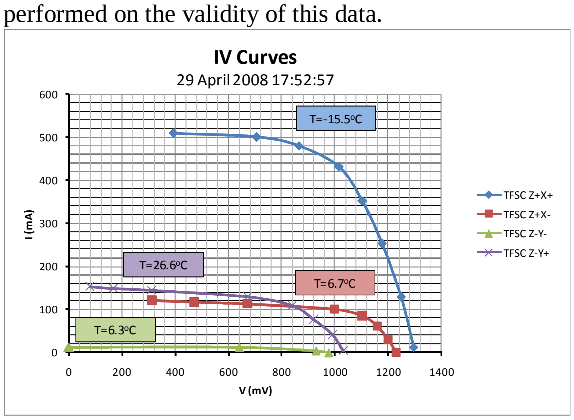

Figure 10: Graph of one TFSC-measurement

After three weeks of operations, more than 120,000 telemetry packets from 238 participating radio amateurs have been received (Fig. 11). Delfi-C3 has received an OSCAR (Orbiting Satellite Carrying Amateur Radio) designator and is now also known as DO-64.

Although operations just started, most of the objectives are already met. Over 60 students have actively participated in the project and have gained unique hands-on experience in designing, building and operation a satellite. The educational and development objectives have been passed successfully and there is no doubt the technical objectives will soon be satisfied as well. Delfi-C^3 is an inspiration to new generations of students to continue the success on new Delfi satellites.

Figure 11: Participating radio amateurs for Delfi-C^3 (© Google)

ACKNOWLEDGEMENT

Delfi-C^3 could not have been made possible without the driving force of motivated students, staff and project partners. A major contribution to the operations of Delfi-C^3 has been made by the radio amateur community world-wide, so a special word of thanks is reserved to the radio amateurs Rick Mann (KI6RLM) for recording the first received signals of Delfi-C^3 and PE1ITR, PA0DLO and VE4NSA for receiving and submitting the most telemetry in the first weeks.

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