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SPACE SYSTEMS SYMPOSIUM (D1.)
Lessons Learned in Space Systems (5.)

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ASSEMBLY, INTEGRATION AND TESTING OF THE DELFI-C^3 NANOSATELLITE

Abstract

At the Delft University of Technology, the Delfi-C^3 3-unit Cube Sat was finalised for launch on PSLV-C9. An overview is presented about manufacturing, assembly, integration and verification activities on subsystems and Proto Flight Model (PFM) until delivery for launch. Delfi-C^3 is the first Dutch university satellite and the fourth Dutch satellite. It was designed and built by the faculties of Aerospace Engineering and Electrical Engineering, Mathematics and Computer Science. Industry partners provided payloads: Autonomous Wireless Sun Sensors and Thin Film Solar Cells.

Attention is paid to the experiences and lessons learned in this student project. The test plan and activities may serve as a valuable scheme for the next university satellite and other cube sats. During the hardware phase of the project, firstly development tests were done (e.g. deployment mechanisms, antenna pattern), followed by functional performance tests of subsystems (electronics, measurement systems, payload interface electronics, power system, communications system and attitude control behaviour). The complete satellite was subjected to a test program, consisting of vibration-, thermal vacuum-, deployment-, communication- and performance tests. With regular health and functional checks, the satellite status was verified for changes during testing.

Keywords:
Delfi-C^3, university satellite, student project, testing, sun-sensor, wireless, thin film solar cells, assembly, integration, test

1 Introduction

At Delft University of Technology, students and staff worked for three years with enthusiasm for the nano-satellite Delfi-C^3 [Ref. 1, 12] on design, manufacturing, assembly, integration and test. On April 28, 2008 the first Dutch university satellite was launched from the ISRO launch centre at Sriharikota as a piggy back on the Indian PSLV-C9. The Delfi-C^3 project evolved from the heritage of satellite case studies to a real satellite with payloads from the customers Dutch Space and TNO Science and Industry. Many modifications, deletions and additions were made to the basic 3-unit cube sat structure, purchased at Pumpkin Inc.

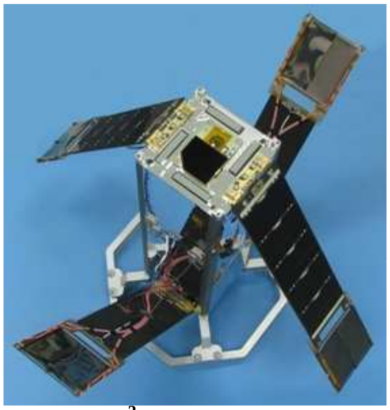

Figure 1 Delfi-C^3 Flight Model on work stand with deployed solar panels

The project had a number of (educational) objectives defined for the mission:

- Perform System Engineering in a realistic context [Ref. 2]
- Hands-on experience with real hardware
- Start of the development line of Delft university satellites [Ref. 3
- Working together in a multi-disciplinary environment
  (university, engineering colleges, research institutes and industry)
- Technology test-bed for in-orbit voltage-current performance of TFSC with varying angles of incidence
- In-orbit performance of the wireless communication of the sun sensors

The Pico-Satellite Orbital Deployer (X-POD) was delivered by UTIAS Space Flight Laboratory, Toronto, which also acted as the launch provider for a number of nano-satellites at Sriharikota.

The in-flight data are transmitted, captured by radio-amateurs all over the world and send via internet to the server at the ground station in Delft [Ref. 4, 5]. As a favour for their support a radio transponder is implemented for use by radio amateurs.

The Delfi-C^3 project was supported by the MicroNed program in the Netherlands.

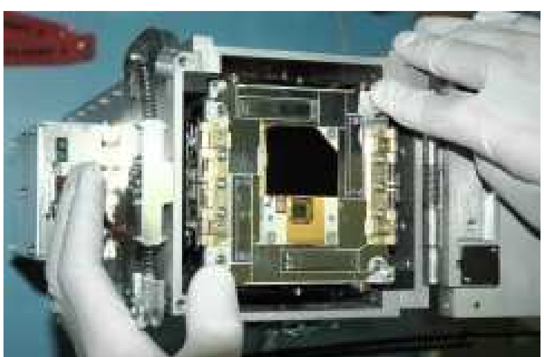

Figure 2 Delfi-C^3 installed in X-POD at Sriharikota (Photo: Courtesy ISRO)

2 Overall Manufacturing Assembly, Integration and Test Philosophy

As Delfi-C^3 is the first satellite of the Delft University of Technology quite a number of topics had to be arranged and decided upon to enable the design, development, manufacturing, assembly, integration and of test the satellite.

2.1 Proto-Flight Approach

A basic choice we have made was to choose a proto-flight model approach. Of course this choice involves a certain risk when something goes not as planned. We tried to limited these risks by purchasing enough spare parts, because with that limited costs are involved. Looking back this has been a good choice. A few times we had to order more off the shelve parts and a number of times we had to order modified PCB’s, but these had a short lead time due to agreements with the supplier. Hardware for both experiments were delivered to us and as such were not involved in our own process, though we designed and manufactured a number of parts for the payloads.

For the manufacturing of mechanical parts we made a detail schedule. This showed that at the university workshops not enough capacity was available to meet the project needs. We solved this mismatch by subcontracting parts at outside shops. But for direct support during development activities, we got a very adequate support.

Another consequence of the proto-flight model approach is that the project could not (always) apply qualification levels to the hardware that was going to fly. We adopted as a rule to test to acceptance level with qualification durations. It worked out well.

Other choices were:

- use a limited selection of metric fasteners (with Torx serration)
- use one series of connectors only (HARWIN Datamate 2 mm pitch)
- make agreements with preferred suppliers (several decided even to sponsor the project)
- use one size of cable as much as possible (i.e. AWG 24)
- try to use COTS hardware (in particular for electronic devices and components; also beneficial when smaller quantities are needed)

We decided to assemble the satellite with as much as possible with standard tooling. The above mentioned choices made this possible to a great extent. Naturally during our work on the satellite some more tools were purchased. Also a number identical tools and equipment was purchased extra to overcome eventual break-downs. Apart from the tooling intended specifically for project needs, we purchased a lot of standard cleanroom equipment, as we were in a start-up phase of the facility.

2.2 Cleanroom & workshop

In parallel to the design and development activities an area was made available to be transferred into a Class 100 000 cleanroom. Due to existing circumstances in the building, we are not able to control the temperature and the humidity. Air from the building was additionally filtered with HEPA filter to better than Class 100 000. We purchased a particle counter and measured particles, temperature and humidity with 30 to 60 minute intervals on-line. Throughout the project the particle measurements normally remained within the required levels with ample margins. A very few times we saw overshoots, but most of these could be traced back to for example too many people in the cleanroom for short periods. A few times we had to stop working and cover the satellite, because of maintenance activities of the university, but these were normally announced on beforehand.

The cleanroom has a limited storage capacity for flight materials (e.g. adhesives, raw materials, parts, precious items and quarantine items). Next to the cleanroom a workshop is located for preparatory work as for example pre-cleaning and some development work. In the meantime the facility has been equipped with a variety of mechanical and electrical equipment. We try to keep this standardised in line with the choices made for the Delfi development line of satellites.

2.3 AIT Plan

At the start a plan was prepared for the whole project. This enabled us to arrange test facilities pretty well in time. This worked rather well; also with the changing population of students on the project and with changes in the project schedule. Baseline was to do all assembly and integration work in the cleanroom at the Aerospace faculty. Activities for electronic assemblies were done at the faculty of Electrical Engineering; these involved design, manufacturing of development PCBs, proto-flight items thermal cycling and calibration.

University facilities used for Delfi-C^3 were:

- Cleanroom at Space Systems engineering (which includes: Vacuum oven, Helmholtz cage [Ref. 6], Radio test equipment, mass properties measurement)
- Mechanical workshop of the aerospace faculty
- GN_2 oven and climate chambers at aerospace test hall
- Electronics assembly at the faculty of Electrical Engineering
- Heat treatment facility at the faculty of Mechanical Engineering

External facilities used for Delfi-C^3 were:

- antenna test range and thermal vacuum facility at National Aerospace Laboratory
- solar cell measurement in the VLASS at Dutch Space; also for joint integration work, where hardware interfaces were involved.
- selection of transmitter flight crystals at the supplier premises
- vibration test at TNO Built Environment and Geosciences, Delft

As a part of the process we also organised excursions to industry and trade exhibitions.

The plan also contained global descriptions and test level requirements for most tests. For detail testing test specifications were written, e.g. vibration test, thermal vacuum test, functional performance (e.g. deployment and sub-system testing). Some small tests (e.g. mass properties)were reported by spreadsheets and/or emails. Software testing was done separately.

2.4 Working with procedures

Though working according to detailed integration and test procedures is not a basic way of working for students, we managed to implement this more and more. Looking backwards also the students were happy with it, as they saw the profits obtained. And of course as an educational institution, one has to allow for the possibility of making mistakes, as this works most times the best to learn how things really to work in practice. Simply said: “gain hands-on experience”

We prepared procedures for:

- working in the cleanroom
- Development testing (these were less detailed)
- Flight test procedures
- Launch operations (manual for: handling, inspection, packaging, installation, red tags, green tags, etc.)

The procedures for the flight hardware detailed the following topics:

- What is the purpose of the activities
- What are the working conditions needed
- What items are needed for the work (also documents)

- What types of tooling and equipment are needed
- What documentation is needed
- Activities list in a table format, specifying the detailed work to be done and columns for who did it and when
- Record were made of: calibration dates of tools used, material batch numbers, procedure variations

A standard list of torque values was added in the procedures for all fastener combinations used.

2.5 Assembly & Integration

Figure 3 Thermal vacuum bake-out of PCB's and the system bus.

After completion of the items to be used for the assembly of the satellite, these were cleaned as needed and brought to the cleanroom. Some times additional treatments were done, as for example bake-out of PCB's or temperature cures of adhesives.

In principle the assembly was done by two ore more persons, whereas in that manner they can control each other to obtain optimum quality of the work as a total quality management approach. This normally limits the number of non-conformances and gives a larger involvement with the project. Furthermore people can replace each other more easily.

The cooperation of space systems engineers, computer engineers and electrical engineers from both faculties of the TU Delft, as well as with students of engineering colleges was very successful. Although there are differences in mindset, people from the various disciplines worked closely together, resulting in a form of self-management between individuals throughout the project.

3 Structure Sub-system

3.1 Structure

As Delfi-C^3 was the first satellite of the Delft University of technology, it has been decided to purchase a cube sat kit as basis. In the course of the engineering process, we found that we had to modify, change and replace many items of the kit. At last only a heavily modified body, a set of mid-plane stand-offs and the FM430 PCB remained from the kit. All other items for the satellite were designed and developed newly: top- and bottom panel, modular antenna boxes, solar array panels with hinges, hold-down and release system, revised PCB stack mounting.

3.2 Modular Antenna Box

The satellite is equipped with two sets of four antennae for uplink and downlink respectively. They are located at the top and the bottom panel of the satellite. Whereas the antennae have to be stowed during launch a deployable type is needed. Many possibilities for the antenna were considered[Ref. 7]. A common design was chosen with the antenna length as only difference. The antenna system is designed as a line replaceable unit in a box. As such it can be replaced after a deployment test or when necessary for any other reason. Presumably the Modular Antenna Box design had the longest development and test period of the satellite. Just before shipment for launch some minor modifications had to be introduced

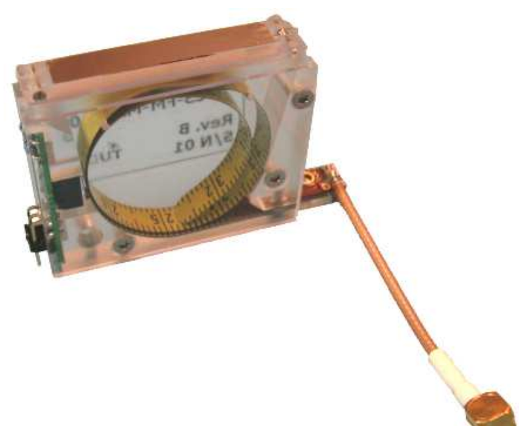

Figure 4 Modular Antenna Box (MAB) with stowed antenna

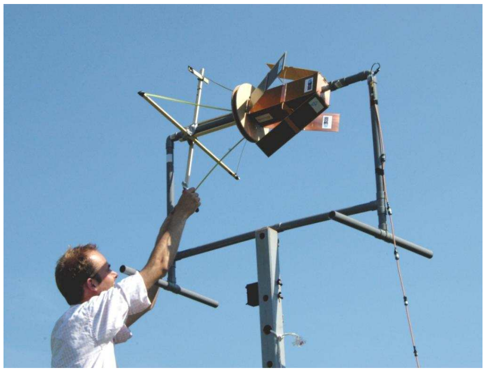

Figure 5 Antenna test set-up on NLR antenna test range

After the baseline design was established, it was tested at the test range of the National Aerospace Laboratory NLR. First, the optimum antenna length (slightly shorter than the theoretical ¼ λ) was determined, after which the antenna radiation pattern was verified. Several iterations were needed, resulting in very good performance as is shown in the flight nowadays.

The mechanical system parameters (rigidity, deployment and cutting times) were first tested on the workbench and subsequently at low and high temperatures in GN_2.

Figure 6 Deployment testing in GN_2 at -30°C

One of the problems encountered, was the large spread in cutting times of the redundant hold-down and release system. A factor of 10 under further identical conditions; it appeared that the COTS resistor, used for cutting, had an unequal heat distribution over its surface.

Fortunately the project was invited to be part in the ESA Student Parabolic Flight Campaign 2006. 16 out of the 42 deployment tests showed failures, resulting in a number of redesigns. With the redesigned system further testing was completed during the satellite system tests (vibration, thermal and functional) successfully on the PFM.

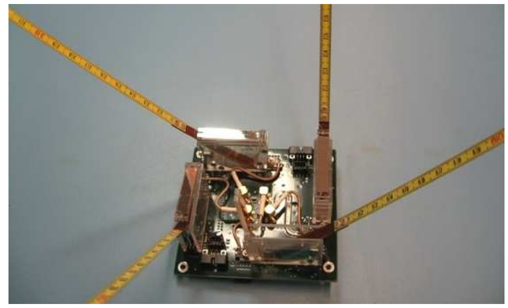

Figure 7 Final design: Interface Control Board with four deployed downlink antennae

But later during functional testing with the spare model in the cleanroom at ambient temperature Murphy surprised with a deployment failure, resulting in further dimensional adaptations of parts and a modification of the antenna tip shape. In flight all antennae deployments were confirmed.

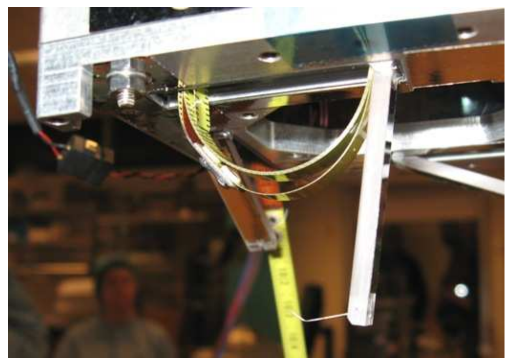

Figure 8 Deployment failure in the last stage of testing.

3.3 Solar Array Panels

Delfi-C^3 has four identical solar panels, each with five regular GaAs solar cells and a pair of thin film

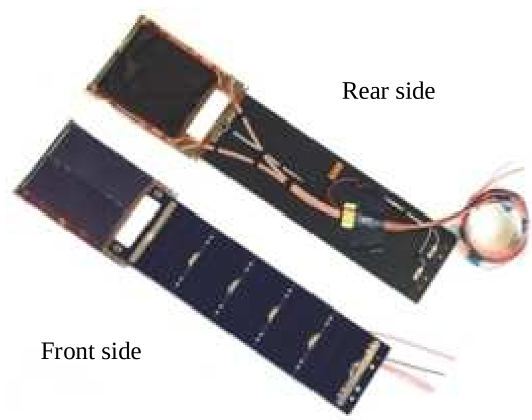

Figure 9 Solar panels with Thin Film Solar Cell assembly attached

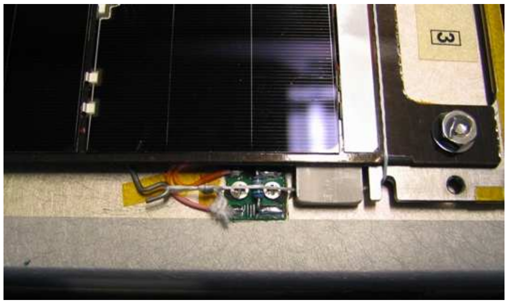

Figure 10 Detail of the hold-down and release system

solar cells on titanium substrates. Wiring is connected from the rear side to facilitate a better routing. Furthermore a titanium temperature strip and a photocell are added for reference purposes. The solar panel hinge two by two on both ends of the satellite. Bronze hinges with stainless steel axles are applied. In the hinges end stops and two springs are incorporated to support controlled deployment. The hold-down and release system employs a Dyneema wire to retain the solar panel flat to the side of the satellite during transportation and launch. It is cut with the same resistor as the antennae. Tension on the Dyneema wire is kept with springs. The system is redundant with two cutting resistors and tensioning springs on both sides of the solar panel. In flight the deployments of all solar panels was confirmed.

4 Electrical Sub-system

4.1 Electrical Power Sub-System

For regulation of the 12V power bus, Delfi-C^3 uses of a custom-designed electrical power system (EPS). The EPS converts the electrical power from the solar arrays to power on the power bus. For this each solar array is equipped with a dedicated step-up converter. For verification of the electrical power subsystem, an input has to be stimulated.

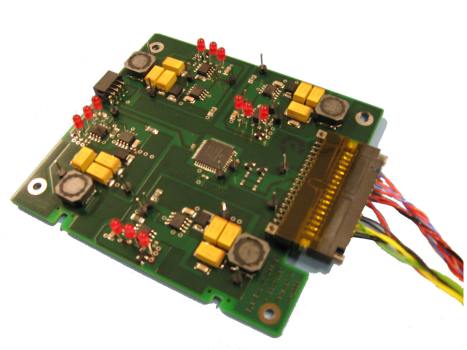

Figure 11 Electrical Power Sub-System Board

Table 1 Electrical characteristics of EPS converter

Parameter	Value	
Input voltage	11.38	V
Input current	142.0	mA
Output voltage	12.11	V
Output current	121.1	mA
Conversion efficiency	90.8	%

Two options were considered:

- Use of a solar cell simulator, which requires an electronic device capable of mimicking the behaviour of a solar cell.
- Use of real-life solar panels. Then an illumination source is needed, which can illuminate one or more solar panels with sun intensity.

The first option was chosen, being more practical in the lab. This has been done by setting the simulator to a particular open circuit voltage and a particular short circuit current. A variable load was connected to the electrical power subsystem board. By tuning this load until the bus voltage would collapse, the boundary of the operational area was found. After measurement of the electrical characteristics, the efficiency was calculated. Results are shown in the table 1.

The solar panels were also tested with a 1000 W. theatre spot as illumination source. The measurements did not result in the operation of the electrical power system in line of expectations. Measurement of the generated array current brought a cascade type of IV curve to light.

Three possible causes were hypothesized:

- High temperature, due to infra-red input on the panel.

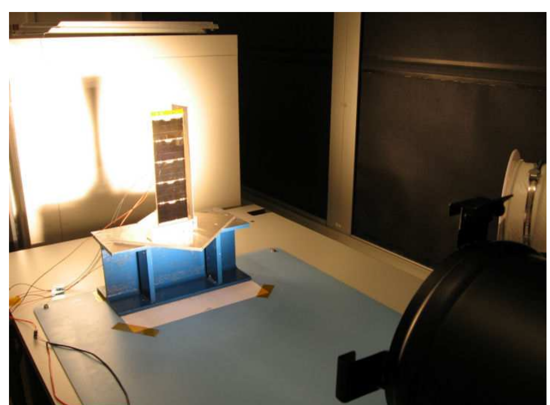

Figure 12 Delfi-C^3 solar panel in test set-up

- Mismatch of spectral response for the GaAs solar cells
- Inhomogeneous illumination.

Eventually, the problem was found to be caused by mainly to a non-homogeneous distribution of light on the solar arrays. This leads to a higher illumination level of some cells and restricts the current flow through the solar panel leading to a cascade type of I-V curve.

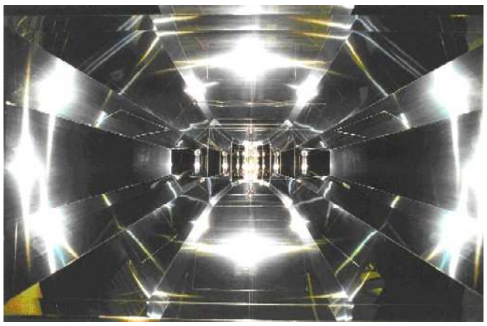

Figure 13 Very Large Area Solar Simulation (Photo: Courtesy Dutch Space)

A better equipped test facility was found in the Very Large Area Solar Simulation (VLASS) at Dutch Space in Leiden. The VLASS applies an argon driven lamp in conjunction with a large reflector array. In this way, it gives a homogeneous beam of light, simulating the Sun.

A series of tests with solar panels in the VLASS illumination beam was done to characterise the electrical power system. By varying the strength of the beam, a dependency of the excitation of the panels on incidence angle was simulated. This resulted in a characterization of the sensitivity of the electrical power system on varying input. The results are shown in table 2.

Incidence angle	Input voltage (V)	Output voltage (V)
0	11.53	12.22
5	11.55	12.22
10	11.52	12.22
15	11.46	12.22
20	11.38	12.22
25	11.32	12.22
30	11.19	12.20
35	10.93	12.20
40	6.74	9.37

Table 2: Sensitivity of solar panel characteristics to incidence angle

4.2 Communication Sub-system

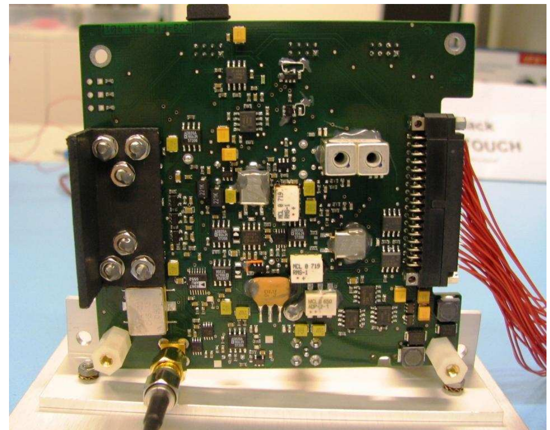

Figure 14 Delfi-C^3 transceiver PCB

Delfi-C3 features a redundant communications subsystem; two (almost identical) transceivers are incorporated on separate PCB's [Ref. 8]. The transceiver design was done entirely at Delft University of Technology. It is based on conventional, off the shelf components. Virtually all components are surface mount types. This has made integration on a single, 4-layer 90*96 mm PCB possible. The communications subsystem has two functions:

- provide telemetry down-link and tele-command up-link
- linear transponder service for radio amateur communication when the satellite is not in the science mode

The transceiver operates in the VHF and UHF amateur radio bands. BPSK modulation was chosen for the downlink telemetry, along with the amateur standard AX.25 protocol. Soundcard demodulation software was designed and distributed to radio amateurs worldwide, allowing them to receive, view and forward telemetry to the Delfi-C3 ground station in real time using nothing more than a simple VHF receiver and personal computer.

The transceiver units on board Delfi-C3 consist of the following sections:

- UHF frontend
- UHF command receiver
- 10.7 MHz linear transponder IF including fast attack / slow decay AGC
- BPSK modulator
- VHF Up conversion stage
- VHF Driver and final stage
- Control electronics

One side of the PCB houses the transmitter and transponder sections, the other the receiver and control electronics. The entire PCB consumes less than 1.7W. Both transceivers show nominal performance after 4 months in orbit.

4.3 System bus

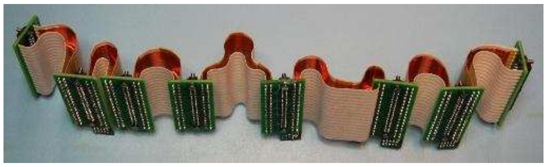

Figure 15 System bus

For the interconnection of the PCBs we considered a dedicated Kapton flex-rigid print. However this meant strict logistics and limited the design flexibility. So we designed a bus with small PCBs, Nomex flat cable and one type of connector. The bus was made and during testing we were faced with crosstalk problems on the I^2C data bus. These were solved by implementation of electrically grounded copper tape between the Nomex interconnects. Later some problems with PIC microcontrollers in the subsystems were solved by adding bus repeater chips on the system bus PCBs. Though we had flexibility in our MAIT phase, we have spent a lot of time and effort designing, manufacturing and removing problems. Furthermore the integration was a critical activity, because the bus was fairly rigid and time consuming to install. Also care had to be taken not to touch parts on the PCBs with the installation tools. The system bus is electrically functioning well. Nevertheless for a next project a Kapton flex-rigid print is preferable.

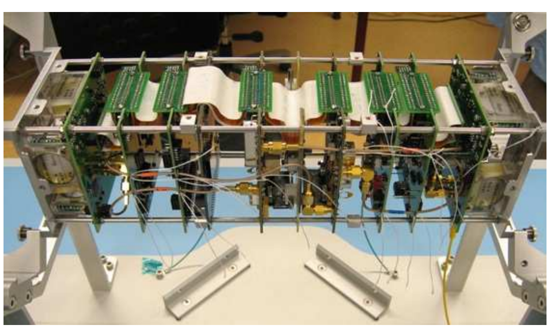

Figure 16 System bus on body stack and coax lines being tied up.

5 Software

The on-board software for Delfi-C^3 has been developed in a late phase of the project. The two main reasons for this were the lack of manpower with computer engineering skills and that for part of the software development hardware was needed first, while some deadlines of the hardware subsystems were not based on this knowledge. Software development is an iterative process were coding, testing, debugging and verification is done at a relative high frequency and many iterations cycles. One of the largest challenges is to verify the performance of other parts of the Command and Data Handling Subsystem (CDHS) continuously when one is focussing on a problem. It occurred that a potential fix for a CDHS related problem was the cause for new problems elsewhere. Therefore version management and system tests with short endurance are very important tools in the last phase of development. Two types of tests were performed to verify the CDHS: interface tests and functional system tests. The purpose of the interface tests was to quickly verify the data links between various subsystems. The CDHS architecture of Delfi-C^3 is redundant with a the nominal CDHS system with I^2C as data protocol managed by the On-Board Computer (OBC mode) and a back-up system based on tone-dialling and decentralized control by the subsystem microcontrollers (OBM mode). The functional tests aimed at the activity flows within the operational modes of the satellite (idle, deployment, science and transponder mode). All CDHS interface and functional tested were passed successfully before the launch of Delfi-C^3, but the enormous time pressure has caused lack of some documentation and rushing of some of the tests. For future projects, more time should be scheduled to perform these tests properly.

6 Payload

The Delfi-C^3 satellite carries the following payloads:

- Four sets of two Thin Film Solar Cell each
- Two Autonomous Wireless Sun Sensors

Electronic circuitry has been developed and tested for in-orbit measurements on these payloads.

6.1 Thin Film Solar Cell Tests (TFSC)

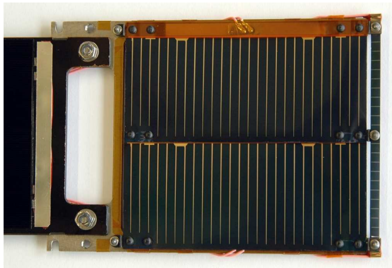

Figure 17 Thin Film Solar Cell assembly attached to solar panel

The Measurement Boards (MeBo) were designed to characterise the following properties:

- Current-Voltage (IV) curves of the cells
- The temperature of a narrow strip of TFSC cell material (thickness 25 mu)by four-point resistance measurement
- The output of a photo-cell, located on the solar panel as reference for the incident sun angle

Two measurement boards are mounted on the satellite; each capable of measuring two sets thin film solar cells.

For a successful verification of the various functions on the measurement board, a simulator was built. This simulator is capable of mimicking the electrical behaviour of the real-life TFSC cells, the titanium temperature strip and the reference photo-cell. With this simulator connected to the interface connector of the measurement board, the circuitry could be verified.

In addition to these functional tests, general check-out tests are performed on the measurement board. These mainly encompass electrical tests, being the confirmation of the presence of voltage levels and the measurement of the current consumption.

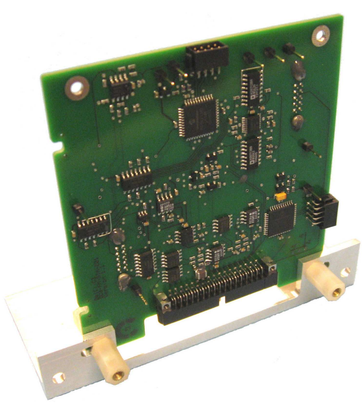

Figure 18 Measurement Board

Furthermore, a data interface test was performed to check the integrity of the data interface from the measurement board to the I^2C data bus running completely over one side of the satellite.

6.2 Autonomous Wireless Sun Sensor tests

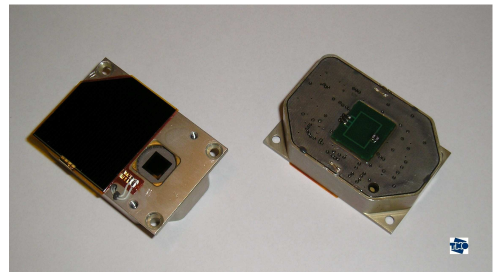

Figure 19 Fully assembled AWSS (Photo: Courtesy TNO)

The AWSS units transmit their data wireless to the receiver on the combination board (COMBO) [Ref. 9, 10]. The COMBO transfers the data to the On-Board Computer (OBC) and is also providing power to the OBC.

Verification of the functions of the combination board is accomplished by an AWSS simulator. This device is taking the role of the AWSS sensor and transmitter. It transmits a signal with exactly the same format, size and frequency as a real-life AWSS.

In addition to the tests with the simulator, real-life AWSS tests were done. The satellite was completely assembled with the AWSS assemblies at the final position. Excitation of the sensor and transmitter was achieved by using a theatre spot as replacement for the Sun to provide energy to the solar cell of the AWSS units and as signal to the sensor.

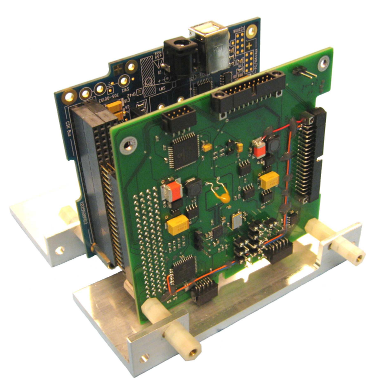

Figure 20 Combination Board connected to the FM430 on-board computer

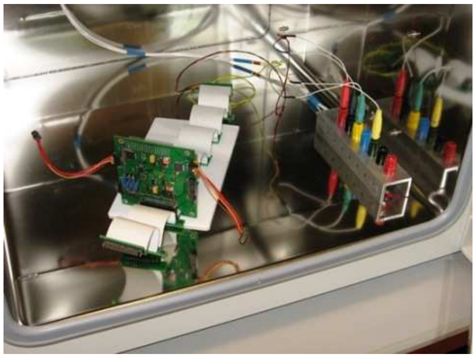

Figure 21 Combination Board vacuum test

In this way, a signal was transmitted by the sensor, which was received by the AWSS part on the combination board. Reading the incoming data from the on-board computer yielded good verification results. Later this real life test was repeated at various moment as a functional check-out. In addition to these functional tests, general check-out tests are performed on the combination board. These mainly encompass electrical tests, being the confirmation of the presence of voltage levels and the measurement of the current consumption. Furthermore, a data interface test was performed to check the integrity of the data interface from the combination board to the I^2C data bus.

7 Ground Support Equipment

7.1 Mechanical Ground Support Equipment

Quite some effort was put into mechanical ground support equipment (MGSE). The most used item is the integration jig. It supports horizontal and vertical access to the satellite; with and without the tube of the cube sat kit.

Figure 22 Integration jig for cube satellites

The sides could be easily reached because of the octagonal rings, which can be rotated in the jig. It has been build-up modular for future use. Other MGSE items made are development test set-up for deployment test and vibration adaptors and a handling tool for insertion into the X-POD. Furthermore some special manufacturing tool (e.g. drilling and calibration jigs) have been made.

7.2 Electrical Ground Support Equipment

The Electrical Ground Support Equipment (EGSE) used were standard PC's, laptops (with serial port), laboratory equipment, pin savers, specific test cabling, oscilloscopes, radio equipment, Spectrum analyzer etc.

8 System Testing

On system level the following tests were done: Sine and random vibration, thermal vacuum, radio communication (inclusive transponder function), deployment of antennae and solar arrays, payload performance and during the whole program several health and functional performance checks.

8.1 Vibration Test

Figure 22 X-POD with Delfi-C^3 PFM inside on the shaker table at TNO Built Environment and Geosciences, Delft in combination with development test set-up solar panel and antenna boxes in front

The Delfi-C^3 PFM has been tested for vibration on three perpendicular axis at acceptance levels with qualification durations, as defined for the NLS-4 launch on PSLV-C9 [Ref. 11]. The fundamental frequencies were checked with low level sinusoidal sweep. Subsequently the satellite was tested on each axis for sinusoidal & random vibration as specified below. Before and after all acceptance level test runs a low level sine test was conducted to check for changes in behaviour.

Fundamental Frequency	Requirement	Measured
Longitudinal	> 90 Hz	> 1500 Hz
Lateral	> 45 Hz	> 1400 Hz

Table 3 Fundamental frequency requirements

Test type	Fre-quency (Hz)	Input level	Sweep rate oct/min
Low sine sweep test	20-2000	0.15 g	2
Sinusoidal vibration test (Y- and Z-axis; PSLV lateral axis)	5.0 – 8.0 8.0 - 100	8 mm (0-P) 3.0 g	2
Sinusoidal vibration test (X-axis; PSLV longitudinal axis)	5.0 – 10.0 10 - 100	8 mm (0 – P) 3.0 g	2

Table 4 Sinusoidal vibration

Frequency (Hz)	Acceptance PSD (g^2 / Hz)	Remarks
20	0.001	
110	0.001	4.686 g_{RMS}
250	0.015	
1000	0.015	Duration: 60 sec
2000	0.004	

Table 5 Random vibration

The vibration test set-up consisted of an adaptor plate with the X-POD on top containing the satellite. Aside the PFM, a development set-up was added with a solar panel and two Modular Antenna Boxes. This made it possible to see the actual behaviour of these items during the vibration tests.

In principle the vibration test went flawlessly. However several times the test was aborted on the safety setting levels. The interruptions originated from high peaks responses due to rattling of the push-out spring in the X-POD. We applied some damping inside the X-POD with glass cloth tape at critical locations. Then the test was finished without further events. No visual damage or degradation to the Delfi-C^3 hardware was observed. The measured fundamental frequencies showed ample margins to the required values.

8.2 Thermal Vacuum Test

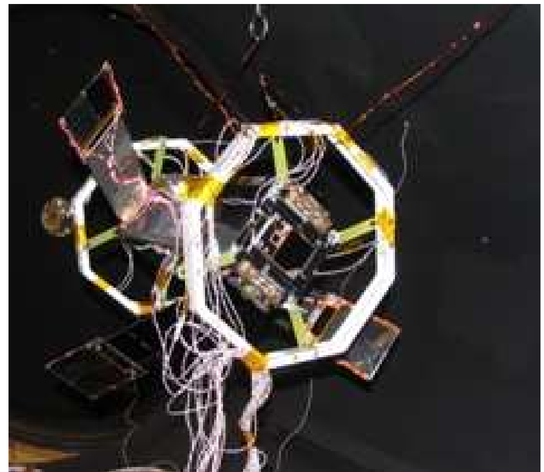

Figure 23 Delfi-C^3 FM inside the thermal vacuum chamber at NLR.

Delfi-C^3 has been tested thermally on satellite level in a thermal vacuum chamber at the National Aerospace Laboratory NLR. The deployed satellite hang from the top of the chamber in the rings of the integration jig, but thermally isolated on glass fibre strips. No guard heating was used on the cabling. The satellite was instrumented with a number of thermocouples on the outside. Furthermore we could measure inside temperatures during the test via the OBC (see table below). The temperature of the shroud of the chamber was varied between -110°C and +80°C for a number of cycles. Even with the limited number of temperature measurement locations it was possible to verify that the desired temperature reference points have been reached during the TV test.

Location	Description	Remarks
TV chamber	Shroud	Thermocouples
MGSE	Ring-1 Ring-2	Thermocouples
Body	Top panel Bottom panel Radiator area	Thermocouples
	Transceivers	on power amplifiers (2x)
	OBC	FM430
Experiments	AWSS Z+ AWSS Z-	thermocouples
	TFSC	4x via OBC

Table 6 Overview of temperature measurement points

It can be safely assumed that the temperatures, for in particular the PCBs, have been reached in the test. These temperatures are all around +40°C for the hot case and about -20°C for the cold case. As a result of this choice, the FM430 PCB has been tested beyond its limit temperatures, but still within the maximum and minimum allowable temperatures of -40 to 85°C. Both AWSS units reached their reference temperatures in hot phase. In the cold phase the Z- AWSS only reached -32.9°C. The results can be anyway considered sufficient given the fact that the Z+ AWSS reached -37.7°C, which is beyond its reference temperature. The solar panels and the TFSC were tested well above the expected limit temperatures; even though no thermocouples could be applied on them. It can be assumed that they have followed the shroud temperature with a very low response time and a small margin to +85°C and -110°C. During the Thermal Vacuum test a shorter response time of the satellite to temperature variations of the shroud has been noticed. This led to an overall reduction of the time to complete the thermal vacuum test with about 30%. The main reason for this is the thermal heat conductions have been kept on the low side in the thermal model. With this choice the cold and hot spots on the satellite are more evident. A reduction on conductivity implies a less smooth thermal model and a faster response time to the variation on the external conditions for the components directly exposed to the heat sources; this helped the design of a more-than-demanding, and therefore safer, thermal control subsystem. On the other hand, a reduction on modelled conductivity also implies an overall increase in the response time for the whole Delfi-C^3 to a change in external temperature.

For this reason, the real Delfi-C^3 reacted faster that the modelled one to the variation of temperature of the external heat source, generally leading to less extreme temperatures and keeping the operations of Delfi-C^3 more on the safe side.

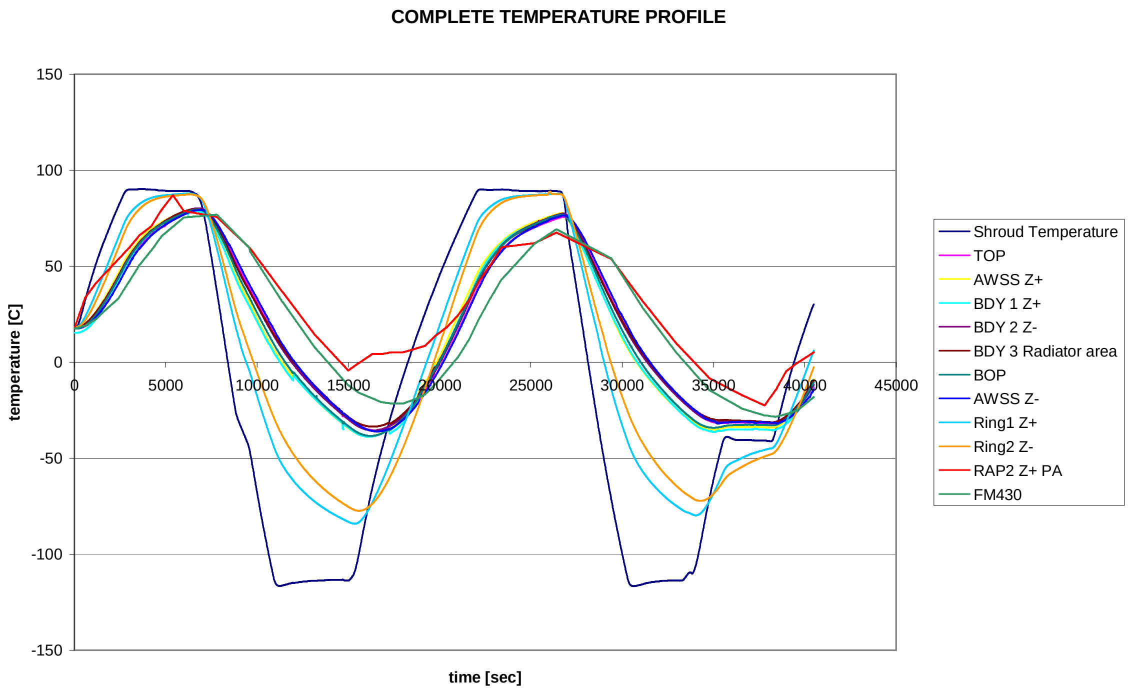

Figure 24 Temperature profiles of Delfi-C^3 FM as measured during thermal vacuum test.

8.3 Satellite health checks and performance tests

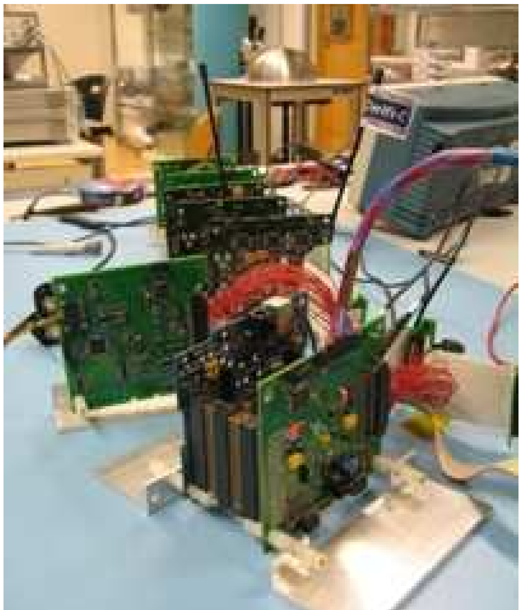

Figure 25 Delfi-C^3 Electronics stack in functional test on the bench before final integration

With regular health checks, the satellite status was verified for any changes occurring during testing. Besides these checks the complete satellite was subjected at intervals to full communication tests and performance tests, including solar array and antenna deployment.

9 Conclusions, Lessons learned, Recommendations & Future

9.1 Conclusions & lessons learned

- The first Dutch university satellite project was very valuable for the students as they had to work in a real working environment with colleagues of different education, customers, suppliers and at intervals under time pressure for reviews, deadlines and deliveries.
- The educational performance can be expressed in the number of students that did work on the project, resulting in 30 MSc thesis, 30 BEng thesis and internships. The students came from TU Delft, various Dutch polytechnic schools and universities throughout Europe. Furthermore, the project has resulted in the start-up of a successful spin-off company Innovative Solutions In Space BV (ISIS) in early 2006.
- System engineering is teamwork: It only works when there is sufficient support from the team members involved
- Working together with industry is valuable; discussions during reviews and working on hardware provides a good platform for projects on the edge of science and industry with challenges for students in their study and possibilities in their later careers
- Well designed mechanical ground support equipment provides safe working for personnel and hardware
- Timely made and well structured procedures provide a good basis during preparation and test of the PFM. Even during development testing this should be implemented, however with sufficient flexibility to cater for unexpected results.
- The experienced launch slip gives on one hand project elongation and costs, while on the other hand it enables finalising small points, that went into the background. A disadvantage with student projects is that it is difficult to keep an experienced team available at all times.
- The fundamental frequencies complied with requirements of launch provider
- The thermal mathematical model was set-up from a quite conservative point of view. This resulted in a faster completion of the thermal vacuum test than expected. Less conservative assumptions should be used for future projects in order to do more realistic, though still conservative, predictions.
- A number products made for Delfi-C^3 can be used directly for Delfi-n3Xt; other with minor modifications. This is in-line with the initiatives for a development line of cube sats at the university.

9.2 Recommendations & future outlook

- We consider that for the next project reporting of development tests should be improved to retain the results better. This is very important in view of the floating population in a student team.
- Next to the students on a project, also a group of staff members should be available to guarantee continuity for a university project,

consisting of for example a project leader, a mechanical thermal engineer, an electronics engineer, a software engineer and technicians to support manufacturing of hardware.

- Time shall be allocated during testing to perform reporting activities. “I will do this later-on” does not work.
- Keeping alive configuration control properly with inexperienced team members is a hard job and requires improvement for the next project.
- We started with a bought-out cube sat kit, but in view of the many modifications needed and the newly designed parts, probably it would have been more efficient to build the satellite from scratch. However within the constraints of the cube sat standard.
- The measurements with the solar arrays, equipped with triple junction cells with the theatre lamp in our laboratory were difficult and did not provide the desired information. A set-up with a lamp with a better spectrum and sufficient power, could deliver more flexibility for in-house testing rather than going externally.

10 Acknowledgement

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