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Delfi-C^3 Preliminary Mission Results

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ABSTRACT

Delfi-C^3 is a three-unit CubeSat launched on April 28th 2008 and has been designed, developed and operated by students of the Delft University of Technology and several Engineering Colleges in the Netherlands. Preliminary results of the Thin Film Solar Cell and Autonomous Wireless Sun Sensor payloads are shown and discussed, as well as the experiences with a third on-board experiment: a transponder for the radio amateur community.

In the first three months of operations Delfi-C^3 has collected 53,000 high quality current-voltage curves of the solar cells (1.3% of the maximum possible) and has performed some 3,500 attitude measurements with the Sun sensor. These data have been collected by a worldwide network of radio amateurs, and have been sent to Delft for further processing. The relatively low yield is caused by a combination of a non-uniform distribution of radio amateurs over the Earth's surface and a design flaw in the Command and Data Handling Subsystem that caused unwarranted recovery actions by the computer watchdog function. The performance of the Attitude Determination and Control Subsystem and the Ground System is shortly discussed as far as they have had an impact on the quantity and quality of the payload data.

Although the mission results are satisfactory, not everything went as foreseen. Some design errors and project management shortcomings became evident prior and during operations. Recovery actions are outlined and lessons learned discussed. Special attention will be paid to the specific constraints related to developing and operating a satellite in an academic environment.

Delfi-C^3 is functioning well, and has entered its second period of scientific data collection after having completed a first three-month period in Science Mode and some three months in Transponder Mode.

INTRODUCTION

Delfi-C^3 is the first satellite of the Delft University of Technology. It is a three-unit CubeSat with a mass of 2.2 kg and a minimum available power of 2.4 W, and has been successfully launched on April 28th, 2008 with an Indian Polar Satellite Launch Vehicle in a sun-synchronous orbit of 635 km altitude. A picture of the satellite is shown in figure 1, while figure 2 defines the Delfi-C^3 coordinate frame.

Prime objective of the Delfi-C^3 mission is to provide students an opportunity to obtain hands-on experience of a real life satellite project [Vaartjes, 2008]. A secondary objective is to provide a means for fast and (relatively) cheap in-orbit technology demonstration. The new technologies flown on Delfi-C^3 are Thin Film Solar Cells (TFSC) developed by Dutch Space in the Netherlands, an Autonomous Wireless Sun Sensor (AWSS) developed by the Dutch institute TNO and a transponder for radio amateurs developed by the Faculty of Electrical Engineering, Mathematics and Computer Sciences of the Delft University of Technology. This paper will primarily address the preliminary results of these three payloads.

Delfi-C^3 has no battery and a passive Attitude Control Subsystem, as the two main payloads TFSC and AWSS only function in sunlight and require a variable orientation relative to the sun vector. Radio amateur frequency bands are used for communication (UHF uplink and VHF downlink). One of the two transceivers (Radio Amateur Platform, RAP) doubles as the transponder for radio amateurs. The design of the satellite is Single Point of Failure (SPF) free, a characteristic that, as will be shown below, has saved the mission in more than one respect. For a full description of satellite and mission is referred to [Ubbels, 2008].

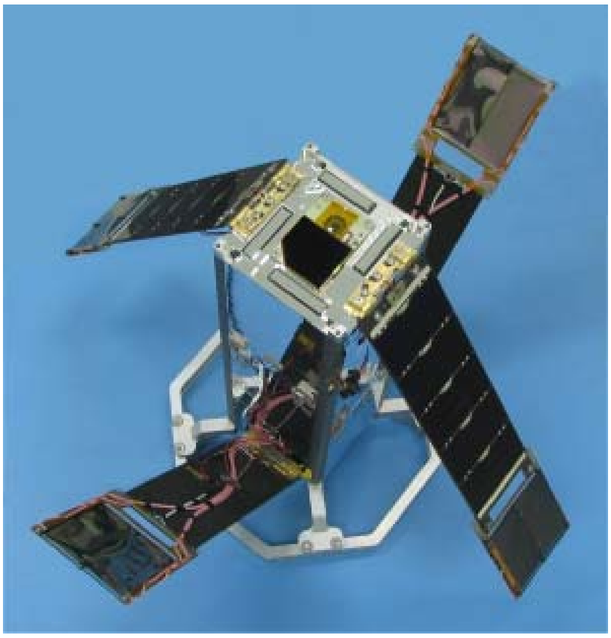

Figure 1 Delfi-C^3 with solar panels deployed prior to thermal vacuum test; the eight antennae are still stowed, as they cannot support their weight under one G.

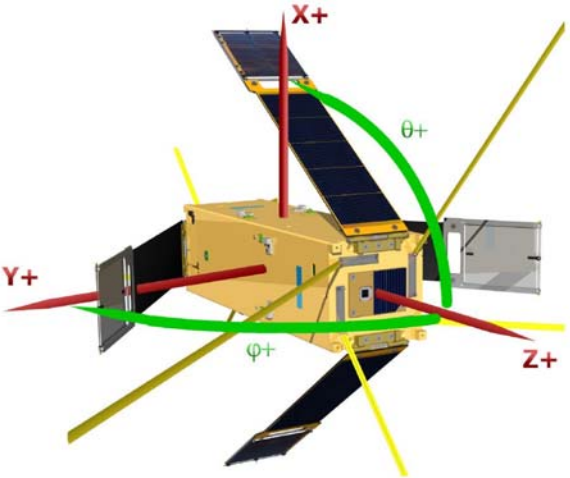

Figure 2 Delfi-C^3 coordinate frame

The total development time of Delfi-C^3 has been about 3 years and more than 60 MSc and BEng students have been involved in the project. Almost all of these students wrote their thesis on their contribution to the project. In total about four full-time equivalent staff have been involved in the project, the man-hour ratio students/staff being about 6:1.

The next section of the paper will address the operations. Section 3 contains a summary of the TFSC data collected and section 4 summarizes the results for the AWSS. Section 5 describes the results of the transponder operations, while section 6 summarizes the performance of the passive Attitude Determination & Control Subsystem.

A reference is made to the performance of the other Delfi-C^3 subsystems, as far as relevant for the TFSC and AWSS data collection. Details on the performance of those subsystems can be found in [Brouwer, 2009].

Finally a short overview is given of the Delfi-C^3 ground system and its performance. The paper concludes with conclusions on the findings up till now and some lessons learned.

DELFI-C^3 OPERATIONS

The launch of Delfi-C^3 took place on April 28th, 2008, with the Indian PSLV-9 flight from Sriharikota, India, exactly as scheduled at 03:53 hrs UTC. Insertion in the 635 km sun-synchronous 10:30 hrs local time orbit took place over the Antarctic outside radio contact with the launch site at approximately 04:40 hrs UTC and Delfi-C^3 and its nine companion satellites were released from the launcher in the next 20 minutes. At 06:39:08 hrs UTC an American radio amateur in California first heard the characteristic sound of Delfi-C^3. At 8:40 hrs UTC the first pass over the Delft Ground station occurred. Nothing was heard. The second pass 96 minutes later still no signal was received. By that time there was serious doubt, whether the updated Two Line Elements (TLE) received from the launch authority, which in indicated a ten-minute shift of the Acquisition of Signal (AoS) time, were correct. So for the third pass the redundant ground station was used to monitor a pass both on the pre-launch TLE and the updated TLE and …. at 11:49:51 hrs UTC Delfi-C^3 was heard loud and clear at the time predicted by the pre-launch TLE. The first solar cell I-V characteristic was seen real-time on the Ground Station monitors.

However, the satellite did not operate nominally. Frequent reboots of the on-board computer were consuming the available flash memory cycles at an unacceptably high rate. The flash memory is used to store any configurational parameter other than the default ones, so also keeps track of the number of on-board computer boot cycles. On April 30th at 10:50:42 hrs UTC the Command and Data Handling Subsystem (CDHS) was set to read-only mode to prevent an early flash memory failure.

After the completion of the three-month Science Mode operations the satellite has been switched, as planned, to Transponder Mode, serving the radio amateur community as communication satellite DO-64, the first CubeSat to do so. End of September there were the first signs of transponder degradation. On October 14th Delfi-C^3 has been switched back to Basic Mode, a simple, housekeeping-only mode, to investigate the problem. In January 2009 it was concluded that the transponder function had failed and on January 29th the satellite has been switched to Science Mode, resuming the collection of data on the two remaining payloads. Up to the day of writing Delfi-C^3 continues its operations.

THIN FILM SOLAR CELL PAYLOAD

Delfi-C^3 carries a set of two Thin Film Solar Cells at the tip of each of the four solar panels (see figure 3). The cells are Copper-Indium-Gallium-diSelenide, vacuum deposited on 25 μm thick Titanium foil.

Figure 3 Thin Film Solar Cell payload; at the left the narrow temperature strip

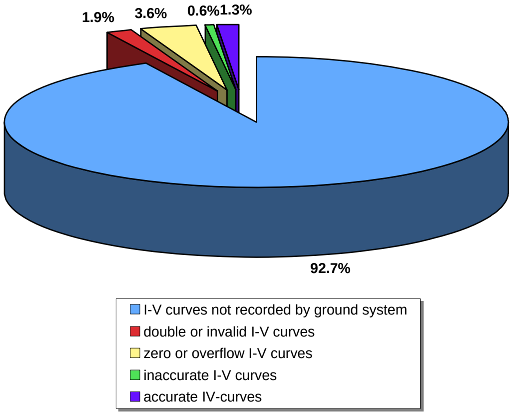

Figure 4 TFSC curves harvested

Special coatings are used to obtain proper optical properties. At the tip of the assembly a narrow strip of solar cell material serves to measure the temperature of the cells by means of a high accuracy four point electrical resistance measurement. Eight points of the current-voltage characteristic of the cells and the resistance of the temperature strip are measured per second by means of two Measurement Boards (MeBo's), ensuring redundancy of the data acquisition. The intensity of the incoming sunlight is measured by means of a photo diode on each panel. Temperature strips, photo diodes and solar cells have been calibrated prior to launch.

In the first three months of Science Mode more than 53,000 accurate I-V curves have been harvested. Although this is a considerable number (and very satisfactory from the point of view of technology demonstration), it is only 1.3% of the theoretical possible number of I-V curves.

This low yield is mainly caused by the non-nominal performance of the CDHS and the fact that the radio amateurs as part of the ground system are not uniformly distributed over the surface of the Earth. The CDHS design has an inherent flaw that quite often prevents data transmission on the bus, leading to either insertion of zero's in the telemetry, arbitrary switch off of subsystems, a reset of the computer or even a fall back to a very limited back-up mode. If the transmitter is the subsystem that is switched-off, no data at all are transmitted. The driver for the CDHS design has been to limit power consumption as much as possible at the expense of increased risk of bus malfunctioning. As a consequence Delfi-C^3 mostly downlinks only valid data during a rather limited period after eclipse or after a pass over the Delft Ground Station, where the transmitter can be switched on again. Also, the accuracy of the on-board measurement system causes data taken at low intensity to be too unreliable to be included in the final data set (see also figure 4).

Figure 5 shows some typical I-V curves of the TFSC, while figure 6 represents all valid data for the +X TFSC assembly taken during a two-week period. This last figure shows a rather bad correlation of efficiency and fill factor with solar cell temperature.

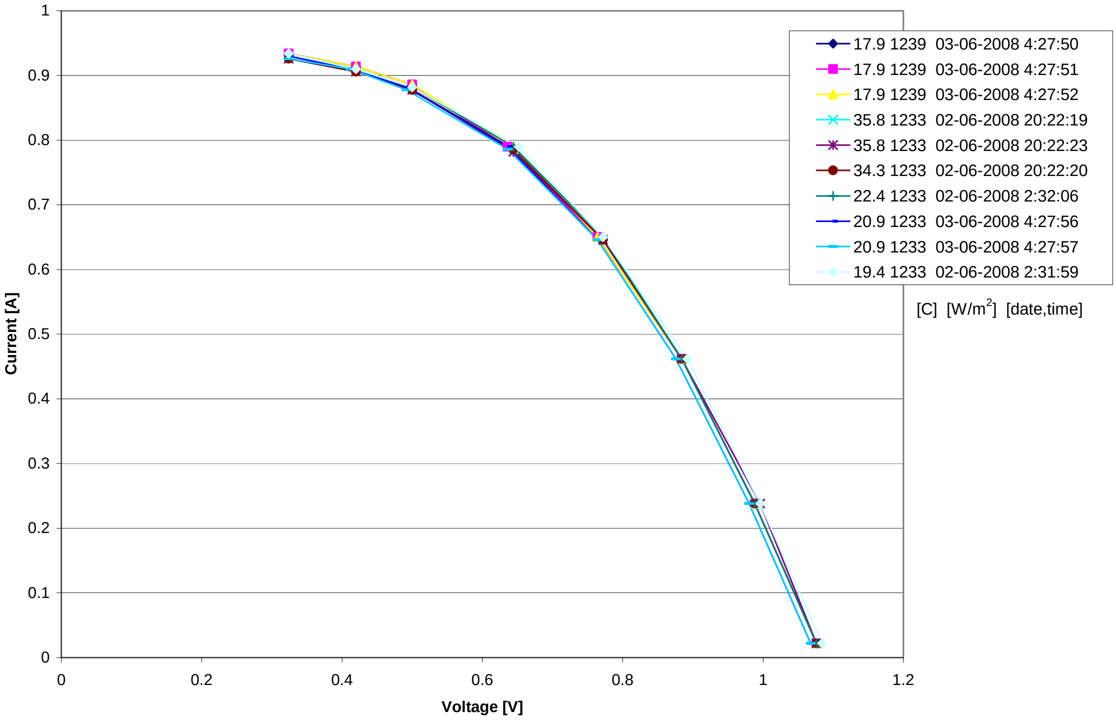

Figure 5 Typical TFSC I-V curves (-X panel)

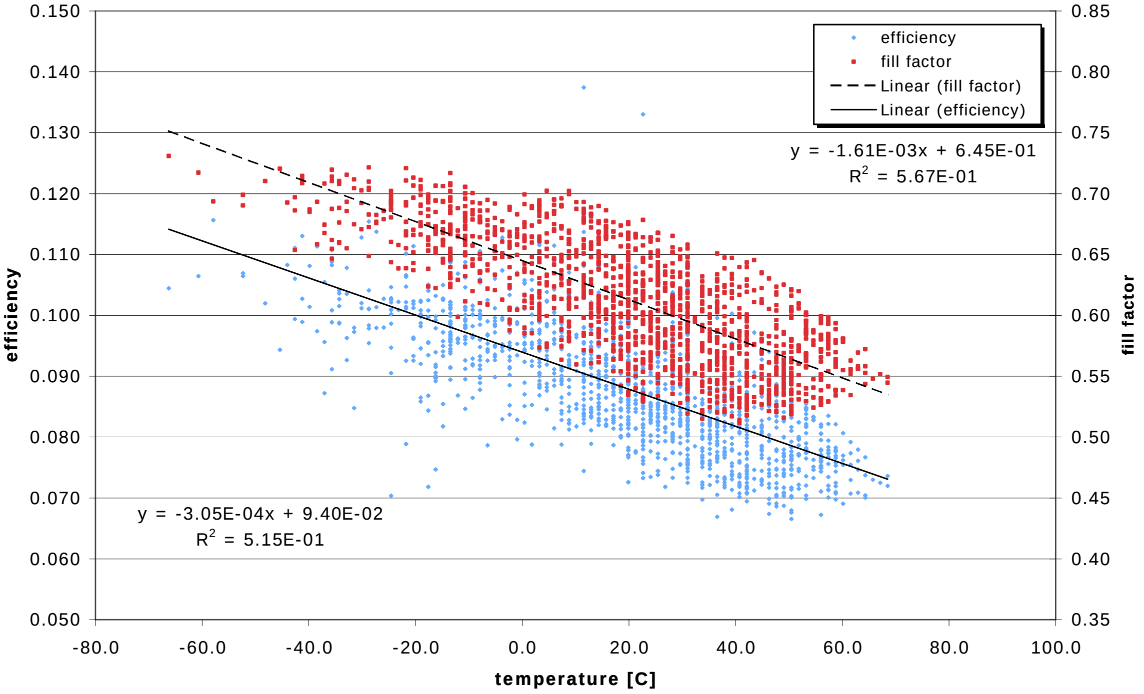

Figure 6 TFSC efficiency and fill factor for the +X TFSC assembly as a function of temperature for the two-week observation period from April 28th until May 5th

Analysis of the relation between temperature and intensity (see figure 7) reveals that the intensity shows the expected smooth behaviour, but that the temperature exhibits unexpected jumps, especially at steep transients of the intensity. Even at rather moderate transients in the intensity this occurs. There seems to be some hysteresis mechanism present in the temperature measurement.

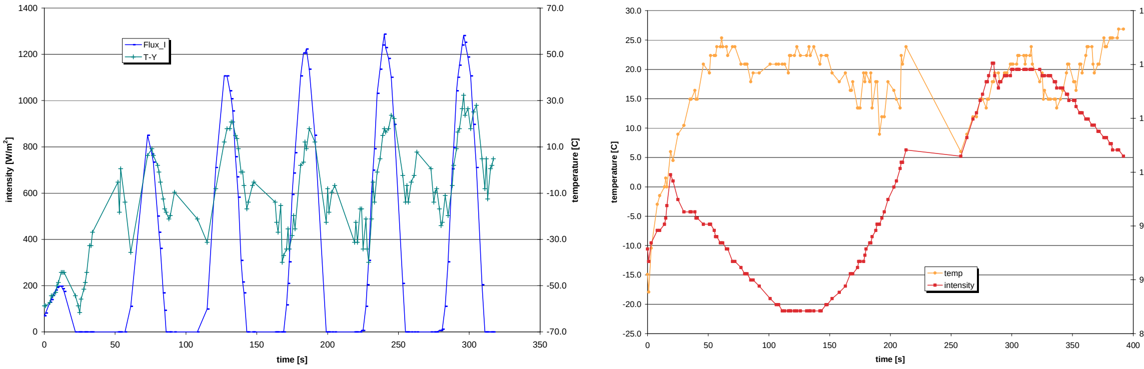

Figure 7 Solar intensity and TFSC temperature as a function of time. Note the apparently random temperature fluctuations even at constant intensity; left -Y panel data taken on May 5th, right –X panel data taken on July 11th

Considering the physical configuration of the temperature strip as shown in figure 8 it seems likely that a rapidly changing electrical resistance due to temperature gradients in the structure are the cause of this behaviour. Ground testing only has addressed the steady state behaviour of the temperature sensor. The exact mechanism of this behaviour still has to be investigated in order to validate the efficiency data obtained. Both detail tests and thermal analysis are envisaged to establish which of the temperature measurements are erroneous.

The overall correlation of the efficiency data (η) and the correlation coefficient R^2 is summarized in table 1. We may conclude that the performance in time seems to be quite consistent.

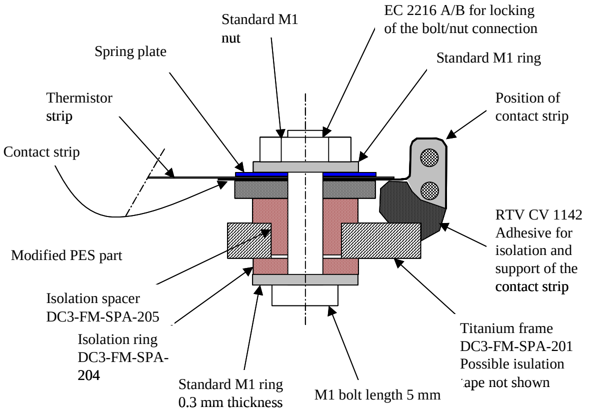

Figure 8 Physical configuration of the temperature strip suspension

Measurement period	*+X assembly*		
	η at 0 C	*slope [--/C]*	*R^2*
April 28 – May	0.0940	-3.05E-4	0.515
May – May	0.0989	-3.24E-4	0.489
May – June	0.0993	-3.47E-4	0.428
June – June	0.0933	-2.16E-4	0.405
July - July	0.0963	-1.93E-4	0.528
Measurement period	*-X assembly*		
	η at 0 C	*slope [--/C]*	*R^2*
April 28 – May	0.0998	-4.58e-4	0.726
May - May	0.1020	-4.45E-4	0.595
May - June	0.0985	-4.33E-4	0.520
June - June	0.0967	-2.69E-4	0403
July - July	0.0995	-4.81E-4	0.640
Measurement period	*+Y assembly*		
	η at 0 C	*slope [--/C]*	*R^2*
April 28 – May	0.0795	-3.03E-4	0.427
May - May	0.0840	-3.30e-4	0.531
May - June	0.0878	-5.15E-4	0.700
June - June	0.0873	-1.82E-4	0.443
July - July	0.0930	-2.52E-4	0.485
Measurement period	*-Y assembly*		
	η at 0 C	*slope [--/C]*	*R^2*
April 28 – May	0.0998	-4.58e-4	0.726
May - May	0.1020	-4.54e-4	0.584
May - June	0.1040	-2.94E-4	0.599
June - June	0.1040	-1.01E-4	0.126
July - July	0.1030	-1.99E-4	0.683

Table 1 Overview of efficiency as a function of temperature and time

AUTONOMOUS WIRELESS SUN SENSOR PAYLOAD

Delfi-C^3 carries two Autonomous Wireless Sun Sensors (see figure 9) at top and bottom side of the body. Both sensors measure automatically the position if the Sun in their field of view when illuminated and transmit the data by means of a radio link to a receiver located somewhere else in the satellite. Some 3,500 measurements have been taken, far less than theoretically possible (see figure 10).

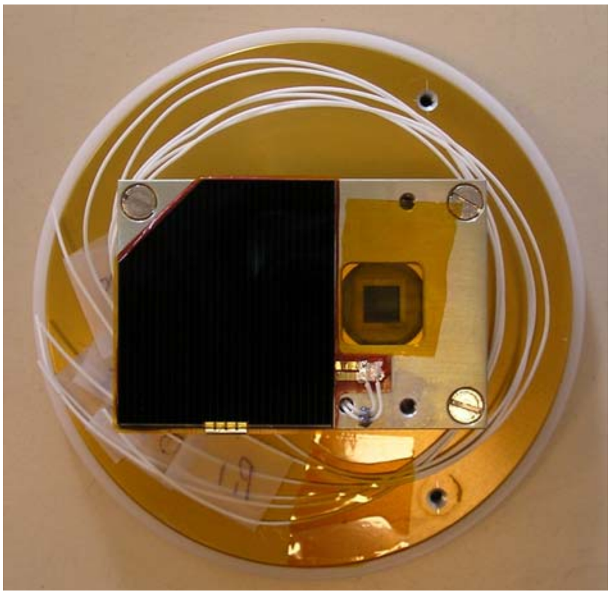

Figure 9 Autonomous Wireless Sun Sensor payload

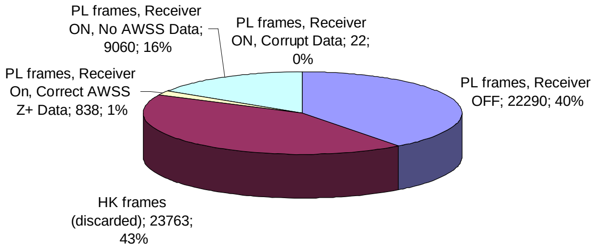

Figure 10 Received AWSS data in the period April 28th until May 11th

Up till now no data of the -Z AWSS have been found in the telemetry. As it was quite difficult to test the AWSS on ground when assembled in the satellite, the proof of correct functioning is primarily based on component and subsystem level testing. Only a qualitative test on system level has been executed, and no explicit, documented evidence of the reception of data from both AWSS has been found. In addition an error in the ground software severely corrupts two out of the five AWSS data frames received per five seconds. This error, a bit shift in data cutting and a reversion of the status byte, is recoverable but needs additional reverse engineering (note that correction of this error may also improve the TFSC data yield, as missing reference diode data in TFSC frames may be reliably interpolated from the data present in the housekeeping frames). Figure 11 shows a typical output of the AWSS. In the lower part of this figure a rotation with a constant rate about X- and/or Y-axis shows up as a straight line, while a constant rotation about the Z-axis only shows up as a circle (segment).

Even with the low yield, however, the data are still useful enough to draw conclusions about the correct functioning of the AWSS, but much work remains to be done.

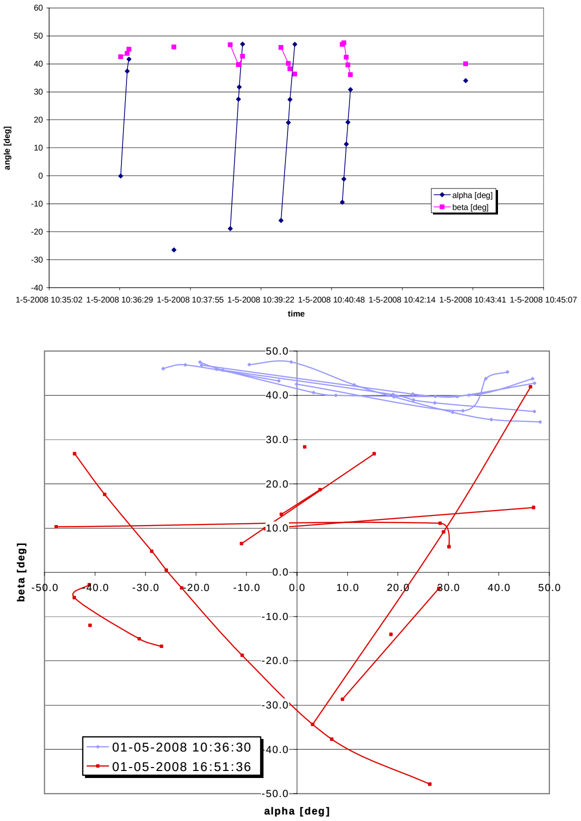

Figure 11 AWSS +Z sun angles; top: AWSS angles α and β as a function of time, bottom: AWSS angles in the AWSS field of view

TRANSPONDER OPERATIONS

After some to months of operation in Transponder Mode, end of September 2008, radio amateurs started to complain about bad quality of the transponder function. Checks in Delft confirmed that it was, to say the least, rather hard-hearing. So on 14 October 14th it was decided to switch the satellite to Basic Mode, a mode in which only essential housekeeping is transmitted, leaving maximum resources available for troubleshooting. Diagnostic tests revealed that the local oscillator and uplink frequency were all right for both RHCP and LHCP polarization. Over 400 W uplink power was required to achieve a marginal downlink performance, which is not useful for normal radio amateur operations. The transmitter was working at full gain, so healthy. The corresponding command receiver was not working either.

The conclusion is that somewhere in the chain between antenna and power splitter, the circuitry common to transponder and transceiver, a short circuit or open connection is present. The failure can be anything: a bad coax cable or solder joint, a failed component, a tin whicker, etc. As no further actions are possible from ground, the transponder has been declared dead, and the satellite has been switched to Science Mode again, continuing full operations using the redundant transceiver.

DELFI-C^3 ATTITUDE CONTROL

Delfi-C^3 has a passive attitude control system, using magnetic hysteresis material to absorb excess angular momentum to achieve a moderate rotation rate, which allows variable exposure of Solar cells and Sun sensors, while ensuring a convenient thermal environment. Simulations using a simple theoretical model predicted that the rotation rate would be reduced within one orbit from a maximum of 10 degrees per second at ejection from the X-POD to the design value of 0.2 to 2 degrees per second. This value was revised after ground tests to about 10 orbits after ejection.

The actual performance was quite different. From the illumination periods of the photo diodes on the solar panels, primarily used to measure the solar illumination of the TFSC assemblies, it could be derived that the angular rate upon ejection was 5.06 ^{o}/s, and was reduced after one week to 4.95 ^{o}/s, to achieve 0 to 0.7 ^{o}/s mid July (see figures 12 and 13). It must be concluded that the models generally used to describe the phenomenon are not correct, and further research in this area is required. This out-of-spec performance has not, however, hampered the mission objectives. The final rotation rate relative to the sun vector is expected to be equal to that of the Earth magnetic field (~ 0.1^{o}/s).

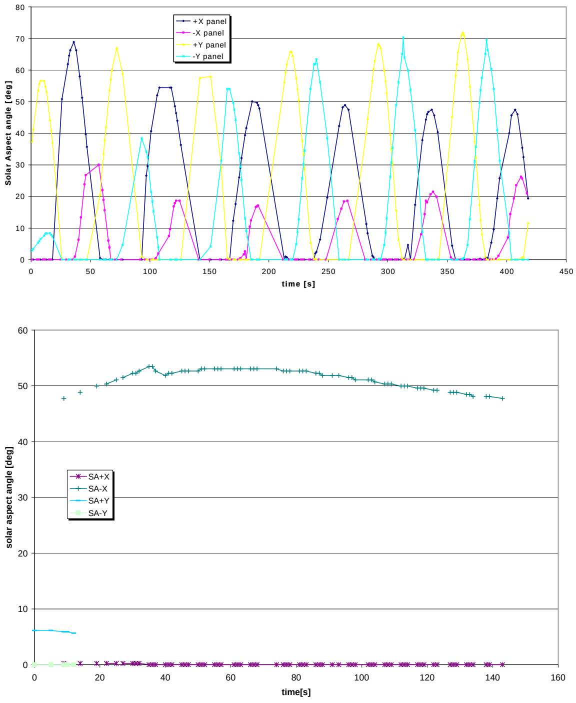

Figure 12 Rotation rate on May 5th (4.95 ^{o}/s) and July 11th (0-0.7 ^{o}/s)

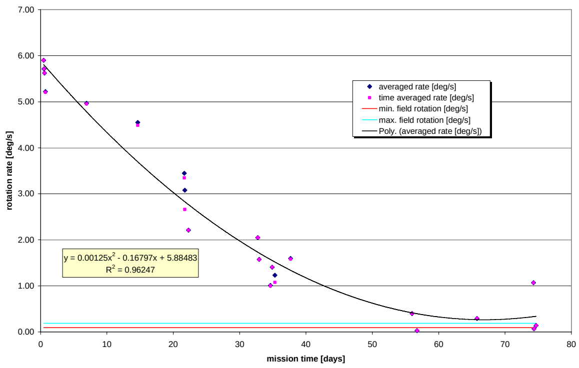

Figure 13 Average rotation rate as a function of time

Although a low rotation rate is favourable for obtaining stable TFSC data at an (almost) constant solar flux, it leads in certain cases to very high temperatures of the TFSC assemblies, closed to the upper allowed temperature limit.

The decrease of the rotation rate corresponds to an average decelerating torque of 1.01 · 10^{-9} Nm end of April decreasing to 7.35 · 10^{-11} Nm mid July 2008 (see figure 14). The decrease of the torque in time is logical, as the quantity of energy removed from the satellite is proportional to the number of rotations. The magnitude of the torque should be compared to a maximum decelerating torque generated by the magnetic hysteresis material based on test measurements of 2 · 10^{-7} Nm at the maximum rotation rate of 10 degrees per second [Poppenk, 2009]. This means that there is a difference of at least two orders of magnitude between ground test and in-orbit deceleration torque.It is clear that some further work must be done to clarify this matter.

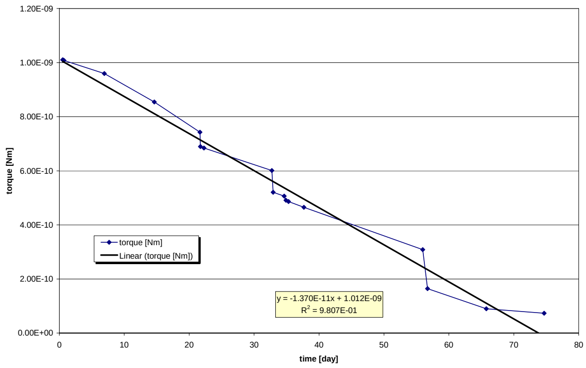

Figure 14 Average decelerating torque during the first three months of the mission.

The rotation rate based on the reference diodes was confirmed by the AWSS outputs, which yielded a rate of 5.2 ^{o}/s on ejection (see figure 15). Also the absolute correlation of attitude based on reference diodes and the AWSS outputs is quite good, as can be seen from figure 16. Although there seems to be a systematic difference for some data points, this is not confirmed by data taken at another time.

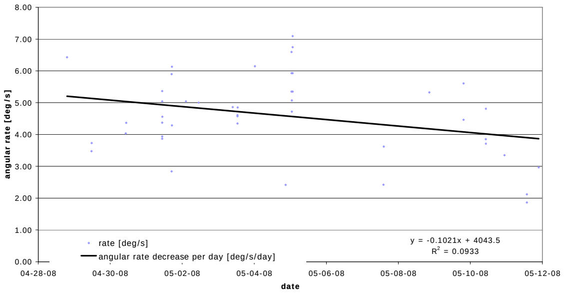

Figure 15 Initial satellite rotation rate based on AWSS data

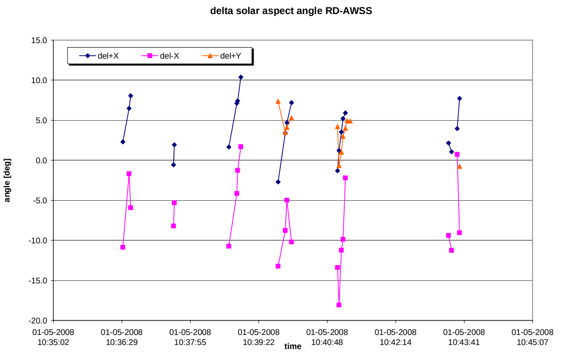

Figure 16 Difference of solar aspect angle as measured by reference diodes and AWSS (data taken May 1st)

DELFI-C^3 GROUND SEGMENT

The Delfi-C^3 ground system is composed of a world-wide network of radio amateurs, the main ground station in Delft and a back-up ground station in Eindhoven, both in the Netherlands, de-central custom designed software to decode the telemetry and to send the data to the central data base at the main server in Delft and at a back-up server in the UK (the so-called RASCAL software package) and post-processing software in Delft. The de-central software give the radio amateur the possibility to see the Delfi-C^3 telemetry (TM) real time and in engineering units on his or her monitor. To achieve this the raw telemetry is cut in suitable portions dedicated to the TFCS payload, the AWSS payload, the housekeeping data and some overview data, needed for the post-processing. This system is illustrated in figure 17.

The data are time stamped on-board with a CDHS boot cycle number and frame number within that boot cycle, and timing information is added at the receiving radio amateur (time received from satellite, time submitted to server), the servers (time received from the radio amateur, sequential reception number). From this it is in nominal conditions quite simple to reconstruct the absolute time with an accuracy better than 2 seconds and to eliminate redundant TM frames. The raw database contains only the cut TM frames, not the original, complete frames as transmitted by the satellite.

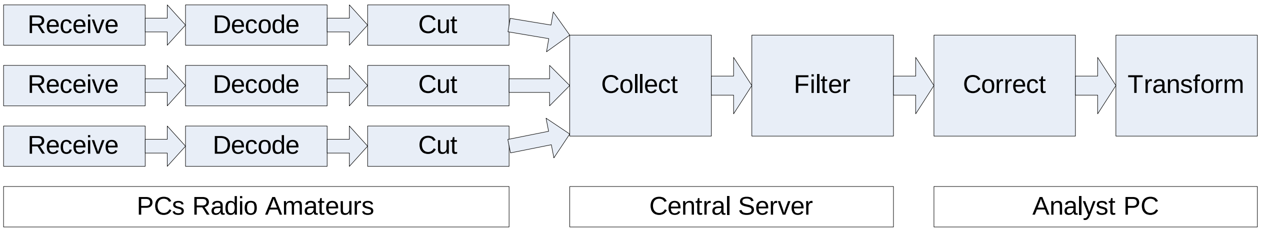

Figure 17 Ground Segment architecture

However, as explained above we were forced to set the CDHS to read-only mode quite early in the mission. This meant that in practice that all data were taken at the same boot cycle number, and that the ground software had to be changed quite rigorously to compare frames with reception times at least 10 seconds apart on their exact content to find and eliminate double TM frames. And even then about 5% of redundant frames slip through.

Modification of the post-processing software had to be done in parallel to the mission operations, which implied that only real time quick look data were available as far as recorded with screen dumps.

This also underlines that ground software development has not had the right priority; almost all effort has been concentrated on getting the flight hard- and software ready. Also, contingency modes have received too little attention. This is also very well illustrated by the fact that an on-board back-up for a computer failure has been designed and implemented (a Voltage Controlled Oscillator, providing performance data for two of the four TFSC assemblies), but the ground software needed to decode it is not operational up till the time of writing this paper.

A second problem caused by the cutting up of the raw TM is that any error in the Rascal software would lead to a corrupted raw database, and that is of course what happened in the Housekeeping (HK) frame. The post-processing software to correct this bug still has to be written (although the procedure to correct it is known already).

It has also been quite difficult to convince the IT services of the University that it was essential to provide timely, real time, reliable and redundant access to the server infrastructure to collect and store the operational satellite data. It was far easier to obtain those services from an outside, specialized company. Although the real time storage issue is solved now, it causes up to this day severe delays in processing the recent flight data.

A last observation to be made is that although reliance on the radio amateur community for data collection certainly has increased the amount of data harvested, the 300 participating radio amateurs are not distributed evenly over the Earth's surface (see figure 18). Also, not all of them have been active in sending TM frames to Delft. A fast examination of the data received in the first and last two weeks period of operations shows that no data were present from some 148 radio amateurs of the 300 (51% in the first period, 86% in the last period). Possibly these numbers are slightly biased by the way the raw data filter works, but the order of magnitude is correct. This combined with the frequent computer resets and temporary fall back to the limited back-up mode some time after sunrise explains the relatively low yield. And of course there is the natural phenomenon that "new" is exciting, but soon you get used to it and interest falls.

The same applies to the discipline of the (ex-) students volunteering to monitor the passes over the ground station and resetting the computer, if a fallback has occurred. Both effects can be clearly seen in figure 19.

Figure 18 Geographical distribution of participating radio amateurs

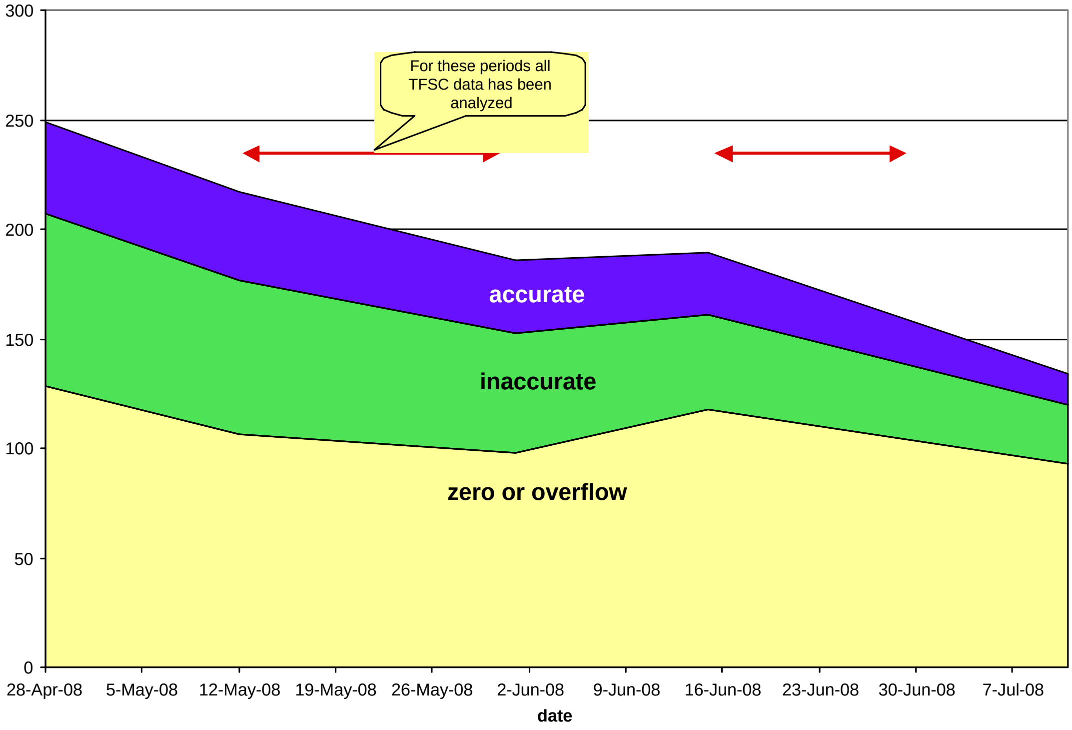

Figure 19 TFSC data harvest as a function of mission time

CONCLUSIONS AND LESSONS LEARNED

Overall performance of the Delfi-C^3 is satisfactory and sufficient data from the two payloads have been and are still being collected.

Additional research is required to correct for the discontinuities in the TFSC temperature measurement by means of thermal modeling and test of a representative structure.

The available attitude data should be processed further to obtain more information on the decelerating torque. Possibly this may also require more tests to estimate the damping torque from the magnetic hysteresis material, but also the mechanical damping torque from the flexible antennae.

The ground software has been designed for the nominal case only, although a number of back-up modes had been implemented on-board. When an off-nominal situation occurred, no means where available to continue production of processed flight data. Also, ground software needs the same (early) attention as flight hardware and software. In the case of Delfi-C^3 the development has been started too late.

The ground segment shall always receive and store the raw telemetry as received. If this is not done, errors in the CDHS design may require much extra effort to correct, or may even not be recoverable at all. So for Delfi-C^3 a Ground System architecture as shown in figure 20 would have be a far better solution, even if it makes the basic Ground Segment design more complex.

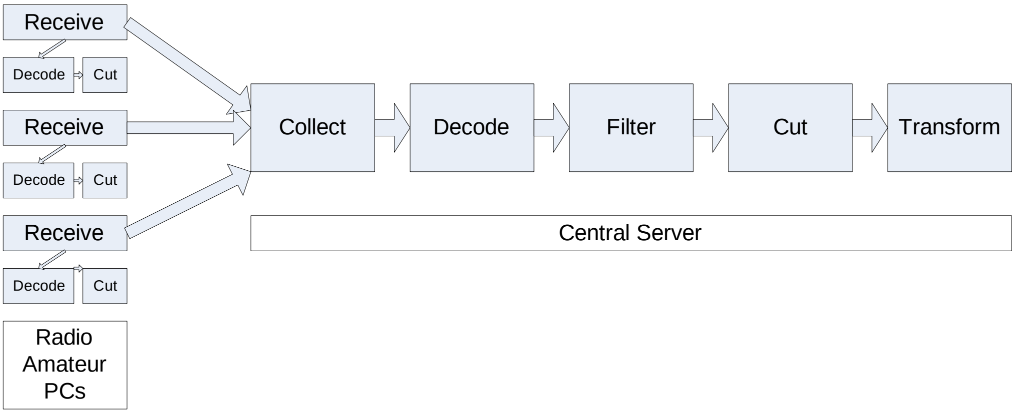

Figure 20 Better solution for the Ground Segment architecture.

Too little attention has been paid to end-to-end testing. For the AWSS this has led to uncertainty whether both sensors have ever been working together at all. [Brouwer, 2008] gives an overview of the test program as has been executed on the Delfi-C^3.

Although testing under flight representative environmental and operational conditions is expensive, cost should never be the single reason to delete such tests. In case of Delfi-C^3 it might have led to early discovery of the missing AWSS data, the TFSC temperature measurement problem, and better insight in the extent of the CDHS problems

If a mission requires a return of more than 10% of the theoretically possible data, the radio amateur network is not a valid option. In that case the satellite requires on-board data storage and a downlink with sufficiently high data rate.

The problems with the CDHS could have been prevented by the following measures:

- The I^{2}C bus clock speed must be < 10% of the clock speed op the slowest node; in Delfi-C^3 some nodes were running al very low speed to safe power, hence the I^{2}C bus clock speed was about 50% of that of the slowest node.
- Better node protection and watchdog functionality.
- Apply structural software testing methods.

On system level extreme care shall be taken in designing the safeguard system. Such a system shall of course protect the satellite against fatal errors, but shall also prevent unnecessary loss of functionality. As an example: although it is technically a double failure, the RAP remaining switched off after a reset (a mechanism introduced as a protection against a short circuit in the the subsystem) has led in the the case of Delfi-C^3 to a loss of 90% of the data collection functionality.

In university or student projects documentation is often a weak point and lack of documentation has certainly nurtured a number of issues experienced with Delfi-C^3. If a project, as Delfi-C^3, extends over two or three student generations, it is essential that strict documentation rules be enforced at the expense of "academic" freedom [Vaartjes, 2008]. Also, care should be taken that academic criteria for thesis work become a major design driver. In Delfi-C^3 there are several examples of unnecessary and even undesired functionality due to strict application of the thesis assignment.

The operational phase of a space project seems to have less appeal than the development phase in an academic environment. Once the thing is in orbit and works, interest and motivation decreases relatively fast. This has a consequence for the staffing of a project: There should be a core staff with relevant experience and capabilities to provide a minimum service for the total mission duration independent of student availability.

The overall conclusion, however, is that all project objectives have been met, and that the project has been (and still is) very successful. The shortcomings are only a challenge to do the next project even better.

ABBREVIATIONS ANS ACRONYMS

ADCS	Attitude Determination & Control Subsystem
AoS	Acquisition of Signal
AWSS	Autonomous Wireless Sun Sensor
BEng	Bachelor of Engineering
CDHS	Command & Data Handling Subsystem
DO-64	Dutch Oscar 64
HK	Housekeeping
I^2C	Inter-IC communication
LHCP	Left Hand Circular Polarization
MeBo	Measurement Board
MSc	Master of Science
PC	Personal Computer
PSLV	Polar Satellite Launch Vehicle
RAP	Radio Amateur Platform
RASCAL	Radio Amateur Satellite Caller Autonomous Logger
RD	Reference Diode
RHCP	Right Hand Circular Polarization
SA	Solar Aspect angle
SPF	Single Point Failure
TFSC	Thin Film Solar Cell
TM	Telemetry
TLE	Two Line Elements
UK	United Kingdom
UTC	Coordinated Universal Time
VCO	Voltage Controlled Oscillator
X-POD	Experiment Pico-satellite Orbital Deployer

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