

First Flight Results of the Delfi-C3 Satellite Mission

W.J. Ubbels

**ISIS – Innovative Solutions In Space BV
Rotterdamseweg 380, 2629HG Delft; +31 15 256 9018
w.j.ubbels@isispace.nl**

C.J.M. Verhoeven

**Chair of Space Systems Engineering, Faculty of Aerospace Engineering & Microelectronics department,
Faculty of Electrical Engineering, Mathematics and Computer Science, Delft University of Technology
Mekelweg 4, 2628 CD Delft; +31 15 278 6482
c.j.m.verhoeven@tudelft.nl**

R. J. Hamann

**Chair of Space Systems Engineering, Faculty of Aerospace Engineering Delft University of Technology
Kluyverweg 1, 2629 HS Delft; +31 15 278 2079
r.j.hamann@tudelft.nl**

E. Gill

**Chair of Space Systems Engineering, Faculty of Aerospace Engineering, Delft University of Technology
Kluyverweg 1, 2629 HS Delft; +31 15 278 7458
e.k.a.gill@tudelft.nl**

J. Bouwmeester

**Chair of Space Systems Engineering, Faculty of Aerospace Engineering, Delft University of Technology
Kluyverweg 1, 2629 HS Delft; +31 15 278 4615
jasper.bouwmeester@tudelft.nl**

ABSTRACT

Delfi-C3 is a 3-unit CubeSat nanosatellite developed at Delft University of Technology by students and staff from the faculty of Aerospace Engineering and the faculty of Electrical Engineering, Mathematics and Computer Science with engineering support from ISIS – Innovative Solutions In Space BV. The project started in December 2004 and the satellite was launched on April 28th 2008 with a Polar Satellite Launch Vehicle from India.

The prime mission objective of Delfi-C3 is to act as a technology test bed for two payloads: Thin Film Solar Cells, as developed by the company Dutch Space, and an Autonomous Wireless Sun Sensor developed by the Dutch research institute TNO, demonstrating on-board wireless sensor capability.

The satellite bus implements a number of novel design concepts. One of which is the fact that the satellite does not incorporate a battery for energy storage since neither of the two payloads require operations in eclipse.

In this paper, some preliminary flight results of Delfi-C3 are discussed with an emphasis on the overall in-orbit performance of the satellite itself. Furthermore, results characterizing the payload and its operations are presented. Finally, the status and summary of operational results of the distributed ground segment is provided.

Delfi-C3 is the first of a series of nanosatellites from Delft University of Technology, designed for technology demonstration, as part of the MISAT research program. An outlook is given to a follow-up mission, which is currently in its conceptual design phase.

INTRODUCTION

Delfi-C3 is a student nanosatellite developed within the MISAT research program (Gill et al. 2007) at Delft University of Technology by students from the faculty of Aerospace Engineering and the faculty of Electrical Engineering, Mathematics and Computer science.³ Furthermore, a number of Dutch polytechnic institutes are involved in the project as well.

Delfi-C3 acts as a technology test bed for two payloads, Thin Film Solar Cells, as developed by Dutch Space and an Autonomous Wireless Sun Sensor for TNO. The Delfi-C3 project kicked off in December 2004, and the satellite was launched successfully on April 28th on board a Polar Satellite Launch Vehicle (PSLV) from India. The satellite is based on a 3-unit CubeSat, with deployable solar panels and antennas.

Delfi-C3 makes use of the amateur radio frequency bands for its telemetry downlink and telecommand uplink. Software is being developed that allows participating radio amateurs to receive, decode, display and forward telemetry to the primary groundstation in Delft. As a return favor, Delfi-C3 contains a low power 40 kHz mode U/V linear transponder, which will be switched on after three months of gathering science telemetry.

SATELLITE OVERVIEW

The satellite is based on a 3-unit CubeSat structure. The satellite does not include an active attitude control system; passive rotation rate damping is used though to limit the rotation rate. Furthermore, the spacecraft is not be operational in eclipse because the primary payloads do not require it to be. Because of this, Delfi-C3 does incorporate a battery.

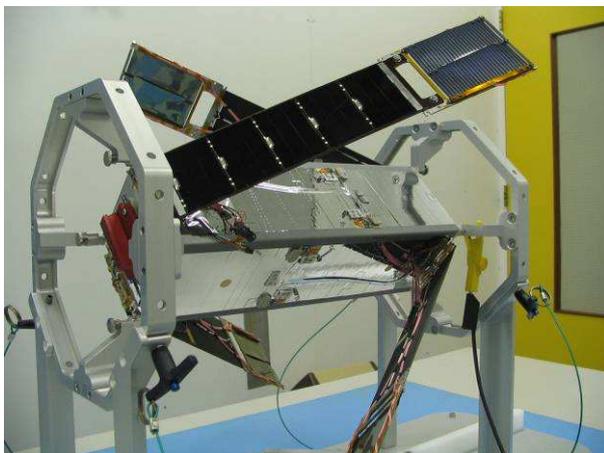


Figure 1: Delfi-C3 Flight Model, solar panels in deployed configuration

These decisions dictated that sufficient power be available under all possible attitudes. Therefore, the satellite features four deployable solar panels which are placed at 35 degree angles with respect to the main body, This ensures that sufficient power is available under all possible attitudes. Each of these panels houses five Gallium-Arsenide solar cells for supplying power to the satellite, and a Thin Film Solar Cell payload, consisting of two cells.

The electrical power subsystem consists of one DC/DC converter per solar panel, delivering 12V DC to the central power bus.

The Command and Data Handling System is based on a distributed architecture, using local microcontrollers per subsystem, which are connected via an I²C bus to a central On Board Computer, based on the MSP430 chip from Texas Instruments. All on-board software was designed with a large degree of autonomy. In principle, the satellite does not require any telecommands in order to be operational. Special attention was given to proper power sequencing and boot procedures, since the satellite experience a reboot every time it exits eclipse.

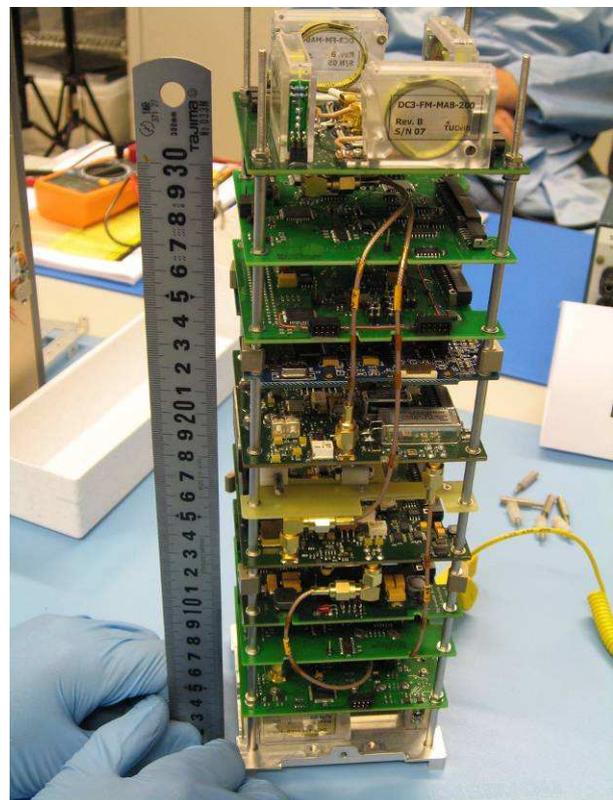


Figure 2: Delfi-C3 board stack

The communications system is based on two redundant transceivers, featuring full duplex capability, with a VHF downlink and UHF uplink, both in the amateur radio bands. For the downlink, Binary Phase Shift Keying (BPSK) was chosen as modulation scheme, because of its efficiency in terms of low required signal to noise ratio in order to obtain a certain Bit Error Rate, compared to other modulation schemes such as AFSK, which is commonly used on CubeSats. The AX.25 protocol is used for telemetry transmission at a rate of 1200 bit/s. Telemetry transmission is continuously on when the satellite is not in eclipse. One of the transceivers is equipped with a linear transponder circuit in order to fulfill the transponder function after three months of science mission. The local oscillators used in both transceivers are overtone crystal oscillators based on a new circuit concept that makes use of injection locked relaxation oscillators for selection of the correct overtone (US patent 6225872 by TU-Delft). The circuit is well suited for complete on-chip integration. When in future the crystals are replaced by MEMS resonators, there will be no off-chip components left, which is of great importance for further miniaturization of spacecraft.

A redundant IV curve measurement system is housed on two separate PCB's, which is used for measuring the TFSC performance. The circuit is based on an innovative sample-and-hold design which loads the solar cells with accurate resistive loads and subsequently measures the resulting voltage and current.

PAYLOAD OVERVIEW

Thin Film Solar Cells

The Thin Film Solar Cell payload is based on the latest development in the area of photovoltaic cells by the Dutch space company Dutch Space. The cells consist of a CIGS photovoltaic layer which is deposited by evaporation on a titanium base layer of 25 micrometers. The cells are integrated tile-wise, ensuring a minimal loss of active cell area. The interconnects are covered by the next cell, with an overlap of 5 mm at the longest side. This mechanical interconnection has a low resistance ($\sim 1\text{m}\Omega$); it is placed between the gilded contact pads under low compressive pressure. The aim of this new type of solar cell is to create a light-weight and low-cost product for future space applications. The target is a 50% cost reduction of solar arrays, while improving the power to mass performance with 50% compared to conventional solar cells. Cost is projected to be lower than 350 Euro per Watt at solar array level, and the power is expected to be more than 100 Watt per kilogram. The cell does not need a cover glass, but it has an emissivity enhancing and encapsulating

dielectric coating. The efficiency is be more than 12% under AM0 light conditions.



Figure 3: Thin Film Solar Cells

The performance of the TFSC payload is tested by determining their characteristic IV-curves and cell temperature per TFSC panel, which consists of two cells. The IV-curves are measured by means of a programmable current sink; the temperatures are measured by determining the electrical resistance of a dummy titanium cell mounted close to the actual TFSC's. This measured data is then transferred to the OBC where it is formatted for transmission to the ground segment.

Autonomous Wireless Sun Sensors

Delfi-C3 houses two analogue sun sensors (located at opposite sides of the satellite) that are fully autonomous and wireless. With the typical internal volume of a nanosatellite already being quite limited, reducing wiring is an important challenge. The sensors have a half-sized GaAs solar cell as their own power supply, making them independent of the satellite's electrical power system. This autonomy is accompanied by a wireless radio frequency link. This link has been made using an adapted commercial off-the-shelf transceiver. Although wireless data communication on board such small satellites might seem a bit superfluous in itself, implementing this technology adds to modularity and results in a flexible "plug and play" system. The autonomous sensor unit, in this case measuring approximately 60x40x20 mm, is a predecessor of an even smaller digital version that can be mounted on e.g. a solar panel sacrificing just a single solar cell.

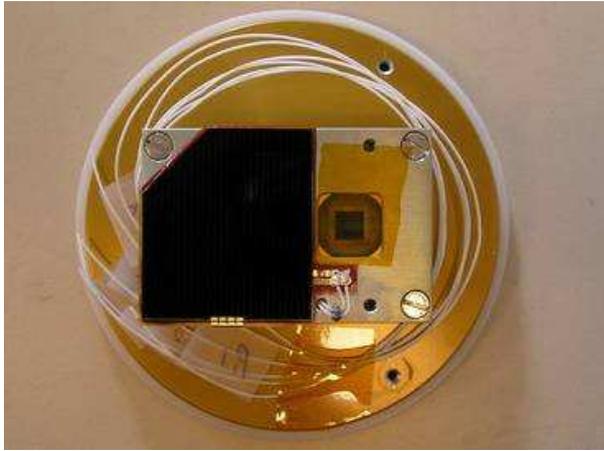


Figure 4: Autonomous Wireless Sun Sensor

The in orbit experiment concentrates on demonstrating the feasibility of the wireless link (immunity for disturbances; no interference with other equipment) and the operation of the sun sensor under variable power supply.

GROUND SEGMENT

A distributed ground segment with internet-based software clients using software defined demodulation is used for collecting telemetry data received by radio amateurs worldwide. All clients connect to a database system which performs processing both payload and housekeeping data which is accessible through an on-line “mission dashboard” thereby providing near-real time mission data to both payload customers and to the satellite design and operations team. The command groundstation is located at TU Delft, with a backup command station at Eindhoven University in The Netherlands.

Telemetry decoding software using software defined demodulation (by using the PC’s soundcard) has been developed which allows radio amateurs to directly decode and display both housekeeping and payload telemetry. Furthermore, the software, automatically uploads telemetry to two redundant servers at the TU Delft groundstation.

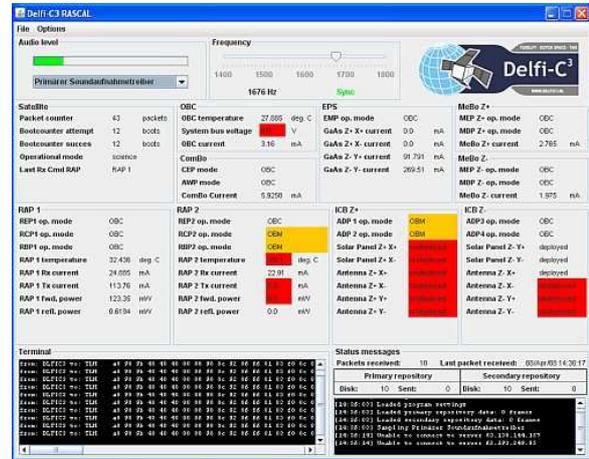


Figure 5: RASCAL telemetry decoding software

MISSION RESULTS

Launch and Early Operations

Delfi-C3 was successfully launched on 28 of April at 03:53 UTC onboard the PSLV-C9 launch vehicle. At 04:10 UTC, Delfi-C3 was injected in to a sun-synchronous orbit at 630 km altitude. At 06:45 UTC, signals from Delfi-C3 were picked up by radio amateur Rick Mann in California, USA. He made a recording of this event and the Delft Ground Station operators where able to verify that this was indeed Delfi-C3 by its characteristic sound. At 11:55 UTC, the TU Delft Ground Station acquired the satellite and was able to receive and decode the first telemetry.

Operations can in general terms be regarded as a great success. The first telemetry showed nominal behavior of all satellite subsystems and all four solar panels and eight antennas were deployed. The onboard software autonomously switched from a 5-minute idle mode to the deployment mode and finally into the science mode. No telecommands where required for Delfi-C3 to become fully operational. The distributed ground system of a network of radio amateurs around the globe has already shown to be very successful. Radio amateurs have not only contributed in receiving 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. Having a downlink in the VHF band, which inherently has a relatively low path loss and low Doppler shift, Delfi-C3’s downlink signal has been received on very simple handheld equipment.

Orbit determination of Delfi-C3 has been difficult in the first weeks. Because PSLV-C9 launched a total of ten satellites in approximately the same orbit, it was very

difficult to find out which observed object corresponded to which satellite. By observing Acquisition Of Signal (AOS) and Loss Of Signal (LOS) times, and matching these to the supplied Two-Line Elements (TLE), Delfi-C3 was associated with NORAD object #32789 two weeks into the mission.

Ground segment results

In the first month of the mission, over 220,000 AX.25 telemetry frames have been collected by a network of over 240 radio amateurs. Up to the time of writing, telemetry is still flowing in at an average rate of 4,500 frames per day. The telemetry decoding software has proven to be very successful, requiring a modest equipment setup (receiver, antenna) in order to properly decode telemetry. The software was written in the JAVA language, and hence is independent of the operating system which is used. Furthermore, since it makes use of the PC's soundcard, no additional hardware is required, thereby making receiving Delfi-C3 accessible to a large part of the amateur radio community. Finally, signal strength observations from the amateur radio community have been helpful in coarsely determining rotation rate.

Satellite bus results

In general, the satellite bus performs nominally. All housekeeping values are within their expected ranges. From the polarity changes of the downlink signal the operations team could deduce an initial rotation rate of Delfi-C3 of 10 degrees per second. This has been confirmed by observing the period of photo-diode outputs on the solar panel. After one month of operations this rate dropped to 6 degrees per second. Both values are considerably above the rotation rates expected, and the decay of the rotation is much slower than theoretically predicted. More detailed analysis is required. Looking at the three most critical satellite bus metric, mass, power and link margin, all three have been satisfied with reasonable margin, as can be seen in table 1.

Table 1: Satellite metrics and results

Metric	Requirement	Actual
Mass	< 3kg	2.2kg
Power	< 3W	2.4W
Link margin	>10dB	15dB

TFSC Payload results

Initial flight data show nominal IV curve data, with all current, voltage and temperature values within the

expected ranges. Since the payload provider, Dutch Space, is mostly interested in degradation of these cells over time, actual degradation data is expected to be available after 2 months into the mission.

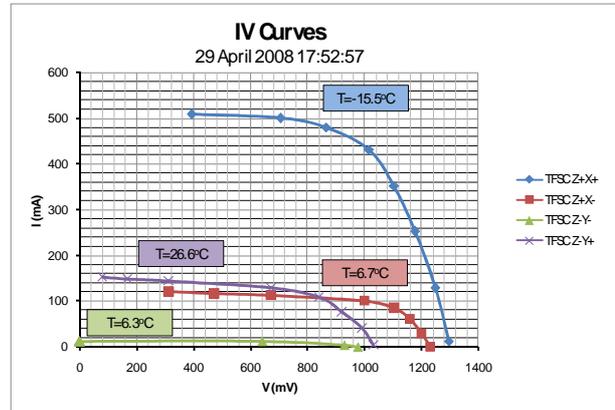


Figure 6: TFSC IV curves and temperatures

AWSS payload results

First data shows valid data from the AWSS payload, and shows that the wireless link is operational. Further analysis is required in order to reconstruct the actual spacecraft attitude.

CONCLUSION

After six weeks in orbit, the Delfi-C3 mission can be considered a 100% success, since:

- All technical objectives have been met
- An abundance of TFSC and AWSS Payload data has been collected
- All educational objectives have been met
- Over 60 students have actively participated in the design as part of their graduation work and have gained unique hands-on experience in designing, building and operating small satellites
- The mission has shown very successful cooperation with the world wide radio amateur community, Delfi-C3 has received an OSCAR (Orbiting Satellite Carrying Amateur Radio) designator, and is now also known as DO-64
- Delfi-C3 is the first Dutch university satellite and has built a foundation for a series of successor satellites, of which the design of the next one, Delfi-n3Xt, has been started already.

ACKNOWLEDGMENTS

The author would like to acknowledge the entire Delfi-C3 team, all students, staff and project partners for the years of hard work and dedication, which have led to the successful launch of Delfi-C3. Furthermore, the author would like to thank the worldwide radio amateur community who have helped a tremendous amount by collecting telemetry data from Delfi-C3, AMSAT, and the International Amateur Radio Union for providing extremely valuable support through all design and mission phases.

REFERENCES

1. J. Bouwmeester, G.T. Aalbers, W.J. Ubbels, "Mission Results and Project Evaluation of the Delfi-C3 Nano-Satellite," Proceedings of the 4S - Small Satellites, Systems and Services conference, May 2008.
2. J. Bouwmeester, R.J. Hamann, R. Amini, Command and Data Handling Subsystem for a Satellite without Energy Storage, Proceedings of the 58th annual International Astronautical Conference, India, September 2007.
3. Gill E., Hamann R., Monna G.L.E., Scherpen J.M.A., Verhoeven C.J.M.; *MISAT: Designing a Series of Powerful Small Satellites based upon Micro Systems Technology*; D.1.2; ; IAC-07-B4.6.05, Proceedings of the 58th International Astronautical Congress (IAF), Hyderabad, India (2007).