Delfi-C3: a Student Nanosatellite Test-bed for in-orbit Demonstration of Micro Systems Technology.

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ABSTRACT

New design solutions for space vehicles or payloads become possible through the use of micro- and nanotechnology. Often, the performance can increase due to the high level of integration of different functions in a single component.

In-orbit demonstration of functionality and performance improves confidence in the technology. Although generally an extensive qualification approach prior to launch is followed, for micro- and nanotechnology, nanosatellites can be a suitable qualification platform. Delfi-C3, a two-year student satellite project of the Faculty of Aerospace Engineering (AE) and the Faculty of Electrical Engineering, Mathematics and Computer Sciences (EEMCS) of Delft University of Technology in the Netherlands, will act as such a technology qualification test-bed for three payloads. A Thin Film Solar Cell experiment will be performed to verify the performance of these cells in the space environment. In addition, an autonomous Sun Sensor using a wireless data link will be demonstrated. The third new technology will be an advanced high efficiency transceiver sized for application in pico- and nanosatellites. Delfi-C3 is scheduled for a piggyback launch in the end 2006 and is a precursor the extensive MiSat program [3], starting in 2005 with the aim to develop micro- and nanosatellites that will demonstrate a wide range of Micro Systems Technology and Micro-Electronics for use in spacecraft. Connected with MicroNed and MISAT, a number of successors for Delfi-C3, based on the CubeSat concept, are foreseen to provide early in-orbit demonstration of these technologies every one or two years.

The paper will shortly discuss the mission and the satellite. It will address the payloads flown and will show how the technical characteristics of the satellite directly derive from these payloads. Several technical solutions will be presented.

INTRODUCTION

Micro- and nanotechnologies are playing an ever increasing role in the development of space systems as these systems typically have stringent size, mass and power consumption constraints. Especially with the current development towards ever smaller spacecraft, up to picosatellites which are lighter than 1 kilogram, it is essential to implement miniaturized subsystems in these spacecraft. Micro Systems Technology (MST) and Micro-Electronics (ME) can be used to provide solutions to this class of very small spacecraft. Highly miniaturized systems are possible if MST or ME is implemented, which results in considerable mass, power and volume reduction. New design solutions for space vehicles or payloads become possible through the use of micro- and nanotechnology. Often, the performance can increase due to the high level of integration of different functions in a single component. In addition, as satellite launch costs are mainly governed by the spacecraft mass, the use of MST and Micro-Electronics ME can reduce mission cost significantly.

Not only do MST and ME provide solutions for nano- and picosatellites, the opposite is valid as well. Since the total development cost of a nanosatellite is typically one or two orders of magnitude smaller than conventional space missions, it enables missions that were previously not possible, even if the lower cost and physical constraints of nanosatellites may result in lower functionality or performance. Using constellations of several satellites is currently being considered by ESA (the Darwin mission, a large baseline telescope, or a swarm of satellites for monitoring space weather) and these could benefit greatly from extensive application of MST and ME.

Another promising application of nanosatellites is the in-orbit demonstration of functionality and performance of nano- and microtechnology. Such a demonstrator mission improves confidence in the technology and can partially replace the extensive qualification programs which traditionally precede the acceptance of technology for use in the space environment. For micro- and nanotechnology, per definition characterized by relatively small size, low mass and low power demand, pico- and nanosatellites can be a suitable qualification platform. These satellites typically have a mass of 1 to 10 kg and the resulting modest mission cost allow technology developers to fly their products on a space mission without taking too much (financial) risks. Several years ago a standard was developed for such satellites, aimed at university projects and other non-commercial applications: the CubeSat concept.

CUBESAT CONCEPT

The CubeSat concept has been developed by Stanford University's Space Systems Development Lab and California Polytechnic State University San Luis Obispo (Cal Poly). The CubeSat program offers developers of small satellites and their payloads cost effective launch services. The CubeSat standard package deal includes [1]:

- A standard physical layout and design guidelines.
- A standard, flight proven deployment system.
- Coordination of required documents and export licenses.
- Integration and acceptance testing facilities with formalized schedules.
- Shipment of flight hardware to the launch site and integration to launch vehicle.
- Confirmation of successful deployment and telemetry information.

This effort led to a first launch of several university CubeSats in June 2003. Since then the concept has been adopted by industry. Commercial CubeSat kits of different sizes and several subsystems are available that can be used as a basis for a complete satellite [2]. Launch services are brokered by Cal Poly and the University of Toronto Institute for Aerospace Studies for as little as $40,000 for a satellite of 1 kg and dimensions of 10x10x10 cm. Over 60 universities and high schools from all over the world are currently participating in the CubeSat program. Student satellite teams from North America, Asia and Europe all work on different CubeSat missions. The CubeSat program can also benefit private firms and governments by providing a low-cost way of flying payloads in space. Although originally intended to offer students the opportunity to gain experience in space technology by working on a real space mission, the nanosatellite concept may also be used for in-orbit demonstration of new micro and nanotechnology.

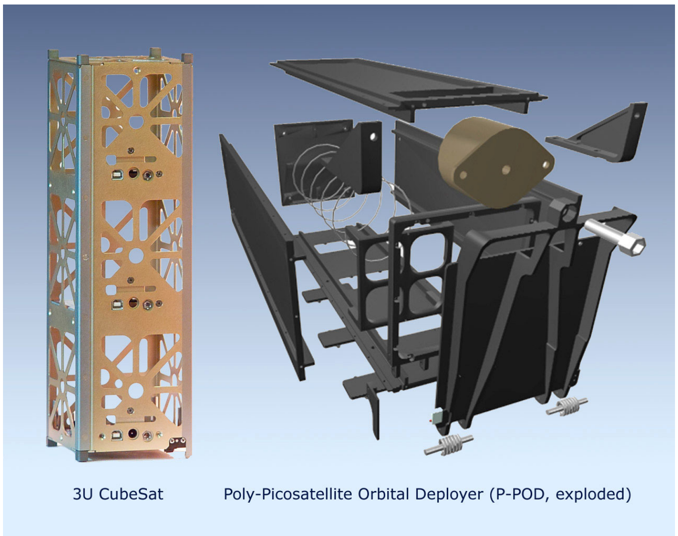

Figure 1: CubeSat and P-POD

A standard (1-Unit or 1U) CubeSat is a 10 cm cube with a mass of up to 1 kg. Within the CubeSat community 2U CubeSats (ION) and 3U CubeSats (Quakesat) are also developed which still have a base of 10x10 cm but their structure height is increased to two- or threefold respectively. In order to participate in a CubeSat Program, all that is necessary is to design and build a satellite according to the CubeSat Standard [1]. The standard physical layout ensures that CubeSat developers can make use of standard available deployment canisters, although this obviously limits the freedom of configuration design. The Poly-Picosatellite Orbital Deployer (P-POD) is one of the standard deployment mechanisms for CubeSats. The P-POD (Fig. 1) was designed at Cal Poly to be a reliable and cost effective deployment system, which can be mounted on most payload adapters of current launchers like the Eurockot Launch Vehicle and the DNEPR. The P-POD is in essence an aluminum box with a spring loaded door. A maximum of three 1-unit CubeSats or one 3-unit CubeSat can be accommodated in the P-POD. The satellites are ejected out of the P-POD by means of a large spring loaded plunger with a deployment force of 44.4 N, giving the satellite an exit velocity of 2.2 m/s [1]. The CubeSats are kept in position by means of Teflon-coated guide rails. These guide rails create an envelope between the P-POD walls and structure that can be used to store solar panels or other deployable systems. The walls of the P-POD can not be used as a hold down system for the deployables themselves, they need to have their own hold down system that is activated 15 or 30 minutes after ejection out of the P-POD depending on the deployable system .

CUBESAT AND TU DELFT

The faculties of Aerospace Engineering and Electrical Engineering, Mathematics and Computer Science of the Delft University of Technology started their CubeSat project, Delfi-C3, in November 2004. Delfi-C3 is scheduled for a piggyback launch in the end 2006 and is a precursor to the extensive MISAT program [3], a five-year program started in 2005, which aims to develop micro- and nanosatellites that demonstrate a wide range of MST and ME applications for use in spacecraft. MISAT is part of the MicroNed program, which promotes, increases and spreads knowledge in the field of MST and MEMS. Special attention is given to problems that obstruct the further application of MST in industry. The goal of the MISAT project is to design and build technology fit for application in a microsatellite prototype that is adaptable and can facilitate a number of scientific space missions. These efforts will eventually lead to low-cost access to space. Using similar or identical micro satellite buses in a constellation or a swarm can provide a platform for missions with many different combinations of payload instruments, while keeping mission cost relatively low. European space scientists have indicated the need for more launch opportunities for which the development of microsatellite missions as proposed in the MISAT program can be a solution. A number of successors for Delfi-C3, based on the CubeSat concept, are foreseen to provide early in-orbit demonstration of technologies under development for MISAT every one or two years.

The idea for Delfi-C3 originated from the desire of Dutch Space to have an early flight opportunity for innovative thin film solar cells (TFSC) prior to their first mission. The main objective of the Delfi-C3 mission is to measure the characteristic current-voltage (IV) curves of eight of these solar cells as a function of operating temperature and angle of incidence of the solar radiation. The cell temperature and incidence angle will also be measured.
Other candidate payloads were selected from the MISAT program [3], [4]. The two applications for the Delfi-C3 mission are an autonomous wireless Sun sensor (AWSS) with its own power supply and wireless data connection (TNO Science and Industry), and a high efficiency Advanced Transceiver developed at the faculty of Electrical Engineering, Mathematics and Computer Science .
The transceiver is used to receive commands from the Delfi ground station and transmit measurement and housekeeping data back to the ground segment. There will be no on-board data storage, so all measured data will be transmitted to the ground segment instantly. The satellite will make use of the amateur radio frequency bands, so the transceiver will be compatible with the amateur satellite (AMSAT) standards.
In addition to the technical mission objectives mentioned before, the Delfi-C3 project has educational objectives as well. Delfi-C3 is a Master's Thesis project and its main educational objective is to provide MSc students as a team with an opportunity to gain hands-on interdisciplinary engineering experience with the design and realization of both mission and systems of a satellite, by providing a challenging real-world application.

MISSION CONCEPT AND HIGH-LEVEL REQUIREMENTS

Important high-level system requirements dictate that the thin film solar cells shall not be body-mounted due to thermal constraints, thus requiring deployable solar panels. Temperature range requirements are mainly dictated by the autonomous wireless Sun sensor's temperature range. These and other requirements led to the decision to use a 3-unit CubeSat measuring 10x10x32.7 cm as the structural basis for Delfi-C3. The four solar panels each contain a frame with an array of two thin film solar cells. Five GaAs-cells on each panel serve as the satellite's power supply.

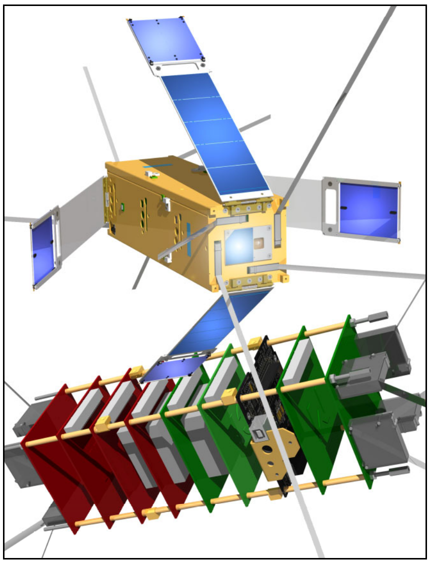

Figure 2: Delfi-C3 internal and external view

Furthermore, the design does not incorporate a battery. Since the TFSC and AWSS payloads depend on the presence of solar radiation, there is no need for the satellite to be operational in eclipse. This avoids the additional complexity that is involved with using a battery. Finally, the satellite design will have no single point failures as far as practicable. It will have a redundant architecture, to ensure that the mission does not depend on the new technologies flown. The Delfi-C3 satellite adheres to the CubeSat Standard, and uses the P-POD for orbit insertion.

SUBSYSTEM OVERVIEW

The satellite's structure is based on the 3-Unit CubeSat structure (Fig. 1) from Pumpkin Inc. The four solar panels of the satellite are deployed to an angle of 35 degrees with respect to the body, which is the optimum angle in order to guarantee the required minimum power provision in any orientation to the Sun. Each solar panel consists of a 1.25 mm thick panel of Carbon Fiber Reinforced Plastic (CFRP) with a kapton layer for the GaAs solar cells and a 1.50 mm thick titanium frame to suspend the TFSC payload at the end of the substrate (Fig. 2).The solar panels are deployed after release from the P-POD by melting wires with overpowering resistors that act as thermal knives

Eight tape measure whip antennas (Fig. 2) are used on the satellite. Four antennas are located on the top surface and four on the bottom surface, configured to create a near omni-directional pattern. The antennas on the top surface are used for the downlink and those on the bottom surface for the uplink. The uplink antennas have a length of 18 cm. The downlink antennas have a length of 50 cm, which is longer than the structure itself. For the antenna deployment Modular Antenna Boxes have been designed to stow and deploy the antennas.

The Electrical Power Subsystem (EPS) collects the power from the four triple junction Gallium-Arsenide solar panels and provides the subsystems with 12 V and 3.3 V. The EPS delivers a minimum power of 2.5 Watts. The Command and Data Handling System has a distributed architecture. The On-Board Computer (OBC) is an ultra-low power Texas Instruments MSP430 microcontroller, which is embedded in a flight microcontroller board, which has been provided by Pumpkin Inc. as part of the CubeSat kit. PIC microcontrollers, located on the subsystem boards, will communicate with the OBC on an I2C serial bus. In case of irreversible OBC failure, the PICs will send a minimal set of measurements directly to the communications subsystem for downlink to the ground segment.

The communications subsystem (COMMS) will perform two functions. First, it will provide the telemetry downlink and telecommand uplink functionality. In addition it will provide a linear transponder service which can be used by amateur radio operators to communicate with each other. The COMMS will be operated either in the telemetry mode or in the transponder mode. The satellite will have an uplink in the UHF amateur radio frequency band (435-438 MHz) and a downlink in the VHF amateur radio frequency band (145.8-146 MHz). The COMMS consists of two redundant systems, the Advanced Transceiver (ATRX) payload and a so-called Radio Amateur Platform (RAP). The RAP functions as a backup option for the Advanced Transceiver. It is built using standard commercial-off-the-shelf (COTS) components, providing telemetry, telecommand and linear transponder functionality.

As the satellite is designed with minimal complexity in mind there is no active thermal control. Passive thermal control surfaces ensure that heat, dissipated in the COMMS power amplifiers, is radiated into space, while insulation layers prevent excessive cooling during eclipse. The Attitude Control Subsystem (ACS) is also passive. A slow tumbling motion is required to allow all four TFSC panels to be exposed to solar radiation. Therefore, rotation rate limitation using magnetic hysteresis materials is applied. The Attitude Determination Subsystem (ADS) uses measurements of the supplied current and voltage of each individual GaAs solar panels to determine the Sun vector with respect to the satellite's body fixed reference frame. Four side mounted Si solar cells are used as an extra reference for the attitude reconstruction algorithm. When the Sun is within the 90 degrees quadrant field of view of one of the two AWSS payloads, the reconstructed attitude data is augmented with the high accuracy data generated by the AWSS. The attitude reconstruction will be performed in the ground segment as it is of no direct use on-board of the satellite.

PAYLOAD OVERVIEW

A. Thin Film Solar Cells

The thin film solar cell (TFSC) payload is based on a new development in the area of photovoltaic cells by the Dutch space company Dutch Space. The cells consist of a CIGS photovoltaic layer, which is vapor-deposited on a titanium base layer with a thickness of 25 micrometers (Fig. 3). The cells will be 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 (~1mΩ); it is placed between the gilded contact pads under low contact 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 will have no need for a cover glass, but it will have an emissivity enhancing and encapsulating dielectric coating. The efficiency will be more than 12 %. The performance of the TFSC payload will be tested by determining their characteristic IV-curves and cell temperature per TFSC panel, which consists of two cells. The IV-curves will be measured by means of a programmable current sink; the temperature will be measured by determining the electrical resistance of an optically identical, dummy TFSC cell, mounted close to the actual TFSCs. A full I-V curve measurement will be completed each second. The measured data is then transferred to the OBC where it is formatted for transmission to the ground segment.

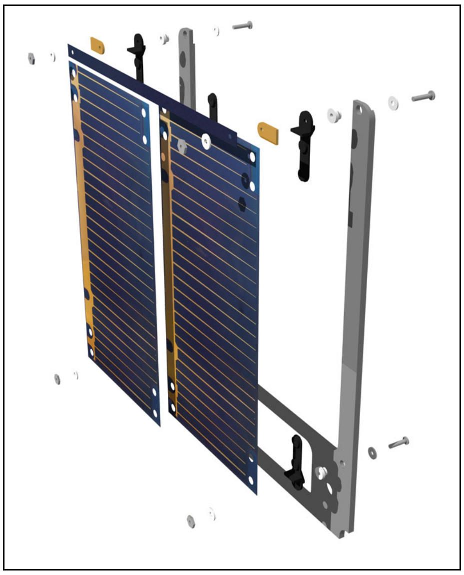

Figure 3: Thin Film Solar Cell Assembly

B. Autonomous Wireless Sun Sensor

Delfi-C3 houses two analogue Sun sensors (located at opposite sides of the satellite) that will be fully autonomous and wireless. With the typical internal volume of a nanosatellite already being quite limited, reducing wiring is an important challenge. The sensors will have a half-sized GaAs solar cell as their own power supply (Fig. 4), making them independent of the satellite's electrical power system. Data transfer autonomy is achieved by a wireless radio frequency link. The link will be either an adapted COTS transceiver or a custom designed Ultra-Wide Band connection, depending on technology readiness.

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: An autonomous sensor unit with no strings attached, measuring approximately 6.0x4.5x1.8 cm. The in orbit experiment will concentrate 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. The Sun sensor experiment aboard Delfi-C3 is a precursor to the micro Digital Sun Sensor which is under development at TNO Science and Industry within the framework of MISAT [3].

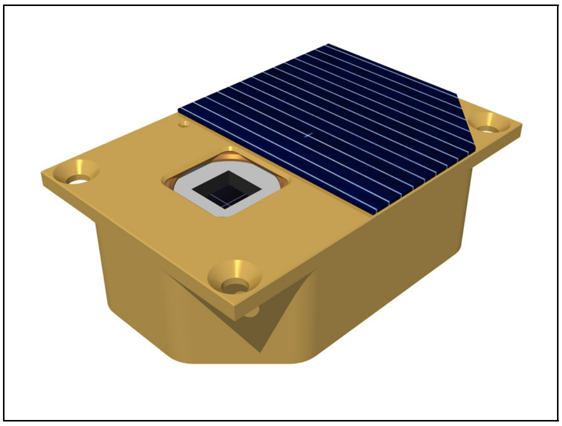

Figure 4: Autonomous Wireless Sun Sensor

C. High Efficiency Advanced Transceiver

The MISAT mission [3], [4] aims at the development of micro systems technology for a cluster of small satellites. For each of these satellites, one transceiver should be able to accommodate all wireless communication. A crucial part in this is the availability of a wide-band, highly efficient and power amplifier (PA) with very good linear performance. In this mission a PA will be tested that utilizes over-all double loop negative feedback, using integrated transformers in the feedback network and in the frequency compensation network. It has been shown that integrated transformers work very well in wide band technology when used as feedback element [5]. Since negative feedback is a powerful means to linearize an amplifier, additional non-linearity of the active part -especially the power stage- can be tolerated. When additional non-linearity can be tolerated, it is possible to increase the efficiency of the power stage. Several experiments have shown that both a higher efficiency and a higher linearity can be obtained using this technique. Space qualification of this technique, where integrated transformers are optimized for wide-band use in feedback amplifiers, is crucial. The circuit diagram is shown in Fig 5. Table 1 shows the improvement that has been achieved in a first experiment comparing amplifiers in the GHz range with identical active parts (and efficiency), one with and one without feedback.

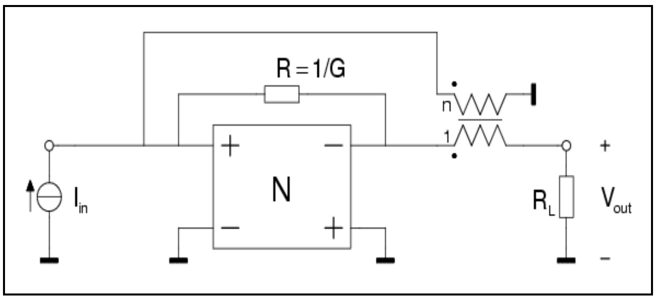

Figure 5: Double loop negative feedback using a transformer

Table 1: Comparison between amplifiers with and without feedback

IM3	**0.9GHz**	**2.0GHz**
FB	-46dBc	-43dBc
No FB	-29dBc	-33dBc
Improvement	17dB	10dB

GROUND SEGMENT

The ground segment consists of three parts, the distributed ground station network, formed by amateur radio operators, a worldwide university ground station network, and the Delfi command ground station at Delft University of Technology (back-up ground station at Eindhoven University of Technology).

As the Delfi-C3 will be transmitting telemetry continuously, the team is inviting radio amateur operators from all over the world to participate in the data collection process. Delfi-C3 will transmit its telemetry data in plain AX.25 frames, a widely used amateur radio standard for packet transmission. Telemetry decoding software will be made freely available to participating radio amateurs so that they can decode and process the telemetry data locally. This data can then be uploaded to the centralized Delfi command ground station via an Internet connection for further analysis. In discussions with other Universities involved in satellite development, it became clear that sharing ground station resources worldwide would be very beneficial. At the moment, such a network is taking shape. At the time of writing, the following Universities are participating in this network:

- Julius-Maximilians University Würzburg, Germany
- Aalborg University, Denmark
- Brno University of Technology, Czech Republic
- University of Bologna, Italy
- Fachhochschule Aachen, Germany
- Delft University of Technology, The Netherlands

The Delfi ground station, located on the roof of the Electrical Engineering building of the TU Delft, will act as the command ground station. This ground station is already operational, and allows for valuable experience in satellite communication to be gained. A backup command ground station is foreseen at the Technical University of Eindhoven.

CONCLUSIONS

Nanosatellites in the CubeSat class are an affordable means to achieve fast pre-qualification of micro technologies. The number of launches as well as the number or teams involved in designing CubeSats is increasing. However, several issues exist that require attention, for example the issue of orbital debris mitigation, which may become a problem with very small satellites without propulsion or other means of de-orbiting, and the use of the radio amateur frequency bands, which prohibits the commercial use of these frequencies.

The Delfi-C3 mission of the TU Delft is the start of a small satellite program in Delft in order to provide technology demonstrations within the scope of the MISAT program. If possible there will be a CubeSat launch every 1.5 to 2 years.

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