Delfi-C^3, past, present and future

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***Abstract*—On April 28, 2008 the Delfi-C^3 satellite was launched from Sriharikota in India to a low earth orbit (635km). It was the first Dutch university satellite built by students and staff. The satellite carries two scientific experiments for industrial partners and also demonstrates new design methods for some of the electronic systems. It also demonstrates that it is possible for a student team to design, build and operate an advanced cube-sat system. The Delfi-C^3 project is one of the efforts of the MISAT cluster in the MicroNed program in combination with support of the faculties of Aerospace Engineering and Electrical Engineering, Mathematics and Computer Science of the Delft University of Technology. As for October 2008, Delfi-C^3 is still functioning properly. Delfi-C^3 is the first satellite of a series that will be built and launched in the near future.**

***Index Terms*—Nano satellites, sun sensors, solar cells, space craft design, space born electronics**

I. Introduction

CUBESATS are becoming more and more the cheap and quick way to space for many different scientific experiments. Cubesats are already very popular as student projects and have significantly contributed to the training of excellent engineers able to work in multi-disciplinary teams. Now they are becoming more mature and considered to be very efficient platforms for in-orbit testing of new technologies and systems. In 2003 a start was made with the MicroNed program to boost the Dutch research in Micro Systems Technology and one of the four clusters in this program was designated to application of Micro Systems Technology in space. This cluster, called MISAT (Micro SATellite) was intended for research on satellite sub-systems. However, during the project it became clear that the implementation and operation of a nano-satellite, which is considerably smaller than a micro-satellite, based on the emerging cube-sat standard was feasible. Since the ultimate proof-of-concept of a satellite system is a launch and operation in space it was decided to start the Delfi-C^3 project. To demonstrate the viability of nano-satellites for in-orbit testing, two industrial partners were invited to contribute to this effort via the contribution of a scientific payload. One payload was already part of MISAT, the other payload from outside the project. A third industrial partner already participating in MISAT took responsibility for the power system and co-supervision of electrical engineering students. A team of students and staff of faculties of Aerospace Engineering and Electrical Engineering, Mathematics and Computer Science of the Delft University of Technology was formed. Also many students of various poly-technical schools in the Netherlands joined the team. In this way in a time-span of slightly more than two years, with a contribution of about 70 students, Delfi-C^3 was brought from ambitious idea to a successfully launched satellite that is still performing well.

In this paper the set-up of Delfi-C^3 is discussed. After this the first scientific results are presented. The paper is concluded with a brief description of current and future projects for new satellites of the Delfi-class.

II. Delfi-C^3 Bus and Payload Systems

A. The bus system

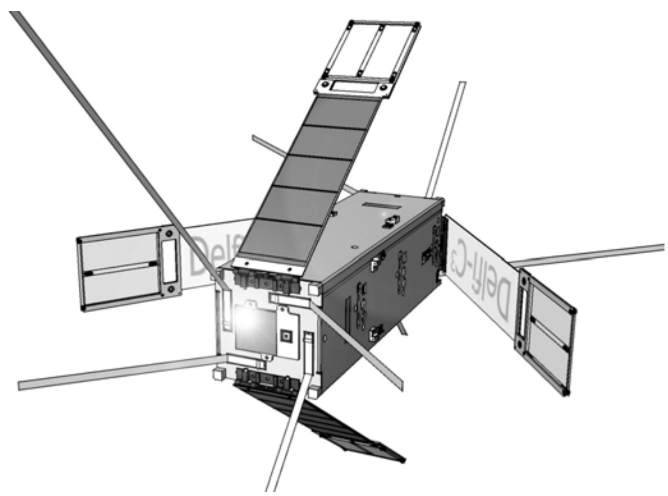

Fig.1. The Delfi-C3 satellite, also known as OSCAR-64 has a mass of 2.5kg. The dimensions are 10x10x30cm. It is equipped with a UHF and a VHF antenna system with deployable antennas with a length of 20cm and 50cm respectively. On the long edges wireless sun sensors by TNO are mounted. The thin-film solar cell experiments of Dutch Space a mounted on the far end of the deployable solar panels.

The bus system of Delfi-C^3 consists of two radio transceivers of which one is also equipped with a linear transponder for use by the radio amateur community, two measurement boards for the solar cell experiment, a distributed power system, with a main power board for interfacing between the solar cells and the local power systems on each of the boards in the satellite. Delfi-C^3 does not carry a battery system. Batteries are notorious sources of trouble in nano-satellites and have even caused missions to fail. Since the main payloads of Delfi-C^3 need illumination by the sun, it was decided that it was not a problem to shut down the satellite during eclipse. After every eclipse the satellite reboots. Via a small non-volatile memory the status before the eclipse is stored. This is important to prevent the satellite to start a deployment cycle for the antennas and the solar panels after each eclipse. Each PCB in the satellite is equipped with at least one microcontroller for power control and error detection. Some boards have a second controller for mode switching and control. The radio boards have a third micro controller for signal processing purposes. The controllers communicate using a redundant standard I^2C bus. Operations are coordinated by a central micro controller on the computer board, but in case of failure each of the other controllers is programmed to put Delfi-C^3 in a decentralized backup mode, with makes it possible for Delfi-C3 to still complete its scientific tasks at a lower data rate. The antenna boards on at both sides of the PCB stack contain a phasing network to obtain the appropriate antenna pattern and micro controller controlled redundant deployment circuits for the solar panels and the antennas. At the center of the PCB stack the "rod-board" contains a small magnet and two rods of magnetic hysteresis material. This board forms a primitive passive attitude control system that makes sure that Delfi-C^3 stumbles at a sufficiently low rate without coming to a full stop. This is important for the performance of the two scientific experiments that are both dependent on the variation of the intensity and angle of incidence of the light of the sun.

B. *The payloads*

Delfi-C^3 carries two scientific payloads. The first experiment is a technology demonstration of thin film solar cells by Dutch Space. The second experiment is a proof-of-concept of a wireless sun-sensor by TNO.

i. The Thin Film Solar Cell (TFSC) experiment tests the latest developed TFSC's of Dutch Space for their performance in space. The main characteristic of photovoltaic cells is the IV curve related to the temperature. In order to gather this information Delfi-C^3 measures sets of two TFSC's in series placed at the tip of each of the four solar panels. The measurement electronics is made redundant using two identical boards that each measure two sets of TFSC's. The TFSC's consist of a CIGS photovoltaic layer which is deposited by evaporation on a titanium base layer of 25 micrometers. The aim of this type of solar cell is to create a light-weight and low-cost product for future space applications. The efficiency is expected to be more than 12 % under AM0 light conditions

ii. As a second experiment, Delfi-C^3 houses two four quadrant sun sensors by TNO located at opposite sides of the satellite which are fully autonomous and wireless. The sensors are powered using their own half-sized GaAs solar cell. Contact with the on-board computer is made using a radio link based on a commercial off-the-shelf transceiver, operating in the 915 MHz band. Wireless data communication enables modularity and flexibility, reduces system weight and volume lacking cables and connectors and is an enabler for "plug and play" construction of nano-satellite missions. The autonomous sensor unit, in Delfi-C^3 measures 60x40x20 mm and is intended as a proof-of-concept for wireless sun sensors. The in-orbit test concentrates on demonstrating the feasibility of the wireless link with respect to EMI and the operation of the sun sensor with a variable sun dependent power supply. The target (within the MISAT cluster) is an even smaller digital version that can be easily mounted on any position on e.g. a solar panel.

III. First Results

A. *Bus system*

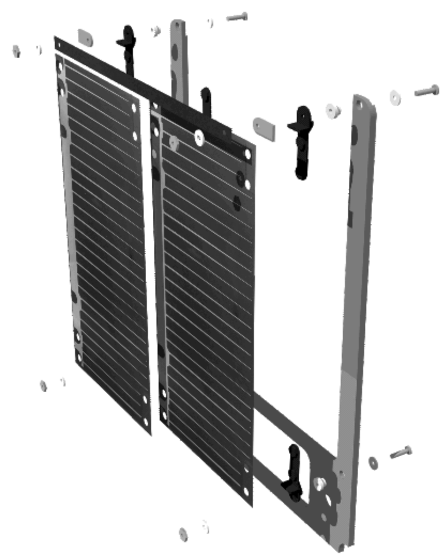

Fig. 2. The TFSC's and their mounting structure by Dutch Space

As for October 2008, the bus system works according to specs. The temperature of the on-board computer is usually around -4°C. The temperature of the power-amplifier on the active radio board starts at around 17°C when the satellite boots after eclipse and reaches an end temperature of around 23°C. This is a good indicator that the thermal design of the satellite has been correct and that the thermal models and their parameters used in simulation were good. Occasionally minor distortion in the output signal when the satellite is in science mode indicates that there are satellite orientations where the power from the solar panels is only just enough. This is slightly less than expected. In transponder mode, with the scientific experiments turned off and the radio transponder turned on there is always more than sufficient power available. The radio transponder is very popular among radio amateurs world wide and was awarded with an OSCAR (Orbiting Satellite Carrying Amateur Radio) from the AMSAT community in appreciation of the quality of the design. For that reason Delfi-C^3 is now also known as OSCAR-64.

B. *Thin film solar cells*

The measurement boards perform well and produce useful information on the temperature and the I-V curves of the TFSC's. All TFSC's are functioning properly and useful results for characterization of the behavior of the TFSC's in space has been delivered. Of course the measurements will be continued the coming years. First results show that the cells seem to perform satisfactory as does the mounting construction and the system for the electrical connections between the separate cells. Detailed results will be presented in a separate paper.

C. *Sun sensor*

As for October 2008 only data of one of the two wireless sun sensors has been collected. Information of the second sensor seems to be missing in the data received. It is not clear yet if this is a software problem with the information still being available in the raw data from the satellite or if it is a hardware problem with the sensor itself. Further investigations are still ongoing. Even though, the first results indicate that the use of wireless (sun) sensors is a valid and viable concept.

IV. FUTURE PROJECTS

A. *Delfi-n3Xt*

The equal sized successor of Delfi-C^3, Delfi-n3Xt, is planned for launch in 2010. It will advance the existing Delfi-C^3 technology with the addition of 3-axis attitude control, high speed data communication and a battery system for eclipse operations. Furthermore, five exciting innovative payloads will be onboard. These payloads are: a micro-thruster system from TNO, TU Delft and UTwente, a multifunctional particle spectrometer from cosine Research BV, degradation research on solar cells from DIMES, a high efficiency transceiver from ISIS BV and SystematIC and a data storage experiment from NLR. Also a first test will be done with a LF radio receiver (<30MHz) using active antenna's for the OLFAR project.

Fig. 3. The planned successor of DelfiC3: Delfi-n3Xt. The dimensions are also 10x10x30cm. It is equipped a Delfi-C3 like VHF antenna system with deployable antennas 50cm for both transmission in the VHF band and reception in the UHF band. Also the OLFAR experiment will make use of these antennas. Delfi-n3Xt has attitude control and is sun pointing.

B. *OLFAR*

Very recently ideas have been developed by ASTRON, TU-Delft and University of Twente to investigate the possibility of implementing a radio telescope in space for the reception of very low frequency radio signals, below 30MHz. In that frequency range extreme hydrogen red-shifts can be measured that are related to events in the early cosmos. Earth bound radio telescopes are not suitable for this purpose due to the ionosphere of the earth. The Orbiting Low Frequency Antenna for Radio astronomy (OLFAR) envisaged will consist of a swarm of nano or even pico-satellites to establish an antenna with an aperture diameter that is in principle unlimited (= scalable, extendable).In the OLFAR project the design of the satellite systems in both hard and software necessary for this mission will be investigated. The proof of concept of cooperating nano-satellites for radio astronomy will most likely be demonstrated via the launch and operation of a small number (2 or 4) of nano-satellites of the Delfi-class. Presently, a group of interested research institutes and industrial partners has been formed and the details of the project are being formulated.

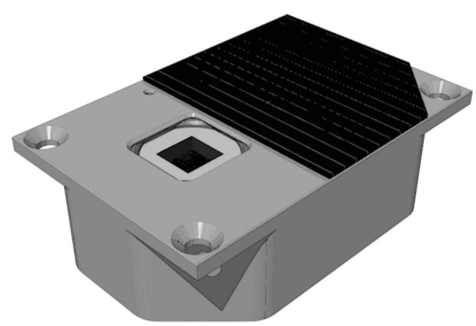

Fig. 4. The wireless sunsensor by TNO

V. CONCLUSIONS

The Delfi-C^3 project has shown that it is indeed possible for a team of students and university staff to design implement and operate a nano-satellite successfully. Support from industry is essential to have an interesting variation in payloads to fly. Nano-satellite projects run in this way can be a very inexpensive and fast way to early stage in-orbit testing of new technologies and prototypes of instruments for larger missions. Also the multi-disciplinary character of these projects and the highly innovative context make them an excellent environment for training engineers. For future missions for planetary and deep-space exploration and other satellite-swarm based scientific projects nano-satellites (and smaller) using the newest MST and ME technologies are likely to become the basic building blocks. Delfi-C3 is just the modest start of an exiting new series of next generation space craft. One of the most concrete examples of the potential of swarms of cooperating highly miniaturized satellites is the OLFAR system. The Delfi-C3 project indicates that it is both technically and economically affordable to develop an innovative small-satellite system like this in the Netherlands.

TABLE I
DELFI-C3 SATELLITE INFORMATION

Quantity	
Altitude	650km
Velocity	7.5km/s
Inclination	97.982 degrees
Period	1h 37m 11s
Weight	2.5km
Power consumption	2.5W
Downlink frequency	145MHz (VHF)
Uplink frequency	450MHz (UHF)

REFERENCES

[1] C.J.M.Verhoeven and W.Jongkind, "MISAT: a satellite colony", 8th International Conference on the Commercialization of Micro and Nano Systems, COMS2003, Amsterdam, The Netherlands

[2] W.J. Ubbels, A.R. Bonnema, E.D. van Breukelen, J.H. Doorn, R. van den Eikhoff, E. Van der Linden, G.T. Aalbers, J. Rotteveel, R.J. Hamann, C.J.M. Verhoeven, "Delfi-C3: a Student Nano satellite as a Test-bed for Thin Film Solar Cells and Wireless Onboard Communication", RAST 2005 (2nd International Conference on Recent Advances in Space Technologies Space in the Service of Society) June 9 2005, Istanbul, Turkey

[3] Nano-satellites, a fast way to pre-qualify new micro-technology R.J. Hamann, Faculty Aerospace Engineering, Delft University of Technology, The Netherlands C.J.M. Verhoeven, Faculty EEMCS, Delft University of Technology A.R. Bonnema, Faculty of Aerospace Engineering, Delft University of Technology, 2005 International Conference on MEMS,NANO and Smart Systems, Banff, Alberta, Canada

[4] Nano satellites for Micro technology Pre-Qualification: The Delfi Program of Delft University of Technology, R.J. Hamann, C.J.M. Verhoeven, A.A. Vaartjes, A.R. Bonnema, 6th Symposium on Small Satellites for Earth Observation, Berlin, 23-26 April 2007.

[5] Gill, E K A (Ch. System Integration: Design of Space Systems), Monna, G L E (EWI Ch. Electronic Circuits Design), Scherpen, J M A (3mE Section Delft Center for Systems and Control) & Verhoeven, C J M (EWI Ch. Electronic Circuits Design) (2007). MISAT: Designing A Series Of Poweful Small Satellites Based Upon Micro Systems Technology. In s.n. (Ed.), *58th International Astronautical Congress* (pp. 1-4). Hyderabad, India: IAF/IAA (ISBN 1995-6258). Available from: 2007 IAF/IAA, Hyderabad, India (ISBN 1995-6258)

[6] Hamann, R J, Verhoeven, C J M , Vaartjes, A A , Bonnema, A R (2007). Nano-satellites for Micro-technology Pre-Qualification: The Delfi Program of Delft University of Technology. In H-P.Roser Valenzuela A. Sandau R. (Ed.), *6th Symposium on Small Satellites for Earth Observation.* Berlin: DLR (ISBN 3-89685-571-9).

[7] Ubbels, W J, Mubarak, F A, Stoopman, M, Verhoeven, C J M, & Hamann, R J (2007). Delfi-C3 Communications Subsystem. In Johnson.D. Heck J. (Ed.), *AMSAT UK 2007* (pp. 5-8). s.l..

[8] Verhoeven C.J.M.; US 6225872 ; "Resonator having a selection circuit for selecting a resonance mode"; May 1, 2001

[9] Micro systems technology: the way to shrink sun sensors; Leijtens, J.; de Boom, K.; van der Heiden, N.,MEMS, NANO and Smart Systems, 2005. Proceedings. 2005 International Conference on, Volume , Issue , 24-27 July 2005 Page(s): 193 - 194

[10] Websites: www.delfispace.nl, www.cansat.nl and www.microned.nl

Chris Verhoeven was born in The Hague, The Netherlands, in 1959. He received the Master's degree in electrical engineering and the Ph.D. degree (on the topic of first-order oscillators) from Delft University of Technology, Delft, the Netherlands in 1985, and 1990, respectively. Presently he is an Associate Professor at Delft University of Technology, Delft, The Netherlands, part time in the Electronics Research lab of the faculty of Electrical Engineering, Mathematics and Computer Science and part time in the Space systems Engineering group of the faculty of Aerospace Engineering. His current research interests are in the fields of design methodology for analog circuits (structured electronic design), with emphasis on amplifier, oscillators, adaptive RF front-ends, space-born electronics and electronics for sounding rockets. Currently he is work-package leader in the MISAT cluster, senior researcher, and supervisor in the Delfi-C3, the Delfi-n3Xt and the OLFAR start-up project and project leader of the educational CanSat project.

Wouter Jan Ubbels was born in Gouda, The Netherlands, in 1981. He holds an MSc. degree in Aerospace Engineering from Delft University of Technology. He has been project manager for the Delfi-C3 satellite for 2 years and has been responsible for daily spacecraft operations. He is co-founder of ISIS – Innovative Solutions In Space BV, a Dutch company which specializes in nanosatellites, nanosatellite subsystems and nanosatellite launches. Presently, he is technical director of ISIS.