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FLIGHT EXPERIENCE WITH THE PICOSATELLITE BEESAT

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Abstract

BEESAT (Berlin Experimental and Educational Satellite) is one of the first picosatellites implementing a fault-tolerant design in a consistent way. Remaining single points of failure were identified and can be eliminated in a future design. The main mission objective is the in-orbit verification of the newly developed reaction wheel system suitable for pico- and nanosatellites. First flight results show, that BEESAT works in the expected way. Numerous experiments have been conducted within one year so far. The BEESAT mission demonstrates that a picosatellite can be a reliable and cost-effective verification platform for a low Earth orbit.

1. INTRODUCTION

Small Satellites with a total mass of less than 10 kg, so called nano- and picosatellites are more and more interesting tools for universities, companies and scientific institutions and organisations. Today picosatellites become interesting not only for hands-on education of students but also as a low-cost tool for Earth remote sensing, for radio amateur communications or for in-orbit verification of new space technologies.

Technology progress allows new opportunities to gather interesting data of Earth remote sensing or to use these small spacecrafts for communication purposes. The technology progress is happen on component level but also on system level. New high performance components for picosatellites like sun sensors, reaction wheels or S-band communication units are already developed and begin to be demonstrated in space.

The BEESAT satellite was designed to test and demonstrate in orbit a set of three reaction wheels suitable for nano- and picosatellites. But also on system level the BEESAT satellite demonstrates a new performance feature in orbit: a picosatellite basing on a single-fault-tolerant design. Usually picosatellites are built by commercial off-the-shelf parts not dedicated to space applications. They are designed and tested on ground for launch and space environment conditions. A certain risk of mission failure due to the use of commercial off-the-shelf parts and components has to be accepted. This risk is further reduced in the BEESAT by a fault-tolerant satellite system design basing on an extensive use of redundant parts, components and circuits. Until now, most picosatellites have not implemented any redundancy due to mass and size constraints. BEESAT is one of the first picosatellites implementing a fault-tolerant design in a consistent way. But redundancy can result in considerable design complexity. So it has to be done carefully. The BEESAT mission demonstrates and verifies in orbit the feasibility of a single failure tolerant picosatellite design.

2. MISSION

The main mission objective of BEESAT is the in-orbit verification of newly developed reaction wheels for a mission lifetime of one year. Mission details are listed in tab. 1. BEESAT was launched on a PSLV rocket into a circular, sun-synchronous low Earth orbit on 23rd of September, 2009. First flight results show, that BEESAT works in the expected way.

Tab. 1. Mission details

Objectives:	1) In-orbit verification of newly developed reaction wheels 2) Education of students in satellite design and operation 3) Verification of picosatellite technologies
Satellite class:	1-unit CubeSat / picosatellite
Lifetime:	1 year
Launch:	23 September 2009, 06.21 UTC with PSLV-C14
Orbit:	≈ 730 km, 98.3° (sun-synchronous)
Operation:	TU Berlin

3. FAULT-TOLERANT DESIGN

BEESAT follows the CubeSat specification with a maximum mass of 1 kg and dimensions of 10 cm x 10 cm x 11.35 cm. Mission critical subsystems or components are implemented redundant to achieve a fault-tolerant system (see fig. 1): the battery with charge regulator from the electrical power subsystem, the communication subsystem, the on-board computer as well as the intersubsystem communication via a controller area network (CAN). Beside the mission critical subsystems and components, following components are redundant: two-dimensional sun sensors, triaxial magnetic field sensor and the magnetic coils in three axes.

The general design principles for BEESAT are as follows:

Use of Commercial off-the-shelf parts Commercial off-the-shelf (COTS) parts offer many advantages in comparison with parts dedicated to space applications. They are generally less expensive, faster shippable, have less power consumption and a smaller package. COTS parts have a wide range of functionality and a higher performance. A drawback is the necessary space qualification. The BEESAT engineering qualification model (EQM) has successfully completed several tests on qualification level: vibration, shock, thermal-vacuum and radiation.

Stack configuration A highly integrated picosatellite can only be implemented in a stack configuration. The BEESAT primary structure contains a stack of several electronic boards, the batteries and the reaction wheel system (see fig. 2).

Redundancy Mission critical subsystems have to be implemented redundant for a single-fault-tolerant system. In BEESAT, the experimental payloads (camera and reaction wheel system) have not been implemented redundant with intent.

Multifunction component assembly A highly integrated satellite is only feasible, if several components of different subsystems are combined to one assembly. The printed circuit board in fig. 7 contains a redundant on-board computer, a redundant terminal node controller (part of the communication subsystem), attitude determination sensors (redundant magnetic field sensor in three axes, angular rate sensor) and temperature sensors. Each solar panel (see fig. 8) contains solar cells, a two-dimensional sun sensor with signal conditioning, a magnetic coil and a temperature sensor. Multifunction component assembly reduces harness and makes the integration of the satellite more easy.

Communication buses A communication bus gives the opportunity for system modularity. A system can be extended with components easily in comparison to traditional point-to-point interfaces. The harness is smaller. With the electrical ground support equipment (EGSE) all communication between the subsystems can be monitored. During development and testing phase, messages can be injected into the communication bus. Thus, the behaviour of a subsystem can be emulated by the EGSE. As a communication bus can fail, it must be redundant (see fig. 3).

Power supply buses A power supply bus gives the opportunity for system modularity. A system can be extended with components easily, if they are compatible to the power bus. In BEESAT, two common regulated voltages are provided: 3.3 V and 5 V. As a power supply bus can fail, it must be redundant.

Remaining single points of failure in BEESAT were identified. They can be found in the electrical power subsystem exclusively and can be categorised as follows: no redundancy for diodes and for the power control and distribution unit (PCDU). Redundant diodes can be implemented as a serial connection of one conventional diode and one ideal diode (transistor circuit). Thus, a trade-off between power loss and circuit complexity is obtained. A redundant PCDU increases the circuit complexity considerably. For the first BEESAT mission this could not yet implemented. Tab. 2 shows a few design details of BEESAT.

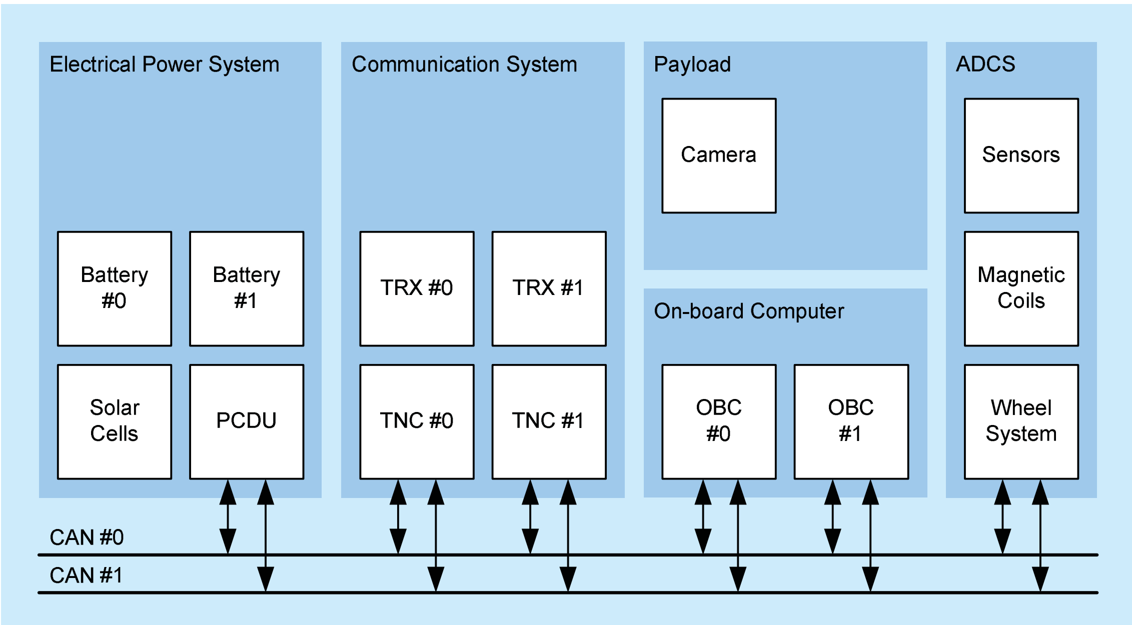

Fig. 1. System design

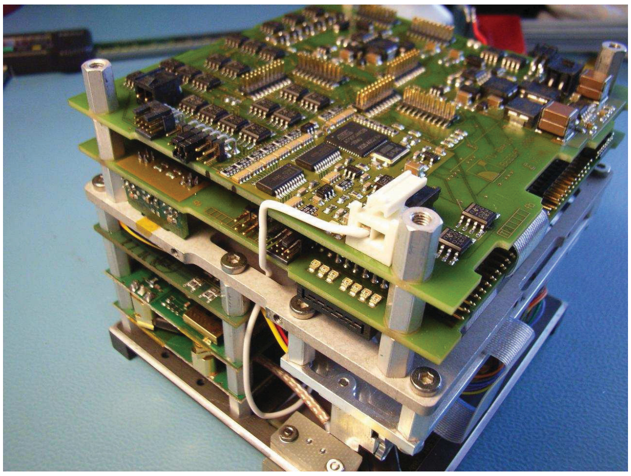

Fig. 2. Stack configuration

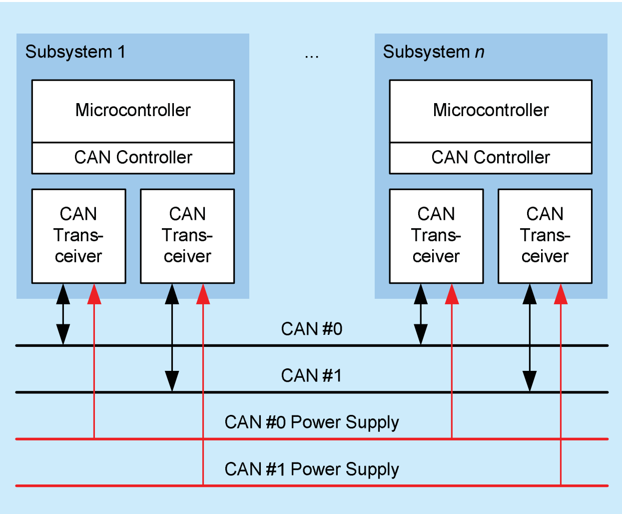

Fig. 3. Redundant CAN

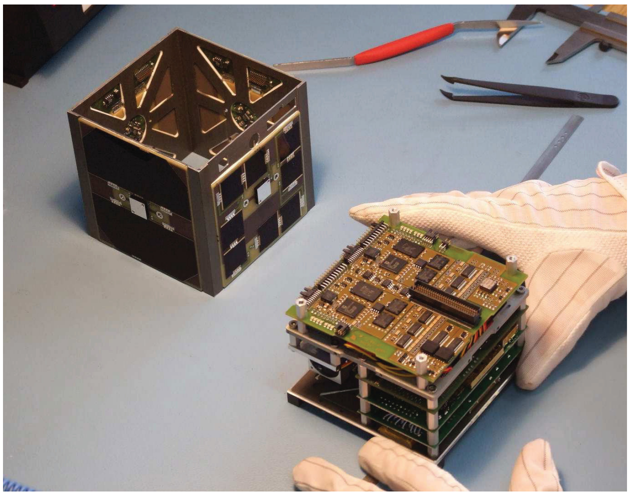

Fig. 4. EQM integration

Tab. 2. Design details

Dimensions:	10 cm x 10 cm x 11.35 cm (primary structure)
Mass:	936 g
Transmitter frequency:	UHF
Transmitter power:	500 mW
Modulation:	GMSK
Data rate:	4800 bit/s uplink 4800 / 9600 bit/s downlink
Measurement:	105 measurement values: 7 voltages 35 currents 26 temperatures 24 sun sensor photo currents 6 magnetic field strengths 3 angular rates 2 signal to noise ratios (SNR) of the UHF receivers
Redundancy:	UHF transceiver, TNC, CAN, on-board computer, battery, charge regulator, magnetic field sensor, sun sensor, magnetic coils
On-board computer:	ARM7-based 32-bit RISC microcontroller NXP LPC2292 with 60 MHz clock, 20 MByte flash memory, 2 MByte SRAM, 150 mW typical electrical power consumption
Switchable components:	24

4. FLIGHT EXPERIENCE

BEESAT works as expected regarding the communication link budget, the electrical energy budget, the thermal budget, the telecommand and telemetry system. There is no indication of degradation in performance or function since the launch. Until now it was not necessary to activate redundant components. BEESAT is operated from the ground station at TU Berlin. The overall rotational speed of the satellite has been stabilized at around 2 °/s. Tab. 3 and Fig. 10 show typical temperatures of several components. Fig. 11 shows the typical development of both battery voltages. BEESAT has a positive energy budget under normal operating conditions.

5. VERIFICATION OF REACTION WHEELS

Numerous experiments with the reaction wheel system have been conducted in orbit. The wheel system behaves like on ground. The change to the satellite's rotation could be measured. Fig. 6 shows the three reaction wheels and fig. 9, 12, 13 the results of a typical wheel test. For further test results see [1].

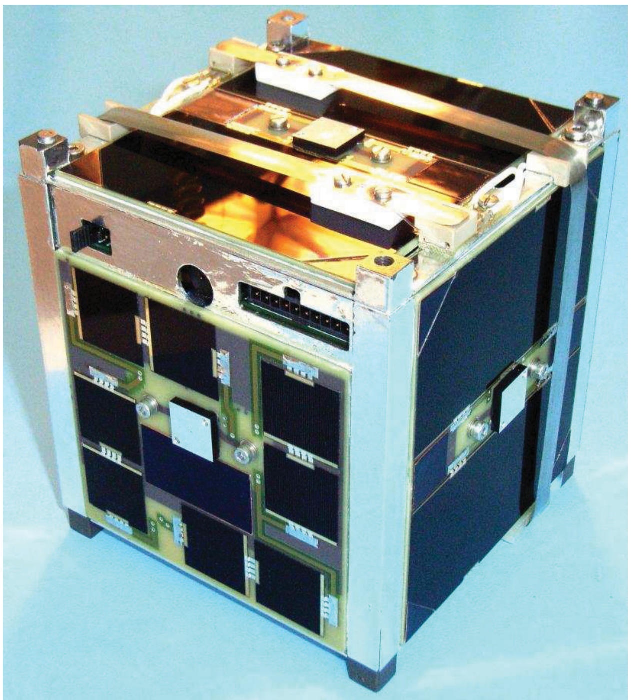

Fig. 5. Flight model

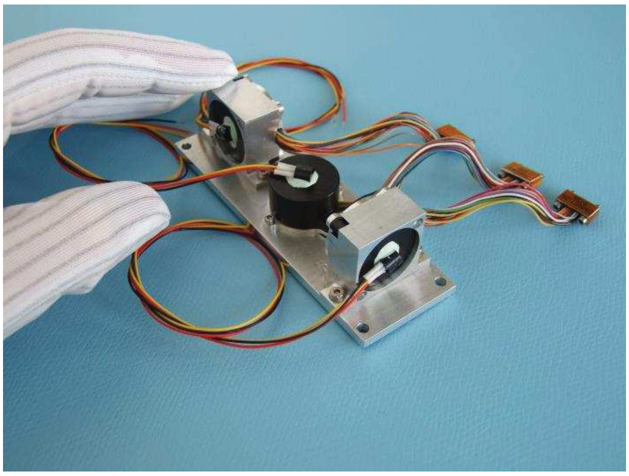

Fig. 6. Reaction wheels equipped with temperature sensors

6. CONCLUSION

BEESAT is the first operational picosatellite basing on a fault-tolerant design with exception to the experimental payloads (reaction wheel system, camera). Remaining single points of failure were identified. The major challenge for a fault-tolerant picosatellite is the implementation of a redundant electrical power subsystem. For the first step, BEESAT has a redundant battery and charge regulator. With a higher integrated design, a fault-tolerant picosatellite is feasible. The first flight results show that the power budget, the communication link and the thermal budget reside steadily within predicted limits. The reaction wheel system was verified successfully in orbit. The BEESAT mission demonstrates that picosatellites can be a reliable and cost-effective verification platform for a low Earth orbit.

7. ACKNOWLEDGEMENTS

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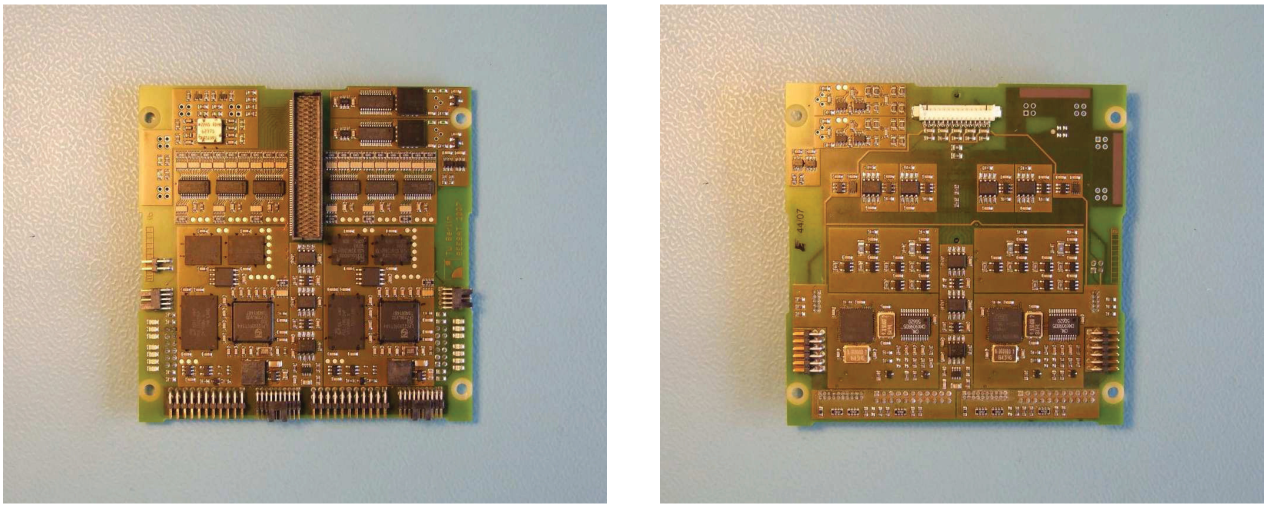
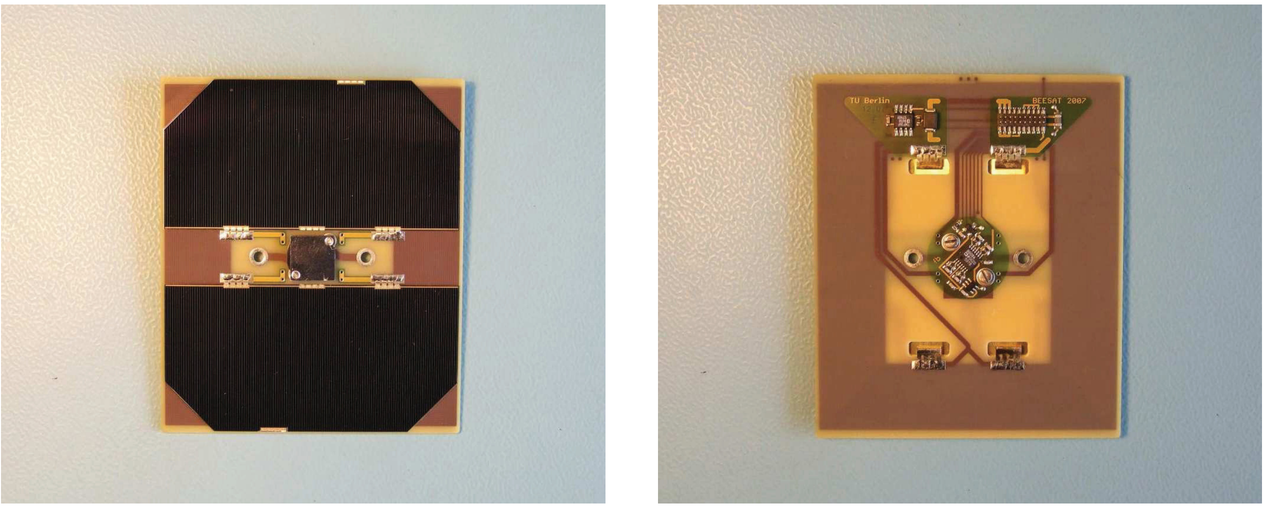


(a) Top side: redundant on-board computer, redundant triaxial magnetic field sensor, angular rate sensor, temperature sensors, analog to digital converters for external sensors

(b) Bottom side: redundant terminal node controller, debug circuitry

Fig. 7. Multifunction controller board



(a) Outer side: two solar cells, two-dimensional sun sensor

(b) Inner side: sun sensor signal amplifier, magnetic coil, temperature sensor

Fig. 8. Multifunction solar panel

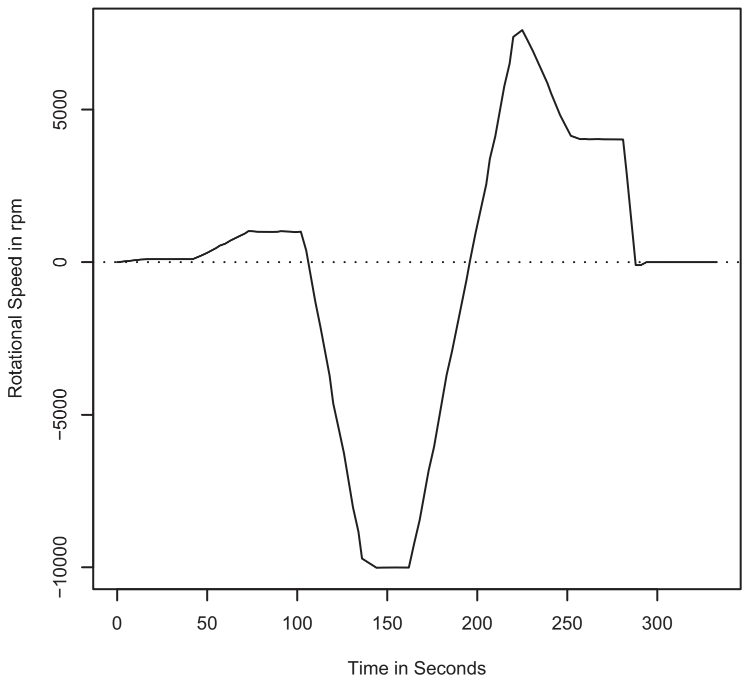
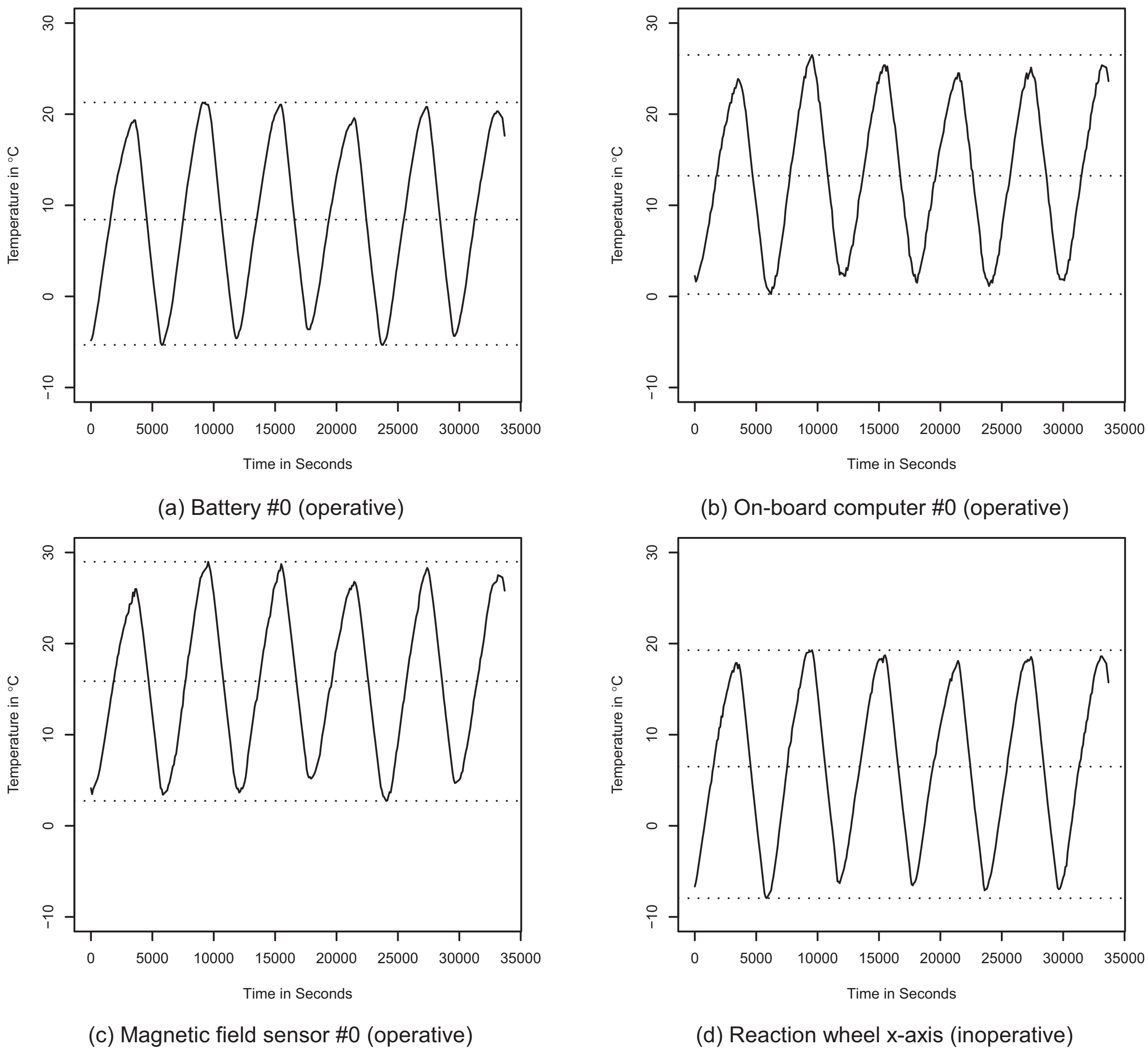


Fig. 9. Typical reaction wheel test

Tab. 3. Measured Temperatures

Component	**Temperature**			
	Minimum	Average	Maximum	Range
	℃	℃	℃	K
Reaction wheel x-axis (inoperative)	–8	6	19	27
Reaction wheel y-axis (inoperative)	–7	7	20	27
Reaction wheel z-axis (inoperative)	–8	7	20	28
Battery #0 (operative)	–5	8	21	26
Battery #1 (operative)	–6	8	21	27
Power control unit (operative)	–1	12	26	27
On-board computer #0 (operative)	0	13	26	26
Magnetic field sensor #0 (operative)	3	16	29	26
Solar panels (inner side)	–14	7	29	43



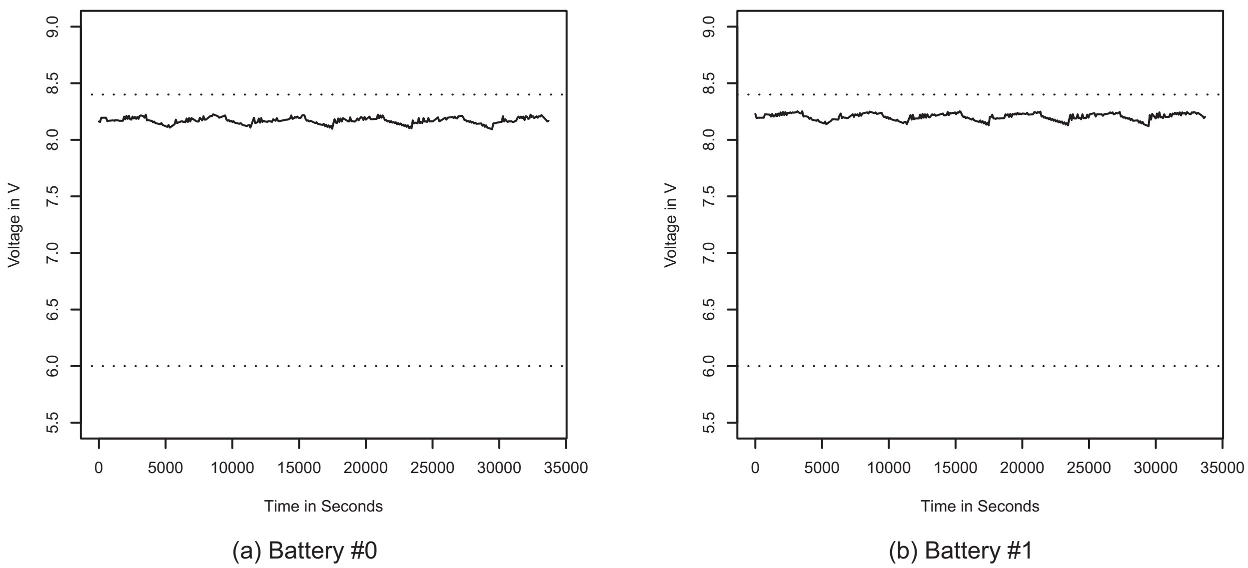
(a) Battery #0 (operative)

(b) On-board computer #0 (operative)

(c) Magnetic field sensor #0 (operative)

(d) Reaction wheel x-axis (inoperative)

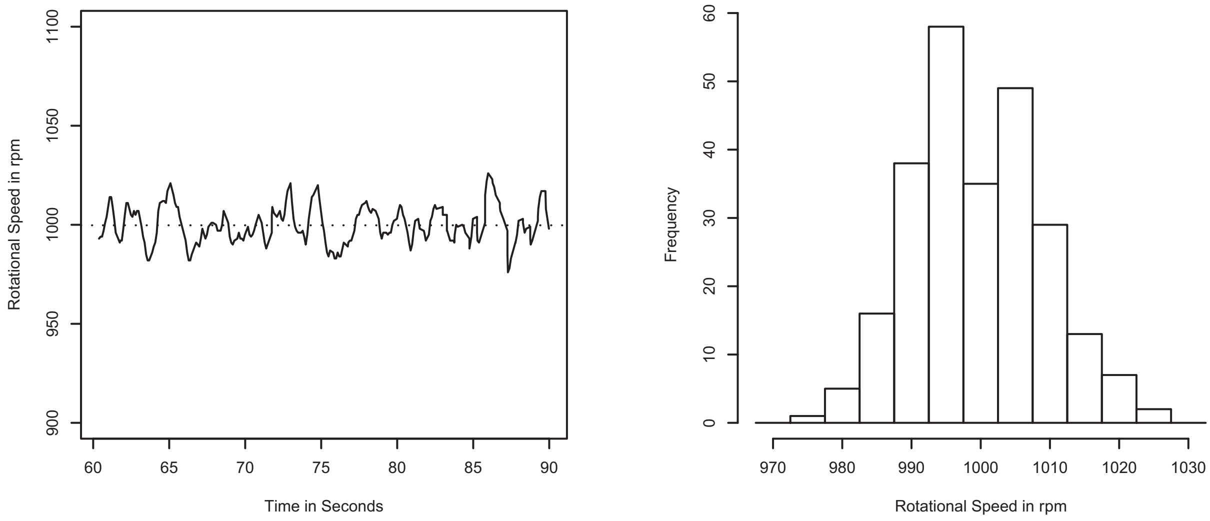
Fig. 10. Typical temperature development over more than five orbits



(a) Battery #0

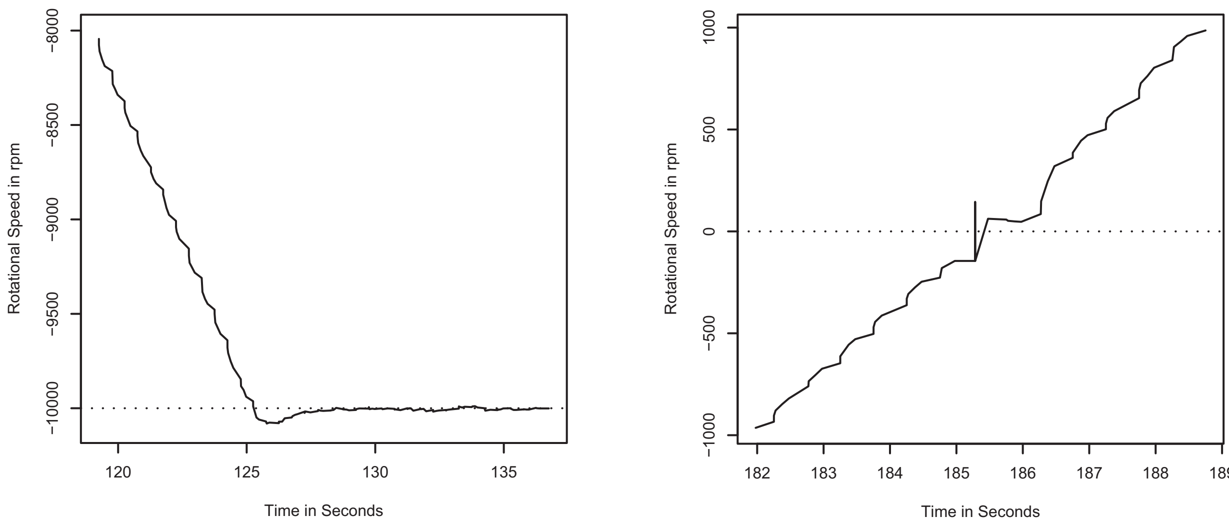
(b) Battery #1

Fig. 11. Typical battery voltage development over more than five orbits



(a) Wheel y-axis (arithmetic mean = 999.8 rpm, n = 253) (b) Wheel y-axis (standard deviation = 9.3 rpm, n = 253)

Fig. 12. Typical rotational wheel speed variation at nominal value of 1000 rpm



(a) Overshooting wheel y-axis (b) Zero-crossing wheel y-axis

Fig. 13. Typical dynamic wheel characteristics