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Nanosatellites—the BRITE and OPS-SAT missions

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Nanosatellites are spacecraft in the mass range between 1 and 10 kg providing a fast and low-cost possibility to test new technology in Space and gain flight heritage. The first Austrian nanosatellite TUGSAT-1/BRITE-Austria, successfully launched in 2013, and a follow-up ESA mission are described in this paper.

Keywords: nanosatellites; TUGSAT-1; OPS-SAT; asteroseismology; in-orbit demonstration

Nanosatelliten – die BRITE- und OPS-SAT-Missionen.

Nanosatelliten sind Weltraumobjekte mit einer Masse zwischen 1 und 10 kg. Sie bieten eine rasche und kostengünstige Möglichkeit, neue Technologien im Weltraum zu erproben und Flugerfahrung zu sammeln. Der erste österreichische Satellit TUGSAT-1/BRITE-Austria, der erfolgreich 2013 gestartet wurde, und eine Nachfolgemission der ESA werden in diesem Artikel beschrieben.

Schlüsselwörter: Nanosatelliten; TUGSAT-1; OPS-SAT; Asteroseismologie; In-Orbit-Vorstellung

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1. Introduction

Nanosatellites are small spacecraft with a launch mass between 1 and 10 kg. The concept of so-called Cubesats was first presented in 1999 by Prof. Bob Twiggs of Stanford University and Prof. Jordi Puig-Suari. The driver behind this idea was originally purely educational. Students should have the possibility to be involved in all phases of a space mission: from design, construction, test, launch to operations and management. Commercial off-the-shelf components and piggy-back launch opportunities helped to reduce the costs of access to Space significantly. The first Cubesats were launched in 2003. While only about 50% of the first University Cubesats were successful due to a number of reasons, the situation has significantly changed in the last few years. By the end of 2013 more than 200 Cubesats had been launched with a record set in 2013. In November 2013, within 30 hours 51 Cubesats were placed into low-earth orbit by DNEPR and Minotaur rockets, notably both being former inter-continental ballistic missiles, now fortunately used for peaceful purposes.

Small satellites have considerably matured since the first projects. Deficiencies which were mainly attributed to the fact that the first projects were built by less experienced teams were cured and professionally-built nanosatellites have a very good operational record of several years in orbit. Space agencies, industry and research organisations have meanwhile embraced the concept allowing to test and to validate in orbit new technology and new operational concepts within short time-frames and at a fraction of the costs of a traditional Space mission. With miniaturisation of key subsystems of a spacecraft such as attitude control, power, onboard computer and communication modules, even scientific, remote sensing and communications missions can be supported by small satellites. Spin-off companies are offering a variety of standard subsystems at low cost. In recent years, payloads for astrobiological, astronomy, earth observation, space weather, communications, electronics, pharmaceutical, technological and amateur radio missions have been flown. (In this context it shall be mentioned that the first small low-cost satellites were already launched in the 1960ies supporting amateur-radio communications.)

In 2005 Graz University of Technology as prime contractor with the Institute of Astrophysics (University of Vienna) and Vienna University of Technology as subcontractors as well as the Spaceflight Lab of the University of Toronto in Canada as external partner a proposal for the implementation of a nanosatellite mission, dedicated to the measurement of massive luminous stars, was submitted to the to the Austrian Science Promotion Agency (FFG). The proposal was accepted and the contract signed in 2006. The spacecraft named TUGSAT-1/BRITE-Austria was successfully launched in February 2013 and is delivering very good scientific data since then.

As a follow-up activity TU Graz as prime contractor with MAGNA STEYR Engineering and the Zentrum für Telematik in Germany as subcontractors recently finished a Phase A/B1 design study for an ESA Cubesat, called OPS-SAT, demonstrating in orbit new technology and operational concepts. OPS-SAT shall be developed starting in Fall 2014 and be ready for launch in 2016/17.

Both missions are described in detail in the following sections showing that demanding scientific and technological goals can be reached with low-cost spacecraft.

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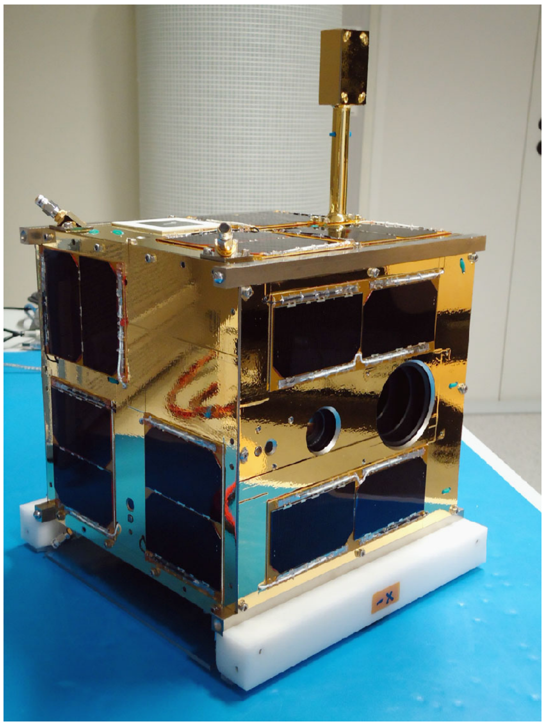

Fig. 1. Flight Model of TUGSAT-1

2. The BRITE mission

2.1 Mission objectives

BRITE stands for Bright Target Explorer and has the goal to observe the brightness variations of stars primarily brighter that magnitude 4 in two spectral ranges (blue and red) over periods of typically 100 days applying photometric measurements. Such observations are not possible from ground due to the turbulence of the Earth atmosphere. Pulsations are measured with a precision of 1 mmag to probe into the interiors and ages of these target stars [1]. Astronomers expect better understanding of the properties of the intrinsically bright stars and improving the theories [5].

Other important goals have been to develop a nanosatellite platform for future technological and scientific missions as well as giving young scientists and engineers hands-on training in the full range of a Space mission.

BRITE consists of a constellation of currently six nearly identical spacecraft, two from Austria, two from Poland and two from Canada. TUGSAT-1/BRITE-Austria was built at TU Graz, whereas UniBRITE was procured by the University of Vienna and built by the Spaceflight Lab of the University of Toronto. Each nanosatellite carries a small telescope with a precise CCD sensor for the photometric measurements. The spacecraft operate in pairs, one having a blue filter, whereas the sister satellite carries a red filter. There are no moving parts (apart from the momentum wheels), thus increasing the reliability of the spacecraft. Measuring in two spectral ranges provides spectral resolution in addition to time resolution.

2.2 The BRITE spacecraft

The BRITE satellite has a mass of 6.8 kg (hence qualifies as a nanosatellite) and a size of 20 × 20 × 20 cm (Fig. 1). The structure made of aluminium is composed of two trays carrying the electronics subsystems, the batteries and momentum wheels. In between these trays the payload bay is located in which the telescope and the fine-pointing star tracker (optically aligned with the telescope) are accommodated. The trays are held together by six panels which are covered with solar cells. The satellite has three nearly identical computers on board [1]:

- the housekeeping computer
- the instrument computer
- the attitude computer

The computers use ARM-7 RISC processors operating at a clock rate of 40 MHz, 256 kB of flash memory for code storage, 1 MB of EDAC-SRAM for storing the instrument data and 256 MB of flash memory for long-time storage of telemetry and instrument data.

The housekeeping computer is responsible for monitoring the health status of the spacecraft and collecting data on e.g. voltages, currents, temperatures and status of subsystems, providing telemetry to ground and accepting commands from the operators.

The instrument computer reads out the CCD sensor and delivers the photometric data to the housekeeping computer for intermediate storage and further download to the ground station. Full frame images, i.e. complete read-out of the 12 Mpixel CCD can be done for reference purposes. In normal operations 32 × 32 or 24 × 24 pixels around a target star in the field of view of 24 degrees are read out. 20 to 30 rasters are collected for one exposure which has a typical duration of one second. During one orbit the observation is carried out for 15 minutes. Figure 2 shows 15 rasters of target stars in the Orion constellation. Figure 3 depicts the full-frame image of Orion taken in December 2013 by TUGSAT-1. This raster photometry significantly reduces the data volume from more than 20 MB (one full-frame image) to 1.3 MB for one observation period of 15 minutes.

A fourth computer system takes care of power management. Due to the limited available power subsystems are turned off and on on demand. For instance, fine-pointing attitude control is only necessary during photometric observations. Hence the star tracker and the instrument will be activated only then. The transmitter on the other hand will only be active during passes over a ground station.

The telescope (Fig. 4) consists of a baffle to prevent stray light from entering, a five lens system, the optical filter (blue in case of TUGSAT-1) and the CCD sensor. In the first design a CMOS sensor was envisaged, but it would not meet the scientific requirements in terms of uniformity of sensitivity over the whole area of the chip. The lens system is deliberately slightly defocused such that a star is not represented by a single pixel but a spot of about 8 × 8 pixels.

A precise attitude determination and control system (ADCS) is key to the scientific quality and clearly imposes challenges for such a small spacecraft. The ADCS system consists of six coarse and fine sun sensors (one on each panel of the spacecraft) and a three-axis magnetometer as sensors for coarse attitude determination. For fine-pointing a commercial star tracker module is utilised. It is basically another small telescope taking images of the background stars. These images are matched with an internal star catalogue from which the attitude in all three axes is determined.

Two types of actuators are available: three miniaturised reaction wheels (Fig. 5) mounted in X, Y and Z axis and three magnetorquers. The magnetorquers are coils in each spacecraft axis interacting with the Earth magnetic field. The magnetorquers are used for detumbling of the satellite and for discharging the momentum wheels (when high levels of disturbing momentums have accumulated).

The attitude control system developed by UTIAS/SFL was specified to provide attitude accuracy down to the arcminute level required to ensure that the target stars are reproducibly positioned in the corresponding raster area on the CCD.

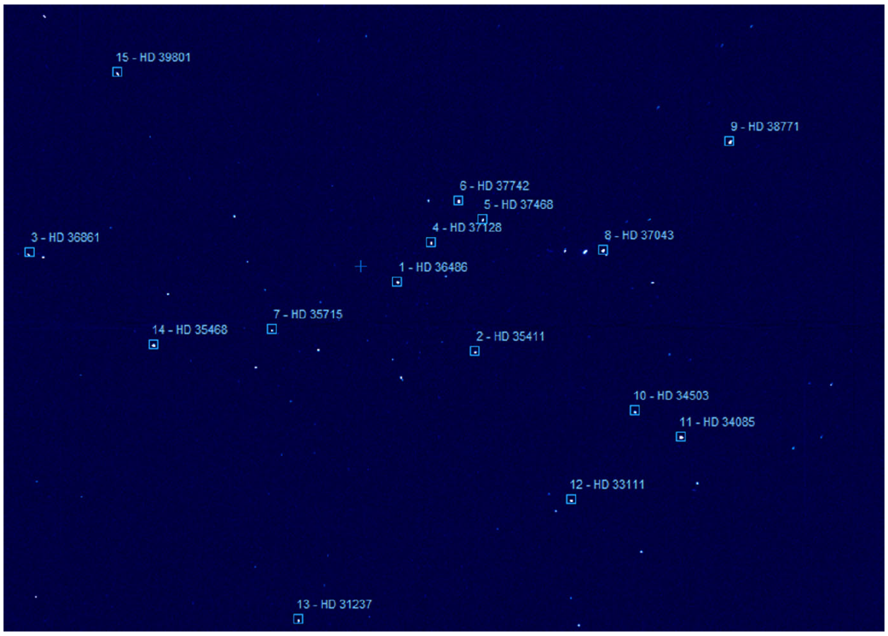

Fig. 2. Full-frame image of Orion, taken by TUGSAT-1. The *squares* around 15 target stars constitute the rasters which are read out from the CCD

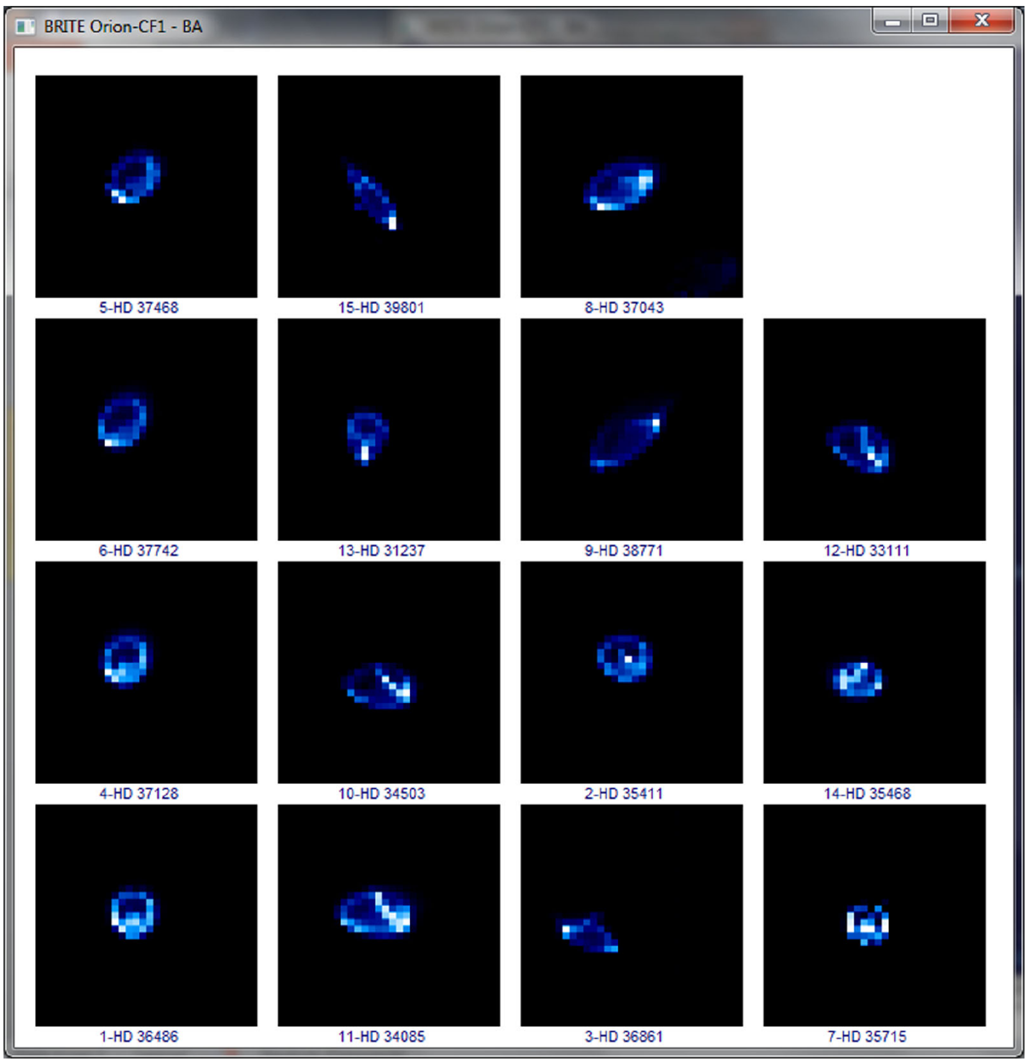

Fig. 3. 15 Rasters of target stars in the Orion field

The power subsystem utilises high-efficiency tripe-junction solar cells delivering 6 W of electrical power on average, 11 W peak. Two sets of Lithium batteries, a primary and a backup set, guarantee power during eclipses. Each battery has its own charge/discharge regulator.

The telemetry system is comprised of a UHF receiver operating in the 430–440 MHz band at a data rate of 9.6 kbit/s. The modulation scheme for the telecommand uplink is GMSK. Four pre-deployed monopole antennas are mounted on the satellite body ensuring that commands can be received in any attitude of the spacecraft.

The downlink is in the Science S-band and supported by a 0.5 W transmitter feeding two patch antennas on opposite faces of the spacecraft to provide near omni-directional characteristics. The data rate is variable from 32 to 256 kbit/s (although the capability of the transmitter is 1 Mbit/s). Scarcity of spectrum in this band limits the data rate to 256 kbit/s. The modulation scheme is QPSK with ½-rate convolutional coding/Viterbi decoding for forward-error correction. The protocol is a proprietary variant of the well-established AX.25 packet transmission standard. Modifications of the protocol are currently made to a broadcast/selective repeat mode to increase the

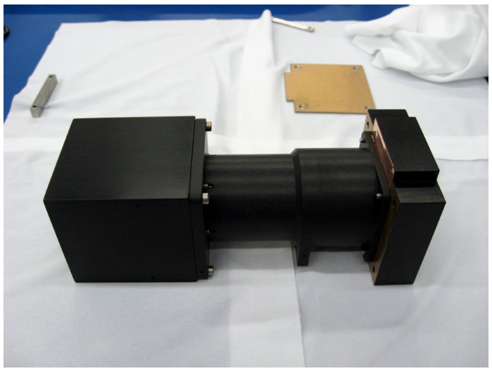

Fig. 4. BRITE telescope

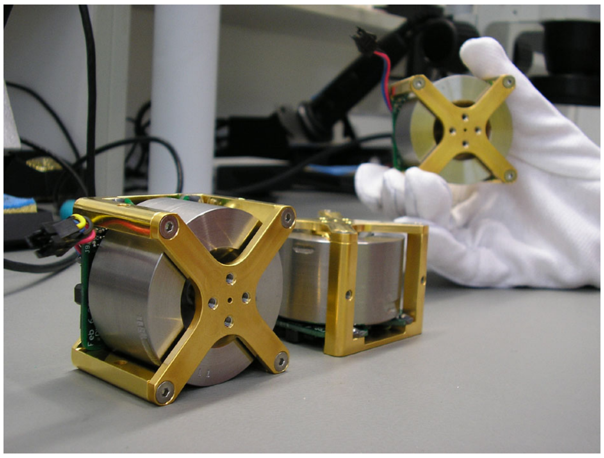

Fig. 5. Momentum wheels

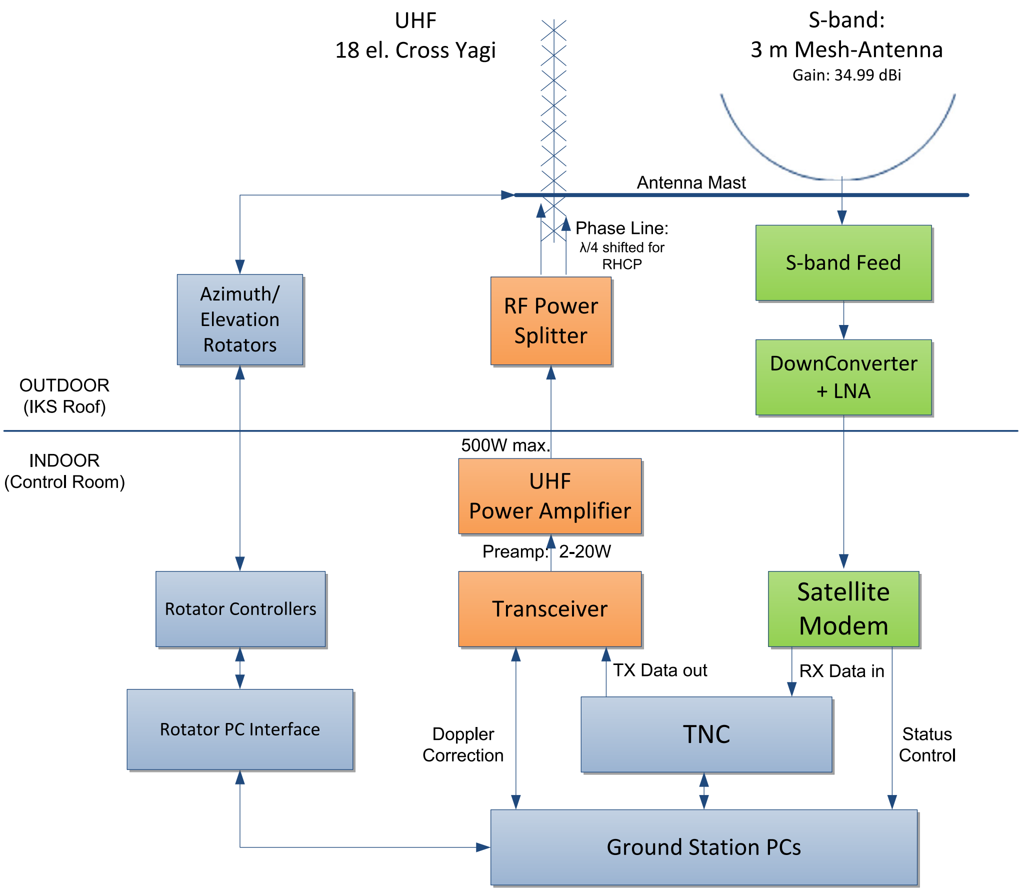

Fig. 6. Block diagram of the ground station

robustness in case of interference which is important as the uplink is in a secondary frequency assignment band.

Thermal control is essentially passive. The surface of the spacecraft is covered by reflecting thermal foils. Long-term measurement of the temperatures in the spacecraft show values of 20–35 °C. Active electric heating (if needed) is provided for the batteries and the CCD.

2.3 Ground station and mission control centre

In parallel to the development and testing of the satellite, a dedicated UHF/S-band ground station was established at the Institute of Communication Networks and Satellite Communications, funded by TU Graz. The block diagram is shown in Fig. 6. A two-axis pedestal holds a 3 m parabolic dish for S-band downlink and a group of two Yagi antennas for the UHF uplink (Fig. 8). A program-track system is used, whereby the antennas (Fig. 7) are pointed to the spacecraft by calculating the azimuth and elevation angles from the orbit equations and the Kepler elements of the spacecraft [3].

A low-noise amplifier directly behind the S-band feed, followed by an S-Band to VHF downconverter feed a standard satellite demodulator which incorporates the Doppler tracking algorithm. On the uplink side the terminal node controller (TNC) handling the communications protocol provides the GMSK- modulated signal. This signal is delivered to the transmitter, an amateur-radio UHF system. The high-power amplifier can provide up to 1 kW of RF power. The link budget can be seen in Table 1 significant link margin is provided.

The mission control centre provides console screens for the antenna tracking, the commands, the telemetry data and two more screens for orbital simulations using STK and video conferences with the partner institutions (Fig. 8).

Fig. 7. Antenna system

2.4 Spacecraft testing

Key to success of all Space missions is thorough testing. The main reason for failures of some university Cubesat missions has been that often it was considered sufficient to conduct only unit-level testing. Thorough system level testing, environmental and electromagnetic compatibility testing is mandatory. All subsystems of TUGSAT-1 were thermally shock tested and underwent thermal cycling. After unit level functional testing the spacecraft subsystems were first integrated on a so-called flatsat where easy accessibility is provided. Full system-level tests were performed, verifying performance of both hardware and software. Then the spacecraft was assembled in the clean room after the solar cells were attached to the six panels. The satellite was vibration tested according to the profile of the launcher (Polar Satellite Launch Vehicle) up to 7 g. A very important and time-consuming task was thermal vacuum testing where the satellite is exposed to representative environmental conditions. In the vacuum chamber the spacecraft was cooled down to −20 °C and heated up to 60 °C. Orbital simulation was performed as well. Then the spacecraft was tested in the EMC chamber verifying that there is no internal interference to the telemetry system. Finally, the satellite was put into a sealed plexiglass box and tested at the Lustbühel Observatory in the Open Field Test, where the communications with the ground station was verified. Furthermore, proper operations of the star tracker and the telescope was verified. Reference images of stars were taken and the point spread function measured which met the expectations.

2.5 Orbit

As it is the case for most small satellites, BRITE-Austria/TUGSAT-1 (together with UniBRITE) was launched as a secondary payload. The launch service contract was signed in 2009 with the Indian Space Research Organisation ISRO and her commercial branch ANTRIX. On 25 February 2013 the Polar Satellite Launch Service (PSLV) rocket took off from the Sriharikota Space Centre in Southern India (Fig. 9),

Table 1. Link budget

	Uplink (UHF)		Downlink (S-Band)	
EIRP	76.14	dBm	24	dBm
Free-space loss	154.16	dB	168.25	dB
Polarisation & atmospheric loss	2.00	dB	2	dB
Receive G/T	−30.97	dB/K	12.7	dB/K
C/No	87.61	dBHz	65.08	dBHz
Data rate	16.00	kbit/s	256	kbit/s
Eb/No	37.96	dB	10	dB
Eb/No required	12.00	dB	4.4	dB
Margin	**25.96**	**dB**	**5.6**	**dB**

Fig. 8. Mission control centre

Fig. 9. **Launch of PSLV-C20 on 25 February 2013 (courtesy ISRO)**

delivering the satellite into a sun-synchronous LEO dusk-dawn orbit of 791 km, resulting in an orbital period of 100.5 minutes. This orbit, determined by the primary payload, the Indian-French remote sensing satellite SARAL, is very good from a power point of view, since the satellite sees sunlight most of the time. Also the SSO orbit was analysed to be very good for the astronomical observations.

2.6 Commissioning and operations

Already three hours after launch contact with TUGSAT-1 could be established during the first pass over the Graz ground station. Telemetry showed excellent health status. After check-out of the on-board computer and the telemetry system, all other subsystems were thoroughly tested. After the verification of the attitude sensors and the actuators, the spacecraft was detumbled using the magnetorquers. The satellite was then brought into coarse pointing mode. On 23 March the first image of the star Delta Corvus was taken, showing that the point spread function and sensitivity meets the specification. Achieving fine-pointing was considerable effort due to the facts that the ADCS system in this configuration had never flown before and only limited tests could be performed on ground. The star tracker needed careful parametrisation. It was also found that it does not deliver stable quaternions while flying through the South Atlantic Anomaly, a region between Africa and South America, where the spacecraft is exposed to high radiation. By adaptation of mission planning this difficulty was solved. During summer 2013 the ADCS system was optimised and the instrument tested in detail. The performance of the attitude control system could be improved by optimising the parameters of the star tracker and mission planning (e.g. determining the required warm-up time of the star tracker prior to transition from coarse to fine pointing). Figure 10 shows the pointing accuracy. The transition from coarse to fine pointing is clearly visible. The pointing accuracy is below 1 arcsecond resulting in an average error of 1.5–1.6 pixels on the CCD (the specification stated 1.5–2 arcseconds and 2–3 pixel error). This pointing accuracy

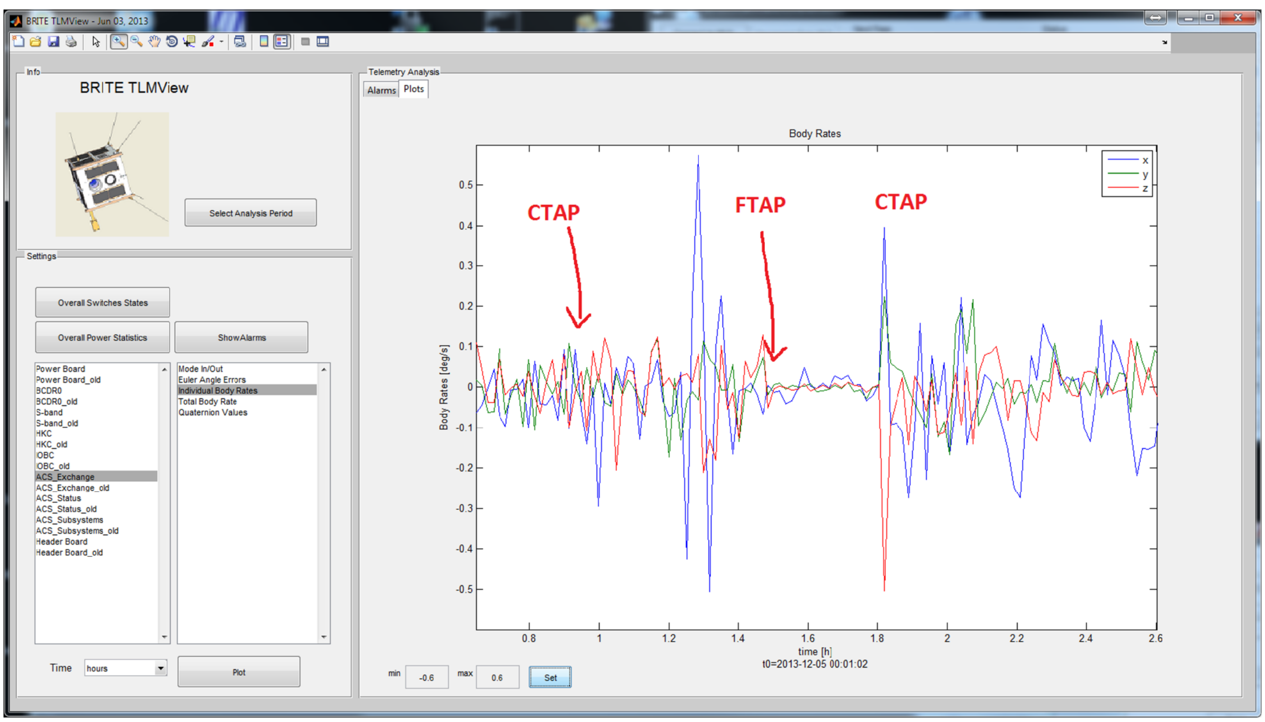

Fig. 10. **Pointing accuracy achieved by BRITE-Austria/TUGSAT-1**

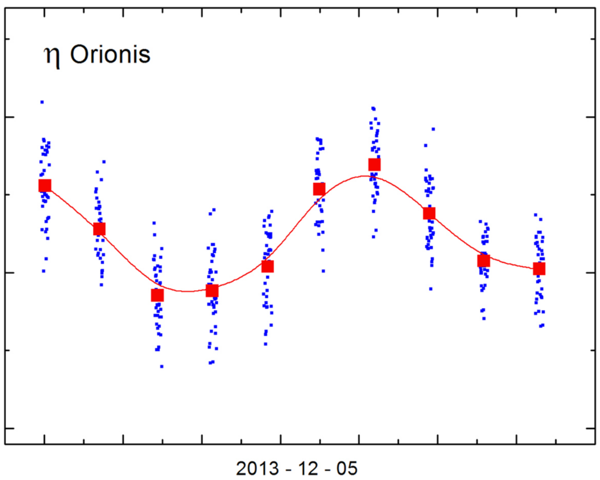

Fig. 11. Light curve for the target star Eta Orionis

exceeding the specification allowed to reduce the raster size from 32 × 32 pixels to 24 × 24 pixels leading to a reduced science data volume per target star. Hence more stars can be observed simultaneously.

Procedures for best data quality eliminating hot pixel effects on the CCD caused by radiation were elaborated by the science team [2, 5].

From November onwards regular science data collection commenced. The first star field was Orion which could be observed until mid March 2014. The BRITE Executive Science Team (BEST) which consists of the PIs of each satellite and astronomers from Austria, Poland and Canada decides on the target fields. The second target field which is currently observed is Centaurus. Up to 30 stars per field have been observed which is an increase of science data by a factor of 15 with respect to the original specification [4, 5].

Figure 11 depicts a light curve obtained from BRITE-Austria measurement data of the star Eta Orionis clearly shows brightness variations due to star pulsations.

The BRITE project shows that demanding science missions can be carried out by nanosatellites.

2.7 The OPS-SAT mission

While the common perception of Space missions is that the most up-to-date technology is used there, in reality the utilised hardware and software is quite old. The processors used for Space are several generations behind terrestrial versions. To give another example, the CCSDS and PUS (Packet Utilisation Standard) telemetry standards were specified three decades ago. The reason is risk aversion which is advantageous for reliability and safety, but not for innovation. On the other hand lots of innovative solutions and patents have been generated, e.g. by ESA, industry and academia, but they suffer that they have never got a chance to gain Space heritage. In order to break the cycle "has never flown- will never fly" the European Space Operations Centre ESOC launched an initiative for the definition of a Cubesat mission to demonstrate new operational concepts and to verify new technology in orbit [6]. A concurrent design facility (CDF) study was carried out by ESA showing the feasibility of the concept. In 2013 an open call for ideas was launched with more than 100 experiments being suggested, followed by an experimenters' day with an attendance of more than 150 participants. In July 2013 a Phase A/B1 study contract was awarded to a consortium led by the Institute of Communication Networks and Satellite Communications of TU Graz with MAGNA STEYR Engineering and the Zentrum für Telematik in Germany as subcontractors. A parallel study was awarded to a consortium under the leadership of GOMSPACE in Denmark.

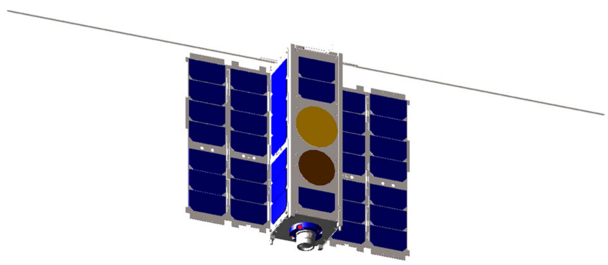

Fig. 12. OPS-SAT with deployed solar arrays

2.8 The OPS-SAT concept

OPS-SAT shall carry a powerful processor payload with sufficient on-board memory in order to carry out advanced software and hardware experiments [6, 8]. In order to support this, the 3U Cubesat having a size of 10 × 10 × 30 cm and a mass of about 6 kg will have to generate about 30 W of electrical power. This can be achieved by two deployable solar array panels (Fig. 12).

Key requirements of OPS-SAT are that at least one configuration must be representative of a standard ESA mission and that the spacecraft has to be inherently safe. Faulty software which experimenters may upload to the satellite cannot jeopardise the mission [7].

To achieve this, in the OPS-SAT design all potential single points of failures have been removed. The spacecraft will utilise a CCSDS-compatible telemetry system operating in S-band. This is relatively new for Cubesats which rely on amateur radio technology and UHF/VHF telemetry.

Figure 13 shows the block diagram of OPS-SAT. There are two sections, the satellite bus and the payload. The satellite bus consists of low-cost COTS subsystems developed for other CubeSat missions. A UHF/UHF telemetry provides a default telecommand and control facility in addition to the CCSDS-compatible S-band transceiver (which is situated in the payload section because it is new technology specifically designed for very small satellites by French industry under CNES funding).

The on-board computer which is planned to be delivered by GOMSPACE together with the UHF/UHF transceiver and the power subsystem has also the task to provide coarse attitude control by using magnetorquers, sun sensors and a magnetometer. The whole satellite bus will be resettable both via UHF and S-band.

Heart of the payload is a processor core using most recent Altera Cyclone V system-on-chip modules with two ARM-9 processors running at 800 MHz, 500 MB of EDAC memory. The module also contains a fairly large Field Programmable Array (FPGA). This makes a vast variety of experiments possible requiring hardware reconfigurability and high processing power.

Since these modules are not radiation hardened, four of these modules will be provided in cold redundancy. Currently radiation tests in the radiation chamber of ESTEC are being prepared. To reduce the risk of radiation damage shielding by 2–3 mm of aluminium will be provided.

To increase safety the consortium has elaborated an advanced FDIR (fault-detection, fault-isolation and recovery) concept. Another on-board double-redundant computer which gained flight heritage

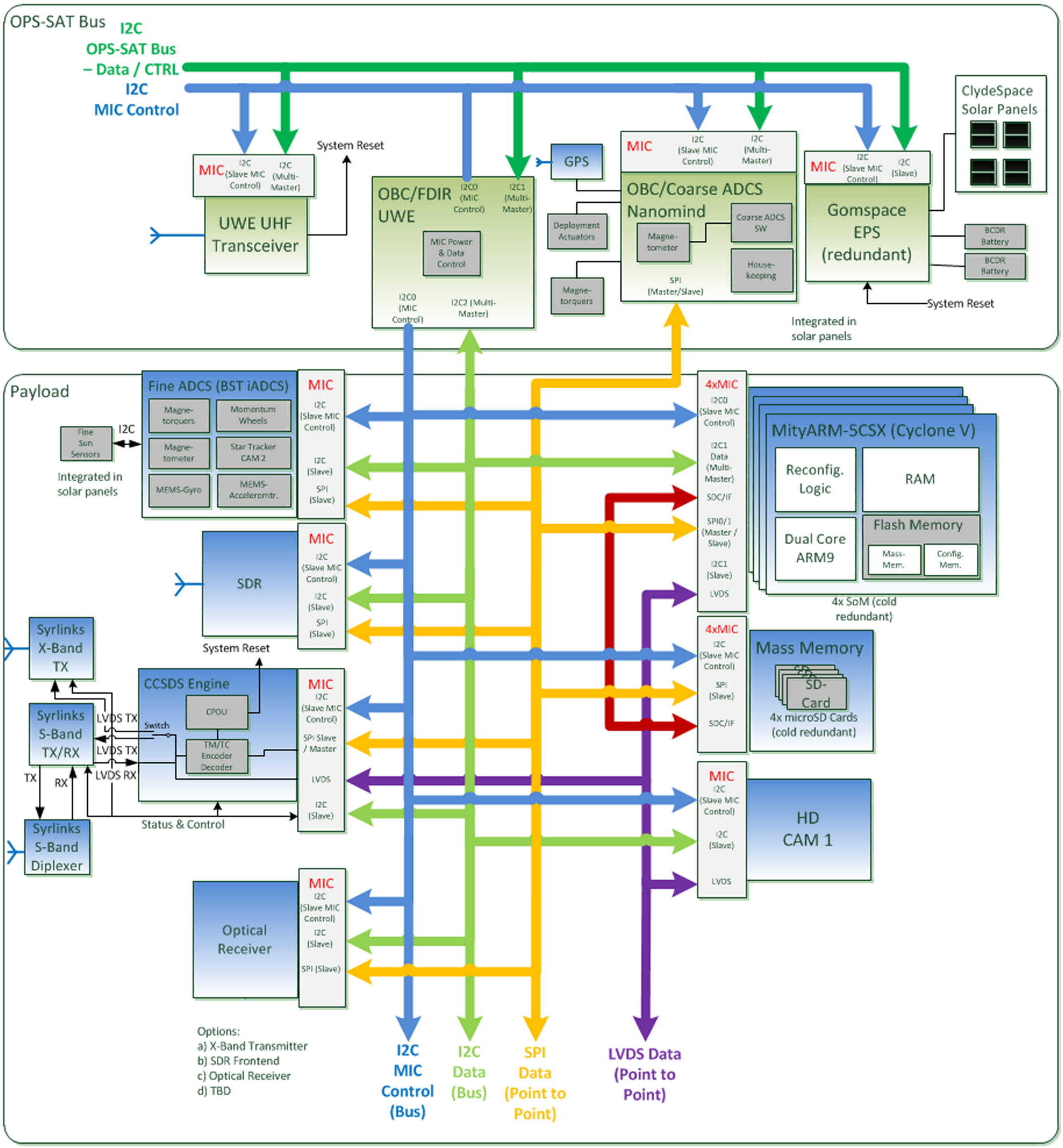

Fig. 13. OPS-SAT block diagram

in the recent UWE-3 mission by the University of Würzburg will control a switchable data and power bus, allowing to turn on and off every module of the bus and make the interconnection as required.

The S-band telemetry system consists of the miniaturised S-band transceiver which supports a data rate of 1 Mbit/s in downlink and 256 kbit/s in uplink. The compatibility with the CCSDS/PUS/SCOS protocol stack is provided by an IP core made available by ESA and integrated in a radiation-hard FPGA. Bypassing of the IP core will be possible allowing to implement new protocols different from the CCSDS standard.

The evaluation of the experiments revealed that there is a high demand for a "high-resolution" camera. Two candidates were selected: a small hyperspectral camera currently under development via an ESA contract and a conventional camera module.

The payload will contain a fine-pointing ADCS system provided by a German company which provides a star tracker and three reaction wheels. The pointing accuracy of this compact system will be below 1 degree. The sensors and actuators will be accessible by the experimenters for attitude control experiments.

In addition OPS-SAT will carry a GPS receiver which allows for precise orbit determination, a key requirement for optical experiments.

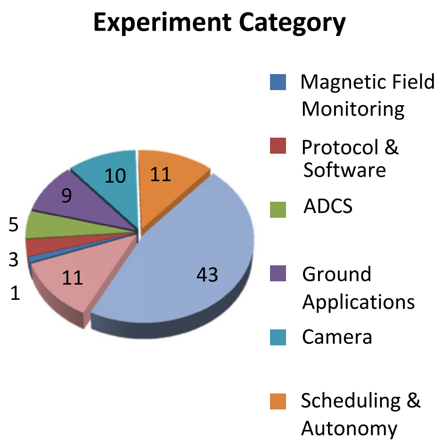

Fig. 14. Distribution of experiments

2.9 Payloads of opportunity

OPS-SAT will have several payloads of opportunity:

- an X-band transmitter with a data rate of up to 50 Mbit/s for high-speed download of data, including streaming video
- a software-defined radio (SDR) front-end for radio signal monitoring experiments
- a small optical receiver for optical uplink experiments using the Laser station at the Lustbühel Observatory
- retro-reflectors on the outer surface of the satellite to determine the exact position by Laser ranging and tracking

2.10 OPS-SAT experiments

The detailed evaluation of the submitted experiment proposals [7] showed that 91 % are feasible and implementable with different levels of effort. The majority falls in the category of on-board software experiments. The distribution can be seen in Fig. 14. The method of preparing and executing of an experiment is as follows: At ESOC there will be a flight-representative flatsat which can be accessed via the Internet by experimenters. To this flatsat the software can be uploaded and tested there. The default operating system is Linux; Java Virtual machine (JVM) is supported as well. When the functional testing of the software is completed, the software images will be transferred to a repository from where operators at ESOC will upload the software using the ESOC ground infrastructure. The primary ground station is NGS-1, a station dedicated to small satellite missions with VHF/UHF/S-band capability. In addition the ESTRACK network may be utilised. File-based operation is foreseen. After execution of the experiment on board, the results can be downloaded and will be stored in the repository at ESOC from where the experimenters can retrieve their respective data.

2.11 Programmatics

The Phase C/D of OPSAT is expected to start in Q3/Q4 of 2014 with a duration of 2 years. This means that the spacecraft can be launched in late 2016/ early 2017 into an orbit which will be chosen such that space-debris guidelines will be met. The operational lifetime of the satellite shall be one year with a possibility for extension. Thus, OPS-SAT will be a laboratory in the sky to test and demonstrate in orbit both new technologies and operational procedures which may be adopted later in big Space missions. It shall also serve the purpose to demonstrate that COTS components can be adopted for certain (shorter) Space missions.

3. Summary

Small satellites experience a high degree of attention. The number of Cubesats has risen exponentially in the last few years. According to studies there is a realistic demand of 1000–2000 Cubesats to be launched by 2020. Industry and Space Agencies are increasingly embracing this technology as it provides an excellent means for low-cost and fast access to Space (a typical Cubesat mission can be made launch ready in about 1.5 to 2 years). The costs range between 200 k€ to 2 M€ including piggy-back launch.

The BRITE mission which will soon consist of a constellation of six satellites constitutes the worlds' first nanosatellite constellation dedication to asteroseismology. At present, the BRITE nanosatellites and the Canadian MOST spacecraft are the only Space telescopes capable of observing bright stars (Hubble and Kepler are designed for faint objects and unsuitable for this task). With 1.5 years in orbit of the Austrian satellites the proof has been provided that nanosatellites can serve demanding science missions.

With the novel OPS-SAT concept a technological mission will be realised in due coarse which will allow to demonstrate in orbit software and hardware re-configurability with state-of-the art processing capability. This mission shall also validate new miniaturised hardware and provide evidence that COTS components can be reliably operated in a Space environment.

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