Modes and More

Finding the Right Attitude for TET-1

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TET-1 (a German abbreviation meaning technology experiment carrier) is a small German satellite bringing eleven technical experiments into space. It was built by Kayser-Threde (Munich) and Astro- und Feinwerktechnik Berlin, and will be operated by GSOC for at least one year. Its launch will be piggy-back with Kanopus-Vulkan 1, an Earth observation mini-satellite of the Russian Space Agency, on a Soyuz FG / Fregat rocket from Baikonur/Kazakhstan, which dependency caused a delay of more than a year. The new technologies to be verified cover a wide field – ranging from an infrared camera to e.g. a new type of GPS receiver or solar cells -- requiring a large number of operational modes and a variety of pointing requirements. TET-1 has no orbit control and the finally achieved injection dictates attitude operations to a large extent; several modes require a specific attitude to reach the desired accuracy. Another challenge to the attitude control system is the high degree of autonomy required. TET-1 is monitored in two consecutive orbits every twelve hours, but uplink capability is limited to only once per day.

I. Introduction

The first Section gives a short overview of the TET-1 mission, the ground station concept, and on-board mechanisms. Design and operational concept of the AOCS system are described in the second Section. This also gives a short overview of the FDIR concept (fault detection, isolation, and recovery) and surveillance. A description of the several experiments is given in Section three. In Section four the requirements of the payloads on the AOCS and the resulting impacts on the mission will be discussed. Conclusions and suggestions for improvements on the follow-on missions TET-2 and BIROS will be presented in the final Section.

A. The TET-1 mission

The primary goal is to offer a platform for the verification of eleven experiments (10 German, one Dutch) in low Earth orbit. Payload comprises among others a new kind of solar cells, new batteries and a new GPS receiver type. The orbit will be Sun-synchronous with a height of 543 km and a resulting period of 95 minutes. The TET-1 bus is based upon the one used for BIRD (Brieß *et al*., 2000), which has already been verified in orbit. Some minor changes were made that however do not affect the qualification status (see Fig. 1). The bus is standard with solar panels for power generation and an attitude control system.

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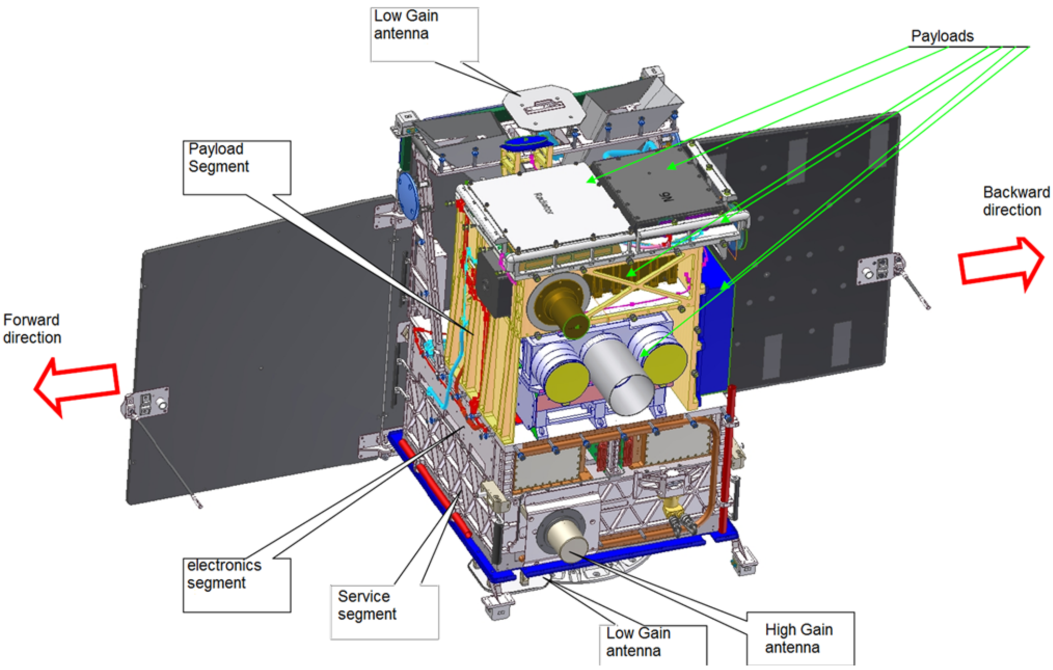

Figure 1. TET-1 design. *View of the TET-1 satellite. Shown are the different segments of the spacecraft (S/C), the arrangement of several payloads and antennae as well as the flight direction. Solar arrays are seen from back. They will be pointed towards the Sun most of the time during operations.*

The attitude and orbit control system (AOCS) itself is very specific, since it has to meet several requirements that are coming from the different experiments. For example, TET-1 has no standard operational mode but uses a distinct mode for each experiment.

B. Ground stations

During routine operations the ground station used for downlink will be Neustrelitz (NSG), Germany. It is planned to have four downlinks per day. Launch date for the Kanopus-Vulkan 1 and therefore also the TET-1 mission is June 7th, 2012. Resulting from this TET-1 will fly at a Sun-synchronous noon orbit. Like a polar orbit, the satellite travels from the north to the south poles as the Earth turns below it. In a Sun-synchronous orbit (SSO), though, the satellite passes over the same part of the Earth at roughly the same local time each day. This can make communication and various forms of data collection very convenient. The specified orbit gives an average total contact time over NSG of 43.5 minutes per day. This value sets the limit for downlink of payload and housekeeping data, whereas satellite operations are limited by the uplink time.

Weilheim (WHM) will be the ground station used for uplink during the routine phase. This is because NSG is not fully equipped yet with S-Band transmitters. Only one uplink contact per day is foreseen and hence payload operations have to be uploaded at least 24 hours in advance. Kayser-Threde already planned all experiments for the first year of mission and delivered a file containing these scenarios (so called "calculation sheet"). The file also contains the exact timing of the different activities planned during the mission. It will be loaded into the mission planning tool (PINTA[5]) used for the TET-1 mission, and a new file containing the necessary procedures (e.g. for mode changes or power switches) will be created. This so called sequence of events will be created about one week in advance, and once per day all time tagged[6] telecommands (TCs) for the upcoming 24 hours will be uploaded.

[5] PINTA = Program for INteractive Timeline Analysis
[6] Time Tagged: TCs will be stored on-board and executed at the time, which was given in the TC

As a consequence of this ground station concept the satellite and especially the AOCS have to be robust against failures and anomalies in order to ensure the safety of the spacecraft and guarantee reliable execution of the experiments.

C. On-board automatisms

The on-board software has to guarantee safe spacecraft operation (surveillance, thermal, and charge control) and the autonomous execution of experiments in order to fulfill the mission goals. The major risk for the spacecraft is to have an attitude where the solar panels are not irradiated by the Sun (it is allowed to fly without Sun but not for too long) and cannot generate enough power to guarantee safe satellite and required payload operations. To ensure that this does not occur, several autonomous safety mechanisms are implemented in the SBC (satellite bus controller) and AOCS software. One of these mechanisms is that some certain dangerous states are defined (e.g. battery voltage too low, temperature too high). The S/C goes to a satellite safe mode and executes a so called "safe list" if any of these cases is identified. This "safe list" contains several commands, which are executed autonomously on-board to recover from any problems, and ensure a safe satellite status.

For execution of the experiments the satellite also has a large degree of autonomy. If there are no conflicts with ground commanding or dangerous situations, mission goals are pursued automatically. With the information in the "calculation sheet", which is converted into executable commands by PINTA and uploaded regularly, the satellite is able to work and execute all payload experiments almost completely autonomously. However it is still possible to intervene from ground once per day, or to make any fine tuning in the sequence.

Another automatic task of the TET-1 satellite is downlink of telemetry. All housekeeping telemetry data from several applications such as the AOCS and the measurements by the SBC (currents, temperatures etc.) are written to a memory. During a flyover saved data are downlinked to the ground station, started by a time tagged command. The TC system can store up to 1000 time tagged TCs and therewith guarantees satellite operations up to one week without ground commanding. For LEOP (Launch and early operation phase) the satellite has a second predefined TC list on board ("LEOP list"), which will be executed autonomously.

II. AOCS

A. Design

The AOCS has to meet several requirements in order to fulfill the pursued mission goals. There are constraints on attitude and rotation rates, but also on sensor and actuator configuration. The AOCS design has to be such that all such conditions are met. Some general confinements are:

- Three axis stabilization and attitude control
- Single failure tolerance on component layer
- Autonomous failure detection
- Attitude determination: < 0.5 arcmin
- Control accuracy: < 5 arcmin
- Pointing jitter: < 2 arcmin/s
- Position determination: < 150m

The design of the TET-1 attitude control system is robust and single failure tolerant. It consists of different sensors for determination of the attitude and the rotation rate of the spacecraft (CSS[7], GPS, IMU[8], MAG[9], and ASC[10]). Four reaction wheels and a magnetic coil system (MCS) are used to achieve the required attitude. One characteristic of TET-1 is that it has no kind of orbit control system. Therefore, no orbit changes and also no collision avoidance are possible during the mission. The arrangement of the several components can be seen in Fig. 2.

This image still shows the GPS antennae mounted on the top of the satellite. Due to design constraints the GPS antennae were moved to the sides and are now installed in +x (forward) and –x (backward) direction, although a mounting on the top would lead to a better coverage due to a pointing direction into deep space most of the time. For

[7] CSS = Coarse Sun sensor
[8] IMU = Inertial measurement unit
[9] MAG = Magnetometer
[10] ASC = Advanced Stellar Compass (Jørgensen *et al.*, 1999), type of star trackers used for TET-1

this reason it can happen that GPS spacecraft are not visible in Sun Pointing Fixed Mode because they are obscured by the Earth, which results in a switch to the other GPS antenna. The solar panels shadow less than 10% of the semi-sphere covered by each antenna. GPS is not used in Auto Acquisition Mode and Safe Mode (will be described in Table 1) as there will not be any payload operations and therefore no necessity of position determination with high accuracy.

B. Modes

As already mentioned several attitude constraints are provided by the different experiments. Therefore, it was necessary to implement different operational modes. But of course some other factors do also have an impact on the AOCS design:

- For uplink/downlink it is necessary to direct the high gain antenna towards the Earth.
- The solar panels are pointed towards the Sun as much as possible in order to minimize the use of the batteries. All modes without full Sun irradiation are limited to 91 minutes by default which will be sufficient for routine operations. This value was chosen by the software engineers and can be changed via telecommand if necessary for any reason (e.g. if it is planned to do target or Earth pointing for several consecutive orbits).
- In order to keep the thermal equilibrium the radiator (-y direction) has to be pointed away from the Sun (during routine in -z direction).

In contrast to many other satellite missions TET-1 does not have one nominal attitude, which is used for routine operations. Instead TET-1 has eight different modes where six are used for routine operations and payload experiments (Table 1):

Mode	Used sensors	Used actuators	Pointing accuracy	Pointing	Experiments executed in this mode
SPM	Same sensors that were used in the former mode	-	N/A	N/A	Pico propulsion
AAM	CSS, IMU, MFS, ONS	RW, MCS	10°	Coarse pointing of solar panels to the Sun	-
SPFM	CSS, IMU, MFS, ONS, ASC, GPS	RW, MCS	24"	$-z_{sat}$ pointed towards the Sun	Li-Polymer battery All solar cell experiments
SPRM	CSS, IMU, MFS, ONS, ASC, GPS	RW, MCS	24"	$-z_{sat}$ pointed towards the Sun, rotation around Sun vector	GPS antennae
EPM	CSS, IMU, MFS, ONS, ASC, GPS	RW, MCS	24"	z_{sat} Nadir, y_{sat} perpendicular to orbital plane	GPS antennae IR camera
IPM	CSS, IMU, MFS, ONS, ASC, GPS	RW, MCS	24"	Free eligible pointing	IR camera in second year of mission
TPM	CSS, IMU, MFS, ONS, ASC, GPS	RW, MCS	24"	z_{sat} pointed to an arbitrary target on earth	IR camera KERAMIS
SFM	CSS, IMU, MFS, ONS, ASC	RW, MCS	10°	Coarse pointing of solar panels to the Sun	-

Table 1. AOCS modes of TET-1. *List of modes implemented in the AOCS. For each mode the used sensors and actuators are listed. Pointing direction and accuracy can be seen as well as the experiments performed in each mode (will be explained in Table 3). Operational modes are Suspend Mode (SPM), Sun Pointing Fixed Mode (SPFM), Sun Pointing Rotate Mode (SPRM), Earth Pointing Mode (EPM) and Target Pointing mode (TPM). During the second year of mission Inertial Pointing Mode (IPM) will be used for special operations. Safe Mode (SFM) and Auto Acquisition mode (AAM) will only be used in case of problems.*

Depending on the mode the satellite has either 1-axis (AAM, SFM) or 3-axis stabilization (IPM, TPM, EPM, SPFM, SPRM). The maximum rotation rate of the satellite is 0.5°/s by default with an acceleration of 0.1°/s² (can be changed by TC if necessary). This leads to a duration of 365 seconds for a 180° slew.

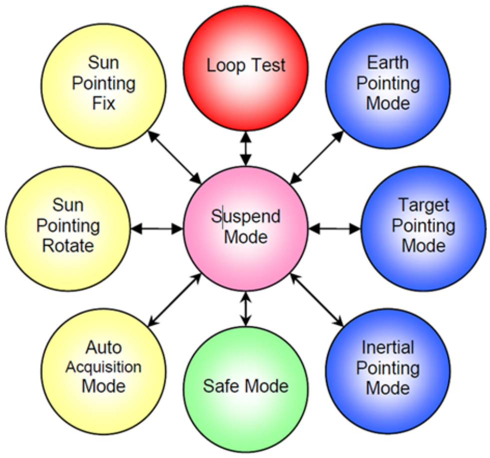

Figure 3. AOCS modes overview. *Shown are the several AOCS modes and which transitions are possible. On the left-hand side are the modes with Sun pointing, on the right-hand side modes with a specific pointing away from the Sun. It can be seen that every transition from one mode to another will take place via Suspend mode. Loop test mode will not be used during routine operations but only for testing.*

If a mode change from A to B is commanded, first of all the mode change deadline will be monitored. This is the maximum time it may take to enter the new commanded mode. Thus it will be prevented that the AOCS is in an undefined state in case of a failed mode transition. Then the S/C will enter SPM using the current configuration of sensors and actuators, but not doing any kind of active attitude control. The next step is a check on all conditions that have to be fulfilled for entering the commanded mode. If this check is successful, the S/C will change its mode from A to B via SPM. In all other cases a transition into AOCS safe mode will ensue.

AOCS Mode	Mode change Deadline		Maximum dwell time	
	[cycle]	[min]	[cycle]	[min]
SPM	6	0.05	3600	30
SPFM	600	5	0	Unlimited
SPRM	600	5	0	Unlimited
EPM	600	5	11000	91
TPM	600	5	11000	91
IPM	600	5	11000	91
AAM	600	5	0	Unlimited
SFM	600	5	0	Unlimited

Table 2. Deadline and maximum dwelling time for AOCS modes. *This table shows the deadlines for the mode changes. Columns two and three show the deadline for transitions (one cycle is 500ms). Last two columns list the maximum dwelling time in a specific mode. An autonomous transition into SFM will follow if either of these limits is violated. Due to power constraints the satellite is not allowed to stay in some specific modes (modes without Sun pointing) for more than about one orbit. For SPM the maximum dwell time is only 1800 seconds because there is no kind of active attitude control and therefore a high risk of a bad attitude, high rotation rates and power loss. If the S/C is not commanded to another mode before the stay deadline is reached, it ends up in AAM. Deadlines can be changed by telecommand if necessary.*

C. EPC module

The AOCS contains the modules “estimator”, “predictor”, and “controller” (see Fig. 4), which in co-operation allow the S/C to have the correct attitude. The estimator takes the data of the sensors (MFS, CSS, ASC and IMU), ONS (On-board navigation system), and from the predictor for calculation of the current attitude. The accuracy will be ≤10" when both cameras can be used. It decreases to ~24" if only one camera is available.

The predictor calculates the future attitude and rotation rates without any control activity based upon the estimator input. The controller then computes size and direction of a kinetic and magnetic torque so as to achieve the desired attitude. This torque then is commanded to the RWs and MCS.

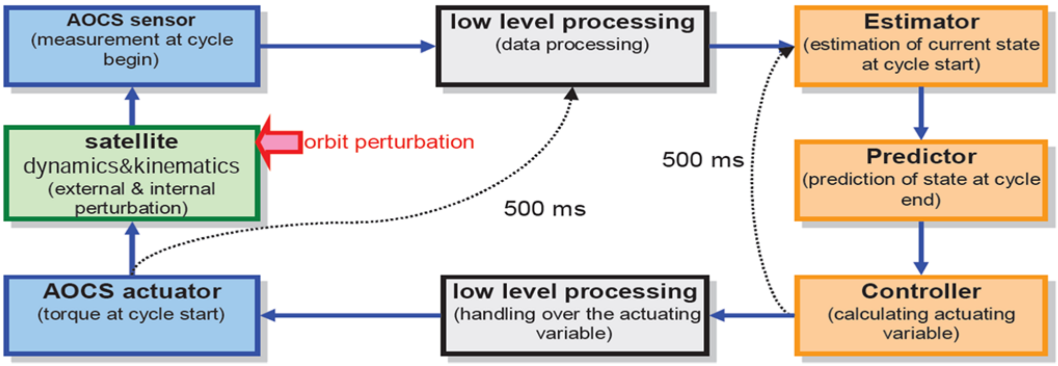

Figure 4. AOCS control loop. *Sensor measurements are processed and delivered to the estimator. With this information the next task predicts a state at the end of the next cycle. The controller determines how the actuators have to be commanded.*

D. Surveillance and FDIR concept

The complete attitude control task is distributed to several applications that are working autonomously. There are several threads running that generate information which is sent to the on-board monitoring system. The thread will be restarted and a log message will be generated if the surveillance does not receive any thread information.

AOCS supervision consists of two steps. It is checked in a first step, if a periodic thread was active within the last cycle. The execution sequence of threads with data exchange will be verified in a second step. In case that one of these conditions was not fulfilled, this is an indication for an error in the AOCS and the information will be written into a log file.

The monitor also has an interface to the satellite bus for reporting events and disturbances within the attitude control system. Based on the health status of the AOCS the satellite bus eventually triggers a safe mode or a reboot. This can happen, for example, if the surveillance task no longer sends a “Keep Alive” message. Thereby the system software recognizes that the AOCS application has stopped working.

Some studies and analyses (e.g. by Robertson *et al*., 2003) showed that for missions with spacecraft mass smaller than 800 kg almost one third of all reported anomalies were within the AOCS. An even scarier fact is that almost 40% of catastrophic failures (total loss of mission) are caused by hardware or software units inside the AOCS. Therefore, it is important to have a robust and fault tolerant design. This is achieved by redundancy of hardware components and by a system to handle these redundancies. Also the AOCS has a robust control loop to react on perturbations or component anomalies. Additionally there exists autonomous monitoring of the timings of all AOCS threads and processes that is performed by a surveillance module.

The highest priority within the AOCS is to guarantee an attitude where the solar panels are directed towards the Sun at any time (except for experiments with specific pointing requirements), especially when a safe mode or other problems occur. The S/C will be commanded to AAM automatically in such cases to ensure that the solar panels are orientated towards the Sun.

There are different layers for failure detection which ranges from low level checks in single sensors and actuators via checks within the EPC layer up to monitoring of received TCs and surveillance of the S/W threads.

The configuration management, which handles isolation and recovery actions, supervises a range of information such as satellite setup, sensor/actuator use and health status, and also the configuration of the EPC. The “use” flag indicates, whether a unit is in the control loop[11] or not, and the “health” status flag signalizes any anomaly detected in the components. AOCS is able to deal with any configuration and thus is very insensitive against failures.

Fault detection already starts on unit level by verifying checksums or correct timing, and is continued on higher level (system level checks are performed by the EPC) by various detection methods such as:

- Matching of measured with predicted state values
- Comparing deviations with tolerance limits
- Cross check of state values

These algorithms are repeated every control cycle (500ms) and anomalies are marked through the health flags within the configuration management system. Due to the redundancies it is possible to keep the most important state values valid even in cases of data gaps or sensor failures. Even a complete loss of some sensors (GPS, CSS and MFS) can be compensated because some variables can also be computed on board by the use of mathematical models.

The AOCS surveillance module monitors both progression of high level threads and defined preconditions for each attitude mode.

III. Experiments

A. Payload operations

TET-1 is carrying eleven experiments which are mostly located on the payload segment. Their arrangement is shown in Fig. 5. The NVS (German abbreviation for payload supply system) is the link between the satellite bus and the several carrying capacities. It provides power, data, and thermal management to the experiments. Additionally it manages payload operations and delivers experimental data to the satellite bus for downlink. Each of the experiments has different requirements to the spacecraft and the AOCS which have to be met. A short overview of the different experiments and their needs is given in Table 3. Another important factor, which has to be taken into account for payload operations, is the power budget. The bus allocates a permanent electrical power of 20W for the payload system when the battery is fully charged.

Orbit and power constraints mean that the scenario to operate the several payload units has to be planned carefully, which can be done by checking the operational parameters and requirements such as:

- Desired attitude of the satellite, e.g. nadir- or Sun-pointing
- Operating time of the payload
- Mean and maximum power used
- Power allocated by the satellite bus (dependent upon solar radiation on solar panels)
- Produced heat
- Data amount to be processed

This information was used by Kayser-Threde to define three different scenarios for payload operation over one year of mission:

- Scenario 1: the several payloads are sequentially operated with a fixed pattern (7 days duration). The complete pattern is repeated each week. This is the standard scenario for the mission
- Scenario 2: twelve times per year dedicated experiments will be carried out for a four day interval
- Scenario 3: three times per year the spacecraft will be pointed towards a target on earth. During an interval of two days specific experiments will be executed while flying over the target.

Experimental data will be extracted, processed and forwarded to the users by the payload data center in Neustrelitz.

[11] When in the control loop, the sensor information is used for attitude determination. For actuators this means that they are used for attitude control.

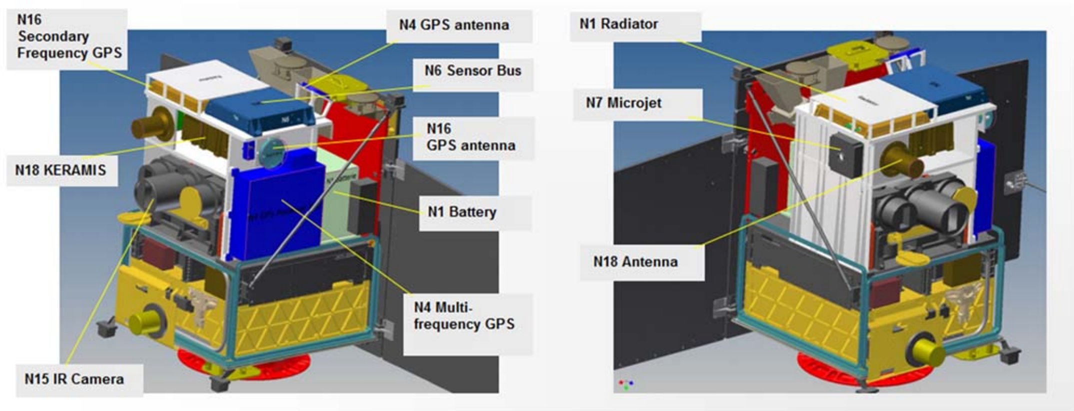

Figure 5. Payload arrangement. *View of the payload segment and location of different experiments. The image on the left-hand side still shows one experiment which was eliminated during the mission preparation (N4 – Multi frequency GPS).5 of the 11 experiments can be seen. The three black cylinders on the back side of the satellite are the baffles of the IR camera (N15). The sensor bus (N6) and the GPS experiment (N16) are mounted on top of the spacecraft. On the side the GPS antenna (N16) and the Li-Polymer battery (N1) are visible. The KERAMIS payload (N18) is mounted above the IR camera. On the right-hand side the radiator of the battery (N1) on top of the GPS payload, the KERAMIS antenna, and the Microjet propulsion system (N7) can be seen. Not visible in this picture are the three solar cell experiments (N2, N8, N9), which are located on the front side, the HW BOSS (N17) and the mass memory (N19). A short description of the experiments will be given in Table 3.*

B. AOCS – GPS – NVS Interface

Detailed attitude determination within the NVS during execution of experiments (e.g. with the IR camera) is necessary for the SBC to provide position and attitude data twice per second. The AOCS communicates with the payload system via the NVS interface by periodically sending data. Therefore the payload supply system always knows the state of the AOCS, as well as the position and attitude of the satellite. The NVS creates a telemetry packet by writing the data within the SBC telecommand into the telemetry packet. AOCS data is saved in the NVS mass memory, the size of one source packet containing data is 78 bytes. It is possible to switch on and off the automatic save of AOCS data to the mass memory by TC and it is off by default after a system startup. GPS data is also sent to the NVS by the SBC, and the NVS generates a TM packet similar to the attitude data. The size of the GPS data packet is 54 bytes and its automatic save can be switched on and off similar to the AOCS telemetry. NVS synchronizes time with the Satellite bus controller once per second and the SBC itself is synchronized to GPS time. The NVS forwards time information to the three N15 cameras automatically. If no pulse per second signal is sent by the SBC, the payload supply system propagates time with its internal accuracy.

IV. Interplay AOCS - Experiments

A detailed description for only three of the experiments is given in this paper, because a full discussion of all would be too long and extensive.

The three selected experiments are the Li-Polymer battery (N1), the pico propulsion system (N7) and the infrared camera (N15). These examples were chosen because their requirements on the AOCS are diverse and most stringent.

A. N1 Li-Polymer battery

The battery will be charged or discharged and parameters such as charge current, voltage, and temperature will be recorded. Charging is of course only possible during Sun phases. The battery will heat up once Sun is back on the panels after eclipses (will last maximum 34 minutes), or after a Target Pointing mode (TPM[12]), and after 20 minutes the charge process will start. Discharging will always be done during eclipses, but heat-up (necessary, because it is possible to have some time interval between charge and discharge) will already start about 20 minutes before eclipse. This is because discharging takes 30 minutes and therefore needs almost the whole eclipse phase.

The measurements of the magnetic field sensors (especially those of MFS2) are disturbed by this experiment. This is because some dipole moment will be generated within the payload during charging or discharging. Battery operations have a very high load on the spacecraft's power system. Therefore, SPFM is prescribed where the star cameras provide the attitude measurements. This means the disturbance effects on the MFS have no impact on attitude determination.

The magnetic field sensors are also used for calculating the torque that is commanded to the MCS for wheel de-saturation. The magnetic coil system is taken out of the control loop during this experiment in order to avoid erroneous commands for wheel de-saturation, because the magnetic field vector, determined by the MFS, is fudged during charge or discharge processes of the battery.

B. N7 Pico propulsion system

The pico propulsion system is based on the Resisto-jet actuation principle (Othman *et al*., 2009). It contains a propellant system from which the working fluid is led to an evaporation chamber via a propulsion feed system. The fluid is heated up in this chamber, whereon it evaporates and expands through a nozzle. The system has two kinds of working characteristics, "pulsed" and "quasi-continuous". Pulse sequences are regulated by temperature. Some algorithms within the payload decide autonomously, if there is enough energy for pulsing, or if one has to wait for the system to heat up. Therefore the behavior is sometimes quasi-continuous.

These pulses create a small torque on the satellite, whose impact on the AOCS can be determined by using the star tracker's attitude information. The prescribed mode for experiments with the pico propulsion system is SPM. All AOCS sensors are active (when powered) and data is collected by the AOCS. However, actuators will not be commanded even if they are switched on. Reaction wheel speed should be around zero because no disturbance torque is desired during the measurement. The run down will take about 20 minutes (based on separation requirements). Furthermore, there is no de-saturation by the magnetic coil system during operation of the pico propulsion system. Another constraint for operating the propellant system is that both ASCs must be able to measure with highest accuracy in order to detect the resulting attitude changes, which are very small (~31 mrad for a one minute pulse). This means interferences by Sun or Moon and shadowing by the Earth are not allowed during this time. The propellant mass is 490g and the thrust is less than 5mN. Resulting acceleration will be $\sim 0.001°/s^2$ which leads to a maximum rotation rate of 0.6°/s at the end of a 10 minute "pulse". This rate can be compensated within a few minutes after enabling actuator commanding again. A 10 min pulsed thrust will lead to an attitude change of the order of 180°. Therefore it is recommended to switch back to SPFM as soon as N7 operations are finished to get the solar panels irradiated by the Sun again.

The battery should be fully charged, which means the experiment should start during Sun phase. The satellite should be in Earth pointing mode (EPM) flying backwards[13], and recording of high rate AOCS data within the NVS has to be activated before SPM is commanded and the experiment is started. During the experiment there will normally not be ground station contact but to check satellite performance after the experiment it is recommended to have downlink within an orbit.

C. N15 Infrared camera

Experiment N15 is a system consisting of three camera modules to analyze high temperature events on Earth, e.g. forest fires or volcanic activity. The cameras are similar to the one mounted on BIRD, but provide more spectral information at visible wavelengths. The payload consists of two IR cameras (near infrared) and one optical camera. They can be operated separately, but are mounted on a conjunct optical bench, which optimally supports mutual alignment. This is necessary in order to reach the mission goals for this experiment. The cameras are connected to

[12] In TPM the spacecraft can be pointed to any target and hence there might be no Sun on the panels
[13] This is necessary in order to get the optimum performance for the propulsion system

each other to make synchronization of imaging possible. Wavelength of the optical module is from 400 to 750 nm, MWIR (Medium wavelength infrared) operates at 3.4 to 4.2 µm, and LWIR (Long wavelength infrared) at 8.5 to 9.3 µm. Processing will be done directly within the NVS by the software N15.1. This is possible because the NVS also gets attitude information from the AOCS. Dependent on the scenery that has to be observed and on the duration of the measurement, the mass memory for data storage has to be reconfigured.

The payload requires an almost Sun synchronous orbit with an altitude of 550 km (+/- 20 km) with an equator crossing around noon. Large deviations from this SSO reduce the amount of interesting objects, a higher altitude would change the ground resolution, and therewith reduce data quality in comparison to BIRD. 3-axis stabilization with nadir pointing is necessary for imaging. It will be possible to rotate the satellite by +/- 30 degree to enlarge the possible observation area. If some rotation maneuvers in order to change the pointing of the IR camera are planned, it has to be taken into account that 30 degree rotations around the roll axis are only allowed in +roll direction due to S/W constraints. The accuracy of images depends on:

- Knowledge of attitude and orientation during imaging
- Accuracy of parameters describing camera orientation
- ASC alignment with respect to the satellite body
- Alignment of the optical sensors with respect to the satellite body

Requirements on the AOCS are dependent on the orbital height as an absolute accuracy of the coordinates of one ground pixel shall be 100m. Further requirements at 570 km altitude:

- Attitude knowledge: 24 arcsec (17 arcsec at 820km[14])
- Pointing accuracy: 6 arcmin (4 arcmin at 820km)
- Stability: 1,7 arcmin/s (1,2 arcmin/s at 820km)
- Drift rate: 0,4 arcsec/s (0,28 arcsec/s at 820km)

V. Conclusions

AOCS on TET-1 has to meet many requirements to guarantee a safe and successful mission. This is achieved by implementing a high degree of autonomy within the attitude control system and a well devised redundancy concept. The experiments flying on TET-1 are another challenge to the AOCS. Several AOCS modes were implemented to ensure successful execution of the experiments, because each of the payloads has different constraints for operations. AOCS shows a variety of operational modes and configurations although TET-1 is just a small satellite mission. The experiments have widely varying requirements, which can all be met without endangering the mission. The spacecraft has some specific characteristics such as the mounting of the GPS antennae or missing orbit control. The latter was not required for this mission and the former is assimilated by the AOCS.

It would be advantageous for upcoming missions such as TET-2 or BIROS to have some kind of propulsion system, because sometimes it can be helpful or even necessary to have the possibility of orbit control. Avoiding collisions will become more important in the future because the amount of space debris is increasing rapidly. The design of the spacecraft should be such that GPS antennae are on “top” of the satellite to avoid shadowing by the Earth or the solar panels. It is also recommended for further experimental carrier missions to not strictly separate the satellite bus and the payload segment. Especially for camera experiments (see N15, Section IV) it would be beneficial to mount the cameras used for experiments on the same optical bench as the star trackers used for operations. This would reduce the path for information and support mutual alignment perfectly. Thus an optimum pointing accuracy could be reached for imaging. It is also proposed to have a more extended on-board FDIR concept to make it easier to investigate unit failures and spacecraft problems.

[14] It was not yet clear which launcher would eventually be used, when the IR camera was designed. Therefore specifications for an orbital height of 820 km were made also.

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