

Attitude Control on TET-1

Experiences of the First Year of Operations

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The micro-satellite TET-1 carries several technology experiments. It is the first in a series offering the possibility of in-orbit verification of new equipment made in Germany by the industrial and scientific aerospace community. TET-1 was launched 22nd July 2012 and is operated by the German Space Operations Center.

Attitude and attitude control is influenced by several of the experiments. Special attitude control modes are required for a number of experiments in order to point the satellite in a prescribed direction or to a specific location on Earth. These comprise an experiment with three infra-red cameras, a pico thruster and finally a new type S-band transponder. The Li Polymer battery was not expected to have any effect on attitude control. However, it was discovered that charging and discharging the battery disturbs the magnetic field sensors, thus a different approach to attitude control is required when it is in use. Implementation of and special demands on the attitude control system for these experiments will be presented.

The mission is experimental with high demands on the attitude control system. The envisaged duration was one year only with a possible prolongation of a further year. Components were therefore not chosen for longevity. However, the actual amount of disruptions due to sensor and/or actuator outages and due to idiosyncrasies in the spacecrafts thermal budget was higher than expected. The ensuing challenges for the attitude control system will be discussed.

A software upload in May 2013 mitigated several of the issues addressed above. The improvements in the software and autonomous on-board reactions will be presented in the final Section together with some recommendations for the follow-on missions TET-2 and BIROS.

I. Introduction

THE first Section gives a short overview of the TET-1 mission, the payload experiments which were performed in the first year, and their impact on attitude control. The German Technology Experiment Carrier TET-1 was successfully launched on 22nd July 2012 and marks the first mission within the OOV (on-orbit verification) program. The eleven payloads on board were tested in a space environment over a one-year period until 31st October 2013. The mission now continues under the name “Firebird” primarily making IR images of the Earth.

A. The TET-1 mission

The primary goal of the mission is to offer a platform for the verification of eleven experiments (ten German and one Dutch) in low Earth orbit. The payload comprises among others a new kind of solar cells, new batteries and a new GPS receiver type. The orbit is Sun-synchronous with a height of 523 km and a resulting orbital period of 96 minutes. The bus is based upon the one used for BIRD³, which has already been verified in orbit.

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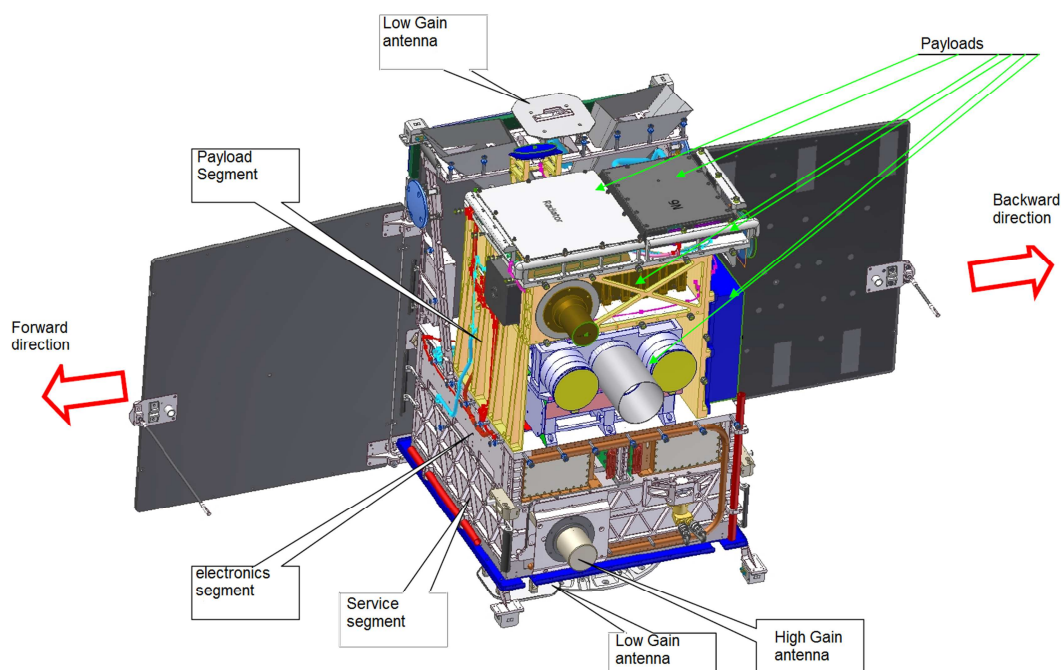


Figure 1. TET-1 design. View of the TET-1 satellite. Shown are the different segments of the spacecraft, the arrangement of payloads and antennae, as well as the flight direction. The solar arrays are seen from the back.

The attitude control system (ACS) itself is very specific because 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 attitude mode for each experiment.

The preferred ACS mode during the first year of operations was Sun Pointing Fix Mode (SPFM)^a. The Sun Pointing Rotate Mode (SPRM)^b had to be used due to thermal issues for a longer test period. The Earth pointing mode (EPM)^c must be commanded for ground station contacts when the high gain antenna is required. EPM is not necessary if downlink with low-rate is enough.

B. Attitude information

Because TET-1 has no orbit control, the determination and control of the attitude came into main focus. There are five types of sensors with high redundancy on-board for attitude determination on TET-1:

- Star Trackers (with 2 Camera Head Units (CHU))
- Inertial Measurement Units (IMU)
- Coarse Sun Sensors (CSS)
- Magnetic Field Sensors (MFS)
- Global Positioning System (GPS) receivers

The following actuators are available for attitude control:

- four Reaction Wheels (RW)
- Magnetic Coil System (MCS)^d

The Star Trackers can determine the attitude most accurately. An accuracy of 1 arcmin can be achieved with one camera, 30 arcsec if both cameras deliver valid data. The aberration correction derived from the GPS data improves these values by up to 29 arcsec. The attitude can also be estimated from the last valid measurement and the rotation

^a x_{sat} -axis points in flight direction, $-z_{sat}$ towards the Sun

^b $-z_{sat}$ points towards the Sun, rotation around the Sun vector

^c Nadir Pointing mode: z_{sat} pointing towards Nadir, y_{sat} -axis perpendicular to orbital plane

^d The MCS was originally foreseen for wheel desaturation only. The S/W update (see chapter III-D) made the MCS available as actuator for attitude control during ACS Safe Mode.

rate derived from IMU, if both cameras deliver invalid, or no data. This is only done for <200 min because the drift of the IMU is 1 °/h⁷.

The attitude can still be determined if only data from CSS and/or MFS are available for attitude determination. The Sun and magnetic field vector are determined by the On-board Navigation system (ONS) model and compared with the measured values. The model has a variance of 0.3° and a maximum error of 0.8°⁷ compared to measured values.

C. Payload

All experiments and their requirements on the ACS are summarily described in Table 1. Figure 2 shows the location of the experiments in the spacecraft. A more detailed description of three interesting experiments has already been presented in Ref. 2. Nevertheless, some influence ACS routine and contingency operations. These are the Li-Polymer battery (N1), the pico propulsion system (N7), the infrared camera (N15) and KERAMIS (N18). These examples were chosen because their requirements and operational impacts on the ACS are diverse and most stringent.

| Payload Name | Description | Requirements on the ACS |
|--|--|---|
| N1: Li-Polymer Battery | Charge and discharge cycles to investigate behavior | <ul style="list-style-type: none"> - Measurements must be in Sun pointing fix mode (SPFM) - No magnetorquer commanding |
| N2: Flexible thin layer solar cells | Measure performance | <ul style="list-style-type: none"> - Sun pointing |
| N6: Sensor bus system and current drain | Verification of application capability of a sensor bus system. The current drain works as a variable electrical load for the experimental solar cells (N2, N8 and N9). | <ul style="list-style-type: none"> - None |
| N7: Pico propulsion system | New kind of propellant system | <ul style="list-style-type: none"> - No active attitude control during experiments in order to measure effects on ACS (Suspend mode) |
| N8: Next generation solar cells | Improve calibrations against specific atmospheric conditions and derive solar cell degradation due to UV and particle radiation | <ul style="list-style-type: none"> - Sun pointing |
| N9: Next generation solar cells (by ASTRIUM) | Test performance, solar cells are integrated in the solar generator and deliver power to the bus when running | <ul style="list-style-type: none"> - Measurements must be in Sun pointing fix mode (SPFM) |
| N15: IR camera | Set of three cameras to detect high temperature events like forest fires | <ul style="list-style-type: none"> - Earth or target pointing mode (EPM/TPM) |
| N16: Secondary frequency GPS | Precise orbit determination and Earth limb sounding measurements | <ul style="list-style-type: none"> - Forward or backward flight direction - Earth pointing mode (EPM) |
| N17: HW BOSS | New kind of H/W Operating system | <ul style="list-style-type: none"> - none |
| N18: KERAMIS | Three experiments to test new satellite to ground | <ul style="list-style-type: none"> - Target pointing mode (TPM) |

| | | |
|---|--|--------|
| | communication modules (receiver, transmitter) | |
| N19: Memory orbit radiation Experiment | Investigate impact of radiation on memory units | - none |

Table 1. List of experiments. A short description of the purpose of each experiment is given in column two, the requirements for ACS in column three.

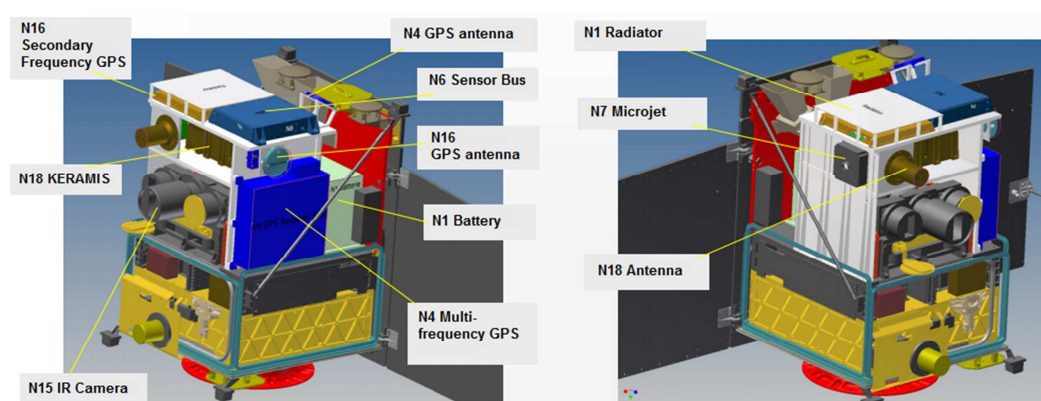


Figure 2. Payload arrangement. View of the payload segment and the location of different experiments. The image on the left-hand side still shows one experiment which was eliminated during the mission preparation (N4 – Multi frequency GPS). The three black cylinders on the back side of the satellite 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 is given in Table 1.

II. Observations of interactions between ACS and experiments

A. N1 Li-Polymer battery

The battery was charged or discharged and parameters such as charge current, voltage and temperature were recorded. Charging is of course only possible during phases with sunlight.

The measurements of the magnetometer (especially those of MFS2) are disturbed by this experiment. This is because a dipole moment is generated within the payload during charging or discharging. Battery operations have a high load on the spacecrafts power system. Therefore, the Sun-pointing mode SPFM is prescribed. In this mode the star cameras provide the attitude measurements, so the disturbances on the MFS have no impact on the attitude determination. During LEOP it was tested whether effects measured on ground can be measured in space. The effect of the magnetic dipole generated by the payload battery on MFS1 can be seen in Figure 3, the effect on MFS2 in Figure 4.

The analysis shows that MFS1 is not noticeably affected. A small jump is seen when charging starts and stops. A different behavior is observed for MFS2, which is mounted closer to the payload battery. The induced moment disturbs the measurements of the magnetic field of the Earth during the entire period of battery operations. An autonomous switch from the measured data to the model of the magnetic field is made after about five minutes⁶. The magnetic field vector, determined by the MFS, is fudged during battery charge or discharge processes. Nevertheless the ACS is still compliant with the requirements⁸.

⁶ The ACS usually uses the model based magnetic field vector instead of the vector derived from the measured data for attitude control. The latter is only used for safety checks. If the vectors differ more than 5°, the algorithm will allocate the error to the model and will deactivate the use of the model. The magnetic field vector derived from the data of the magnetometers will be used.

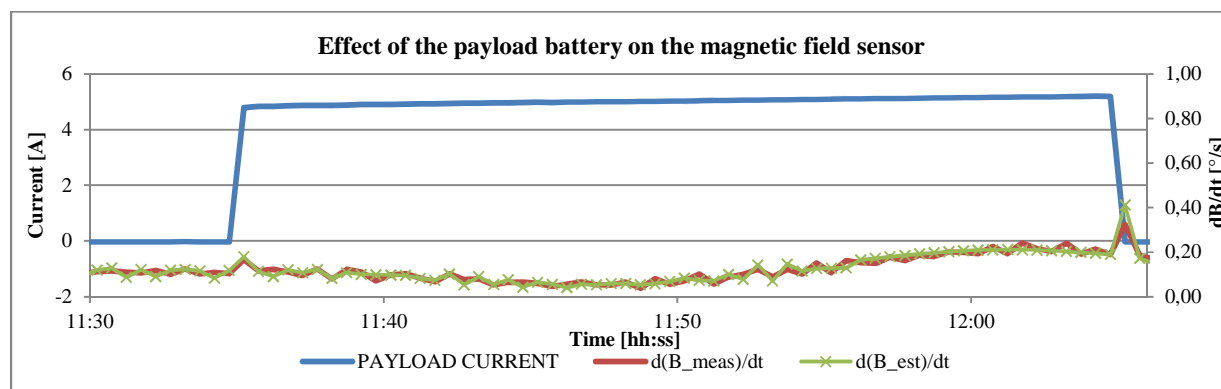


Figure 3. Effect of payload battery on magnetometer 1 (DoY207, 2012). The charge current (blue line, axis on the left-hand side) of the payload battery indicates the N1 switch-on and switch-off. The time derivatives of the measured magnetic field vector and of the estimated magnetic field vector are displayed in red and green (axis on the right-hand side). The latter is calculated by the estimator module and is used by the ACS software.

The magnetic field vector is also used as input for reaction wheels desaturation using the magnetorquers. The MCS is taken out of the control loop during this experiment in order to avoid erroneous commanding.

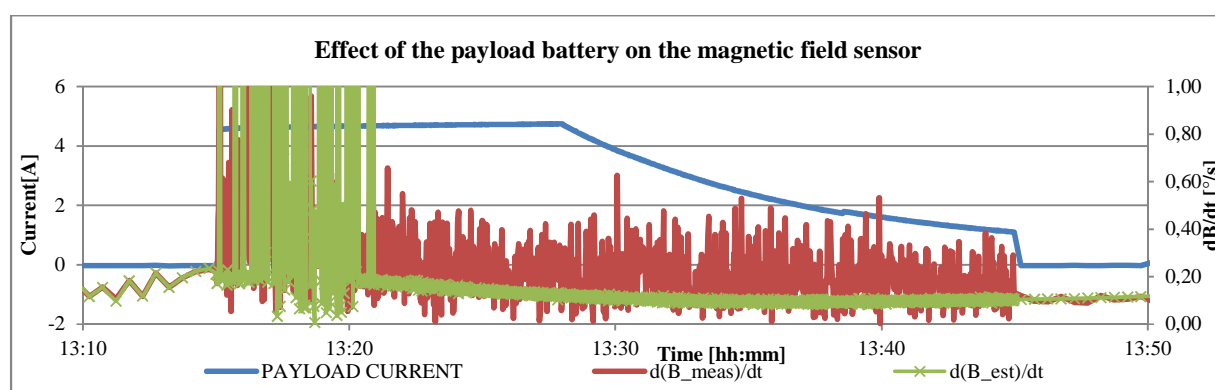


Figure 4. Effect of payload battery on magnetometer 2 (DoY208, 2012). The charge current (blue line, axis on the left-hand side) of the payload battery indicates the N1 switch-on and switch-off. The time derivatives of the measured and estimated magnetic field vectors are shown as red and green lines, respectively (scale on the right-hand side).

B. N7 Pico propulsion system

The pico propulsion system is based upon the Resisto-jet actuation principle⁴. It contains a propellant system from which the working fluid is led into an evaporation chamber via a propulsion feed system. It is heated there, evaporates and then escapes through a nozzle when this is opened.

The torque from a 1 sec. pulse is ≤ 50 Nm. Measurements with the star cameras are used to determine the effect on the attitude. The Suspend Mode is needed for experiments with the pico propulsion system. All ACS sensors are used but no actuators will be commanded.

There were two operational scenarios: one in which the pico thrusters were switched on for about two minutes only in order to perform a health check and a second where the thruster were also allowed to fire. It is not possible to command the start of the pulsing by command, because this is governed by temperature.

Scenario two was tested 13 times. Pico propulsion was activated either for 14 or 22 minutes. In order to meet the requirements no torques are commanded to the reaction wheels and wheel desaturation is also disabled ascertaining that only the pico thrusters influence the attitude. The accumulated thrust duration was approximately 4 minutes in the 14 min. and 12 minutes in the 22 min. experiment. A maximum of 0.725 rpm rotation rate around the S/C z-axis was observed in the first experiment, which is caused by a mean acceleration of $0.018 \text{ }^\circ/\text{s}^2$ and an attitude change of

123.56° (again around the z-axis of the S/C) (see Figure 5). At the end of the 22 min. experiment TET was accelerated to a mean rotation rate of 1.6 rpm around the z-axis of the S/C.

The pico thruster can thus easily control the attitude of a 100 to 150 kg⁹ satellite.

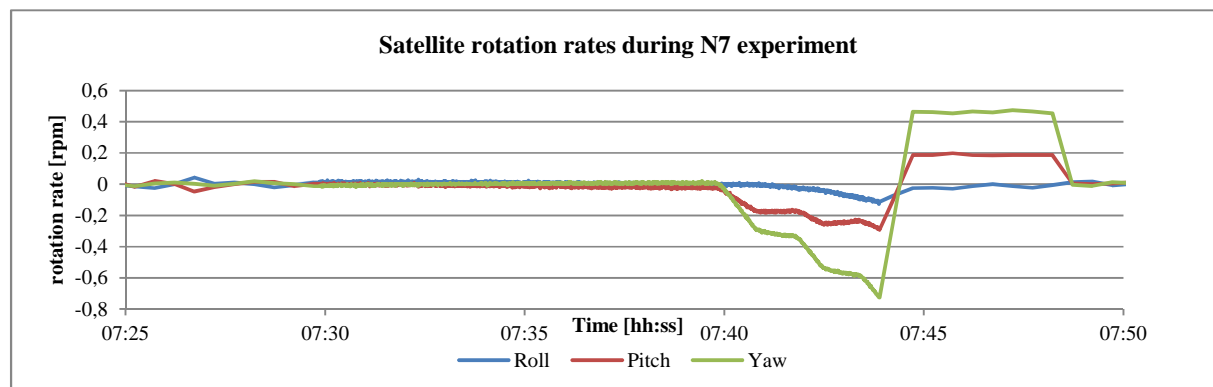


Figure 5. N7 experiment on DoY172, 2013. The experiment started at 07:29. TET-1 was commanded into SPM. Around 07:40 N7 was heated up enough to start autonomous pulsing. After 4 minutes N7 was switched off and TET was commanded to nominal attitude mode SPFM. It needed around 5 minutes to slew back and to compensate this deviation.

C. N15 Infrared camera

This experiment comprises three cameras to detect high temperature events on the Earth, e.g. forest fires or volcanic activity. There are two IR cameras (near infrared) and one optical camera. Processing is done directly within the NVS (German abbreviation for payload supply system). This is possible because the NVS also gets attitude information from the ACS. It might be necessary to reconfigure the mass memory for data storage depending on the scenery that has to be observed.

The experiment was designed to match the TET orbit. Deviations from this Sun-synchronous orbit (SSO) reduce the amount of interesting objects; a higher altitude changes the ground resolution and therewith reduces data quality in comparison to BIRD^f. 3-axis stabilization with nadir pointing is necessary for imaging. It is possible to rotate the satellite by +/- 30 degree to enlarge the area observed.

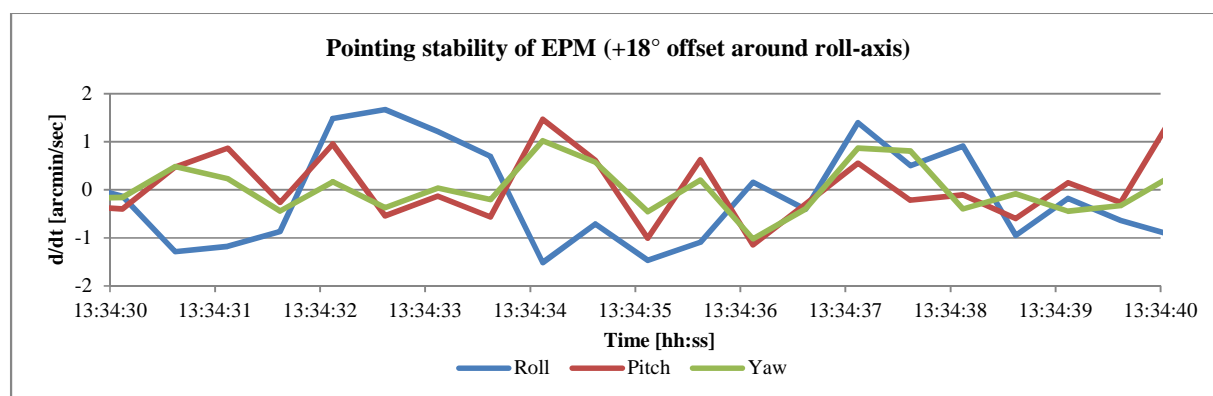


Figure 6. Stability of the spacecraft during Nadir Pointing. One example of a N15 data take: the rate errors in EPM is shown. Once TET-1 reaches nadir pointing the stability remains below 1.7 arcmin/s during the 10 s of the data take.

This experiment is essential for the upcoming scientific DLR Earth observation mission “FireBird” in which TET-1 and BIROS (launch planned 2015) will form the space segment. The attitude stability of the commanded pointing

^f Satellite launched in 2001³

during an N15 data take is displayed in Figure 6. The pointing meets the required stability¹⁰. Thus the Firebird mission can be supported without any restrictions.

D. N18 KERAMIS

KERAMIS comprises three experiments probing new techniques and modules for data transmission in the Ka-band. Among others, high-frequency modules for transmission and reception in the Ka-band have been qualified for use in space. An S-band transponder was used for a bi-directional transmission of measurement data.

The experiment serves as a transponder providing up and down-link. Target pointing Mode (TPM) was needed for the transmission. A constant signal from the ground station in Weilheim (WHM) was transmitted to the satellite. Some TET-1 contacts over WHM were used for this experiment and normal up-and down-link had to be suspended during this experiment. No real time monitoring was possible.

III. Challenges for ACS

A. Data from reaction wheels flagged unhealthy

On TET-1 four RW 90-2 “smart” wheels of the German manufacturer Astro-Feinwerktechnik Adlershof GmbH are used. They are mounted in a triangular pyramid configuration.

Several issues with the reaction wheels were a major point of concern to ACS during the first year. The communication between the ACS software thread and the RWs was interrupted several times because wheels were flagged “unhealthy”. The first response was a power cycle by switching the relay of the corresponding wheel off and on again. No particular wheel could be identified as the root cause of the problem because each of the four wheels was delivering invalid data for roughly the same amount of time.

Detailed analysis identified two possible causes for the unhealthy data. The smart wheels are designed such that a reset occurs autonomously if an inconsistency is recognized. In this case an internal counter increments by one step for each occurrence. Data will be flagged unhealthy if the counter exceeds 20. It was not possible to reproduce this behavior and the large amount of reboots on ground, so the most likely explanation is an effect of the radiation in space, although no correlation with space weather was found.

It is possible to restart the wheels not only by a power cycle (relay switching) but also by performing a soft reboot. The latter would have solved the contingency described above and would have been better for the operational lifetime than the actually commanded power cycles. It also was decided to reset the error counter weekly.

The second cause could be a freeze of the RW’s core processing unit (CPU). Again this behavior had not been observed in pre-launch tests and it was tried unsuccessfully to reproduce it. It is most likely caused by radiation as well, although no direct correlation with tests and space weather could be found. A soft reset does not solve the problem and only a power-cycle brings back the wheel into control loop.

The two different failure cases cannot be distinguished in the telemetry. Thus a power cycle was commanded in all fourteen cases that occurred so far.

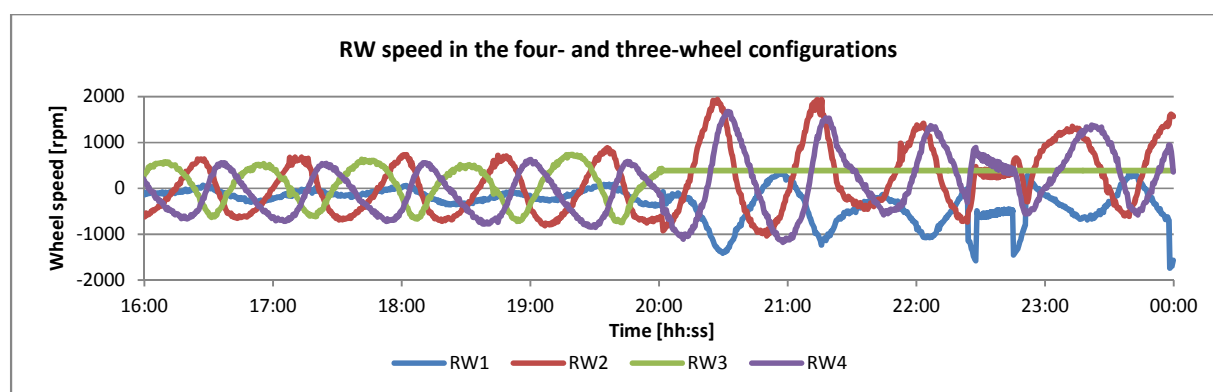


Figure 7. Wheel speed in the four- and three-wheel configurations. RW3 was isolated around 20:00, commanded torque dropped to zero and its speed remained constant (green line). Attitude control was taken over by RW1, RW2 and RW4 in a three-wheel configuration leading to higher load and higher amplitude in the wheel speeds.

B. IMU outages

The IMU stopped delivering valid data for more than five hours six times during the past year. Both IMU-1 and IMU-2 had three outages each. Two times a drop to Safe Mode followed because of low battery power due to the ensuing attitude deviations. The problem could always be mitigated by commanding a power cycle (of the hardware).

An IMU outage has severe consequences on the attitude control. There are two IMUs on-board, but they are operated in cold redundancy. This means that a switch or a restart has to be commanded unless the data flow resumes by itself. Until then the ACS will use a rotation rate derived from (in sequence of preference and/or accuracy)

1. the star trackers,
2. Sun sensor and magnetometer data combined,
3. the magnetic field measurements,
4. Sun sensor data.

The rates as determined from the star tracker quaternions are just as accurate as the ones derived from the IMU. In this case TET-1 fulfills the OOV requirements without any constraint. A combination of data from Sun and magnetometer is the second best solution. The accuracy, however, is so much lower that experiments such as N15 are influenced negatively. In eclipse only the rotation rate derived from the magnetic field measurements is available. The time derivative of all three components of the magnetic field vector can be determined. However, the accuracy of each of the three axes is very different due to the orientation of the satellite with respect to the magnetic field. As a consequence the attitude errors can increase from 30° during phases with sunlight to 180° in eclipse (see Figure 8).

The IMU outages could have two possible causes:

1. A freeze of the IMU
2. A link problem between IMU and ACS

Tests and analyses did not provide any exhaustive explanation for the outages.

Introducing an additional FDIR (Fault Detection, Isolation and Recovery) mechanism reduced the consequences and operational effort necessary after an IMU outage. It simply switches the relay autonomously off and on again when communication between ACS and IMU is interrupted (see chapter III-D).

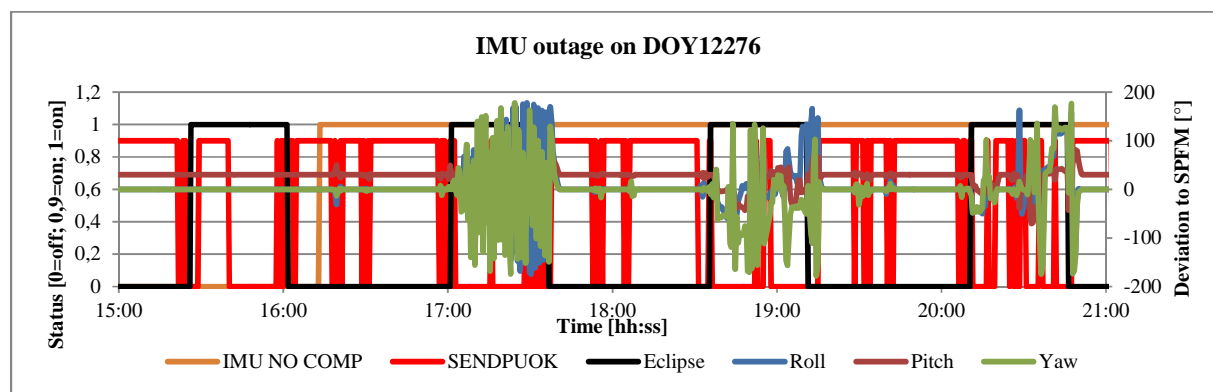


Figure 8. Attitude deviations during one of the outages of IMU-1. Attitude[§] deviations increased from 5° to 180° due to the outage. In this case the rates were determined from Sun sensor and magnetometer data. The noise is seen to increase by a factor of 100 during eclipses where only magnetometer data can be used. In this instance there was no information from the star trackers due to blinding and too high rotation rates of the satellite.

C. Loss of one RW

The increased operational load due to outages of reaction wheels and/or IMUs resulted in the loss of RW1 on the 222nd day of the mission. Since then TET-1 is flying with a three-wheel configuration.

[§] Commanded attitude mode in this instance was SPFM with a bias of 30° in pitch.

An IMU outage occurred at a moment that the satellite was in Sun Pointing Rotate Mode (SPRM)^h. One hour and ten minutes later all four RWs were isolated by the ACS. The RWs were rebooted all at once by the nominal procedure (power cycle) five times. However, at each next contact they were again not used by the ACS. Recovery was only achieved by rebooting the reaction wheels 2, 3 and 4. This strongly suggests that the root cause of the problem lies with RW1. Following analysis showed that it was irretrievably lost.

The high attitude deviations due to the IMU outage caused not only high loads on the actuators but also temperatures increasing up to 95 °C on the reaction wheel bus. There are thermal cutoffsⁱ embedded into the wheels. Because the temperature of the whole system heated up, the threshold of the fuse of RW1 decreased that much, that the amount of current flow needed to operate the wheel triggered the fuse. This led to a collapse of the communication interface of the whole wheel bus and an outage of all four wheels.

Lowering the temperature of RW1 would have increased the threshold of the fuse again. But the high temperatures were not visible^j in the TM available to the operations team.

In this critical phase an EEPROM read error occurred in the internal processor of RW1. It continued working with firmware default values. It continued using these obsolete values for the field orientation after it was taken back into the ACS loop which results in a very high idle current. This led to increasing temperatures of the motor and caused damage to the isolation of the winding. The consequence was a short circuit in the winding, which is irreversible. Thus reaction wheel 1 is definitely lost.

D. Mitigation measures

A software upgrade was installed on 3rd May 2013, the prime incentive being an improved FDIR functionality. The main points were:

- The internal error counter of the RWs will be set to zero if no error occurred over the last two hours. Resets of the counter are logged. This new feature was implemented in order to mitigate the operational effects of the events described in chapter III-A.
- The ACS is now capable to restart autonomously units by a power cycle if the communication to these is interrupted. The new FDIR was designed an autonomous power cycle can be defined by a new command for the units described in Table 2. It also limits the overall maximum number of reboots. The new concept safeguards against RW errors as described in chapter III-A.

| Unit | Trigger | Persistence | In ACS loop |
|------|------------------|-------------|-------------|
| IMU | No data | 5 sec | No |
| RW | Isolation by ACS | - | No |
| MCS | No communication | 10 sec | Yes |
| MFS | No communication | 10 sec | No |

Table 2. Units that are allowed reboot autonomously

- If there is a non-nominal RW mode after switch-on, this wheel will be excluded from the control loop but telemetry will still be available. It is not possible any more for ACS to overwrite the internal status of the wheel, as was the case in the previous software. The monitoring of the RW status after the switch-on is important. Failure in monitoring it closely was one of the causes that led to the loss of RW1.
- A safe mode using the magnetic torque rods as the sole actuators was designed, which will be used automatically when one of the remaining wheels starts having problems.

^h During the Sun Pointing Rotate Mode the Star Trackers are pointing towards the Earth and thus are unusable for most of the orbit.

ⁱ The Threshold of the fuse is temperature depended. An increasing temperature lowers the threshold of the fuse. Current is not interrupted immediately when the threshold is reached but after a persistency.

^j The default temperature limit stored in the firmware is 100 °C instead of the 80 °C written in the EEPROM.

^k There was no explicit monitoring of the status included in the nominal flight procedure for restarting of the RWs. With this procedure the wheels were set into use already shortly after a power cycle. Thus the ACS software could not recognize that there possibly was an EEPROM read error and a failure mode. It just sent the first control commands to the wheels overruling the failure message.

- If the rotation rates of the satellite are derived from magnetic field measurements only (see Section II), the ACS control will be suspended completely. This FDIR was developed to reduce the load on the RWs if the rates are poorly determined.

IV. Conclusions

The TET-1 OOV mission is a success despite some severe challenges to the ACS. The definite loss of one RW was caused by a fatal chain of events. The thermal problems of the bus and the ensuing non-nominal operations resulted in a poor determination of the attitude which in turn increased the load and temperature of the actuators leading to outages and errors.

New FDIRS were implemented to safely continue the mission with three reaction wheels only. Board-autonomous responses improved the robustness of operations and eliminated payload interruptions caused by outages of ACS units.

TET-1 was an experimental mission with high demands on the attitude control system. The envisaged mission duration was one year only with a possible prolongation of a further year. Components were therefore not chosen for longevity. However, the actual amount of disruptions due to IMU and/or RW outages was higher than expected.

Experience is useful and transferable for following missions such as BIROS that will be launched in 2015. Problems caused by the design cannot be repaired in flight. It was shown that more information on the status of the ACS and its units is useful to diagnose contingencies earlier and to handle them better. This info will be available indeed in the upcoming BIROS mission.

Acknowledgments

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