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High Torque Wheels for agile Satellite Maneuvers - in Orbit Experiences and future Steps with Recuperation of Energy

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Abstract

Agility is a necessary skill for several tasks. This applies in particular to remote sensing applications, but is also useful for optical communication from satellite to ground. While discussing a new reconnaissance satellite, the need for suitable actuators for agile maneuvers was identified several years ago. Developments for robotics at DLR (e.g. ROKVIS experiment on board the ISS (2004-2011) resulted in the possibility to further develop the reaction wheel principle for the special application "high torque" for fast accelerations. This was in competition with the widespread use of control momentum gyros (CMG). It was decided to equip the small satellite BIROS (launch 2016) with three “High Torque Wheels” (HTW) as additional technological payload. With this down-scaled version of the HTWs, the proof of the concept should be made under real conditions in space. This included various agile satellite maneuvers such as for “in track stereo”, scanning up to 5 parallel image strips on ground or switching between different targets on ground. This of course required changes to the ACS and the power supply system, which was a reuse of technology from the DLR small satellite TET-1. The attitude control system (ACS) uses several “attitude modes” for a comfortable and autonomous attitude control of the satellites in space. This was extended by a special “Fast Slew Mode”, which was developed for fast maneuvers using HTWs. The standard satellite slew rate is 0.5 degrees per second with a freely selectable single slew axis. A fast slewing maneuver intends to reorient the satellite by up to 30 degrees within 10 seconds. Actually however, the satellite achieved angular speeds of up to 10 degrees per second in space. A fast slew maneuver is finished, when all the HTWs are nearly stopped and the default ACS actuators took over the remaining angular momentum. This process of momentum exchange between the actuator systems was one important aspect of investigations. Another test case was the usage of these 3 experimental HTWs as actuator of the ACS. After successful completion of the first experimental phase in orbit the work will be continued by improving the fast slew maneuver algorithms and by preparing a second experimental phase in space including active payload cameras in the defined image scenarios. The HTW will be equipped now with an energy recuperation system storing electrical energy instead of kinetic energy within a spinning CMG.

Keywords: Attitude Control, Agility, High Torque, Recuperation

1. Introduction

Within the framework of the Earth observation mission “Firebird” [1] the two small satellites TET-1 (launch 2012) and BIROS (launch 2016) are used for technological experiments beside the primary mission objectives. One secondary mission goal is dealing with agility. The motivation has different sources. In the surrounding of the German HiROS project (high resolution optical satellite, project was stuck in the design phase some years ago) some open points related to agility and image quality had been identified. Another driver for motivation were optical space to ground communication payloads on board of BIROS. A fast switch between different optical ground stations along the satellite’s ground track requires fast slew maneuvers of the satellite when the optical payload is pointing with the whole satellite.

So, agility had to be defined for our small satellites. Agility means something different for a turtle than for a frog. What are agile maneuver scenarios for BIROS? We had to define the kinematic values as satellite rate and angular accelerations. Then the dynamic parameters as angular momentum and required torque could be derived. Finally, the new actuators – the HTW- for BIROS could be designed. The attitude control system had to be modified. Instead of 4 reaction wheels in a tetrahedron configuration the ACS has now 3 more actuators available. The HTW has more angular momentum capacity, produces more torque and draws more electrical energy out of the power system. Therefore, some considerations about "safety" were made - operational safety as well as some technical protections and precautions on board. The topics are the transfer of the required energy from battery to kinetic energy and heat and the exchange of angular momentum between the satellite body, the default RW-90-wheel system and the experimental three HTW.

A last point of motivation came from image quality. By using a CMG for high torque, it is required to charge the CMG with kinetic energy and angular momentum before a high torque maneuver is possible. Especially the stored angular momentum will couple with the satellite rate and any change of the satellite rate due to attitude control. This coupling is nonlinear and can disturb the attitude control especially in cases, where linear controllers (like PID) are used. The possibly caused deviations /oscillations could be misunderstood as “vibrations” coming from the CMG. In order to overcome this the idea was to use a strong wheel which is used for maneuvers only and remains stopped during any normal operations of the satellite. There was no need for storage of angular momentum inside.

2. Agility

The typical tasks of BIROS are going to Sun orientation for battery charging and doing Earth observations in a nadir orientation. For any change of the so-called target attitude (this is target orientation quaternion $\boldsymbol{q}$ and the target satellite rate vector $\acute{\boldsymbol{\omega}}$) BIROS and TET perform a single axis slew maneuver from initial to target attitude. The default slew rate is 0.5 deg/s – but of course split into three different x,y,z components of the satellite rate.

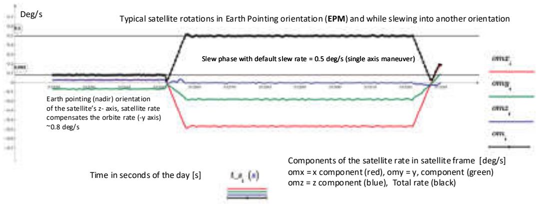

Figure 1 A typical single axis slew maneuver of BIROS

Earth observation is connected with compensation the orbit rate of 360 deg within one orbit

Sometimes the satellite performs inertial pointing and like Sun pointing it is not connected by default with any satellite rotation.

The target pointing – this means the alignment of the direct line between satellite position and a fixed target coordinate on the Earth with a selectable but fixed satellite axis – could be assumed to be agile. In fact, the satellite's rate is changing from nearly orbit rate (far from target) up to a peak in the order of 1 deg/s in the moment of closest approach to the target and will be finally go down again to the level of orbit rate. But even this a little bit agile maneuver can be performed with the default BIROS AOCS system as it is already implemented in the elder TET-1 satellite.

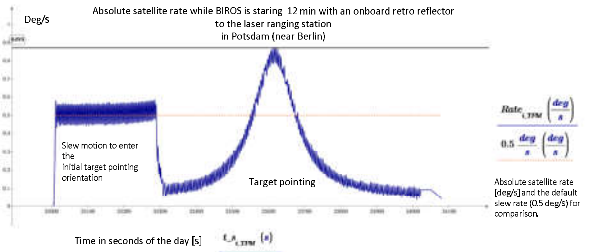

Figure 2 total satellite rate profil during a 12 min target pointing

The required rate exceeds the default used rates only by a factor of two or even less.

2.1 The used agility definition

For the purpose of the Firebird mission the agility is defined by two points: The required satellite rate exceeds the typically available rate by a factor of 4 or more and can not be provided by the default and unmodified AOCS.

Analysing the following scenarios, it was found, that an agile rate of about 30 deg/10 s complies with all of them. This comes out of a pure kinematic analysis only [2] and this means, it is independent of the size of the satellite for similar orbits.

2.2 Agile BIROS maneuvers

The scenarios fulfil requirements of the optical main payload cameras. And the scenarios comply with the needs of optical space to ground communication.

2.2.1 In track stereo

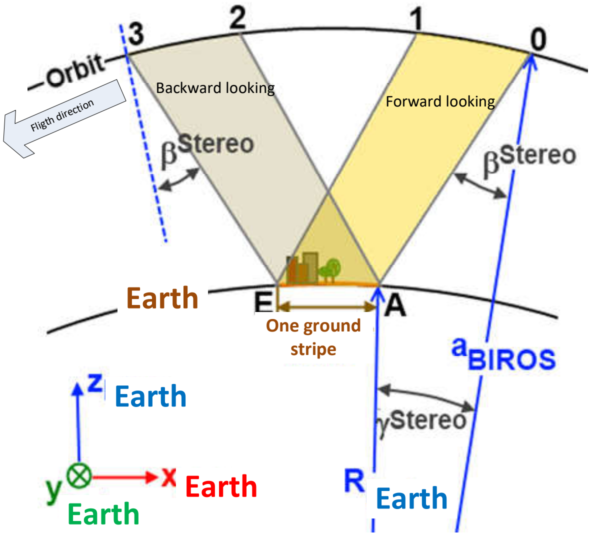

Figure 3 In track stereo scenario with forward and backward-looking CCD line sensor

This is a repeated scan (at least double) of the same ground area by first a forward and then a backward-looking orientation of the CCD line scanner attached to the satellite body.

2.2.2 Large area

This is the extension of a ground swath width by putting several parallel image stripes side by side together. In order to do this the satellite has to be tilted forward, nadir and backwards and in the same time off nadir. (Figure 4)

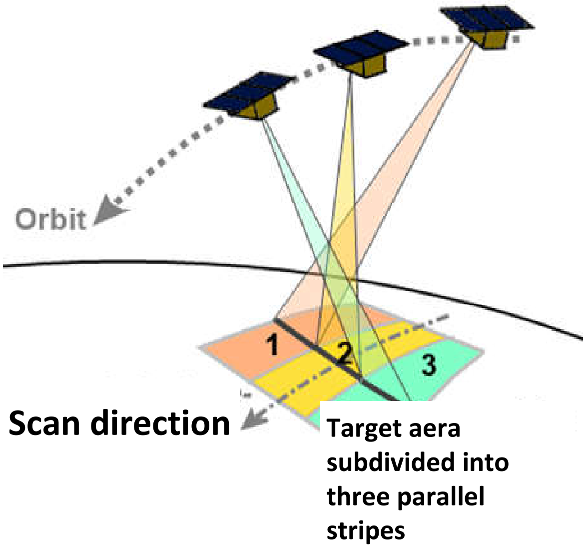

Figure 4 the large area imaging scenario for line scanners

2.2.3 Multiple target pointing

This is a sequence of several target pointing orientations with different targets on ground.

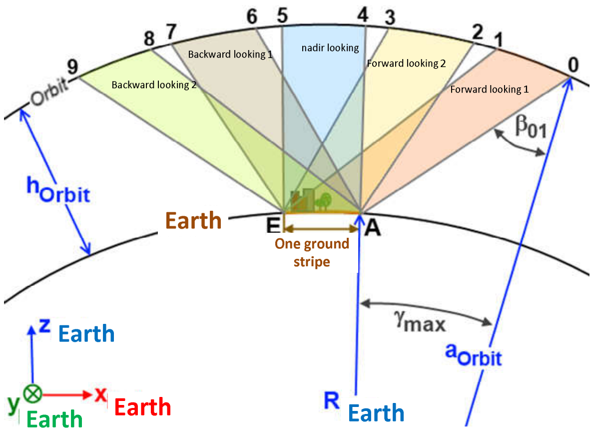

Figure 5 change detection imaging scenario for a CCD line scanner

By using a fast slew back to Sun, the maximum slew angle could be 180 deg. This takes a default slew maneuver ~ 360 seconds to go there. By using the agile fast slew this can be don within 60 seconds. The satellite enters the Sun orientation 5 times earlier than without agility and needs one acceleration phase of some seconds with high torque. The agility is here finally power saving.

3.Kinetic energy and angular momentum

Attitude control is control of the satellite's angular momentum vector in order to follow a predefined attitude profile. This target attitude profile, can be described by a quaternion $\boldsymbol{q}(t)$ as a function of time and a rate vector $\boldsymbol{\acute{\omega}}$ as a function of time $\{\boldsymbol{q}_{\text{target}}, \boldsymbol{\acute{\omega}}_{\text{target}}\}$. The link between the target attitude and the actuators is given by the dynamics of the rigid body motion. The actuators can convert electrical energy into kinetic energy and heat and can produce torque. The reaction wheels produce internal torque and exchange it with the angular momentum of the satellite.

The satellite rotation is connected with an angular momentum vector and kinetic energy.

Assuming the absence of external torques the overall angular momentum vector in inertial frame remains unchanged (Conservation law). This means, the angular momentum vector of a wheel system **L**_wheel compensates exactly the angular momentum vector **L**_sat of the satellite's rotation. In a simple stationary situation for a perfect spherical and homogenous satellite it would be for one wheel like this

$$Lwheel = J\_wheel \cdot \omega\_wheel = -J\_sat \cdot \omega\_sat = -L\_sat$$

Here stands $\boldsymbol{\acute{\omega}}$_wheel for the wheel rate of the rotating mass with the axial moment of inertia J_wheel, and accordingly the satellite rate $\boldsymbol{\acute{\omega}}$_sat and a moment of inertia of the satellite J_sat.

The kinetic energy of a wheel is

$$Ekin\_wheel = \frac{J\_wheel}{2} \cdot \left(\omega\_wheel^2\right) = \frac{L\_wheel^2}{2 \cdot J\_wheel}$$

And the satellite accordingly. While the angular momentum of satellite and wheel are in the same order and in a perfect world without external forces and torques compensating each other is the exchange of energy different.

$$\frac{Ekin\_sat}{Ekin\_wheel} = \frac{J\_wheel}{J\_sat}$$

The ratio between the kinetic energy of wheel and satellite is characterised by the ratio of the moments of inertia. This is for BIROS and the default RW 90 wheels in the order of 1: 20000 and ~1:1200 for HTW and satellite. Figure 6 shows as an example only the y contribution to the kinetic energy (light green, lower curve) and the HTWy (dark green) versus the angular momentum of HTWy and along the satellit's y-axis.

BIROS was in that time performing an in track stereo maneuver with two fast slew maneuvers.

Each vertical line intersecting both curves in the diagram connects HTWy with the satellite rotation and defines a possible pair. In order to make the curve of the satellite clearly visible, the energy was multiplied by a factor of the moments of inertia ratio (principal moment of inertia of the BIROS y axis (approximately)

$$factor := \frac{6\ kg \cdot m \cdot m}{Jzz\_HTW} = 1203.4$$

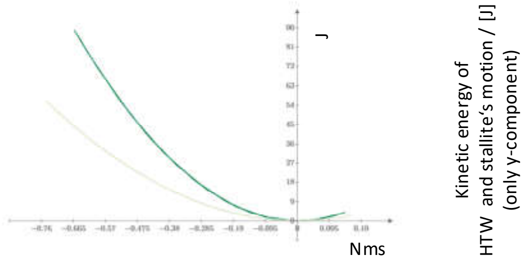

Figure 6 kinetic energy versus angular momentum, y components of HTW and satellite in the same time

The AOCS of the Firebird satellites is designed to minimise the overall angular momentum in a best case all the time. The reaction wheels are really working as reaction wheels and do not store a remarkable amount of angular momentum. It depends on the daily program, but wheel speeds in a range < 100 rpm are typical. (Full range is 7200 rpm and the remaining momentum bubble in the wheel system is in the order of some mNms. Thus, even the kinetic energy level inside the wheel system is very low.

The kinetic energy of the satellite motion is defined by the target attitude and the necessary slew maneuvers from one target attitude to another one. This cannot be changed. Reducing the dissipation of electrical energy and the conversion into undesired heat inside a satellite is related to the reaction wheels. There is the energy and this becomes even more important with HTW on board.

Within 10s the HTW system shall deliver the torque for accelerating its rotating masses and exchange the angular momentum with the satellite body. In the same time the kinetic energy of satellite rotation will increase. After again10s the HTW begin to break, reduce the angular momentum and the kinetic energy to zero. Most of the energy is converted back to electrical energy and then finally into heat by using a resistor on board of BIROS.

3.1 Momentum and energy budgets for agile maneuvers

The different agile scenarios permit the estimation the required Torque and angular momentum.

In track stereo with two images and a stereo angle of 20 degrees yields 0.14 Nm torque and 0.7 Nms angular momentum capacity for a maneuver within 17 seconds.

A single target pointing with a fast slew of 30 deg/10 s would require 0.21 Nm torque and 1.05 Nms angular momentum capacity.

The large area scenario with a slew angle of 30 deg would need 93.3 s (BIROS orbit parameters used). In that time each fast scan had to be performed within 12 seconds. The individual tilt angles are ~17.5 degrees and therefore the required torque is in the order of 0.12 Nm and the momentum capacity in the order of 0.61 Nms.

4. High Torque wheels development for BIROS

The design parameters reflect the needs of the found agile scenarios and the limits of the BIROS payload compartment. The scenario analysis yields a maximum time for one agile fast slew maneuver of ≥ 10 s.

Mass	< 2.7 kg
Power	≤150 W
Dimensions	∅ 200 mm x 100 mm
Torque	≥ 0,21 Nm
Angular momentum	≥ 1,05 Nms

Due to the fact, that the maneuver requirements are not depending on the satellite size (and mass and inertia) there is an additional topic and this is scalability. The design had to allow up and down scaling of the HTW for dedicated projects. The implementation as part of the BIROS AOCS should be eased using the same power and date interfaces and the same protocols for command and telemetry.

Figure 7 HTW flight model

The final flight model parameters of the HTW are:

Mass	< 2.3 kg
Power	
maximum	< 150 W
stand by	< 2 W

electrical power supply	18…34 V
Data interface	RS 485
Dimensions	∅ 197 mm x 92 mm
Inertia of rotating mass I_{zz}	0.005 kg*m^2
Torque (max@nominal rate)	≥ 0,21 Nm
Angular momentum $\lvert \mathbf{L} \rvert$	≥ 1,05 Nms
Wheel rate (maximum)	3000 rpm

(This is limited by AOCS software for down scaling the wheel to the needs of BIROS)

Temperature ranges	
Operational	-15…. +40 °C
Non-operational	-25 … +50 °C

The HTW uses the housing, bearing concept and some other components from the RW-250 reaction wheel. [3]

4.1 Implementation into BIROS satellite

Figure 8 shows the mechanical installation at BIROS behind the main payload cameras and the picosatellite eject mechanism SPL. [3]

The HTW principal axes are aligned with the BIROS x,y,z axes. There is no redundancy because it is an experimental payload.

The implementation from algorithms and software point of view was done like just extending the default wheel system of 4 RW-90. This means the three HTW use the same redundant bus system und the same data protocols. In order to separate the HTW usage from the default AOCS behaviour a special new attitude mode was implemented. It is called fast slew mode (FSM). This attitude mode was entered only for changing the target attitude in a fast way and by sing the HTW. FSM is the “agility” attitude mode of BIROS

An attitude mode consists of a target attitude $\{\boldsymbol{q}_{\text{target}}, \dot{\boldsymbol{\omega}}_{\text{target}}\}$, minimal configurations of sensors, actuators and software modules in the ACS loop and entry, stay, exit conditions. For this special attitude mode FSM, the design was extended by the target attitude mode as command parameter. In order to hand over as fast as possible to the new required attitude mode, the FSM control algorithm uses already the target attitude definition of this next commanded target attitude mode. Each fast slew maneuver is a single axis maneuver directly from initial kinematic attitude $\{\boldsymbol{q}_{\text{initial}}, \dot{\boldsymbol{\omega}}_{\text{initial}}\}$ to the target kinematic attitude $\{\boldsymbol{q}_{\text{target}}, \dot{\boldsymbol{\omega}}_{\text{target}}\}$.

Another topic was the usage of these special high torque wheels for default AOCS control tasks.

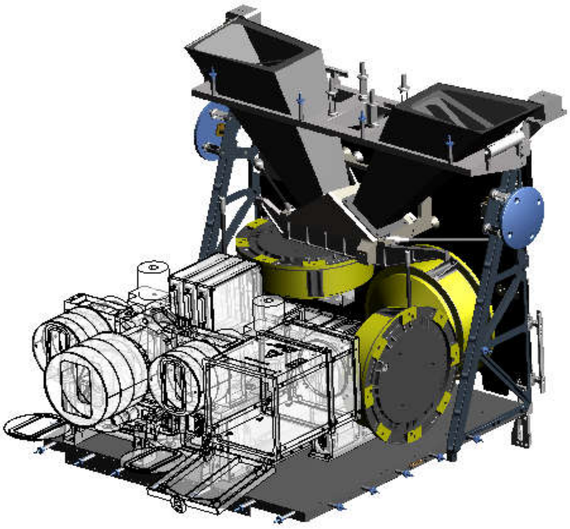

Figure 8 Three HTW implemented at BIROS payload compartment

The idea was to transfer the actual angular momentum from the default wheel system to HTW, stop the default wheels and let the HTW control the satellite even for non-agile standard maneuvers.

4.2 HTW tests on ground

The final tests on ground used a special engineering model of BIROS (EM-ACS) mounted on an air bearing test stand. (Figure 9). This air bearing test stand permits to test the complete AOCS with realistic accuracies and satellite behaviour. The external disturbances are <10^{-4} Nm. Figure 10 shows the three mounted HTW at the BIROS EM-ACS.

4.3 HTW tests in orbit

4.3.1 HTW checkout

After BIROS launch (22.6.2016) some check out tests have been done. The HTW rates are set 5 times to ±1800 rpm. This is below the limit of 3000 rpm and was used only for checking the post start behaviour. The attitude control was set into the attitude mode “suspend mode” (SPM). In SPM the telemetry and communication with all powered devices is active, but there will no control command going to any actuator. The HTW received its commands_from the onboard command queue_prepared and_loaded up for this test in advance. In SPM the telemetry and communication with all powered devices is active, but there will no control command going to any actuator._The HTW received its commands_from the onboard command queue_prepared and_loaded up for this test in advance.

The reaction of the satellite is shown in the lower part of Figure 11. Even during this cautious test, the satellite achieved a satellite rate of almost 10 deg/s and entered definitely the region of agile maneuvers.

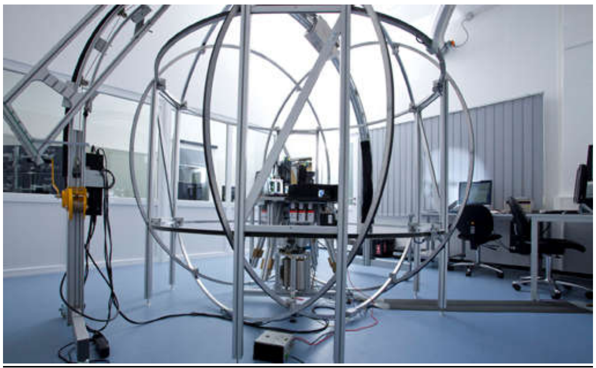

Figure 9 air bearing test stand with external Helmholtz Coil system and BIROS EM-ACS

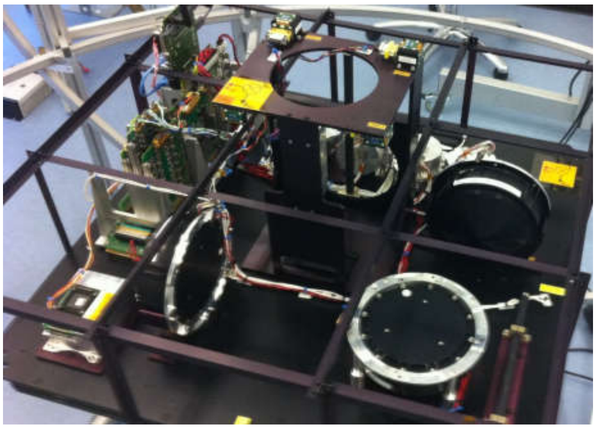

Figure 10 three HTW mounted on the BIROS EM-ACS

All HTW survived the launch and the BIROS power system survived the HTW power consumption during 10 times acceleration and breaking within 200 seconds for each HTW.

4.3.2 Further AOCS test in orbit

For one day in 2017 the diagram of the commanded attitude modes shows the activities of BIROS at this day BIROS started this day in Sun pointing orientation. Figure 3 shows the components of the satellite rate (r,g,b dots correspond to x,y,z components of the satellite rate over ~ 1 hr). The black curve gives the total rate with an average value of ~0.04 deg/s = 2.4 arc minutes/s. This is the AOCS noise of BIROS. The corresponding angular momentum is on average 9 mNms in the wheel system and 5 mNms for the satellite rotation (Jitter, see Figure 14). The kinetic energy levels in the wheel system are in the order of 200 mJ (or 200 mWs) and of 3.5 µJ for the satellites jitter motion.

The next orientation is Earth pointing. The rate components in Figure 16 show the x and z component of the satellite rate (in sat frame) with a mean value zero and a mean y-component which corresponds the orbit rate and holds BIROS in the nadir orientation. The AOCS uses the default RW-90 wheel system. The HTW are off.

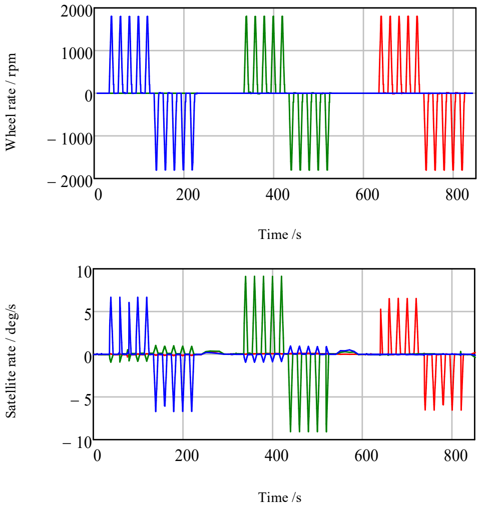

Figure 11check out tests with the x=red, y=green, z=blue HTW, the components of the satellite rates are given in deg/s, x=red, y=green, z=blue

day.

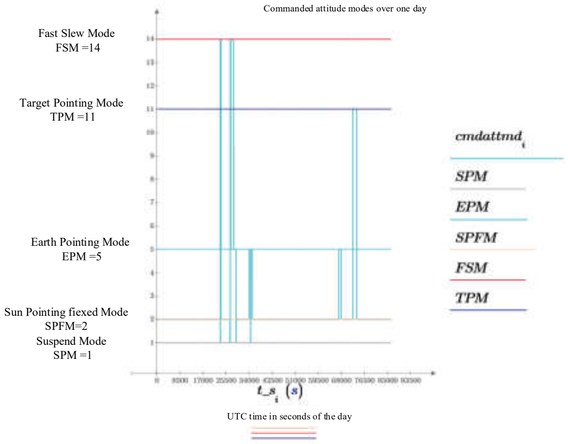

Figure 12 The commanded attitude modes over one HTW test day

Figure 17 shows the y component of the angular momentum vector L_sat of the satellite body (negative values) in satellite frame and the RW-90 reaction wheel system's angular momentum vector component in the same frame. The corresponding angular momentum is presented in Figure 18. Comparing it with the Sun pointing the wheel systems holds on average 12.5 mNms in Earth pointing instead of 9 mNms in Sun. The computation of the angular momentum vector of the

RW 90 reaction wheels uses the moment of inertia of the rotating masses with 417 $*10^{-6}$ kg$*$m^2. This was given by the manufacturer.

pointing and the satellite has on average 8.5 mNms instead of 5 mNms in Sun pointing.

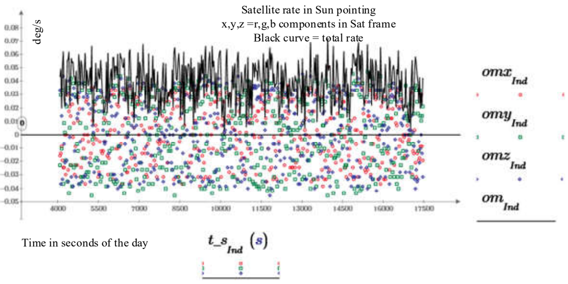

Figure 13 Satellite rates during Sun pointing

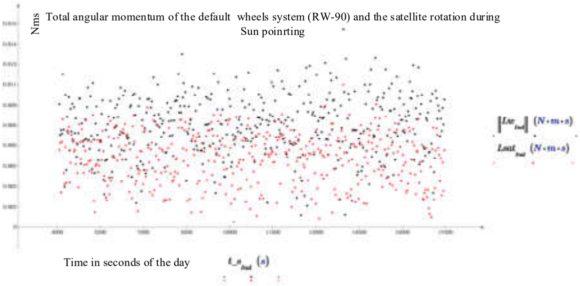

Figure 14 the total angular momentum of Satellite and wheel system during Sun pointing

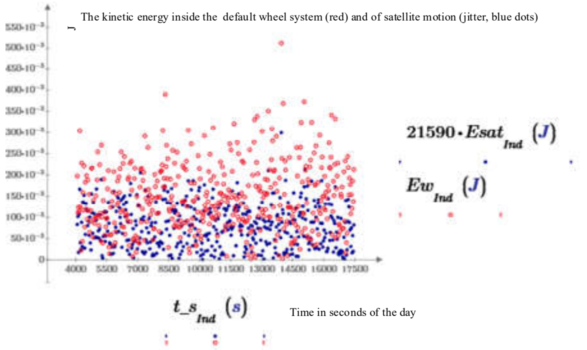

Figure 15kinetic energy in the wheel system and of the satellite's jitter motion in Sun pointing

The next orientation is Earth pointing

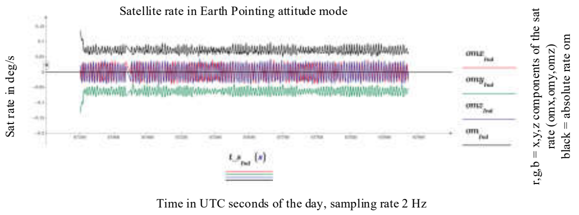

Figure 16 Satellite rate components in Earth pointing; default ACS configuration

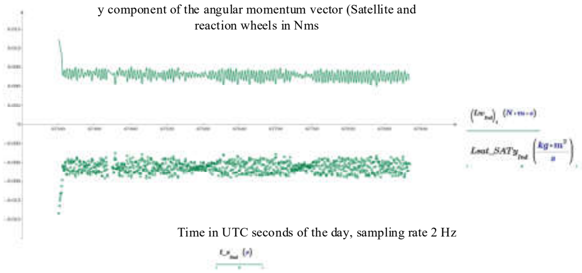

Figure 17 The y component of angular momentum vector (satellite = green dots; wheel system = green line)

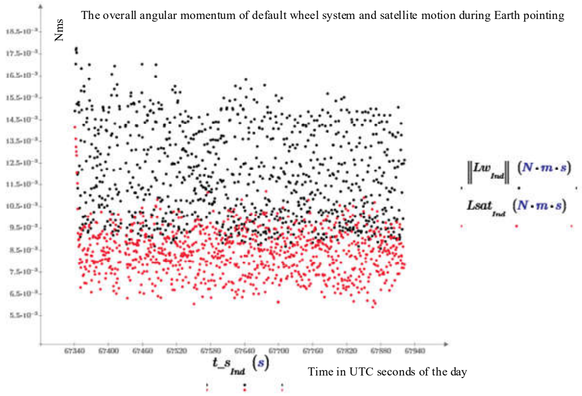

Figure 18 the total angular momentum of Satellite and wheel system during Earth pointing

To compute the vector **L**_wheel from 4 individual wheel rates the tetrahedron 3x 4 mounting matrix ***A_w*** of all 4 reaction wheels is used. The special feature of the tetrahedron is that three out of four wheels can completely compensate or double the momentum of the fourth. This permits the storage of kinetic energy without a real angular momentum vector and is called “dead angular momentum” by the Firebird AOCS team.

$$A\_w = \begin{bmatrix} 0 & 0.8165 & -0.8165 & 0 \\ -1 & -0.3333 & -0.3333 & -0.3333 \\ 0 & -0.4714 & -0.4714 & 0.9428 \end{bmatrix}$$

The computation of the satellites angular momentum vector uses the principal moments of inertia of the satellite body with deployed solar panels, a released picosatellite (BEESAT 4) and one full bottle of cold gas. These figures came out by the designer's computation with the CAD system and are of course connected with some uncertainties. It gives the right order of typical expectations for angular momentum on board during here the Earth pointing and the wheel system holds always a small amount of collected angular momentum from external disturbances. So, the difference is both - external disturbances and uncertainties in the computation. The computation uses the coordinate frame of the principal moments of inertia axes – the MOI frame. By using the transformation matrix, the angular momentum can be computed from the vector of satellite rate and the principal moments of inertia along the axes of MOI frame

4.3.2 Agility tests in orbit

The first agile test was entering the Fast Slew Mode and going to Earth pointing. The task was making an agile maneuver and then holding the satellite in a good accuracy in Earth pointing orientation.

The rate components in Figure 19 are given in r,g,b colours = x,y,z component. Black curve belongs to the absolute rate and these values reaches 11.6 deg/s during the fast slew. The yellow curve above the rates gives the commanded attitude mode. It was here the fast slew mode FSM in the beginning and steps don to 5, this is the ID of the Earth pointing mode EPM. The HTW wheel stop can be seen. The attitude control in EPM was done by using the default wheel system and with respect to some small but remaining momentum inside the HTW. This "cool down" of HTW and handing the small remaining momentum to the default wheels was one important part of the tests in space.

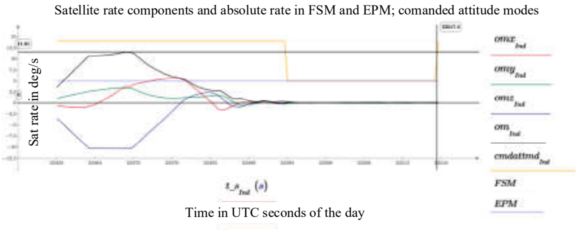

Figure 19 Satellite rates during fast slew to Earth Pointing

Another interesting test was the "in track stereo scenario". It was performed to support a forward, nadir and backward-looking imaging sequence with the active infrared camera system of BIROS. The rate peaks within the fast slew maneuver are in the order of 6 deg/s. The imaging sequences in Earth pointing had been controlled with the default wheels system. The HTW were keeping a low wheel speed for this time (see Figure 20and Figure 21). BIROS comes with a default slew by RW90 wheels and enters the first EPM phase. This was given in the command timeline on board with enough time before the target area is reached. After taking the first (forward) picture BIROS enters the FSM mode and the first rate peak of ~ 6 deg/s indicates a fast slew into the exact more nadir orientation. (In fact, the target was a little bit beside the nadir ground track). After taking the second picture again a fast slew changed the BIROS orientation now into the backward looking one. The density of data points in Figure 20 Figure 21 is changing due to the different rates of house keeping data. But the little zoom in in Figure 21 shows the typical distribution for Earth pointing at the satellite rate. In the same time the HTW rate components are jumping up to 1200 rpm (30% of full well) within the fast slew phase. (Figure 22). Figure 23 shows for the same time a "zoom" and between the two fast slews and after completing the second fast slew the HTW are freezing their rates, while the default AOCS is controlling with RW 90. This can be seen more in detail in Figure 24.

The remaining constant HTW wheel rates are below 30 rpm this corresponds with ~0.016 Nms. The value depends on the algorithms to stop an HTW by dumping a remaining angular momentum into the default system. This was one experience of the first HTW experiment Phase in orbit. This mechanism has to become more efficient in the future. 16 mNms are nearly 50 % of the RW90 capacity. Corrections require a software upload to the BIROS satellite bus controller (SBC).

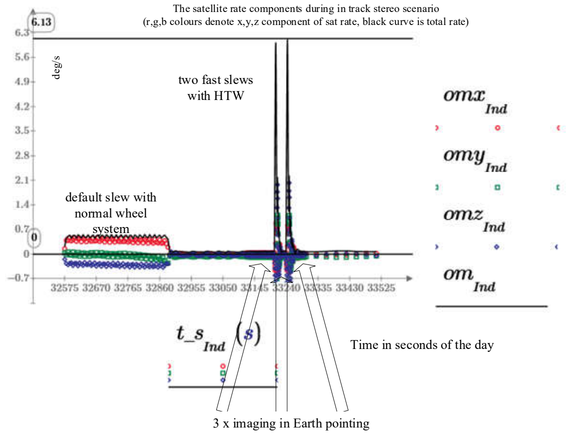

Figure 20 The satellite rate during in track stereo (3 images, 2 times fast slew)

The test with running cameras was asked by the Firebird science community. The imaging of a target under three or more different viewing angles coud help them to compute local atmospherical signal corrections. The fast slew motion causes two times in the scen a blured part.

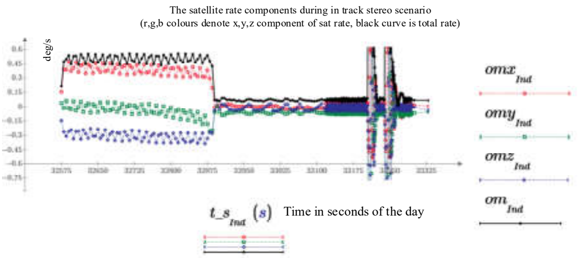

Figure 21 A "zoom in" of Figure 20

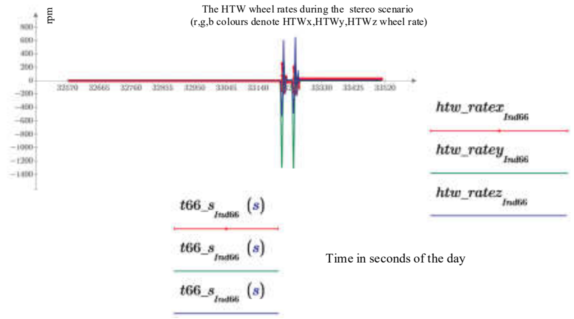

Figure 22 HTW wheel rates during in track stereo

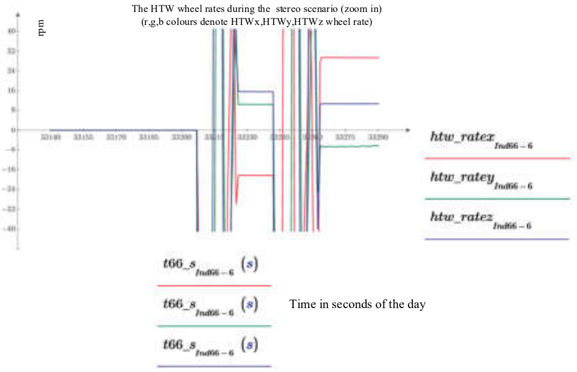

Figure 23 Zoom in of Figure 22 ; HTW hold a low rate during imaging

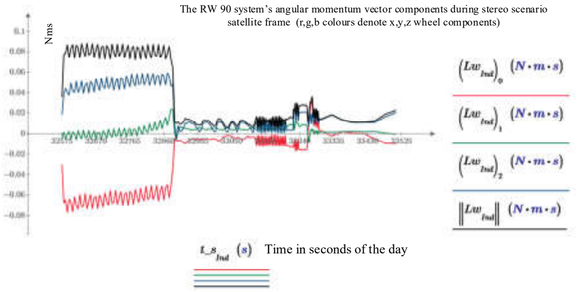

Figure 24Angular momentum vector of the RW 90 system during in track stereo scenario

The infrared scene shows some bright (warm) lakes, exactly the target region. So the test was a success even for the fire science community.

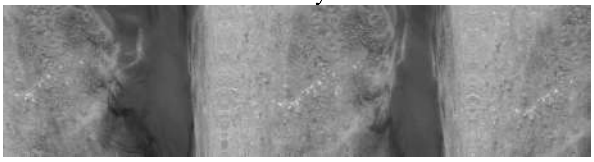

Figure 25 The running IR line scanner during the 3 times in track stereo maneuver

Figure 26 The target area three times (zoom in from Figure 25)

At this day several FSM test had been performed. The satellite bus current over the whole day is shown in Figure 27. The energy peaks have to be handled by the BIROS power system and only the setting of the safe mode threshold for bus current up to 12 A was to do. Otherwise the bus surveillance would switch off all payload system when such peaks are detected.

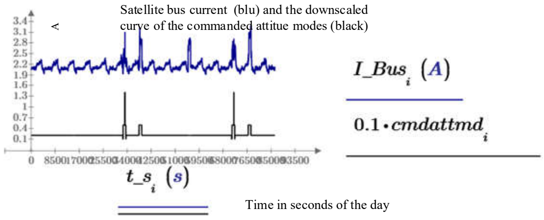

Figure 27 Overal satellite bus current and the controlled attitude modes over one day

4. Recuperation of energy

Without energy recuperation on board of BIROS any unusable energy coming out of the HTW is converted into heat. The <150 W electrical power over 10 seconds in a fast slew maneuver are <1500 Ws of energy. For BIROS it was a little bit down scaled to ~100 W. At the minimum voltage of 18 V on board it could draw < 6 A. Even the high angular momentum vector of a HTW can be dangerous for the satellite and operations. So, during the experiments it was realized that there is a controllable way to reduce an undesired high momentum in the HTW system by a commanded constant deacceleration by small week torque commands to the HTW. Via the default attitude control the default wheel system (RW 90) will take over this angular momentum without disturbing the attitude control. The momentum inside the default wheel system is slowly increasing. But due to the always active momentum reduction by the magnetic coils system on board, the overall momentum comes to nearly zero. In this way we transferred kinetic energy and momentum from HTW to RW90 and via magnetic torquer system out of the satellite.

But recuperation of energy inside the satellite can have advantages. First of all, it is the idea to minimise the content of mechanical energy inside a satellite. Mechanical energy can disturb AOCS and may be some payload operations. The kinetic energy is concentrated in the wheel system due to the Jwheel/Jsat ratio.

The second point is the decoupling of a HTW system from the default power system of a satellite. The power system shall never suffer from a high request for electrical energy in a short time and shall never be confronted with electrical energy “coming back” to the power system.

Therefore, an extension for super capacitor-based energy recuperation was designed. Comparing with a CMG the new system shall charge a super cap with electrical energy only slowly and without “disturbing” the satellite’s power system. There is no additional angular momentum.

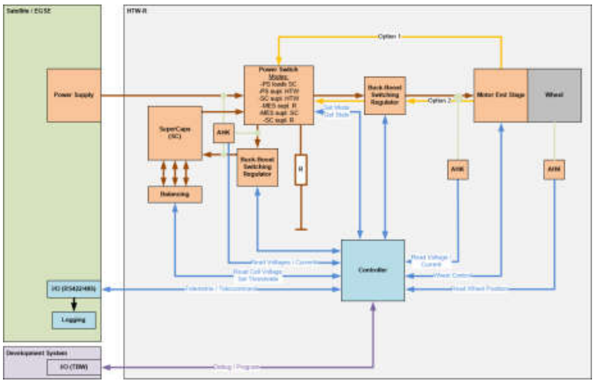

Figure 28 The energy recuperation system design

The system consists of a power source, a “power switch”, two back boost switching regulators, a wheel with drive and drive electronics and one main controller.

The experiment control in the lab is done by an electronic ground support equipment EGSE.

In the charging phase the power switch lets the electrical energy flow to the super cap. (Figure 29) When the HTW starts, it draws the energy via power switch from the super cap. When the HTW turns backward and starts to break, the released electrical energy flows back via back boost to the super cap. (Figure 31). In case, the system has some issues there is an emergency exit for the energy and this is a resistor. The energy is burnt.

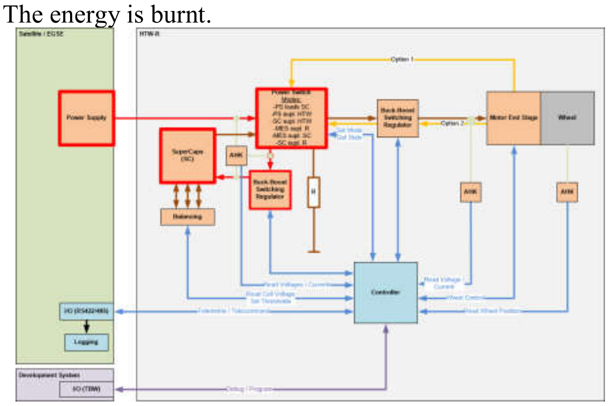

Figure 29 collecting electrical energy in a super cap

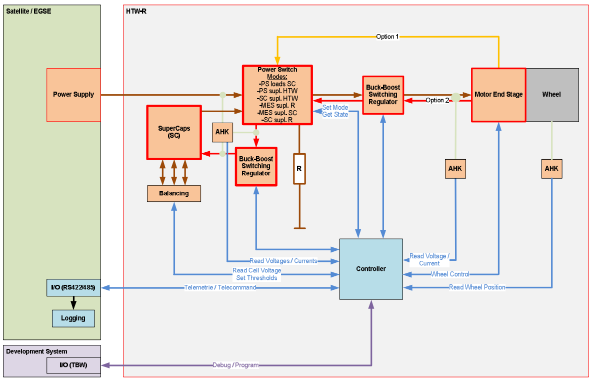

Figure 30 Energy recuperation

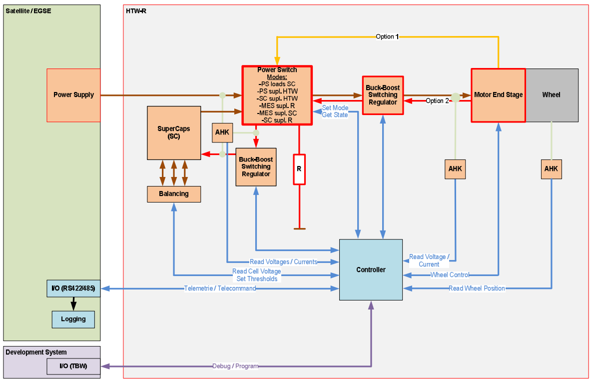

Figure 31 Recuperation and charging emergency exit

The system is based on finished DLR in house projects dealing with super caps and with storage of electrical energy in structural elements like housing for example. The discussed recuperation lab experiment is still in a phase A like status right now. As part of this project it is planned to finish the high torque wheel experiments on BIROS in space and to perform further tests on the air bearing test stand. Due to the pandemy there is a delay in the project.

5. Discussion

Agility is helpful and extends the bandwidth of Earth observation scenarios. The way to approach agility step by step by “abusing” the Earth observation satellite BIROS for technological experiments was really helpful and is sometimes surprising. For example, in case the satellite has a downlink antenna with a sharp beam profile it is not recommend to do agile satellite sport while the mission operations have contact with the satellite. We did not prepare this interface to ground control carefully enough and everybody in the control room was wondering about the broken link. Our experiment was losing exciting star camera image data. The star cameras are the only instrument on board of BIROS which are able to proof that the satellite is not moving or vibrating right after a fast slew but during a slew. These data had been sent to deep space instead of sending it to ground.

6. Conclusions

BIROS and TET demonstrated over years in space, that wheels with nearly no speed and a lot of “zero crossing every day” will survive and stay reliable. The experiments with the HTW showed already that a fast slew and stopped high torque wheel will not disturb something or somebody on board. The next step must be the smart treatment of kinetic energy, recuperation and angular momentum exchange on board.

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