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## ABSTRACT

The DLR small satellite mission BIRD is dedicated to the remote sensing of hot spot events like vegetation fires, coal seam fires or active volcanoes from space. For these objectives a new generation of infrared array sensors are developed suitable for mall satellite missions. The demonstration of the performance of these sensors will be realized by the micro satellite mission BIRD. A lot of new small satellite technologies are developed to fulfil the high scientific requirements of the mission under the constraints of a micro satellite mission. That means the total mass of the complete spacecraft is 92 kg. The paper describes mission objectives, the payload, the spacecraft and the first results of the BIRD mission.


## INTRODUCTION

Small satellites have to meet a big challenge: to answer high performance requirements by means of small equipment and especially of small budgets. Out of all aspects the cost aspect is one of the most important driver for small satellite missions. To keep the costs within the low-budget frame (in comparison to big missions) the demonstration of new and not space-qualified technologies for the spacecraft is one key point in fulfilling high performance mission requirements.

Taking this into account the DLR micro-satellite mission BIRD has to demonstrate a high performance capability of spacecraft bus by using and testing new technologies basing on a mixed parts and components qualification level. The technology experiments of BIRD shall demonstrate the limits and the advantages of using new developed components, methods, algorithms and technologies.

The basic approach for accomplishing high performance capability for scientific mission objectives under low-budget constraints is characterized by using:

- state-of-the-art technologies,
- a mixed strategy in the definition of the quality level of the EEE parts and components,
- a tailored quality management system according to ISO 9000 and ECSS,
- a risk management system,
- extensive redundancy strategies,
- extensive tests especially on system level,
- large designs margins (over-design),
- robust design principles.

## MISSION OBJECTIVES

For hot spot events as forest and vegetation fires, volcanic activity or burning oil wells and coal seams a dedicated space instrumentation does not exist. Sensors being used now for the observation of these events have some drawbacks because they are not designed for the hot spot investigation. For the near future there are missions planned with a new generation of cooled infrared array sensors. The German BIRD (Bi-spectral Infrared Detection) mission will answer a lot of technological and scientific questions related to the operation of a compact bi-spectral infrared push-broom sensor on board of a micro satellite and related to the detection and investigation of fires from space.

Therefore, the BIRD primary mission objectives are:

- Test of a new generation of infrared array sensors adapted to Earth remote sensing objectives,

- Detection and scientific investigation of High Temperature Events such as forest fires, volcanic activities, and coal seam fires,
- Test and demonstration of new small satellite technologies.

The secondary mission objectives consist in:

- Test and demonstration of on-board classification by means of a neural networks circuit

## THE SPACECRAFT BUS

A basic mission constraint is the launch as a piggy-back or auxiliary payload into a Low Earth Orbit because of the costs. This requires a micro-satellite solution. Some basic features of the BIRD spacecraft bus (see fig. 1) are

- compact micro satellite structure with high mechanical stability and stiffness
- envelope qualification for several launchers
- cubic shape in launch configuration with dimensions of about 620 x 620 x 550 mm³ and variable launcher interface
- mass ratio bus : payload = 62kg : 30kg
- high peak power of 200W @ 20min, and av. power 60W
- advanced thermal control system with radiators, heat pipes, MLI, temperature sensors and contingency heaters
- new developed high-performance spacecraft bus computer with integrated latch-up protection and
- error detection and correction system
- three-axis stabilization of the spacecraft by an attitude control system in state space representation
- integrating the payload platform with its structure, thermal and power requirements
- on-board determination of the spacecraft position and velocity by the on-board navigation system basing on receiving and on-board processing of GPS-data
- S-band communication with high bit rate (2.2 Mbps) and low bit rate.

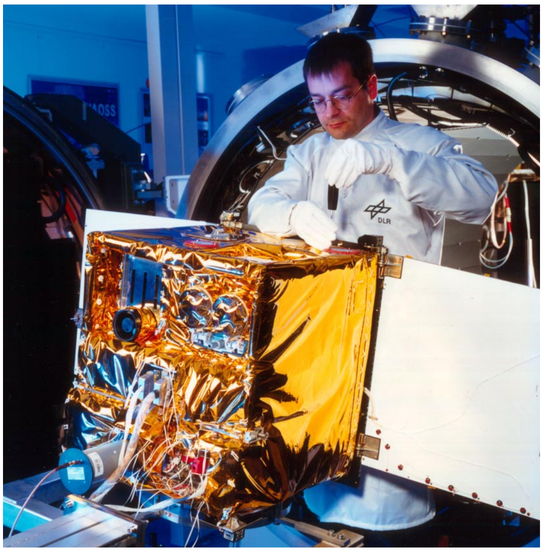

Figure 1 BIRD in front of the Space Simulation Chamber

BIRD is an experimental satellite. The duty time of the payload is 10 minutes in one orbit. The data of one duty cycle can be stored in the 1Gbit mass memory and will be transmitted during the next pass to a German ground station. Simultaneously data take and down-link are possible, too.

## THE PAYLOAD

The multi-sensor system consists of the following main parts:

- an infrared array sensor system basing on cooled CdHgTe-detectors in a medium infrared (MIR) channel and in a thermal infrared (TIR) channel,
- a CCD camera with a red (VIS) and a near infrared (NIR) channel,
- a payload data handling system,
- an on-board neural network classificator.

The instruments' parameters are given in Tab. 1.

Table I. CHARACTERISTICS OF THE INSTRUMENTS OF BIRD'S MAIN SENSOR PAYLOAD

| | **WAOSS-B** | **Infrared Sensor System** |
|---|---|---|
| Spectral bands | VIS: 600-670nmNIR: 840-900nm | MIR: 3.4-4.2µmTIR: 8.5-9.3µm |
| Focal length | 21.65mm | 46.39mm |
| Field of view | 50° | 19° |
| f-number | 2.8 | 2.0 |
| Detector | CCD lines | CdHgTe Arrays |
| Detector cooling | Passive, 20°C | Stirling, 80-100 K |
| Pixel number | 2880 | 2x512 staggered |
| Quantisation | 11bit | 14bit (for each exposure) |
| Sampling step | 185m | 185m |
| Swath width | 533km | 190km |

## LAUNCH AND ORBIT PARAMETERS

The acceptable parameters for the launch opportunity selection for BIRD regarding to orbit altitude and inclination were: h = 470 – 900 km and
i = 53° - 99°, respectively, (a sun-synchronous orbit was preferred). The Indian launch opportunity PSLV-C3 was selected. The BIRD satellite was launched at 22. Oct. 2001 with the PSLV-C3 from Shar/India successfully into a sun-synchronous low Earth orbit (see Tab. 2).

Table 2: ORBIT PARAMETER OF THE BIRD MISSION

| | **Parameter** |
|---|---|
| Circular orbit radius | 6949.8 km |
| Orbit inclination | 97.669 degree |
| Orbit altitude, av. | 572 km |
| Orbit type | sun-synchronous |
| Equatorial crossing time in descending node | 10:30 local time |

## FIRST RESULTS OF PAYLOAD OPERATIONS

### Hot spot detection

On 4, 5 and 9 January, 2002, BIRD performed imaging of bush fires in the area of Sydney, Australia. Fig. 2 shows the MIR band of these images (the imaged stripe of January, 9 was slightly shifted to the east). In order to represent a high dynamic range of the images, MIR pixel temperatures below 330 K are coded as grey levels while a color coding is used for higher MIR pixel temperatures (as discussed below, these are only fire pixels). The image of January, 4 reveals catastrophic bush fires with ex-tended fire fronts. On January 5, the intensive burning continues in the northern part of the scene but may be partly suppressed in the southern part (however, here the situation is not quiet clear because of the cloudiness). In the image of January, 9, most of the fires in the northern part of the scene are extinguished probably by human fire fighting and by rains, leaving only small residual sources of burning. More burning areas are observed in the central and southern part of this scene.

### Retrival of equivalent fire temperature and hot spot areas

Fig 3 shows a BIRD image fragment of the northern part of the scene of January, 5 in the MIR, TIR and NIR spectral bands and illustrates results of fire detection and of equivalent fire temperature retrieval. They were obtained using the BIRD hot spot detection algorithm that includes the following tests:

- adaptive MIR thresholding to detect potential hot pixels,
- NIR thresholding to reject strong sun glints,
- adaptive MIR/NIR radiance ratio thresholding to reject weaker sun glints, clouds and other high-reflective objects,
- adaptive MIR/TIR radiance ratio thresholding to reject warm surfaces,
- clustering of the detected hot pixels and equivalent fire temperature and area retrieval using the bi-spectral technique.

Most of the detected hot clusters are located at the border of fire scars and correspond to fire fronts, while only a few small clusters are located inside the fire scars indicating sources of residual burning. The fire scars can be recognized by their lower NIR radiance and are partly obscured by smoke. The TIR image shows only a few small hot spots.

As a result of the hot spot detection, all 'color-coded' pixels with the MIR temperature above 330 K are recognized as fires in this fragment (as well as in the

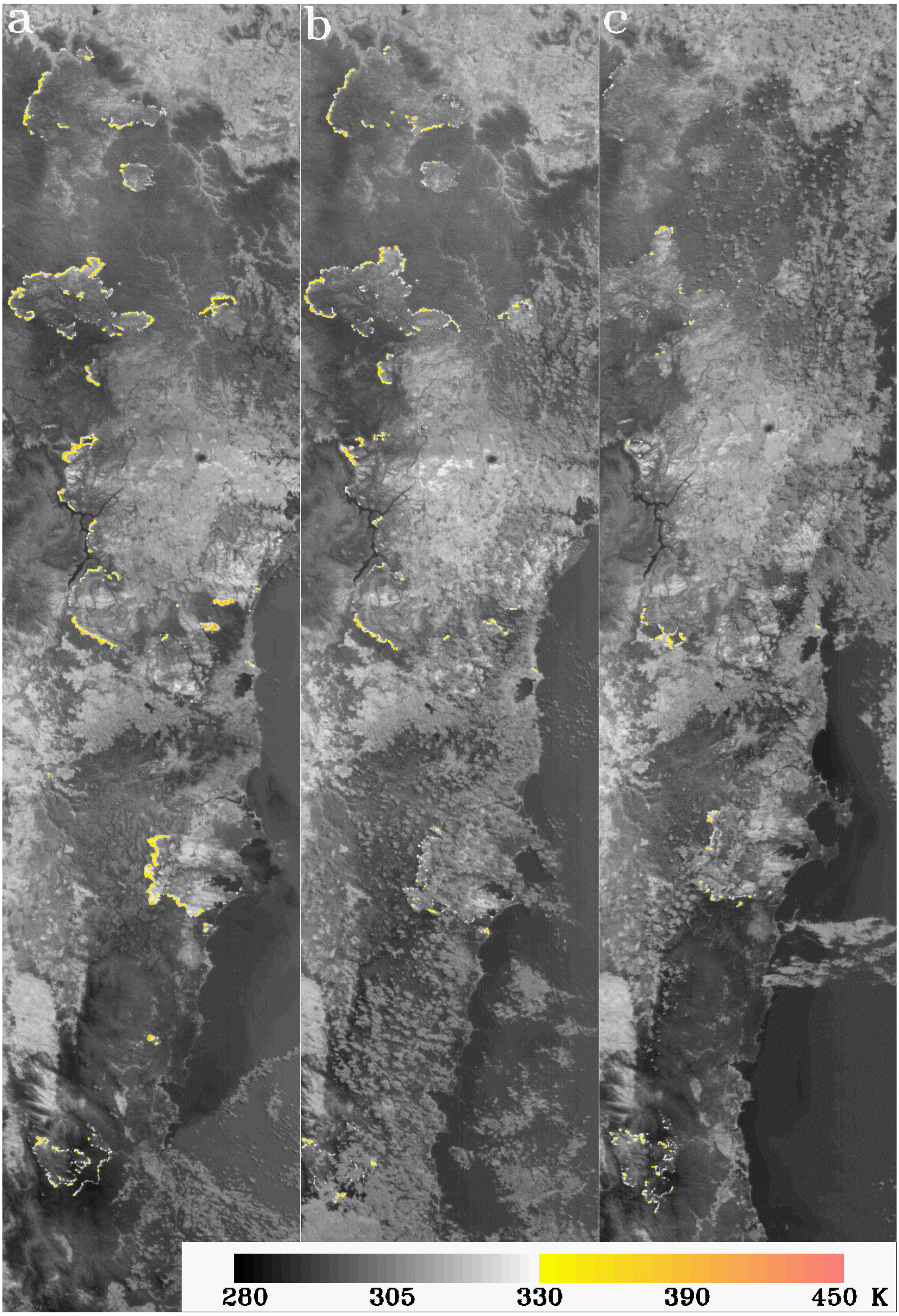


Figure 2 Images of bush fires in the area of Sydney obtained by BIRD in the MIR spectral band:
a – January 4, 2002; b – January 5, 2002; c – January 9, 2002;
the color-coded pixels with the MIR brightness temperature above 330 K are recognized as fires

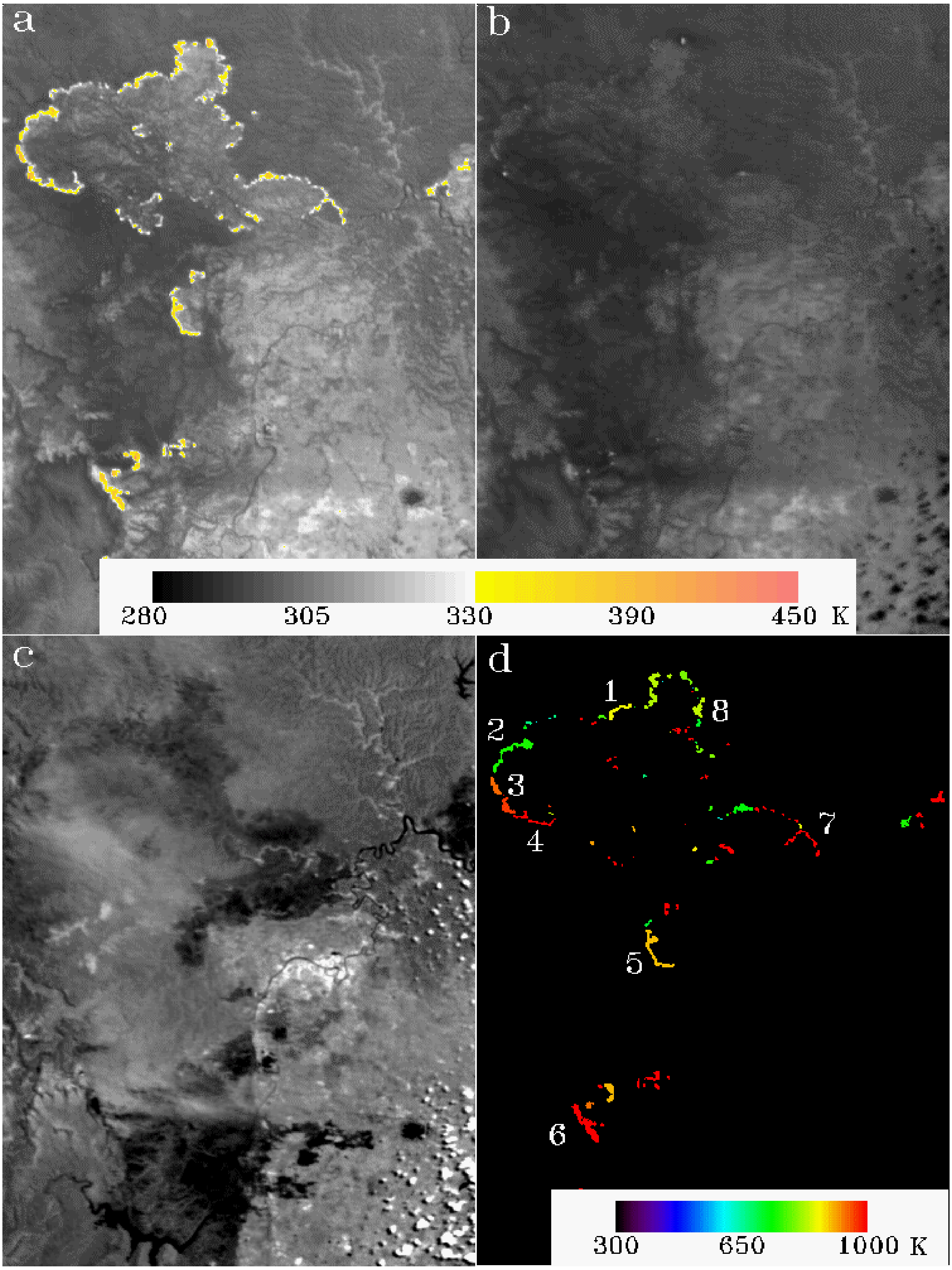

Figure 3 Fragment of the scene of the 5th January, 2002: a – MIR image; b – TIR image; c – NIR image; d – detected hot clusters; the black-and-white and color coding of the MIR and TIR images represents their pixel brightness temperature; the color coding of the hot clusters represents their equivalent fire temperature; the numbering of fire fronts corresponds to separate fire fronts.

entire scenes in Fig. 2). Some pixels with a lower temperature are also recognized as fires, what is confirmed by their location at the fire fronts. On the other hand, several white spots with the MIR pixel temperature of up to 328 K, which are seen in lower right part of the MIR image in Fig. 3a, are rejected as false alarms due to their relatively low MIR/TIR radiance ratio. Fig. 3b and 3c show that these areas have a relatively high TIR temperature and a low NIR radiance and thus evidently correspond to fire scars heated by the sun. This type of objects could produce false alarms if data of the sensors with a MIR channel saturation at ~320 K (like AVHRR) is used for fire detection.
Totally, 544 hot clusters were detected in Fig. 2 a-c.

The equivalent fire temperature and area are the temperature and area of a homogeneous fire at a uniform background (as estimated from the neighboring pixels) that would produce the same MIR and TIR radiant fluxes as the actual non-homogeneous fire. The hot clusters in Fig 3d are color-coded accordingly to their equivalent fire temperature. For most of the detected hot clusters, fire temperature was in the range of 650-900 K. The application of the Bi-spectral technique to hot clusters rather than to single hot pixels permits to avoid large re-trieval errors of fire temperature and fire area due to:

- inter-channel MIR/TIR geometric co-registration errors,
- difference of the point spread function of the MIR and TIR channels.

However, fire temperature and area still remain sensitive to errors in the TIR background radiance estimation (though this effect is reduced for clusters in comparison to single pixels). In the case of small fires, this makes the equivalent fire temperature and area applicable rather for a qualitative than for a quantitative analy-sis.

## ORBIT EXPIRIENCE AND RESULTS OF TECHNOLOGY EXPERIMENTS

According to the need to decrease the spacecraft costs and keep high performance characteristics of the spacecraft bus the BIRD satellite demonstrates new developed technologies at moderate costs in space. These are in particular:

### Low-Cost Star Sensor

An autonomous star sensor is necessary for the high precision attitude information. In the field of micro-satellite technologies there is a need for small and autonomous working star sensors in a low-cost price range. The BIRD star sensor development in close co-operation between Jena-Optronik and DLR shall fill this gap in the market. The sensor has a robust and compact electro-optical design with a total mass of 1,2 kg. The sensor consists of a CCD matrix camera in combination with an internal star catalogue and an image analysis software for star identification and search. The sensor delivers the attitude information in quaternions. The sensor is calibrated on calibration facilities in the lab and is tested by field experiments on ground looking into the clear night sky. One of the technological objectives in BIRD consist in the test and verification of the star sensor under real space conditions.

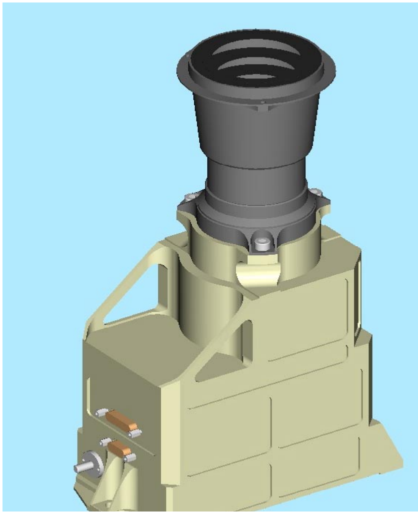

Figure 4 Star Sensor Astro 15, mass 1.2 kg

### First Results

First test in orbit showed that both star cameras determine their orientation reliably and with the right sign. They even will remain logged in if the slewing rate reaches up to 0.5 °/s.

### High Precision Reaction Wheel

For BIRD a reaction wheel system with 4 wheels in combination with 2 x 3 magnetic coils are applied. Up to now, it does not exist a big choice of different types of reaction wheels on the market. Basing on the reaction wheel development of the Technical University of Berlin (Prof. Renner) a new type of high-performance reaction wheel for micro-satellites was developed for BIRD in close co-operation between Astro- und Feinwerktechnik Adlershof GmbH, TU Berlin and DLR.
These reaction wheels are characterized by

- high control precision by means of smart control electronics,
- low level emitted vibrations, due to the advanced mechanical design and the high level of alignments and balancing,

- integrated electronics and robustness of assembly.

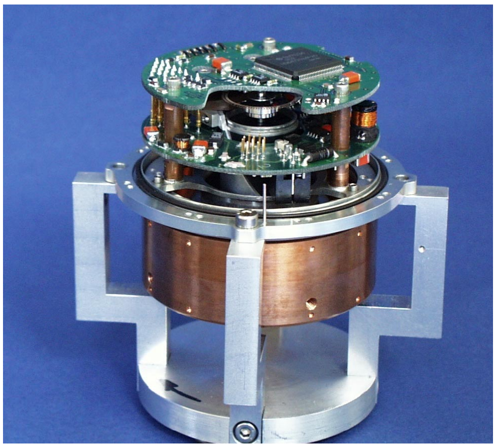

Figure 5 BIRD reaction wheel assembly

The torque generated by reaction wheels has a random deterministic noise part due to torque and force irregularities. To minimise the effect of torque noise on the pointing error budget a wheel state feedback with a Kalman filter is implemented into the wheel control processor. Inputs of the reaction wheels are rate acceleration (torque) or revolutions per minute or their variations. The reaction wheels were space-qualified and intensively tested including long-term behaviour in labs, test facilities and test chambers. But the high precision of control activities in space cannot be verified under lab conditions. For this the experimental determination of control activities is necessary in space. The main points are:

General objectives:

- space demonstration of the torque noise reduction by means of the internal feedback control of the reaction wheel for micro-satellites
- investigation of the wheel behaviour under space conditions

First results

Already on ground there was shown that the torques with a medium error rate of $10^{-7}$ Nm and with a variance of < 0.0016 Nm are effected. Therefore, the pointing errors for BIRD range lower than 22 arcsec. Because of the precise internal control the occurring errors are almost independent on the speed and the commanded torque when the determined by the wheel itself acceleration reserve is kept. This was sufficient in orbit, so far. All 4 reaction wheels have been working without any interference since the very beginning.

Autonomous Attitude Control

The attitude control system of BIRD is characterised by different sets of low and high performance sensors and actuators (see Fig. 6). They are controlled by the spacecraft bus computer. In order to accomplish high performance characteristics in the attitude control of the micro-satellite BIRD at moderate costs new components are developed. They comprise:

- a combination of two star sensors with different lines of sight for measurement of the attitude with a high precision in all axes,
- high precision reaction wheels for micro-satellites in tetrahedron arrangement,
- a low-mass magnetic coil system for desaturation of the wheels,
- high-autonomously working attitude control system basing on a state-space representation of the attitude estimation, prediction and control,
- real-time operational system embedding the attitude control software,
- combination of the attitude control with an on-board navigation system.

These new developments are to be tested in space with emphasis on their typical performance parameters, their limits and their behaviour in a complex environment. These investigations are a part of the space-technology demonstration.

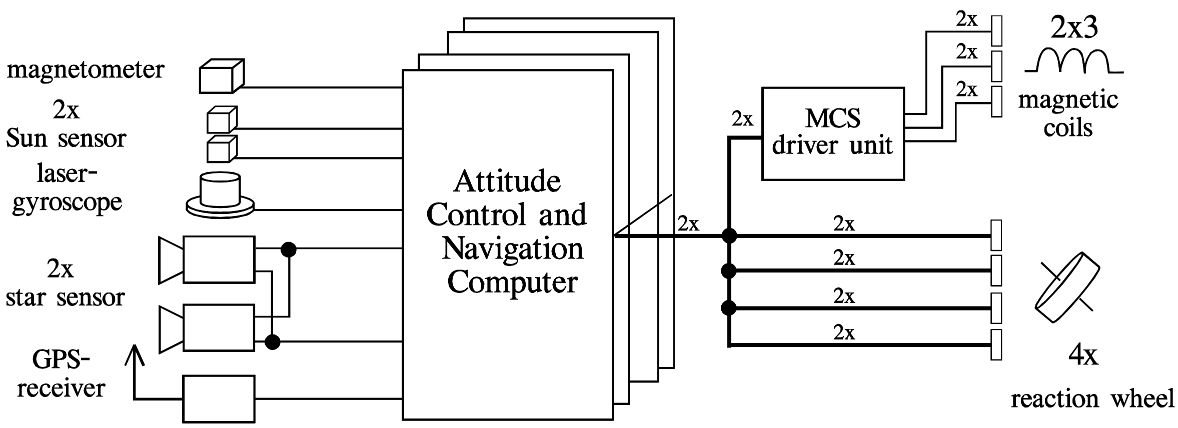


Figure 6 Block scheme of the ACS system

The redundancy conception includes the cases of cold, warm, hot and functionally redundancy of the components. Dependent on the results of the on-board failure detection system a autonomous decision on-board about the used sensor/actuator combination and the required attitude mode is possible and can be carried out, if enabled from ground.
But not only the redundancy conception can be controlled either by ground commands or by the spacecraft autonomy. The attitude control of BIRD can also be done in two generally ways:

- ground control of all actuator activities (with regard to the sensor signal evaluation) for attitude control by means of time tagged low-level command sequences and procedures including the ground controlled execution of command procedures for attitude mode set-ups and transitions,
- on-board evaluation (estimation and prediction) of the attitude sensor signals and autonomous execution of all actuator activities of attitude control for the ground controlled time-tagged or event controlled attitude modes.
- The autonomous attitude control procedure of the BIRD spacecraft bus has to be verified and investigated under real space conditions with regard to suitability and limitations for future spacecraft bus developments.

First Results

The first acquisition from an initial revolution with about 5 °/s up to the stable sun-pointing was perfectly performed, the mean damping acceleration was 0.1 °/s². The magnetic torquer system minimized the angular momentum very well. With an activated desaturation system practically no angular momentum exists any longer. The remaining jitter movement is lower than 6 arcmin/s. Commanded revolutions are effected high-precisely. The autonomous configuration of the ACS was repeatedly if not always involuntarily tested and turned out to be very reliable. Even, when the gyro-system shortly failed the satellite remained in an acceptable sun-pointing position although in this case its slewing rate could be derived only from the sun-sensor and the magnetometer.

Spacecraft Bus Computer

The Spacecraft Bus Computer (SBC) controls all activities of the satellite bus. The SBC receives, stores and processes the commands, gathers and evaluates the housekeeping data of all subsystems and partially of the payload and controls the telemetry and science data formatting and transmission activities on-board. Furthermore the Spacecraft Bus Computer is also the attitude control computer of BIRD, it means the complete hard- and software of the attitude control system is embedded in the SBC. Summarising these the SBC of BIRD has to fulfil the following general requirements:

- handling of a lot of different electrical and data interfaces
- controlling of different software tasks and algorithms
- controlling of time depend activities and software loops
- high processing performance (near real time)
- processing of high and low data rates
- monitoring of all spacecraft activities including the SBC-activities
- failure tolerant
- high robustness of all monitoring and control activities.

Figure 7 BIRD board computer by Fraunhofer FIRST

Subsequently the SBC is a computer system characterised by a high complexity resulting from its different interfaces to all subsystems, its components and its software modules. But the SBC has to work very reliably, robustly and failure tolerantly. However, the property of high complexity stands in opposition to the requirement of high reliability. To solve this conflict two measures to do are taken:
implementation of measures into the SBC for improvement the reliability and robustness of the SBC Board (latch-up detection and protection, redundant processing and memory structures)
implementation of a high redundant structure of 4 SBC boards and watchdog circuits for failure detection and recovery.
The new hardware technologies of the Spacecraft Bus Computer has to investigated in BIRD with reference to their behaviour in the real space environment.

First results

The board computers are functioning from the very beginning without problems, as it does the implemented unix-based operational system. Some bursts of high-energy radiation and extremely high particle density caused a switch to the redundancy structure or into the safe mode. By this the functioning of the redundancy structure was demonstrated. So was the latch-up safety control implemented on the computer card.

On-Board Navigation System

The Onboard Navigation System (ONS) of BIRD is part of the satellite's Attitude Control System (ACS) and allows the demonstration of the concept of autonomous navigation for passive satellites. Based on a low-cost GPS receiver, an advanced orbit determination and orbit prediction system assures, that precise position and velocity data are available onboard, even in the absence of GPS measurements. This allows to support the ACS with data that are required for the Earth-pointing of the satellite during the image data takes and the communication with the ground.

Moreover, the precise position data are applied for tagging of the BIRD image payload data already onboard, a procedure called geo-coding, that is demonstrated for the first time on a spacecraft. This, in turn, significantly accelerates the process of image data restitution and evaluation.

The ONS also supports a GPS-based precise time synchronization of the onboard clock. To that end, an advanced clock model is implemented, that makes precise absolute times available onboard, even for long time intervals. This leads to less frequent synchronization commands form the ground and facilitates the spacecraft operations.

Finally, the system is capable to estimate mean orbital elements from GPS data in the form of standard Twoline elements, that are commonly applied for the exchange of orbit data. Twoline elements will therefore be transmitted to the ground station, where ground station contacts are computed using Commercial-off-the-Shelf tools. This concept demonstrates a novel concept for combined ground-space autonomy and consequently avoids the supply of orbit data from the control center. Furthermore, shadow transit times and ground station contact times are computed autonomously onboard and thus demonstrate the high potential of increased autonomy for satellite operations, applicable to a wide range of future missions.

First results

Already some days after launch of the satellite the ONS was put into operation as a technology experiment. After the smooth start it was possible to determine the current orbit position on board of the satellite with an accuracy of 10 m in any direction. The comparison of the orbit positions given by the satellite and these ones retrieved at GSOC by means of an independent orbit determination and a highly precise orbit modelling served as a proof of this capacity. The status now is: an accuracy of 5 m in all axes was performed. The technology experiment was closed, and the ONS carried on in the routine phase. BIRD demonstrates the high-precision on-board orbit determination, and on-board generation of Twoline elements.

On-Board Classification Experiment

The general trend in remote sensing is on one hand to increase the number of spectral bands and the geometric resolution of the imaging sensors which leads to higher data rates and data volumes. The on-board data handling storage and the down-link of huge data volumes in a short time is very expensive in power, mass, volume and money. Comparable huge expenses are necessary on ground to receive, to pre-process, to archive and to retrieval the data. But the user process the data, do a calibration as good as necessary, extract and/or transform features and finally classify the information content in a limited number of classes in the field of its interest. The related processes need a certain time so the high-level data products are ready with a time delay in the order of days till weeks.

For a group of remote sensing tasks, like disaster warning and hazard detection or dedicated monitoring of limited remote sensing parameters (environmental pollution parameters, condition parameters a. s. o.) a quick classification and a short response time is mandatory. For this kind of tasks the solution can be solved (within a limited cost frame) only by implementation of a high level data processing chain on-board the satellite. Powerful processing technologies and algorithms allow for this kind of tasks to implement the processes of data pre-processing, calibration, correction of distortions, feature extraction and classification of data on-board of the satellite. Solving the problems of geo-referencing or geocoding on-board of the satellite to, high-level data products can be send to the final user directly without delay. Furthermore the total costs can be decreased dramatically because the data volumes and the data downlink rates can be highly reduced. For this reasons by means of the BIRD mission the autonomous thematic data processing on-board of the satellite will be demonstrated and investigated in detail.

A complete pre-processing chain is implemented onboard and will pre-process the data ready fore feature extraction and classification. To limit the impact of seasonal atmospheric and illumination variations to the classification results an adaptive , i. e. a learning system is implemented on-board of the satellite. Additionally, a new designed and to tested on-board navigation system (ONS) will deliver the orbit position without delay and with a high precision. In combination with the attitude information and a global Earth terrain model the on-board classification experiment of BIRD will demonstrate the feasibility of solving of high-level data processing tasks on-board. With the on-board neural network classificator experiment a the autonomous classification till to a high level data product will be done on-board of the satellite. The thematic data reduction will be made by a multispectral supervised classification. For this classification a special hardware based on the neural network processor NI1000 was designed. This neuronal network is able to "learn" on-board BIRD by an upload of new training vectors for desired classes to be separated. Because using a neuronal network it is possible to reach high data rates for the classification process. Before the feature extraction and the classification process can start an on-board data preprocessing has to carried out like the co-registration of multi-sensor data and data normalisation.

First results

June 14 2002 for the first time on board of the BIRD satellite a scene was classified by means of the neural network classification experiment. For this the classes water, warm clouds, cold clouds, fire, land surface, and non-classifiable were defined. The classificator was “teached and trained” using the characteristics of the Australian bush fires of January 4, 2002. In follow-up experiments the working method of the neural network classificator was investigated and demonstrated.

Experimental Ground Station

In the frame of the small satellite project BIRD, an Experimental Ground Station (EGS) is developed. The basic idea of the EGS consist in the philosophy to give the user only regional limited data, for which a high performance ground station is not necessary. Thus the data volume to be received can be reduced. Many local authorities, such as agriculture or fire combat departments for example, needs only regional limited data to do a more efficient work in their region. The basic idea of the EGS is therefore, to analyse the capabilities and limits of a low-cost ground station, which outputs only the data, which is needed by the local end-user. The antenna size of such a Station can be small, which is one of the important cost drivers. The low-cost aspect of the system leads to a design, which incorporates the extensive use of existing commercial-of-the-shelf (COTS) hard- and software. A common PC with a Pentium class CPU is used for data reception and processing as well as for commanding. In order to have a compact size and a easy transportable system, most of the baseband-hardware is built into the PC.

The software for the downlink is intended to receive, display and store payload and housekeeping data. Payload data can be processed with a separate software, which uses algorithms developed by DLR. Special effort is made to implement fire detection algorithms. The housekeeping data can be displayed online, so that the health of the satellite can be monitored in real time or past data can be stored in order to analyse the satellite systems during no-contact times. In case of detected anomalies, alarm messages can be forwarded by means of pager call, SMS, e-mail or fax. Automatic update of two line elements directly from the BIRD satellite will be possible. The software for the uplink of telecommands allows also to send other data to the satellite, which can be used e.g. to update the on-board software or to support the classification algorithm.

First results

The ground station receives and processes BIRD data. The housekeeping data are visible on-line when being received. The received payload-data (image data) can be decommuted, pre-processed, and displayed in a quick-look mode almost in real time.

## SUMMARY

- Temperature and area extent of vegetation fires or other hot spots can be evaluated from space.
- The new infrared array sensor system suitable for small satellite missions was tested in space successfully.
- Pixel co-registration of the BIRD-channels RED, NIR, MIR and TIR is functioning.
- Several new micro-satellite technologies are tested successfully in space.
- The thematic on-board data processing by means of an neural network classificator are tested successfully in space.
- Direct reception of satellite data by end user are demonstrated.
- The BIRD spacecraft bus is a new adaptive platform for further science or Earth watch missions supplementing already planned missions.