BIRD - a Microsatellite for Hot Spot Detection

by
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Abstract

The BIRD mission of the German Aerospace Centre shall demonstrate the scientific and technological value and the technical and programmatic feasibility of a remote sensing small satellite mission under low budget constraints. The payload -a new generation of cooled infrared detectors- is adapted to the mission objective - the investigation of hot spots caused by forest fires or volcanic activities completed by the diagnosis of vegetation conditions and changes.
BIRD –the **B**ispectral **I**nfra-**R**ed **D**etector- is a three-axis stabilised spacecraft within a volume of 0.21 m³ and a mass of 88 kg. In flight configuration with one fixed and two deployed solar panels, providing 40 W average and 200 W peak power, the spacecraft dimensions are 620x 1600x 620 mm³.
Although compatible to several launchers due to the highly compact design, the launch is scheduled for mid 2000 as a piggy-back payload. To fit in this time scale a modular design was chosen for parallel development, manufacturing and integration of all functional segments.

The article gives an overview of the mission objectives and some of the main design aspects as well as shows the status of work of the space segment.

Introduction

The growing interest on the investigation of fire as indicators for influences on the natural environment from space is reflected in several mission studies. So also DLR initiated in 1994 the FIRES proposal [1] which was oriented on a design-to-performance approach. This and the mission concept based on a spacecraft in the 300 kg- class was not able to fund. To materialise the main ideas the BIRD concept was established. Turning to a strict design-to-cost philosophy and a down sizing of the satellite by a factor of 3 the BIRD microsatellite mission for investigation of hot spots and vegetation exploration could be implemented within the DLR.
However one of the primary objective now is to operate a new generation of imaging infrared detectors in space which is embedded in a set of ambitious scientific tasks of the science community. The build-or-buy decision for the spacecraft bus was also very much influenced by the special requirements of the payload. Thus the space segment design, which the article is focused on, is performed as a modular concept which can be adapted to other payloads with similar budget needs too.

Mission Objectives and Requirements

Besides the detection and identification of hot spots, caused by vegetation fires, industrial hazards and burning oil wells a variety of scientific objectives emerges from related natural events - volcanic studies, investigation of clouds and atmospheric properties (pollutant emission) and vegetation analysis (aridness, re-cultivation).
The analysis of scientific objectives leads to several requirements, here provided by Table 1. for the scientific instruments.

Table 1 - Functional mission requirements on the BIRD payload

Task	*Spectral*	*Radiometric*	*Geometric*		*Other*
			GSD	***Swath Width***	
Hot-spot detection hot-spot classification observation of vulcanoes	*3.4-4.2 µm 8.5-9.3 µm 1 VIS/NIR channel*	*Temperature estimation within dynamic range >2000, saturation limit at T<1300 K, rad. Resol. within IR >12 bit*	*< 300 m*	*As large as possible, min. >100 km*	*Different visir angles at VIS/NIR*
Determination of VI3 and comparison with the NDVI	*840-890 nm 600-670 nm 3.4-4.2 µm*	*≥ 7 bit (VIS/NIR) ≥ 12 bit (MWIR)*	*100 m – 300 m*	*Small*	*Integer pixel size ratio of VIS/NIR and IR pixels*
Improvement of Leaf Area Index	*840-890 nm*	*≥ 7 bit (VIS/NIR)*	*100 m – 300 m*	*Small*	*Different visir angles*
Realtime detection of clouds, cloud investigation	*Min. 3 VIS/NIR channels + 1 TIR*	*Dynamic range >1000*	*≤ 1 km*	*Minimum > 100 km*	*Stereo cabability*
Test and evaluation of multi-sensor-multi-resolution technique, test of on-board neural network classification	*3.4-4.2 µm 8.5-9.3 µm 1 or more VIS/NIR channels*	*≥ 7 bit (VIS/NIR) ≥ 12 bit (IR)*	*100 m – 300 m*	*Small*	*Integer pixel size ratio of VIS/NIR and IR pixels*
Technological experiments concerning IR-system	*3.4-4.2 µm 8.5-9.3 µm*	*Range-level + drift- and detectivity control, vibration isolation, pixel alignment*			

The technological objectives can be categorised according to three aspects:

1. Space operation of new infrared detectors with
- qualification of integrated cooler-detector unit
- investigation of cooler vibration impacts on sensor MTF and AOCS performance
- long term stability of cooler performance
- dynamic range control of IR- detectors
- study of the stability of line-of-sight of the sensors and pixel co-registration

2. Test of a thematic on-board classificator with
- geometrical and radiometrical correction of sensor signals
- geometrical correction of systematic spacecraft errors and spacecraft attitude
- orbit propagation model and geo-referencing
- Earth geoid shape and local altitude correction

3. Development of small satellite technology with
- concept for extremely unsteady power consumption
- thermal management of varying point sources
- high performance attitude control system
- partly autonomous observation modes

The requirements on orbit and operations are determined by the fact that BIRD is foreseen for a piggy-back launch. That means that the design has to fit in several scenarios. At least a LEO from 450 to 900 km (500 km preferred) with an inclination >53° is required.
The operational lifetime is 1 year with a 10 min duty cycle over land regions. This restriction is coming from the limited data volume which is able to handle in a store-and-forward manner with at least one Mission Operation Center and another small experimental ground station for payload data receiving. Besides that it underlines the characteristic of the BIRD mission to be a demonstrator and not an operational system.

Scientific Instruments

Infrared Camera - First Steps

Direct detection of hot spots with the required high resolution is not compatible with the limited resources of a microsatellite. Therefore special techniques in the subpixel range for BIRD were developed [2]. Based on staggered IR-line arrays a first two-channel imaging system called IRCAM was built. The main parameters of the detector are given in Table 2.

Table 2 – IR-Detector parameters for BIRD

Detector material	*HgCdTe*
Spectral channels	*3.4 – 4.2 µm* *8.5 – 9.3 µm*
Detectivity	$10^{10} cmHz^{1/2}/W$
No. of elements	*1024 (2 Arrays available)*
Array format	*2x512 staggered*
Element size	*30 x 30 µm*
Element stagger	*15 µm*
Max. pixel rate	*5 Mhz (4 outputs)*

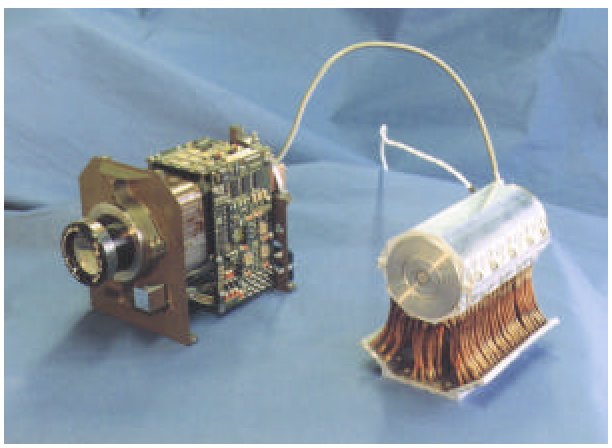

Fig. 1 – One channel of IRCAM - Sensor Head with cooling engine

The detector of the IR-camera head as shown in figure 1 is cooled to 80 K operating temperature by a separate Stirling cooler. This system was intensively tested under laboratory and airborne conditions. Several airborne campaigns demonstrated the feasibility of the BIRD imaging concept (see Figure 2).
The system performance allowed the detection of hot spots with a size of a tenth of the GSD if the temperature is 800 K or higher. That means from the proposed BIRD orbit fires in the 30 m range are able to identify.

Fig 2. – Airborne experiment results: hot plate of 1m² with 200°C (cross marked) detected from 3000 m altitude. MWIR-image above, LWIR below

However the first results also identified the main disadvantages of the design- the high power consumption for cooling (40 W cool-down, 32 W operation per channel) and the significant influence of thermal radiation coming from the instrument inner structure. The ladder is namely caused by the fact that due to cost reasons IR-lense and cold shield design inside the dewar of the detector was insufficiently adjusted.
This was the reason to change the approach for the flight model of the BIRD- IR-camera.
The IR-electronic unit, providing A/D conversion, detector control and calibration operation as well as digital data handling for both channels was kept unchanged.

Hot Spot Recognition Sensor (HSRS)

Equipped with the same detector as before a integrated detector/ cooler design was developed and qualified (see Figure 3). It consumes a factor of 4 less power. Together with a new lens design the inner radiation disturbances could be decreased significantly.

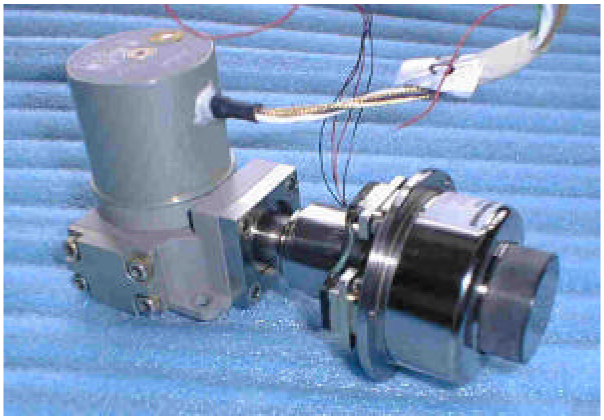

Fig.3 – Miniaturised integrated detector/ cooler assembly

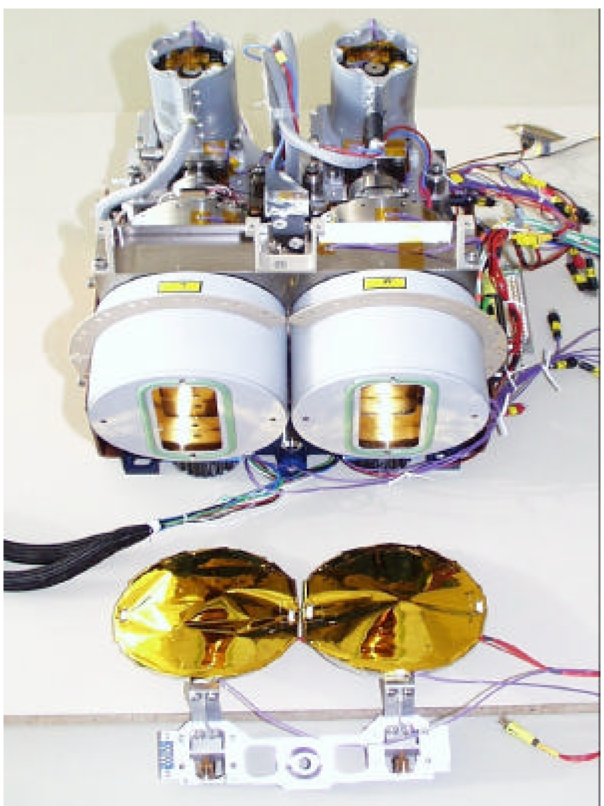

Fig.4 – Engineering Model of the HSRS Camera Head, calibration covers separated

Due to the strong requirement of the co-alignment stability in the line-of-sight of the MWIR to the LWIR channel (±0.2 arcmin @ duty cycle) the original design of two independent camera heads were combined in one optomechanical structure with a special thermal control system. As shown in Figure 4 a cover in front of the IR-lenses is foreseen contai-ning a heatable blackbody for in-flight calibration purpose. The inherent total failure risk is minimised by a separation mechanism that rejects the cover sytem in emergency cases.

Wide Angle Optoelectronic Stereo Scanner (WAOSS-B) – an Example of Hardware Reuse

This instrument is the VIS/NIR-sensor of the BIRD payload. Actually developed for the MARS-96 mission a flight spare model will be used and modified slightly.

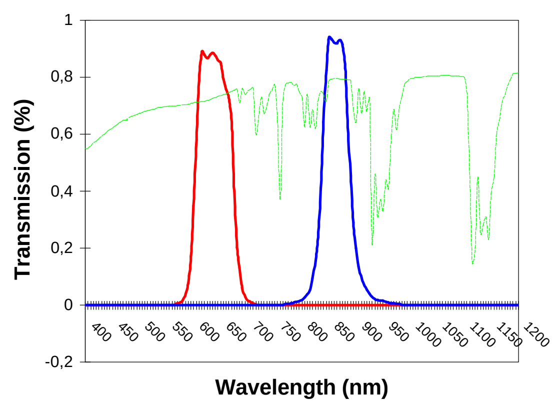

Fig. 5 - Spectral bands of WAOSS-B (NIR doubled)

New lenses with integrated filter providing narrow spectral bands over a wide field of view of 50° (see figure 5) will adopt the instrument to the tasks of vegetation exploration. On the other hand the in-track stereo capability is a important feature for the cloud investigations.

Due to the modular electronic concept of WAOSS-B almost no hardware modification are needed and the re-configuration is concentrated on the software side.

A special requirement was set to the power system of BIRD because the camera electronics of WAOSS-B was developed for a 28V DC standard bus voltage.

BIRD-Instrumentation as an independent Multi-Sensor Assembly

The development of the BIRD components was from the beginning sub-system-oriented. In the case of the payload the functional architecture allows full integration as well as calibration and test independently from the spacecraft. The interfaces are reduced to a minimum (power, telemetry/ telecommand, structural and thermal attachment) which have to be defined early but realised on the very end of the development timeline.

Payload Data Handling System (PDH)

The PDH is the functional integrative part of the scientific payload. It has data interfaces to all instruments, the spacecraft bus computer (SBC) and the down-link telemetry channel.
Three kinds of tasks are assigned to the PDH:

- distribution of high level commands and Housekeeping extraction out of the payload data stream
- science data storage, telemetry frame generation and down-link
- on-board thematic data compression

Each of the two functional redundant PDH-subsystems is based on a TMS320C40 digital signal processor equipped with 1 Gbit mass memory. Advanced multi-chip module technology allows to compress the size of the processor module to one standard European Size printed circuit board.

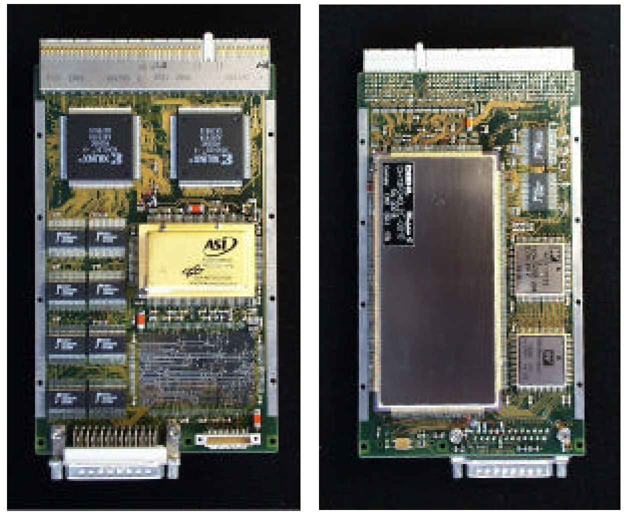

Fig. 6 – Both sides of the PDH processor board, Mass memory (1 of 2 assembled) left, 3D-MCM-processor hybrid right

Figure 6 provides the status of this development.

Other technological experiments are the fibre optic interconnects or on-line real-time parallel processing. Also the tests of the on-board geo-coding facility and different classification algorithms with the neuro-chip NI1000 are of experimental character.

Technical Data Overview

To summarise this section Table 3 gives the main technical data of the payload calculated from an altitude of 450 km.

Table 3 - Main technical parameters of the BIRD scientific instruments

	HSRS - MWIR	HSRS - LWIR	WAOSS-B
Spectral bands	3.4 - 4.2 um	8.5 - 4.2 um	forward 600 - 670 nm nadir, backward 840 - 900 nm
F-number	2.0	2.0	2.8
Focal length	46.39 mm	46.39 mm	21.65 mm
Pixel size	30 x 30 um	30 x 30 um	7 x 7 um
No. of pixels	2 x 512 staggered	2 x 512 staggered	3 x 5184 (2884 illum.)
Instantaneous FOV	2.22 arcmin	2.22 arcmin	1.11 arcmin
FOV across track	19 deg	19 deg	50 deg
FOV in track	n.a.	n.a.	+25 , 0, -25 deg
Ground pixel size	290 m	290 m	145 m
Swath width	148 km	148 km	418 km
Quantization	14 bit	14 bit	11 bit
Data rate (aver./ peak)	693/ 4790 kbps	693/ 4790 kbps	597/ 600 kbps
Power consumption	42 W incl Electr. Unit	42 W incl. Electr. Unit	18 W
Mass	7.3 kg Camera Head + 6.5 kg Electronic Unit		8.4 kg

Development of the Spacecraft Bus

Spacecraft Modes - Task of Attitude and Orbit Control

To operate the BIRD payload nearly all functions of a classical remote sensing spacecraft have to be fulfilled. Due to the high impact on cost and spacecraft size an early decision was to do without any propulsion system. So no active orbit maintenance can be provided and a consequence of that is the limited lifetime to approximately one year (450 km altitude).

Other constraints are:

- the push-broom principle of the scientific instruments – slew rate of < 1°/s ,
- requirement for pointing accuracy of ± 5 arcmin with a pointing knowledge of ± 0.2 arcmin per axis,
- the need for optimal Sun-pointing to generate sufficient power.

200 W peak power are needed for the detection mode. Together with the data volume constraints this mode is defined as the duty cycle which can be worked out in three adjacent orbits for 10 min each.

Basically 6 modes of operation of the spacecraft are defined:

1. Sun pointing mode – accumulation of energy
2. Earth pointing mode G – coarse, data downlink
3. Earth pointing mode F – fine, remote sensing
4. On-board processing and experimental sensor data classification
5. Remote sensing and down-link at night-time
6. In-flight calibration mode – Moon or deep space pointing.

The required 3-axis stabilisation is provided by a set of components with any new developments among them.

Fine Attitude Actuator – Reaction Wheels

After separation of the spacecraft from the launcher at first 3 pairs of magnet torquers with a dipole moment of 3 Am² will decelerate BIRD's initial movement. A concept without magnet field sensor is under consideration. The magnet torquers are part of the secondary structure and serve as a corset for the multi-layer-insulation at the same time.

Reaching a slew rate below 4°/s the spacecraft motion is taken over by 4 reaction wheels which are oriented according to the planes of a tetrahedron. This wheel is under qualification (see figure 7) with the parameters given in table 4.

Table 4 – Parameters of the BIRD Reaction Wheel

Angular momentum	*>0.2 Nm*
Slew rate (BIRD specific)	*2 – 4°/s*
Voltage	*16 – 24 V*
Power (Steady state/ maximum)	*1.2 W/ 9 W*
Mass	*< 1 kg*
Dimensions	*dia. 80 x 80 mm*
Temperature range	*-15°C – +50°C*
Vibration load	*10 g rms, 20 g @ 5 msec*
Friction	*< 0.3 mNm*
Electro-mech. time constant	*10 s*

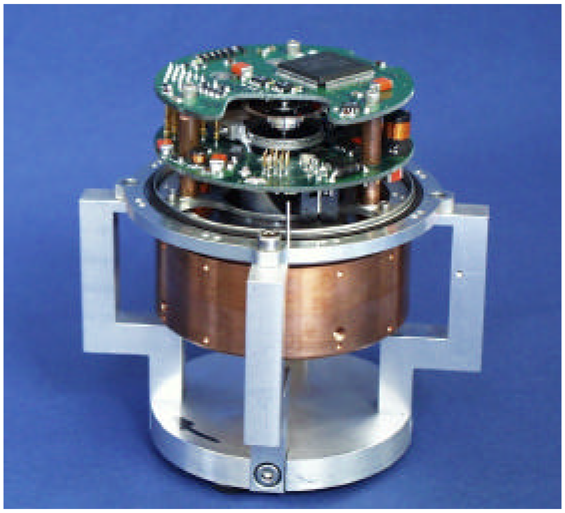

Fig. 7 – Flywheel and control electronics of the BIRD Reaction Wheel on an integration spider

The accompanying attitude sensor is an integrated laser gyroscope containing sensors for all three 3 axis with an resolution of 2.7 arcsec at a drift of 1°/h. The attitude data can be delivered with an update rate of < 100 Hz. The size is comparable with that of one reaction wheel.

Fine Attitude Detector – Star Sensors

Another important development is the star sensor which will be outlined for BIRD in two configurations. It is dedicated to the high-accuracy attitude control tasks during data acquisition from Earth. However one of the star sensors is switched on all the time during mission. According to the figure 8 one points in orbit normal position and the other is oriented 30° off that direction towards off-nadir side.

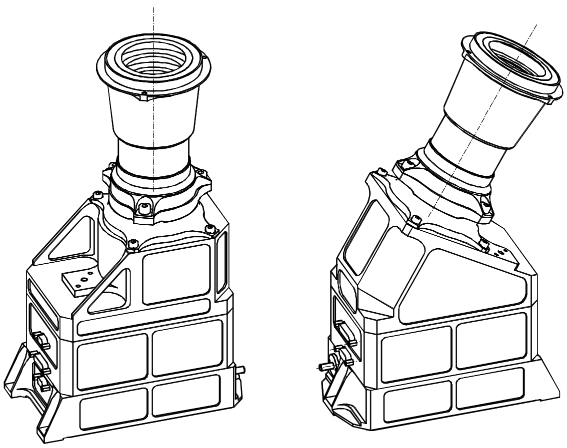

Fig. 8 – Modular design of the BIRD Star Sensor twins

Including an own processor it provides a fully autonomous attitude determination with 100% probability. The sensor inter-link capability is implemented for improvements of the roll axis accuracy. The main technical data are given in Table 5.

Table 5 – Parameters of the BIRD Star Sensor [3]

FOV	15° x 15° 24° x 24° optionally
Sun exclusion angle	45°
Star accuracy	≤ 2.5 arcsec
Line of sight accuracy	≤ 1.0 arcsec pitch/ yaw ≤ 10 arcsec roll ≤ 1.0 arcsec (2 sensors)
Sensitivity	6.0 mv @ ti = 100 msec
Update rate	up to 10 Hz
Slew rate	≤ 0.8°/s full accuracy
Power	5 W Sensor 1 W Peltier
Dimensions	70 x 130 x 230 mm³
Mass	1.2 kg
Life time	2 – 5 years LEO

The AOCS is controlled by the Spacecraft Board Computer and completed by a GPS as shown in the figure 9.

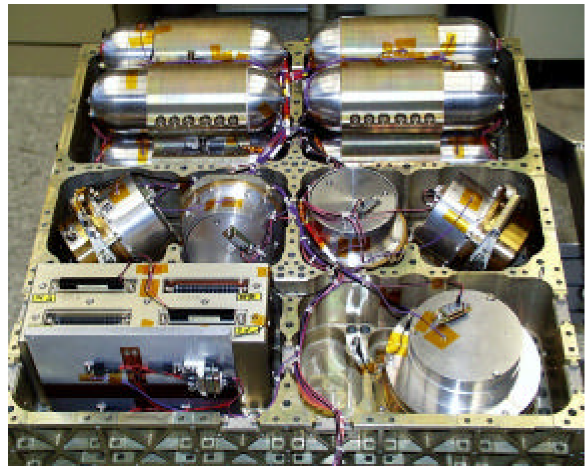

Fig. 9 - BIRD Service Segment with 4 reaction wheels (middle), Laser-Gyro (right), GPS (box left) and the both battery stacks with 2 x 4 NiH2 cells (2,5 V, 12 Wh each) plus power control unit.

BIRD Architecture - a Highly Integrated Modular Design

Structural Concept

Configurations of small satellites are mostly difficult to structure because there is a strong interaction of geometrical and functional requirements within a small volume.
Commonly, payload and subsystem components in combination with the satellite structure have to be developed in an integrated and highly iterative design process considering the spacecraft as one complex device.

According to the figure 10 the primary structure of the BIRD architecture is a cube-shaped tower of three segments:
1. Service Segment as the basic segment with separable launcher interface containing batteries, reaction wheels and gyroscope as well as the GPS system
2. Electronic Segment as a container of payload, spacecraft electronics and the communications package
3. Payload Segment as a platform for the scientific instruments and the star sensors.

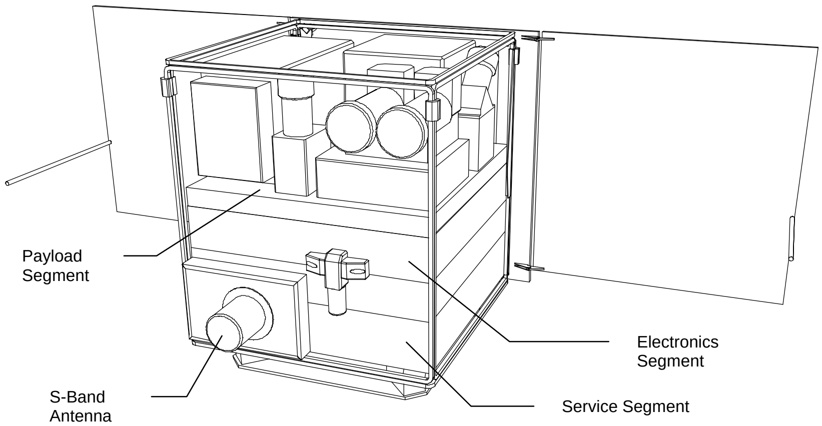

Fig. 10 - Flight configuration of BIRD

The configuration is completed by the secondary structure namely the solar cell system of three solar panels, two of them deployable, the antennas and magnet torquers.

Besides the fact that the highly compact design is open for more than one launch opportunities the modular concept comprises growth potential for alternative applications. Any payload with dimensions of 460 x 460 x 250 mm³ could be adapted and supplied with an average power of about 50 W.

Parallel development, manufacturing and integration relaxes the time scales of the project. The figures provided on the next chapter are taken within few months from the begin of 1999 and demonstrate the effectiveness of this approach during the development of the Structure Thermal Model (STM) already. It is an important step for the design verification and minimises the risks to build the Proto-Flight Model.

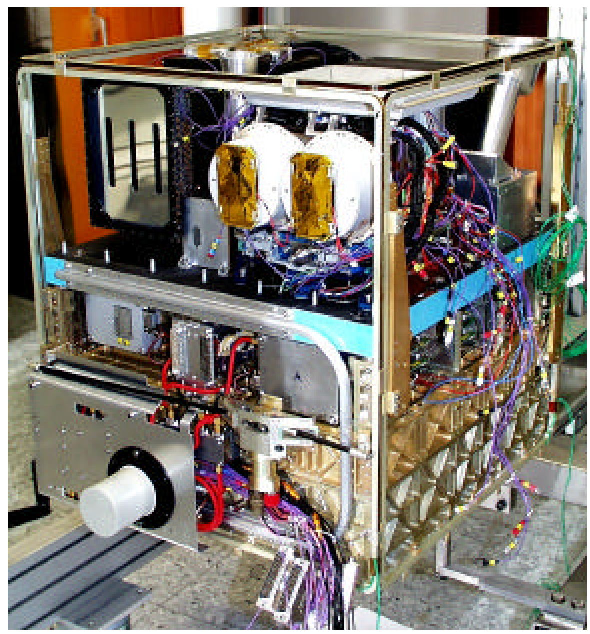

Fig. 11 - STM under integration, on top the Payload Segment with WAOSS-B, Star Sensor 1 and HSRS-MWIR/ LWIR from the left, below the telecomms package and the release mechanism of the solar panels

<u>Environmental Tests - Irreplaceable</u>

Figure 11 gives an impression of the STM- integration - the first time the whole spacecraft appeared. The comparison to the figure 10 shows the consistence of the design presented in Phase A and B of the project.
All main interfaces could remain stable, mass and size have grown not more than 10 %.

Thermal Design and Test

Thermal-vacuum testing was focused on two problems. How the dynamic of power dissipation influence the temperature profile of the satellite and how sensitive the design would be due to the changing, because not sun- synchronous, orbit conditions. Here hot (much sun incidence) and cold (long eclipse) cases were studied.

The thermal design itself is strictly passive. The basic elements are the bottom plate serving as radiator and the heat pipes leading from the payload as the main hot spot to it. All other problems are solved by spot heating or element-oriented heat dissipation.
Figure 12 provides the STM before TV-Test in flight configuration. All honeycomb structure of the solar panels is covered inside by highly sun-reflective and heat-dissipating coating.

Special attention was raised on the technology for the structure of the scientific instruments. The base line to build with CFRM to fulfil the requirements of co-alignment has the main disadvantage to be a thermal insulator in-plane (measured coefficient 0.55 W/mK). With the help of a intermediate layer of 3 mm CFC (Carbon Fibre Carbon) in combination with two CF-honeycomb panels at least an thermal conduction coefficient of 60% of a comparable aluminium structure could established.

The thermal-vacuum test was combined with in-situ measurements of the optical orientation. Deviations of 1 arcmin over the duty cycle and 3 arcmin over the simulated orbit influences (hot/ cold case) could be detected.

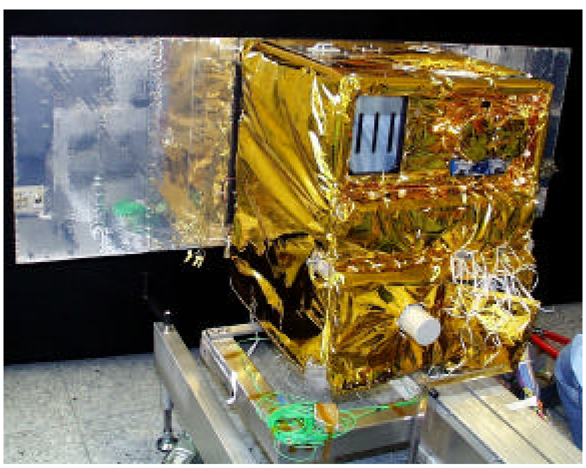

Fig.12 – BIRD equipped with multi-layer-insulation before TV-Test

Figure 13 provides some of the temperature profiles of BIRD components. Beginning from thermal equivalent room temperature firstly the cool down characteristics was checked without payload operation (Basic mode 40 W dissipation). Then 5 orbit cycles after another with remote sensing sequences where simulated without critical results.

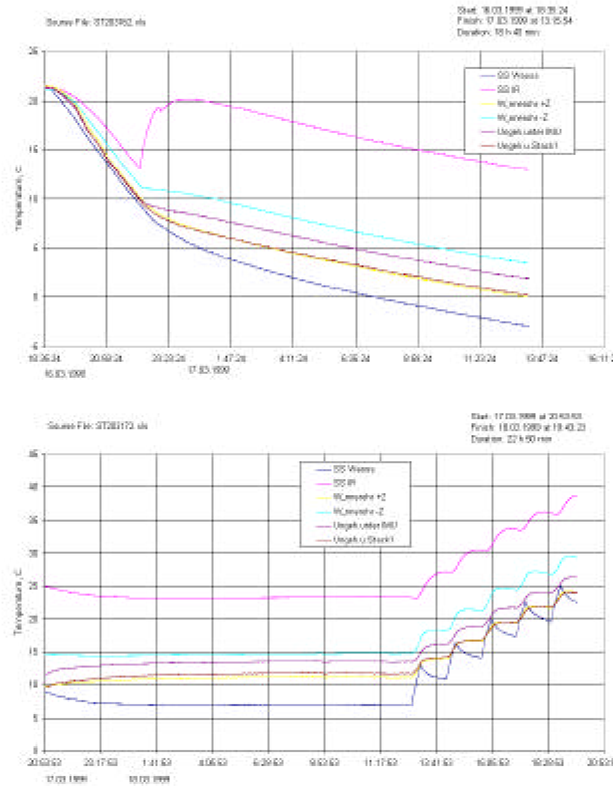

Fig. 13 – Graphs of thermal cycles of the BIRD STM under TV-test

Mechanical loads and vibration testing

To launch a spacecraft piggyback is surely a draw back because there is no specific launch fixed at the beginning of the design process. Therefore top level requirements where set due to possible launch options. Actual in the BIRD case the flexibility has extended to a status that two kinds of separation systems can be adapted to the bottom segment with slightly modification of attachment interfaces and CoG adjustments.

To reach enough stiffness to avoid interference effects with the natural frequencies of the launch vehicle a design goal of 100 Hz was set for the BIRD's natural frequency.

First analysis with the help of FEA resulted in 115 Hz which gives some margin to the elasticity of the separation mechanism. The full verification of the serviceability of the design was given by tests.

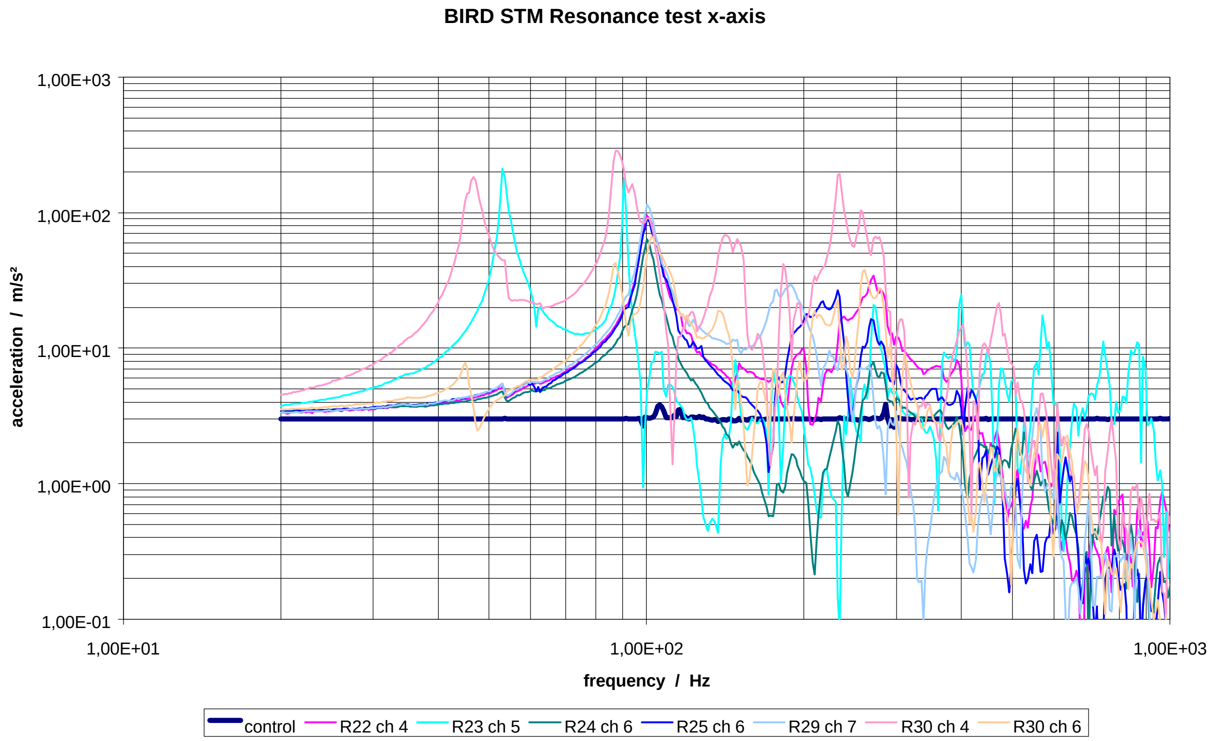

Fig. 15 –Results of one of the resonance surveys during vibration testing, Level of power spectrum density 0.05 g²/Hz ± 6 db/oct** [4]* ***indication:
R 22 – HSRS Electronic Unit
R23 – Magnet torquer Nadir
R24 – HSRS Camera head
R25 – WAOSS-B
R29 – PDH electronic board
R30/4 – Solar panel
R30/6 – Bottom Segment

Next steps – the Proto-Flight model

With the pleasant results of the STM-phase the manufacturing of the Proto-Flight has started already. Currently the work is concentrated on the preparation of integration and test environments for instance an air-bearing facility for AOCS-Tests and the calibration concepts.
Another key point is the initiation of the electrical functional process including the telecommunications equipment as well as the programming of the desired software.
Flight readiness is dedicated to mid-2000 but the launch date is determined by an affordable launch opportunity and could also be in 2001 [5].

The authors have to thank all the BIRD team members providing the content of this article with their work which regrettably could not cover all activities.

Abbreviations

GSD – Ground Sample Distance
FOV – Field of View
MTF – Modulation Transfer Function
LEO – Low Earth Orbit
CFRM – Carbon Fibre Reinforced Material
CoG – Centre of Gravity

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