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Project description

The Micro-Satellite *Flying Laptop*

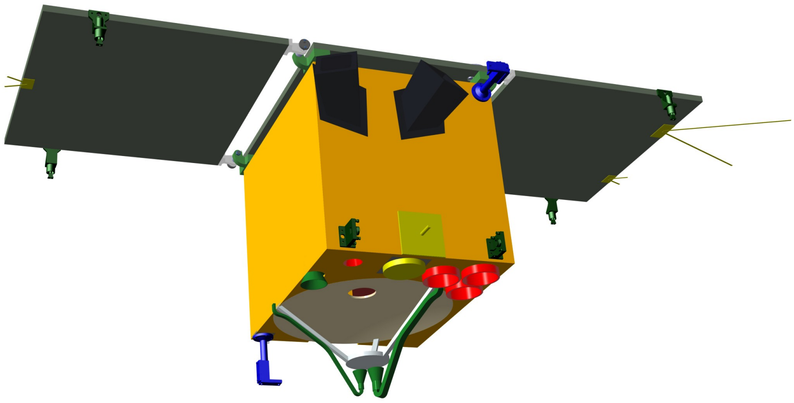


Figure 1: Flying Laptop

STUTTGART SMALL SATELLITE PROGRAM

Through technical minimization, micro-satellites are currently of increasing interest. Their possibilities as well as their scope of missions is growing steadily. Today, payloads with a mass of just a few kilograms are able to perform measurements that would have been unthinkable a few years ago. Another advantage is the fast and cheap development of micro-satellites, which makes them a suitable platform for technology evaluation. Hence, they provide the ideal opportunity to test new systems in space within a short timeframe and low budget.
Within the Stuttgart Small Satellite Program the Institute of Space Systems at the University of Stuttgart will develop and build several small satellites. The existing ground station of the Steinbeis Transferzentrum Raumfahrt is currently being upgraded and extended to allow satellite communication in different frequency bands (UHF, VHF, L-band, S-band and Ka-band). Direct access and control of the satellites is ensured by operating all equipment in-house. Furthermore, a satellite integration room is being set up at the laboratory section. After the completion of several testing models, the following four small satellites will form the core of the program:

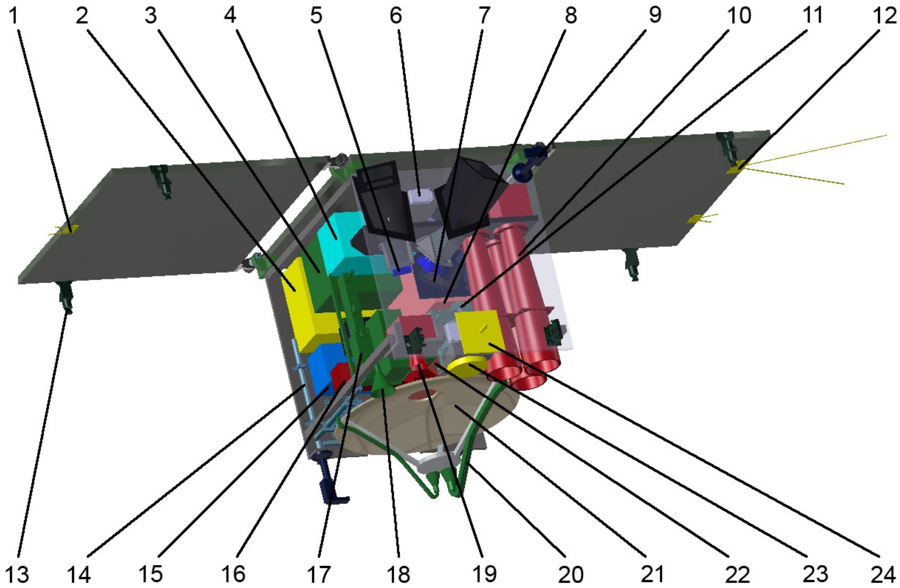
- Flying Laptop: Earth Observation & Technology Demonstration
- Perseus: Propulsion Testbed & Technology Demonstration
- BW1: Lunar Mission
- Cermit/Desire: Reentry Vehicle

The *Flying Laptop* will be the first satellite to be launched in 2007. The project is described below.

THE *FLYING LAPTOP*

1 INTRODUCTION

The primary mission objective is to demonstrate and qualify new small-satellite technologies for the future projects. As a secondary objective, multiple scientific earth observation experiments are planned. The satellite body has a cubical shape with an edge length of 60 cm and a mass of about 100 kg. Figure 2 shows the general design of the satellite including its components. The launch as a piggyback payload is planned for 2007. A polar, sun-synchronous, low earth orbit below 1000 km is being pursued. As scientific payload the satellite is equipped with a 3 camera system (MICS), a thermal infrared camera (TICS) and a Ka-band communication system with a high power travelling wave tube amplifier (TWT). The last two are intended to make dual use of a cassegrain mirror system. The on-board computer consists of a reconfigurable, redundant and self-controlling field programmable gate array (FPGA) with high computational power.



1 - S-Band Antenna LG	9 - Sun Sensors	17 - TWT
2 - Communication Unit	10 - MICS	18 - Ka-Band Low Power
3 - Ka-Band Electronics	11 - Gyros	19 - PamCam
4 - On-board Computer	12 - VHF-Antenna	20 - Feed Horns
5 - Star Tracker	13 - Deployment Device	21 - Cassegrain System
6 - Magnetometers	14 - Magnettorquers	22 - Li-Ion Battery
7 - Reaction Wheels	15 - Ultra Stable OSC.	23 - S-Band Antenna HG
8 - Power Control Unit	16 - TICS	24 - UHF-Antenna

Figure 2: Design of the Flying Laptop

Many of the currently listed facts will become more accurate as time progresses, and updates will follow.

2 SCIENTIFIC RESEARCH

Beside the demonstration of new technologies the Flying Laptop will use its payloads for applications of earth observation. The geometrical resolution of the cameras is comparable to the resolution of Landsats TM+ and for example time series started by Landsat can be continued. This section will give further information about the different experiments in the field of remote sensing currently planned for the Flying Laptop.

2.1 Bi-directional Reflectance Function and the Directional Brightness Temperature

The reflectance of most surfaces shows anisotropic behavior, which means the reflectance varies with solar and viewing positions. This effect is shown in figure 6 and is mathematically described by the bi-directional reflectance distribution function (BRDF) which characterizes how for a scene with given properties, the reflectance observed varies with the angles of observation and illumination:

$$f(\lambda, \Theta_s, \varphi_s, \Theta_v, \varphi_v) = \frac{L(\lambda, \Theta_s, \varphi_s, \Theta_v, \varphi_v)}{E(\lambda, \Theta_s, \varphi_s)}$$

L is the radiance reflected into a direction defined by the zenith angle θv and azimuth angle φv of the view direction, E is the irradiance from the sun direction (θs, φs) and λ the wavelength of radiation. The dimension of the BRDF is given in sr-1. Commonly used is the bi-directional reflectance factor $BRF = \pi f(\lambda, \Theta_s, \varphi_s, \Theta_v, \varphi_v)$, which has no dimension. Soil and vegetation normally show different reflectance characteristics. Generally, natural surfaces are rough. Soil consists of grains which are separated by pores containing water and gas. The reflectance properties of soils are attributed by the coherent scattering of the particles, by the incoherent radiative transfer propagation between the different particles and by the shadow hiding. The latter generates mainly the sharp peak in the bi-directional reflectance at zero phase angle, called hot spot or opposition effect. Vegetation exhibits anisotropic reflectance caused mainly by the very complex volumetric scattering within the leaves canopy and also shadow casting. For vegetated surfaces the composition of shadowed and illuminated components depends highly on the canopy architecture, which is affected by the type of plant species, the growing stage, and the health conditions. Canopy gaps have a strong impact on the BRDF. A typical application, where knowledge of BRDF is demanded, occurs when images acquired during several orbital overpasses or overflights are to be mosaicked together to form a large one. Due to the BRDF, strong brightness contrasts might appear where the swaths are joined together. A wide field of view sensor observes one margin of a swath under another viewing angle relative to the sun than the other one. Therefore a bidirectional reflectance effect can often be observed as a brightness gradient. For a quantitative analysis in spectral, temporal and spatial domain a correction of the BRDF effect is needed. The necessity of an angular correction of satellite data and the normalization to standard viewing and illumination conditions was

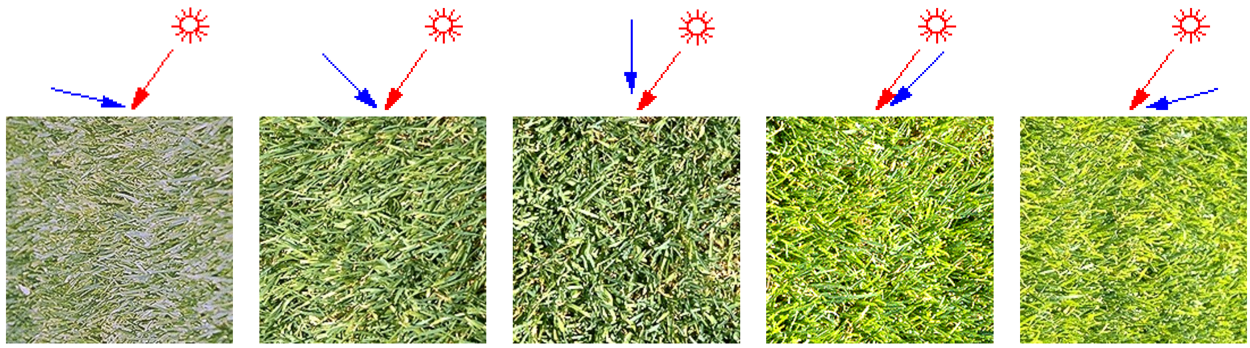


Figure 3: Bi-directional reflectance effect of grass. (Source:http://www.geo.unizh.ch/rsl/research/)

a mainspring for the forcing of the experimental and theoretical investigation of the BRDF. The BRDF correction allows us to compare different images and to improve the classification accuracy.

Furthermore the BRDF is the fundamental quantity for the calculation of the albedo which plays an essential role in the radiation- and energy balance of the planets. The specific use of the angular dependence of the reflectance will also improve the retrieval of biophysical parameters of land surfaces. Last but not least the BRDF is necessary for the calibration of airborne and spaceborne sensors.
Several empirical, semi-empirical and theoretical models have been developed for the description of typical BRDFs. The normalization to standard viewing geometries, the calculation of the albedo and the multiangular retrieval algorithms are mostly based on the application of appropriate models. For the completeness of our knowledge about the BRDF and for the understanding of the potential of BRDF for remote sensing we are arranging a mission scenario for BRDF measurements using the Flying Laptop.

In order to measure the bi-directional reflectance factors, the Flying Laptop will operate in the target pointing mode. That means that the attitude of the satellite is controlled in such a manner, that the same ground pixel is observed from different directions. The goal is to achieve a pointing accuracy of 11 arcseconds. The extension of the area under observation which must assumed to be homogeneous should be noticeable larger than twice the maximum pixel size resulting from the maximum viewing zenith angle. Hence large forests or desert areas could be chosen for this kind of measurement.

Mixtures of foliages and soil are thermally heterogeneous and the measured angular distribution of the surface brightness temperature depends on the perspective and the sun position.
Our knowledge about the Temperature Directional Distribution (TDD), also called Directional Brightness Temperature (DBT) is still very poor. But this information is essential both for the data use of wide angle sensors and for a correct validation and calibration.
However the atmosphere has an impact on the BRDF as well as on the DBT. Not only the surface scatters anisotropically but also the atmosphere impacts the traveling radiance in the different directions in an unequal manner because of the angular dependent scattering by air molecules and aerosols. In addition the surface and the atmosphere are coupled by multiple scattering which tends to smooth the directionality of the radiance. Also the transmission and emission of the atmosphere are anisotropic and influence the measured surface temperature.
Therefore, angular and spectral ground based measurements and measurements using airborne and spacebone instruments have to be combined in order to separate the different contributions. The Institute of Space Systems is going to prepare such multi-level experiments.

2.2 Using the Ka-Band for scientific investigations

The use of higher satellite communication frequency bands is required to implement broad band links. It is therefore necessary to identify and predict the combined effect of different propagation impairments.
Rain attenuation is the dominant propagation impairment at frequencies above about

10 GHz. In addition, gaseous absorption, cloud attenuation, melting layer attenuation, and tropospheric refractive effects become increasingly important with increasing operating frequencies. Some prediction models are available for the estimation of the individual components. But methodologies that attempt to combine them are widely missing. This is partly due to paucity of reliable measured data. This applies especially to Central Europe. The Flying Laptop can help to fill this gap. In order to provide a useful database for the identification of the overall impact of every significant attenuation effect along the given paths we invite and ask relevant research institutions and groups of the appropriate operational services to join us and to work with us together in a fruitful partnership.

The inherent potential of spaced based measurements for providing global measurements of rainfall has long been recognized. However, the development of appropriate techniques for a quantitative estimation of rainfall has met limits for a long time. During an experiment monitoring the 12.5 GHz and 19.8 GHz data from the Olympus Satellite it was realized that the attenuation difference could be useful for measuring rainfall. Thus some dual-frequency horizontal microwave links for measuring the path-averaged rainfall were built and tested during some experiments in Europe. It could be shown that a strong relationship between the rain rate and the differential attenuation of the Ku- and Ka-frequency bands exists. The strength of the method analyzed during these campaigns is that it is not necessary to make assumptions about the drop size distribution or other rainfall characteristics. The Flying Laptop will – in addition to the Ka-band – be equipped with a Ku-band transmitter, in order to test the findings. The acquisition will be performed in the target-pointing mode using the Ka-band and the Ku-band signal.

3 PAYLOAD

3.1 Thermal Infrared camera system (TICS)

Uncooled micro-bolometers are of increasing interest in the field of infrared technology. Especially for small satellites, the concept of an infrared system without a cooler has tremendous advantages. Power consumption, size and costs can be reduced significantly. For the Flying Laptop a temperature stabilized micro-bolometer with 320 x 240 pixels is planned. The sensor will operate from 8 – 12 µm wavelength, excluding the ozone absorption band from 9.3 – 9.7 µm.

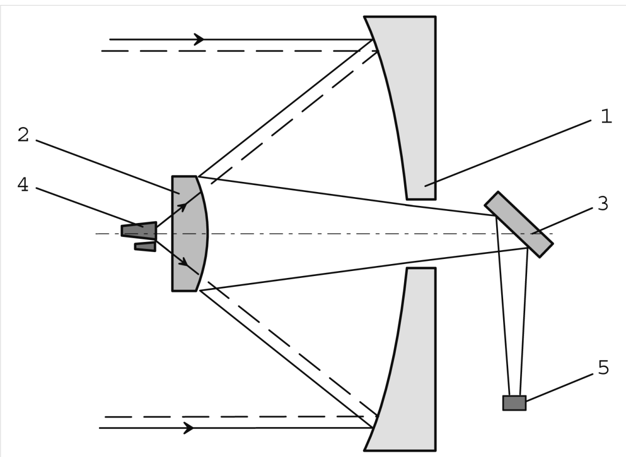


Figure 4: Cassegrain System: 1 primary mirror, 2 secondary mirror, 3 deflection mirror, 4 feed horns, 5 infrared sensor

The optical design of the infrared camera system will consist of a cassegrain system, designed as a dual system (for the infrared and the Ka-band system), and an adjacent relay-optic. This will lead to a ground sample distance (GSD) of 50 m. With the dual design of the cassegrain system, the Flying Laptop achieves a fast optic with approximately f/1.6. The mirrors will be made of carbon fiber for temperature stability. Currently a test mirror is fabricated to analyze the surface quality and thermal resistance.

3.2 Visible and near infrared camera system (MICS)

For the visible and near-infrared spectral range, a camera block of three single CCD array cameras is planned, one each for the following spectral bands:

- Green: 530 – 580 nm
- Red: 620 – 670 nm
- Near-infrared: 830 – 890 nm

The use of an area array sensor has advantages for the measurement of the BRDF and allows easier referencing on ground. The GSD will be 25 m, half the resolution of the infrared camera. A sensor with anti-blooming system is preferred in order to drain off the high electron rates resulting from cloud reflections. Calculations with an atmospheric radiation transport program have been done to receive an impression of the expected radiance at the satellite. With these calculations, it was possible to determine the expected signal to noise ratio, in order to estimate the performance of the system. Two imaging modes will be used as described in the ACS section and shown in Figure 5. In the target pointing mode high performance images can be taken for scientific purposes. The earth pointing mode allows the imaging of large stripes.

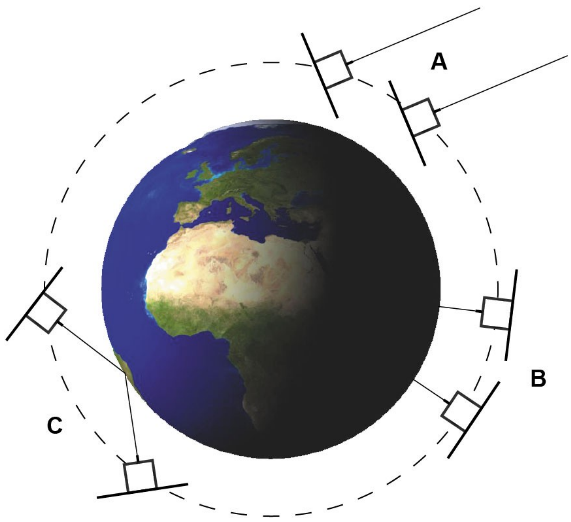


Figure 5: Imaging modes: A inertial pointing, B earth pointing, C target pointing

4 SATELLITE BUS

The mechanical structure of the Flying Laptop is divided into the service module, the core module and the payload module as shown in Figure 6. The launch adapter is attached to the back plane of the service module. All modules are made of aluminum due to its high heat conduction properties. In order to ensure the alignment of the cameras (MICS) to each other and to the star cameras, both components are attached to an optical bench made of carbon-fiber-reinforced plastic (CFRP) for thermal stability. The focus distance of the TIR camera and the Ka-band antenna is also influenced by thermal extension. Hence, the primary mirror and the retaining structure of the secondary mirror will also be produced from the temperature stable CFRP. For TICS the primary mirror demands a medium surface roughness of approx. 0.8 µm.

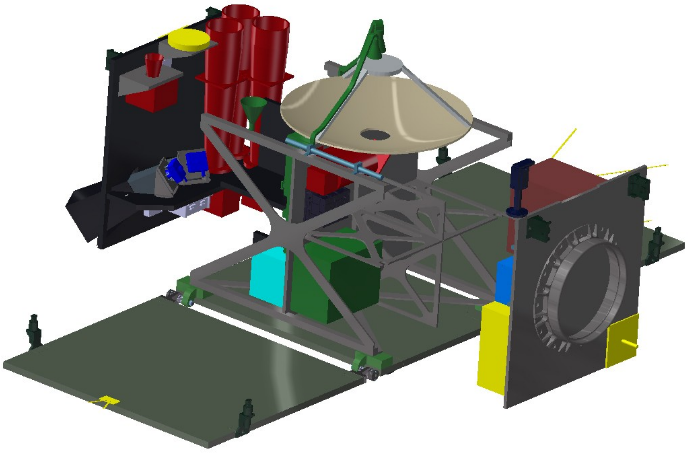


Figure 6: Modular design of the Flying Laptop Payload Module; Core Module; Service Module

The thermal system of the Flying Laptop is intended to be passive by using the dissipated heat of the internal components. The surface is mostly covered by multi layer insulation (MLI) and the heat is released by a radiator on the back plane of the service module.

4.1 Attitude Control System

The Flying Laptop is a 3-axis stabilized micro-satellite. The attitude control system (ACS) needs to provide high accuracy pointing and maneuvering capabilities in accordance with the selected earth observation instruments. This is a big challenge for a micro-satellite and can only be achieved by a thorough control concept and high performance sensors and actuators.

Figure 2 shows the actuators and sensors of the ACS. The actuators consist of reaction wheels and magnetic torquers. Four Teldix RSI 01-5/28 reaction wheels are aligned in a tetrahedron configuration and each has an angular momentum capacity of 0.12 Nms. Three magnetic torquers (torque rods) dump the momentum accumulated by the reaction wheels. The moment of inertia in the x, y and z axis of the satellite is estimated to be around 4 kgm^2.
The attitude motion is monitored by five different types of sensors: a 3-axis magnetometer, Sun sensor, rate sensors, autonomous star sensor and GPS receivers. The ZARM AMR-magnetometer uses a magneto-resistive sensor and has a digital interface. For the measurement of the angular velocity, four fiber optical rate sensors will be used. A star tracker, the micro Advanced Stellar Compass (µASC), from the Technical University of Denmark will provide a pointing knowledge of better than 2 arcseconds. After the satellite is stabilized and rotates with a slew rate of less than 1.2 °/s the star tracker delivers regular attitude updates. To provide full accuracy about all axes and to decrease the probability of blinding during maneuvers, a second camera head unit is mounted on the satellite with its optical axis tilted away from the first one. To support accurate target-pointing of the spacecraft during imaging and ground station contacts, the satellite will be equipped with a GPS navigation system. Three Phoenix GPS receivers are provided by DLR/GSOC and are locked to an ultra stable 10 MHz crystal oscillator for an orbit and attitude determination experiment. For image acquisition three different attitude control modes are defined and shown in Figure 5: inertial-pointing mode, nadir-pointing mode and target-pointing mode. In the target-pointing, also known as spotlight mode, the satellite points to a fixed spot on the surface of the earth during a fly-over. This allows longer integration times for the cameras which is a significant advantage for the scientific measurements. The slew rate for this maneuver is 1 °/s (max.) and follows a non-linear bell-shaped curve over time. This is the most demanding mode of the satellite in terms of control algorithms.

4.2 FPGA On-Board Computer System

The Flying Laptop will probably be the first micro-satellite using a fully processor-less primary on-board computer (OBC) that consists of field programmable gate arrays (FPGAs). The OBC is based on a Xilinx Vertex-II Pro with approx. 3 million system gates and a maximum clock frequency of 200 MHz. The OBC will further consist of 4 MB of synchronous static RAM for high speed data processing, 2 x 128 MB DDR RAM and 1 GB Flash. Via a modem, a user programmable EEPROM can be reconfigured from the ground station. In case of failure, the original FPGA configuration is restored from a PROM.

With a software-to-hardware compiler it is possible to directly generate the logical configuration of FPGA gates from a C-like high level language without producing the machine code for a processor. Through this approach massive parallel processing is possible. To make the system fault-tolerant and to address radiation issues, four equal independent nodes will work together. Depending on the state of the system 1-4 nodes will run at the same time and are dynamically switched on or off. A complete start-up of a single node takes only 10 ms. The high flexibility of the on-board computer system will be used to operate the Flying Laptop in a so-called Rent-A-Sat mode. It is possible to configure the system for customer preferences (i.e. The characteristics of a certain processor can be simulated through the hardware). With this versatility the system is well-suited for OBC software or component firmware validation in space.

The OBC system is currently under development by the Steinbeis Transferzentrum Raumfahrt in cooperation with the Fraunhofer Institute for Computer Architecture and Software Technology.

4.3 Communication System

For telemetry and telecommand UHF (low gain) and S-band (low and high gain) antennas will be installed on the satellite. Beside S-band communication, UHF offers the possibility to utilize amateur radio equipment. As payload the Flying Laptop will be equipped with a Ka-band traveling wave tube (TWT) amplifier. During a ground station fly-over, the TWT will operate with an RF transmission power of 57 W (170.5 W DC input) which is unique for a micro-satellite. With this subsystem a data rate of 100 Mbit/s will be available. The Ka-band signal with a GSD of 25 km can also be used as radar emitter with measurement towers on ground. The satellite’s cassegrain system with its 50 cm primary dish provides the antenna reflector for the Ka-band communication and is also used as the optical system for the thermal infrared camera. The TWT is the design driver for the battery system to handle its high power requirement.

5 Functional Verification Approach for the *Flying Laptop*

Setting up a verification environment for reliable system-wide tests is new to micro-satellite projects, but it is one of the enabling technologies for proving the required attitude control system accuracy. In this context a software-based functional verification system reduces the check-out environment complexity and huge costs can be saved.

This model-based verification environment for small satellite applications is under development in close cooperation with EADS Astrium and will be set up in parallel to the Flying Laptop development. It is characterized by high real-time capabilities to represent the spacecraft hardware in its exact operational modes and response times. Software models of the spacecraft components will be created successively in adequate detail in order to provide the particular test bench functionality. Latest commercial improvements in hardware and software technology allow the real-time test benches to be set up using standard computers and a Linux operating system kernel which supports real-time performance.

A Software Verification Facility (SVF) is in progress to support the on-board software development process. The schematic structure of the SVF is illustrated in Figure 7. It is used to debug, validate and verify the on-board software and prove the overall system dataflow functionality. In this test bench configuration the real-time simulator (RTS) consists of a real-time spacecraft simulator (S/C SIM), an on-board computer simulator (OBC SIM) and a central control system (CCS) which provides a TM/TC interface, simulator control and debugging interfaces.

The SVF supports real-time or accelerated software simulation of the whole spacecraft system. This is achieved by implementing all spacecraft components by its hardware-specific software models into the spacecraft simulator. The real-time simulations are supported by space environment models, thermal and power models and a spacecraft dynamics module.

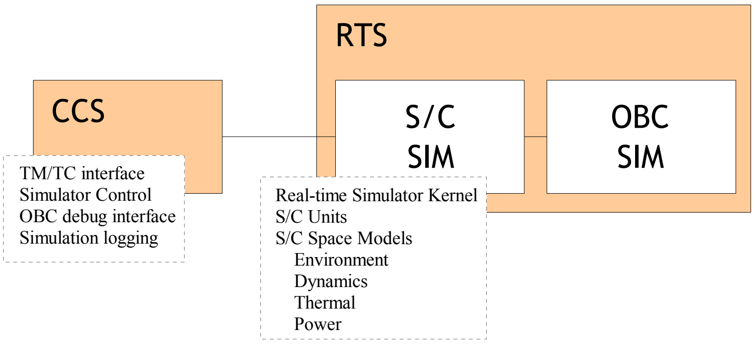


Figure 7: Block Diagram of the Software Verification Facility

In the next step a FlatSat test bench with high real-time performance will be arranged as initial hardware check-out environment including the on-board computer and all other equipments as hardware in the loop (refer to Figure 8). It will be set up well before spacecraft integration using test harness to maintain single component up to system-wide check-out procedures and finally complete mission scenario simulations. All required software models of the hardware components, especially those of the attitude control system (ACS) sensors, will be re-used in this environment to provide correct output of space environment data and spacecraft dynamics. A powerful computer based on the standard i686 processor architecture and operated on a real-time Linux derivate forms the backbone of the Real-time Simulator. Multiple PCI-Bus interface cards will be used as interfaces between the flight hardware components and the spacecraft simulator.

Finally the protoflight test bench supports a functional verification test environment throughout the flight hardware qualification process.

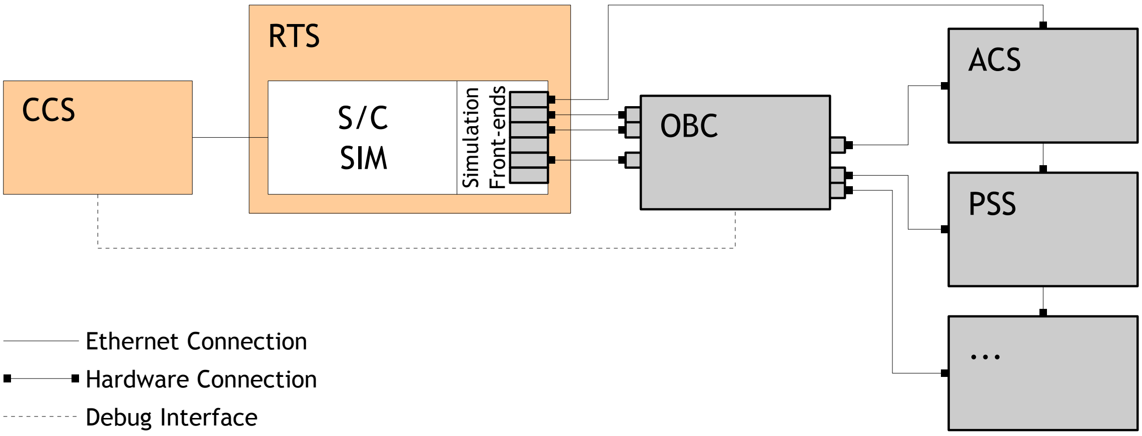


Figure 8: Block diagram of the FlatSat test bench which integrates flight hardware (grey shaded) in the simulation loop

CO-OPERATION PARTNERS

- AGI – Analytical Graphics Inc.
- AMSAT Deutschland e.V.
- AONIX GmbH
- ASP – Advanced Space Power Equipment GmbH
- DLR – German Aerospace Center
- DIEHL & EAGLE PICHER
- DTU – Technical University of Denmark
- EADS Astrium
- FIRST Fraunhofer Institut
- LITEF GmbH
- O.S.T. - Opto-System-Technik
- RWE Space Solar Power GmbH
- TELDIX GmbH
- TESAT Spacecom GmbH & CO.KG
- TZR – Transfer Zentrum Raumfahrt
- Theta System Elektronik GmbH
- ZARM Technik GmbH