

FLYING LAPTOP – MICRO-SATELLITE OF THE UNIVERSITY OF STUTTGART FOR EARTH OBSERVATION AND TECHNOLOGY DEMONSTRATION

G. Grillmayer, M. Lengowski, S. Walz,
H.-P. Roeser, F. Huber*, M. v. Schoenermark, T. Wegmann

Institute of Space Systems, University of Stuttgart
Pfaffenwaldring 31, 70550 Stuttgart, Germany
flyinglaptop@irs.uni-stuttgart.de

*Steinbeis Transferzentrum Raumfahrt
Roetestr. 15, 71126 Gaeufelden, Germany

ABSTRACT

This paper describes the first micro-satellite within the Small Satellite Program at the University of Stuttgart, Germany. The *Flying Laptop* is scheduled to be launched as a piggyback payload at the end of 2006. The mission objectives are divided into two parts: scientific observations and technology demonstration. The satellite will be equipped with a camera payload system operating in the visual and near infrared spectrum as well as a thermal infrared wavelength. In addition a high speed broadband communication system with a Ka-band traveling wave tube amplifier is flown. Both systems, the Ka-band and the thermal infrared camera, use a cassegrain system which is designed as a dual system. To achieve the planned scientific measurements, a high performance attitude control system with a pointing accuracy of 11 arc-seconds is necessary. A target-pointing mode will be used. The core of the satellite is a reconfigurable, redundant, self-controlling field programmable gate array (FPGA) on-board computer system with high computational power. This computer system makes it possible to offer the 'Rent-a-Sat' mode, that provides a platform for software testing in space. By using commercial off-the-shelf components (COTS), the cost and the development time can be kept low. The design, integration, testing, and future operation of the *Flying Laptop* will be carried out by the Institute of Space Systems.

1 INTRODUCTION

Micro-satellites are currently of increasing interest through technical minimization. Their possibilities as well as their field of missions is growing steadily. Today, payloads with just a few kilogram mass are able to perform measurements that would have been unthinkable 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 is currently being upgraded and extended to allow satellite communication in different frequency bands (UHF, VHF, S-band and Ka-band). By operating all equipment in-house, direct access and control of the satellites is ensured. After the completion of several testing models, the following three small satellite missions will form the core of the program:

- **Flying Laptop:** Earth Observation and Technology Demonstration
- **Cermit / Desire:** Re-entry Vehicle and Technology Demonstration [1]
- **BW1:** Lunar Science Mission and Technology Demonstration [2]

The *Flying Laptop* will be the first micro-satellite within the Stuttgart Small Satellite Program and is scheduled to be launched as a piggyback payload at the end of 2006.

2 MISSION

The main mission objectives of the *Flying Laptop* are Earth observation and technology demonstration with regard to the later planned missions. In order to realize such a mission a cost-effective protoflight approach is used - a single flight model will be built, qualified, and flown. Further, commercial off-the-shelf (COTS) products are being used to allow development within three years. With an integration room, Yagi and dish antennas on the roof, and a small ground control center, the institute possesses the necessary infrastructure in order to realize this mission.

The *Flying Laptop* has a cubical shape with an edge length of 62 x 62 x 55 cm and a mass < 100 kg. A sun-synchronous 700 km polar orbit is being pursued. Figure 1 shows a general design of the satellite including its components.

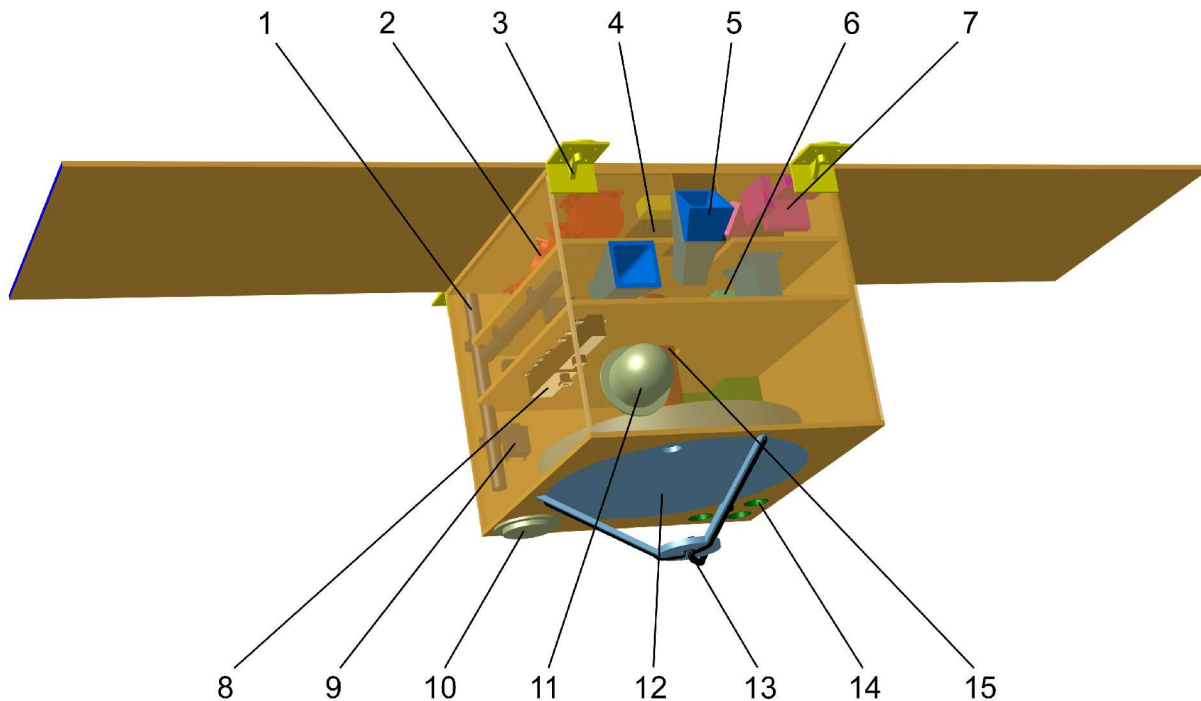


Figure 1: Satellite Flying Laptop

- | | | |
|---------------------|-----------------------|----------------------------|
| 1 Magnetic torquers | 6 On-board computer | 11 S-band (LG) |
| 2 Reaction wheels | 7 Rate Sensors | 12 Cassegrain system |
| 3 GPS-Antennas | 8 Traveling Wave Tube | 13 Feed horns |
| 4 Batteries | 9 Magnetometer | 14 VIS/NIR camera system |
| 5 Star cameras | 10 S-band (HG) | 15 Thermal infrared sensor |

3 SUBSYSTEMS

3.1 Power Supply

The power supply for the satellite is generated by five solar panels with an overall size of $>1 \text{ m}^2$. GaAs triple junction cells, the newest generation of solar cells with an efficiency of 26% will be used. In order to protect the instruments against direct sunlight during the uncontrolled orbit injection phase, the panels are folded like a roof as shown in Figure 2. After de-tumbling and testing of the attitude stabilization the panels will be deployed.

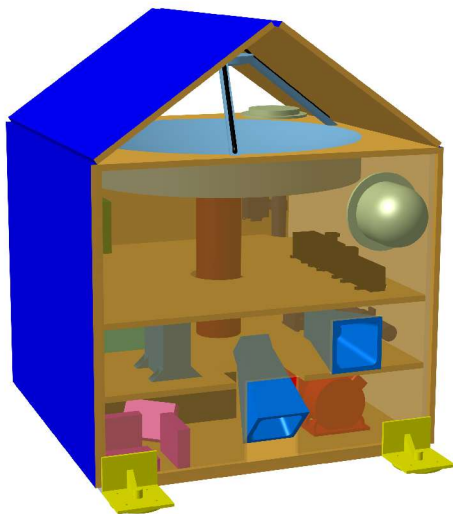


Figure 2: Launch configuration

Through continuing development of Li-Ion batteries the expected lifetime (number of cycles) has been increased. Offering advantages such as lightweight, compact design and lower cost the Li-ion batteries were selected as the first choice for this mission. The power system is capable of delivering $\sim 200 \text{ W}$ for several minutes. The bus voltage is 28 V.

3.2 Attitude Control System

The Attitude Control System (ACS) is currently being designed. The *Flying Laptop* is a 3-axis stabilized micro-satellite. The ACS needs to provide high accuracy pointing (11 arc-seconds or 0.00306°) 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 through innovative control concepts and high performance avionics.

Figure 1 shows the actuators and sensors of the ACS. The actuators consist of reaction wheels (2) and magnetic torquers (1). The four 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 (9), coarse Earth/Sun sensors, rate sensors (7), autonomous star sensor (5) and three GPS receivers (3). The magnetometer uses a magneto-resistive sensor and has a digital interface. The Earth/Sun sensors provide coarse measurements of the Sun and Earth vectors in the range of 1° - 5° . Three fiber optical rate sensors will be used for the measurement of the angular velocity. The star sensor is the most sophisticated sensor on the satellite and provides a fine pointing accuracy of less than 2 arc-seconds. After the satellite is stabilized and turns with less than $1.2^\circ/\text{s}$ the star sensor provides regular attitude updates. To provide full accuracy about the roll axis and also to increase reliability, a second star camera is mounted on the satellite with its optical axis tilted 45° 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 based navigation system. Three Phoenix GPS receivers will be provided by the DLR/GSOC.

In normal operation mode the satellite is stabilized inertially using information from the rate sensors, Earth/Sun sensors, the magnetometer, and the GPS. The pointing accuracy is low, and the stability is determined by the drift of the fiber optical rate sensors, which is about $6^\circ/\text{h}$. This mode is also used as a sun-pointing mode to recharge the batteries.

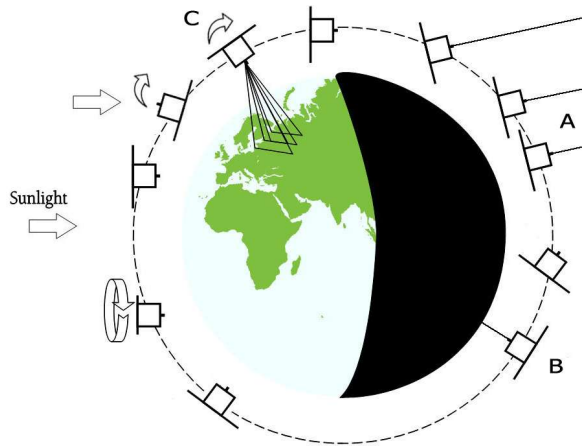


Figure 3: Operational modes, Inertial-Pointing Mode (A), Earth-Pointing Mode (B), Target-Pointing Mode (C)

For image acquisition three different attitude control modes are defined and are shown in Figure 3:

Inertial-Pointing Mode:

The star sensor is used to provide high accuracy pointing knowledge of less than 2 arc-seconds. To enter this mode the slew rate needs to be below the threshold to ensure the use of the star sensor data in the control loop.

Earth-Pointing Mode:

This is a further improvement of the inertial pointing mode where the slew rate is set to a constant value to ensure that the satellite always points towards the Earth's center (nadir) in order to allow a push-broom type of image recording.

Target Pointing Mode:

The target-pointing or spotlight mode is necessary in order to achieve the planned scientific measurements. In this operational mode the satellite points to a fixed spot on the surface of the Earth during a fly-over. The maximum slew rate for this maneuver is 1 °/s and follows a non-linear bell-shaped curve over time. This is the most demanding mode of the satellite in terms of control algorithms.

3.3 On-board Computer System

The *Flying Laptop* is probably the first micro-satellite using a fully processor-less primary on-board computer that consists of field programmable gate arrays (FPGA). Because non-radiation-hardened FPGAs are intended

to be used, an adequate computer architecture was developed to address radiation issues. This concept consists of two hot and two cold redundant arrays. If the two hot redundant arrays differ from each other a majority voting with the two cold redundant arrays is initiated. The system includes 1 Gbit primary hard disk memory, 1 Gbit mass memory and 200 MB telemetry storage. The on-board computer system is currently under development at the Fraunhofer Institute in Berlin, Germany.

3.4 Communication

To control the satellite from the institute's ground station the following communication frequencies (up-link /down-link) are installed: UHF, S-band (2.0 / 2.2 GHz) and Ka-band (30 / 20 GHz). All these frequencies can be used for telemetry and telecommand. Next to the standard S-band communication frequency, UHF offers the possibility to adopt amateur radio equipment. In this way partners and universities can build up a low-cost ground station. On the other hand, the Ka-band allows broadband communication with data rates of up to 100 Mbit/s. For the Ka-band, a traveling wave tube (TWT) amplifier will be implemented on board with a maximum transmission power of 70 W. The satellite's cassegrain system, with its 50 cm primary dish, will be used as the antenna. A more detailed description of the Ka-band antenna is shown in Figure 5 below.

3.5 Payload

Two different camera systems will be mounted on the satellite. For the visible and near infrared spectral range, a camera block of three single cameras with area array CCD sensors is planned, one each for the following spectral bands:

- Green: 530 - 580 nm
- Red: 620 - 670 nm
- NIR: 820 - 870 nm

This arrangement simplifies the optical design because the filter can be directly placed in front of the optics. Therefore, a simple double Gauss optic can be used without the need of chromatic aberration

correction. Another advantage is the redundancy of the system. The planned ground sampling distance is 25 m.

The second camera system measures the thermal infrared wavelength (8 - 12 μm , without the ozone absorption band 9.3 - 9.7 μm), using an uncooled microbolometer sensor. The sensor is temperature stabilized and cooled by Peltier elements in order to achieve the desired signal-to-noise ratio. To attain a ground resolution of 50 m, the cassegrain system will also be used as the objective, as explained in the technology evaluation section.

4 SCIENTIFIC RESEARCH

With its cameras and the Ka-band antenna (the latter is also proposed to be used as radar transmitter) the *Flying Laptop* will contribute to research in the field of Earth observation through remote sensing. The following subjects are of special interest:

4.1 BRDF Measurement

For the analysis of spaceborne remote sensing data the Bi-directional Reflectance Distribution Function (BRDF) plays a decisive role. The BRDF describes the anisotropic distribution of reflected light from a body under various insolation and observation angles [3]. Depending on the direction of the sun (insolation angle) and the position of the observer (observation angle) the reflectance of the target differs. An example of the different colors of grass is shown in Figure 4. The BRDF is important for observation of surfaces for the following

tasks:

- BRDF correction in time series
- correction of the radiance gradient
- classification of surfaces
- derivation of albedo
- derivation of geophysical and geochemical parameters
- vicarious calibration

In the target-pointing mode, this function is measured in different spectral bands (visible, near infrared, and thermal infrared). The cameras continuously take images of the same ground segment during a fly-over or pass. A homogeneous ground segment is important for the measurement; therefore, deserts or large forest areas are ideal candidates.

4.2 Precipitation Measurement

In meteorology a network of rain gauges and precipitation radars are utilized for precipitation measurements. However, our knowledge in this field is still inadequate, especially over sea and mountain areas. Remote sensing of precipitation is widely used to obtain increased spatial and temporal accuracy. With remote sensors the rainfall cannot be directly measured. Experiments have shown, however, that the differential radio signal attenuation in a horizontal path through rain in two different frequency ranges (between 10 and 40 GHz) is linearly dependent on the rain rate [4]. This relation is independent of the droplet size and this project will test for vertical propagation. The acquisition will be performed in the target-pointing mode using a Ka-band and a Ku-band signal.

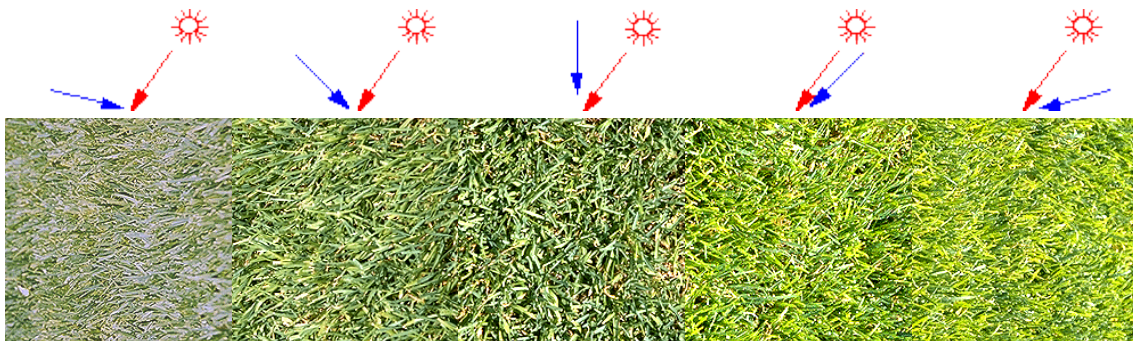


Figure 4: Bi-directional reflectance effect of grass. (source:<http://www.geo.unizh.ch/rs/research/>)

4.3 Ka-band Attenuation and Trace Gas Detection

Because thorough data of the band gaps in continental Europe for the upcoming use of the Ka-band in the communication sector does not exist, the Ka-band antenna with its large bandwidth will be used for detection of atmospheric attenuation within this frequency range. Transmission in the Ka-band is influenced by:

- attenuation through rain
- attenuation through clouds
- attenuation through gases
- instability of the atmospheric refraction index
- phase transformation from ice particles to water droplets
- depolarization through aspherical hydro meteors

We intend to retrieve the total content of the trace gases ammoniac (NH_3), nitric acid (HNO_3) and methylidyne (CH) that have small absorption bands in the frequency ranges of the Flying Laptop's down-link (19.7 – 20.2 GHz) and up-link (29.5 – 30.5 GHz). A list is shown in Table 1.

Table 1: Absorption bands of selected trace gases in the Ka-band frequency range of the Flying Laptop [5]

Frequency [GHz]	Trace Gas
19.757	NH_3
19.838	NH_3
19.933	CH
19.955	CH
20.097	HNO_3
29.577	HNO_3
29.914	NH_3

4.4 Multispectral Earth Observation

First, the three on-board cameras, as well as the thermal infrared camera, will record sequences of multispectral Earth images. It is possible to take simultaneous images with all spectral cameras (green, red, near and thermal infrared), thus the images are well-

suited to be used in the so-called trapeze method (vegetation-index-temperature-diagram). The spatial resolution of the cameras is comparable to that of other satellites (e.g. Landsat 5 and 7); consequently, related applications can be addressed. Second, the Ka-band antenna with its high power will also be used as a radar transmitter. The signal will be transmitted from space, but the reflected signal needs to be captured with the help of measurement towers on the ground, not at the satellite. These measurements offer the capability to address local scientific questions in this area.

5 TECHNOLOGY EVALUATION

The *Flying Laptop* will evaluate new innovative technologies such as the FPGA on-board computer and the Ka-band communication system.

The resulting experience from these evaluations will influence the design of the planned lunar mission.

5.1 Ka-band Communication

Communication in the Ka-band frequency range is necessary to allow self-controlled communication for the planned lunar mission. In order to achieve a suitable performance in the S-band frequency range a dish of 30 m size would be required. By using higher frequencies in the Ka-band, the ground station dish size can be decreased to 3 m diameter, which makes the installation of ground equipment affordable and enables the Institute of Space Systems to perform high data rate satellite communication on its own. A Ka-band dish is in preparation.

The *Flying Laptop* cassegrain system (Figure 5) with its 50 cm primary mirror (1) works as a dual system. First, it provides the antenna reflector for the Ka-band communication; second, it is used as the optical system for the thermal infrared camera. The optical path is illustrated in Figure 5. With the help of a beam splitter (3) the two wavelengths are divided at a central opening of the main mirror, where the infrared radiation passes through and the Ka-band signal is reflected to the secondary

mirror (2). A thin grating metalized onto a slightly curved germanium lens will be used as the beam splitter. The feed horns for the Ka-band (5) are placed in the center of the secondary mirror (2). By combining these two complex systems, a compact design is achieved which suits the requirements of a micro-satellite.

Another highlight of this mission is the implementation of a TWT amplifier with a transmission power of 70 W. The use of a TWT operated in this power range is unique for a micro-satellite.

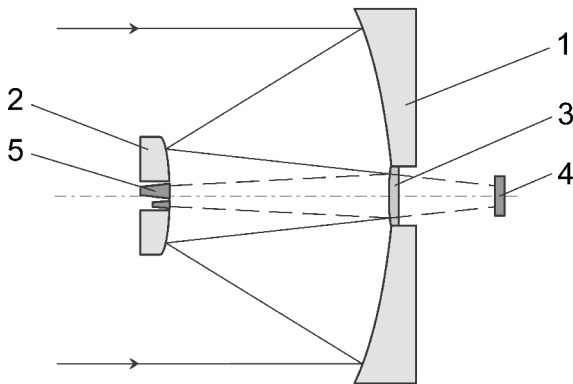


Figure 5: Dual use cassegrain system
 1 Primary mirror (50 cm)
 2 Secondary mirror (12 cm)
 3 Beam splitter
 4 Infrared sensor
 5 Feed horns

5.2 FPGA On-board Computer System

Comparing the performance of current spaceborne computer systems with commercial PC's, one recognizes that the evaluation of space proof systems is difficult and therefore the performance unsatisfying. Today's computer used in space are years behind commercial technology. This shows the need for new systems. With a software-to-hardware compiler it is now 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. Using an on-board computer architecture with several reciprocal checking FPGA's, one obtains a safe system that even exceeds the performance of current PC's through its ability of parallel real time processing.

5.3 'Rent-a-Sat' Mode

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. Interested companies can rent the satellite as a development platform in space. 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 'Rent-a-Sat' system is well-suited for software or firmware validation in space. Another important advantage of FPGAs is the fact that the gates are reconfigurable within milliseconds. A basic control system is continuously running in the background for security. In case of mishandling or failure the original system can be reconfigured within milliseconds.

6 CONCLUSION

The *Flying Laptop* will be the first micro-satellite built at the University of Stuttgart within the Stuttgart Small Satellite Program. This mission will collect important scientific data for the determination of the BRDF. A new precipitation measurement method will be practically demonstrated and the Ka-band signal will be used for various experiments in the high frequency range, where currently little data has been obtained. Further, the new on-board computer system and the broadband Ka-band communication are necessary steps in the development of spaceborne technology toward realization of the planned lunar mission.

At the moment, most of the satellite's components are being selected and the Critical Design Review is scheduled for the end of 2004. Integration and testing will be conducted by the Institute of Space Systems.

7 REFERENCES

- [1] M.H. Graesslin, H.-P. Roeser, "Cermi: Controlled Earth Reentry Mini-Vehicle to Improve Technology", IAC-04-V.6.09, 55th International Astronautical Congress, Vancouver, 2004
- [2] R. Laufer, M. Auweter-Kurz, M. Lengowski, A. Nawaz, H.-P. Roeser, M.

- v. Schoenermark, H. Wagner, "An All Electrical Small Satellite for a Technology Demonstration and Science Mission to the Moon", IAC-04-Q.2b.05, 55th International Astronautical Congress, Vancouver, 2004
- [3] M. v. Schoenermark, B. Geiger, H.-P. Roeser (ed.), "Reflection Properties of Vegetation and Soil", ISBN 3-89685-565-4, Wissenschaft und Technik Verlag, 2004
- [4] A.R. Rahimi, A. R. Holt, G. J. G. Upton, R. J. Cummings, "The Use of dual-frequency microwave links for measuring path-averaged rainfall", J. Geophys. Res., 108(D15), 4467, doi:10.1029/2002JD003202, 2003
- [5] H.M. Pickett, R.L. Poynter, E.A. Cohen, M.L. Delitsky, J.C. Pearson, H.S.P. Mueller, "Submillimeter, Millimeter, and Microwave Spectral Line Catalog", J. Quant. Spectrosc. Rad. Transfer 60, 883, 1998