THE ASOLANT/RUBIN-5 TECHNOLOGY DEMONSTRATION MISSION – SYSTEM DESCRIPTION AND FIRST FLIGHT RESULTS

M. Markgraf [(1)], S. Vaccaro [(2)], I. Kalnins [(3)], P. de Maagt[(4)], O. Amend [(3)]

[(1)]*Deutsches Zentrum für Luft- und Raumfahrt (DLR)*
German Space Operations Center, D-82234 Wessling, Germany
tel: +49.8153.28.3513, fax: +49.8153.28.1450, Email: markus.markgraf@dlr.de

[(2)]*Laboratoire d'Electromagnétisme et d'Acoustique, Ecole Polytechnique Fédérale de Lausanne, Switzerland*

[(3)]*OHB-Systems AG, Bremen, Germany*

[(4)]*ESTEC, European Space Agency, Noordwijk, The Netherlands*

ABSTRACT

This paper addresses the Asolant/Rubin-5 flight experiment conducted onboard the upper stage of a Cosmos rocket in late 2005. The main objective of the project was to flight-qualify a newly developed combined solar cell/antenna device, the so-called Advanced SOLar ANTenna (ASOLANT) technology. In order to assess both, the reception as well as emission of R/F signals, two different devices were involved in the mission. One was linked to a space-borne Phoenix-S GPS receiver to examine the receiving performance. A second device was designed to send out S-Band beacon signals generated by the SAFIR-S amateur radio transmitter to evaluate the radiation characteristics. Moreover, both ASOLANT devices supplied the electrical power for the onboard systems. Telecommand and telemetry functionalities were provided by an ORBCOMM communicator making use of the ORBCOMM satellite network to relay data between space and ground. This unit, furthermore, served as onboard computer.

The experiment was launched along with eight multinational payload satellites. It was designed to remain attached to the rockets upper stage after burn-out. Due to a separation failure of one of the co-passengers, the primary mission objectives could not be fully met. Nevertheless, a sufficient number of data was retrieved to confirm the good overall performance of the ASOLANT devices. Roughly ten month after the launch, still most system components are operational and experiment data are transmitted to ground. Following a description of the main flight system components and the overall system architecture, the paper summarizes the hitherto obtained experiment results.

1. INTRODUCTION

In the morning of October 27, 2005, a Russian Cosmos 3M rocket successfully took off from launch pad 132 at Plesetsk Cosmodrom. Besides eight multinational payload satellites, the vehicle carried the ASOLANT/Rubin-5 experiment onboard the upper stage, firmly attached to the payload adapter. The Asolant/Rubin-5 mission is part of a technology demonstration project jointly conducted by the Ecole Polytechnique Fédérale de Lausanne (EPFL) and OHB System AG, Bremen under contract of ESA and with contributions from various international companies and research institutions. The key objective of the mission is to validate a novel technology developed by scientist and engineers at EPFL - the so called Advanced SOLar ANTennas (ASOLANT) [1] - in a real space-flight mission. The basic idea behind this technology is to integrate solar generator and planar antenna structures, which often compete for the limited space on the surface of a satellite, in a single lightweight, compact and cost-effective device. Following the successful demonstration of the potential of this innovative approach in numerous ground tests, Asolant/Rubin-5 aimed at the first in-flight validation of the ASOLANT technology.

The ASOLANT flight experiment itself was composed of the following sub-systems:

- two types of ASOLANT devices, one for GPS signal reception on the L1 frequency and the second for data transmission in the S-band,
- a "Phoenix-S" space-borne GPS receiver developed by DLR/GSOC [2] and used during the mission for the processing of the received GPS signals,
- the "SAFIR-S" amateur radio unit [3] for the emission of a S-band beacon signal as well as

- for space-to-ground transmission of a sub-set of relevant flight data,
- and finally the Rubin-5 unit, providing key functionalities, such as power supply, experiment control, collection of measurement data, telemetry transmission and enclosure.

Apart form the above listed core components the overall flight system comprised the following additional experimental devices:

- a meteoroid and space debris detector developed by OHB-Systems and Fraunhofer Institute for High-Speed Dynamics [4].
- a low-cost CCD camera designed and implemented by students of the University of Applied Science Bremen
- various sensors, like a 3-axis magnetometer temperature and pressure sensors, providing a useful set of housekeeping data.

This paper is organized as follows: the subsequent section provides a conceptual overview of the flight experiment and describes the overall system architecture. Special emphasis is given to a more detailed description of the key components forming the Asolnat/Rubin-5 experiment. The second part of the paper addresses the performed on-ground tests and covers the final flight preparations conducted in Plesetsk. Finally, the available flight data are presented and discussed.

2. FLIGHT SYSTEM DESCRIPTION

This section addresses the basic concept, layout and major components of the Asolant/Rubin-5 flight experiment. For practical reasons, the system is introduced in reverse order, commencing with the description of the individual core system components:

- the Rubin-5 unit,
- the ASOLANT devices,
- the Phoenix GPS receiver,
- the SAFIR-S amateur radio module.

Thereafter, at the end of this section, an overview of the overall system architecture is provided.

2.1. Rubin-5

Rubin-5 was the fifth mission conducted within the framework of OHB's Rubin-X experimental space technology program ([5], [6]). Main objective of this program is to provide a flexible and versatile platform for validation and demonstration of new technologies in space as well as performing scientific experiments at low costs and short time-to-flight. Key characteristics and common element of all so far accomplished flight experiments is the exclusive use of the commercial ORBCOMM communication satellite network for telemetry and telecommand purposes.

Figure 2.1 BIRD-RUBIN attached to the upper stage of a COSMOS-3M launcher

Bird-Rubin (Fig. 2.1) was the first mission accomplished within the Rubin-X program. The experimental module was launched in Mid-2000 on board a COSMOS-3M rocket along with the CHAMP and MITA research satellites. The mission demonstrated the feasibility of the proposed communication concept in an impressive manner. During the five-day mission duration a total of 1600 SMS-like data packages have been sent out and successfully received on ground.

ORBCOMM System Overview

The ORBCOMM communication system is a satellite-based wide area, packet switched, two-way data communication system [7]. It is designed for alphanumeric message transmission similar to two-way paging or email communication. The system can be divided into the following three main segments:

- The space segment: a constellation of currently 30 operational satellites in space, arranged in seven orbital planes with inclinations between 45° to 108° and flying at altitudes from 710 km to 820 km. ORBCOMM is licensed by the FCC to launch and operate up to 48 satellites.
- The ground segment, composed of geographically distributed Gateway Earth Stations (GESs), Gateway Control Centers (GCCs) and finally the main Network Control Center (NCC) responsible for managing the constellation.
- The subscriber or user segment, consisting of the so-called subscriber communicators (SCs): mobile or stationary user terminals used for e.g. personal messaging or in remote monitoring and tracking applications.

The specific network structure enables a two-way transmission of information on a near real-time basis between almost any two places on the globe and – as demonstrated by the small satellite program Rubin-X – also to and from space.

Communication between subscriber communicator and the ORBCOMM gateways is accomplished through the space segment, where the satellites serve as data relay stations. While the gateway earth stations establish the physical link between the ORBCOMM satellites and the ground segment as they pass overhead, the gateway control center provides the capability to complete the communication link with the terrestrial end user. For the final data transmission, usually a private or public data network is used, for example a dial-up connection or the internet and standard email services. The RF communication within the system is operates in the very high frequency (VHF) range, between 137 MHz and 159 MHz.

The functional design of the ORBCOMM system and the interrelationship between the three main segments is outlined in Fig. 2.2

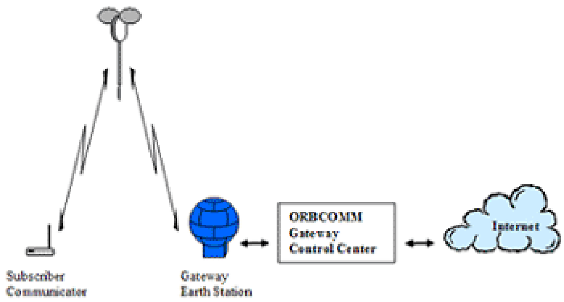


Figure 2.2. ORBCOMM system overview [8]

In general, two basic transmission modes for communication between SC and terrestrial-based customer are supported:

1. In case a SC can establish a link to an ORBCOMM satellite that currently has access to an Earth gateway stations, messages are directly transmitted between ground and mobile subscriber in almost real-time.

2. However, if the corresponding ORBCOMM satellite is presently not within the range of a ground station, it can still support message transmission in a store-and-forward mode. In this mode, the relaying satellite stores the self-contained data packages, the so-called GlobalGrams, in its onboard memory an dumps them to ground during the next pass over a gateway station. This service element is available for data transfer in both directions. It is needless to say that the real-time characteristic is inevitably lost in the store-and-forward mode. In terrestrial applications, typical average delay times of less than 15 minutes have been observed.

As stated above, the ORBCOMM system is designed for small packet data transmission only. Although a maximum length is not specified for individual messages, the practical maximum size was found to be between 500 and 1000 characters per message. In the store-and-forward mode the length of each message is limited to 182 characters.

The use of shorter messages is furthermore advisably, since the system processes and forwards only complete and error-free received messages. Corrupted or incomplete messages are refused and a retransmission is requested. This implies that the probability of a successful transmission decreases with the length of a message.

To take advantage of the store-and-forward mode as well as to increase the transmission probability - the maximum message length has been restricted to 180 characters for all data messages generated and transmitted in the Asolant/Rubin-5 project, for both communication directions.

The QuakeGlobal Q2000 ORBCOMM communicator

Today, a wide range of subscriber communicators for a broad spectrum of applications is offered by numerous manufacturers. The communication devices are available with many different features. The most basic models provide simply a serial port, power input and VHF connection, while more advanced SCs feature multiple analog and digital input and output ports, wide-range power input, integrated GPS receiver, battery charging circuitry and the capability to load and execute customer developed software. Common to all models is the core software which ensures reliable transfer of data to and from the terminal, adhering to the ORBCOMM VHF communication interface specification.

Figure 2.3. QuakeGlobal Q2000 Compact ORBCOMM GPS modem [9]

For the Asolant/Rubin-5 flight experiment, the Q2000 Compact ORBCOMM GPS Modem by Quake Global, Inc. [9] has been selected (Fig. 2.3). The Q2000 represents a versatile, feature-rich data communicator accommodated in a rugged housing and specially designed for operation in a hostile environment. Nevertheless, it has to be stressed that – in analogy to most other devices employed in the flight system – the modem is entirely build on COTS technology and thus not specifically suited or qualified for use in space. Experience gained in earlier flight projects, however, have shown, that the utilization of the Q2000 in short-duration LEO missions is well justified.

Key features of the Q2000, apart from the VHF modem functionality, include:

- 4 analogue input lines
- 8 digital input lines
- 4 output switches
- 2 RS232 serial ports
- a CPU with flash memory for the storage and execution of user written software
- a GPS chip set (for terrestrial use only)
- a battery buffered real-time clock

The Quake modem features an ARM7TDMI RISC processor running at a clock speed of 14.7 MHz. Application code can be developed in standard C language and converted into an executable binary file via a windows-based software development environment shipped together with the communicator. A user-friendly Application Programmer's Interface (API) greatly facilitates the interfacing of the user application with the core modem software. Messages are exchanged between modem and user code through a dedicated transport layer that can be accessed from both sides via API calls.

All the above features make the Q2000 ORBCOMM communicator a flexible and powerful tool. The individual input ports can be configured in a highly flexible way, e.g. to monitor a connected sensor and report at periodic intervals or on certain events. Two standard serial communication ports enable the data exchange with peripheral units. The output switches can be used to control connected equipment. Alarm conditions can be pre-programmed allowing an automatic and adequate reaction on certain critical events.

The above listed features are functions commonly associated with the functions provided by a dedicated onboard computer in satellite projects. However, the fact that all theses functions are already incorporated in the modem renders the use of a separate onboard computer, at least theoretically, obsolete. Within the Asolant/Rubin-5 project, two Q2000 modems were employed for exactly these purposes. Besides being used merely for TM/TC purposes, the Q2000 communicators furthermore served as onboard computer and data handling system with the main objective to:

- monitor and control the various sub-systems
- acquire and store the experiment data
- compile and transmit the telemetry messages
- process received commands and
- manage the power system.

In addition to the two ORBCOMM modems, the Rubin-5 unit comprised the rechargeable batteries providing power for the entire flight system, the battery charging circuitry and a standardized enclosure accommodating most of the peripheral units. A more complete description of the overall system architecture is provided at the end of this section.

2.2. The Advanced SOLar ANTennas (ASOLANT)

One of the major engineering challenges in the design of a space vehicle is to cope with the restricted space available on the surface of a satellite. Most spacecraft use both, solar arrays to generate electrical power for the onboard systems, and antennas for communication purposes or possibly to fulfil their scientific objectives. A more efficient coexistence of both elements could lead to a reduction in size and mass and thus to a cost saving. Therefore, the approach of integrating antennas and solar cells into a single space-saving unit suggests itself as a promising remedy for the above problem. Necessary prerequisite for the success of such an approach is, however, a good compatibility of both elements, solar cells and antennas. In particular printed antennas, nowadays commonly used in microwave communication, are well suited for such an attempt.

The idea to combine planar antennas and solar cells within a single device is first mentioned in literature in 1996 in a paper by M. Tanaka [10]. Main goal of the addressed study was to install a high-gain antenna on a small-scale satellite without reducing the space available for solar cells. This has been accomplished by adopting a "semi-integrated" design, where the solar cells were attached to the surface of a single printed antenna element. However, both components still remained functionally separated from each other. Nevertheless, tests results showed an excellent performance of the combined device, with the solar cells having very little impact onto the radiation characteristics of the antenna.

In the subsequent years an independent initiative was launched by a group of scientists at the Ecole Polytechnique Fédérale de Lausanne, aiming to explore alternative integration methods and making use of more advanced manufacturing technologies. Main scientific goal of the works was to further optimize the "performance-to-surface" ratio without losing sight of the implementation effort in terms of costs. The study included the investigation of different types of printed antennas, e.g. patch antennas and slot antennas, a comparison of single antennas versus antenna arrays as well as tests with Gallium Arsenide (GaAs) and amorphous silicon (a-Si) cells ([1], [11]).

A major step forward in the optimization could be achieved by using tailored solar cells manufactured in arbitrary shapes. This effort led to an improved utilization of the available space and allowed a more condensed layout. Likewise resorting to (slot) antenna arrays instead of a single antenna element notably improved the possibility to influence and customize the radiation pattern, gain and polarization of the antenna without scarifying too much space.

Another research objective was to arrive at a design were both, the R/F and the DC functionality, are physically merged together on a common substrate. In case of slot antennas the solar cells can e.g. be deposited or even directly grow onto the metallic antenna ground plane, into which the slot structures are cut or etched.

Several different prototypes of "SOLar cell ANTenna" (SOLANT) devices have be designed and implemented in the course of the project for a wide range of frequencies and applications. So far, however, the concept could only been evaluated in ground tests. The primary goal of the Asolant/Rubin-5 project was now, to assess the outcome of the research work in a real space mission. To this end two different antennas have been manufactured and integrated within a GaAs based solar panel (Fig. 2.4). One antenna has been designed to receive signals from the Global Positioning System (GPS,) while the second device was intended for the transmission of S-Band beacon signals. In this way it became possible to separately examine both transmission directions, the signal emission as well as reception, in a single flight experiment.

Figure 2.4 Picture of the both ASOALNT devices manufactured for technology demonstration mission.

The sketch in Fig. 2.5 illustrates the identical structure of the both multi-layer ASOLANT devices. The bottom plate of the panel is a thin aluminium layer that acts as ground plane for the antenna. It is separated from the main antenna layer by a 30 mm thick polyurethane open cell foam core. The antenna layer is composed of a RT/duroid 5870 laminate that serves as dielectric layer, coated by a thin conductive substrate on both sides into witch the antenna structures are etched. The top side of the antenna layer is covered by a 5 mm honeycomb structure. The upper layer of the device is a FR4 epoxy laminate that serves as antenna radome and carrier substrate for the solar cells at the same time.

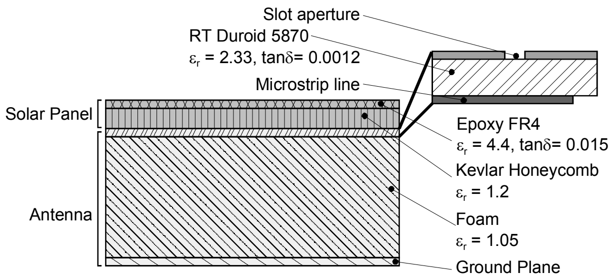


Figure 2.5 Schematic view of the cross section of the ASOLANT devices illustrating the different layers [1].

The solar cells have been deposited directly onto the FR4 epoxy top layer of the ASOLANT devices. The identical layout used for both photovoltaic panels is depicted in Fig. 2.6. The interconnection leads linking the individual cells have been etched (red lines in Fig 2.6) directly on the FR4 plate using a standard PCB manufacturing process. The cells are arranged in two strings, each comprising eight photovoltaic cells connected in series. Under ideal illumination conditions each string provides approximately 500 mA at a DC voltage of 9 V at the terminals.

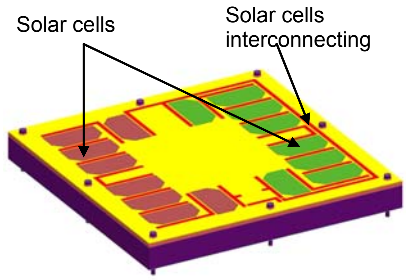


Figure 2.6 Top view of the ASOLANT devices illustrating the solar cell layout [1].

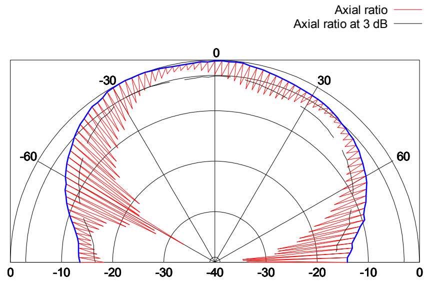
In the centre of the panels, a square zone of 170 mm x 170 mm has been left free of solar cells. Inside this area the thin slot antennas are located. As successfully demonstrated in previous experiments, most of the free surface could have been likewise filled with solar cells., Since, however, this would have required specifically shaped cells to properly account for the position and size of the slots and, due to fact that the costs for the tailored fabrication of such cells would have exceeded the project budget, it was decided to leave this space free of the cells. Still, the manufactured flight units are entirely appropriate to demonstrate the potential of the novel technology.

The key characteristics for the both devices are compiled in Table 2.1 below

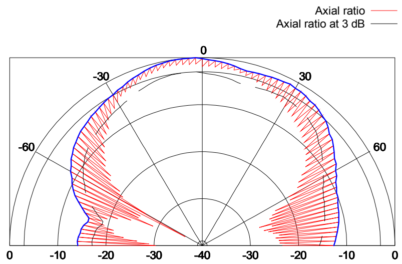
Table 2.1 Summary of key figures for the both ASOLANT antenna elements

GPS-Antenne	
Frequency:	1575 MHz (GPS L1)
Polarisation	RHCP
Impedance	50 ohms
VSWR	< 1.5:1
Gain	3 dBic
S-Band-Antenne	
Frequency:	2.4-2.45 GHz
Polarisation	RHCP
Impedance	50 ohms
VSWR	< 1.5:1
Gain	> 5 dBic

To verify the proper functioning and performance of the flight units after the final assembly, several laboratory tests have been conducted with both devices. The radiation patterns have been measured using the spinning dipole technique [1] in order to evaluate the circular polarization characteristics of the antenna. Two scans have been performed in the two orthogonal planes along the two median planes of the antenna. The plots in Fig 2.7 (a) and (b) exemplary show the radiation patterns for the GPS antenna.



Horizontal Plane



Vertical Plane

Figure2.7 Measured radiation pattern of the GPS antenna (a) for the horizontal antenna plane and (b) for the vertical antenna plane.

Complementary to the performance assessment tests, a series of basic environmental tests has been conducted to ensure a proper and reliable functioning of the ASOLANT units under the conditions encountered in space. Key issues covered by the test program included resistance to vibration and shock as well as thermal-vacuum conditions.

2.3. The Phoenix GPS Receiver

Within the past two decades, GPS receivers have evolved to a widely accepted and utilized navigation sensor for all kind of vehicles and applications including satellites and rockets. Nowadays, the vast majority of LEO satellite projects rely on GPS sensors as main source for position and velocity information required for orbit determination and orbit keeping as well as for maneuver planning.

The GPS receiver selected for the Asolant/Rubin-5 experiment is the Phoenix-S GPS tracking sensor developed by DLR/GSOC for low Earth orbit (LEO) satellite applications [2]. This receiver represents a low-cost single-board GPS navigation sensor for tracking of L1 C/A code and carrier signals on 12 parallel channels. The Phoenix receiver combines commercial-off-the-shelf (COTS) hardware components with a GPS signal processing software specifically designed for navigation of LEO satellites and rockets. The Phoenix employs a commercially available hardware platform, the MG5001 receiver board, manufactured by Sigtec Navigation Pty., Australia [12].

Figure 2.8 MG5001 GPS receiver board employed as hardware platform for the Phoenix GPS sensor for space applications

The MG5001 (Fig. 2.8) is built around the GP4020 chip of Zarlink, which combines a 12 channel correlator for L1 C/A code and carrier tracking, a microcontroller core with 32 bit ARM7TDMI microprocessor and several peripheral functions (real-time clock, watchdog, 2 UARTS etc.) in a single package. The MG5001 board further provides a 512 kByte flash EPROM for storing the receiver software and a 256 kByte RAM memory for run-time code and data. Supplementary to the external memory modules, the GP4020 chip provides a fast internal RAM of 32 kByte size. It is battery buffered and can serve as non-volatile memory for critical receiver parameters almanac, broadcast ephemerides and orbit elements of the user spacecraft.

A major concern in the development of space equipment is the environmental robustness of the involved components. Especially the use of COTS components requires a thorough and careful testing prior to utilization onboard satellites. Therefore, the Phoenix hardware platform has undergone a complete series of environmental tests including thermal-vacuum testing, vibration and shock testing and total-ionizing-dose as well as single-event-effect radiation testing. The obtained results have demonstrated that the system is well suited for most middle- and small-scale satellite projects with a typical life-time from several months up to a few years.

Other then for the hardware, the receiver software employed in the Phoenix significantly differs from the firmware used in terrestrial receivers. A major obstacle in the operation of GPS receivers onboard a space vehicle results from the pronounced relative motion of the host vehicle and the navigation satellite. This motion results in a frequency shift of the incoming signal, the so-called Doppler-shift, which has to be accommodated in the signal acquisition and tracking.

The Phoenix receiver employs a wide-band 3rd order phase-locked loop with FLL assist for carrier tracking and a narrow-band carrier aided delay-lock loop for code tracking. This ensures robust tracking and minimizes systematic steady state errors even under high signal dynamics. The receiver provides raw pseudorange, carrier phase and Doppler measurements with typically noise levels of 0.3 m, 0.5 mm and 0.06 m/s respectively. Furthermore, it offers carrier phase smoothed pseudoranges (ca. 6 cm/s noise level) and carrier based range-rate measurements (accurate to 1-2 cm/s). All measurements are properly synchronized to integer GPS seconds and a 1 pulse-per-second hardware signal is generated at the same instant.

Apart from the signal tracking, the specific signal conditions encountered onboard an Erath orbiting satellite have an adverse impact onto the signal acquisition process. The high Doppler shift dramatically increases the frequency search space and therefore results in notably extended cold start times of the receiver. Especially in light of an intermitted operation, with short activation periods only, this can result in a complete failure to provide a valid navigation fix.

As a remedy for this problem a position-velocity aiding concept has been developed and integrated into the receiver software. It makes use of an analytical orbit propagator, in the present case a NORAD SGP4 propagator, to obtain coarse reference values for position and velocity of the host satellite which, in turn, is used to analyze the current GPS satellites visibility and to predict the expected frequency shifts. The knowledge of the Doppler shift effectively removes the adverse impact of the high signal dynamics and reduces the complexity of acquisition problem to that of a terrestrial receiver. This allows an optimized receiver start with typical times to first fix of less than 2 min.

In general, the employed orbit propagator provides coarse position and velocity solutions for arbitrary epochs based on a set of orbital elements stored in non-volatile memory of the receiver. Typically, an initial set of elements corresponding to the target orbit is loaded into the receiver during the launch preparation phase. However, the pre-loaded orbital elements apply for a particular launch epoch only and a launch delay normally calls for an update of the stored elements. For the Asolant/Rubin-5 experiment, however, an external update of the orbit elements in case of a late introduced launch delay was excluded due to a missing communication link at the launch site. Therefore the receiver software had to be supplemented by an additional task which checks for a potential launch delay at the first receiver activation in space. Subject to the identified delay the orbit elements are then automatically updated. This mission specific software modification has been successfully validated in a series of GPS signal simulator tests conducted before system integration.

Despite the fact that Phoenix receivers are regularly used in European sounding rocket projects (Fig. 2.9) for flight safety and post-facto performance assessment purposes [13], the Asolant/Rubin-5 experiment marks the maiden flight of the receiver in a satellite mission. Over the next years Phoenix-S receivers will, furthermore, be flown on a number of upcoming European and international satellites projects such as ESAs Proba-II mission, the Singaporean X-Sat satellite or the Swedish Prisma formation flying mission.

Figure 2.9 Launch of a MAXUS rocket form the European space center ESRANGE, Kiruna, Swede.

2.4. The SAFIR-S radio amateur equipment

The fourth basic component making up the core of the Asolant/Rubin-5 flight experiment is the amateur radio unit "SAFIR-S", designed and implemented by the German radio-amateur society "Arbeitskreis Amateurfunk und Telekommunikation in der Schule e.V" (AATiS) [3]. Primary purpose of the radio-transmitter equipment is to generate different types of messages and signals and to transmit them through the ASOLANT S-Band antenna in order to allow an assessment of the transmission characteristic and performance. Secondly, the system was intended as a redundant telemetry system in case of problems with or a malfunction of the ORBCOMM communicator.

A major benefit of involving radio amateur groups into (low-cost) space projects is the worldwide popularity of amateur radio. Radio amateurs are commonly well-organized in a global network. A large number of mostly private ground stations are operated all over the Earth, even in rarely populated areas of the world. Taking advantage of this worldwide infrastructure can contribute to notably reduction of the costs associated with the operation of a satellite. The engagement of radio amateurs in such space projects is, however, not a one-way street. Usually the collaboration is based on mutual interest and benefit. Such projects typically offer a unique chance for the radio amateur community to obtain a flight opportunity for their equipment onboard a spacecraft at low or even no cost.

The SAFIR-S module is composed of an S-Band transmitter and a microcontroller. The employed S-Band transmitter is a slightly modified commercial 13 cm packet radio (PR) transmitter (Fig. 2.10) designed and marketed by ID Elektronik.

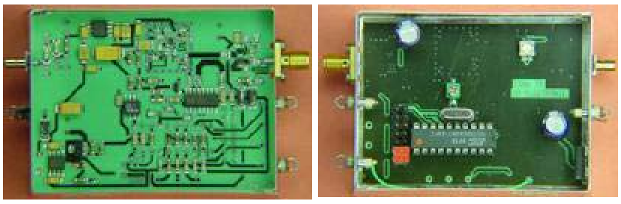


Figure 2.10 Top and bottom view of the main PCB of the 13 cm PR transmitter employed in the SAFIR-S unit

The key facts for the selected transmitter are summarized in Table 2.2.

Table 2.2 Key characteristics of the ID Elektronik S-Band PR transmitter

Transmitting frequency	2401.9 MHz
Transmitting power	100 mW (typ. 150 mW)
Power supply	9-15 V DC
Current consumption	approx. 300 mA
Dimensions	55 x 74 x 30 mm

A small tailor-made microcontroller board (Fig 2.11) built around Atmels ATmega32 processor has been employed as data source for the PR transmitter in the SAFIR-S system. A serial link to one of the both ORBCOMM communicators allowed a data exchange between both units. The microcontroller board, furthermore, featured an ISD1416 single-chip voice recorder/playback device with an onboard non-volatile memory cell for storage of up to 16 second of voice data. Power for both components transmitter and microcontroller was provided by the Rubin-5 unit.

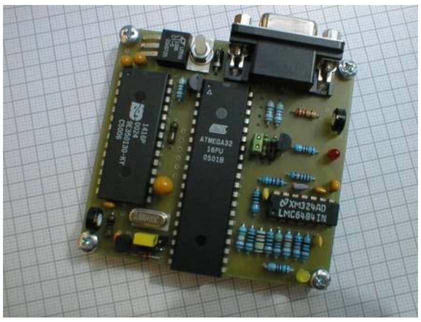


Figure 2.11 Tailor-made microcontroller board

The SAFIR-S system was configured to automatically generate and send out the following message sequence upon system activation:

1. Following switch-on through the Rubin-5 unit - and after a short system initialization phase - the data transmission is commenced with a 10 second long FM modulated voice message.
2. Following a 5 second period of inactivity an approximately 1 second long data package is emitted containing key parameters reflecting the current status of the SAFIR-S system itself.
3. Thereafter the system enters into an endless loop. In a first step, the SAFIR-S unit acquires and temporary stores a subset of experiment and navigation data submitted by the Rubin-5 unit. Subsequently, these data a merged with a set of SAFIR-S status information and finally packed for transmission. This process is typically accomplished in about 12 seconds. Thereafter the transmission is initiated and, subject to the amount of data received form the ORBCOMM modem, completed within 3 to 15 seconds.

Step 3 is repeated as long as the system is powered. Upon reboot the transmission sequence is restated with step 1. All data messages are transmitted at a baud rate of 9600 using AFK modulation and the AX.25 protocol.

Due to the limited power budget of the Asolant/Rubin-5 system, a continuous operation of the SAFIR-S system was not feasible. It was therefore planned to operate the transmitter in an intermitted modem. It was intended to activate the unit for 10 minutes every 20 minutes, yielding a duty-cycle of 50%

2.5. Flight System Architecture

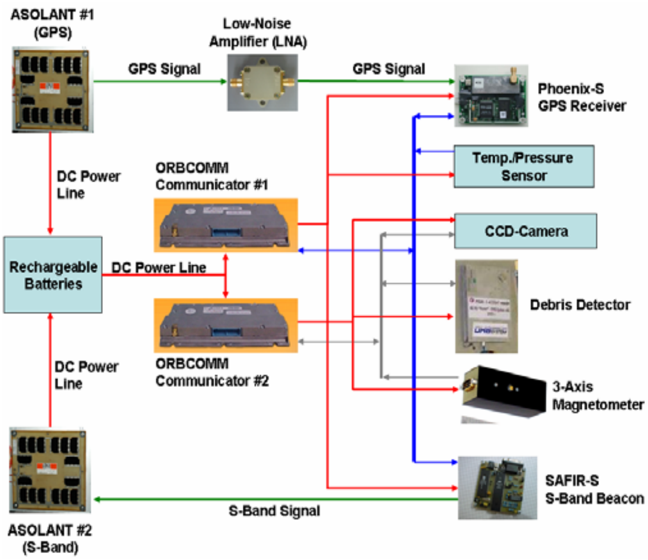


Figure 2.12 Layout of the Asolant/Rubin-5 flight experiment

This section provides a structural overview of the overall flight system architecture. The schematic diagram in Fig 2.12 depicts the individual sub-systems of the Asolnat/Rubin-5 experiment and how these were linked with each other.

The core of the flight experiment was constituted by the two QuakeGlobal Q2000 ORBCOMM communicators, providing the TM/TC and onboard computer functionalities in a single device. To keep the system architecture simple, both modems operated completely independent from each other. A communication link did not exist and, hence, a data exchange was excluded. While modem #1 was connected to the temperature and pressure sensors and the Phoenix GPS receiver, modem #2 was linked to the CCD-camera, the 3-axis magnetometer and the debris detector. All devices shared a common powers supply, a rechargeable battery pack directly connected to the solar cell arrays of the both ASOLANT devices. Activation and deactivation of most peripherals was accomplished through the configurable switching outputs of the both ORBCOMM modems.

The ORBCOMM units, the accumulator pack, the GPS receiver and the SAFIR-S unit were accommodated in a standardized hermetic Rubin experiment container, while the magnetometers and the CCD camera were housed in separate enclosure. The ASOLANT devices and the debris detector were attached directly to the payload adapter of the Cosmos-3M rocket, without the need of a dedicated housing. While the S-Band antenna was connected to the output port of the SAFIR-S transmitter in a direct manner, a dedicated low-noise amplifier (LNA) has been incorporated into the R/F line between GPS antenna and receiver providing adequate signal amplification for the R/F input of the Phoenix. A view into the open Rubin experiment box is provided in Fig 2.13.

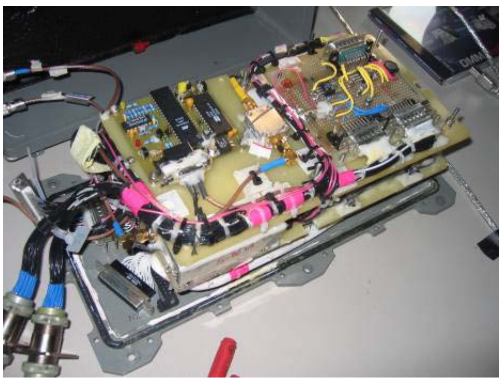


Figure 2.13 Rubin-5 box during the assembly phase.

3. TESTING, INTEGRATION AND FLIGHT RESULTS

3.1. Model and Test Philosophy

In light of the explicit cost- and effort-reduction strategy pursued in the Rubin-X program and, furthermore, against the background of limited budget for the ASOLANT flight experiment, a very simple model philosophy has been adopted for the project. For most sub-system a single unit has been built-up only, employed as engineering model and flight model at the same time.

For the same reasons the test concept in the Asolant/Rubin-5 project has been confined to the minimum number and types of tests necessary to still ensure a reliable operation in space. In particular, no specific environmental test program has been conducted. This appeared justified in view of the fact that most devices have either been qualified previously for space utilization in independent test programs, like the Phoenix GPS receiver, or have already been successfully flown in past space missions, like the ORBCOMM modems and the batteries. Solely the ASOLANT devices have undergone a more comprehensive test program comprising thermal-vacuum, vibration and shock testing, since this was integral part of the ESA-funded development activities.

Figure 3.1 Ground testing of the Asolant/Rubin-5 system at OHB, Bremen, Germany

The majority of conducted tests served to verify the proper functioning and to assess the performance of the individual system components as well as to ensure compatibility between the various sub-systems. The picture shown in Fig. 3.1 has been taken during an open-sky test carried out at OHB shortly before hardware delivery to Russia. The test involved all core components of the flight system except for the SAFIR-S module, which has not been ready for integration and testing at that time. Main objective of the test was to validate proper functioning of the TM/TC system, the solar panels and the GPS receiver.

3.2. Flight System Integration

Subsequent to completion of the functional tests with the completely assembled Asolant/Rubin-5 equipment, the hardware was shipped to Russia for a mechanical and electrical fit- and interface-check with the payload adapter of the Cosmos rocket. All system components have been placed and fixed at their final location and the tailored cable harness, provided by the Russian project partners, have been installed. The mounting locations of the individual experiment components are illustrated in Fig 3.2 showing the payload adapter before integration of the remaining payload satellites.

Figure 3.2 Cosmos payload adapter with installed Asolant/Rubin-5 flight experiment prior to satellite integration

While the ASOLANT devices, the debris detector and the box, accommodating the magnetometer and the CCD camera, remained attached to the payload adapter after completion of the fit checks, the main Rubin box was detached and brought back to Germany for further software optimization and testing. Only two days before the scheduled launch date the box was finally shipped to Russia and installed on the rockets payload adapter. A final system check, the final battery charging and an update of the GPS receiver related initialization parameters were performed after the mounting of the fully assembled payload adapter on top of the rocket motor (Fig 3.3). These activities took place shortly before installation of the faring and only 24 hours prior to the scheduled launch. This illustrates well the high level of flexibility provided by the Rubin-X concept and the feasibility to access the experiment unit even at a very late stage of the flight vehicle preparation.

Figure 3.3 Fully assembled payload adapter mounted on top the Cosmos-3M rocket.

3.3. Launch and First Flight Results

After a total delay of several months caused by technical problems with the prime payload, the Cosmos-3M rocket was finally launched on 27 October 2005 from Plesetsk, Russia's northern cosmodrom. At 6:52 UTC time the rocket successfully took off from launch pad No. 132 carrying the Asolant/Rubin-5 experiment along with seven multinational payload satellites onboard.

Roughly 150 seconds after leaving the launch pad, faring separation took place at an altitude of roughly 83 km. Simultaneously, the Asolant/Rubin-5 experiment was activated through the onboard control system of the Cosmos launcher. In a first stage of the flight experiment, however, only modem #1 and some basic sensors have been switched on, while modem #2 and most peripheral devices remained deactivated.

Within a few minutes thereafter the first system message - a "switch-on" message - has been received on ground via standard email, confirming the successful activation of the Asolant/Rubin-5 system. In the subsequent four minutes, between 7:11 and 7:15 UTC, another 8 housekeeping data messages were sent to ground. These messages indicated an unusually low battery voltage. Later investigations revealed that, apparently due to an undetected incompatibility between the external main experiment switch and the Asolant/Rubin-5 electronic, the accumulators have been unintentionally discharged within the 24 hours between the final system checkout and launch.

A first set of magnetometer measurements for all three axes was captured around 24 minutes after launch at about 7:17 UTC. The data were, however, only transmitted to ground about one and a half hour thereafter. Most likely this delay was due to the critical voltage level reported in the previous messages. Upon reaching a critical threshold the modem was configured to automatically switch into a sleep-mode as part of the safety philosophy implemented in the onboard software.

Subject to the measured battery voltage, the peripheral devices are gradually deactivated to cut down the energy consumption. In a final step the modem suspends itself for a defined period of time in order to prevent a complete discharging of the batteries and a potential destruction of these. The diagram in Fig 3.4 depicts the recorded raw magnetometer readings for the three axes. The data indicate a nominal and stable flight of the rocket during this phase of the ascent.

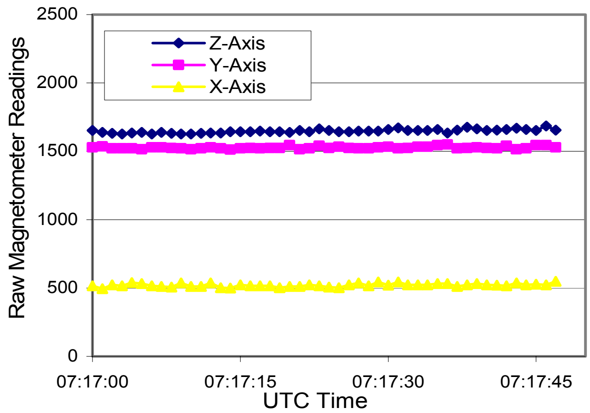


Figure 3.4 Raw magnetometer reading captured during the boost phase, about 24 minutes after launch.

About 35 minutes after leaving the launch pad, the Cosmos-3M rocket successfully entered the intended target orbit and began to deploy the payload satellites. While satellite number one to six have been separated as scheduled, satellite number seven, the Russian Mozhaetes-5, apparently failed to detach from the booster. An independent confirmation of the separation failure was later provided by the data collected and transmitted by the Asoant/Rubin-5 system. The occurrence of this contingency had unfortunately several direct as well as indirect, unfavorable implications onto the Asolant/Rubin-5 project.

On the one hand, one of the two ASOLANT devices, the GPS antenna unit, was almost completely shadowed by the Mozhaetes-5 satellite, which was attached on the launch adapter directly above the combined solar cell antenna. This severely affected both functionalities of the device: the GPS signal reception as well as the electrical power generation, through the solar cells. Especially the latter effect posed a major problem to the energy budget of the entire flight system. As a workaround, the activation schedule for the various sub-systems has been reconfigured via ground command during the first days in orbit in order to reduce the average power consumption.

On the other hand, the missing separation impulse of Mozhaets-5 resulted in a roughly one order of magnitude too high residual spin-rate of the upper stage compared to the expected value. The upper stage of the Cosmos launch vehicle is not equipped with an active attitude control system. However, usually the separation system is designed such that the sum of the individual separation impulses acting on the upper stage yields zero. One could thus expect a nearly stable attitude of the vehicle after completion of the separation sequence. During earlier COSMOS missions typical residual spin rates of less than 1 deg/sec have been observed. Due to the Mozhaetes-5 separation failure, however, the launch vehicle upper stage did not achieve the intended balance of separation impulses and, as a consequence, a residual spin rate of about 10 deg/sec was measured by the onboard magnetometer in the afternoon of the launch day (Fig 3.5).

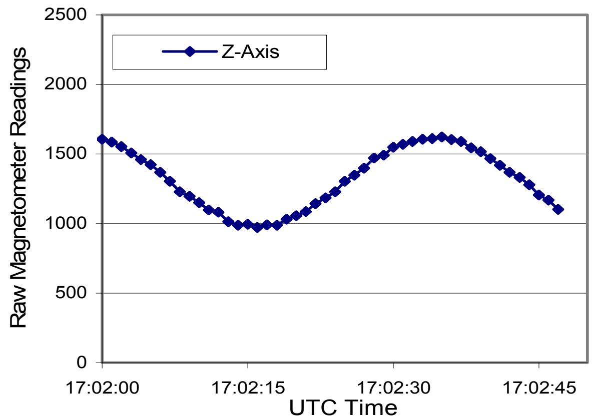
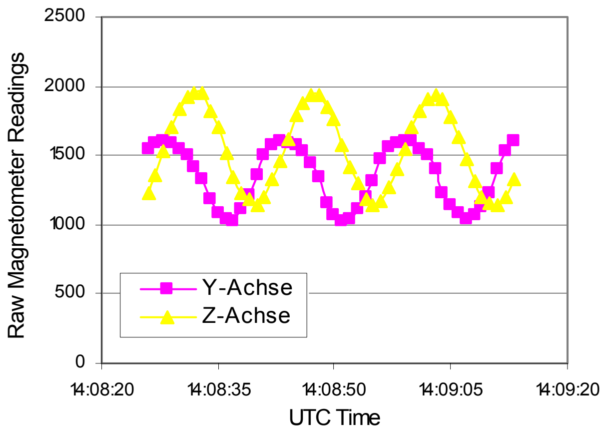


Figure 3.5 Residual spin rate observed after completion of the separation sequence

An analysis of the magnetometer data obtained during the subsequent days revealed an even further increase of the spin rate of the upper stage. Fig. 3.6 and 3.7 illustrate the raw measurements recorded on the second day in orbit and a week after launch, respectively.



3.6 Spin rate of the upper stage on the second day after launch

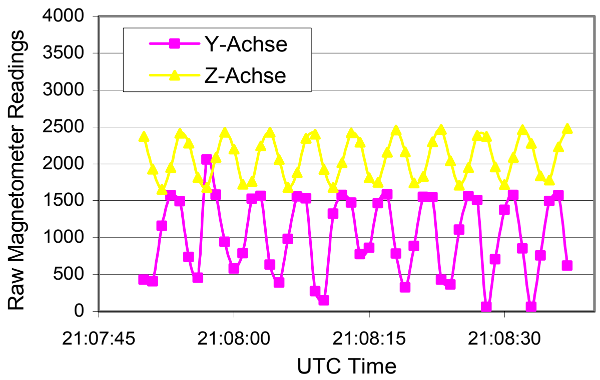


Figure 3.7 Spin rate measured on Nov 4, 2005, about one week after launch

A conclusive explanation for the encountered phenomenon could not yet be found. According to Russian space experts, possible causes for the observed spin-up of the upper stage could be e.g. residual propellant escaping through a leak in a fuel tank of the upper stage or classical energy transfer between different rotation axes of the vehicle, or even a combination of both. The maximum recorded spin rate amounted to roughly 12 revolutions per minute and was reached about 7 days after launch. Thereafter the attitude motion stabilized on a near constant value.

Despite the adverse overall conditions experienced by the Asolant/Rubin-5 flight experiment during the past 10 month in orbit a large number of telemetry emails has been retrieved on ground, providing a broad range of interesting experiment data. Even though the high rate of rotation causes some drop-outs in communication with the ORBCOMM satellites, the problem did not completely inhibit a message transfer, neither in the down-link nor in the opposite direction. The diagram in Fig 3.8 represents the number of daily received emails.

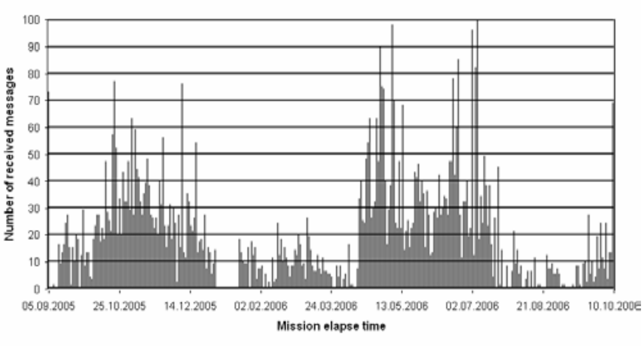


Figure 3.8 Number of received messages per day since experiment start .

On good days, up to 100 messages have been successfully received on ground. The days and phases with poor numbers of received emails can be best explained by the limitations in the energy budget due to the absence of one of the two solar panels and the temporary deactivation of the modems in order to prevent a deep discharge of the batteries.

Fig 3.9 and 3.10 show two exemplary pictures captured by the CCD camera provided by students of the University of Applied Science Bremen. The first image was taken in the lower resolution mode (80 x 64 pixel) while the second was shot in a higher resolution mode (320 x 240 pixel).

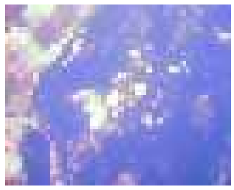


Figure 3.9 Low resolution image (80 x 64 pixel) captured above the Golf of Mexico.

A comparison with an image obtained from a weather satellite flying across the same region and taken at a similar epoch suggests that the first picture shows a part of the coast line of the Golf of Mexico.

Figure 3.10 High resolution picture (320 x 240 pixel) taken above Europe.

Besides exposing students with the various aspects of a space project, the main goal of this experiment was to demonstrate the capability of an ORBCOMM based TM/TC system to also transmit larger amounts of data. For the down-link the files have been first compressed and than split into small data packets taking into account the maximum allowed message length of 180 bytes. On ground the received emails have been processed in a reverse manner.

As to what concerns the GPS receiver, the shadowing of the antenna severely inhibited a reception of a sufficient number of satellites required to provide a valid navigation solution. Nevertheless, several GPS messages have been received indicating the occasional acquisition of GPS signals. In particular, a regular update of the GPS Almanac inside the receiver - a coarse description of the GPS constellation transmitted by each satellite and used to predict the GPS visibility – has been recognized. Such an update requires usually a continuous connection to a GPS satellite for at least a few minutes. This observation can be taken as clear evidence of the basic functioning of the ASOLANT GPS device and thus as successful proof-of-concept for the new technology.

Regarding the SAFIR-S radio amateur experiment, a single ground contact has been reported in November 2005 [14]. Despite a large effort devoted by the radio amateur community to the reception of further beacon signal from Asolant/Rubin-5, this remained the only documented contact.

At the moment of writing this paper (Sep. 06), still most of the sub-systems are in operation. An average of about 20 to 50 emails is received each day, providing lots of useful and valuable information about the system status.

4. SUMMARY AND CONCLUSIONS

The paper presented the Asolant/Rubin-5 technology experiment conducted onboard the upper stage of a Russian Cosmos-3M rocket. The main goal of the project was to demonstrate the feasibility and validate the performance of the ASOLANT technology - a novel and innovative approach combining solar cells and antennas in a single unit - in a real space mission. The core experiment was made up of the Rubin-5 unit, two different ASOLANT devices, a space-borne Phoenix GPS receiver and the SAFIR-S amateur radio transmitter. Moreover, the overall flight system comprised a prototype debris detector and an experimental CCD camera as well as various housekeeping sensors.

Despite various limitations imposed by the separation failure of the Mozhaets-5 satellite, major mission objectives were accomplished. The ORBCOMM based TM/TC system transmitted, and still transmits, about 50 to 100 telemetries emails per day to the ground. A considerable amount of status and experiment data was obtained from space since launch in late 2005. The available data provided a successful proof-of-concept for the novel ASOLANT hybrid technology. However, a more qualitative and quantitative assessment of the transmission characteristics of the antenna devices was not feasible, due to the impact of the not properly separated co-passenger on the experiment. Therefore, a re-flight of the ASOLANT system is currently under consideration.

Furthermore, the fact that after about 10 month in orbit, most sub-systems are still operational has demonstrated the durability and reliability of the employed standard devices and components. This further supports the idea to use COTS technology in low-cost satellite projects as an interesting and promising alternative to costly space-qualified components and devices.

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