SED

Student Experiment Documentation

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Mission: BEXUS 18

Team Name: ARCA

Experiment Title: Advanced Receiver Concepts for ADS-B

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CHANGE RECORD

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1	2014-02-14	All	PDR
1.1	2014-02-24	1.3, 2.1, 2.2, 2.3, 2.4, 3.1, 4.5	
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Abstract:

Keywords: BEXUS, SED – Student Experiment Documentation, ARCA, Aircraft, ADS-B

CONTENTS

PREFACE

ARCA (Advanced Receiver Concepts for ADS-B) is a team from the university for applied sciences in Jena which was selected for the BEXUS (Balloon Experiments for University Students) 18 project.
The team wants to build a Mode-S ADS-B receiver which receives messages from aircrafts.
For the team this project represents the first step into the space business. Because of the increasing number of aircrafts in the modern world such a receiver could be mounted on a small satellite to be used as a relay station for Mode-S ADS-B messages.

ABSTRACT

In the modern world, the aircraft is a common way of transportation. With thousands of flights every day, of course, the need for tracking planes, monitoring their position and health status arises.

At the moment, most airplanes are only tracked in densely populated areas. The main goal of the experiment is to show, which advantages an aircraft-based ADS-B surveillance system could have, using a stratospheric balloon for demonstration and evaluation.

One experiment goal is not to resort to using pre-built electronics, but instead develop, verify and produce the different parts of the experiment ourselves.

The receiver will listen to Mode-S aircraft traffic, decoding DF17 position reports and log them on-board as well as downlink them to the ground station. There the data will be plotted by user interface software for a quick look analysis and be saved for careful interpretation afterwards.

1 INTRODUCTION

1.1 Scientific/Technical Background

In the modern world, the aircraft is a common way of transportation. With thousands of flights every day, of course the need for tracking planes, monitoring their position and health status arises.

As flight numbers increase, there is a chance that people tend to lose track of flights and for example a crash may not be noticed instantly. Our experiment tries to evaluate the feasibility of high altitude monitoring of Mode-S (ADS-B) transmissions to allow less dense areas to be monitored. Future possibilities may include a net of Pico-satellites in orbit to monitor the whole earth surface. Other possible uses arise, for example making flight routes more effective by saving fuel – if flight route changes could be made more flexibly.

The subject doesn't seem to be far-fetched, as Iridium NEXT satellites will include a system to monitor ADS-B-transmissions and Iridium will provide that data for money to airlines as soon as 2015.

1.2 Mission Statement

Many aircrafts (about 80%) transmit tracking data via Mode-S (ADS-B). The status quo is that this data is only observed in regions with dense population.

The objective of the ARCA experiment is to receive Mode-S transmissions in high altitude and evaluate the possible problems and advantages such surveillance would have.

To do that, the electronics, including the receiver will be developed, built and tested by the team on its own.

1.3 Experiment Objectives

Primary Objectives:

- Analysing Mode-S (esp. ADS-B) data reception possibilities in great height (scientific)
- Developing and building a system, which is able to receive ADS-B data without relying on pre-built hardware (technical)
- Characterisation of the implemented systems and algorithms (technical)

Secondary Objectives:

- Evaluating the maximum radius, in which airplanes can be received

1.4 Experiment Concept

The payload will, consist of an electronic box and an externally mounted antenna. The electronics box contains a RF receiver and demodulator, an FPGA decoder and an ARM SoC running Linux for data storage, analysis and communication to ground support. The received and demodulated signals (Mode-S downlink at 1 Mbit/s) are processed by an FPGA, decoding the data in real time and are then transmitted to the main processor to be logged and transferred to ground support.

1.5 Team Details

1.5.1 Contact Point

For any questions regarding our experiment, please contact the team leader, Severin Haas. You can reach him via mail (severin@e-sev.de) or via mobile phone +49 178 8287 494.

Address:

Jenertal 1

07749 Jena

Germany

For mails concerning the whole team you can also write to:

arca@e-sev.de

1.5.2 Team Members

Severin Haas, Project leader

Severin studies Electrical Engineering with the main focus on embedded systems at the University of Applied Science in Jena. Besides that he is interested in signal processing, astronomy and likes to photograph.
In the ARCA team he is responsible for project management, testing, outreach work and the ground control software.

Hannes Zöllner, Electronics developer

Hannes is currently working on his Ph.D. in the topic of analyzing COTS-microcontrollers and –memories for the usage in space applications.
His main interest is the development of hardware. Therefore he is responsible for the electronics development in the project.

Stefan Biereigel, Software developer

Stefan studies Electrical Engineering with focus on embedded Systems at the University of Applied Sciences Jena. His personal interest lies in the Radio

Communication field, with special focus on Software Defined Radio (SDR) technology. He is responsible for Software implementation and the FPGA Receiver Design.

Johannes Willenbücher, Mechanical designer

Johannes studies Mechatronics with focus on information technology at the University of Applied Science Mannheim. Before university, he completed an apprenticeship as a motor mechanic and electrician. Having experience with construction and CAD software, he is responsible for the mechanical design of the experiment.

Sebastian Udich, Thermal simulation engineer

Sebastian Udich finished his engineer’s degree in Mechatronics and his Master of Science in Space Electronics at Ernst-Abbe-Hochschule Jena. He is now writing his doctorate (in cooperation with Technical University Ilmenau) about modeling and simulation of ceramic semiconductors. He is responsible for thermal management and simulation of the experiment payload.

2 EXPERIMENT REQUIREMENTS AND CONSTRAINTS

2.1 Functional Requirements

F1: Removed.

F2: The experiment shall detect data from airplanes (ADS-B) during the whole flight.

F3: The experiment shall distinguish between different airplanes.

F4: The received data shall be saved on a flash card.

2.2 Performance requirements

P1: Deleted.

P2: The experiment shall only receive data at a frequency of 1090MHz.

P3: The experiment shall have a storage capacity of 16GB.

P4: The experiment shall be able to receive a minimum of 5 messages per second.

P5: The experiment shall receive Mode-S ADS-B data with a data rate of 1Mbit/s.

2.3 Design Requirements

D1.1: After CDR deleted.

D1.2: The experiment shall be designed to prevent the electronics from temperatures below -20°C to ensure safe operating conditions.

D2: The experiment shall work at the vibration profile of the BEXUS balloon.

D3: The experiment should not harm the gondola and other experiments.

D4.1: The experiment must be designed to use the E-Link downlink.

D4.2: The experiment must be designed to use the E-Link uplink.

D5: The experiment shall not use more than 0.5 Ah of the gondola battery.

D6: The experiment shall not be air-tight and be equipped with holes.

D7: The experiment shall not be heavier than 2kg.

D8: The experiment box shall not be bigger than 0,2m x 0,2m x 0,2m.

D9: The receiver should decode the incoming data at a frequency of 1090MHz.

D10: moved to F4.

D11: The antenna shall have a gain of at least +7dBi and be optimized for 1090 MHz

D12: An antenna shall be mounted outside of the gondola, facing downwards while flight.

D13: The antenna shall receive with omnidirectional characteristics.

2.4 Operational Requirements

O1: The experiment shall be able to work autonomously, without control by the ground station.

O2: The experiment shall save all data before the balloon is cut off to prevent data loss in case of short power outages.

O3: Removed.

O4: Moved to D12.

O5: Moved to D13.

O6: The other BEXUS experiment must not emit any EM-interference at a frequency of 1090MHz.

2.5 Constraints

The experiment must comply with the BEXUS schedule and guidelines.

3 PROJECT PLANNING

3.1 Work Breakdown Structure (WBS)

Figure 1 Work Breakdown Structure

WP	Task	Responsible Person	Supporter
1.1	Create timetable	Severin Haas	
1.2	Planning	Severin Haas	Stefan Biereigel
1.3	Communication	Severin Haas	
2.1	Build antenna	Hannes Zöllner	Stefan Biereigel, Severin Haas
2.2	Design frontend	Severin Haas	Stefan Biereigel
2.3	Design decoder	Hannes Zöllner	Stefan Biereigel
2.4	Design power supply	Hannes Zöllner	
2.5	Build frontend	Hannes Zöllner	Stefan Biereigel, Severin Haas
2.6	Build decoder	Hannes Zöllner	Stefan Biereigel, Severin Haas
2.7	Build power-supply	Hannes Zöllner	Stefan Biereigel, Severin Haas
3.1	Write decoder software	Stefan Biereigel	Severin Haas
3.2	Write main computer software	Stefan Biereigel	Severin Haas, Hannes Zöllner
3.3	Write ground station software	Severin Haas	
4.1	Create structure	Johannes Willenbücher	Team
4.2	Draw CAD	Johannes Willenbücher	
5.1	Create concept thermo simulation	Sebastian Udich	
5.2	Design simulation	Sebastian Udich	
6.1	Temperature test	Severin Haas	Team
6.2	Vacuum test	Severin Haas	Team
6.3	Shock test	Severin Haas	Team
6.4	EMC test	Severin Haas	Team
6.5	Endurance run	Severin Haas	Team
7.1	Create homepage	Severin Haas	Team

7.2	Twitter	Severin Haas	Team
7.3	Planning events	Severin Haas	Team
7.4	Produce podcast	Severin Haas	Stefan Biereigel
8.1	Write PDR SED	Severin Haas	Team
8.2	Write CDR SED	Severin Haas	Team
8.3	Write IPR SED	Severin Haas	Team
8.4	Write EAR SED	Severin Haas	Team
8.5	Write final SED version	Severin Haas	Team

3.2 Schedule

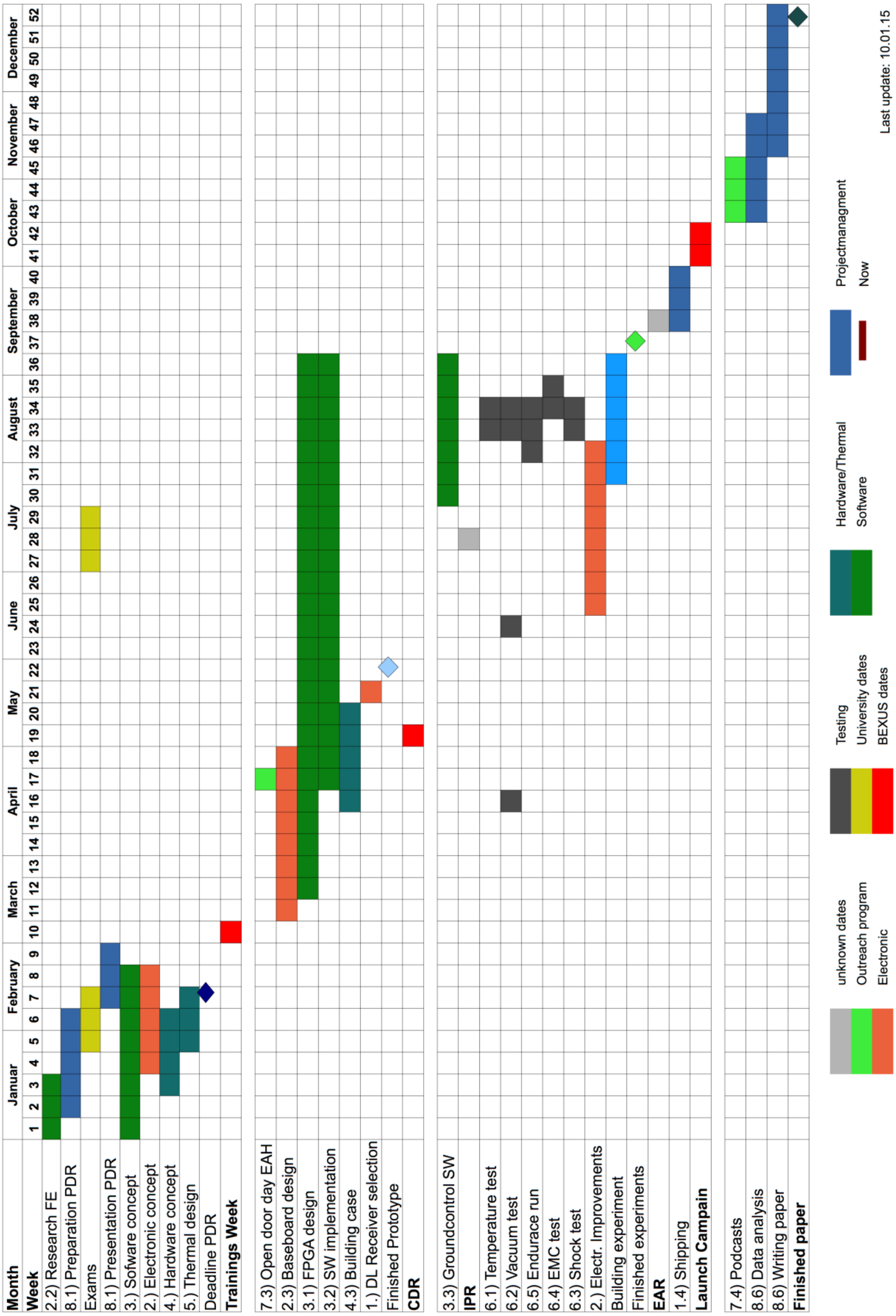


Figure 2 Schedule

3.3 Resources

3.3.1 Manpower

Stefan Biereigel spends about 15 hours per week to work on the experiment. In peak times much more. From 30.06.2014 to 19.07.2014 he is writing exams, so the available time is lower.

Severin Haas spends about 15 hours per week to work on the experiment. In peak times much more. From 30.06.2014 to 19.07.2014 he is writing exams, so the available time is lower. From mid November 2014 to end of January 2015 he is going to write his bachelor thesis. In this time he has to reduce the work to a lower level.

Sebastian Udich will spend about 5 hours per week to work on the experiment.

Johannes Willenbücher can spend 7.5 hours per week to work on the experiment. In peak times he can spend much more time.

Hannes Zöllner can spend about 7.5 hours per week to work at the experiment. In peak times, of course much more.

3.3.2 Budget

Overview over project budget:

Item	**Price**
Parts Main computer	150€
PCBs Main Computer	200€
Parts Baseboard	120€
PCBs baseboard	160€
Antenna	40€
Aluminium case	100€
Cabling, Connectors, etc.	80€
bladeRF-Board (Test and Verification equipment)	430€
Software license	25€
Shipping	120€
Total	**1425€**

All components listed above will be the costs for 2 experiments, which are sponsored by BMWi/DLR and administrated by ZARM.

At the moment, the team consists of 5 team members. We want to give all team members the possibility to travel to the launch campaign in October 2014.

To finance the fifth person, we made an application at our university to support us with paying the open flight ticket to Kiruna. Our project was funded by the “Studentische Forschungs und Entwicklungsprojekte”-program with 1500€. We will use this money to give all team members the possibility to travel to launch campaign and for buying some of the components needed for the experiment.

If the self-built receiver cannot be finished in time or does not work well enough, there will always be the possibility to buy a semi-professional receiver (Mode-S beast). One receiver costs around 400€. See Risk Register for further information.

3.3.3 External Support

During the whole process we are consulted by Prof. Burkart Voss from our faculty. He is also the leader of the master course space electronic.

Additionally, we will get technical support from the "institute of integrated circuits" of Prof. Jürgen Kampe. There, we can use the available climatic cabinet for testing.

To test the electromagnetic compatibility of the experiment, we can use the GTEM cell from Prof. Ludwig Niebel in our university.

Vacuum tests can be done at the physics department of Friedrich Schiller University, Jena and with desiccators available at EAH Jena.

3.4 Outreach Approach

To inform the public about our project and the results we have done the following things:

Website: We created a website (http://bexus-arca.de) where we describe our experiment and the concept in detail. Additionally there will be updates about reached milestones and general project status updates. Currently the website is still in progress, so there is not much content. We will update it in the next weeks.

Twitter: During the whole project we are tweeting news and information at the short message service Twitter. The account name is @BEXUS_ARCA (http://twitter.com/BEXUS_ARCA)

Podcasts: In January 2014, we talked to Markus Völter, responsible for podcast 'OmegaTau' (http://omegataupodcast.net). Together we planned a few podcast episodes about the REXUS/BEXUS program, ESRANGE and science done with high altitude rockets and balloons, including the ARCA experiment. For the first mentioned subjects he is planning to talk to scientists and experts from ESA, SSC, and DLR etc in the end of this year (2014).

In addition, the following the outreach actions have taken place or will take place:

- We presented our experiment at the open house event of our university on 12.04.2014.
- We gave an interview to the public relations department of EAH Jena, which led to the publication of some articles in print media (TLZ, OTZ papers) and online (Jenapolis, JenaTV).
- At the training week, we got the possibility to present our experiment and the REXUS/BEXUS program to a film team. The interview and presentation will be aired on ServusTV in “TM Wissen”, a science show broadcasted on a weekly basis.
- Our university hosts a picture gallery of the student training week, featuring our experiment and experiences.
- On the website of the electronic engineering department of EAH Jena, a project page will be hosted, making available technical information on the experiment
- For the university, a poster was designed, presenting different experiment aspects as well as the REXUS/BEXUS-programme in general. This poster was shown during the day of research (“Tag der Forschung”) at our university.
- We presented the REXUS/BEXUS-program in a Masters course for Space Electronics at EAH Jena, and got in contact with possibly interested people.
- We presented the REXUS/BEXUS-program to pupils of tenth grade from Friedrich-Schiller-Gymnasium Zeulenroda.
- We are going to give an interview to our local university student radio station „Campusradio Jena“.
- We created a poster about the launch campaign in Kiruna which is shown to everyone in our university department.
- A newspaper article about the ARCA project, REXUS/BEXUS and the launch campaign was published at Jenapolis, a regional news website.
- At the website of our university department a picture gallery was created.

3.5 Risk Register

Risk ID
TC – technical/implementation

MS – mission (operational performance)
SF – safety
VE – vehicle
PE – personnel
EN – environmental

Probability (P)
A. Minimum – Almost impossible to occur
B. Low – Small chance to occur
C. Medium – Reasonable chance to occur
D. High – Quite likely to occur
E. Maximum – Certain to occur, maybe more than once

Severity (S)
1. Negligible – Minimal or no impact
2. Significant – Leads to reduced experiment performance
3. Major – Leads to failure of subsystem or loss of flight data
4. Critical – Leads to experiment failure or creates minor health hazards
5. Catastrophic – Leads to termination of the project, damage to the vehicle or injury to personnel

Table 3-1: Risk Register

ID	Risk (& consequence if not obvious)	P	S	P x S	Action
TC10	Components are damaged during test	A	1	A1	Redundant components
MS10	Deleted after PDR.	-	-	-	-
MS20	EM interference by e.g. other experiments on the ADS-B frequency (1090 MHz)	C	2	C3	Other experiments must be sure that their experiment is not transmitting RF at this frequency
MS30	Loss of connection to E-Link	B	1	B1	Store data to flash during flight
MS40	Water landing	A	3	A3	The data storage shall be water resistant; data is transmitted to ground support while the experiment is in flight.
MS50	Short power outage	A	1	A1	Electronics shall reboot automatically
MS60	Too few airplanes to receive	A	2	A2	Prefer a day flight to have a higher chance to receive airplanes

SF10	Loss of the Antenna	A	4	A4	The antenna should have a good mounting at the gondola.

4 EXPERIMENT DESCRIPTION

4.1 Experiment Setup

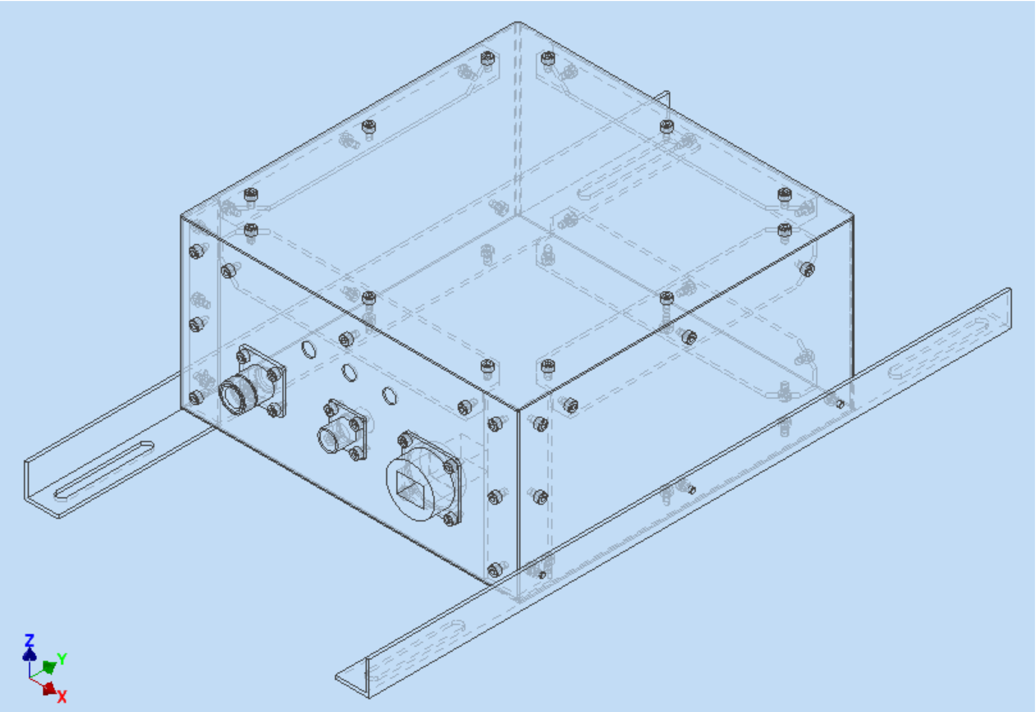
The ARCA experiment will consist of a radio frequency receiver, listening on the ADS-B frequency (1090 MHz). The received signals will be processed by the demodulator and a signal processor. They will be filtered and logged with the help of an embedded computer. Some of the received data will be downlinked to ground support, where the team can monitor the correct operation of the experiment. There will be an uplink command interface available to the team, with help of which the experiment can be reset and controlled manually.

4.2 Experiment Interfaces

4.2.1 Mechanical

The experiment will be contained in a small aluminium box. The antenna, to be mounted outside of the gondola will be strapped to the gondola frame.

The drawing below gives an overview of the mechanical interfaces.



Picture 1 Experiment Case

The antenna will not be mounted on a bracket (as was planned up to CDR), but instead the feeding coaxial cable will be fixed to the horizontal gondola frame bars with the help of cable ties.

This technique has advantages: While the antenna is rigid (to maintain its RF properties), it can swing freely and will not break off by touching the ground. It also reduces security risks; as such a flexible construction is unlikely to hurt someone. The antenna is kept in place and from falling off the gondola this way. This way of mounting the antenna was suggested in the CDR, as the bracket may have imposed mechanical difficulties.

4.2.2 Electrical

The experiment needs connections to the power system. We will use the recommended connector type MIL–C-26482P with 8-4 insert arrangement MS3112E8-4P. As we want to be able to use the up-/downlink of the E-Link system, there will be an Ethernet connector Amphenol RJF21B with insert code A.

To see if different subsystems of the experiment are running there will be 3 5mm LEDs mounted at the front panel:

- Dual LED I:
    - Green, Power, experiment is connected to a power source
    - Red, Alive, the on-board computer is running. This will be indicated with a flashing of the second LED
- Dual LED II:
    - Green, The experiment is connected to Ethernet and a link is established
    - Red, Data is transmitted/received via Ethernet
- Single LED:
    - Red, ADS-B data packet was received (Flashing)

All LEDs are mounted in LED mounts, to increase visibility in bright light conditions.

4.2.3 Radio Frequencies

The experiment will use the standard Mode-S ADS-B frequency of 1090MHz. As the antenna needed for reception will be mounted outside the gondola, there will be an N-female connector next to the power and network connectors on the front panel.

The Antenna will be a collinear antenna, consisting of at least seven stacked elements, giving a length of about 1m.

The use of this frequency was discussed again at CDR, as it usually is restricted for BEXUS experiments. We are aware of the ATC transponder on the E-BASS-System.

4.2.4 Thermal

There will be no thermal interfaces. The box is shielded as outlined in the “thermal design” section below in a way that the experiment can stay at a comfortable temperature while on BEXUS flight.

4.3 Experiment Components

Table 4-1: Experiment summary table

Experiment mass (in kg):	2
Experiment dimensions (in m):	0,2x0,2x0,1
Experiment footprint area (in m^2):	0,04
Experiment volume (in m^3):	0,004
Experiment expected COG (centre of gravity) position:	near the base of the box, in the middle of the footprint area

The information in the table lists the dimensions of the E-Box. For mounting purposes, the experiment spans two L-profiles between the gondola rails.

Antenna Dimensions:

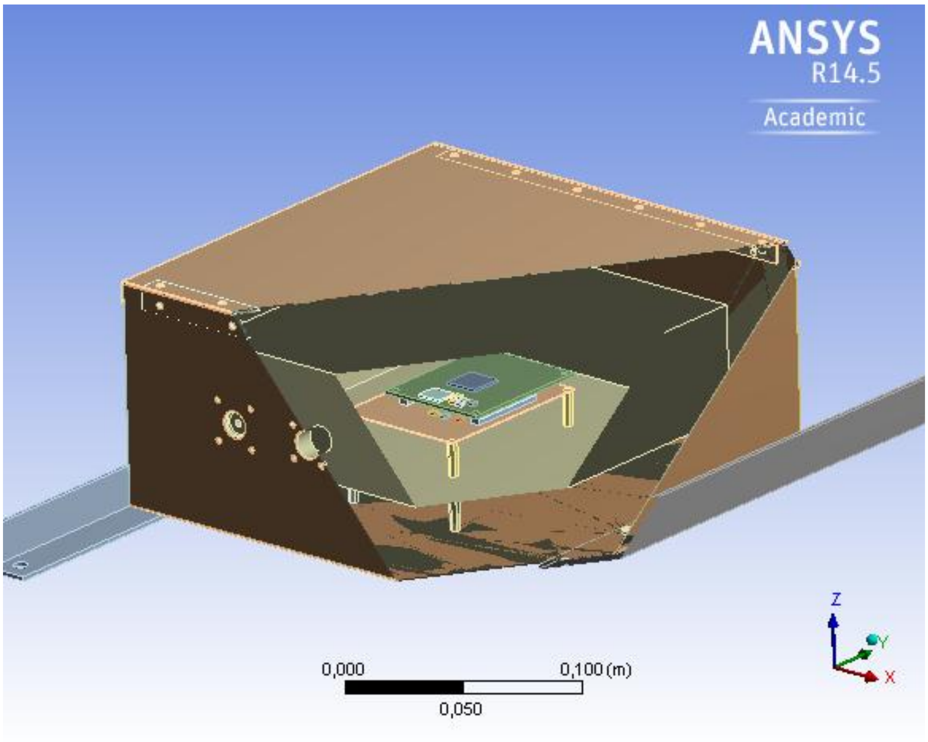
Antenna mass (in kg)	<0,5
Antenna length (in m)	1
Antenna diameter (in m)	< 0,05
Antenna COG:	In the middle

4.4 Mechanical Design

As the experiment consists mostly of electronic components (circuit boards), the design will be quite small. It will be housed in an aluminium box and will be fastened to the gondola via the provided mounting brackets. The drawing in Chapter 4.2.1 shows mechanical dimensions of the experiment box, as seen from the outside. The experiment box mainly consists of two bent aluminium sheets and multiple L sections, which are screwed together and attached to the experiments mounting rails. To ensure easy access to the experiment setup, the top is made of a separate aluminium sheet.

To protect the electronics inside the box against temperature influence, the experiment will be using anti-static Styropor parts cut in shape to insulate the box and to support any cabling to the front panel. The PCBs are fixed by bolts to the base of the box, which are guided through the Styropor. This mounting technique is very weight-efficient and guards efficiently against shock and temperature transients, as Styropor has high thermal resistance.

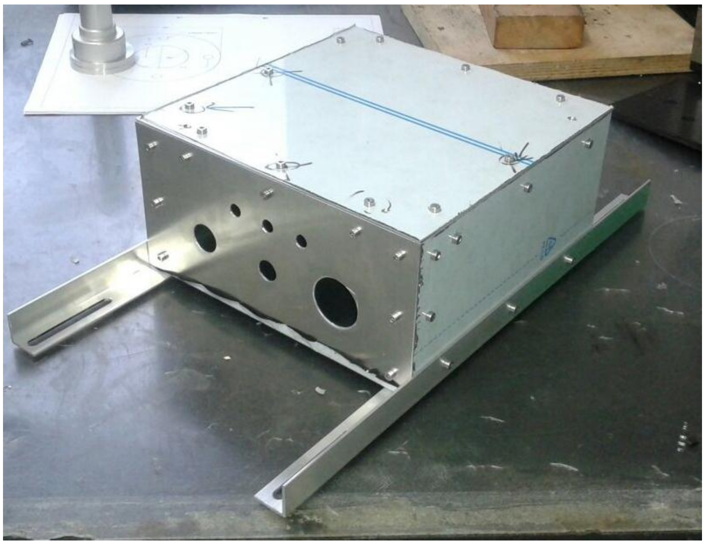
Mounting of the PCBs is visualized in the following image:



Picture 2 PCB mounting in the experiment case

The experiments mounting rails provide elongated holes to account for any tolerances. All Screws will be secured by lock washers (where applicable), nuts and thread lock adhesive, as suggested in training week. To ensure maximum safety, all sharp edges will be removed in the manufacturing process.

In picture 3 you can see the ready built case for the experiment.



Picture 3 Case

Note: To avoid duplicating text, the relevant aspects of the antenna mechanical design and mounting is written about in 4.2.1.

4.5 Electronics Design

The electronics are made up of various blocks, distributed on the two experiment PCBs as follows:

- RF receiver – on baseboard
- ADC and FPGA demodulator / decoder – on baseboard
- ARM computer – on ARM computer board
- Ethernet PHY for ARM computer – on baseboard

RF receiver

The first design of the RF receiver and demodulator used the well-known and often-used “miniADSB” circuit. As it proved not to be working well enough under BEXUS operating conditions (heavy oscillation, leading to reduced input sensitivity), we redesigned it to fit our needs.

It now consists of an input SAW filter tuned to 1090 MHz with low insertion loss (2.3dB), an amplifier stage (15dB), followed by another filter (2.3dB) and yet another amplifier (15dB) feeding into the final filter and detector to demodulate the (On-Off-Keying) amplitude modulation. The achieved goal of splitting the high input gain of the first design (35dB) into two amplifiers is that the system does not oscillate anymore, because feedback into the sensitive LNAs is reduced. The demodulated data is low-pass filtered and brought into the digital domain by a 16MS/s ADC. The RF receiver is located on the experiment baseboard.

FPGA-based demodulator

The following FPGA will be an Altera Cyclone IV FPGA that carries out the necessary signal processing to decode the ADS-B signal. It filters noise and interference from the received signal, demodulates the data and transmits the correctly decoded frames to the embedded ARM computer. The FPGA and ADC is located on the experiment baseboard.

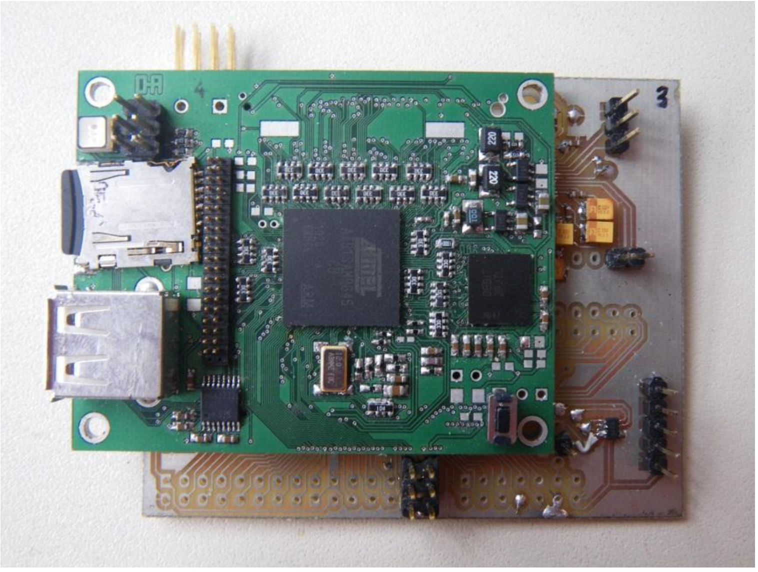
Backup Plan:

If problems arise with the self-build Front-End and the FPGA decoding unit (we are not able to finish in time, or results are not good enough), there will be the opportunity to buy a finished semi-professional Mode-S (ADS-B) receiver. This receiver will cost around 400€. See risk register for more information.

There will be no huge changes in the software of the ARM computer required, as the protocol implemented on the FPGA is compatible to the protocol used in the Mode-S Beast and nearly every other Mode-S receiver on the market.

ARM embedded computer

This ARM computer was developed by Hannes Zöllner in his Master Thesis with focus on low power consumption and reliability. The schematics for the computer can be found in the online repository as well as the schematics of the receiver and the FPGA base board.



Picture 4 Picture of existing ARM SoC board, including an old base board

For keeping time, the RTC on the on-board computer will be buffered via a "gold-cap" (super-capacitor). This is a small "side-experiment", as we got input from the PDR board to evaluate how well gold-caps do in space conditions.

After PDR, we tested if different super-capacitors can survive in a near vacuum. They actually resist the vacuum perfectly. We will equip the ARM-computer with such a super-capacitor for buffering the RTC. See "Experiment Test and Verification" for further information.

As the experiment will only receive on 1090MHz and not be able to transmit RF, we do not expect any interception of mandatory communication systems of the BEXUS gondola or interference with other experiments. With this design, we can guarantee not to produce unwanted interference, locally and for remote receivers.

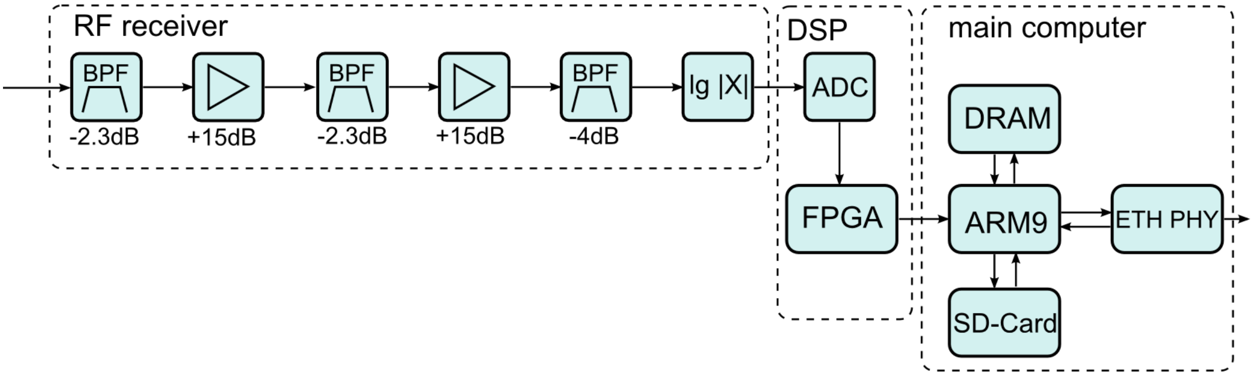
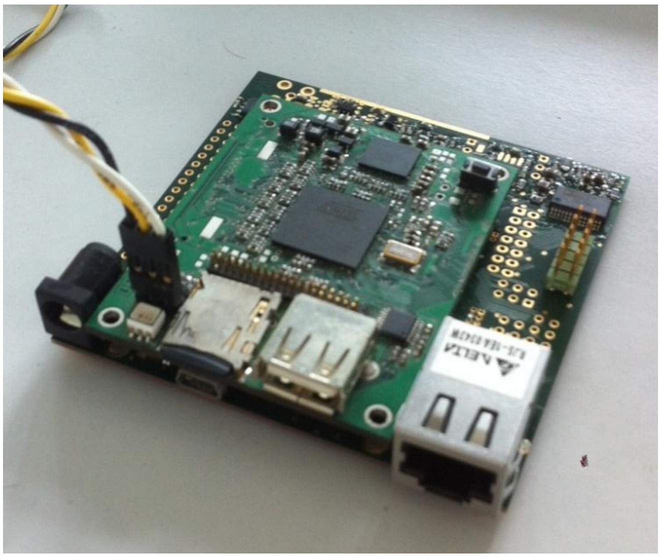


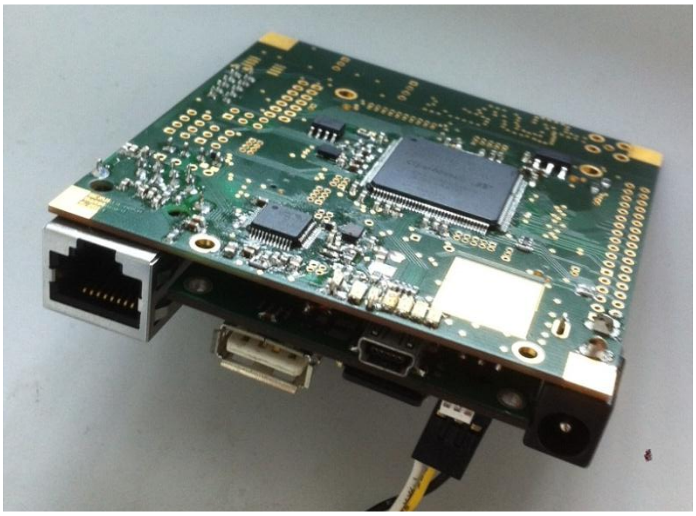
Figure 3 The electronics concept

For further analysis and tests of the receiver, the bladeRF-SDR-platform will be used, to verify receiver functionality and perform measurements. It will also be used to stimulate the experiment at the launch campaign and can be helpful in troubleshooting. It is possible for us to generate Mode-S frames and add artificial noise and other interference for robustness-testing.

As transmission power is very low and all frame check sums are guaranteed to be invalid, no real transmissions of aircrafts are intercepted.



Picture 5 The built ARCA baseboard (bottom) with ARM-board (top)



Picture 6 The built ARCA baseboard (top) and some connectors

The electronics schematic and layout is finished, any remaining problems were discussed and solved after CDR.

All PCBs are assembled and ready for further testing. The first receiving tests were very good and the receiving quality excellent. The team could receive air planes from a distance up to 380km. These tests were done with a smaller antenna than that which will be used during the experiment.

Grounding strategy

The experiment box will not be connected to battery ground. Battery ground will only be used on both the PCBs on ground planes. Mounting spacers will not have low impedance electrical contact to the PCB ground planes. Ethernet is an electrical insulated interface, meaning there is no ground connection needed to the Ethernet Switch. Ethernet Shield will not be connected to GND in our experiment and should therefore be connected in the Ethernet Switch. The coaxial antenna cable outer conductor will not make any contact to the case, to not cause a ground loop.

Potential problems and solutions:

At CDR, there were concerns about the following aspects of the receiver:

- RF sensitivity is too low
- RF rejection of out-of-band transmitters (for example GSM) is not high enough, therefore decreasing input sensitivity
- RF gain is fixed, therefore a strong signal can overload and/or destroy the receiver input
- RF parts are not shielded enough

These concerns were all discussed and taken into consideration when finishing the electronics design:

To calculate RF sensitivity, a hand calculation for approximate expected receiving strength was done:

For a medium-size Aircraft, Mode S transmission power of 200W was estimated. By using the free-space path loss as a model for power distribution in air (without obstructed sight of the target), the following estimation of the link budget can be done.

- System input sensitivity

  The output voltage of the AD8313 detector starts to become linear at a level of -70dBm. Assuming a minimum link margin of 5dB (resulting in 100mV detector output swing), -65dBm are needed at the input of the AD8313. Total System gain is calculated as follows:

  $$G = G_{Ant} + G_{LNA1} + G_{LNA2} + G_{Filt1} + G_{Filt2} + G_{Filt3}$$

  $$G = 7dB + 15dB + 15dB - 2{,}3dB - 2{,}3dB - 4dB = 28{,}4dB$$

  See figure “Electronics Concept” for details.

  This requires the minimum input signal (neglecting noise figures at this point) to equal

  $$P_{min} = -60dBm - 28{,}4dB = -93{,}4\ dBm.$$

- Transmission Power

  $$Pplane = 200W \triangleq 10\log\left(\frac{200W}{1mW}\right) = 53dBm$$

- Free-space path loss in dB is calculated by

  $$FSPL_{dB} = 10\log\left(\frac{4\pi f\ [Hz] d\ [m]}{c}\right)^2$$

- Maximum free space path loss can be calculated by

  $$FSPL_{max} = P_{plane} - Pmin = 146{,}4\ dB$$

  By changing the free-space path loss equation to the distance, the maximum reception distance can be estimated.

  $$d_{max} = 460km$$

  As packet decoding was observed to be working well at less than 100mV input swing and bigger airplanes tend to have transmission power of up to 500W, even planes further away might be heard.

To approximate RF out of band rejection, the datasheet of the input filter gives an impression:

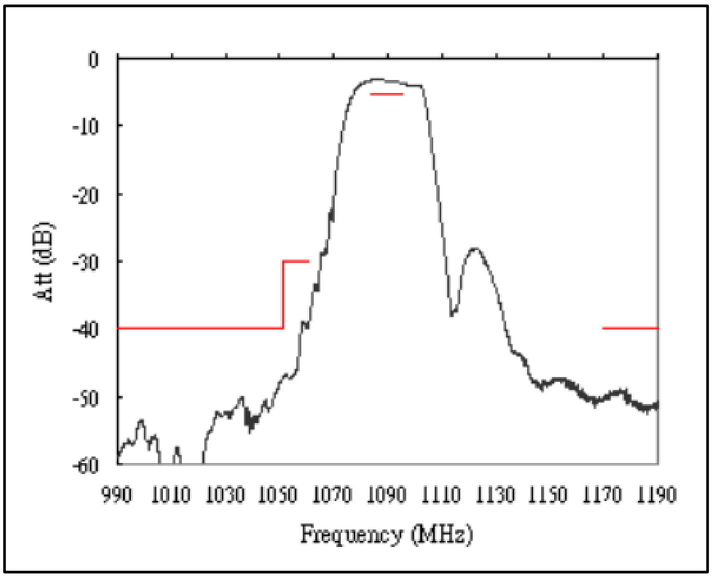


Figure 4 TA0232A transfer function

As GSM and primary radar applications were expected to be the biggest problematic jammer above urban areas, the filter transfer function outside the pass band has to be considered. For P-/E-/R-GSM, operating downlink at up to 960MHz, stop band attenuation of -50dB to -60dB is achieved. As one of these filters is applied before every amplifier section, attenuation (worst case) is about -85dB. This is believed to be enough margin for the receiver to work properly.

Regarding the in-band input overloading / receiver defect concerns, the following calculation was done:

The nearest transmitter is the BEXUS on-board ATC transponder, located about (worst case) 10m distant from the ARCA receiver antenna. The ATC transponder transmissions were estimated every 6 seconds for <1ms (discussion at CDR) with 200W (=53dBm) (as per datasheet) peak power. Maximum input power into the receiver is 0dBm (see TA0232A datasheet). Free-space path loss at 1090MHz at a 10m distance equals at least 53.2dB. As the ARCA receiving antenna has high attenuation in the upward direction (towards the ATC transponder), further damping of the input signal is expected. For further input protection, additional countermeasures were taken.

To be sure, the experiment prototype was tested with input levels of >0dBm and no degradation of performance or defects could be measured.

Regarding to shielding concerns of the RF demodulator stage components

On the base board (containing the RF demodulator) a separate area was reserved for the RF demodulator. Also a possibility was provided to solder a shielding cap over the demodulator. The RF traces are surrounded by vias and backed by a solid ground plane.

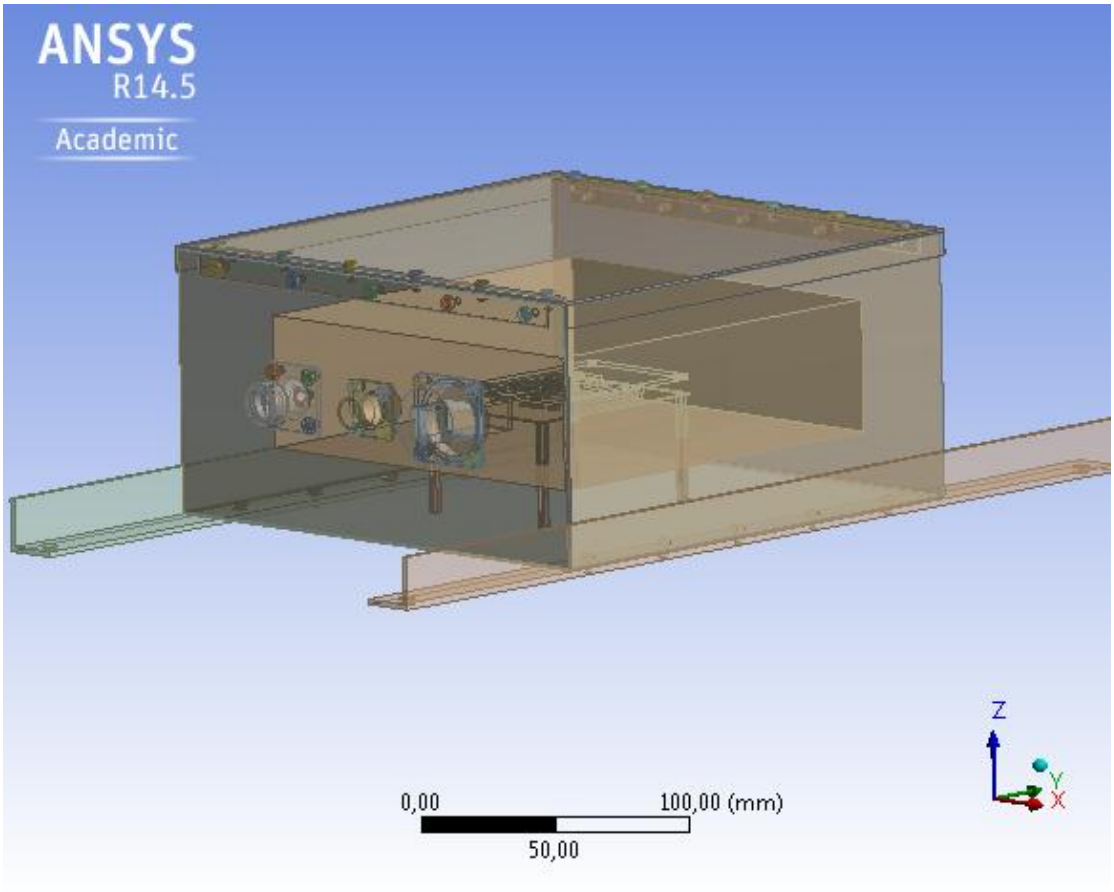
4.6 Thermal Design

As the experiment payload will mainly consist of circuit boards and wiring, the sensitive electronics will have to be kept in the operational limits as specified in datasheets. We will use parts that can handle an extended temperature range of at least -40°C to 75°C where possible. From previous flights and the ISO Standard Atmosphere Model we can expect temperatures of down to -80°C. As the air pressure is very low, heat transfer by air convection is reduced and therefore direct heat transfer to the circuit boards would then be necessary. The box encasing our payload will be lined with shielding material, minimizing the heat exchange with the cold air outside. Thermal simulation results showed, that extra heating is not needed, as the insulation is good enough and the power dissipation seems to be at a level, where electronics neither get too hot or too cold.

The insulating Styropor will form a “box in box” in the experiment, leaving small room of air for the electronics, so no direct contact is made. Holes in the styropor will help to guide any wiring to the front panel connectors.

Electrical power is converted to heat distributed as follows:

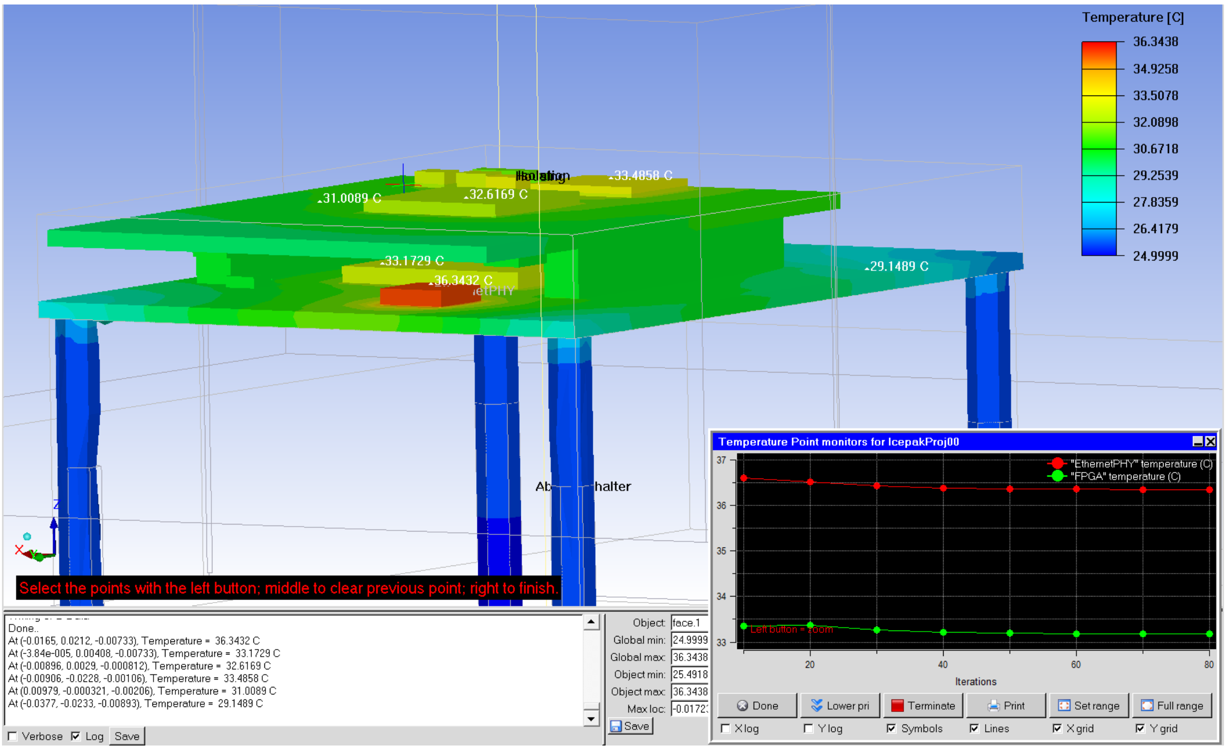
Device	**P**
ARM board	200mW
Ethernet PHY	145mW
Ethernet Jack	145mW
RF Front-End	100mW
FPGA	250mW
ADC	80mW
Sum:	920 mW



Picture 3 Thermal insulation concept

After discussion with the thermal design experts at CDR and reviewing our thermal simulation model thoroughly again, we found the error that caused the Ethernet PHY to be overheating:
Even though power dissipation in the datasheet is said to be 290mW, only about half of that power is converted to heat in the IC. The other half is dissipated in the magnetics (transformers) of the LAN-Jack. An application note by Texas Instruments (AN-1540, Page 7, Table 4) confirms this theory.

By using the corrected power dissipation values and the preliminary power dissipation of the up to date FPGA design, simulation results are now very close to the measurements taken in real-life conditions.
Simulation results and comments can be seen below.



Picture 4 Static simulation (laboratory conditions)

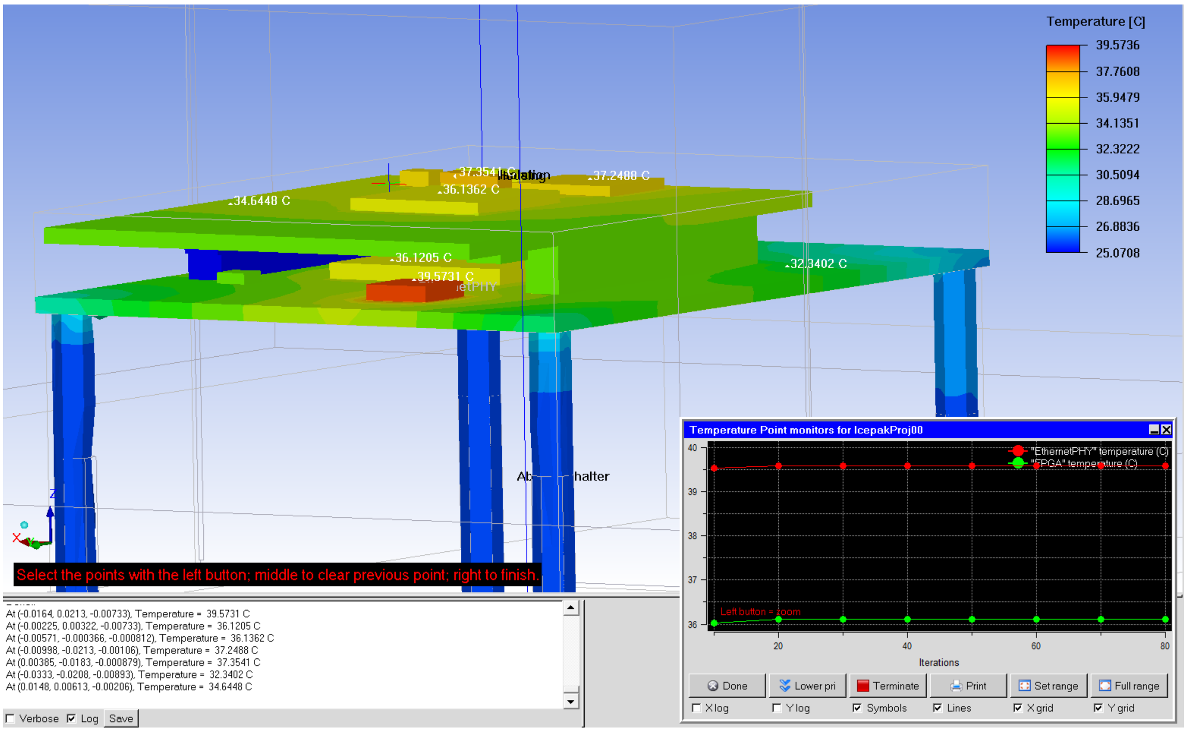
This picture shows the static simulation result at room temperature (25°C) and normal air conditions (sea level air pressure). Maximum temperature is seen on the Ethernet PHY at 36°C. Measurements with an IR thermometer on the prototype yielded 34.5°C, so simulation error is at <5%. All other ICs are in the 31°C-33°C range, warming up the PCBs very evenly.

The following boundary conditions were assumed:

Condition	Value
Environment Temperature	25 °C
Air pressure	1013 mbar
Emission coefficient el. components	0,9
Emission coefficient PCB	0,35
Emission coefficient ESD-styrofoam	0,042
Emission coefficient Aluminium surfaces	0,09

Table: Boundary conditions for static simulation at room temperature

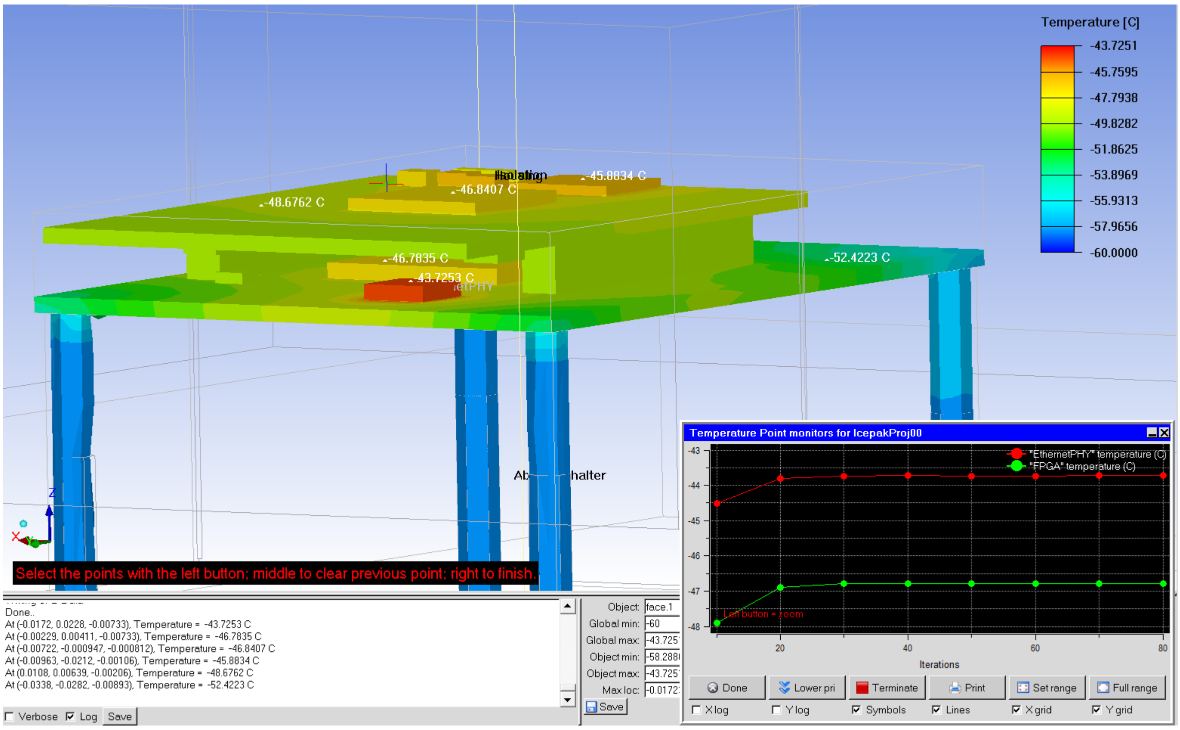
From the vacuum test at FSU Jena (see test plan), we collected temperature results of the main power dissipating components (FPGA, Ethernet PHY, ARM processor) over the course of nearly 2 hours. These results can be verified with the Icepak simulation as well:



Picture 5 Temperature profile of simulated vacuum test

Maximum temperatures of 39°C were measured in the test (near the stationary temperature, after nearly 2 hours), the simulation shows similar results.

From these results, the final simulation for the BEXUS flight profile can be derived. The density of air at 35km height was found to be 0,02g/cm³, based on which Icepak can calculate the remaining convection. Temperature was assumed to be -60°C.



Picture 6 Static Simulation Result of -60°C environment, near vacuum

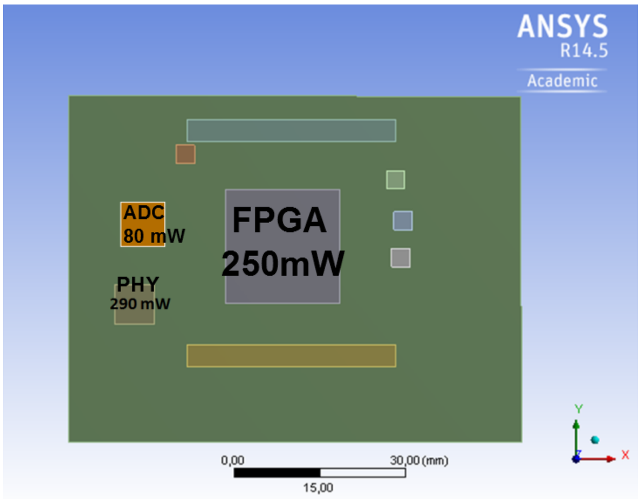
This simulation assumes the inside air temperature of the box to be -60°C at the start of the simulation. As this is not true (BEXUS gondola will happen at ~0°C), the temperatures in the box will be higher than -43°C. But, this static simulation tells us that no experiment components overheat (because of missing convection) nor cool down too low (worst case inside air temperature was assumed) even in heavy conditions.

As the model behaviour now fits the prototype and meets our expectations, a final transient simulation can be done, where a full BEXUS flight profile (preparation, waiting for launch, ascend, float, descent) is modelled.

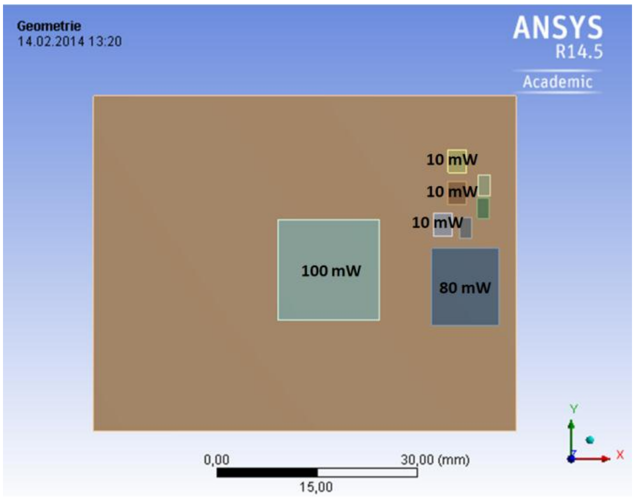
As the correctness of the thermal design model is an experiment goal as well, various temperature sensors will be placed on the experiment PCBs and on the experiment box wall. The logged data can be used for post-flight analysis.

4.7 Power System

The supplied power to the experiment is internally converted to various other voltages (see below). The dissipated power is distributed over the two boards as seen in the following images.



Picture 7 Power dissipation on the baseboard



Picture 8 Power dissipation on the ARM Computer Board

Table 4-7: Power consumption

Device	U/I	P
ARM board	5V/40mA	200mW
Ethernet PHY	3,3V/88mA	290mW
HF Front- End	3,3V/30mA	100mW
FPGA	5V/50mA	250mW
ADC	3,3V/25mA	80mW
	Sum:	920 mW

As reception and decoding are running the entire mission, peak and average power are the same for every part of the electronics.

Note: As we were not able to measure the currents for every supply voltage on the FPGA and ARM boards, the current and power is based on the supply voltage for the entire board (5V for the FPGA development board and the ARM board). Appropriate maximum ratings for the load-bearing capacity of the voltage regulators are taken into consideration by sticking to the design of development boards and reference implementations in datasheets and by using datasheet values for maximum currents on every voltage rail.

Power supply concept

The experiment will get a 28V power supply from the BEXUS gondola. This voltage will be distributed to different voltages which will be needed by the experiment. The first switching regulator will convert a big range of input voltages to 5V. These are used as an intermediate voltage. On the ARM board, 1.0V, 1.8V and 3.3V are needed. 3.3V and 1.0V can be used as the I/O and core-voltages of the FPGA, as well as the 3.3V supply the Ethernet PHY, the ADC and the RF receiver. The FPGA needs one more voltage for the analogue PLLs, which is 2.5V. It is generated by a LDO regulator directly on the base board.

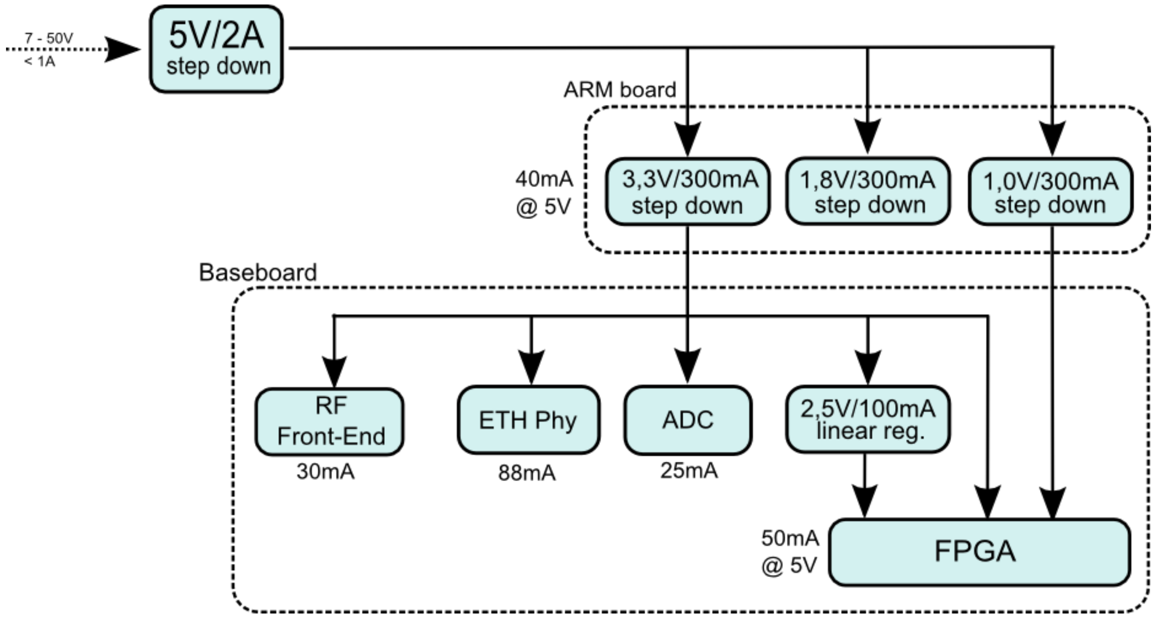


Figure 5 Power supply concept

4.8 Software Design

Outline

The software running on our payload will be divided in two main parts:

- Mode S Data decoding, done completely in an FPGA
- Data processing and up/downlink management on an embedded Linux ARM SoC

The FPGA was chosen because ADS-B Data has a high data rate of 1Mbit/s. The experiment concept includes oversampling that signal with a factor of 16 with 10 bits of digital resolution. Processing that amount of data in real time seems unfeasible in a microcontroller with sufficient power consumption and will therefore be realized inside an FPGA. The Digital Signal Processing architecture is outlined in the image below. The signal processing flow was first implemented in MATLAB and fed with various test signals, sampled by a fast DSO (Digital Storage Oscilloscope). That way we are able to verify operability and correctness of the algorithm implemented. Afterwards the algorithm was implemented in VHDL and verified with the MATLAB results.

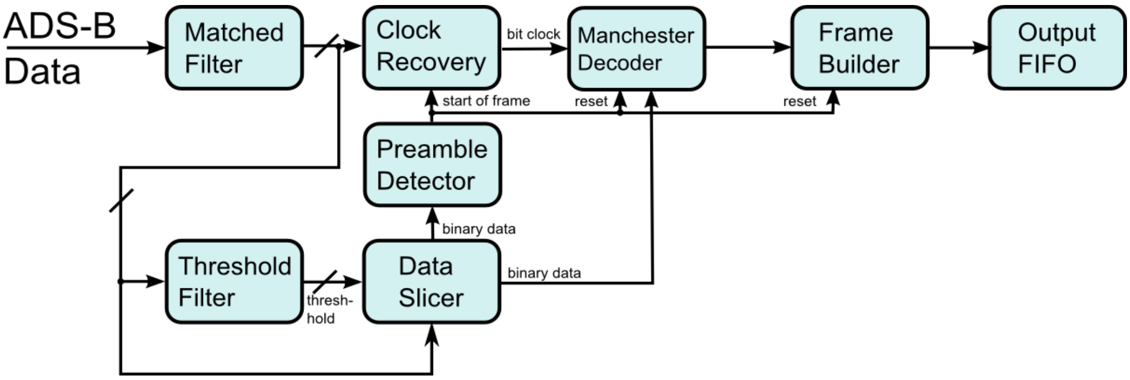


Figure 6 Signal processing concept

For the on board computer, GNU/Linux was chosen as the operating system because of its widespread use in embedded computing, high reliability and because it is available on the ARM platform.

Various daemons monitor health status of the experiment (temperature inside the box) and process the incoming data from the FPGA and handle the up/downlink commands issued.

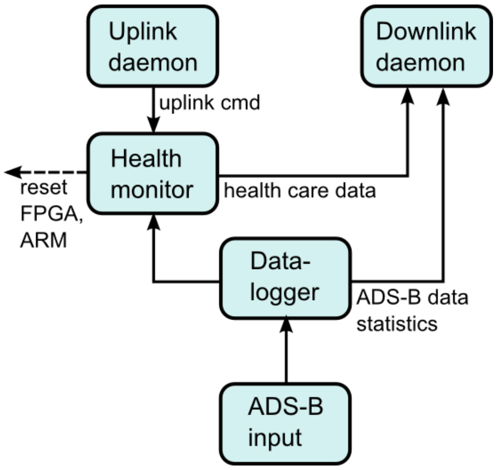


Figure 7 ARM Software concept

The ARM SoC also interfaces to a 100Mbit/s Ethernet PHY, which enables communication with the Up-/Downlink system. Various statistics and raw data will be downlinked to ground support. The SoC will also be able to receive uplink commands for manual control of the experiment.

4.8.1 FPGA Design

The DSP architecture outlined above works as follows:

Any incoming Signal, demodulated by the RF frontend and digitized by the ADC is read into the FPGA. The Matched filter in the first stage optimizes signal/noise ratio of incoming ADS-B signals and improves SNR for interfering signals. This is also known as a correlation receiver, as the matched filter effectively carries out correlation between the (known) symbol waveform and the input signal.

The data slicer recovers digital (1/0) information from the input signal. A threshold for the data slicer is generated by a pair of peak-detecting, discrete RC filter equivalents. The filters are working at a higher precision than the input signal. In order to not degrade the input signal, a margin of about 20dB should be done, corresponding to >3bit more processing width on internal calculations.

The digital data is constantly monitored for appearance of preamble patterns. If a preamble is present, a 'start of frame' signal is issued to the timing clock recovery, to the frame decoder and to the Manchester decoder.

The recovered clock can be used to decode the Manchester-encoded bits in the data stream, which is then done by the Manchester decoder. The decoded bits are fed into the frame controller, which keeps track of position in the packet, possible errors and decides between long and short packets used in Mode S transmissions.

The decoded packets are fed into a FIFO which is connected to an UART module. Through the UART, data is sent to the ARM computer for analysis, error correction and logging. The timing recovery unit will only be implemented if it is needed. Previous experiments show, that the timing holds well enough for all data packets, so that fixed symbol timing is sufficient.

The FPGA design source code is publically available at github [9] and open for review by all team members. For testing of implementation correctness, an ADS-B data generator was implemented as well, to be able to “close the loop” and verify the receiver correctness. A 1090MHz generator and a RF switch (stimulated by the implemented ADS-B generator) were used to generate input to the RF frontend, connected to an ADC breakout board. It was possible to decode the sent packets correctly. Tests showed that no significant bit errors occur even at low voltage levels (therefore assuring us of the working dynamics in the RX design).

4.8.2 ARM Software design

All software running on the ARM with Linux will be programmed in the C programming language. This allows us to access hardware like the serial port in a direct manner. As the ARM CPU is running at just 400MHz, the increased overhead generated by high level languages is avoided.

Uplink/Downlink modules

These software modules manage the communication via E-Link over Ethernet to ground support. They offer connection to the frame logging module. Each of the two modules is listening on one network socket for incoming connections. A TCP port is reserved for uplink commands and requests, on another port, status data and ADS-B frames will be sent to ground support. They use inter-process communication to get status data and ADS-B frames and to talk to the health/status monitor. See 4.9 for supported uplink commands.

Frame logging module

This software module listens to the decoded frames from the FPGA coming in over the ARM serial port. It logs all incoming frames into an appropriately (uniquely) named file for later analysis including timestamps. Via inter-process-communication the incoming frames and statistic information is communicated to the uplink/downlink module.

Health/status monitor module

This module will monitor the different temperature sensors placed on the PCBs of the experiment. It is also able to issue reset commands to the internal watchdog and the FPGA to handle software failures.

Watchdog

The watchdogd software of Linux is used to continually send activity information to the watchdog. If, for example because of a software failure, this information is missing for too long, the system automatically performs a hard reset. This will hopefully help recovering from unforeseen software conditions.

Ethernet communication

The connection between the experiment and the ground support is done via Ethernet, utilizing the E-Link system. Data is transmitted using TCP/IP. Usage of TCP is justified for two main reasons: The connection has to be initiated by ground support, which makes sure data is only sent when ground support equipment is operating. Also, the connection is flow-controlled, which includes acknowledgement of packet delivery and retrying in case of delivery failure. This is a useful feature for radio links (such as the E-Link System), because packet loss may go unnoticed.

There are two types of data transmitted via such a connection by the ARCA experiment:

Type 1 data are status messages. These include health information (temperature, state of the experiment) and received ADS-B data. These are sent once per second if less than N ADS-B frames are received. If there are more, every N received ADS-B frames one message is sent to ground support.

Data	**Length in Bytes**
Frame Type Indicator (0x01)	1
Temperature data	Max. 8 (depending on number of installed temperature sensors on board)
Timestamp in standard UNIX time format	4
Length indicator for following payload, in Number of Frames (N)	2
Payload (ADS-B data packets)	N*14

Type 2 packets are uplink command acknowledgements. These messages include the remotely executed command number and an acknowledgement indicator or the returned error code.

Data	**Length in Bytes**
Frame Type Indicator (0x02)	1
Command Number repeated	1
ACK (0x00), NAK (error code)	1

For uplink, only one type of data message is used, which includes uplink command requests. These messages include the remote command number and an execution parameter.

Data	Length in Bytes
Frame Type Indicator (0x03)	1
Command Number to be executed	1
Optional parameter	1

4.9 Ground Support Equipment

As ground Support Equipment, only a standard consumer-grade notebook with an Ethernet port will be necessary, as all information from our experiment can be visualized on such a device.

To have a good tracking of the whole experiment during the flight, we will have ground station software, where all necessary parameters are displayed.

Two different kinds of data sets are defined:

- Health-data
- payload data (ADS-B messages)

The ground station software handles all E-Link (Ethernet) communication with the experiment. This software also splits the received data into health data and payload data. All necessary information is displayed on a GUI. This information includes:

- Temperature data of all temperature sensors
- CPU load

Besides that, there will be possibility to send commands to the experiment. These commands are:

- Get temperature
- Get CPU Load
- Reset FPGA
- Reboot the ARM computer
- Write out all files which are opened at the moment

The ground support software will be programmed in the Python programming language, using wxPython for easy visualisation of health data (temperatures on the PCBs and in the box) and for issuing remote commands.

The ground support notebook will also run a copy of the “PlanePlotter”-Software for visualizing the planes received by the experiment (payload data).

PlanePlotter data is input via the TCP/IP-Interface of the remote experiment control software.

5 EXPERIMENT VERIFICATION AND TESTING

5.1 Verification Matrix

Table 5-1: Verification table

ID	Requirement text	Verification	Status	Test No.
F2	The experiment shall detect data from airplanes (ADS-B).	T, R	Done	9
F3	Removed	-	-	-
F4	The received data shall be saved on a flash card.	R	Done	-
P2	The experiment shall only receive data at a frequency of 1090MHz.	A, S	Done	-
P3	The experiment should have a storage capacity of 16GB.	R	Done	-
P4	The experiment shall be able to receive a minimum of 5 messages per second.	T, R	Done	9
P5	The experiment shall receive data with a data rate of 1Mbit/s.	A	Done	-
D1	The experiment shall work at the temperature profile of the BEXUS balloon.	A, T	Done	2
D2	The experiment shall work at the vibration profile of the BEXUS balloon.	T	Done	3
D3	The experiment shall not harm the gondola and other experiments.	T	Done	4
D4.1	The experiments shall be designed to use the E-	R, T	Done	8

	Link downlink.			
D4.2	The experiments shall be designed to use the E-Link uplink.	R, T	Done	8
D5	The experiment shall not use more than 0.5 Ah of the gondola battery.	A, R, T	Done	5
D6	The experiment shall work at the air pressure profile of the BEXUS balloon.	T	Done	1
D7	The experiment should be not heavier than 2kg.	A, T	Done	7
D8	The experiment size should not be bigger than 0,2m x 0,2m x 0,2m.	A	Done	-
D9	The receiver should decode the incoming data at a frequency of 1090MHz for the duration of the BEXUS mission.	R, T	Done	9
D11	The antenna shall be designed to receive optimally at a frequency of 1090MHz.	A, T	Done	9, 10
D12	The antenna shall have omnidirectional characteristics for optimal receiving performance.	A	Done	-
O1	The experiment shall work autonomously, without control by the ground station.	R	Done	-
O2	The experiment shall be able to enter a secure mode after the balloon is cut off.	R	Done	-
O3	Removed.	-	-	-
O6	The other BEXUS	T	Done	11

	experiments shall not emit any EM-interference at a frequency of 1090MHz.			

5.2 Test Plan

Table 5-2: Vacuum test

Test number	1
Test type	Vacuum test.
Test facility	Friedrich Schiller University Jena or Ernst-Abbe-University for applied science (EAH-Jena).
Tested item	The whole experiment (system level test).
Test level/procedure and duration	Acceptance test, 24h
Test campaign duration	-
Test campaign date	First week of September 2014.
Test completed	It was difficult to arrange an appointment for this second test and the component vacuum test went very well, this test was skipped.

Table 5-3: Thermal test

Test number	2
Test type	Thermal test.
Test facility	EAH-Jena.
Tested item	ARM-Board, baseboard, RF-front-end (component test). Later: the whole experiment (system level test).
Test level/procedure and duration	Acceptance test, 3h
Test campaign duration	-

Test campaign date	First half of September 2014.
Test completed	Done, see test report 5-3-1 and 5-3-2

Table 5-4: Mechanical test

Test number	3
Test type	Shock test.
Test facility	EAH-Jena. Solid surface.
Tested item	The whole experiment (system level test).
Test level/procedure and duration	Qualification test. 1s
Test campaign duration	-
Test campaign date	First week of September 2014.
Test completed	Not done, because the experiment worked well after the transport to Kiruna.

Table 5-5: EMC test

Test number	4
Test type	EMC test.
Test facility	EAH-Jena. GTEM chamber.
Tested item	ARM-Board, baseboard, front-end, the whole experiment (system level test).
Test level/procedure and duration	Acceptance test, 1h
Test campaign duration	-
Test campaign date	First half of September 2014.
Test completed	Done, see report 5-3-6.

Table 5-6: power consumption test

Test number	5
Test type	Power consumption test
Test facility	EAH-Jena.
Tested item	The whole experiment.

Test level/procedure and duration	Qualification test.
Test campaign duration	10min.
Test campaign date	27.08.2014
Test completed	Done. See test protocol 5-3-5.

Table 5-7: Experiment size test

Removed

Table 5-8: Weight test

Test number	7
Test type	Weight measurements.
Test facility	EAH-Jena.
Tested item	The whole experiment.
Test level/procedure and duration	Qualification test.
Test campaign duration	-
Test campaign date	First week of September 2014.
Test completed	Done, see test protocol 5-3-7.

Table 5-9: Experiment E-Link test

Test number	8
Test type	E-Link test.
Test facility	Esrange
Tested item	The whole experiment.
Test campaign duration	-
Test campaign date	October 2014.
Test completed	Done, see test protocol 5-3-8.

Table 5-10: Endurance run test

Test number	9
Test type	Endurance Run.
Test facility	EAH Jena.
Tested item	The whole experiment.
Test campaign duration	Many hours.
Test campaign date	First half of September 2014.
Test completed	Done, see test result 5-3-9.

Table 5-11: Antenna test

Test number	10
Test type	Antenna test.
Test facility	EAH-Jena.
Tested item	The receiving antenna.
Test campaign duration	-
Test campaign date	First week of September 2014.
Test completed	Done, see test result 5-3-10.

Table 5-12: Experiment interference test

Test number	11
Test type	Interference test.
Test facility	Esrange
Tested item	The whole experiment together with all other experiments of BX18.
Test campaign duration	-
Test campaign date	08. October 2014.
Test completed	Done, see test report 5-3-11.

Table 5-13: Super-capacitor test

Test number	12
Test type	Vacuum test.
Test facility	EAH-Jena
Tested item	Super-capacitors (also called gold-caps), different types of foam for thermal insulation.
Test campaign duration	~24h in near vacuum.
Test date	15. – 16.04.2014
Test completed	Successfully done. See test protocol 5-3-3.

Table 5-14: Vacuum test II

Test number	13
Test type	Vacuum test.
Test facility	FSU Jena
Tested item	All experiment components (FPGA Eval Board, ARM Computer, Ethernet PCB) except RF front end
Test campaign duration	~2h in near vacuum. (1mBar)
Test date	18.06.2014
Test completed	Successfully done. See test protocol 5-3-4.

Table 5-15: static load test

Test number	14
Test type	Static load test
Test facility	EAH Jena
Tested item	Experiment box.
Test campaign duration	2min. max. 60kg load.
Test date	First week of September 2014.
Test completed	Done, see report 5-3-12.

5.3 Test Results

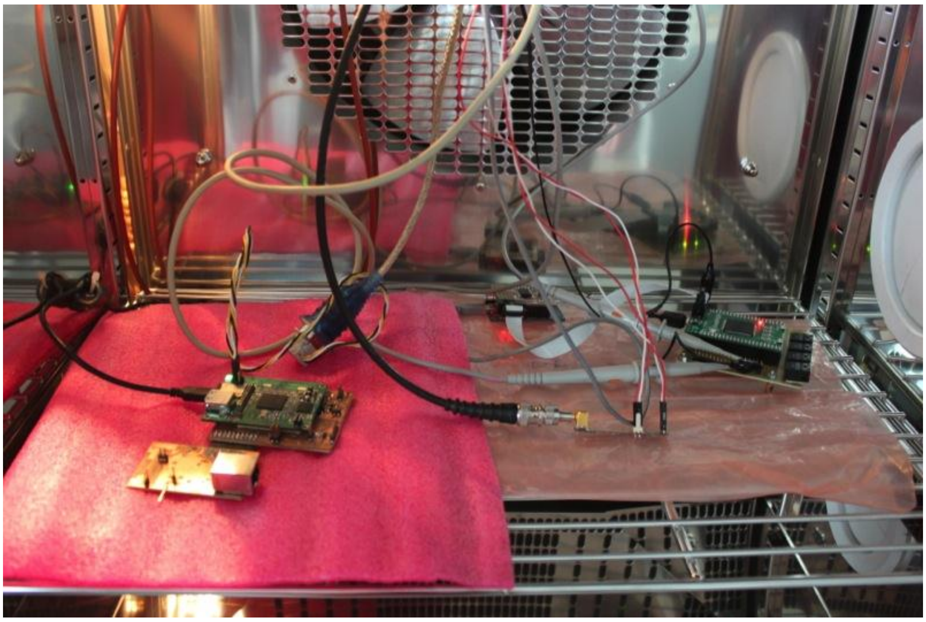
Table 5-3-1: Thermal test

Test number	2
Test type	Thermal test.
Test facility	EAH-Jena.
Tested item	Component test: ARM-Board, FPGA Base Board, RF-front-end.
Procedure and duration	Acceptance test, 1.5h The above mentioned items were put into a temperature chamber and powered up. Then the following cooling/heating procedures was done: • Cooling down from 23°C to -60°C in 30min • Holding a temperature of -60°C for 30min • Warming up again to 23°C in 30min During the whole time each component was monitored separately: • ARM-Board: During the test a Linux system was running and monitored via serial connection. To see if it's running the program top was executed. • RF-front-end: With a spectrum analyser running in tracking mode a signal of 1090MHz was fed into the front-end. With a voltage meter the amplitude at the front-end output was measured. • FPGA board: During the test the FPGA runs a program which generates ADS-B frames and receives them with the current working receiver design. Input and output data was monitored with an oscilloscope.
Test campaign duration	6h, including build-up and 1.5h testing.
Test date	15.04.2014
Test completed	Done. All components worked well at a temperature of -60°C for 30min. We experienced a short drop out of serial data from the FPGA for about 30 seconds, which is OK for testing the FPGA out of its specification (down to -40°C).

Test installation:

Picture 9 Thermal Test Setup 1

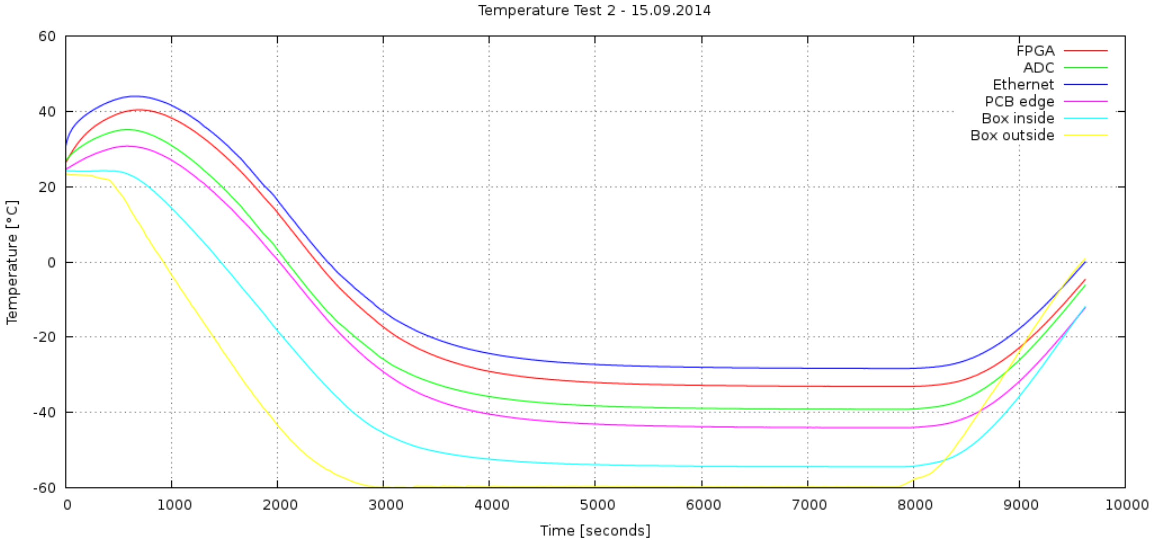
Components placed in temperature chamber:



Picture 10 Thermal Test Setup 2

Table 5-3-2: Thermal test II

Test number	2
Test type	Thermal test.
Test facility	EAH-Jena.
Tested item	Whole experiment.
Procedure and duration	Acceptance test, 1.5h The experiment was put into a temperature chamber and powered up. Then the following cooling/heating procedures was done: • Cooling down from 23°C to -60°C in 30min • Holding a temperature of -60°C for 30min • Warming up again to 23°C in 30min During the whole time the experiment was monitored and used in the same mode as it will be running during the BEXUS flight.
Test campaign duration	3h, including build-up and 1.5h testing.
Test date	15. September 2014
Test completed	Done. Everything worked fine.



Picture 11: Temperature plot during the temperature chamber test.

Table 5-3-3: super-capacitor test

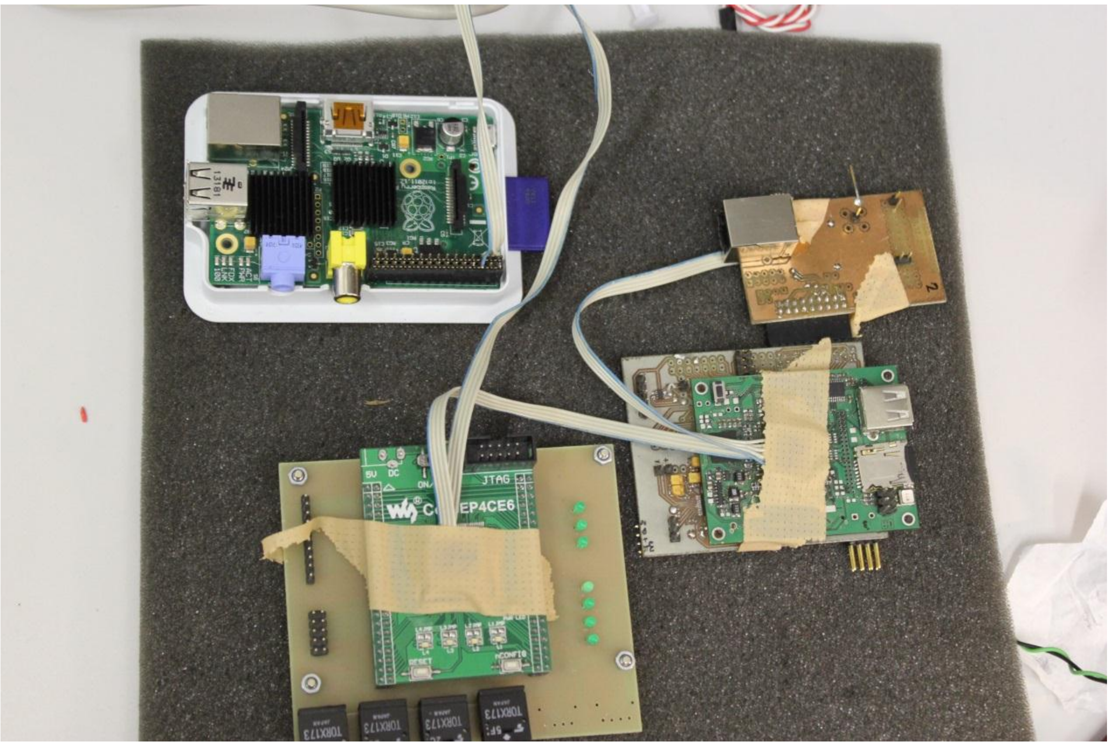
Test number	12
Test type	Vacuum test.
Test facility	EAH-Jena.
Tested item	3 different aerogel super-capacitors.
Procedure and duration	3 different aerogel super-capacitors were placed in a vacuum chamber. The air was pumped out and the chamber was closed for nearly 24h.
Test date	15. – 16.04.2014
Test completed	Successfully done. After air was filled in the chamber all 3 capacitors were ok and resisted the vacuum. No mechanical deformation or measurable electrical degradation occurred.

Table 5-3-4: Vacuum test II

Test number	13
Test type	Vacuum test.
Test facility	FSU Jena
Tested item	All experiment components, these include • The FPGA evaluation board

	• The ARM computer • Connected to the Ethernet PHY
Procedure and duration	The FPGA was permanently loaded with the most recent receiver design and the ADS-B generator was used to generate dummy data for the receiver to decode. The ARM was running Linux, listening to data from the FPGA via UART. The Ethernet PHY was connected to the ARM CPU. TMP100 Temperature sensors were fixed on all three main components, where doubts of thermal properties remained. An independent computer was used to read the temperature sensors every minute and record the data for future analysis. The vacuum chamber was evacuated very fast (much faster than at ascend of the BEXUS gondola) to about 1mBar, where it was held for nearly 2 hours. After that, temperatures were expected to be within small margin of stationary levels and air was let in again.
Test date	18.06.2014
Test completed	Successfully done. The temperature trend can be seen in Chapter 4.6. As expected from the thermal simulation, no problems were found. The highest measured temperatures were about 40°C, which is <20K difference to room temperature.

Test Setup for Vacuum Tests: All components are equipped with temperature sensors



Picture 11 Vacuum Test Setup

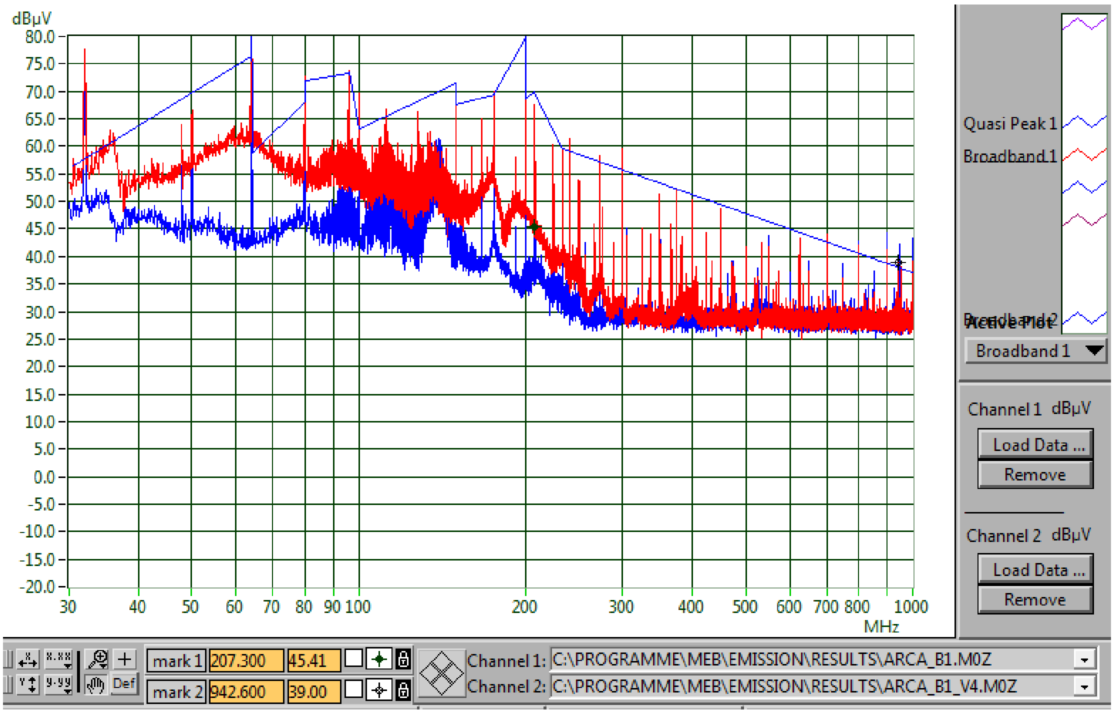
Table 5-4-5: Power test

Test number	5
Test type	Power test
Test facility	EAH-Jena.
Tested item	Whole experiment.
Procedure and duration	The whole experiment was switched on and the power consumption was measured. Measured current: 100mA at a voltage of 10V. P = 100mA * 10V = 1W
Test campaign duration	10min.

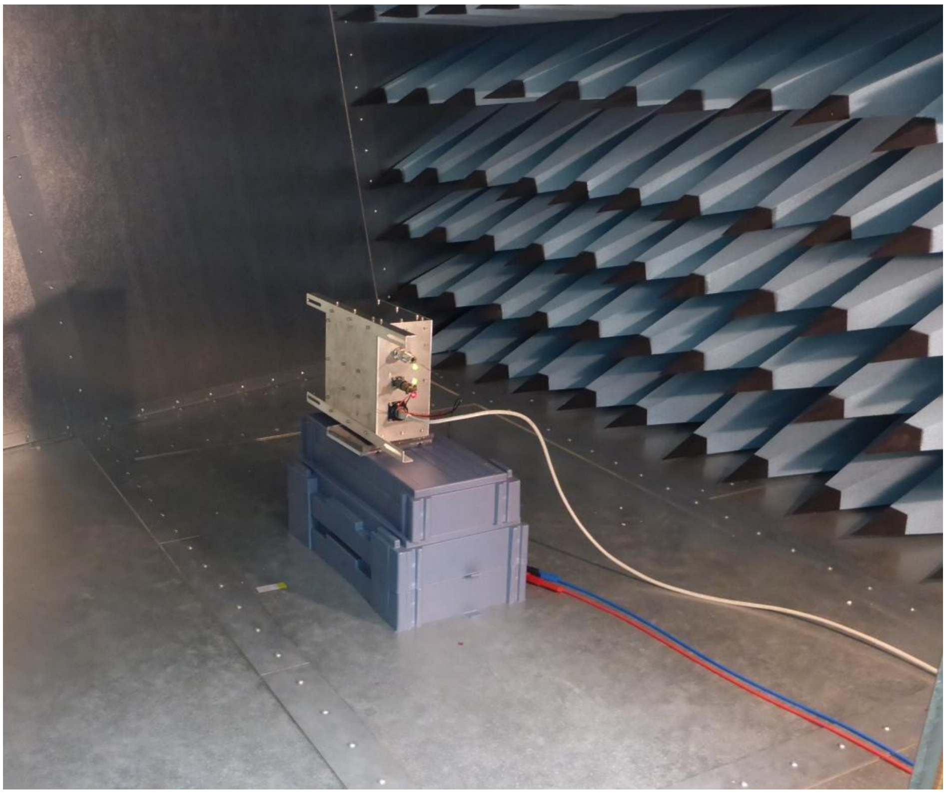
Test date	27.08.2014
Test completed	Done. The test result shows that the experiment fulfils the requirements.

Table 5-3-6: EMC test

Test number	3
Test type	EMC test.
Test facility	EAH-Jena.
Tested item	Whole experiment.
Procedure and duration	Acceptance test, 30min. The experiment was put into a GTEM chamber and powered up. Then the electro-magnetic levels of the experiment were measured in every direction.
Test campaign duration	2h, including build up and measurements.
Test date	18. September 2014
Test completed	Done. Some spikes are higher than the maximum ratings (thin blue line). But the thin blue line is basically for consumer electronic devices and therefore a bit more restrictive than the industry regulations.



Picture 12: EMC test results



Picture 12: Experiment placed into the GTEM chamber

Table 5-3-7: Weight test

Test number	7
Test type	Weight test.
Test facility	EAH-Jena.
Tested item	Whole experiment.
Procedure and duration	The experiment was put onto the weight and the weight was measured.
Test campaign duration	2min.
Test date	15. September 2014
Test completed	Done. Weight: 1.5kg

Table 5-3-8: E-Link test

Test number	8
Test type	E-Link test.
Test facility	Esrange, Kiruna.
Tested item	Whole experiment.
Procedure and duration	Acceptance test. All experiments were build into the gondola. The experiments were powered up and different tests with different E-Link signal strengths were made.
Test campaign duration	4h.
Test date	08 & 09. October 2014
Test completed	Done.

Table 5-3-9: Endurance run

Test number	9
Test type	Endurance run
Test facility	EAH-Jena

Tested item	Whole experiment.
Procedure and duration	Acceptance test. The experiment was build up and the groundstation was set up next to it. Everything was powered up and ran for 12h.
Test campaign duration	12h.
Test date	Mid September 2014
Test completed	Done, everything works fine.

Table 5-3-10: Antenna test

Test number	10
Test type	Antenna test
Test facility	EAH-Jena
Tested item	Antenna.
Procedure and duration	Acceptance test. The experiment was build up and the antenna was placed outside the building. We could receive air-planes from a distance of 380km, so we can say, that the antenna works fine.
Test campaign duration	12h.
Test date	Mid September 2014
Test completed	Done.

Table 5-3-11: Interference test

Test number	11
Test type	Interference test.
Test facility	Esrange, Kiruna.
Tested item	Whole experiment together with the other experiments of BEXUS18.
Procedure and duration	Acceptance test. The experiment was placed into the gondola and every experiment was switched on one after another.

Test campaign duration	12h.
Test date	08. October 2014
Test completed	Done, everything works fine.

Table 5-3-12: Static load test

Test number	14
Test type	Static load test.
Test facility	EAH-Jena
Tested item	Experiment case.
Procedure and duration	Acceptance test. The experiment placed onto the floor and a load of 65kg was placed onto the case.
Test campaign duration	5min.
Test date	Mid September 2014
Test completed	Done, everything works fine.

6 LAUNCH CAMPAIGN PREPARATION

6.1 Input for the Campaign / Flight Requirement Plans

6.1.1 Dimensions and Mass

Table 6-1: Experiment mass

Component	Weight
Aluminium box	0,95kg
Baseboard	0,1kg
ARM board	0,05kg
Cables	0,1kg
Antenna	0,3kg
Sum:	~1,5kg

Table 6-2: Experiment mass and volume

Experiment mass (in kg):	~1,5kg
Experiment dimensions (in m):	1 box: 0,2 x 0,2 x 0,1 1 downward facing antenna: 1,5 x 0,05 x 0,05
Experiment footprint area (in m^2):	Box: 0,04 Antenna: 0,0025
Experiment volume (in m^3):	Box: 0,008 Antenna: 0,00375
Experiment expected COG (centre of gravity) position:	Box: [0.1, 0.1, 0.05] Antenna: [0.75, 0.025, 0.025]

6.1.2 Safety Risks

The only safety risk that exists in our opinion is a mechanical fault of the antenna, causing it to fall off the gondola and injuring people on the ground. This case can be surely prevented with a good mounting.

As the antenna feeding cable is used to hold the antenna itself, there will be no additional safety line. This was discussed at CDR and confirmed to be OK.

6.1.3 Electrical Interfaces

Table 6-3: Electrical interfaces applicable to BEXUS

BEXUS Electrical Interfaces		
E-Link Interface: E-Link required? Yes		
	Number of E-Link interfaces:	1
	Data rate - downlink:	~20kByte/s
	Data rate – uplink	~1kByte/s
	Interface type (RS-232, Ethernet):	Ethernet
Power system: Gondola power required? Yes		
	Peak power (or current) consumption:	1 W
	Average power (or current) consumption:	1 W
Power system: Experiment includes batteries? No		
	Type of batteries:	-
	Number of batteries:	-
	Capacity (1 battery):	-
	Voltage (1 battery):	-

6.1.4 Launch Site Requirements

- Space for 5 people (5 chairs + tables)
- If possible, an external monitor for the ground station
- Tests to be performed before the launch:
  - The system should be powered on and running in its normal mode
  - Test if ADS-B messages are received (see the flashing LED at the experiment box)
  - All messages from the experiment (scientific data and housekeeping data) will be analysed to ensure a fully operational experiment.
- An external power supply is required
- Internet access via cable or WIFI.

6.1.5 Experiment Shipping

Both built experiments were shipped via a spedition to Kiruna. During IPR this idea was mentioned by ZARM. They organized everything with the spedition.

The experiments and all other needed stuff were packed into an aluminium box (Zarges box) with the dimension of 80x60x60cm.

As discussed at IPR the parcel was picked up in Jena on 19. September 2014.

Additional equipment for experiment testing in Kiruna was either be brought in the flight baggage or shipped in the parcel.

6.2 Preparation and Test Activities at Esrange

The following tests should be possible after the experiment is mounted in the gondola and power is applied:

- Power is applied: Power LED (LED1, green) comes on
- <1 min later: 'Alive' LED (LED1, red) blinks periodically (ca. 1 Hz)
- E-Link is connected: Link LED (LED2, green) is on
- E-Link data is transmitted/received: Act LED (LED2, red) flashes
- Stimulation with bladeRF test transmitter: RX LED (LED3, red) flashes, also if ADS-B is received from planes

To verify, that the experiment is working, in phases where E-Link is not available before start of the balloon, visual inspection of the LEDs is sufficient.

For testing the experiment out on the launch pad (before launch preparations have begun), a portable power supply was built. This way, the experiment (especially the RF receiver) functionality can be tested far from EM interference sources.

6.3 Timeline for Countdown and Flight

The experiment will capture data from the release of the balloon till the end. There is no special timeline planed.

During the flight every 5min a new file will be written to reduce the risk of data loss during the flight caused by e.g. power failures.

Before launch and during rollout at Hercules the antenna will be fixed to the gondola structure to prevent a damage. Before the launch we have to release the antenna from the gondola premounting. Because of that we need a late access to the experiment and the possibility to speak to the ARCA ground station via radio-communication.

After the release of the antenna there have to be 2m space between gondola and ground to prevent a damage of the antenna.

ARCA would like to capture data in high altitude as long as possible at daylight. This means around 2h at flight level.

We would like to be notified 15min before the balloon cut off to have the possibility to save and downlink the data.

6.4 Post-Flight Activities

After the experiment is finally back at Esrange, the memory flash will be taken off the experiment and the data will be copied. This data includes all log files taken by the experiment containing the received ADS-B packets.

This action requires opening the experiment (Unscrewing the top), removing the Locktite from the SD card and taking it out. A Micro-SD adapter configured for read only access is used to access the data, to prevent accidental data deletion.

6.5 System success

Table 6-4: System success table

Subsystem	**Description**	**Percentage**
RF front end	Receive data from airplanes in a distance of <300km.	30%
	Receive data from airplanes in >300km distance.	40%
FPGA receiver	The data stream is received but a few message decoding problems exist.	5%
	The data stream is received and all messages are decoded correctly.	30%
ARM computer	The data is received but minor problems (e.g. communication, restarts necessary etc.) existed.	5%
	The data is received and all data is saved correctly.	15%
Ground support	Data is correctly received by the ground station but the commands do not work perfectly.	
	Data is correctly received by the ground station and the commands do work perfectly.	

Thermal	Some components get too hot or cold to work perfectly but do still work. Simulation results are off.	1%
	All components are in the right temperature profile and are working correct. Simulation results are according to real behavior.	5%
Power System	Power system fails to work stable	0%
	All components receive their necessary power to work correct.	5%

7 DATA ANALYSIS AND RESULTS

7.1 Data Analysis Plan

Because the goal of the experiment is, to evaluate which advantages an aircraft-based ADS-B monitoring system could have, the received data will be analysed under the following criteria:

- What is the average range of received planes?
- What is the maximum range of received planes?
- Number of packets per second/minute
  - Is there a need for other (better performing) reception concepts?
- Are single planes traceable without interruption?

But, as stated in the experiment objectives, not only the receiver performance matters for the success of our experiment. As a whole system was developed, without relying on off-the-shelf parts, the following criteria are also to be analysed:

- Did all parts of the electronics work as they should? Why and where did errors occur?
- How well does the thermal simulation match the measured temperatures?
- Did the mechanical design prove robust enough?

7.2 Legal issues

The reception and publication of ADS-B data received from airplanes is not illegal (see [8], German article). To make sure the experiment is not problematic for legal reasons, we will not publicize any raw ADS-B data received during the whole flight, but only statistical information. By doing that we can guarantee that nobody’s privacy will be invaded by publishing the SED.

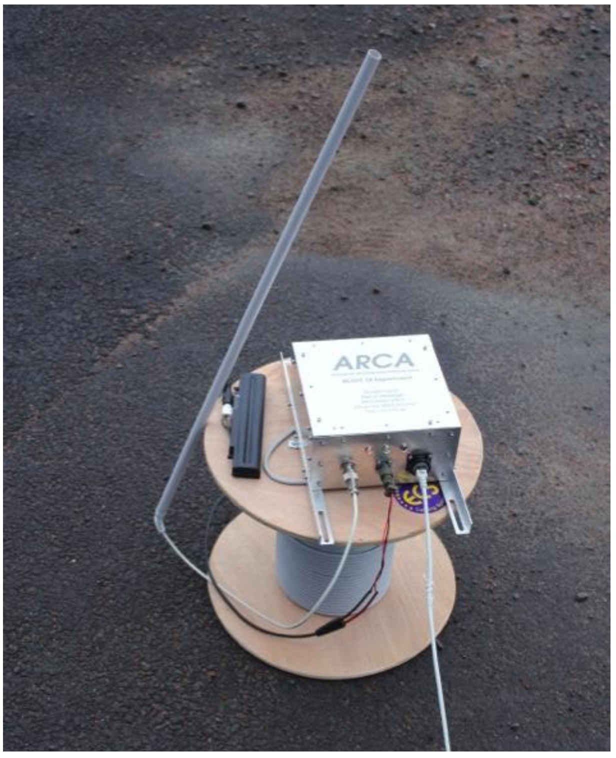
7.3 Launch Campaign

At the first day everything was unpacked from the shipping box and the last things were assembled. After that the experiments were tested. Therefore the antenna and the experiment were placed outside of the dome and were connected via Ethernet cable to the ground-station.

After some time we could see 2 airplanes which travelled in the North-Western part of Scandinavia. Even when there were only 2 airplanes received, this was a good sign, because the Esrange facility is placed in a valley, were the reception conditions are relatively bad.

After that last power cut-off tests and communication tests were done and all were absolved successfully without any incidents.

The remaining days at Esrange were quite calm and gave us room to prepare for the upcoming launch.



Picture 13: Experiment test outside the dome

Picture 13: ARCA Experiment placed into the gondola

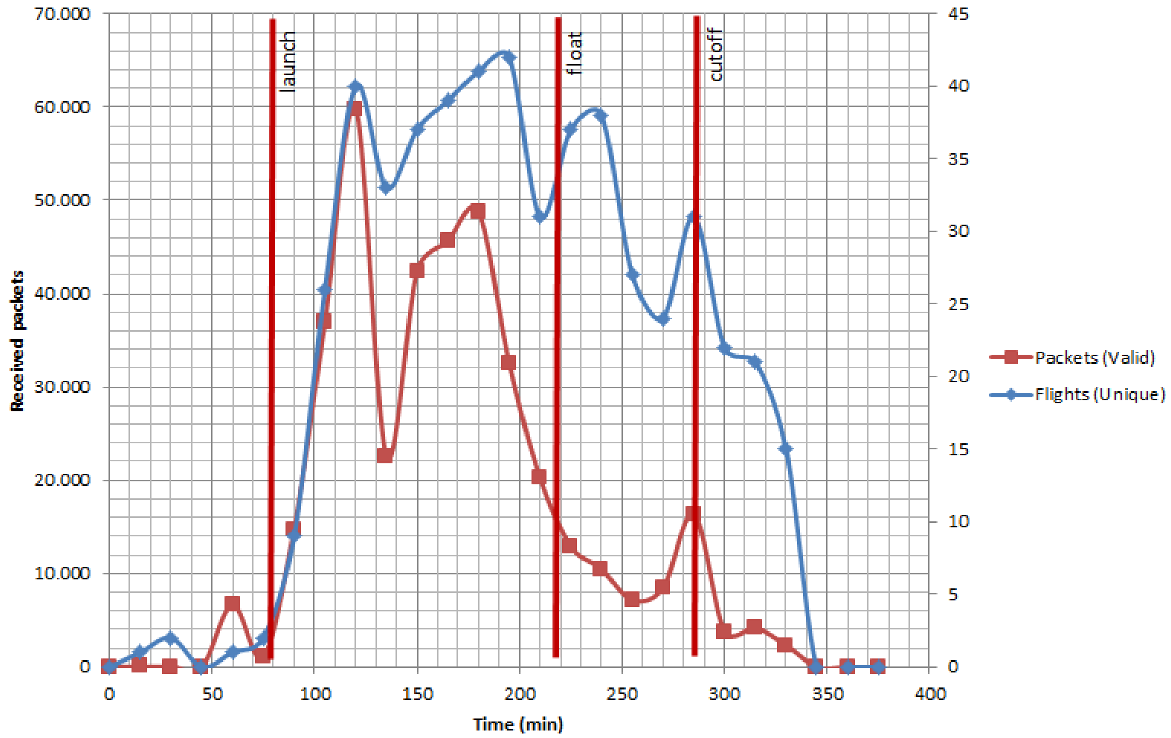
7.4 Results

7.4.1 Experiment results

During flight, we faced several unexpected conditions. First, at an altitude of ~7km, we noticed first “drop outs” of received packets. It seemed that there were periods (~30 seconds long), where not a single packet was received. This was unusual because in these altitudes many planes should have been ‘visible’ and always seemed to cause a continuous stream of packets.

As the balloon ascended further, these dropouts seemed to get more frequent and longer. Eventually, the data rate in peaks dropped from >50 packets per second to about 2-5 packets per second. Dropouts seemed not to be periodic and occurring before the receiver. After arriving back at home, a receiver test indicated that the receiver is still intact and was not the cause of the problem.

The data rate over time is indicated in the following diagram.

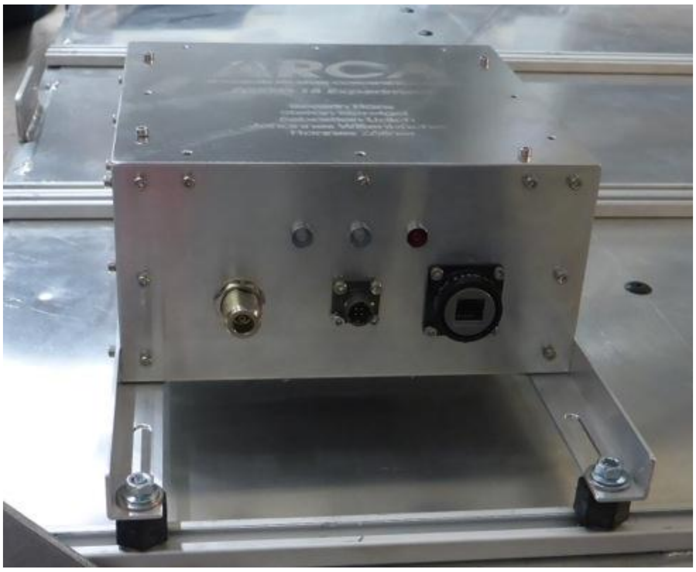


Nevertheless, we were able to track airplane routes continuously as seen in the following picture:

Picture 14: Recorded airplane tracks during the flight, visualised with planeplotter.

7.4.2 Hardware design

The plain case structure turned out to be pretty robust and reliable. We used vibration-reducing dampers for the attachment of the experiment to the gondola to protect the PCBs at the gondola landing. Afterwards, there were no shock-related damages visible on the experiment.



Picture 15: Experiment mounted in the gondola onto shock dampers.

Also, the application of thread lock adhesive and lock washers has proven itself. After the flight and landing, there were no loose screws and even the threads of the screws for the lid fixation in the aluminium l-sections, which have been tightened and loosened several times during assembly and testing were in a good shape.

7.4.3 Electronics design

All over, the electronics development was very successful. During the fabrication, only some minor directly fixable bugs were detected. In detail they were:

- An unpopulated power-connection-resistor for the supply of the ethernet-PHY-chip.
- A swapped population of a series- and a pullup-resistor. So, the PHY was not configurable at all because a config-interface-line was stuck at VCC.
- A missing power-connection at one FPGA-power-pin due to a text in the schematics at the position where the connection should have been. This resulted in a non-responding FPGA. This bug was fixed with a 5mm long wire bridge at the PCB.

After fixing these points, the electronics worked always reliable until the end of the project including all absolved tests.

7.4.4 Software

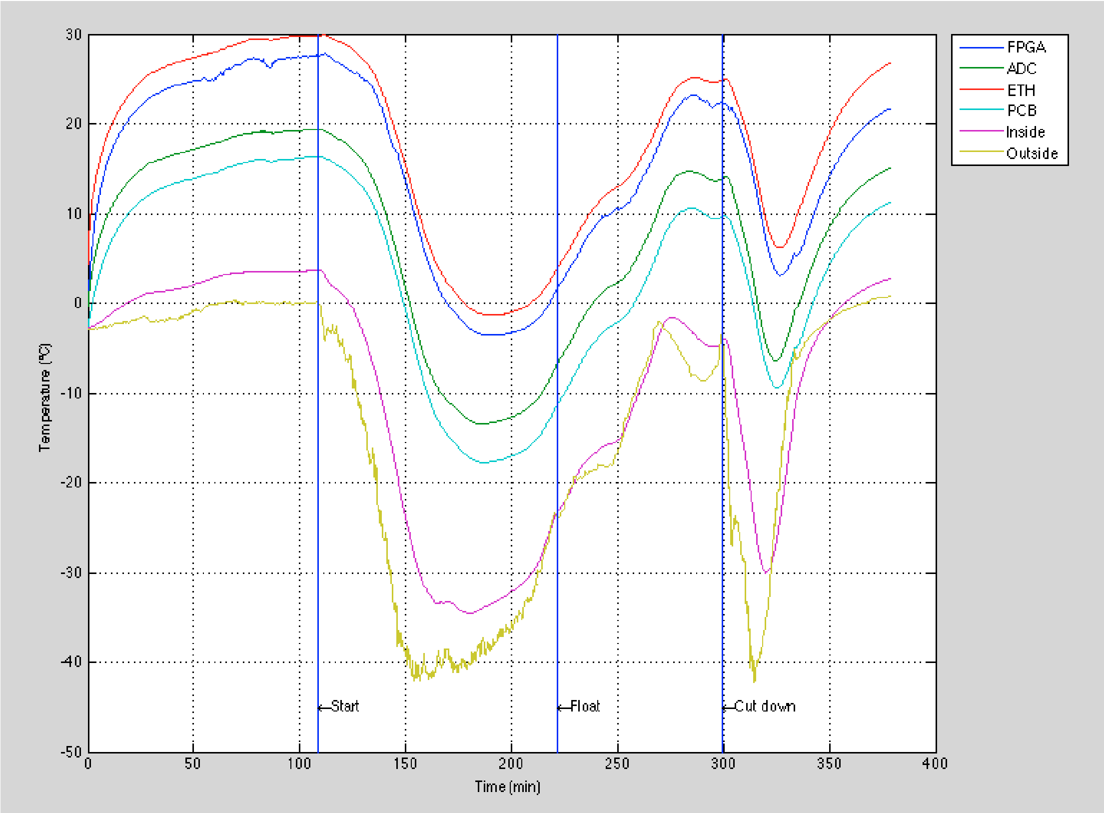
As software development was finished long enough before launch campaign, we were able to conduct many software tests on flight software. This, combined with an open, git-based software development model, led to very well-tested software that exposed no problems during flight. All communications worked as expected and no crashes or other difficulties could be noticed.

By design, each software module had its own watchdog, which would have reset it eventually and log every crash.

The FPGA code proved also to be very reliable, eliminating needs for additional security measures.

7.4.5 Thermal

The measured temperature trend is shown below:



Picture 14: Recorded airplane tracks during the flight.

Before launch, outside temperatures were at approx. 0°C and a thermal steady state was reached before launch at 08:49 UTC. While ascending, the temperatures outside dropped to -40°C quite fast, caused by the cooler air in higher altitudes. Interestingly, the temperatures began to rise again approx. 1 hour after launch. This was most probably caused by the increasing solar radiation experienced. In the late float phases we reached equilibrium temperatures of little below 0°C on the case outside and ~20°C inside the experiment. All measured temperatures are well within operating conditions.

To be honest, we did not take solar loads into consideration when making thermal approximations, as none of the former BEXUS flights we looked into had sun-exposed experiments. From our experience, solar heat radiation can clearly be taken into account for thermal design of a BEXUS experiment when conducting a day flight. Luckily, we developed our experiment to withstand both day- and night-flight conditions, so were not affected in problematic ways.

7.5 Lessons Learned

7.5.1 Antenna

The antenna was the part that caused the most severe trouble.

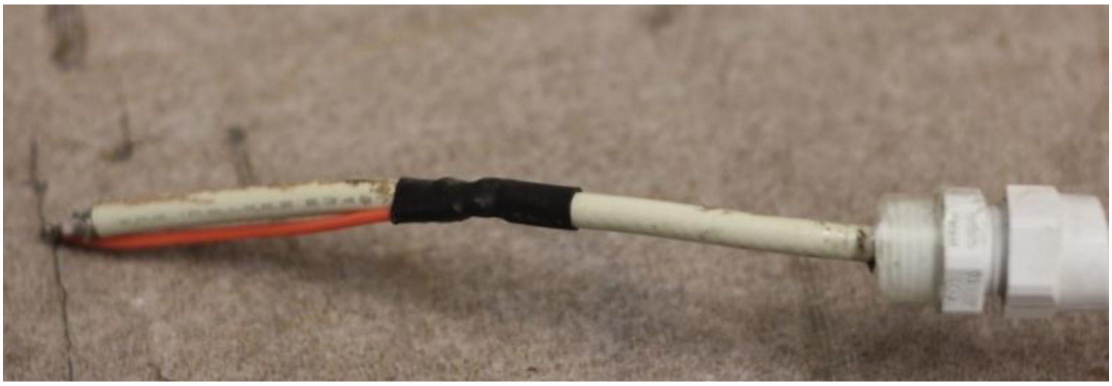
After the flight, we only got back the cable with the first segment of the antenna-wire and – later - the housing-pipe. Many speculations were made about the reason of that. One option is, that it was torn apart in trees during landing. But that doesn't correlate with the data dropout during ascend.

Another option and the most probable cause is in the antenna construction itself. The segments were movable inside the protecting pipe. And maybe, during fabrication of the device, the shielding wires were partially damaged while cutting the isolation off the used coaxial wire.

Those two points in combination with thousands of shakings during tests, using, and especially the transport to Esrange let the antenna brake during flight at an altitude of about 7km.

What has been learned out of that is that a better construction would have been putting the cable segments into one long transparent heat shrinkable tubing without any plastic-pipe around. So, the antenna is completely flexible, inspectable and has no 'moving parts'.

Possibly, this trouble might have also been avoided by more team internal reviews. So, maybe the damaged shielding wires would have been detected.



Picture 14: Broken antenna after the flight.

7.5.2 Electronics

The fabrication of new ARM-Boards caused trouble. We wanted to order from the same company like some years ago, where the first revision of the PCBs were produced with the same specification. Their response was, that the parameters are out of spec and not producible. So, another company and some layout changes were needed, what took several more days for fabrication than planned. For next projects it is important to check the design rules of companies again, also when there were prior orders with same parameters.

8 ABBREVIATIONS AND REFERENCES

8.1 Abbreviations

Add abbreviations to the list below, as appropriate and delete unused abbreviations.

ADS-B	Automatic Dependent Surveillance - Broadcast
AIT	Assembly, Integration and Test
ASAP	as soon as possible
BO	Bonn, DLR, German Space Agency
CDR	Critical Design Review
COG	Centre of Gravity
CRP	Campaign Requirement Plan
FPGA	Field Programmable Gate Array
DLR	Deutsches Zentrum für Luft- und Raumfahrt
DSP	Digital Signal Processing
EAT	Experiment Acceptance Test
EAR	Experiment Acceptance Review
EIT	Electrical Interface Test
EPM	Esrange Project Manager
ESA	European Space Agency
Esrange	Esrange Space Center
ESTEC	European Space Research and Technology Centre, ESA (NL)
ESW	Experiment Selection Workshop
FAR	Flight Acceptance Review
FST	Flight Simulation Test
FRP	Flight Requirement Plan
FRR	Flight Readiness Review
GSE	Ground Support Equipment
HK	House Keeping
H/W	Hardware
ICD	Interface Control Document
I/F	Interface
IPR	Interim Progress Review
LDO	Low Dropout Voltage (Regulator)
LED	Light Emitting Diode
LNA	Low Noise Amplifier
LO	Lift Off

LT	Local Time
LOS	Line of sight
Mbps	Mega Bits per second
MFH	Mission Flight Handbook
PCB	Printed Circuit Board (electronic card)
PDR	Preliminary Design Review
PST	Payload System Test
RBF	Remove before Flight
RTC	Real Time Clock
SED	Student Experiment Documentation
SNSB	Swedish National Space Board
SNR	Signal to Noise Ratio
SODS	Start of Data Storage
SOE	Start of Experiment
STW	Student Training Week
S/W	Software
T	Time before and after launch noted with + or -
TBC	To be confirmed
TBD	To be determined
WBS	Work Breakdown Structure
ZARM	Zentrums für angewandte Raumfahrttechnologie und Mikrogravitation

8.2 References

(Books, Paper, Proceedings)

[1] EuroLaunch: **BEXUS User Manual** (2012), **REXUS User Manual** (2012)

[2] European Cooperation for Space Standardization ECSS: Space Project Management, **Project Planning and Implementation**, ECSS-M-ST-10C Rev.1, 6 March 2009

[3] SSC Esrange: **Esrange Safety Manual**, REA00-E60 , 23 June 2010

[4] European Cooperation for Space Standardization ECSS: Space Engineering, **Technical Requirements Specification**, ECSS-E-ST-10-06C, 6 March 2009

[5] European Cooperation for Space Standardization ECSS, Space Project Management, **Risk Management**, ECSS-M-ST-80C, 31 July 2008

[6] European Cooperation for Space Standardization ECSS: Space Engineering, **Verification**, ECSS-E-ST-10-02C, 6 March 2009

[7] Project Management Institute, **Practice Standard for Work Breakdown Structures – second Edition**, Project Management Institute, Pennsylvania, USA, 2006

[8] Empfang und Dekodierung von Flugzeug-Positionsdaten erlaubt. Rechtsanwalt Michael Riedel, DG2KAR. http://www.lawfactory.de/PDF/FUNKAMATEUR_2010_03.pdf

[9] ARCA-FPGA github repository http://www.github.com/thasti/arca-fpga

APPENDIX A – EXPERIMENT REVIEWS

Preliminary Design Review – PDR

PDR took place in Kiruna, Sweden. All team members, except Johannes Willenbücher, have been there. Most feedback received from the PDR board was positive, but the following problems were identified:

- Heating should not be necessary as planned
- It would be more sensible to invest in better thermal insulation
- Having 5 people in the team could prove being not enough
- It could be hard to collaborate well, if one team member is from a university far away
- FPGA design is a high risk factor, because it constitutes a single point of failure

We tried to overcome these problems: The thermal concept was reworked and is in stable condition. For an experiment of our size, five people seem to be enough, work is progressing well. For eliminating the point of failure (FPGA design), a backup plan (using a commercial ADS-B receiver) was derived.

Critical Design Review – CDR

CDR took place in Noordwijk, Netherlands. All team members have been there. The SED was described as containing too little information, lacking some experiment details.

We tried to address this problem until IPR, but as the issue date of the IPR SED is directly in the middle of our exam phase, we were not able to successfully fix all mentioned problems. This fact was mentioned to ZARM and acknowledged.

Interim Progress Review – IPR

IPR was held at EAH Jena with all team members from Jena and Julia Grünhage, Dieter Bischoff and Simon Mawn from ZARM. Also attending was Prof. Voß, our mentor from university during this project.

The overall experiment progress was reviewd and last good advices concerning the mechanical design practise were given. All open topics were discussed with satisfying results.

Experiment Acceptance Review - EAR

The EAR took place in our university in Jena. During EAR all team members were involved and could participate. Also Prof. Voß, our mentor during the whole project, took part during the meeting with the experts from ZARM.

After a discussion about the building process of the experiment and a detailed talk about the upcoming launch campaign, we made a demonstration of the working experiment.

APPENDIX B – OUTREACH AND MEDIA COVERAGE

After the PDR and trainings week in Esrange we wrote a press release together with our university press office. It was published in the following newspapers and their websites:

- Our university website:

  http://www.fh-jena.de/fhj/fhjena/de/presse/ap/Seiten/140409_Wissenschaftliche_Feuertaufe.aspx

- JenaTV:

  http://www.jenatv.de/wissenschaft/Wissenschaftliche_Feuertaufe-21338.html

- Jenapolis.de

  http://www.jenapolis.de/2014/04/09/studenten-der-fh-jena-entwickeln-raumfahrttechnologie/

- TLZ, Friday 11. April 2014. TLZ is a local newspaper for Jena.
- Jenapolis, 07. Januar 2015:
  http://www.jenapolis.de/2015/01/07/ballonexperiment-auf-schwedischer-raumfahrtbasis/

APPENDIX C – ADDITIONAL TECHNICAL INFORMATION

All Schematics and technical drawings can be found in the project repository, as including them here would degrade quality significantly. As the schematics are relatively complex, they wouldn't be readable in this document.

APPENDIX D – REQUEST FOR WAIVERS