BEXUS30 – ELFI: Measuring Schumann resonances in the atmosphere

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Abstract

The ELFI project was one of nine BEXUS experiments carried in two stratospheric balloons in 2021. The aim of the experiment was to develop a system for the non-stationary measurement of electromagnetic waves in the extremely low frequency range. The Schumann resonances that are part of this range are especially important for meteorological research. For the planned use of the system on a stratospheric balloon, various requirements and aspects regarding the measurement environment had to be considered during the development. The system is based on a magnetic loop antenna connected to a signal processing unit, the Analog Front-End. The antenna has special characteristics to enable the measurement of Schumann resonances. Due to the necessary high sensitivity of the antenna, a deployment mechanism was developed to lower the antenna for the measurement, thus reducing the influence of interference from the electronics or actuators of other experiments on the gondola. After the balloon is launched, the mechanism is extended, and the antenna is lowered below the gondola. The Analog Front-End has several stages that filter, amplify and digitalize the signal measured with the antenna. An on-board computer, built from reliable general-purpose hardware, performs the measurement, organizes and stores the measurement data, and provides communication with the ground station. Hence, monitoring and control of the experiment through the ground station was possible. In addition, an algorithm for automatic gain control was integrated to allow flexible measurement of different amplitudes.

In several testing periods the system was validated for functionality and reliability. Through numerous preliminary tests, frequencies from reference sources could be detected, e.g., 50 Hz of the power supply network or 16.67 Hz of the railroad power supply. Underground measurements confirmed that the system is suitable for detecting low frequencies. Furthermore, the system was tested and confirmed to be usable under extreme conditions like low temperatures and low air pressures. The developed deployment mechanism with scissor arms was proved to be robust and flexible. Both hardware and software worked as expected and are reliable and adaptable to different conditions. During final tests in an almost interference-free area our system was able to record optimal signals, in which the Schumann resonances could be detected. Based on these successful results, the system was ready to be deployed on the stratospheric balloon to perform measurements in the atmosphere.

Keywords

BEXUS, Extremely-Low-Frequency, Schumann-Resonances

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Acronyms/Abbreviations

AFE	*Analog Front-End*
AGC	*Automatic Gain Control*
BEXUS	*Balloon Experiments for University Students*
ELF	*Extremely-Low-Frequency*
OBC	*On-board computer*
OS	*Operating system*
SPS	*Sample(s) per second*
SR	*Schumann resonances*
TLE	*Transient luminous event*

1. Introduction

The experiment is designed to develop a system for capturing electromagnetic waves in the extremely low frequency (ELF) band in reference to varying ambient conditions. Of special interest in this band are the frequencies of the Schumann resonances (SR), e.g., 7.83, 14.1, 20.3 Hz as shown in Figure 1. The SR are the result of the earth's atmosphere acting as a resonant cavity. This resonator uses the ionosphere and earth's crust as waveguides and the atmosphere in between acts as the dielectric material. The waves are mostly excited by the global lightning activity or transient luminous events (TLE). TLEs are events which cause transients with the first mode of the SR as the dominant contributor (Q bursts first described by Boccippio et al. in 1995 [2]). Thus, SR are particularly of interest for meteorological research.

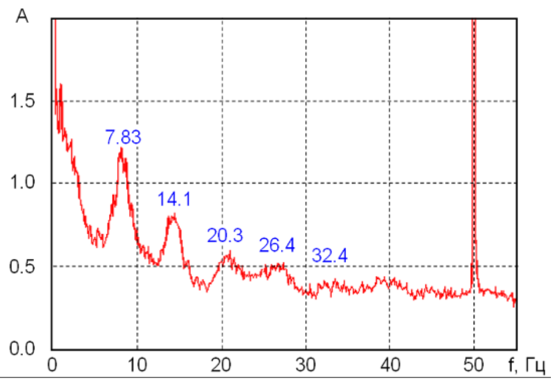

Figure 1. Typical ELF spectrum with SR [1]

The ELF spectrum is typically measured with fixed antennas on ground level. Those antennas are either built as ground dipoles, huge loop antennas or induction coil antennas. Out of these options only the loop antenna is a viable option for our requirements. Because measuring the ELF band needs those elaborate receivers there seems to be no data about the behaviour of the Schumann resonances on different altitudes. The aim of the ELFI experiment is to design a system that can perform non-stationary ELF measurements. Subsequently the system shall be deployed, and the measured data shall be analysed and compared with the ground level data.

2. Experiment setup

The experiment basically consists of an on-board computer (OBC), a signal conditioning unit, called AFE, and a loop antenna. The OBC as well as the signal conditioning unit will be placed in a box inside the gondola. The loop antenna will be mounted on a scissors lift, which will be attached on one side of the gondola. The scissors lift is designed to be extendable below the gondola during the flight. The experiment is designed with the requirements for the deployment on a BEXUS stratosphere balloon.

2.1. Mechanics

The mechanical parts of the experiment are the electronics box, called Braincase, the scissor mechanism with the antenna and the mounting plate, called Prime, to which the scissor mechanism with the antenna is mounted to. The Braincase is mounted inside the gondola whereas the Prime is attached to the outside of the gondola as shown in Figure 2.

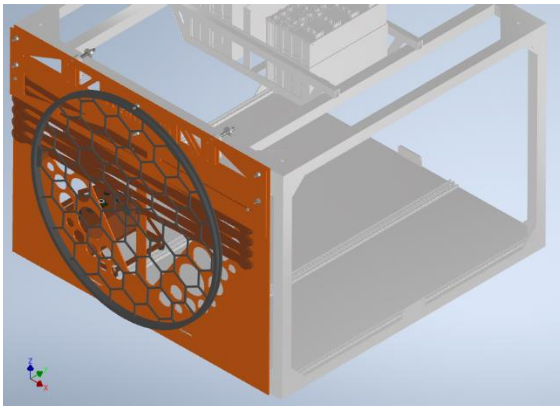

Figure 2. Prime, antenna, scissor mechanism and Braincase mounted on gondola

2.2. Electronics

Main part of the electronics is the developed AFE for signal conditioning shown in Figure 3. It includes two amplifier stages, a filter stage, and an analog-digital-converter (ADC). The stages have the following characteristics:

- 1st stage: non-inverting input amplifier with adjustable gain 19.667 – 57
- 2nd stage: 4th order low pass filter with 2 stage Sallen-Key architecture and Chebyshev characteristic, cut-off frequency 14 Hz, 0 dB attenuation
- 3rd stage: non-inverting output amplifier with adjustable gain 43.68 – 1001
- ADC: 24-bit Delta-Sigma ADC with SPI, TI ADS1220 with integrated programmable gain amplifier [3]

For the amplifier and filter stages the ADA4528 operational amplifier was used because of its high precision, ultralow noise, and zero-drift properties [4]. The operational amplifiers use a dual-ended power supply integrated into the AFE. The AFE is implemented on a single board with a 4-layer design (signal layer, ground layer, positive + negative layer) to ensure a good amount of capacitance between the single layers.

The antenna shown in Figure 2 is a magnetic loop antenna with a coil and a special frame. The coil has about 2649 turns of wire with a wire length of 6,660 m and a resistance of 3,623.7 Ohm. It is connected via a shielded 2-wire cable directly to the AFE. The frame has a diameter of 80 cm and to ensure robustness and flexibility it has a honeycomb structure and is made of Pertinax.

Another important part of the electronics is the power supply system. When mounted to the gondola of the BEXUS balloon, all experiments are connected to the battery power supply. Unfortunately, it does not provide a stable voltage during the whole flight and has only a few protections against e.g., short circuit caused by an experiment. Additionally, our experiments' power system needs to be isolated from the other experiments. To achieve this, we partially reused the IMUFUSION power board from the previous BEXUS IMUFUSION experiment of the University of Applied Sciences Nordhausen [5]. It provides the required voltages of 5 V and 12 V. Separate DC/DC converters are used to power the OBC and the Gear motor.

2.3. *Software*

The software system is divided into the OBC software and the ground station software. The OBC software performs all measurements during the experiment and in parallel takes care of data storage and transfer between the experiment and the ground station.

The *Raspberry Pi* runs the Linux distribution *Raspberry Pi OS* as the underlying operating system (OS). This was chosen because it is a reliable base system which can handle the parallelism and measurement timing according to our requirements. Thereupon the OBC software is implemented as a Python script. It performs multiple tasks in parallel by utilizing the threading capabilities of the SoC and the OS. A total of six threads and two timers are used to achieve asynchronous behavior and meet measurement timings. Two dedicated threads are responsible for performing the ELF and inertial measurements with two timers providing a sample rate of 2000 samples per second (SPS) for ELF and 1 SPS for inertial measurement. Two other threads take care of the data management, the storage of the measurement data on the internal memory and backup storage and the transmission of the data to the ground station. Another thread is used for automatic gain control (AGC). The AGC algorithm collects a subset of the ELF measurement data and evaluates it against predefined thresholds. This allows it to detect long-lasting saturation and then decrease gain or increase gain when the signal has small amplitudes. The main thread of the application initializes all other threads and is responsible for the communication with the ground station.

The ground station software is also implemented in Python and running on a usual

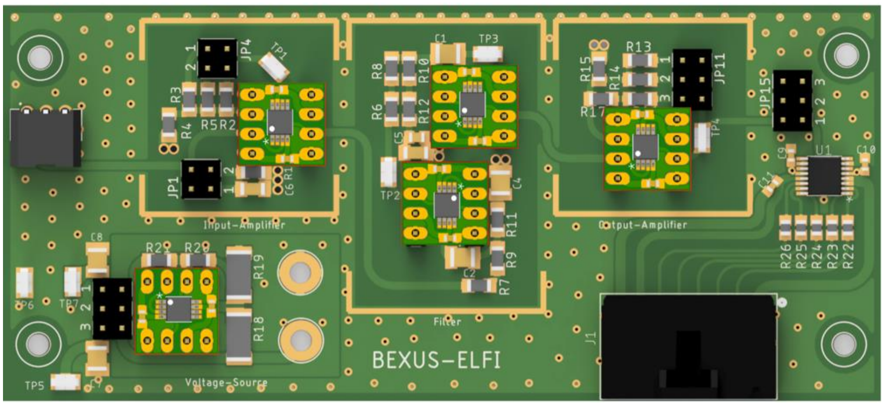

Figure 3. Developed Analog Front-End (AFE) for signal conditioning

PC. It provides network sockets for the communication. The received measurement data is decoded and stored in a local database for redundancy. The user interface of the ground station allows monitoring of the experiment with live plots of all measurements and FFT plots. The ground station is also used to trigger the release mechanism of the antenna.

3. Preliminary tests

The system had to be tested extensively in preparation for Campaign Week on ESRANGE. For this purpose, the hardware and software as well as the mechanics of our system were subjected to several tests.

3.1. Requirements

3.1.1. Mechanics

The mechanics of our experiment must be robust against shocks, vibrations and movements. The winch must ensure a smooth lowering of the antenna. Furthermore, the scissor arms must be able to withstand various movements of the gondola so that the antenna does not hang unsecured on the gondola.

3.1.2. Hardware

The hardware of our system should be prepared for the corresponding environmental conditions. Since we expect very low temperatures and air pressures during the flight, the hardware must be robust against temperature fluctuations, air pressure differences and alternating humidity. Furthermore, there must not be errors caused by vibrations, shocks, or even electromagnetic fields. Electromagnetic compatibility was particularly important here since the other experiments of the BEXUS30 balloon were close to our system.

3.1.3. Software

Since it is an essential part of our experiment, a test of the entire software was particularly important. Both the integration of the individual sensors and the programming had to be tested extensively so that no malfunctions occur during the flight. The system should correctly receive the data from the sensors as well as the antenna in real time, store it and send it to the ground station in appropriate intervals. Above all, the measures ELF data should be provided with appropriate timestamp so that the data can be correctly evaluated afterwards. Furthermore, the system should be able to receive commands from and transmit the measured data to the ground station. Another requirement is that the integrated monitoring systems successfully handle recoverable errors. The redundancy mechanisms shall ensure that no data loss occurs.

3.2. Test execution

3.2.1. Hardware and mechanics tests

The hardware requirements were tested during the Thermal Vacuum Week at ZARM in Bremen. The hardware and software were subjected to a vibration test during the trip to Bremen. The system was able to record and store all sensor reading during the trip. In a special thermal vacuum chamber at ZARM, both the electronics and the winch could be exposed to very low temperatures and air pressures. Both the hardware and the winch worked as expected even at temperatures of -60 °C and air pressures of almost 0 mbar.

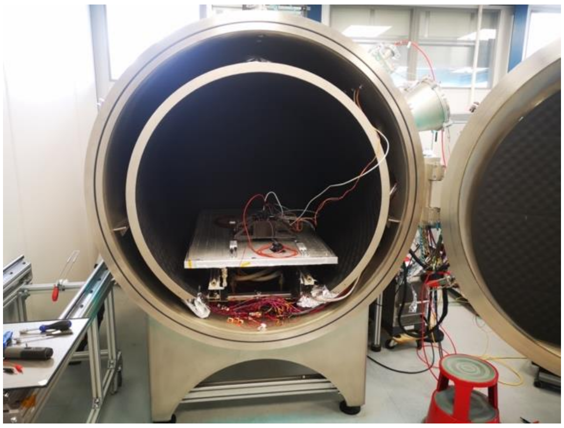

Figure 4. Thermal-Vacuum chamber at ZARM

Furthermore, a first deployment test of the antenna was carried out. For this purpose, the prime with part of the scissor arms and the antenna was lifted by crane to a height of about 3 m. The antenna was then lowered quietly and reliably by the mechanism. The deployment test was later repeated on ESRANGE, but with a total height of 5 m and using all the required scissor arms. Both tests in ZARM and ESRANGE were successful.

3.2.2. Software and interference tests

The hardware in combination with software could already be tested extensively during the design phase. The various components were first tested separately from each other. First, the reading of the corresponding sensors as well as the ELF data was checked. After this was successful, the measured values were stored and read again with an external device to ensure data integrity. Next, the communication to the ground station was checked. The data was sent from our OBC to the ground station and evaluated there. The sent and stored data were again checked for errors. Furthermore, the appropriate communication between the ground station and the system was checked, i.e., whether the system can react to the sent commands. A long-term test in which the system had to measure, store, and transmit data continuously over 24 hours was also carried out. Over this period, all data could be measured, stored, and sent correctly. There were no data errors and neither overheating nor other hardware failures occurred.

Furthermore, the system was tested external error sources. For example, during the launch campaign on ESRANGE, a check was made to figure out of the system was still functioning after a power loss, communication failures or similar. In addition, an interference test was performed. The aim of this test was to check the electromagnetic compatibility of our system. For this purpose, our system including the antenna was mounted on the gondola, and then the other experiments of BEXUS30 were added individually. Thus, we could check whether the other experiments would influence our ELF measurement. Fortunately, this was not the case; the experiments did not interfere with our system. We also tested our system for loss of connection to the sensors. The system was able to respond accordingly to the communication errors. There was no overall failure of the system.

3.2.3. Free-field test

The last thing to be tested was the antenna. For this purpose, several tests had already been carried out at the University of Applied Sciences in Nordhausen. The measured signals of the antenna were either viewed directly on the oscilloscope or stored with our system and analyzed later. The measured frequencies were particularly striking – both 50 Hz and 16.67 Hz were dominant.

Figure 5. Free-field test setup on ESRANGE launchpad

Since we were unfortunately unable to measure the Schumann frequencies there, an open-field test was carried out in Sweden. For this, our OBC and the antenna were moved to the launchpad of ESRANGE to find an environment as free of interference as possible. The test took place three days before the launch of the experiment. The primary goal of the test was to measure and prove the SR. Furthermore, the gain factor of our AFE had to be adjusted accordingly. Since the measurements during the tests in Nordhausen were disturbed by 50 Hz and 16.67 Hz, a suitable amplification factor could not be set prior to the launch campaign. The gain of the AFE should be set so that the internal gain of the ADC, which was set by the AGC, remains between 8 and 32. With this setting, we have enough margin for any in-flight fluctuations. Several test runs were necessary to determine a suitable gain factor. Each run included setting a gain on the AFE, recording the signal for a few minutes, and then evaluating the recorded data. Many different options were

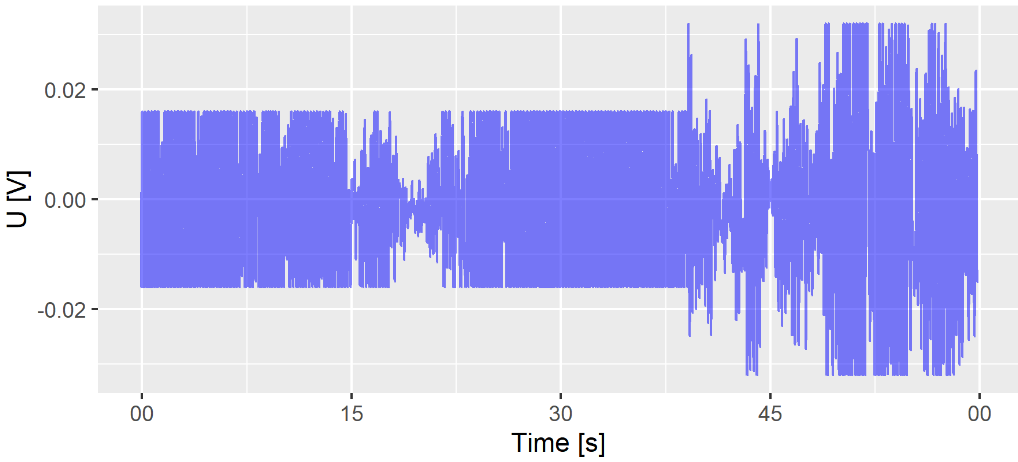

Figure 6. Signal measured during free-field test

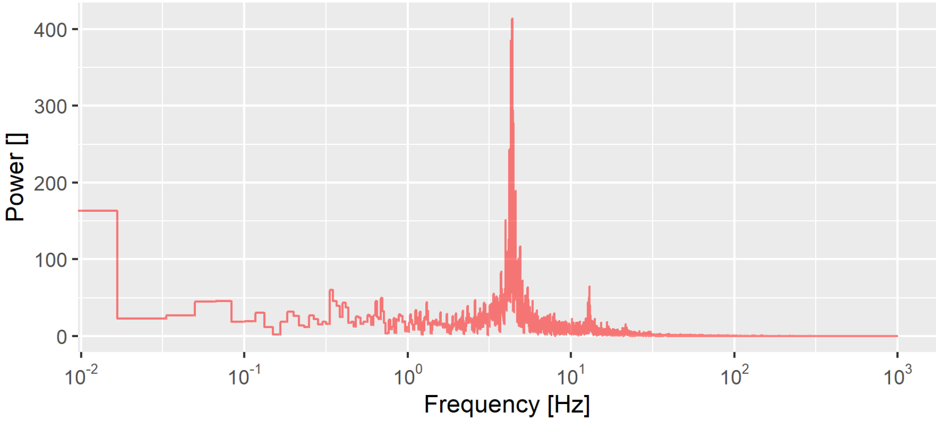

Figure 7. FFT analysis of signal in Figure 6

tried and compared to find the best possible setting for the system. The finally used gain was 1653 (input amplifier: 29, output amplifier: 57) with the AGC gain moving between 8 and 16.

4. Discussion

Both the mechanical and hardware tests ran without any major problems. The system proved to be very robust and reliable, so it met the requirements. The tests of the software also went very well. The individual components of the system functioned flawlessly, and errors were either avoided or handled appropriately, so the system should not have any problems during the flight.

The free-field test on the ESRANGE site delivered first satisfactory results. For example, the first Schumann frequency could be measured even before determining a suitable gain factor. Figure 6 shows a first measured voltage curve. It shows very well how our AGC works. The measured voltages were initially in the range of ±0.016 V. With a maximum voltage U_{max} of 2.048 V, this corresponds to an amplification of 128 of the integrated PGA. It can be seen that the measured voltages were very often in saturation for the first 40 seconds. The AGC then reduced the gain of the PGA to 64 to counteract the saturation of the signal. The voltage response is now in the range of ±0.032 V. Since this gain is still too large, the gain of the AFE was further reduced. Figure 7 shows the corresponding frequency spectrum calculated by an FFT. The frequency spectrum records a high peak at about 7.8 Hz. Furthermore, there is a smaller peak at about 12 Hz. Since the second Schumann frequency is at 14.1 Hz, it cannot be assumed that this is this frequency. It is noticeable that neither 16.67 Hz nor 50 Hz of power supply systems can be found. This indicates a very low interference environment. As a result, the voltage of the AFE was sufficiently reduced so that the measured voltages in the follow-up tests with an internal gain of the PGA were between 8 and 16.

5. Conclusions

Extensive testing of the individual components of our system ensured the functionality and safety of our experiment. Although the software as well as the mechanics presented us with greater challenges, the best conditions for a successful flight were created.

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