SDR Helix Antenna Deployment Experiment (SHADE) on board BEXUS

Melina Koukou[1], Vasilis Vellikis[1], *Ioannis Varvaringos*[1], *Konstantinos Koutropoulos*[1], *Ioannis Myrsinias*[1], *Despina Ekaterini Argiropoulos*[1], *Andronikos Dourmisis*[1], *Orestis Rafail Nerantzis*[2], *Ioannis Ioannou*[1], *Elli Loukaridou Kizili*[1], *Spyros Megalou*[1]

Abstract

In the field of space travel, space communications has always presented a slew of obstacles and hurdles that must be overcome in order to complete a successful mission. Space limits inside a satellite or spaceship, vast distances between satellites and ground stations, and a phenomenon known as "Faraday Rotation" in the ionosphere are only a few of the most typical issues. Satellite antennas must be small, compact, efficient, and circularly polarized as a result of the aforementioned issues. The helix antenna is an excellent answer for all of the requirements. In this work we develop a deployment and pointing mechanism of a helix antenna operated with software defined radio algorithms. The features of helix antennas are exceptional, and they are especially suitable for satellite communication. Three coaxial cylinders, two stepper motors, one pulley, and one thread make up a deployment-pointing mechanism. The mechanism deploys the antenna along its longitudinal axis and turns it horizontally towards the ground station. During the flight, the antenna is deployed and retracted. Under different positioning situations, the GPS, an altimeter, and a compass calculate the gondola's position in order to rotate the antenna towards the Ground Station and close the communication link. The antenna's rotation mechanism is triggered by the integrated attitude determination and control system algorithms in order to correct the pointing and orientation towards the Ground Station. The antenna uses software defined radio algorithms to achieve weight and volume reductions while maintaining high efficiency and reconfigurability. The experiment includes a high-definition camera that provides real-time information on the antenna's orientation and condition. SHADE's flight on the BEXUS 28/29 balloon resulted in effective deployment and transmission, as well as the ability to receive and decode transmitted packets. The rotating mechanism met the pointing requirements, and all of the sensor's data was correctly saved to our system. Throughout the trip, there were no signs of thermal risk.

Keywords

Antenna Deployment, Helix Antenna, REXUS/BEXUS, Software Defined Radio, Stratospheric Balloon

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[1] Corresponding author: Aristotle university of Thessaloniki, Greece, mkoukou8@gmail.com

[2] University of Macedonia, Greece

Acronyms/Abbreviations:

ADCS	*Attitude Determination & Control System*
AUTH	*Aristotle University of Thessaloniki*
BER	*Bit Error Rate*
DMCS	*Deployment Mechanism Control System*
FEM	*Finite Element Method*
GHz	*Giga-Hertz*
GMSK	*Gaussian Minimum Shift Keying*
GNSS	*Global Navigation Satellite System*
GS	*Ground Station*
HCS	*Heating Control System*
HPBW	*Half Power Beam Width*
LNA	*Low Noise Amplifier*
OBCS	*Observation Control System*
PA	*Power Amplifier*
RX	*Receiver*
SDR	*Software Defined Radio*
SHADE	*SDR Helix Antenna Deployment Experiment*
SSC	*Swedish Space Corporation*
TT&C	*Telemetry Tracking and Command*
TX	*Transmitter*
TXCS	*Transmission Control System*

1. Introduction

In space telecommunication systems, closing long distance links and Faraday rotation are major challenges faced by engineers. Stratospheric balloons and other high-altitude platforms regularly use monopoles to communicate with the ground station, as their omnidirectional properties nullify any need for beam steering. Nevertheless, monopoles have low gain and linear polarization that could be easily affected by Faraday rotation; therefore, they require high power consumption to establish a link. Helix antennas could offer a solution to these issues, with their good gain/cost trade-off and circular polarization that they provide. Even though they are widely used in aerospace communication systems, the geometry of this antenna type, resembling a relatively long and wide spring, often violates the volume restrictions set in space applications.

In addition, following a present tendency in research and industry to replace conventional communication circuits with software cores, Software Defined Radio (SDR) technologies are gradually established in the space sector. SDR offers accurate signal processing applications without unnecessary physical components in small sized modules.

SDR Helix Antenna Deployment Experiment (SHADE) is an SDR operated helix antenna with a spring-based deployment mechanism and a Ground-Station-Tracking automation system. A helix antenna, protected by a teflon cover, is operated by an SDR module that transmits data to the ground station. To compensate for the narrow beamwidth, an automation system has been developed in order to ensure that the antenna will always point at the ground station and maintain Telemetry Tracking and Command (TT&C) applications. Moreover, a deployment mechanism has been implemented which exploits the antenna's spring characteristics ensuring a reduced size for the system.

The experiment's potential was recognized by REXUS/BEXUS programme [1], [2] and SHADE was designed, implemented and had a successful flight on board a stratospheric balloon.

The structure of the present paper is firstly the Introduction, secondly the Mechanical Design followed by the Thermal Design; after that is the section of the Electronics and Software and then the last technical section, the Telecommunications section. The final sections include the Testing and Verification and Conclusion, on which the lessons learned are described, acknowledgments and references are also cited.

2. Mechanical Design

The Mechanical Design aimed to satisfy the following requirements. 1) The antenna's deployment 2) the antenna's controlled rotation 3) the overall fixation of the experiment on the gondola 4) BEXUS space and weight limitations 5) the safety of the experiment's assembly during the "cut-the-rope" phase. To accomplish these requirements, the mechanical design consisted of 1) the Antenna's Casing, which contained the helix antenna, 2) the External Box, which contained the rotational mechanism and the motors for deployment and rotation respectively 3) the Electronics Box and 4) the fixation of a camera to monitor the operation of the experiment. The degrees of freedom of the experiment and its major parts are presented in Figure 1.

To satisfy the requirements: 1) the natural length of the helix antenna was chosen to be longer than the length of the deployed case, so the spring's tension would result to the complete deployment of the case. The antenna's casing consisted of three co-axial cylinders, made by Teflon, which is an electromagnetic neutral material, has a low shrinking ratio at low temperatures and it has a low friction coefficient (solid lubricant) to facilitate deployment.

The clearance tolerances were carefully designed to achieve the translational movement. JS7 group has been chosen for the internal surface of the external cylinders and g6 for the external surface of the internal cylinders. Continuing, the deployment was controlled by a thread, tighten on the edge of the smallest cylinder. From the other side the thread was tighten to a pulley controlled by an electric stepper motor. An intermediate pulley was used to minimize the friction of the thread while entering the antenna's casing (Fig. 2a). Dyneema fine SK78[3] has been chosen as thread's material since its tensile strength exceeded the stress requirements.

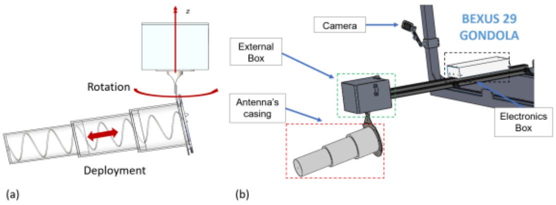

Figure 1. a) Degrees of Freedom of the experiment b) the experiment's assembly on the BEXUS Gondola.

2) The external box (Fig. 2c) contained the rotational mechanism that consisted of a spur gear-pinion mechanism with a transmission ratio of 2.6, the hollowed axis supported by two bearings, paved the passage of the thread and power supply cables to the antenna and assured the rotation of the antenna. In addition, it contained the stepper motor responsible for the rotation (assembled to the pinion) and a stepper motor that controlled the deployment of the antenna (assembled to the pulley). The external box has been fabricated by aluminum profiled rods and aluminum plates for simple assembly and quick access to the internal components. The Electronics Box was made by folded aluminum plates, and it contained all the electronic components. It was fixed on the main aluminum profile with bolts with T type nuts.

3) The fixation of the experiment (Fig. 2b) on the gondola has been designed on a profiled aluminum rod that connected the External Box with the Electronics Box. It was fixed on the gondola's trails using corner connectors and rubber bumpers, which secured the experiment of any resulted shocks (especially during the cutting the rope phase and the landing).

4) To assure the safety of the experiment and avoid material failures that could lead to any falling part, various numerical Finite Element Method (FEM) simulations have been conducted for stress and modal analysis. Furthermore, to increase the safety, all the external parts were tied to the gondola's main skeleton with Dyneema rope SK75.

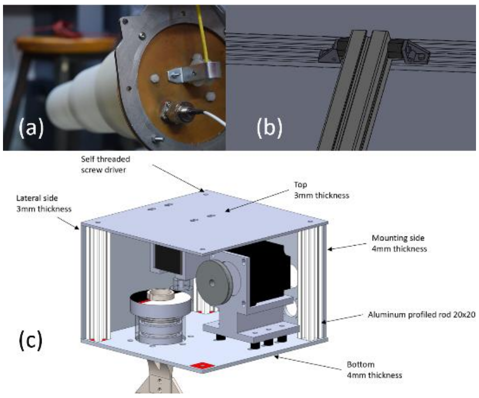

Figure 2. a) Pulley in the base of antenna casing b) Fixation with rubber bumpers on gondola's trails c) Structure and internal components of external box.

3. Thermal Design

During the flight, the experiment was expected to be exposed in harsh atmospheric conditions, which could potentially damage the sensitive electronic parts. To avoid any malfunctions of the components, both the internal and the external part of the experiment were insulated. The thickness and the material of the insulation were determined based on calculations and data retrieved from multiple simulations, using a plethora of parameters.

Due to the differences in the density of the atmosphere, the main source of heat transfer was not the same for the entirety of the flight. Therefore, to acquire more accurate results, the flight was divided in two phases, the floating and the ascending phase, which were studied and simulated separately. It is important to note that during the ascending phase the main heat transfer sources are conduction and convection. Contrastingly during the floating phase due to the lower atmospheric density, convection can be omitted and heat transfer via radiation becomes more significant.

For the thermal calculations, both the enclosure inside the gondola and the external, were considered black bodies and the heat dissipated from each electronic component was computed as 10% of its power consumption.

Both the internal and the external box were insulated externally with a layer of 30mm thick extruded polystyrene, which was ultimately selected due to its low thermal conductivity factor as well as it being a rather lightweight material. The aluminum box outside the gondola containing the stepper motors was further insulated internally using a 10mm thick layer of expanded polyethylene, while flexible heaters were attached on the motors to ensure that they would constantly operate within their operating temperature limits.

4. Electronics & Software

From the electronics' perspective, SHADE was divided in the subsystems shown in Table 1. Each subsystem was implemented as an independent prototype and got tested. Subsequently, the design of the PCBs took place in order to merge the experiment into one main circuit.

Table 1. Subsystems and components

Deployment Mechanism Control System (DMCS)	Stepper Motor, Stepper Driver, Altimeter
Attitude Determination Control System (ADCS)	GPS, Magnetometer, Stepper Motor, Stepper Driver, IMU
Power Control System (PCS)	DC-DC converters
Observation Control System (OBCS)	Camera
Transmission Control System (TXCS)	SDR module, Bandpass Filter, Amplifier
Heat Control System (HCS)	Temperature Sensor, Heaters

The system was designed with the "Fault-Tolerance" principles to make sure that it will be functional in case of a subsystem's failure. Every subsystem operates as an isolated process, in order to be decoupled from other subsystems and to constrain possible unexpected errors/malfunctions within the boundaries of a single process. For the communication between our experiment and the control station, TCP/IP protocol was used over a radio link, connecting the gondola and the ground station, and was provided by SSC. Furthermore, to enhance control of each subsystem, two modes of operation were implemented: manual mode which was based on remotely executed commands, and automatic mode. In the event of a loss of connectivity, the application runs in automated mode, ensuring that the various activities are completed in the proper order. The software modules/scripts were deployed on a raspberry Pi. Also a second raspberry pi was used for the camera-related operations, such as heavy computational processes of image capturing. Last but not least, the system logged all the data from the sensors and transmitted them to the GS for visualization and post-processing purposes. Below is a brief description of every subsystem.

The ADCS is responsible for the antenna's positioning and rotation. The antenna had to aim towards SHADE's GS during flight time, for solid communication to take place ensuring the success of the experiment. In order to fulfill this requirement, special algorithms were designed that took into consideration data from a compass, a GNSS RX, and gave as output the rotation of the stepper motor, that was responsible for the bearing/pointing of the antenna.

The DMCS is responsible for the deployment and the retrieval of the antenna, either automatically (based on altitude data) or manually. The TXCS is responsible for transmitting data to the SHADE's and SSC's GS. The HCS is responsible for the control of the temperature of the external box, based on temperature data and using a cluster heater. Finally, the OBCS is responsible for camera-related operations, such as image capturing.

The flow of SHADE experiment can be described as follows. The antenna gets deployed either automatically (above an altitude or a specific time), or manually (by command). Following a confirmation of successful deployment, ADCS is actuated and TXCS starts to transmit data to the SHADE's and SSC's GS. In case of unsuccessful deployment, the antenna is retrieved and redeployed until success. The antenna is retrieved, either below a certain altitude or by command, after having interrupted the ADCS. During the experiment, HCS continuously adjusts the external box's temperature. At the same time, OBCS captures the experiment flow providing visual control from SSC GS.

5. Telecommunications

Present SHADE Telecommunications subsystem was designed to provide an effective communication interface for high altitude platforms. It consists of a flight segment and a ground segment. The flight segment is responsible of transmitting the data collected through the flight. The ground segment receives and processes the data sent from the flight segment. The basic telecom subsystems are presented below:

5.1. Helix Antenna

The helix antenna was chosen due to its use in a variety of space applications offering suitable electromagnetic characteristics; relatively high gain, wide bandwidth and circular polarization [4], [5]. The system was operated at 1.43GHz and the transmitting and receiving antennas were designed and manufactured by the team to match the specific frequency band. Specifically, the TX helix antenna made of Stainless Steel 302 with 7 turns, to achieve a Gain of 11 dBi and a HPBW of 36 deg. The S11 parameter of the antenna should be less than -15dB at 1.43GHz proving the suitability of the material for its chosen application, exploiting both its spring elasticity and its electromagnetic conductivity.

5.2. Flight Segment

Being powered by the Raspberry Pi, an SDR module computed with GNU Radio algorithms generated the TX data and channeled them through a Power Amplifier and a 1.4GHz filter to the TX helix antenna. The ADCS system ensured constant pointing of the antenna towards the ground segment regardless of the rotation of the BEXUS gondola. The output power of the SDR module was -10dBm which strengthened with the 25dBm Gain of the PA and the antenna gain, provided the required power for the signal to reach the ground segment for approximately two hours of flight.

5.3. Ground Segment

To complete the designed telecommunication system, the ground segment consisted of a copper helix antenna with three turns in order to have a wider receiving angle, followed by an LNA and the respective 1.4GHz filter. Continuously the received signal was split to feed both the custom RX SDR module and a digital spectrum analyzer for maximization of the experiment’s results.

5.4. Digital Signal Processing

The transmitting and receiving algorithms and techniques were implemented using GNU Radio. A GMSK scheme was selected to modulate the generated data, as its differential nature ensured TX/RX clock synchronization, while a packet encoder and decoder were used to lower the BER. The algorithms were translated into Python source code files and were executed within the SDR modules.

6. Test and verification

A series of 22 tests were run to ensure that the experiment was working as planned. At first, each component was put through testing on its own. After the assembly and integration was completed, the experiment was tested in a thermal and vacuum chamber in full operational mode. The most important tests are examined in subsections 1, 2, and 3.

6.1. Thermal Test

To simulate the thermal conditions of stratosphere the experiment was placed in a thermal chamber capable of reaching temperatures close to -70°C. The experiment presented normal functionality through the whole thermal test (~2.5 hours). Both motors remained fully functional during the whole test while reaching a temperature steady state at -22.5°C, proving there will be no issue of freezing. Furthermore, the electronics box reached a steady state at -30°C with the amplifier being at -12°C and the raspberry at -20°C.

6.2. Vacuum Test

To test the experiment under the low pressure conditions of the stratosphere, the experiment was placed in a vacuum chamber capable of lowering the pressure close to 50 mbar. The experiment presented full functionality during the whole test. No mechanical or electrical failure were observed. Temperature of all components stayed in nominal levels and no malfunctions were observed.

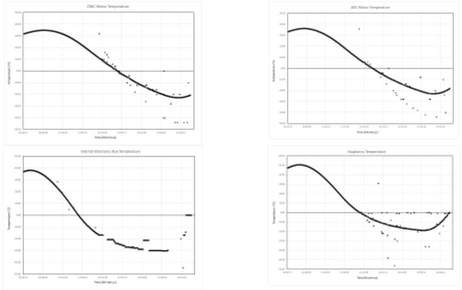

Figure 3. Thermal test results

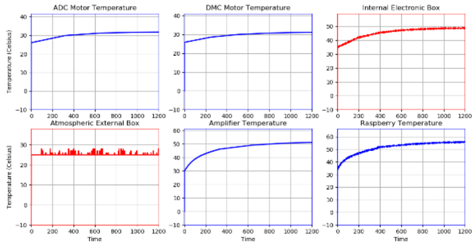

Figure 4. Vacuum test results

6.3. *Antenna propagation test*

At first, the helix antenna was placed in an anechoic chamber to measure its basic characteristics. The calculated gain of the antenna was 11dbi and the Half Power Beam Width (HPBW) of the antenna was 36deg. The measured S11 was 18dB at 1.4 GHz.

To simulate the link between the helix antenna and the ground station, an analog test scenario was created. The helix antenna was placed on a tripod 3.3 meters away from a log-periodic antenna with known characteristics. Both antennas were connected to SDR modules and a test file was sent. The receiving SDR managed to receive the file without any errors.

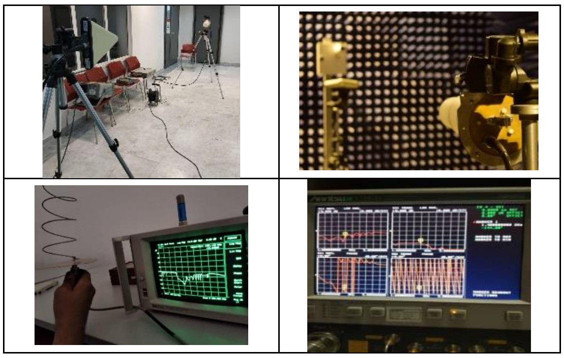

Figure 5. Antenna propagation test set-up and results.

7. Launch Campaign.

SHADE was launched successfully with BEXUS 29 gondola and recovered intact. Communication with the experiment was achieved and all measurements during the flight stayed within predicted threshold. The operation of the experiment was nominal; the deployment of the antenna was successful and no re-tries were needed. After that, image and text data were transmitted to the SHADE's GS and successfully decoded. The pointing system acted as expected, since throughout the whole flight time (until communication was lost) the communication dropouts were almost non-existent. However, an incident occurred when the gondola was above the 12km; the GPS signal was lost. After further investigation was conducted, the source of the problem was the permissions of the GNSS module. As it turned out, military permission is required to use GNSS modules after the altitude of 12 km. Because of that, after the incident the ADC System was operating on manual mode.

8. Results and discussion

The manufactured model was tested in full operating mode on BEXUS 29 stratospheric balloon, meeting all requirements. The maximum point-to-point distance, where communication was still nominal, was 138 km. After that point the signal power started to drop below the desired levels and communication was therefore lost. In an overall approach the experiment fulfilled the predefined requirements and laid the foundations for its use on space applications. In the year covering its development from concept to launch at the ESRANGE Space Center, SHADE offered collaboration between students from different backgrounds, practical application of theoretical knowledge and overall a valuable educational opportunity with multiple lessons learnt.

9. Conclusion.

In this work we designed, constructed and tested a deployable helix antenna operated by SDR. The system is intended to be used in small satellites and high-altitude platforms. Future plans include further research on the deployment mechanism, miniaturization of the model and product design.

Figure 6. SHADE on stratosphere

Acknowledgements

This work was supported by Aristotle University of Thessaloniki (AUTH), AUTH research committee, BETA CAE Systems, Hellenic Aerospace Industry, Swedish Space Corporation (SSC), German Aerospace Center (DLR), Swedish National Space Agency (SNSA), European Space Agency (ESA) and Center of Applied Space Technology and Microgravity (ZARM)

References

[1] SSC, BEXUS User Manual, 2018

[2] SSC, Esrange Safety Manual, 2013

[3] Dyneema fiber website: https://www.dsm.com/dyneema/en_GB/our-products/dyneema-fiber.html, last visited: 20th March 2022.

[4] J. Krauss, R. Marhefka, Antennas for all applications, Tata McGraw-Hill, 2008

[5] T. Yioultsis, E. Kriezis, Microwaves theory and applications, Tziola, 2016