SPRING DRIVEN EXPANDABLE REFLECTOR FOR DEPLOYABLE ANTENNAS

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ABSTRACT

Solid dish antennas are a widespread technology nowadays, employed in many communication systems. Despite this, the mass and volume of this type of antenna are sometimes not compatible with the characteristics of space systems and their operating environment. This prevents their use in many more applications in which, actually, solid dish antennas could be very useful. Deployable antenna structures seem to offer a promising solution to this problem by combining an optimized structure with the same features of a solid dish.

This paper presents a new design for a parabolic reflector, able to extend its surface through a radial opening, umbrella-like mechanism. The light structure and the compact initial configuration of the reflector make this device a great option for those applications in which the physical constraints are a particular issue. The deployment is initiated by a single actuation system which releases the arms, making the reflector to expand its surface by nine times, compared to the stowed configuration. Furthermore, this design is characterized by an innovative system that exploits a central fixed parabola[1]. This guarantees operativeness also in the event of unexpected behaviour of the deployment system, overcoming the need for other antennas for redundancy, otherwise required to assure that the correct functionality of the system is not compromised.

This kind of technology could be used, for instance, to implement an aerial stratospheric telecommunication system, composed of high-data-rate microwave radio link, or for interception of communications and radar signals, for military and intelligence, for Earth observation in low and midrange-frequency radar, deep space observation and remote sensing. This paper presents a detailed 3D prototype design and experimental test results. In addition, the major reliability parameters of parabolic reflectors, namely surface accuracy, stiffness of the dish and deployment actuation, will be analyzed and discussed in order to highlight their potentialities for future space and planetary missions.

The potential of this new concept was recognized by SNSB/DLR/ESA who selected it for a flight experiment on its REXUS/BEXUS project[2].

I. INTRODUCTION

A parabolic reflector, frequently referred to as “dish”, collects an incoming parallel beam of radio waves and concentrates them into its focal point, also called focus, where the actual antenna is placed. This part is sometimes referred to as the antenna feed. To achieve the maximum gain, it is necessary that the shape of the dish is accurate within a small fraction of a wavelength, this to ensure that the waves headed from different parts of the antenna reach the focal point in phase[3].

The aim of this experiment is to develop a deployable reflector, assess its mechanical functionality and map the accuracy of its surface during the flight[4]. In this project, the antenna feed is not considered, as the test requires operating conditions that cannot be recreated on the balloon (for example the distance between testing emitter and receiver should be higher than the Fraunhofer distance, that in this case exceeds the spatial dimensions of the balloon). The reflector characterisation is valuable regardless the used wavelength and without considering all the factors that affect the efficiency of the feed itself. Investigations on a matched feed may be carried out as an advancement of this work.

II. EXPERIMENT CONCEPT

A picture of the whole system is shown in Fig. 1. The expansion of the useful surface is possible thanks to the Deployment subsystem, composed of six folding arms. Each one is made of a primary rib, a secondary rib and a rocker. These arms are connected in a loop by four joints forming the simplest movable closed chain linkage, called "Four-bar linkage". The Actuation subsystem initiates the expansion phases, freeing the arms that are able to rotate, dragging and unfolding the membrane. The membrane is composed by twelve quadrangular, doubly-curved surfaces, clamped together with the ribs. Three inspection cameras, two of which are mounted on the top profile of the gondola and one on the

TABLE I. MAIN CHARACTERISTICS OF DREX

	Optics Geometry
Configuration	Prime focus, front feed, parabolic
Projected aperture	0.96 m, hexagonal
Dish dimensions	0.36 m in compact configuration 0.96 m in deployed configuration
Focal lenght	0.3375 m
	Dimensions and mass of the reflector in launch configuration
Diameter/Length	0.36 m / 0.11 m

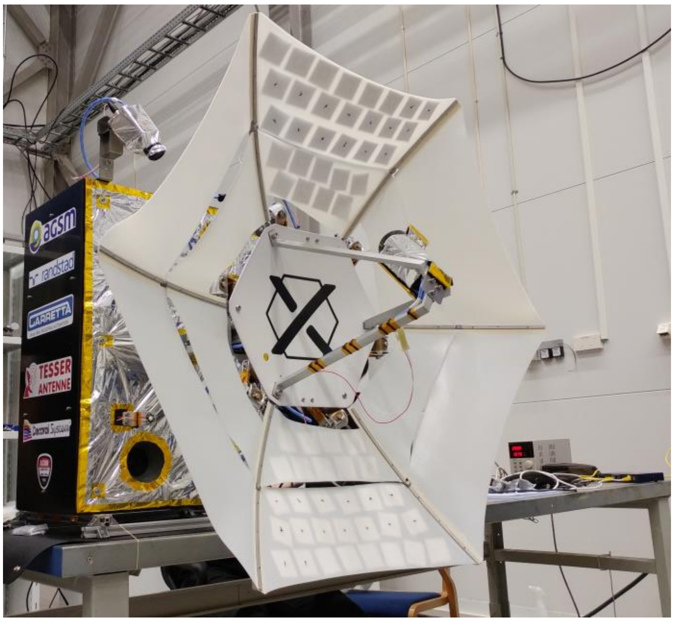

Figure 1: Deployable Reflector Experiment

parabola focal point, record the deployment for further post-flight kinematic analysis. The Frame subsystem represents the backbone of the entire structure. It connects the Reflector, the external portion of the experiment, with the Case, the internal part that contains all the electronics and the stereo vision subsystem. Table 1 shows the most important characteristics of the system.

The deployment procedure consists of three stages, shown in Fig. 2, each characterised by a specific configuration of the reflector elements:

- The reflector covers one ninth of the totally deployed dish extension and it is fixed to the case. The primary ribs are linked to the vertices of the central hexagon frame by hinges, featuring preloaded springs for the deployment actuation. A set of six secondary ribs, linked to the primary ribs, allows a wider aperture. In this configuration, the membrane is folded, and each primary rib is collapsed behind the central hexagon with the secondary rib overlapping (Fig. 2/A).
- The deployment is initiated by a thermal cutter process. The actuation mechanism is based on a single actuation. A precise amount of current flows into a resistive wire which heats up and cuts a cable that is responsible of keeping the mechanisms locked. Each circular membrane is unfolded and moved to acquire the nominal parabolic shape. The deployment rate is controlled by rotary dampers coupled to the hinges, that act against the springs to maintain a constant rate of movement and ensure a smooth deployment (Fig. 2/B).
- The ribs are aligned to the diagonals of the central hexagon and the membrane is maintained in tensioned condition. The reflector reaches an operative reflective surface of 0.658 m^2 (Fig. 2/C).

An inaccurate shape of the dish degrades the signal strength. Distortion of the deployed antenna dish may cause the reflected signal beams to focus off-centre of the focal point. Poor focus of these reflected signals reduces the quality of signal transmission, making the dish ineffective. This represents a critical point of the overall design of the antenna dish, as a failure concerning the membrane would defeat the primary purpose of the entire project.

Inaccuracies in the shape of the dish may be caused, among all, by factors like thermal expansion/contraction of materials, inaccurate manufacturing of components, poor assembly of the antenna unit, or by an unequal force distribution between different ribs.

Two stereo vision systems were meant to be used to precisely acquire data on the membrane shape. The stereo vision is a process that allows to transform a pair of images, captured by two different cameras, into a cloud of points with depth value information associated. This cloud of points, called depth map, is obtained by applying geometry laws to the distance between the same physical point captured by the two pictures, called disparity. In this way, a precise 3D image of the membrane can be built, and it is possible to calculate an efficiency index using a finite elements simulator.

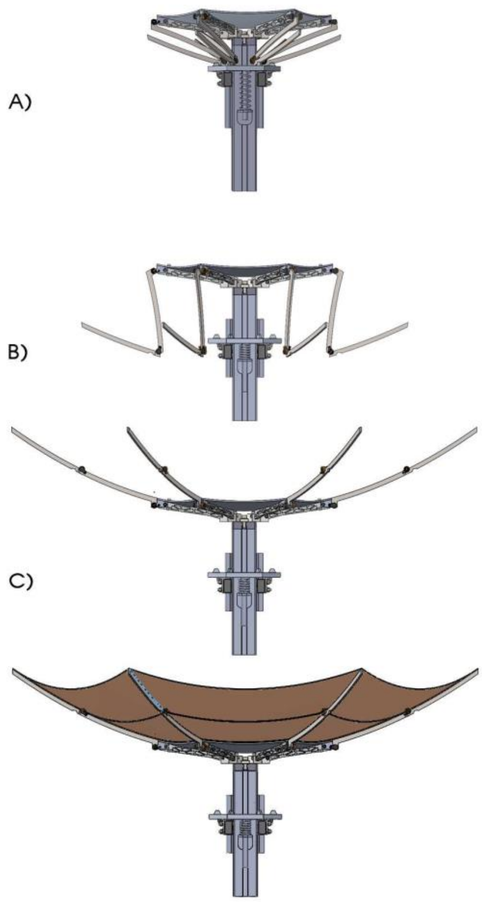

Figure 2: Deployment sequence, A, B, C not representative of the membrane.

III. Experiment Milestones

DREX was selected for the 10th cycle of the REXUS/BEXUS programme and scheduled to fly with the BEXUS-24 platform. In this section, the main stages of its development, from the initial idea to the manufacturing and assembly, are described. Each stage is thought to represent a milestone of a typical space mission, from design phases to reviews by experts from the major aerospace agencies in Europe[5].

A. Early design (September 2016 – December 2016)

The first concept of DREX, illustrated in the proposal form, was already comprehensive of the two main systems, that are the Reflector and the Case.

The overall configuration was close to the definitive one, except for some aspects:

- the strut profile mounted on the Reflector was meant to host two RF transmitters to test the reflectivity of the membrane;
- the Reflector was mounted close to the case to minimize the momentum due to the gravity acceleration;
- the axes of the hinges were designed to be parallel to the axis of the parabola, in this way the ribs in stored configuration lie along the sides of the fixed central hexagon, as shown in Fig.3.

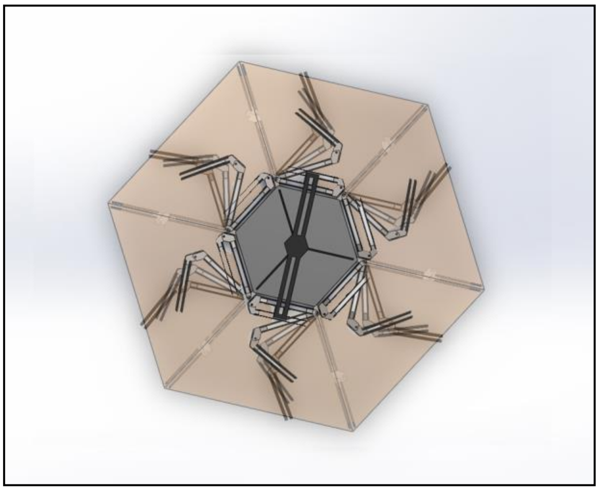

Figure 3: DREX deployment early configuration.

This step was the first level of evaluation of the participants to this educational programme. The experiment was pre-selected, and the team was invited to ESTEC, ESA's European Space Research and Technology Centre in the Netherlands, to present a more detailed version of the experiment concept.

The mechanical design had some major adjunction and the team started to study elements of the deployment and actuation subsystem. A spring-damper mechanism was studied in order to obtain a controlled deployment and a burn-wire mechanism to actuate the deployment. The RF transmitter was removed due to unfeasibility of the test and it was replaced with an inspection system, composed of three cameras seeing different parts of the Reflector.

The process flow and the data utilization were established, along with a first mass and link budget

B. Preliminary Design Review (Febraury 2017)

After the Selection workshop the team was selected for the REXUS/BEXUS programme. As first task, the commission asked the team to provide its first version of the SED, the Student Experiment Documentation, a document descriptive of the experiment in all its aspects.

The first review of the experiment, the Preliminary Design Review, was held at the DLR GSOC site in Oberpfaffenhofen, in Germany. At this stage, several changes to the design were applied:

- the objectives and the requirements of the experiment were defined;
- the axes of the hinges were rotated, causing the membrane to fold under the fixed central hexagon and not along its sides, reducing the footprint of the folded configuration and relaxing the requirements on the membrane;
- preliminary deployment analyses were performed to study the behaviour of the overdamped spring-driven mechanism and the membrane. Kapton and Silicone Film were selected as the two best possibilities for the membrane material;
- a preliminary electrical design was studied, mostly involving COTS component;
- the software was in an early design phase, with a higher-level block scheme and divided into processes;
- cameras of the stereo vision systems were selected and the relative distance between the Reflector and the Case was adjusted to ensure the best optical configuration for the triangulation.

C. Critical Design Review (May 2017)

The second review of the experiment took place at ESTEC, in the Netherlands. It was meant to evaluate the final design of the whole experiment, which could not be modified anymore.

The mechanical design was completed and defined in every critical point. The actuation (Fig, 4) and the deployment (Fig. 5) mechanism were finalised and advanced numerical model of the deployment were performed, along with FEM analysis of the Case and of the Reflector. The final configuration of the spring-driven deployable mechanism involved one clock spring and one rotary damper for each joint. These springs exploit a constant torque in time. Reducers provide the damping required to control the deployment speed of the spring driven mechanism. This practically means that a constant and controlled rate of deployment can be achieved. The speed, when reaching the extended configuration, can be calculated and controlled.

The team had to design a custom version of constant torque spring to fulfil the requirement (2,2Nm) varying the width, the thickness and the distance between storage and torque spool, as well as the length to obtain a 180° degrees rotation. The actuation is triggered by the Thermal Cutter. It is a Hold Down Release Actuator that secures the deployable appendages during launch and releases them when needed.

The thermal cutter system is also based on redundancy and reliability. The nichrome burn wire release mechanism uses a nichrome burn wire that, when the mechanism is activated, heats up and cuts a Vectran cable allowing the deployment to actuate. To activate the nichrome wire, a constant current of 1.60 Amps is necessary to ensure a successful and reliable cut. A specific version of the mechanism was designed and tested for the experiment. A Vectran cable is used as a pulley, connecting locker slab to the fixed structure. As the locker slab tries to descend, the cable tenses and prevents an unforeseen deployment[6].

Silicon rubber was chosen as the material for the membrane, thanks to its stretch capability, and its final shape was established. The design of the stereo vision subsystems was completed, defining the application of AR markers to the backside of the membrane to create contrast points to be detected by the software. These points would have then been triangulated with the double point of view system to create a 3D map of the membrane during the flight.

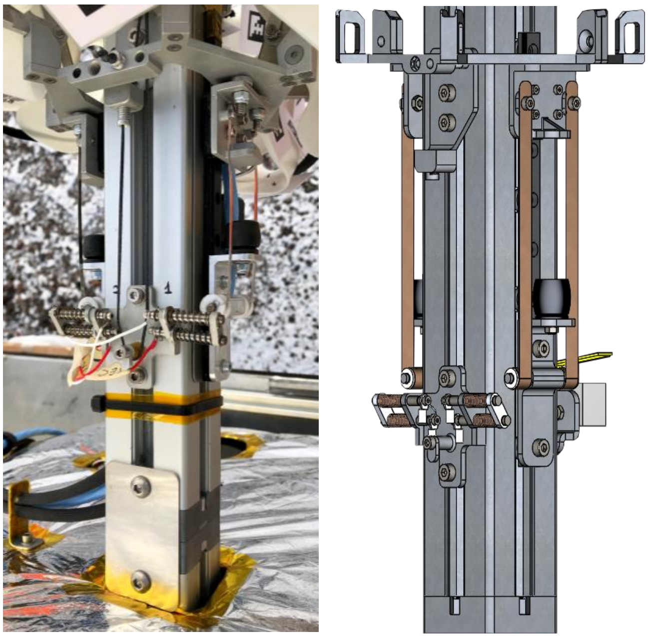

Figure 4: CDR design and final configuration of the actuation subsystem.

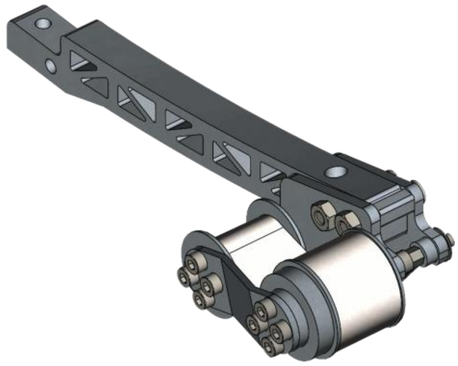

Figure 5: View of the deployment subsystem.

D. Last phases (June 2017 – September 2017)

During this period, the last two reviews took place: the Integration Progress Review (IPR), in July, and the Experiment Acceptance Review (EAR), in September, both hosted by the laboratory of the Industrial Engineering department, at the University of Padova. In both cases, experts from ESA and SSC evaluated positively the status of the experiment. The launch campaign readiness was confirmed soon after.

Regarding the completion of the experiment, the team faced funding issues and deliveries delays of some components, but the whole system was assembled in all its subsystems before the departure towards Esrange Space Centre, in Sweden, where the launch campaign took place.

IV. Flight Data

DREX flew successfully with BEXUS-24 platform in October 2018. However, due to electrical issues occurred during the Late Access manoeuvres on the ground, the actuation subsystem was damaged, and the deployment could not be performed during the flight. Nevertheless, the experiment was functional for almost four hours from the launch event and several data could be acquired. The temperature probes provided a thermal profile of several components (Fig. 6).

Furthermore, a set of images from the stereo vision cameras and few videos from the inspection cameras were acquired. An example of an image from the stereo vision cameras is shown in Fig. 7. The structure of the whole experiment was recovered in good conditions, as it perfectly withstood the landing.

The Case structure and the Reflector were intact and showed no signs of yielding. A post-flight deployment was then performed. The damaged components were replaced, and the system overall conditions were tested.

All the mechanisms were perfectly functional: springs were loaded in stowed configuration without any loss of pre-load angles, the damper performed nominally during the post flight test as well as the thermal cutter and the actuation mechanisms.

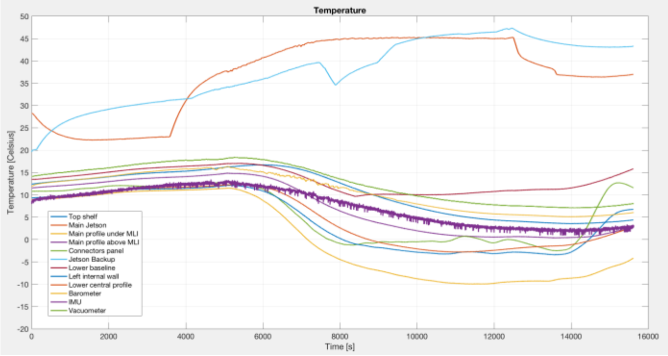

Figure 6: Temperature profiles of several components during BEXUS-24 flight.

V. Lessons learned and Conclusions

The REXUS/BEXUS programme gives to students the opportunity to participate to a real space mission. The programme requires the teams to meet deadlines, prepare scientific documentation and expose their work to a group of experts from international space agencies and companies.

The teams have to put effort in fund-raising and money management as well as public relationship and outreach activities. The programme is challenging but rewarding as well. Students have to learn how to realize their idea by themselves, developing engineering and team work skills that cannot be learned only with a purely academic formation.

The team faced some problems regarding:

- delivery on time of some mechanical components;
- development of the new technologies for the membrane;
- finding of the shelf components for the deployment subsystem;
- electrical issues during the Late Access procedures, just before the launch.

The most important lessons learned as results of the issues encountered were:

- keep in close contact with the manufacturing companies, especially if the material is sponsored and programme some spare time to forecast unexpected problems;
- start the characterisation of new technologies early in the project and never underestimate the time necessary to develop them. In a prototype approach, further tests are required to characterise the performance of the system;
- to reduce the overall complexity and cost of an experiment, it is critical to evaluate the available components in the design phase. The team was not able to find springs and dampers that could match the requirement and certificated to withstand the stratosphere environment, thus a custom set of springs was designed, and a test campaign was conducted to assess the performance of the dampers;
- never underestimate the integration between systems of different nature, like mechanical and electrical, because it can be critical in specific conditions. Indeed, the malfunction of the deployment during the flight can be related to an issue of this nature.

In conclusion, despite the electrical problem that occurred on the ground, the experiment was able to withstand the stratosphere environment, the deployable mechanism performed well in the post-flight test, the electronics and the stereo vision subsystem performed nominally during flight. The developed know-how about the deployable mechanism as well as stereovision techniques will be a useful asset for future projects involving expandable antennas.

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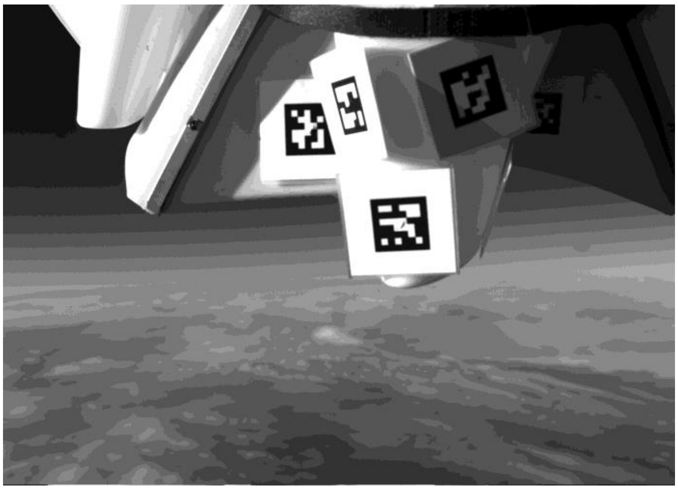

Figure 7: Image taken by stereo vision camera during BEXUS-24 flight.