D.An.CE
Deployable ANtenna for CubEsats

PRINCIPAL ACADEMIC TUTOR
Prof. Ladislau Matekovits, Department of Electronics and Telecommunications
Politecnico di Torino

EXTERNAL INSTITUTIONS
Argotec s.r.l.

EXTERNAL TUTORS
Eng. Gianmarco Reverberi
Argotec s.r.l.

Eng. Alessandro Balossino
Argotec s.r.l.

Eng. Luca Vigna
Argotec s.r.l.

TEAM MEMBERS

Agnese Tortelli
Materials engineering and nanotechnology
Politecnico di Milano

Giulia Mancini
Architecture, built environment & interiors
Politecnico di Milano

Giuseppe Napoli
Space engineering
Politecnico di Milano

Lorenzo Vecchietti
Areonautical engineering
Politecnico di Milano

Marta Bottani
Telecomunication engineering
Politecnico di Milano

Matteo Parpanesi
Civil engineering
Politecnico di Milano

Executive summary

CubeSats, lightweight satellites with a size comparable to a shoebox, represent the next frontier for the space industry. They are accessible to companies of all sizes and can provide various and flexible services. However, the small platforms pose tight requirements at launch in terms of mass and volume. Since antennas requires large surfaces for high-gain communication, they are the most impaired payloads by this limitation. Deployable antennas, stowed during the launch, are the predominant solution, but the state of the art suffers from unsatisfactory overall performance.

The D.An.CE project aims to bridge this gap by designing a high-gain deployable antenna able to comply with the CubeSat platform standards. The starting point of the project was a set of requirements assigned by the stakeholder, Argotec. By means of thorough state-of-the-art research and requirements examination, four concepts have been developed and a trade-off analysis allowed to select the most promising design. On this basis, electromagnetic and mechanical studies as well as simulations refined the concept. Remarkably, the deployment capability of the design required a dedicated assessment through a prototype, which was realised with a 3D-printing technique and manually assembled.

The final design is a Fabry-Perot-based Partially Reflective Surface (PRS) antenna mounted on a reliable self-deployable lightweight scissor-structure support. The developed solution will disclose new and profitable applications for CubeSat in the future providing services which today are achievable only by larger and more expensive satellites. Indeed, in the context of the growing lunar economy, a high-data-rate communication infrastructure will be essential for future missions around and on the Moon's surface. The project addresses this need by proposing an antenna that can be mounted as payload on a CubeSat constellation operating at X-band (8-12 GHz) and relaying data with Earth.

Key Words
Cubesat, Antenna, Deployable, Telecommunication, Space

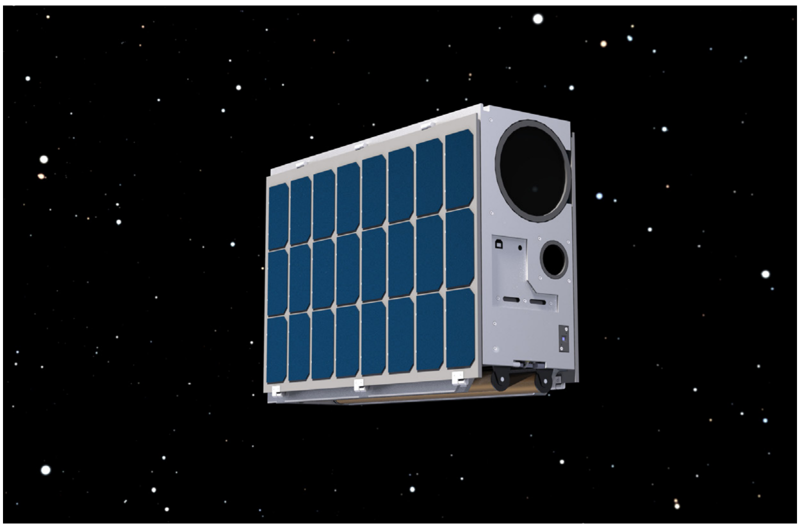
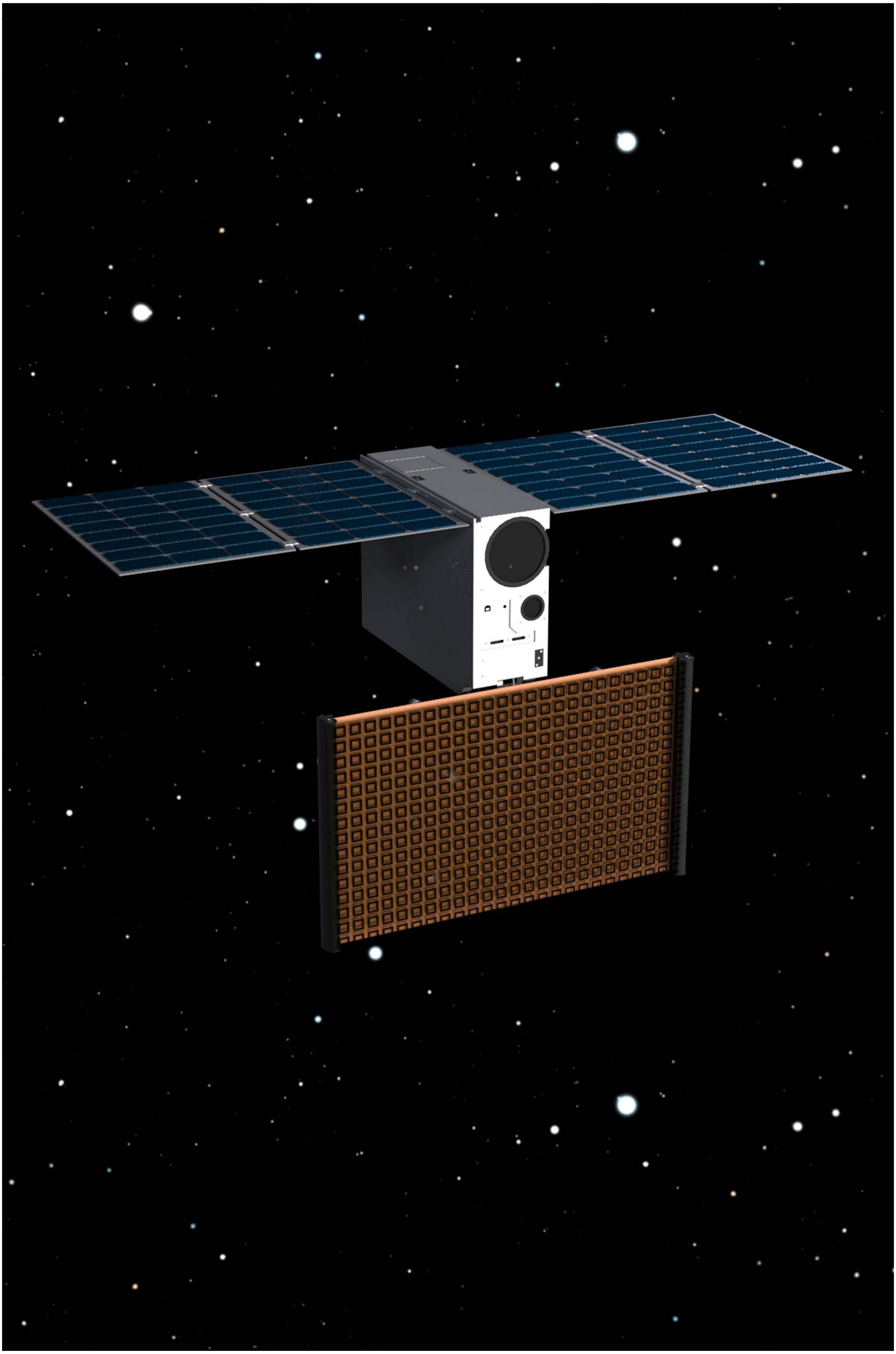


Image 1. Stowed CubeSat



Project description written by the Principal Academic Tutor

CubeSats are a new class of spacecrafts with reduced dimensions and weight and standard form factors: these satellites are becoming increasingly popular for communication, technology demonstration and exploration missions. Given the small dimensions of this class of satellites, there are technical challenges and technical gaps that need to be addressed to make CubeSats more competitive than today for some applications: the implementation of effective communication systems is one of the most interesting topics in the field.

Advanced antennas are a key element for the development of new advanced communication systems that would allow the implementation of ambitious missions with CubeSats both in Earth Orbit and in Deep Space.

Deployable systems are one of the possible subclasses, since they are small at launch that expand in orbit. Their design requires a strong interdisciplinary approach since several aspects have to be considered during the design phases: among others, it is necessary to consider the telecommunication aspects (antenna parameters such as gain, beam-width, return-losses etc.), the mechanical design (deployment, loads), the selection of the materials (space environment, thermal stability), the compatibility with the target platform, the definition of the manufacturing techniques and cost.
Large extension surface is the main requirement of high gain, that in turn allows larger distance between ground station and satellite, aka, possible use in deep-space environment. The second challenge consists in the proper illumination of the surface. Reflectarray, one of the possible manifestations, requires external (to the antenna) feed system. Alternatively, the feeding mechanism can be modified to be located within the antenna volume, contributing to further miniaturisation and complexity reduction. For example, using a Fabry-Perot like arrangement, that consists of partially reflecting surface (PRS) above a ground plane, a classical reduced dimension electric dipole or slot in the ground plane can be used as feeder. The propagation mechanism between the two layers corresponding to a waveguide like structure gives rise to multiple reflections between the two boundaries. Proper design of the PRS allows obtaining the desired field distribution on the surface both in terms of amplitude and phase, hence controlling the radiation. PRS can be realized, for example, considering 2D (quasi)-periodic arrangement of single radiators of identical or different shapes. For space saving, cost-effective manufacturing and low loss targets printed structures are in poll-position, that can be realized by consolidated technology available at large scale.

Within the project, different tasks have been efficiently developed by the multidisciplinary team. The main aspects are described below.

Team description by skill

The team is composed by six people with various backgrounds, five engineers and an architect, who have worked on different fields of the project.

In the first phase, the whole group has carried out researches on the actual state of the art to better understand the problem to be adressed. Then, during the concept generation stage, all members have contributed in the elaboration and selection of the most promising solution. During the simulation stage each component have analysed a peculiar aspect of the designed antenna.

In particular Agnese has dealt with space-qualified material selection, Giulia has worked on design refinement managing the prototype, Marta has studied the electromagnetic features of the antenna and Giuseppe, Lorenzo and Matteo have worked on the deployable mechanism and CAD modelling. To conclude, all team members have contributed in the construction of the prototype.

Goal

DANCE aims at designing and prototyping an innovative high gain antenna suitable for CubeSat platforms.

CubeSats represent the next frontier for the space industry. They are lightweight, compact, and accessible to companies of all sizes. They can be assembled quickly compared to traditional satellite missions and provide flexible services such as Earth monitoring, deep-space explorations, and quick response to emergencies.

In the last years, several missions based on CubeSats have been proposed to implement communication systems. However, the development of this type of mission must deal with the limitations imposed by the platform.

Considering that the target platform is a 6U or a12U CubeSat (1U=10cm^3), an interesting opportunity is to develop deployable antenna systems to have large structures in orbit while limiting the volume at launch.

In this context, three pillars acted as a framework throughout the project development and guided every decision:

- High-gain communication, which means designing an antenna having a wide emitting surface;
- Realizing a mechanism that can safely and reliably deploy in space;
- Ensuring the structure's stiffness prevents failures throughout its life; when stored, transported, launched, deployed, and finally used.

In addition, the biggest challenge is to comply with CubeSat dimensions, weight, and power requirements.

Understanding the problem

The understanding of the problem follows different phases, which include analysing the project requirements provided by the industrial partner Argotec (Table 1), trying to apply such requirements to a use case in order to assess the expected performance in advance, and finally conduct a detailed state-of-the-art analysis to have a clear view of the existing solutions.

Furthermore, the project requirements are subdivided into different categories: functional, operational, physical, and environmental requirements. Functional requirements concern electromagnetic parameters such as operating frequency, gain, polarization, etc. Operational requirements refer to lifetime and reliability, while physical requirements impose limits on mass and volume. Finally, environmental requirements concern the temperature that must be tolerated and radiation assurance.

FUNCTIONAL	OPERATIONAL	PHYSICAL	ENVIRONMENTAL
Operation in one or more bands	Operational lifeti-me > 3 years	Volume ⩾ 1,7 U	Stowed temperature range -10 / +50 (°C)
Circular polarization	Stowed lifetime > 6 months	Mass ⩽ 2 kg	Deployed temperatur range -60 / +80 (°C)
Return loss < -20dB	Ground lifetime > 2 years		Compatibility to launch environment
Cross-polarization discrimination > 20 dB			Total Radiation Dose (TID) > 50 krad
Axial-ratio < 3 dB at boresight and central operating frequency			
Gain > 35 dB at central operating frequency			

Table 1. Project requirements

In order to properly design a system, it is fundamental to access the target mission requirements so that the expected system performances can be determined in advance and the necessary mitigation strategies can be put in place. Moreover, a target mission helps define the antenna's placement over the satellite to avoid obstructing other sub-systems such as the solar panels.

The target scenario selected is an X-band operating communication CubeSat designed to orbit around the Moon at 384.000 kilometers from the Earth.

Specifically, the X-band (7-12GHz) was selected in this context as the optimum operating frequency given the nearly saturated condition of the S-band (2-4GHz) and the limited attenuation experienced by the signal traveling through the terrestrial atmosphere. On the other hand, higher frequency bands such as K (18-27GHz) and Ka (27-40GHz) would increase the complexity of other sub-systems such as the power amplifiers and the radio.

The selected use case merged with the project requirements allowed for a preliminary link-budget computation, a design tool accounting for all power gains and losses that a communication signal experiences in a telecommunication system, from a transmitter through a communication channel to the receiver.

From the expected performances derived from the link-budget calculation, it was possible to derive additional requirements that allowed to discard the unsuitable types of antenna that emerged from the state-of-the-art analysis (Table 2).

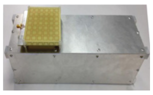
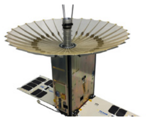
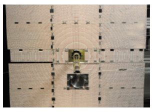
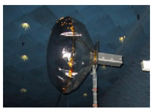
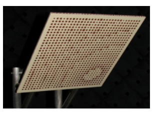
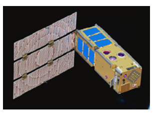
				Advantages	Drawbacks
HGAs	**Large stowage volume (> 0.5 U)**	**Slot array**		• Excellent efficiency • Thermal • Simple deployment • High TRL for 100-kg smallsat	• Stowage volume complex deployment • Narrow band • Single frequency • Low TRL for CubeSat
		Mesh reflector		• Excellent efficiency • Thermal • Infinite bandwidth • High TRL	• Stowage volume (1.5 U for 0.5 m/3 U for 1 m) • Complex deployment • Max aperture < 1 m^2
		Reflectarray		• Stowage efficiency • Medium cost • Compatible with 6 U • Medium TRL	• Low efficiency • Narrow bandwidth • Max aperture < 1 m^2 • Complex deployment (Feed) • Thermally affected
		Membrane		• Stowage efficiency • Medium cost • Compatible with 6 U • Large aperture > 1 m^2	• Low efficiency • Complex deployment • Poor surface accuracy • Low TRL
		Inflatable		• Stowage efficiency • Infinite bandwidth • Simple deployment • > 1 m^2	• Poor surface Aaccuracy • High SLL • Low TRL
	Small stowage volume (< 0.1 U)	**Metasurface**		• Excellent stowage efficiency (No feed deployment needed) • Simple deployment (Hinges based)	• Low efficiency • Max aperture < 1 m^2 • Narrow bandwidth • Low TRL
		Reflectarray		• Stowage dfficiency • Simple deployment • Low SLL • Low cost • High TRL	• Low efficiency • Narrow bandwidth • Max aperture < 0.6 m^2 • Tx only • Thermally affected
		Patch Array		• Stowage efficiency • Nondeployable • High reliability • Controllable SLL • Low cost • High TRL	• Max aperture is greater than the side of the CubeSat • Feed loss limits the gain

Table 2. State-of-the-art analysis

Following this approach made it possible to select the antenna types to further analyze within the current project. Specifically, the most interesting antenna types are reflectarrays and membranes. Reflect arrays can be designed to deploy in various ways but suffer from the need for external feeding. On the other hand, membranes present the advantage of a minimal mass but suffer from low efficiency due to vibrations and external feeding.

Exploring the opportunities

Based on the challenges we set for the project, the performance assessment derived from the link budget, and the state-of-the-art analysis, it was possible to move on to the phase of concept generation.

Throughout this phase, different concepts were generated, using the basic antenna types previously selected: reflectarrays and membranes.

Spiral Membrane
The spiral membrane is an antenna attached to beams rolled up inside a compact cylindrical structure with holes. The beams exit from the case thanks to a mechanical rotation. The antenna is deployed from the CubeSat through a spring, and the central space of the structure is used for the feed.

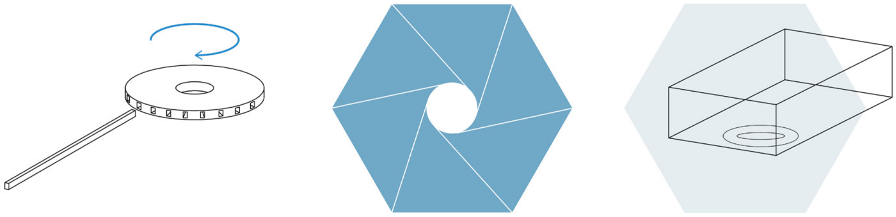


Image 3. Spiral membrane concept

Foldable Circle Membrane
The foldable membrane is a circular membrane with flexible borders. The folded antenna is made of 3 overlapped circles realized through three twists of the structure. The borders are realized with a material with high elastic properties that becomes rigid after an electric pulse. The feed is external and realized through a deployable beam.

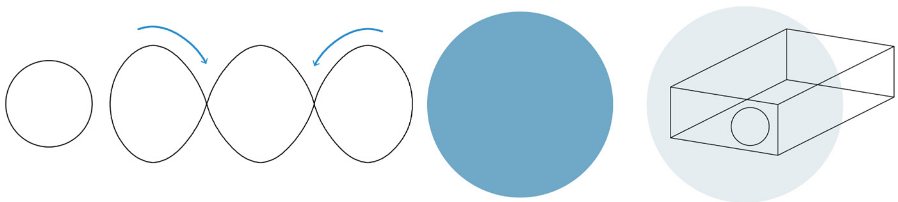


Image 4. Foldable circle membrane concept

Meterstick Membrane
The meterstick membrane is mounted on a deployable structure. The base of the structure is fixed, and the deployment occurs upwards. The structure resembles a meter, and it is deployed using foldable tubular booms that become rigid when they reach the straight position.

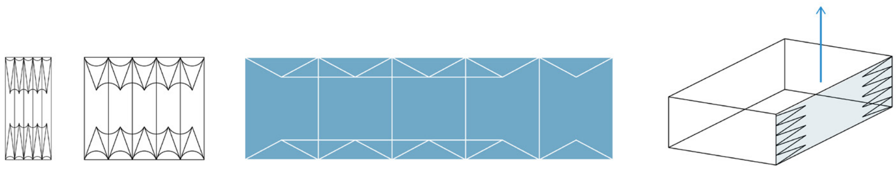


Image 5. Meterstick membrane concept

Rotating Antenna

The rotating antenna is a reflectarray composed of rigid panels made of a composite material. The antenna deploys through a rotation following the deployment mechanism of origami.

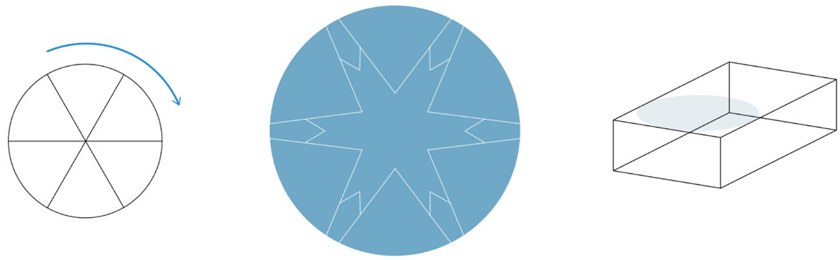


Image 6. Rotating antenna concept

The different concepts were then evaluated and compared through a tradeoff analysis. Five criteria were selected, and weight was assigned to express their relevance.

CRITERIA	DESCRIPTION	RATIONALE	WEIGHT
Deployed Area / Stowed Area	The ratio between deployed and stowed area	The deployed surface must be much more extensive to the stowed volume to comply with the platform requirements	0.30
Structural stability	Stability to vibrations	The antenna must be stable to vibrations	0.25
Structure reliability	Reliable to launcher loads	The antenna must be stiff and must deploy efficiency	0.15
Stowed volume	Occupied volume once the antenna is stowed within the satellite	The antenna must occupy a small volume when stowed	0.25
Cost	Cost of the antenna structure	The antenna must be not too expensive	0.05

Table 3. Criteria selection and weight

To each antenna concept and each criterion was then assigned a score ranging from -2 to 2. The total score was computed by summing the individual scores, multiplying by each weight, and dividing by the criteria.

	Deployed / Stowed Area	Structural Stability	Structural Reliability	Stowed Volume	Cost	TOTAL
Spiral Membrane	2	1	1	0	1	1.15
Foldable Membrane	1	-2	2	2	1	0.65
Meter Membrane	2	1	1	1	1	1.30
Rotating Antenna	-1	2	0	2	2	0.60

Table 4. Concept evaluation scores

The tradeoff analysis highlighted that the most suitable solution in this context is the meterstick membrane concept.

Generating a solution

The final antenna design was born from the meterstick membrane concept.

IDA (Internally-powered Deployable Antenna) is a Fabry-Perot based Partially Reflective Surface (PRS) antenna mounted on a self-deployable scissor-structure support.

The main features of the design are:

- Internal feeding that allows saving space in the stowed configuration;
- Large periodic structure with an internal cavity that allows very directive communications, which indeed grants the possibility to transfer significant data volumes;
- Lightweight because it is realized through membranes and composite materials;
- Self-deployable through a reliable mechanism based on elastic hinges;
- Passive distancing mechanism between the two membranes based on applied tensions to avoid additional mechanical complexity.

Multi-disciplinary simulations allowed to verify that the proposed design satisfies the assigned requirements (Table 1). Most importantly, *IDA* achieves 26.3 dBi gain at X-band central operating frequency, it occupies 0.77U stowed volume, and it is compatible with the launcher's loads.

Main bibliographic references

Chahat, Nacer, et al. "Advanced cubesat antennas for deep space and earth science missions: A review." IEEE Antennas and Propagation Magazine 61.5 (2019): 37-46.

Maden, Feray, Koray Korkmaz, and Yenal Akgün. "A review of planar scissor structural mechanisms: geometric principles and design methods." Architectural Science Review 54.3 (2011): 246-257.

Bai, Jiang-Bo, et al. "Folding analysis for thin-walled deployable composite boom." Acta Astronautica 159 (2019): 622-636.

Arya, Manan, et al. "Large-area deployable reflectarray antenna for CubeSats." AIAA Scitech 2019 Forum. 2019.