Small satellite deployable thin membrane antenna review

Mayank[1], Ville Lundén[1], Tuukkaa Kuuramaa[1], Samuli Nyman[1], Jaan Praks[1]

[1] Department of Electronics and Nanoengineering, Aalto University, Espoo,Finland

Corresponding author: mayank@aalto.fi (https://orcid.org/0000-0001-9792-5912)

***Abstract*— Deployable thin membrane antennas play a pivotal role in enhancing the communication and mission capabilities of small satellites. These antennas offer a lightweight and compact solution to achieve high gain and wide bandwidth, addressing the stringent size and weight constraints typical of small satellite platforms. This review provides a comprehensive analysis of advancements in thin membrane antenna technology for small satellites, focusing on designs operating across L-band to Ka-band frequencies. Various antenna configurations, materials, and thicknesses are evaluated to identify performance trends in lightweight, high-gain solutions tailored for compact satellite systems. Key parameters such as operational frequency, antenna size relative to wavelength, gain, material selection, and overall mass are analyzed to explore the technical trade-offs inherent in optimizing these antennas for small satellite architectures. Our analysis reveals that innovations in flexible and ultra-thin materials have enabled the development of wideband, high-gain solutions increasingly suitable for deployment on compact spacecraft. This review highlights both state-of-the-art advancements and existing challenges in thin membrane antenna technology, offering valuable insights to guide future research and development. By addressing these challenges, the study establishes a foundation for equipping small satellites with next-generation antenna capabilities that can meet the growing demand for satellite-based data services in modern communication systems.**

Keywords— Thin membrane, small satellite, deployable antenna

I. Introduction

In recent years, the growing demand for high-data-rate communication has placed increasing pressure on the capabilities of small satellites. Unlike their larger counterparts, which benefit from greater power budgets and larger volumes to host high-gain deployable antennas, small satellites are severely constrained in both size and available power. These limitations directly impact the achievable transmission rates, as small satellites typically operate with reduced antenna aperture sizes and limited transmission power. Although small satellites have traditionally been restricted to low data rates — especially in the UHF band with rates typically below 10 kbps — the growing maturity of small satellite technologies and commercial ambitions are driving the need for higher throughput and access to higher frequency bands.

To address these challenges, integrating large deployable antennas within the restricted volume of small satellites, such as CubeSats, presents a promising solution. A key requirement in this context is the design of antennas capable of achieving high gain without compromising on stowage volume. Higher gain antennas enable higher data rates without demanding significant increases in transmission power. However, this advantage comes with the trade-off of stricter pointing accuracy requirements, often requiring advanced and power-consuming attitude control systems. Nonetheless, the trade-off is considered acceptable given the data rate benefits.

Among the most attractive solutions for achieving large apertures within small satellites are antennas based on thin membrane materials. These materials, characterized by their low weight, flexibility, and compactness when stowed, enable the realization of large deployable structures that are compatible with the mass and volume limitations of small spacecraft. Thin membrane antennas offer the unique combination of light weight, large aperture, and low stowage volume, making them highly suitable for next-generation small satellite missions. Furthermore, these antennas can be configured into various forms such as parabolic reflectors, reflectarrays, active phased arrays, waveguide-based systems and metasurfaces, depending on mission requirements.

This paper aims to provide a comprehensive overview of thin membrane antenna technologies tailored for small satellite applications. The work reviews various membrane materials and their relevant properties, investigates the relationship between frequency and surface accuracy, and presents a comparative analysis of antenna gain versus aperture size for different membrane-based designs. The remainder of the paper is structured as follows: Section I introduces the concept and advantages of thin membrane antennas. Section II details specific antenna architectures and their performance characteristics. Section III provides a comparative evaluation of different designs, while Section IV concludes with insights into future developments for small satellite antenna systems.

II. Small satellite Membrane antennas

A. *Origami reflect array antenna*

A reflectarray antenna design based on origami principles is presented in [1]. As illustrated in Figure 1, the antenna features a thickness of 2.29 mm with a surface RMS of 0.125 mm. Operating in the X-band frequency range, it achieves a gain of 26.2 dBi. When stowed, the area of the antenna is reduced by a factor of five compared to its fully deployed configuration. The design incorporates RO3010 substrate material for the printed reflector elements, while flexible Kapton tape is utilized to enable the folding and unfolding mechanism.

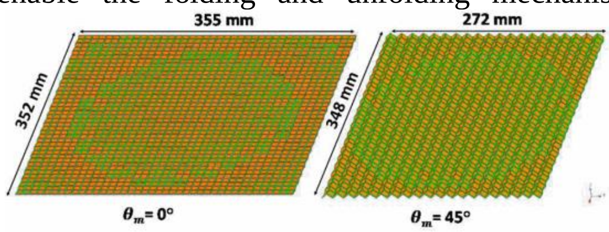

Figure 1: Miura-ori foldable reflectarray for different folding angles

A flat-panel origami-based reflectarray antenna design is introduced in [2]. As depicted in Figure 2, the antenna achieves an aperture efficiency of 60% and a gain of 26.4 dBi. The design utilizes an RO4003 substrate for the reflector elements, while a polyamide-layer Kapton is employed for the flexible hinge mechanism.

Figure 2: Hexagonal twist RA prototype using panels and flexible hinge mechanism. The deployment sequence presented from left to right.

Figure 3 illustrates another origami-based thin membrane reflectarray antenna analysed in [4]. This design features a thickness of 0.8 mm and utilizes RO4003 as the substrate material. Due to its low surface RMS, the antenna experiences a loss of 2.5 dB, resulting in a gain of 29.7 dBi within the X-band frequency range. Designed for a 3U CubeSat, it achieves a deployed aperture area of 0.41 m^2 while maintaining a compact stowage volume of 1U.

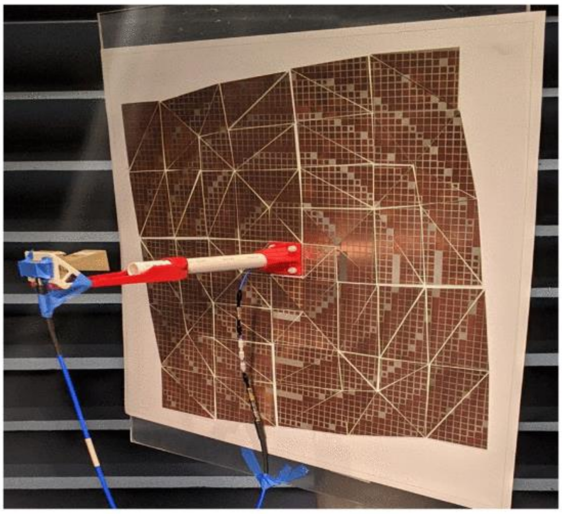

Figure 3: Thin membrane origami reflect array antenna test setup in anechoic chamber.

B. *Large deployable reflect array*

Figure 4 presents a 1.5 m × 1.5 m reflectarray antenna that can be stowed within a cylindrical volume of 20 cm in diameter and 9 cm in height, as described in [3]. The complete antenna system, including the deployment mechanism, has a total mass of 1.75 kg and provides a gain of 39.6 dBi in the X-band. The antenna features a 3D deployment mechanism with a centrally positioned feed, deployed at an F/D ratio of 0.67 to effectively illuminate the reflectarray surface. A small pyramidal horn antenna with a beamwidth of 74° is used as the feed. The membrane has a thickness of 5 mm, incorporating a top copper layer with cross-dipole elements, ‘S’-springs to create a hollow cavity and reduce the overall dielectric constant, and a lower copper layer serving as the ground plane. Designed for a 6U CubeSat, this concept achieves a surface RMS of 0.5 mm.

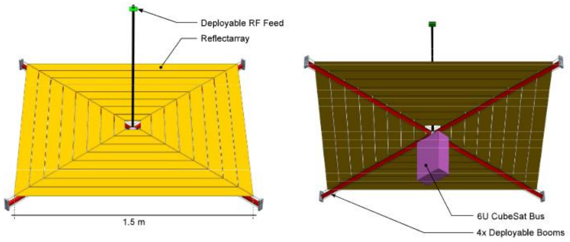

Figure 4: Conceptual design of a large deployable reflect array antenna for a 6U CubeSat..

Another variation of the same antenna is a lightweight composite reflectarray antenna proposed in [7], as shown in Figure 5. This design features an aperture area of 5 m² with a membrane thickness of 0.6 mm, achieving a surface RMS of 0.5 mm. The antenna employs a cylindrical stowage mechanism and utilizes a linear boom for deployment. Designed for the S-band frequency range, it offers a gain of approximately 20 dBi.

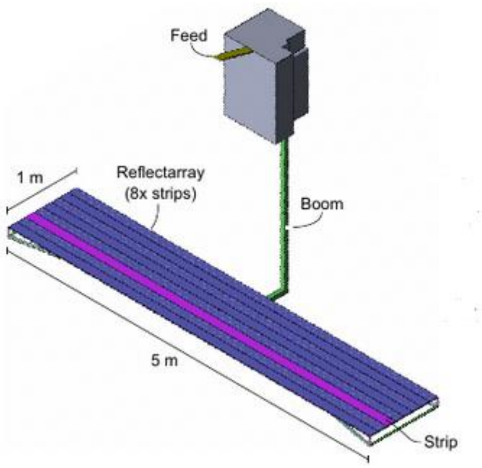

Figure 5: reflect array design concept

C. *Thin membrane high gain antenna*

A deployable thin membrane high-gain antenna, as illustrated in Figure 6, has been presented in [5]. This design utilizes polyamide Kapton and achieves a surface RMS of 0.81 mm. With a large aperture area of 14 m², the antenna operates in the X-band frequency range, providing a gain of 33 dBi.

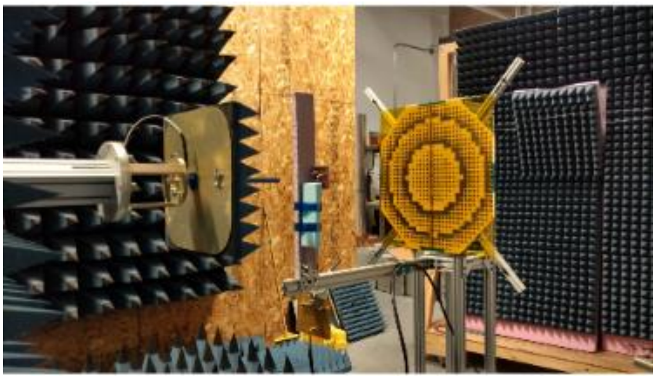

Figure 6: Conceptual design of a large deployable reflect array antenna for a 6U CubeSat..

D. *Thin membrane microstrip array antenna*

A microstrip array antenna has been presented in [6], as shown in Figure 7. This S-band antenna is fabricated using printed electronics on polyamide Kapton material. It employs a linear boom deployment mechanism and achieves a gain of 30.5 dBi with an aperture area of 1.53 m². The design attains an aperture efficiency of 56% with a beamwidth of 3.4°. With a stowage volume of 2U, it can be easily accommodated within a 6U CubeSat. The impact of wrinkles and folds has been analysed, revealing a performance loss of 1.9 dB due to these structural deformations.

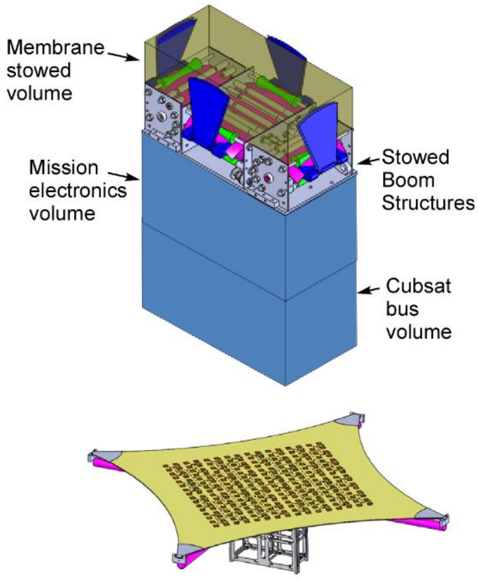

Figure 7: Thin membrane origami reflect array antenna test setup in anechoic chamber

E. *In plane feed antenna*

An in-plane feed antenna is proposed in [8] as shown in Figure 8. Due to in-phase gradient, the feed is offset, and surface waves are radiated in a high directive beam by utilising a phase mapping technique. The proposed antenna operates in S band offering a gain of 9.6 dBi. The antenna has an aperture size of 0.019 m^2.

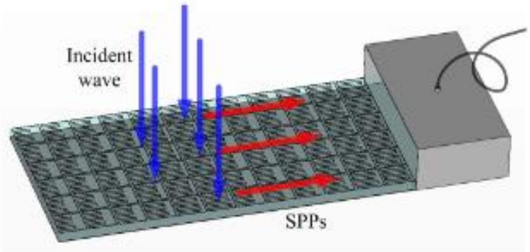

Figure 8: Schematic illustration of the proposed offset antenna.

III. QUALITATIVE EVALUATION

In literature, many different antenna types have been considered as promising candidates for small satellite thin membrane antennas, including origami antennas, thin membrane antennas, and thin membrane reflectarrays. These antennas can offer low stowage volume, low mass and high gain performance making them a suitable small satellite missions. In this section, we provide a qualitative comparison of different types of proposed thin membrane antennas. Table 1 summarizes their features and performance in terms of frequency, gain, thickness, surface RMS and size.

Antenna type	Freq. band	Gain (dBi)	Thickness (mm)	Surface RMS (mm)
Origami (Miura-Ori)	X band	26.2	2.29	0.127
Panel origami	Ku Band	26	0.0206	0.1
Origami (thin membrane)	X band	29.7	0.8	-
Thin membrane reflect array	X band	39.6	0.518	0.5
Membrane composites reflect array	S band	-	0.638	0.5
DaHGR	X band	33	-	0.81
Thin membrane microstrip antenna	S band	30.5	-	-
Offset feed antenna	S band	9.6	5	-

Table 1: Comparison between all types of proposed thin membrane antennas for small satellites.

Our analysis reveals that various reported thin membrane antennas operating across different frequency bands primarily utilize materials such as Kapton, polyamide, RO4003, and RO3010. As shown in Figure 9, Kapton is the most used, serving either as a flexible hinge or as a substrate material due to its high temperature tolerance while keeping the density comparable to other flexible materials. The identified design challenges of current small satellite antennas include achieving high gain, wide bandwidth, multi-band performance, low profile, and polarization control. Higher frequency antennas operating in the X and Ka bands offer the highest gains of existing small satellite thin membrane antennas.

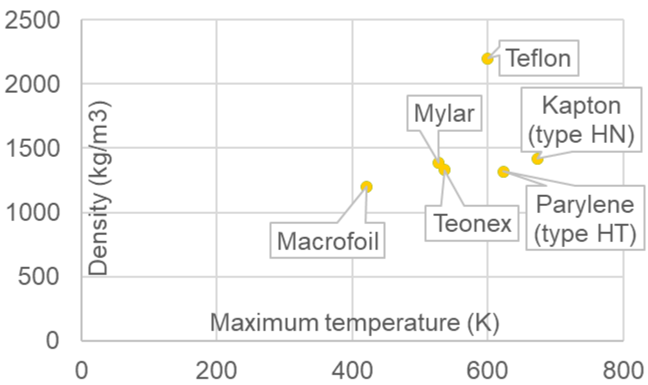

Figure 9: Thin membrane mechanical and thermal properties.

Figure 10 illustrates the gain performance of different thin membrane antennas across various frequencies and sizes. Notably, thin membrane antennas exhibit scalability advantages over other antenna types. It is particularly noteworthy that these antennas can achieve high gains of up to 40 dBi.

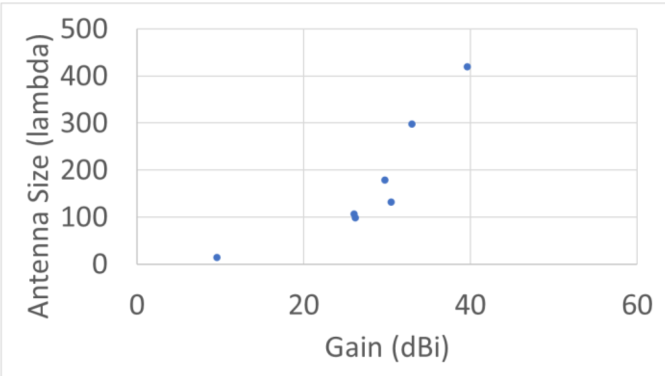

Figure 10: Thin membrane antenna gain vs antenna size plot.

IV. CONCLUSION

In this paper, we have presented a survey of different proposed thin membrane antenna designs for small satellites. Firstly, the antennas were categorized according to their design features. Their individual performance was analysed in terms of gain, bandwidth, aperture efficiency, size, and material used along with their thickness. The reviewed antennas were also classified and evaluated based on their operating frequencies. To conclude, thin membrane antenna materials were surveyed to analyse various available options, and respective antenna designs with these materials were then analysed for their gain performance. We observe that lightweight high gain antennas are feasible for small satellites by utilizing thin membrane materials for the antenna implementation.

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