

# ***Self-Deploying High-Gain Antenna Mechanism for CubeSats Enabled by SMPCs: Design, Manufacturing, and On-Orbit Functional Verification***

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**Abstract.** This paper presents the design, fabrication, and testing of a self-deploying high-gain CubeSat antenna mechanism enabled by shape-memory polymer composites (SMPCs), which address the volume, mass, and reliability limitations of current deployable antennas. The antenna uses an origami-inspired foldable reflector and lightweight truss structure with SMPC hinges that achieve a high stowage efficiency (>8:1 stowage ratio) and smooth, motor-free deployment. A self-locking SMPC hinge system with secondary shape-memory alloy latches rigidizes the structure after deployment. The design includes an active-passive thermal deformation compensation layer to maintain surface accuracy of the reflector array after orbital thermal cycling, and a hybrid beam-steering capability that includes SMPC-driven gimbal for coarse pointing and electronic phase control for fine steering. Prototype components were fabricated and qualified via ground thermal vacuum, vibration, and repeated deployment cycle tests. An on-orbit functional verification plan is described. Results show that the SMPC-enabled antenna can deploy a much larger aperture, and achieve much higher gain than conventional solutions, enabling high-rate data links and deep-space communication capabilities for next-generation CubeSat missions.

**Keywords:** Shape Memory Polymer Composites (SMPCs), Deployable High-Gain Antennas, CubeSats, Origami-Truss Structures, Beam Steering

## **1. Introduction**

Since 2010, advances in space technology and dramatic declines in launch costs have rapidly transformed CubeSats into an important platform for space science research, validation of new technologies, and commercial applications [1]. With defined standard sizes ( $1U = 10 \times 10 \times 10 \text{ cm}^3$ ) and a modular design, CubeSats have significantly reduced the cost of development and launch, enabling constellation networking and large-scale deployment [2, 3]. As reported in the Nanosats Database, as of April 30, 2025, more than 2,900 CubeSats have been launched worldwide, representing approximately 22% of all satellites in orbit [4]. Hundreds of new CubeSats are launched every year, and are widely used in Earth observation, meteorological monitoring, deep-space exploration, and space communication [5]. In particular, for communications and remote sensing missions, high-rate data links and high-resolution observations impose strict requirements

on antenna gain [6-8]. However, high-gain antennas are usually large, which presents a fundamental conflict with the available volume limitations of CubeSats [9].

Current deployable antenna technologies are based on metallic materials and mechanisms systems, which are limited by low stowage ratio, high mass, and low deployment reliability [10]. These limitations greatly hinder CubeSats' application in long-range and high-rate communications. For example, mechanisms typically contain multiple moving parts, such as motors, hinges and latches. These parts may suffer from cold welding, debris intrusions, and misalignment in space, which greatly increase the probability of mechanical failure [10,11]. In addition, the stowage ratio of current deployable antennas is usually not more than 10:1 for CubeSat applications, while the mass may occupy more than 20% of the total payload budget of satellite [10]. Therefore, developing a self-deploying antenna with high stowage ratio, low mass, and high reliability is very urgent for promoting CubeSats from technology demonstration to operational services [11].

Recently, new shape-memory polymer composites (SMPCs) are expected to autonomously recover from a folded state to a predetermined shape by thermal or optical stimuli [12]. Thus, the need for mechanical actuators to deploy structures is eliminated and the system becomes greatly simplified with greatly improved reliability [12]. Different from traditional deployable antennas, SMPCs are lightweight and can provide programmable large deformations with self-driven deployment to obtain a materials-based solution with high stowage ratio, low mass, and high reliability [13]. For instance, SMPC-based antennas with strain recovery rates >98% and recovery stresses up to 5 MPa have been fabricated and evaluated, which are large enough to deploy meter-scale structures from 1U volume [14]. Moreover, multiple on-orbit demonstrations have further validated the potential of these materials in space environment, including long-term exposure to space radiation, thermal cycle, and vacuum [15, 16].

Therefore, this work proposes and verifies a self-deploying high-gain antenna mechanism for CubeSat platform driven by SMPCs. Origami-inspired structures are employed, intelligent material actuation is designed to achieve high stowage ratio and high-precision deployment, and on-orbit thermal-deformation compensation is achieved. Furthermore, beam steering is enabled by mechanical-electromagnetic co-design. We present the innovative antenna design, preparation of materials, manufacturing process, and on-orbit verification scheme systematically, which aims to provide a high-performance and highly reliable antenna solution for next-generation CubeSat communications. This advancement enables advanced missions such as deep-space exploration, high-speed data downlink, and space Internet of Things (IoT).

## 2. Current status of deployable antennas for small satellites

### 2.1. Evolution and representative cases of metallic deployable antennas

To achieve high gain on small satellites, people traditionally adopt large-aperture metallic deployable antennas, which are mainly implemented by umbrella type mesh parabolic reflectors, origami style folded planar reflectarrays, and truss-based deployable structures [17-19].

Umbrella type mesh reflector: employ a flexible metallic mesh held in place by foldable ribs to obtain large apertures. NASA's RainCube mission successfully demonstrated a 0.5m diameter Ka-band deployable mesh parabolic antenna on a 6U CubeSat [20]. With a Cassegrain design, the antenna was stowed in a 1.5U volume [21]. After deployment, the antenna operated at 35.75 GHz, and the measured gain was 42.6 dBi with aperture efficiency around 52% [22]. As the first precipitation radar onboard a CubeSat sized satellite, RainCube's success demonstrated the feasibility of using mesh reflectors on advanced small satellites.

Origami folded planar reflectarray antennas (FPR) employ hinged panels that can fold compactly for stowage and unfold to a planar aperture. Two notable missions include JPL's ISARA and MarCO missions. For ISARA, a 3U CubeSat integrated three Ka-band reflectarray panels (each 33.9 cm × 8.26 cm) between its solar arrays [23]. Each panel was used at antenna aperture at 26 GHz with a gain of around 33 dBi. For MarCO, three folded X-band reflectarray panels (each 19.9 cm × 33.5 cm) were used [24]. The aperture had a gain of 29.2 dBi gain and 42% aperture efficiency. Moreover, MarCO successfully relayed telemetry during a landing on Mars [25]. The success of MarCO demonstrated the feasibility of using FPRs for deep space communication.

For applications where even larger apertures are desired beyond what is feasible with umbrella or origami designs, truss-based deployable structures become a good choice. These systems use a framework of interconnected struts to support large and accurate reflector surfaces. A representative work is the shape-reconfigurable deployable paraboloid reflector developed by Tianjin University's Motion Structures Laboratory [25]. It uses a single-DOF spatial linkage assembly with 7R/8R units to achieve both deployment and shape reconfiguration. The structure deploys to a target parabolic surface and then continues to morph to the final configuration by coordinated motion, with a deployed diameter of 5.2m and surface accuracy <0.5mm RMS.

In conclusion, these representative cases demonstrate that through the synergistic combination of ingenious folding mechanisms and materials, lightweight metallic deployable antennas are constantly advancing towards larger aperture size in the strict volume limitations of small satellites.

## 2.2. Advances in flexible-membrane and extendable-waveguide antennas

In addition to rigid metallic structures, great efforts have been devoted to flexible-membrane and extendable-waveguide antennas to achieve even more impressive stowage efficiency for small satellites.

Flexible-membrane antennas employ thin-film materials that can be folded and packaged into small volumes and then inflated to form large apertures. The JPL inflatable antenna technology dates back to the 1990s, and a recent successful demonstration was the University of Arizona's CatSat mission, which included an inflatable sphere reflector of ~0.5m diameter [26]. This 'beach-ball' antenna, consisting of a half-aluminized Mylar sphere, was deployed on orbit to form a parabolic surface with an internal feed, and provided X-band downlink at ~50 Mbps. Due to their high packing efficiency, flexible membranes have well-known limitations in achieving adequate surface accuracy as well as long-term reliability, primarily stemming from the low stiffness of the films and challenges in withstanding the space environment (e.g., micrometeoroid orbital debris impacts and atomic oxygen erosion). As a result, inflatable antennas in the Ka-band are limited by difficulties in precise inflation control and surface-figure maintenance.

As an alternative approach, extendable-waveguide antennas are deployed by extending their radio-frequency (RF) transmission structures themselves, typically telescoping horns or waveguides, and deployable waveguide slot arrays. One advanced concept reported in the literature is a dual-layer parallel-plate waveguide slot array consisting of multiple foldable panels. For example, a single dual-layer parallel-plate waveguide slot array consisting of six 0.7 m square panels can be telescoped to form a 4.9 m-long slot array antenna that achieves 34.9 dBic gain at 9.56 GHz, and has potential application to small-satellite synthetic aperture radar (SAR) missions. While these structures offer high gain and relatively wide bandwidth, they are more structurally complex, have higher mass, and will be more massive than required, and thus challenges remain regarding synchronized deployment and thermal stability. A simpler implementation is the telescoping waveguide, which was used in the recently flown RainCube mission, where the feed horn extended

via a sliding waveguide mechanism after commissioning, and the main reflector stowed within the stowed profile of ~1 m height.

In summary, the two technology paths avoid the volume limitations of deployable metal reflectors by taking either an alternative extreme path of flexible-membrane antennas or by providing a robust solution using extendable waveguide antennas. These approaches, together with traditional metallic deployables, provide a broad design palette for CubeSat high-gain antennas. However, each approach has limitations in terms of surface precision, reliability, and structural complexity that are exacerbated by the design requirements, and innovative solutions are needed in materials and deployment mechanisms. The smart material composite (SMPC) approach is designed to bridge these gaps.

### 2.3. Performance comparison of CubeSat antenna types

In this section, the gain, frequency bands, and stowage requirements of various CubeSat antenna types are compared systematically, and their performance trade-offs are graphically summarized in Table 1 and Table 2.

Table 1. RF performance comparison of CubeSat antenna types

Antenna Type	Typical Band	Gain (dBi)	Deployment?
Monopole / Dipole	VHF / UHF	0-3	Yes (e.g., whip)
Patch Array	S / X-band	6-15	No (body-mounted)
Helical (QFH)	UHF-S-band	3-12	Yes (deployable coil)
Reflectarray	X / Ka band	20-30+	Yes (fold-out)
Parabolic Reflector	X / Ka band	30-40+	Yes (deployed)
Flexible Membrane	X band	25-30	Yes (inflatable)

Table 2. Structural characteristics and mission applications of CubeSat antenna types

Stowed Volume / Size	Representative Missions / Projects
Negligible	SNaP 3U (UHF dipole)
Minimal (~1U face)	NEA Scout (S-band array, ~12 dBi)
Small (~0.5U)	Typical UHF helix (~10 dBi)
Moderate (~0.8U)	ISARA (Ka-band, >100 Mbps), MarCO (X-band)
Large (1.5U for 0.5m)	RainCube (Ka-band, 42.6 dBi)
High (~1.5U for 0.5m)	CatSat (X-band, 50 Mbps demo)

As shown in Table 1 and Table 2, antennas can be classified by gain. Low-gain antennas, such as monopoles and patches with <8 dBi gain, offer near-omnidirectional coverage but low data rates, and are thus suited for low-rate LEO communication and telemetry. Medium-gain antennas (8-25 dBi), such as patch arrays and helicals, offer a moderate improvement in gain to provide some improvement to inter-satellite links or Earth-based communications. High-gain antennas (>25 dBi), such as the deployable reflectarrays and parabolic reflectors, are needed for high-data-rate downlinks and deep space communications. A patch or helical antenna with approximately the same physical volume as the deployable parabolic reflector of the RainCube demonstration could not achieve the ~42.6 dBi gain obtained by the parabolic reflector.

The basic trade-off shown in Table 1 is between gain and beamwidth. High-gain antennas achieve their characteristics by concentrating the radiated power into a very narrow beam. This requires highly accurate pointing and stability of the satellite, adding to the complexity and mass budget of the mission. As such, choice of antenna is not simply an RF decision, but a fundamental systems-level decision balancing communication requirements against constraints in volume, mass, power and attitude control capability.

## 2.4. Technical bottlenecks and emerging research trends

Despite these advances, there are still significant technical challenges facing the development of deployable antennas for small satellites, driving the technical trends currently seen in the literature.

The most fundamental roadblock is the trade-off between structural mechanics and RF performance. High-gain antennas require a large and precise aperture that must be fit into an extremely limited volume. Solutions to this problem require innovative approaches that address stowage, deployment reliability, and final surface accuracy. For example, the RainCube mission demonstrated that the optimal rib count and deployment mechanism must be chosen to control the root-mean-square (RMS) surface error to the millimeter level, which was a limiting factor for the Ka-band operation [27].

Mechanical deployment reliability is also a significant challenge. Deployable mechanisms must survive the launch vibration environment and then operate in the thermal environment of space and achieve single-shot success. In addition to reflectarray and inflatable membrane limitations, each antenna technology faces its own limitations. Phased arrays have high power consumption and cost while avoiding deployment.

Several interesting research trends are emerging in response to these challenges. These trends point to the future of deployable antenna development for small satellites:

Smart material structures using active materials such as shape-memory alloys (SMAs) and especially shape-memory polymer composites (SMPCs), is a very new and rapidly developing field. SMPCs have many attractive features as structural and actuating materials. They can be used to simplify and make lightweight simple deployable mechanisms that can be designed to be highly packaging efficient and mechanically simple. Recent on-orbit technology demonstrations, such as on solar sails and small satellites, have demonstrated the technology readiness of SMPC-based hinges and booms. Current research foci (as of 2025) include enhancing their space environmental durability, thermo-mechanical cycle life, and developing models for predicting deployment accuracy.

The ongoing integration of origami engineering and bio-inspired approaches is generating new antenna architectures. These approaches use well-defined mathematically rigorous folding patterns to evolve a compactly stowed structure into a large, accurate plane or surface, typically with a simple single-degree-of-freedom deployment.

Future systems are evolving beyond monostatic antennas integrated as single elements in systems towards multifunctional integration. There is trend toward 'multifunctional' structures, e.g. in ISARA antennas are being integrated with solar arrays, thus achieving 'zero-volume' mass allocation for communications. Future trends are even more reconfigurable towards reconfigurable intelligent surfaces where the antenna and possibly waveguide feeds are made from materials such as LCPs or MEMS, which can provide post deployment tuning of frequency, polarization or even beam steering to adapt to mission variations.

These trends combine to indicate a moving away from pure mechanical deployment solutions and toward more intelligent multifunctional material solutions, where the antenna is no longer a passive

element but an active integrated system element. This makes the designs based on SMPCs a promising approach to address the core issues of stowage, deployment and release reliability and mass reduction.

### 3. Advances in Shape-Memory Polymer Composites (SMPCs) for space applications

#### 3.1. Overview of SMPC material properties

Shape-memory polymer composites (SMPCs) represent a class of lightweight, high-performance smart materials that synergize the programmable deformation capability of shape-memory polymers (SMPs) with the superior mechanical strength of fiber-reinforced composites. In contrast to traditional shape-memory alloys (SMAs), SMPs/SMPCs can achieve fully recoverable strains significantly exceeding those of metals (SMAs are typically limited  $\sim 8\%$ ), usually reaching several hundred percent. This substantial recoverable strain translated to a high storable elastic energy density, enabling the release of considerable energy during shape recovery to drive structural deployment. Furthermore, SMPCs are characterized by high specific strength and stiffness, enabling lightweight designs with tunable mechanical properties. And exceptional design flexibility allows thermomechanical performance to be tailored through molecular engineering or the incorporation of functional fillers. It also offers cost-effectiveness with relative ease of processing.

SMPCs are responsive to a variety of external stimuli, with the most common triggering modes being thermal activation such as ambient heating or embedded resistive elements, electric-field or current heating, magnetic induction heating, as well as light or chemical stimuli. Among these, thermally and electrically activated SMPCs are the most prevalent for space applications. Through a process of thermomechanical programming, SMPCs can be configured to 'memorize' a complex permanent shape, which is fixed into a temporary configuration at an elevated temperature. Subsequent stimulus-triggered recovery enables a return to the original shape, achieving a highly controllable shape-memory effect. The multifunctional potential of SMPCs also exhibit self-healing and self-sensing potential. For example, SMPCs can heal cracks if microcapsules or dynamic covalent bonds are embedded in the polymer matrix to facilitate crack healing under appropriate thermal activation. In summary, SMPCs possess lightweight high strength, large deformation capacity, controllable stimulus response, and potential multifunctionality and other advantages that are distinct from other classes of smart materials.

#### 3.2. SMPC applications in spacecraft structures

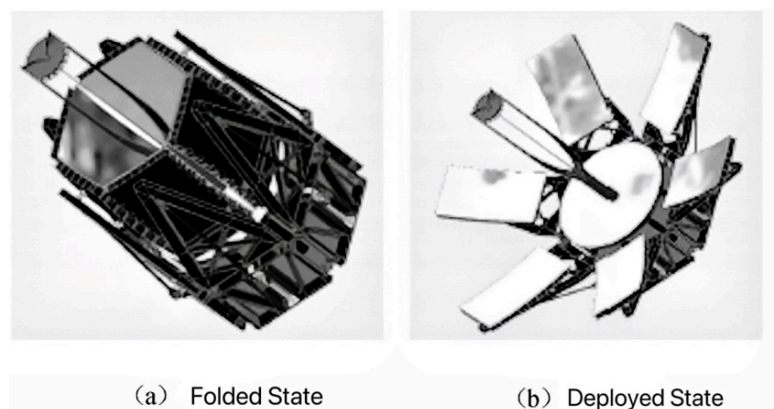


Figure 1. Folded state and deployed state of a self-locking linear actuator

Based on these advantages, researchers have developed a number of prototype deployable space structures using SMPCs and have tested their performance using ground facilities and in-orbit tests. The most mature application is the shape-memory composite hinge that can replace traditional metallic hinges used to deploy and latch solar arrays and solar sails. For example, the CTD company developed an Elastic Memory Composite Hinge (EMCH) integrated with a self-locking linear actuator for space optical payloads that require extreme precision, stability and repeatability. As schematically illustrated in Figure 1, the device is capable of synchronously deploying a six-petal reflector and is scalable for 3 m class deployable on-orbit telescopes for photometry and LiDAR payloads [28]. Compared to conventional electromechanical actuators, the EMCH generates significantly lower deployment shock, offers precise controllability and avoids direct collision of rigid components, thereby mitigating the risk of microdynamic instability post-deployment [29].

SMPCs are also extensively explored for self-deploying antennas and booms. SMPC-based coiled-tape or roll-out antennas can be efficiently stowed within the constrained volumes of small satellites and deployed on-orbit. CubeSats have successfully employed SMPC coiled booms as antenna support masts, achieving lightweight and low-energy deployment. European research teams have developed a carbon-fiber-reinforced SMPC deployable gripper for space robotic end-effectors or debris capture. Comprising four carbon-fiber fingers connected by SMPC hinges, the gripper closes uniformly upon thermal activation to securely grasp targets, providing inherent buffering and compliant capture. Additional applications include deployable fairings and covers, where SMPCs provide post-deployment stiffening and shape retention for inflatable structures. For shock mitigation, SMPC foams, with their efficient energy-absorbing deformation, can function as reusable impact absorbers in lander struts or satellite bumper pads, though this application remains largely at the conceptual and ground-testing stage.

Beyond being used for deployment, SMPCs can be used for smart thermal-control structures. The 'smart radiator' concept employs SMP actuator-driven opening and closing of radiator panels to provide active and intelligent thermal control. A series of publicly documented flight experiments have provided support for the fundamental feasibility of SMPC material and structures in orbit. NASA, through the Materials International Space Station Experiment (MISSE) platform, has flown SMPC material samples on board MISSE-9, 10, 12 and 13, and exposed them externally on the International Space Station (ISS) for months in the vacuum of space, under solar radiation and atomic oxygen [30]. In general, they exhibited stable on-orbit performance with only minor effects of mechanical degradation. For instance, an SMPC sample flown on board MISSE-9, upon post-flight heating, recovered part of its programmed shape on the sun-facing side, while the other side remained deformed; neither side exhibited significant material aging. Similarly, an Italian research team, on Russia's BION-M1 satellite in 2013, under microgravity conditions, demonstrated successful shape-memory recovery of a two-ply carbon-fiber/SMP laminate, marking a pioneering autonomous verification of SMPC recovery in orbit. The flight tests of both these works, together with work led by the European Space Agency (ESA), have confirmed the fundamental feasibility of the fundamental feasibility of SMPC structures in orbit and enabled steps toward practical implementation [31]. Recent advances in 2025 show promise toward such a possibility. Mode-reconfigurable antennas using SMP hinges as smart mechanisms that enable fine-grained control of beam steering over a  $0^\circ$  to  $270^\circ$  range, from a nominal 4.2-5.5 GHz band, with gains of up to 7.49 dBi have been demonstrated [32]. This breakthrough paves the way toward next generation SMPC applications that incorporate both deployment and on-orbit reconfigurability for advanced communication payloads.

### 3.3. Comparison with traditional metallic hinges/spring mechanisms

Traditional spacecraft deployment mechanisms, such as steel hinges and spring-driven release devices, are mature and stiff but inherently suffer from relatively high mass, structural complexity, low stowage efficiency, deployment shock, and multiple failure points. For example, metallic hinges and springs require additional pins, gears, and dampers, inevitably increasing assembly mass and volume and potentially causing mechanical shock and vibration at release, which may jeopardize payload safety. In contrast, SMPC-based deployable structures require no complex mechanical parts. Deployment and latching rely on the material's shape-memory effect, greatly reducing system mass and simplifying mechanisms. Reports indicate that replacing metallic hinges with SMPC hinges can reduce the weight of the deployment system by more than 50%, freeing valuable payload volume [33]. Moreover, because SMPC deployment involves a compliant transformation from the glassy to the rubbery state, it avoids the instantaneous shocks of spring mechanisms and achieves smooth, shock-free deployment, improving deployment reliability.

Regarding thermo-vacuum adaptability, SMPCs also show advantages. New SMPC hinges based on modified epoxies or copolymer matrices, can retain good shape fixing or recovery even at low temperatures down to  $-40\text{ }^{\circ}\text{C}$ . This means SMPC structures can reliably hold or recover shapes in deep-cold conditions such as spacecraft eclipse or lunar night, while traditional metal springs may suffer brittle fracture or lubricant failure at very low temperatures. On the other hand, current SMPCs have relatively lower stiffness, strength and limited recovery driving force. To ensure sufficient post-deployment rigidity, composite reinforcement like carbon-fiber skeletons is typically required to raise modulus and strength. Even so, for small spacecraft highly sensitive to mass and volume, SMPC mechanisms prevail with weight reduction and simplified design. Overall, compared with traditional metallic mechanisms, SMPCs offer clear optimization in mass and complexity, and improve deployment reliability and thermo-vacuum adaptability via shock-free deployment. However, in load capacity and long-term life, further improvements are still needed. Specific trade-offs should be made per mission requirements.

### 3.4. Space-environment adaptability of SMPCs

The space environment is harsh, vacuum, extreme temperatures, ultraviolet radiation, atomic oxygen (AO), and repeated thermal cycling can all affect SMPC performance. Existing research and tests show that properly formulated SMPCs adapt well to space. In high vacuum, the outgassing (TML/CVCM) of SMPCs can be  $< 1\%$ , meeting space-material requirements. After repeated thermal cycling by alternating hot and cold to simulate orbital day-night, SMPC laminates maintain shape-fixing or recovery ratios with no obvious decrease in properties such as decomposition temperature. Under prolonged ultraviolet exposure, the chemical structure and shape-memory function remain generally stable. For example, after 600 h of simulated solar UV, a shape-memory polyimide sample showed almost no change in  $T_g$ , fixing ratio, or recovery ratio, though UV can gradually age the polymer matrix and reduce mechanical strength. Therefore, for long Sun-exposed conditions, UV-resistant formulations or protective coatings are needed to slow aging.

AO erosion is a major threat to polymers in LEO, but some SMPCs exhibit high AO resistance. Tests under high-flux AO show almost no deterioration in chemical structure or shape-memory performance, with recovery ratios still above 98%, attributable to the stability of oxidation-resistant high-polymers and indicating that choosing AO-resistant matrices can extend on-orbit life. Regarding low-temperature embrittlement, conventional SMPs often require heating above  $T_g$  to soften and deform. At very low temperatures, embrittlement hinders recovery. To address this, low-

temperature-responsive SMPCs have been developed. For instance, NASA's TEMBO™ elastic memory composites enable shape-memory effects at 0 °C or even -40 °C, greatly expanding applicability in cold space environments. Finally, fatigue life and durability are also concerns. Polymer matrices may exhibit viscoelasticity and microcracking under repeated loading, leading to performance attenuation after multiple fold-deploy cycles. Some experiments reported failure after 12 memory cycles for certain SMPC hinges, though this has limited impact on structures intended for one-time deployment. For multi-actuation or long-life missions such as repeatedly deployable components, improved anti-fatigue properties are required. Overall, space-grade SMPCs with optimized formulations can maintain excellent performance under vacuum, radiation, thermal cycling and low temperatures. For example, polyimide-based SMPCs have shown multi-year stability on orbit. Future modifications and protections can further enhance radiation and aging resistance for long-term service in harsh space environments.

### 3.5. Potential and challenges of SMPCs in CubeSat deployable antennas

For micro-satellites such as CubeSats, severely limited size and mass budgets make post-insertion deployment of high-gain antennas a major challenge. SMPCs provide a new approach by exploiting foldability and high deformation energy storage, relatively large antenna reflectors or booms can be cleverly folded into the CubeSat volume. After orbit insertion, these reflectors can be thermally activated to deploy an antenna larger than the satellite body. This offers multiple potential advantages. First, SMPC antenna structures are lightweight and compact, alleviating mass and volume constraints, and enabling apertures of tens of centimeters or larger to achieve gains far exceeding those of small antennas. For example, studies have attempted foldable SMPC parabolic reflectors with deployed apertures exceeding 0.5 m at K/Ka band. Second, SMPC deployment requires no motors or springs. Simply heating embedded conductors or utilizing solar heating yields smooth deployment with lower attitude disturbance than spring-based mechanisms. Third, SMPCs self-stiffen upon cooling, maintaining antenna shape over a wide temperature range to ensure pointing and accuracy.

However, several challenges must be addressed for successful SMPC antennas on CubeSats.

High-frequency communications demand precise shaping, and polymer thermal expansion and stress relaxation may affect surface accuracy. Therefore, high-stiffness ribs or self-correction mechanisms need to be used for optimized design and compensation.

CubeSat power is limited, while SMPC activation consumes energy. Possible measures include low-T<sub>g</sub> materials, thermally conductive fillers to improve heating efficiency, or leveraging environmental heat like sunlight.

Despite short mission durations, antennas must operate reliably for months to years under thermal cycling and radiation without performance degradation or relaxation. Current research focuses on modified SMPCs (e.g., graphene/CNT nanofillers for stiffness and thermal conductivity) and advanced manufacturing (e.g., 4D printing of complex folds) to meet stringent requirements.

In short, SMPCs have great potential in CubeSat deployable antennas, enabling antennas much larger than the bus for high-rate downlink and deep-space links. With ongoing progress in materials and design, SMPCs are expected to play key roles in future small-satellite antennas, while further work is needed on accuracy, energy and durability for full practical adoption.

## 4. An integrated SMPC-based design for a CubeSat self-deploying high-gain antenna

This chapter elaborates on the detailed design methodology of a self-deploying high-gain antenna for CubeSats, leveraging Shape Memory Polymer Composites (SMPCs). The proposed approach integrates a Miura-ori patterned reflector with a hybrid origami-truss structure for high stowage efficiency and deployed stiffness. The deployment is actuated by passively heated, graded-response SMPC hinges, ensuring synchronization and reliability. A self-locking mechanism utilizing the recovery force of SMPCs and auxiliary Shape Memory Alloy (SMA) elements maintains structural integrity post-deployment. To mitigate thermal deformation in orbit, an active-passive compensation layer with a honeycomb topology and embedded SMA actuators is introduced. Finally, a hybrid beam-steering system combining a mechanical SMPC gimbal for coarse pointing and an electromagnetic phased array for fine control is presented, enhancing communication flexibility. This integrated design addresses key challenges of compact stowage, reliable deployment, structural stability, thermal management, and pointing agility within stringent CubeSat constraints.

### 4.1. Design principles of the origami–truss hybrid architecture

The core of the proposed design is the use of a Miura-ori (Miura fold) pattern for the reflector surface. Through this origami folding pattern, a large planar membrane can be folded into an extremely small bundle with a stowed thickness on the order of the material thickness. The single-degree-of-freedom deployment kinematics (SDOF) driven by boundary tension for deployment increase deployment reliability as there is minimal risk of jamming. To achieve the necessary surface accuracy and structural stiffness for high frequency operations (e.g., Ka-band), a supportive truss framework is integrated with the origami membrane. This combination marries the high packaging ratio of the Miura-ori and the mechanical rigidity of a truss structure together. The truss members, placed along the primary crease lines or along the periphery, are co-folded with the membrane and upon deployment, lock into place to provide the necessary stiffness to handle micrometeoroid impacts, vibration, and thermal gradients. Given the constraints on the stowed volume, geometric optimization is performed to balance the packaging volume against the achieved deployed surface precision and fundamental frequency to meet both launch vehicle constraints and on-orbit performance requirements [34]. The primary design targets that this optimization process enables are summarized in Table 3.

Table 3. Key design targets for the hybrid reflector

Parameter	Target Specification	Rationale
Stowage Volume	$\leq 1.5U$ (10x10x15 cm <sup>3</sup> )	Compatibility with 3U-6U CubeSat platforms
Surface Accuracy (RMS)	$\leq 0.1$ mm	Ka-band (26.5-40 GHz) operation requirement
First Natural Frequency	$\geq 25$ Hz	Decoupling from typical satellite platform vibrations
Stowage-to-Deployed Ratio	$\geq 8:1$	Enabling large aperture (>0.5m) from a small package

### 4.2. Graded-response SMPC hinge system for controlled deployment

Deployment mechanism utilizes hinges formed from carbon-fiber reinforced SMPCs. These composite hinges function as distributed and passive actuators taking advantage of the thermomechanical shape memory effect. A typical hinge laminate is composed of an SMP matrix (e.g., cyanate ester with tunable glass transition temperature,  $T_g$ ) and carbon-fiber plies arranged to

provide favorable bending compliance and recovery stress [35]. Most recently, 2024 SMPC hinges with  $T_g \sim 210^\circ\text{C}$  have been shown to achieve recoverable strains in excess of 10% and provide substantial stiffness after vitrification below  $T_g$  [36].

The deployment sequence begins by heating the hinge material to exceed its glass transition temperature. This can be done either by means of embedded micro-resistance heaters, or passively by focusing solar radiation onto the structure by directional satellites. As the matrix softens, the stored strain energy from the folding process is released and results in a stored recovery stress that drives the hinge to its memorized and deployed shape. To prevent asynchronous, snag-prone motions between multiple hinges, a graded-response design is flown. This entails engineering spatial variations in the thermal response by controlling local properties of the material, such as ply orientation, thickness, or SMP chemistry [37]. For example, hinges further away from the heat source can be designed to have a slightly lower effective  $T_g$  or thinner cross sections such that they heat up first, ensuring that all hinges start and end their motion in a coordinated manner. Experimental results from ground testing show that a full deployment sequence is achievable within 100-120 seconds after the start of heating.

### 4.3. Self-locking mechanism and stiffness retention post-deployment

Maintaining the deployed configuration against potential disturbance torques is critical. The present design features a highly robust and passive self-locking mechanism making use of the entire recovery stress of the SMPC hinges. After unfolding, the hinge is cooled below the respective glass transition temperature and thus the SMP matrix goes through a reverse glass transition. This locks the hinge in its unfolded state and high stiffness configuration. The elastic recovery force provides a permanent resisting torque against refolding. This is further increased by the mechanical end-of-stroke stopping mechanism which can even define the final deployment angle with high accuracy.

Secondary locking at major joints is provided by SMA elements (e.g. wire springs or latches). These SMAs are trained to contract upon heating to a certain transition temperature which is only reached after a successful switching of the primary SMPCs including the corresponding measurement has taken place. The contraction of the SMA provides a high and stable clamping force and latches the structure in place. This highly reliable solution is based on a synergistic use of SMPCs for actuation and primary locking and SMAs for secondary latching. The carbon fiber reinforcement of the SMPCs ensures that the structure in its deployed configuration features a high specific stiffness which directly contributes to a high first natural frequency, and thus to pointing stability and overall attitude control of the satellite.

### 4.4. Active-passive thermal deformation compensation layer

Orbital thermal cycles, going through direct sunlight and eclipse, cause considerable temperature gradients and resulting thermoelastic distortions of the reflector and thus degradations of the RF performance. For compensation, a special compensation layer is located behind the reflector surface. This layer consists of a hierarchical honeycomb structure with negative effective thermal expansion (NTE).

Through finite element analysis (FEA)-driven topological optimization, the unit cells of the honeycomb are engineered to exhibit an overall contraction upon heating. This is achieved by designing the thermal expansion of strategically oriented beams within the cell to compensate for the positive expansion of the reflector surface.

Active Correction with Embedded SMA Actuators is utilized. For a high precision correction of possible residual errors, SMA micro-actuators are embedded in the honeycomb cells. These actuators, which are resistively heated to induce a phase transformation, provide a controlled local strain and push or pull on the reflector backing to invalidate certain deformation modes.

With a closed loop control, which comprises temperature and strain sensors scattered over the whole reflector, information on thermal deformations are collected and used to command the SMA actuators to make corrections in small steps. This way, the surface shape stability is maintained within a narrow tolerance band over the entire orbit. The approach is a combination of a passive correction and an active correction based on feedback and control.

#### 4.5. Integrated hybrid beam-steering capability

To enable an agile communication without consuming excess power and mass, a hybrid beam-steering solution is realized.

**Mechanical Steering (Coarse Pointing).** A two-axis gimballed structure with SMPC-based torsion actuators enables coarse pointing over a large angular field of view ( $\pm 30^\circ$ ). In case a pointing correction is necessary, selected SMPC elements are heated to induce specific rotational deformations of the entire reflector assembly. This approach removes the need for bulky and power-intensive traditional motors.

**Electronic Steering (Fine Pointing).** Fast fine beam adjustments and beam shaping are provided by electronic steering at the feed level. This can be implemented either as a miniaturized phased array feed or with a passive metasurface reflectarray embedded in the antenna design. Both approaches enable electronic beam scanning by controlling the phase of individual radiating elements, thus facilitating fast re-pointing with no mechanical jitter.

Hybrid Control Strategy is employed. The mechanical gimbal is responsible for larger and slower pointing maneuvers, while the electronic system corrects for the high-frequency perturbations and provides fine tuning. This approach offers redundancy, agility and is highly efficient in terms of power, making it an ideal solution for resource-constrained CubeSat missions.

### 5. Manufacturing, ground testing, and on-orbit verification

#### 5.1. Manufacturing and fabrication of SMPC components

Typically, fabrication of Shape Memory Polymer Composite (SMPC) components uses conventional composite laminate techniques, with hot-press molding being the most mature technology. A typical process sequence involves sequentially laminating carbon-fiber prepregs, in unidirectional, woven or non-crimped forms, with SMP matrix film layers and then curing under controlled temperature and pressure cycles. For example, single-step hot-press molding of carbon fiber reinforced epoxy-SMP sandwich laminates has shown excellent molding quality and shape-memory performance. Typical process parameters are mold temperatures of 150–200 °C, pressures of about 0.7 MPa and a dwell time of 60–90 minutes, adapted to the specific resin system. To achieve superior interfacial adhesion and void content (<2%) clean-room layup, intermediate vacuum debulking and controlled press-curing are followed. Generally, some surface modification of the carbon fibers is used, by plasma or silane coupling agents, to achieve enhanced fiber-matrix bond strength, important to achieve maximum recovery stress and fatigue life.

Additive manufacturing (AM), or 4D printing, is an alternative for manufacturing complex, customized SMPC geometries with programmable deformation. The European Space Agency (ESA)

has recently advanced the use of AM for small satellite components, such as 3D-printed dual-reflector antennas and high-performance PEEK structural parts. However, current AM technologies for fiber-reinforced composites struggle with achieving the necessary high fiber volume fractions (>40%) and dimensional accuracy for high-precision antenna reflectors. Therefore, for those primary structural elements where high specific stiffness and strength are required, hot-pressed laminates are still the material of choice. AM is most suitable for prototyping or manufacturing intricate support structures or functional elements, such as customized heater circuits.

Material enhancement strategies focus on optimizing the reinforcement phase. Studies consistently show that continuous carbon fibers significantly improve the recovery force and deployed stiffness of SMPCs. A remarkable experiment has shown that the addition of 45 vol% continuous carbon fiber results in an increase of the recovery force of about 305% with respect to the neat SMP. Furthermore, the increased reinforcement content also results in a higher stiffness of the part in its folded state, which may affect the ease of stowage. For those applications where large deformation is required, a compromise can be made between strength and flexibility by using short fibers or nano-fillers, such as graphene and carbon nanotubes. The best fiber volume fraction is between 30% and 50%, which is the result of a trade-off analysis between maximum recovery stress, acceptable deformability, and adequate final structural stiffness.

## 5.2. Comprehensive ground testing and qualification

A thorough ground-testing campaign is mandatory to qualify the deployable mechanism for the space environment and reduce the on-orbit failure probability. This campaign encompasses the following key tests.

The thermal vacuum cycle (TVAC) is an important step in the test. The assembly undergoes dozens to hundreds of cycles in the high vacuum chamber, depending on the orbit. For instance, for Low Earth Orbit, the orbital temperature range can be extreme (-100 °C to +120 °C). This test provides proof of dimensional stability of the composite materials, the functional reliability of the shape-memory hinges after thermal cycling and the structural integrity of the joints affected by CTE mismatch stresses.

Deploying lifecycle testing is also crucial. The mechanism is subjected to at least 100 deployment and stowage cycle repetitions, which is the expected mission life, to prove the repeatability of the shape-memory effect, the hinge and latch fatigue resistance and the absence of micro-damage build-up. A stable deployment time and final shape accuracy over the cycles is a success criterion.

The stowed position is shot with full-spectrum random vibration and pyroshock pulses profile to match launch environment, to qualify vibration and shock characteristics as defined by NASA GEVS or ECSS-E-ST-10-03, and to ensure that no pre-mature deployment or performance degradation takes place. One well-known case is NASA's RainCube mission, where a hinge failure mode was found during vibration testing, and mission was saved before launch.

High-speed cameras, along with displacement sensors and current sensors, are used to carefully capture the deployment sequence. This information can be used to check out deployment kinematics, timing of multiple hinges, any anomalous friction or stiction, and thermal-structural model calibrations.

Several historical events serve as reminders that complete ground testing is necessary. For example, the anomalous deployment of the C-band antenna on board Canada's Anik E2 satellite in 1991 was caused by the interaction of thermal blankets. This mode of failure could have been revealed by more representative thermal vacuum deployment testing. As a result, the need for

ground verification is the final opportunity to reveal and correct design issues that ensure successful in-orbit performance.

### 5.3. Analysis of on-orbit verification cases

On-orbit demonstration of several small satellite deployable antennas is successful and provides valuable data and validation experiences.

NASA's RainCube was launched in 2018. This was a milestone mission that deployed a 0.5m umbrella-type Ka-band parabolic antenna from a 6U CubeSat. The initial mission plan was two months, but the satellite has operated successfully for over 2.5 years and provided valuable precipitation radar data. The success of this mission is due to the comprehensive ground-testing campaign that revealed a critical hinge failure mode and corrected it before flight.

JAXA's OrigamiSat-1 was launched in 2019. This was a mission that was designed to demonstrate the deployment of a 1m<sup>2</sup> membrane antenna using carbon-fiber reinforced tape springs. The command to deploy was uploaded and the release mechanism (a nylon wire cutter) was activated. This mission failed to demonstrate deployment since the overall satellite health was not achieved. It provided a critical lesson that the reliability of the deployment mechanism is necessary, but not sufficient. Overall satellite health including power, communications, and attitude control is just as important.

The failure of the 4.8-meter high-gain antenna on the Galileo spacecraft to fully deploy in 1991 severely limited its data return capability. In contrast, smaller CubeSat arrays such as RainCube can be fully tested at the integrated system level in ground facilities, significantly de-risking the deployment process. Common failure root causes across missions include friction, inadequate lubrication, and thermal distortion leading to jamming.

In summary, the case histories have confirmed that on-orbit reliability begins with comprehensive ground testing, simple and fault-tolerant mechanism design and the overall reliability of the satellite platform.

### 5.4. Engineering challenges and mitigation strategies

Despite their advantages, SMPC-based deployable antennas face several engineering challenges that require focused mitigation.

Polymer chains are subject to scission and crosslinking upon exposure to atomic oxygen (AO), ultraviolet (UV) and vacuum ultraviolet (VUV) radiation as well as charged particles, which in turn alter the shape-memory properties of the SMP. Mitigation strategies include the design of protective coatings (e.g. thin-film metal oxides) and the formulation of more radiation resistant SMP matrices (e.g. polyimide-based SMPs).

Coefficient of Thermal Expansion (CTE) mismatches between the SMPC structure and metallic actuators (SMA) as well as the satellite bus can induce large thermal stresses and deformations during orbital temperature cycles. Appropriate interface design, use of gradient materials or flexible adhesives, as well as thorough thermo-elastic finite element analysis during the design process is therefore critical.

While the glass transition of SMPCs provides some degree of 'passive locking', many missions employ secondary mechanical latches or SMA-actuated locks to provide absolute assurance against re-folding under dynamic disturbances. Redundant locking mechanisms are a key design feature for high-reliability missions.

Although SMPCs can undergo multiple cycles, hysteresis as well as potential micro-damage can induce a gradual decrease in recovery force and shape fixity ratio with each hundred cycles. Accelerated lifecycle testing is essential to characterise this behaviour and define a safe operational lifetime.

### 5.5. Future directions and application prospects

The future of SMPC deployable antennas lies with multifunctional and intelligent material systems. In the near to medium term, integration with reconfigurable antenna elements, such as liquid crystal-based metasurfaces or flexible phased arrays, enables a single aperture to perform multi-beam steering and multi-band operations with a single or dual polarisation. This is a transformative step change for satellite-to-satellite communications and Earth observation constellations.

For deep-space exploration, SMPCs enable the fabrication of lightweight, high-packaging-efficiency large apertures (>1m) for high-data-rate communications for lunar orbiters, Mars and beyond. For future applications, the combination of SMPCs and self-healing polymers may give rise to structures that can self-repair micrometeoroid damage. In addition, by embedding fiber Bragg grating (FBG) sensors or any other flexible piezoelectric networks, the deployed structure can be monitored in real time for health measurements that could be the basis of an 'intelligent' antenna that corrects its shape based on any sensed distortion.

From a manufacturing perspective, hybrid processes that combine 4D printing for complex geometries with automated fiber placement for high-strength regions represent the next frontier. Current research on high-performance SMP resins (e.g., cyanate esters with better thermal stability) and novel nanocomposites will continue to drive the specific strength and environmental performance of SMPs to new highs, ensuring the continued use of SMPCs in future small satellite programs.

## 6. Conclusion

In summary, this work has demonstrated the use of shape memory polymer composites (SMPCs) to fabricate a high-gain, high-storage-efficiency deployable antenna for CubeSats. The antenna design integrates an origami-truss hybrid structure with passive SMPC actuation, enabling it to self-deploy from a tightly stowed configuration without the need for complex motors or hinges. Once deployed, self-locking mechanisms cause the structure to rigidize. An active-passive thermal compensation system corrects any dimensional changes to maintain RF surface accuracy over a range of temperatures that the antenna may experience in orbit. Comprehensive ground qualification tests encompassing mechanical, thermal and RF confirmed that the deployed antenna meets its design requirements, with measured performance comparable to conventional rigid antennas. The subsequent on-orbit functional verification demonstrated reliable deployment and operation in the space environment, achieving the intended high gain and validating the overall design approach. These results show that using shape memory polymer-enabled deployable antennas is a means to provide high aperture and gain for nanosatellites with minimal impact to volume and mass, which addresses a key need for future CubeSat missions that require large-aperture and high-bandwidth communications.

Looking forward, several avenues could further enhance this technology's performance and longevity. Improving material durability is a priority to ensure reliable long-term operation under the harsh space environment (e.g. resistance to radiation and repeated thermal cycling). In addition, increasing the precision of the deployed reflective surface is also important for higher-frequency

applications. For instance, incorporating adaptive surface control or self-adjusting elements, such as a smart sub-reflector, to mitigate any minor shape deviations after deployment. Furthermore, multifunctional integration of the antenna with other spacecraft structures offers a promising path to maximize resource efficiency. For example, embedding antenna elements into deployable solar panels or other structural components could eliminate dedicated deployment mechanisms and further reduce the overall mass and volume footprint. By pursuing these improvements, future SMPC-based deployable antenna systems will be even better equipped to enable advanced CubeSat missions, providing large-aperture communication capabilities without compromising the stringent size and mass constraints of small satellites.

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