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AN ULTRA-COMPACT HELICAL ANTENNA FOR SMALL SATELLITES

Dr Geoffrey Knott
geoffrey.knott@surrey.ac.uk

Dr Andrew Viquerat
a.viquerat@surrey.ac.uk

Department of Mechanical Engineering Sciences & Surrey Space Centre
University of Surrey, United Kingdom, GU2 7XH

Space data services provide the largest market value to the global space industry. With the increasing use of small satellites that lower costs and lead times, the entrepreneurial space age has begun. However, advances in technology miniaturization are required to improve small satellite capabilities, which are limited by small volumes and low power consumption. This paper presents a deployable antenna for small satellites capable of achieving high-gain radiation performance despite being ultra-compact. The antenna is a helically curved boom that is deployed from a coil. The boom is an open slit tube. A ground plane comprised of four metallic booms supporting a sparse mesh is deployed by stored strain energy. A prototype of the antenna system has been built to test and validate the deployer mechanism, deployment strategy, and dimensional stability of the helical antenna and ground plane. The architecture builds on proven space technology, specifically the deployer mechanism of the InflateSail de-orbiting drag sail that successfully demonstrated low-Earth orbit space-debris removal in 2017. In this work, the deployer unrolls the helical boom whilst the sail itself is repurposed to boost the radiation performance of the helical antenna.

I. INTRODUCTION

In recent years extremely small satellites have been developed in response to trends in the space industry to achieve more for less cost. Communications remain a major bottleneck for CubeSat functionality[1]. CubeSats require compact deployable solutions given their extremely small volume and low power that restricts the size and types of antenna available for use. Typically, monopole and dipole antennas are used for telemetry and data transmission. These omnidirectional antennas operate around 146 MHz for uplink, and 437 MHz for downlink and produce low-gain characteristics (maxima of 2.06 dB and 3.35 dB, respectively[2]) providing poor data rates on the order of Kbps. Data rates a thousand times greater on the order of Mbps are required for multimedia download. High-gain antennas enable sensitive and low power communication systems. Low power consumption is crucial given the few Watts of available power in a CubeSat. Good sensitivity is important for applications where the incoming signals are weak *e.g.* Automatic Identification System (AIS) signals for maritime surveillance. The United Kingdom is a global leader in small satellites and maritime products, services, and investment opportunities[3]. Indeed, this paper presents a novel deployable helical antenna concept for enhanced space-based AIS receivers.

II. SYSTEM OVERVIEW

The small satellite helical antenna in Fig. 1 comprises of a 100 mm x 100 mm x 100 mm cube housing one helically curved bistable composite slit tube[4], centred above a planar square mesh ground plane. The helical element is made from bistable composite in order to achieve compact stowage without the need for additional constraint mechanisms that increase the satellite mass, occupy valuable storage volume, and increase overall design complexity. Four straight metallic booms support the ground plane for improved radiation characteristics *i.e.* gain and directionality.

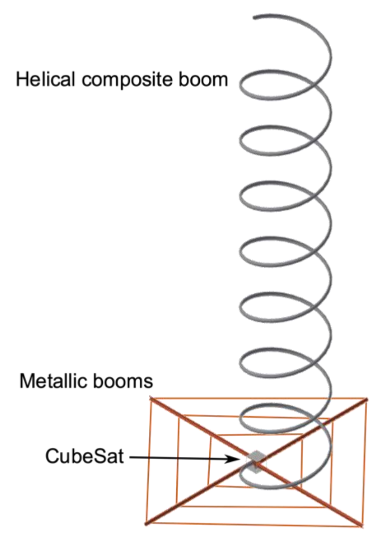

Fig. 1: A rendering (to scale) of an 8-turn helical antenna deployed from a 1U CubeSat, with dimensions optimized for operation at 162 MHz.

The helical antenna considered in this work is designed and optimized for receiving space-based AIS signals in axial mode at 162 MHz using Kraus' formulas[5]. These formulas are presented in equations [1]–[5] and highlight the large antenna dimension which contrast to the CubeSat dimensions. The design equations for an axial mode helical antenna are,

$$C = \lambda = 1.85\,\mathrm{m} \qquad [1]$$

$$S = \frac{\lambda}{4} = 0.46\,\mathrm{m} \qquad [2]$$

$$R = \frac{\lambda}{2\pi} = 0.29\,\mathrm{m} \qquad [3]$$

where C is the helical circumference, S is the spacing between each turn of helix, and R is the helical radius. For instance, a 7-turn helical antenna ($N = 7$) is calculated to achieve half-power beam width (HPBW, a measure of directionality), and gain (G, a measure of efficiency) of:

$$\mathrm{HPBW} = \frac{52^\circ}{C}\sqrt{\frac{\lambda^3}{NS}} = 39.4^\circ \qquad [4]$$

$$G = 10.8 + 10\log\left(\frac{NC^2S}{\lambda^3}\right) = 13.2\,\mathrm{dBi} \qquad [5]$$

Given equations [1]–[3] the 8-turn helical antenna illustrated in Fig. 1 has a diameter of 580 mm and axial length of 3,680 mm. The square ground plane has sides of 1380 mm.

II.I Ground Plane

The flat ground plane is constructed of a sparse wire mesh connected to four straight metallic booms in a square arrangement, as shown in Fig. 2. The metallic booms are ~1024 mm long in order to achieve a square of sides ~1380 mm. These dimensions were selected to be approximately three-quarters the operating wavelength (0.75 x 1851 mm) – the minimum size required to achieve good radiative performance[6].

Preliminary designs considered bistable composite booms for the stowage, deployment and support of the ground plane. However, metallic booms were selected for their electrical conductivity and strain energy deployment, which frees up the internal CubeSat volume to be dedicated to the helical boom, and electrical conductivity. Composites considered were glass- and carbon-fibre, which would require additional manufacturing processes to enable the function of an antenna ground plane: namely that glass-based booms require insertion of thin conductive wire/mesh, and the electrical capability of carbon-based booms requires further investigation into the radiative performance, which is dependent on operating frequency and the fibre orientation of each ply of the composite.

The primary advantages for a using a mesh rather than a gossamer *i.e.* thin film or membrane, are the simpler construction, folding and stowage, minimal thickness once wrapped around the exterior, and eased tolerances for connecting quadrants together.

The booms are stowed around the four exterior sides of the CubeSat for three reasons:

- Allows multiple points of connection between the booms using wires to distribute loads and provide tension to ensure full deployment is achieved, as opposed to a single pair of connections at the boom tips that can cause high buckling loads during unrolling and introduces uncertainty in achieving full deployment,
- The roots of the four booms may be attached to the CubeSat chassis at two points providing rigidity as opposed to a single connection at the central spindle (Fig. 3),
- All available interior volume is prioritised to accommodate the stowed, long helical boom.

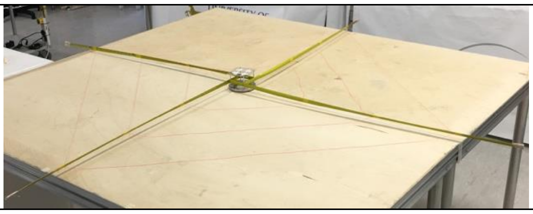

Fig. 2: The ground plane booms and connecting wires.

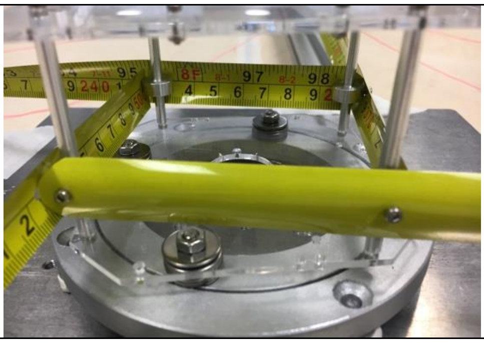

Fig. 3: Connection between booms and CubeSat chassis.

II.II Helical Antenna

The primary requirements of the helical boom are to compactly stow and provide the optimal geometry for a helical radiating element, as shown in Fig. 4.

The present bistable helical boom prototype is made from glass-fibre/polypropylene-resin, achieves a bistable coil diameter of ~110 mm, coiled height of ~120 mm, and is ~19.8 g/m, based on a prototype boom of mass 76.76 g with length 3870 mm. (The free space inside the coil is available for accommodating additional helical turns.) The stowed-to-deployed volume (*i.e.* packaging ratio) is approximately 1:106 per helical turn. This can be improved 2.5x by trimming the cross-section to a coiled height of 50 mm to achieve a superior packaging ratio of 1:255 per helical turn.


Fig. 4: The helical boom, coiled and deployed.

Subsequent prototypes will achieve more compact coils of diameter 46 mm and height 50 mm for packaging ratios of 1:1,400 per helical turn, in addition to higher stiffness and lower mass (closer to 12 g/m). Glass-based composite booms with integrated conductive elements have also been tested.

III. SYSTEM BEHAVIOUR

III.I Antenna Deployment

Steel booms *i.e.* 'tape measures' were used in this prototype deployment testing, as shown previously in Fig. 2, with snapshots of the deployment test shown in Fig. 5. The CubeSat is connected to a turntable to provide free rotation. The four booms of the ground plane are oriented in the same direction (*i.e.* concave side facing anti-clockwise) and supported by a simple gravity compensation rig comprised of a wire connected to the free tip of the booms and guiderail rollers positioned above, aligned along the boom axes.

The ground plane is stowed by buckling and wrapping the booms ~100 mm along the length around the exterior of the CubeSat, and locking into position using a simple catch mechanism which can be released to initiate the strain energy deployment. Upon release the first 2-3 turns of the ground plane rapidly unfold in the clockwise direction after which the CubeSat begins to spin anti-clockwise in reaction. As a consequence the deployment is no longer sequential and the spinning CubeSat begins to unfold the interior folds of the ground plane that are nearer the boom root. As most of the boom length straightens, deployment decelerates until each boom exhibits a single bend, which eventually unwraps and the ground plane is fully deployed with the wires in tension. At this point the structure is stable enough to simply rotate clockwise and anti-clockwise by hand at one end of a boom.

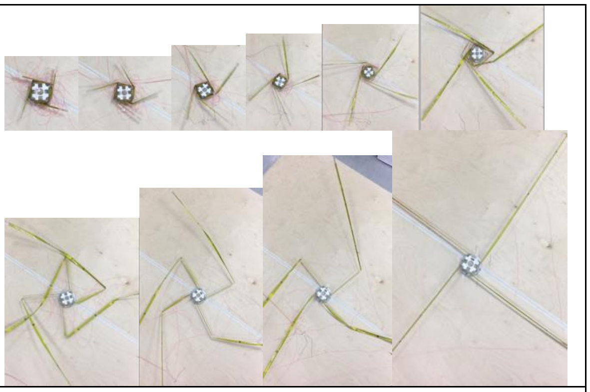
Fig. 5: Video snapshots of the ground plane deployment test. The duration of the sequence is 4 seconds.

Copper-beryllium (CuBe) booms will be selected for the final design primarily due to high electrical conductivity which is beneficial for the ground plane function. The CuBe booms are currently under investigation to optimize boom geometry and integration into the CubeSat: radius of curvature and arc-length affects the root connection, stowed size, stored strain energy released during deployment, and deployed stiffness. Each of CuBe boom is approximately 43 g/m.

As shown in Fig. 6 deployment of the helix is achieved using a DC motor installed internally and connected to a centralized spindle to which the helical boom root is attached. (A structure is used to support the helix during on-Earth deployment.) This enables controlled unrolling, which is essential for a large, low stiffness structure, and retraction. Controlled deployment may also provide valuable verification opportunity in the commissioning phase during which AIS signals may be received before all helical turns are unrolled.

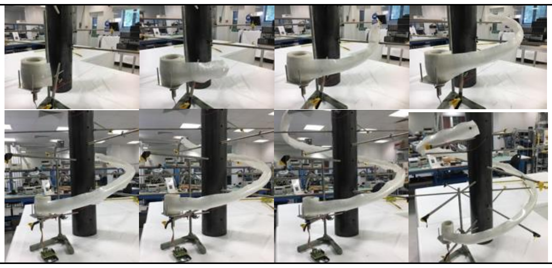

Fig. 6: Snapshots of the helical boom deployment.

III.II Antenna Performance

Two elements are critical for the system to function as a high-gain antenna: the helix and the ground plane. The helical section provides the radiating element and enables circular polarization, whilst the ground plane reduces back lobe radiation by reflecting signals in the direction of the helical axis, as shown in Fig. 7 – in practice this is the Earth-pointing direction. Simulations modelling comparing solid and mesh ground planes confirmed minimal effect to radiative performance.

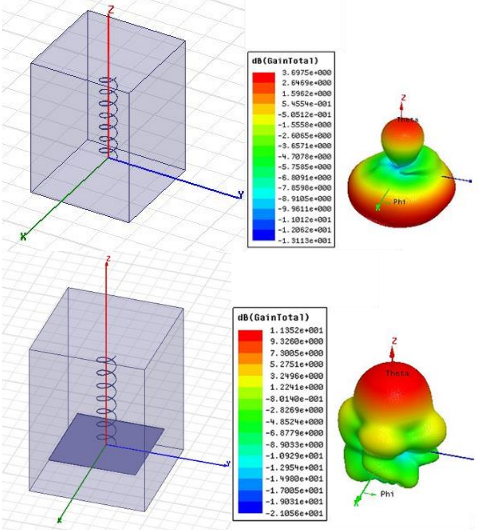

Fig. 7: Simulations of helical antenna radiation pattern and performance, and the effect of a ground plane.

IV. CONCLUSION

The antenna system presented demonstrates the early proof-of-concept for an ultra-compact helical antenna for small satellite platforms. The system builds on proven space architecture and utilises a new form of bistable composite – helically curved slit tubes – to achieve high packaging ratios and enable high-gain radiation performance for low frequency applications.

The separate antenna elements presented may be arranged and integrated in more ways than in a single 1U CubeSat platform. For instance in a 3U CubeSat the ground plane may be fixed to and deployed from the bottom section of the main body of the satellite, and a suitable method used to deploy and position the top 1U section approximately ¼-wavelength away (~460 mm) – this section would be dedicated to the helical boom antenna. Designing an offset between the helix and ground plane is beneficial for impedance matching.

Future work will focus on optimizing and integrating CuBe booms for the ground plane, improving the dimensional stability of the helical boom, and integrating an 8-turn, 14 m-long helix into a 1U CubeSat.

ACKNOWLEDGEMENTS

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