Deployable Bistable Composite Helical Antennas for Small Satellite Applications

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An ultra-compact deployable helical antenna is presented, designed to enhance space-based reception of Automatic Identification System signals for maritime surveillance. The radio frequency performance (i.e. peak gain and directionality) is simulated at 162 MHz using ANSYS High Frequency Structure Simulator and evaluated over a range [0.5–8] of helical turns. Established and commercially available omnidirectional antennas suffer interference caused by the large number of incoming signals. A 7-turn helix with planar ground plane is proposed as a compact directional-antenna solution, which produces a peak gain of 11.21 ± 0.14 dBi and half-power beam width of 46.5 ± 0.5 degrees. Manufacturing the helical structure using bistable composite enables uniquely high packaging efficiencies. The helix has a deployed axial length of 3.22 m, a diameter of 58 cm, and a stowed (i.e. coiled) height and diameter of 5 cm — the stowed-to-deployed volume ratio is approximately 1:9,800 (0.01%). The use of ultra-thin and lightweight composite results in an estimated mass of 163 grams. The structural stability (i.e. natural vibration frequency) is also investigated to evaluate the risk an unstable deployed antenna may have on the radio frequency performance. The first vibration mode of the 7-turn helix is at 0.032 Hz indicating the need for additional stiffening.

I. Introduction

THIS work presents a deployable helical bistable composite structure for small satellite applications, as shown in Fig. 1. A space-based Automatic Identification System (S-AIS) receiver is envisaged that comprises of a single, centralized helical antenna positioned above a ground plane. The subsystem utilizes four straight and one helical bistable composite slit tube (BCST) co-coiled to stow inside a 1U CubeSat form factor.

Fig. 1 Small-satellite S-AIS receiver subsystem comprising of multi-functional BCSTs, monopole antennas, and gossamer ground plane (left). A helical BCST prototype is presented (right)

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BCSTs are open-section tubular structures that exhibit two stable configurations, deployed and coiled — analogous to a tape measure — but with the added benefit for no required constraint to remain stowed. This bistable behavior enables many lightweight and compact deployable structures, particularly effective in small satellite applications.

Five BCSTs simultaneously unroll during the deployment phase as shown in Fig. 2. The helical BCST unrolls to form a helix whilst four straight BCSTs extend to deploy a pre-folded gossamer ground plane. (The ground plane is illustrated in the final, fully deployed step — its stowage and unfolding are not presented in this work.) Copper strip/mesh is embedded within the helical BCST to provide the conducting antenna element and the gossamer may be stowed in a separate space from the BCSTs. In addition, the four straight BCSTs incorporate monopole antennas, which enable omnidirectional CubeSat communications for housekeeping and telemetry over 146 MHz (uplink) and 437 MHz (downlink) frequencies. In this case, these are fixed to the free ends of the BCST booms but they may also be directly embedded within.

Fig. 2 Deployment of the S-AIS receiver subsystem — a 4-turn helical antenna is presented. The deployed ground plane is shown in final step

A. Helical Antenna Design

In helical antenna design, directionality and gain are purely geometrically dependent [1, 2]. When the operating frequency and helical antenna dimensions are so intimately coupled, the first problem arising is how to shrink the packaged size, and secondly how to deploy the antenna in space. There are many stowage and deployment methods being investigated such as scrunch-up, roll-up, origami-folded, and actively controlled deployment mechanisms. AISat featured a 57 cm diameter, 4 m long helical antenna that deployed like a spring and was designed to receive AIS signals at 162 MHz [3, 4]. Inherently small helical antennas (i.e. designed and optimized for higher frequencies) fit easily inside CubeSat volumes [5–9]. Promisingly, compact high-gain antennas designed for low frequencies of 300 MHz approaching those of AIS can be made to fit in small satellites [10–12], although their uncontrolled deployment methods lead to highly unpredictable pointing and vibration effects on the satellite.

The helical antenna considered in this work is designed and optimized for receiving S-AIS signals in axial mode at 162 MHz using Kraus’ formulas [2]. These formulas are presented in (1)–(5) and highlight the large antenna dimensions required — compared to CubeSat dimensions — for operation at such low frequencies as was the case for AISat. The design equations for an axial mode helical antenna are,

$$C = \lambda = 1.85 \text{ m} \quad (1)$$

$$S = \frac{\lambda}{4} = 0.46 \text{ m} \quad (2)$$

$$R = \frac{\lambda}{2\pi} = 0.29 \text{ m} \quad (3)$$

where C is the helical circumference, S is the spacing between each turn of helix, and R is the helical radius. A seven-turn helical antenna is modeled ($N = 7$) to produce half-power beam width (HPBW, a measure of directionality),

and gain (G , a measure of efficiency) of:

$$\text{HPBW} = \frac{52^\circ}{C} \sqrt{\frac{\lambda^3}{NS}} = 39.4^\circ \quad (4)$$

$$G = 10.8 + 10 \log \left(\frac{NC^2S}{\lambda^3} \right) = 13.2 \text{ dBi} \quad (5)$$

The significant engineering challenge in achieving a small-satellite deployable solution is apparent from these calculations (1)–(3). The deployed helix has a diameter of approximately 60 cm and a height of 3.2 m whereas a ‘1U’ CubeSat volume is only 10 cm x 10 cm x 10 cm. Furthermore, a flat, square ground plane with sides 1.39-2.78 m (i.e. $3\lambda/4$ to 1.5λ m, respectively) is desirable in accordance with established antenna design principles [2], which requires the four straight booms to be approximately 1-2 m long. This is possible using ultra-compact BCSTs, which generally lend themselves to deployable structures applications. In fact, BCSTs are particularly suited to low-frequency antenna structures — which require large dimensions — due to their very high packaging efficiency and tuneable deployed geometry.

B. Straight & Helical Bistable Composite Slit Tubes (BCSTs)

In the mid-1990s the concept for a rollable helical tube was proposed and verified [13–15], which could serve as the antenna and structure for such. Manufactured out of copper beryllium alloy, the helical tube was 60 cm in diameter and featured a slit along its length so that it could be flattened and rolled up into a compact coil measuring a few centimeters in diameter. Using this versatile structure, a compact coil could be housed inside a CubeSat, launched into space, and unroll into a large helical antenna for S-AIS reception.

The coil required constraint to prevent uncontrollable deployment, analogous to a tape measure, which was provided by the technician’s hands in that case. In addition, a deployment strategy is required for unrolling the coil in space. Coiling the booms around a central spindle and compressing the structure using rollers and springs forms a suitable mechanism that is typically used in CubeSats for these two purposes [16], however, mechanisms add mass and complexity with neither being desirable for achieving a simple and low cost CubeSat. A solution removing the need of constraint presents itself by replacing the copper beryllium alloy with bistable composite material.

Bistable composite materials exhibit attractive and versatile behavior [17]. Their mechanical characteristics are achieved by tailoring the composition and deployed shape, allowing them to occupy either one of two transferable and stable, unconstrained configurations. This material presents a simpler and lower mass alternative that recently enabled the InflateSail mission to successfully demonstrate the first in-space deployment of a drag-sail for satellite deorbiting [18, 19]. Recent advances for modeling the bistable behavior of new forms of BCST have been developed [20, 21], capable of introducing additional curvatures into the tubular structure to enable the design and manufacture of ultra-compact and deployable BCST helices that can be deployed from the same form of deployer mechanism.

Achieving high deployed dimensional stability is a recurring challenge. This is a greater concern given that the cantilevered helix presented does not incorporate a central mast, which is typically used in traditional non-deployable and static antenna structures. Unlike the helical antenna, monopole antennas (e.g. exactView-9 [22]) do not require additional stiffening. Others have tried to address this by incorporating axial stiffeners [3, 4] and a webs of composite strips [11]. Another approach deploys a compressed helically curved composite spring that is axially tensioned using polyimide tapes, to address the effects of creep on the deployed dimension, which arise in the stowed state [23].

C. Applications: Space-Based Automatic Identification System (S-AIS)

AIS is a maritime safety and vessel traffic system regulated by the International Maritime Organization that is used for identification, monitoring, and collision avoidance of large ships [24]. The regulation “...requires AIS to be fitted aboard all ships of 300 gross tonnage and upwards engaged on international voyages, cargo ships of 500 gross tonnage and upwards not engaged on international voyages and all passenger ships irrespective of size. The requirement became effective for all ships by 31 December 2004”.

AIS operates at 162 MHz in the very high frequency band (i.e. 30-300 MHz) and coverage depends on the altitude of the antenna used. Ship-to-ship communications range is typically 37 km (20 nautical miles) whereas shore-to-ship is around 74 km (40 nautical miles) and limited by ships disappearing over the horizon. This creates demand from shipping companies for deep-sea vessel and shipping-route monitoring to ensure their assets are safe, particularly from piracy along certain routes. A promising solution in achieving long-range identification and tracking services at marginal

cost takes the form of S-AIS receivers in low-Earth orbit (LEO) [25]. S-AIS would have line-of-sight to the horizon of more than 1,850 km (1,000 nautical miles). The Canadian Advanced Nanosatellite eXperiment-6/Nanosatellite Tracking Ships (CanX-6/NTS) satellite demonstrated this for the first time in May 2008 [26], and with an original target lifetime of one month continued to operate for over four years. Pioneering S-AIS missions over the 2007-2010 period proved promising but yet lacked global coverage, constellations of small and cheap satellites would be required for this [27]. A number of these early demonstrators would begin to comprise the first ever, and first European S-AIS services, exactAISTM and LuxSpace, respectively. Other S-AIS businesses such as Spire Global underline growth in the emerging and global, Earth-observation space economy.

However, AIS was not originally designed for in-space reception leading to some technical challenges that limited the performance of early S-AIS [28], namely the interference of AIS signals being transmitted simultaneously from thousands of vessels captured in the wide coverage area of omnidirectional antennas. (As an analogy, this is similar to over-exposure when recording an image.) The busiest shipping routes, ports, and their local vicinities may bare host to over 5,000 ships at any one moment. As a result of this coupled with AIS's technical limitations, ship detection *probability* becomes a key metric in S-AIS mission analysis and design [29]. Detection probability is inversely proportional to the number of ships within the coverage area, but is proportional to observation time. Observation time can be increased with the swath width, however in doing so, the coverage area and number of ships simultaneously observed are increased culminating in decreased detection probability.

Higher flexibility and lower cost S-AIS missions are possible with fewer satellites with targeted coverage approaches using directional antennas. This is far better than non-directional antennas, which observe areas up to 5,000 km in diameter thus becoming overwhelmed by large volume of incoming signals. In August 2014, AISat demonstrated the first in-space use of an axial mode (i.e. directional) helical antenna to detect AIS signals from ships [3, 4]. The satellite operated at an altitude of 660 km and used a narrow beam targeted at a much smaller area just 750 km in diameter. With detection probability greatly improved, Earth-surface coverage, which had now been sacrificed, may be recovered using beam-forming (i.e. pointing) techniques [28].

II. Method

Two main aspects of the helix are investigated: radio frequency (RF) performance, (i.e. peak gain and HPBW) and; mechanical properties of the structure that comprise of the stowed and deployed geometry, stowed-to-deployed volume ratio, natural vibration frequency, and estimated mass.

A. Deployed & Stowed/Coiled Configuration

The helical antenna formulas presented in (1)–(5) drive the deployed helical structure dimensions of $R = 29$ cm, $S = 46$ cm, and axial length, or height (i.e. number of helical turns multiplied by the helical spacing). The geometry for one turn of the helical BCST including its cross-section profile is presented in X-Y-Z coordinates in Fig. 3. Carbon-fiber/epoxy-resin unidirectional composite material strips with the mechanical properties provided in Table 1 are considered and may be engineered to be bistable through an antisymmetric laminate scheme of plies that are suitably aligned at an angle from the longitudinal axis of the boom. The size of the bistable coil (i.e. the stowed configuration) is predicted using a recently developed strain energy based model [21]. The helical structure dimensions from (2) & (3) are implemented into the helical BCST model and in addition consider a tube cross-section radius of $r = 1.6$ cm, which subtends an arc of 180 deg. The helical BCST model predicts an untwisted bistable coil is produced with a radius of $r_{coil} = 2.37$ cm using a middle ply fibre angle of $\beta = -34$ deg in an antisymmetric laminate of $[\pm 45^\circ/\beta^\circ/\pm 45^\circ]$ as presented in Fig. 3. The helical BCST coil has a height of approximately 5 cm providing sufficient margin for stowage within a 1U CubeSat volume.

B. Radio Frequency Simulation

In order to evaluate the potential 162 MHz S-AIS reception performance of the helical antenna, ANSYS High Frequency Structure Simulator (HFSS) [31] is used to model, simulate, and determine RF properties including radiation pattern, peak gain, and HPBW [32]. The antenna material is modeled as a helically curved ribbon of perfect electrical conductor — the ground plane is also modeled as perfect conductor material. A suitable feed line is modeled and excited using a lumped port with match impedance of 50 Ω . Due to ground plane effects on the achievable antenna gain and directionality, two sizes of square, planar ground planes are simulated of sides 1.39 m ($3\lambda/4$ m) and 2.78 m (1.5λ m), and 2 mm thickness, as shown in Fig. 4 — one result for the total gain and radiation pattern is presented.

Fig. 3 One turn of a deployed helical BCST and its predicted bistable coil using recently developed models [21]

The simulation result indicates a peak gain of 11.07-11.35 dBi and HPBW 47-46 deg depending on the size of ground plane for a 7-turn helical antenna, which closely match the values calculated in (4) & (5). This simulation setup in HFSS is used to produce the RF results for N -turn helical antennas. Discrepancy of +2 dBi and -7 deg from Kraus' relatively optimistic formulas arise for a number of reasons including neglecting the cross-section shape of the antenna and assuming an infinite ground plane.

Table 1 Unidirectional (UD) ply mechanical properties [30] and laminate composite layup scheme

Property	Value	Units
UD longitudinal modulus, E_1	77.372	GPa
UD transverse modulus, E_2	4.0	GPa
UD Poisson ratio, ν_{12}	0.309	-
UD shear modulus, G_{12}	3.293	GPa
UD thickness, t	0.057	mm
UD mass density, ρ	1000	kg/m ³
Layup scheme	$[\pm 45/\beta/\pm 45]$	Degrees
Number of plies	3	-

Fig. 4 HFSS simulation setup and RF results for a 7-turn helical antenna as outlined

C. Natural Frequency Simulation

The natural frequency of cantilevered helical BCSTs in zero gravity is investigated using the finite element (FE) approach in this section. The helical model is created in SolidWorks 2015 [33] and imported into pre-processor software HyperMesh V12.0 [34] to create and setup composite FE models for analysis. The FE solver Nastran [35] is used to determine the free-vibration frequencies and modes of fixed-free helical BCSTs. Post-processing is performed in HyperView. One end of the helical BCST is fixed to the central spindle of the CubeSat deployment mechanism whilst the deployed end is free as shown in as shown in Fig. 5. Modeling of the boom-spindle connection is simplified by modeling the spindle as a flat constraint. Shell elements CQUAD4 based on the Kirchhoff-theory in Nastran are adopted due to their robustness in modeling thin shell structures. A typical mesh size of 10 mm x 10 mm is chosen for the FE models of BCSTs to achieve better convergence.

Fig. 5 Natural frequency simulation setup of cantilevered helical BCSTs in zero gravity using SolidWorks

III. Results & Discussion

The helical antenna RF performance, natural frequency, stowed-to-deployed volume ratio and estimated mass for given number of helical turns are presented in Table 2 and plotted in Fig. 6.

The results show that RF performance can be improved through the addition of helical turns i.e. lengthening the helix. The peak gain increases with number of turns and is improved by 67% from one to eight turns, 9.42 to 11.64 dBi. (Note that gain is measured using a logarithmic scale so for instance, an increase of +3 dBi indicates a doubling of the gain.) The HPBW decreases relatively linearly with number of turns, by -8.3 deg/turn on average. A consequence for selecting long helices to optimise the RF performance is the poorer deployed dimensional stability, which is decreased as indicated by the natural frequency plot showing an exponential decline as the helix is lengthened. The natural vibration frequency is the weakest aspect of the helical BCST that needs improving. Future designs could address this by using axial stiffeners — an approach used on AISat — to achieve suitable precision of the deployed structure, such as the helical spacing, which is critical for producing the desired RF performance. The axial length ($= N \times S$) and estimated mass ($= \text{boom length} \times 3 \text{ plies} \times 4 \text{ g/m}$) scale linearly with the helix length, whereas the stowed-to-deployed packaging ratio as a percentage rapidly decreases to approximately 0.01% and continues to improve despite increasing helical length. The uniquely high packaging efficiency demonstrates BCST effectiveness — particularly in achieving curved deployed geometries — in small-satellite applications.

Table 2 Helical BCST antenna performance and mechanical/physical properties as a function of the number of helical turns. RF performance for ground planes of sides (a) $3\lambda/4$ m and (b) 1.5λ m are presented

Number of helical turns	RF properties (for each ground plane, presented as $a-b$)		Mechanical/physical properties (helical BCST only)			
	Peak gain, dBi	HPBW, deg	Natural frequency, Hz	Axial length, m	Mass, g (<i>est.</i>)	Packaging ratio
0.5	7.37–7.59	69–94	3.57	0.23	12	1:700
1	8.95–9.42	70–84	0.83	0.46	23	1:1,401
2	8.92–9.04	66–59	0.36	0.92	47	1:2,802
3	9.16–10.31	63–55	0.17	1.38	70	1:4,203
4	9.86–10.54	54–55	0.10	1.84	93	1:5,604
5	10.40–11.05	53–51	0.06	2.3	116	1:7,005
6	10.71–11.14	51–49	0.045	2.76	140	1:8,406
7	11.07–11.35	47–46	0.032	3.22	163	1:9,807
8	11.33–11.64	45–44	0.025	3.68	186	1:11,208

Properties of the helical BCST antenna presented are compared with alternative solutions in Table 3. The alternatives presented include two S-AIS receivers — an omnidirectional monopole antenna as used on exactView-9 [22] and a directional helical antenna as demonstrated on AISat [3, 4] — and three more helical antennas for non-AIS applications, which use various deployment methods and designed to operate at different frequencies. These are 365 and 400 MHz [9, 11], and in the range 300-600 MHz [10, 12]. Although a direct comparison cannot be made between these AIS and non-AIS antennas, the details are insightful for the relative capabilities of each antenna solution and deployment.

Superior BCST packaging efficiency enables a helical antenna solution both with a smaller satellite footprint — than achieved on AISat and the folded conical log spiral antenna — and a 7-turn helix capable of stowing to 0.01% its deployed volume. This translates to a stowed-to-deployed volume ratio of over 1:9,800, far superior to AISat (ratio of approximately 1:36, limited due to large satellite footprint) and the scrunch-up helical antenna designed for 400 MHz with a ratio of 1:300. The helical BCST establishes a new class of ultra-compact deployable structure with high packaging efficiencies superior by at least two orders of magnitude to other deployable tubular structures. In addition, BCST deployability enables controlled/actuated and even partial deployment, and potentially retractability to enable new operational possibilities e.g. stowage of the helical antenna in preparation for large attitude control adjustments.

The estimated helical BCST mass is half (54%) that of the composite strip, which has the advantage of smaller dimensions for its operation frequency, and a fifth (19%) of the AISat composite spring. In addition to achieving a lighter and more compact antenna the peak gain and HPBW may be improved to match that of the 10-turn helix used on AISat by adding two more turns. The natural frequency, as discussed previously, may be improved with axial stiffeners of negligible mass.

Fig. 6 Helical antenna performance and mechanical properties plotted against the number helical turns. The RF results plotted are for a helix with a 1.5λ m-sided ground plane

Table 3 Comparison of small-satellite deployable antennas designed for S-AIS and other frequencies. ‘—’ indicates unknown value

Antenna	Peak gain, dBi	HPBW, deg	Natural frequency, Hz	Axial length, m	Mass, g
Monopole (exactView-9) [22]	2.15	omni.	3.2	0.93	6
Prestressed spring (AISat) [3, 4]	14	39	0.18	4	860
Pantograph [9]	8	—	—	0.5	—
Composite strips [11]	13	40	0.1839	1.38	303
Conical log spiral [10, 12]	>5	—	—	0.185	—
This work	11.21 ± 0.14	46.5 ± 0.5	0.032	3.22	163

IV. Conclusion

A small-satellite helical antenna for S-AIS reception is presented with the primary structure made from bistable composite. The uniquely high packaging efficiency of BCST structures lend themselves to ultra-compact deployable applications, particularly for achieving curved geometries given the relatively decoupled relationship between the stowed

and deployed size. This is apparent for the 7-turn helical antenna presented, which achieves a stowed-to-deployable volume ratio of 1:9,800, a packaging efficiency unseen in the deployable structures literature. Future designs will mitigate the low natural frequency of the deployed structure to ensure good dimensional stability.

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