CATSAT: A 6U Inflatable Antenna technology demonstration mission

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ABSTRACT

This paper describes the design, development and flight testing of a half-meter spherical membrane reflector antenna built out of reflective and clear Mylar segments. A custom-built line feed optimized for operation at 10.5 GHz is used for spherical correction. The antenna system has been jointly developed by the University of Arizona and FreeFall Aerospace, Inc as primary payload to be demonstrated on-orbit on the University of Arizona's 6U LEO mission CATSAT, nominally scheduled to launch no earlier than September 2022. The launch is a part of NASA's CSLI program. The mission has been designed for a low earth sun-synchronous orbit. With the primary objective being the demonstration of high data rate transmission from the inflatable antenna system. This paper describes the mission and pre-flight development activities. We present key results from integration and testing activities and future work planned.

INTRODUCTION

Small satellites such as CubeSats, while providing low cost access to space, are limited in allowable payload mass and volume and available power. Communication systems on board these satellites face significant challenges due to low available mass and volume. Enabling science quality data at high down-link rates from small satellites would need a high gain antenna (HGA) approach. HGA's typically require large surfaces which when constructed out of thermoplastic membranes provide a potential low-risk scalable solution for small satellite platforms. This work builds up on the authors previous work on spherical membrane reflector antennas for small satellites. On the authors previous work on spherical membrane reflector antennas for small satellites [1]–[4].

High gain reflector antennas (HGA) deployable from CubeSats have been limited to aperture diameters of about 0.5 m. Most of these have employed paraboloid mesh reflector geometries deployed using rib structures and linkage mechanisms. On-going efforts to scale up these designs to 1 m^2 apertures have necessitated alternate approaches due to inherent complexities of the design. As such, this methodology does not provide a low-risk path to even larger deployed apertures. Inflatable structures offer a mechanically simple and scalable pathway towards deploying apertures with much larger sizes. Employing inflatable reflectors have shifted our focus towards spherical reflector geometries. Spherical shapes are natural to inflated membranes as opposed to parabolic shapes. While spherical reflectors are less efficient than parabolic reflectors, by enabling membrane technology, they can allow much larger deployed apertures from small satellites. Our work leverages from our extensive experience working with spherical inflatable antenna designs. Over the last few years, we have developed key enabling technologies to develop a CubeSat based spherical inflatable antenna system optimized for X-band operations as shown in figure 2. These include an on-orbit inflation pressure regulation system, a gossamer axisymmetric line feed and a packaging and deployment system.

This paper describes progress made over test prototypes [5] towards flight qualification and on-orbit demonstration of the inflatable antenna system. The inflatable HGA has been selected for launch by NASA's CSLI program as a technical demonstration mission on board a 6U platform. The mission is named CATSAT and is being run by the University of Arizona in partnership with FreeFall Aerospace, Inc and Rincon Research Corporation. Figure 1 shows a graphical illustration of CATSAT with its antenna deployed on orbit.

We describe developmental progress towards mechanical and RF design of the membrane antenna and line feed system, antenna stowage and packaging system, and expected on-orbit performance analysis. The CubeSat is set for nominal launch in September 2022 and deployment in a sun-synchronous at an altitude of about 550 km. The flight hardware includes a 6U CubeSat bus provided by Gomspace Inc.

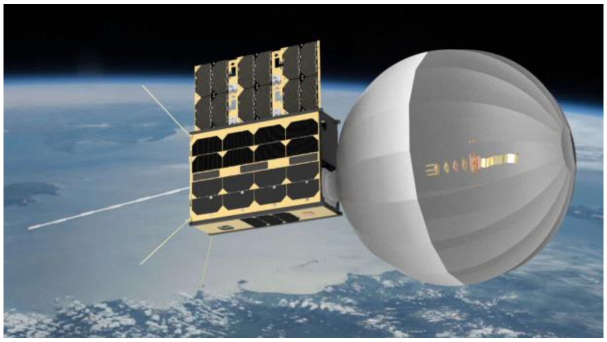

Figure 1. Representation of the inflatable HGA on CATSAT

RELATED WORK

Membrane inflatables constructed out of materials with low elastic moduli offer ultra-lightweight structures with high stowage to deployment compaction ratios. ECHO 1 and 2 balloon mission by NASA in the 1960s [6] were among the first successful attempts.

Figure 2: Echo balloon experiment

Goodyear developed inflatable structure concepts for inflatable truss structures for search antennas, spherical inflatables for radar calibration and lenticular parabolic reflectors [7]. An orbital demonstration of a lenticular inflatable paraboloid was conducted on the Inflatable Antenna Experiment flown by NASA on space shuttle mission STS-77 in May, 1996. The structure consisted of a parabolic reflector with inflatable support beams that deployed out of a box [7]. Unpredicted dynamic modes caused the mission to be a partial success.

Low cost platforms such as CubeSats face the constraints of low available mass and volume. Enhancing the performance of antennae on board spacecraft can be done using the following pathways: a) Co-operative/ Collaborative communication: The concept utilizes spacecraft in formation to relay data towards earth. Cooperative communication can be achieved by combining signals via coding and structuring network architectures or by collective beam forming using an array of antennas. Due to a high redundancy, they offer a reliable and failure safe means of communication. However, to effectively synchronize they need very precise coordination. The precision requirements would further increase with high frequency bandwidths since phase and time knowledge would be harder to get at fractions of the wavelength [8]. B) High Gain Antenna (HGA) technology: The two dominant factors governing an antenna's performance are transmission power and antenna gain. For CubeSats, transmission power of available systems is limited to a maximum of a few watts. More powerful systems introduce significant thermal and weight management complexities. A more viable strategy for communications system performance is gain improvement.

High Gain Antenna (HGA) technology has received renewed attention as an enabling technology for high data rate CubeSat telecommunication systems. HGA's include Microstrip Patch Arrays (MPA), rigid deployable Parabolic Reflector Antennas (PRA) and Folded Panel Reflectarrays (FPR) [9]. PRA's have been developed for the Ka band are expected to achieve an efficiency of about 60% occupying a 1.5 U stowage volume for a diameter of 50 cm. They are scalable and have low mass density. However, they are mechanically complex and depend on a complex rib deployment structure to unfurl. FPR's offer high gain (30 – 35 dB) for a low stowage volume. They also deploy using a simple spring release mechanism. Their biggest limitation, however, is their scalability. Inflatable antennae have the potential to provide high gains with a highly scalable, low cost, low weight and reliable deployment mechanism. Inflatables provide a means of 'physical amplification' that is scalable and known to be less complex.

MISSION DESCRIPTION

CATSAT has been selected for launch under NASA's CLSI program on-board its ELaNa 43 mission set for launch NET September 2022. The 6U CubeSat among others is set to be launched in a 550 km altitude sun-synchronous orbit on-board Fire-Fly Aerospace's Black Alpha rocket. Figure 3 shows an overview of the deployed system. Primary payload systems include the following:

1. An X-band inflatable antenna system.
2. A High frequency whip antenna system.
3. An instrumentation module.
4. An inflatable surface metrology module.

The CubeSat is designed for a primary mission lifetime of 6 months.

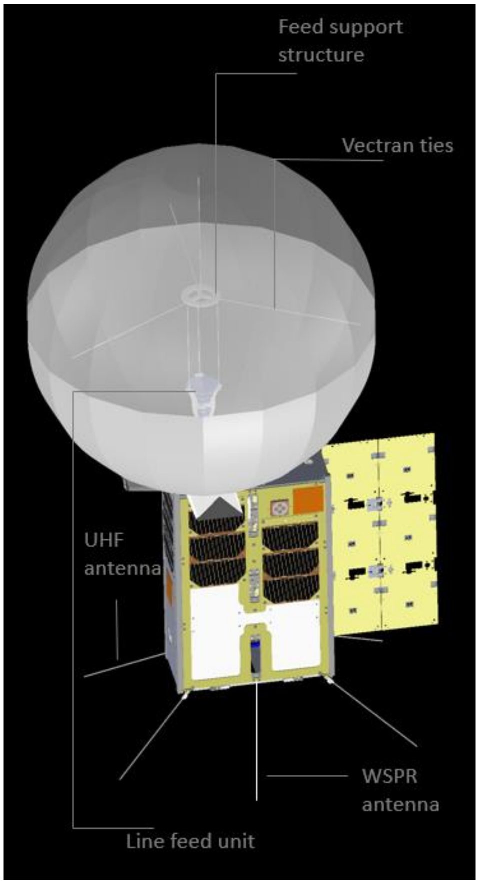

Figure 3: CATSAT Overview

Figure 4 shows a system level description of major CubeSat sub-systems that CATSAT is comprised of. The primary objective of the mission is to demonstrate the feasibility of inflatable antenna technology in Low Earth Orbit (LEO) space. For this, a primary mission requirement is high speed downlink of HD Earth images from an on-board HD camera. This will be done using an an X-band link using the 0.5 m inflatable antenna system. The inflatable membrane antenna system will be deployed from a 1.5 U packaging and deployment system.

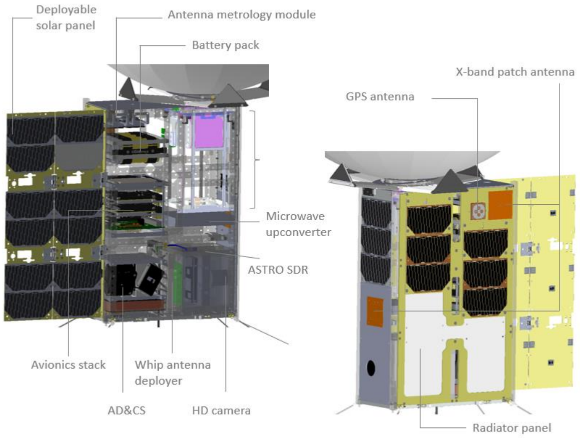

Figure 4: CATSAT System Description

A secondary objective of the mission is to attempt to measure ionospheric structure along the terminator. This will be done using Weak Signal Propagation Reported (WSPR) segments of the HF spectrum. A 0.5 m length whip antenna shall be deployed for a 0.1U stowed form factor which will receive WSPR signals. An on-board SDR and FPGA processing unit is used to process these signals. WSPR signals from worldwide networks of amateur radio stations shall be a part of the experiment. Figure 3 shows a concept of operations.

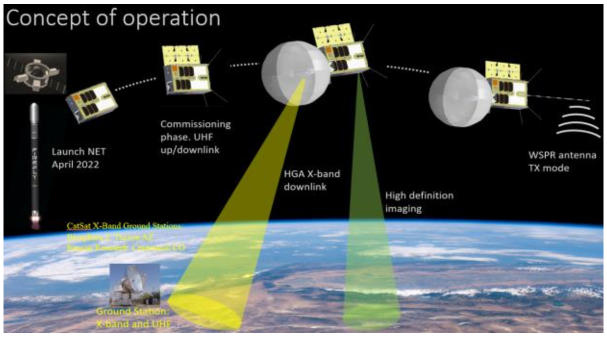

Figure 3: Echo balloon experiment

The following sections describe detailed efforts towards the integration, testing and payload systems development towards flight readiness.

RESULTS AND DISCUSSION

1.5 U Inflatable antenna system

Figure 5 shows the basic construction of the antenna. It consists of a spherical membrane reflector and line feed to correct of spherical aberration. The advantage of a spherical geometry is that it is the natural shape taken by inflatables and is much easier to achieve in comparison with a parabola. A 1.5 U packaging and deployment system has been developed and tested for flight. Figure 6 shows the system and a deployment sequence.

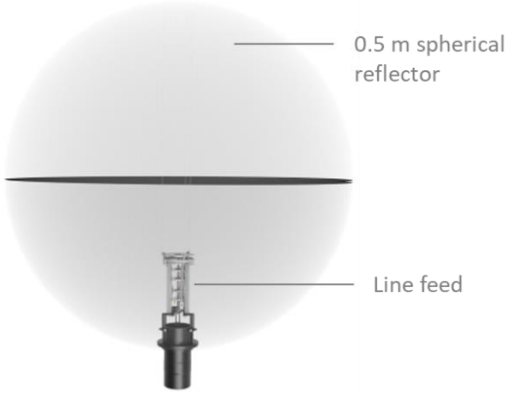

Figure 5: Inflatable antenna system

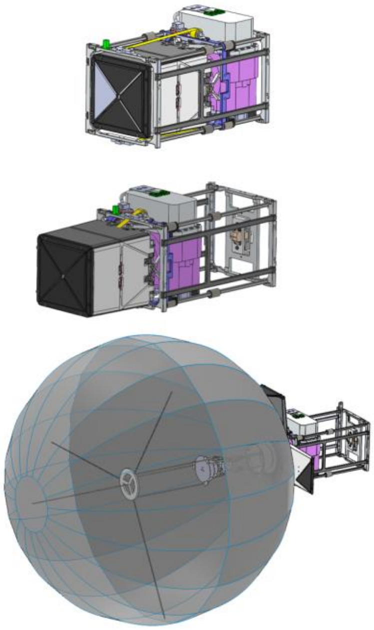

Figure 6: 1.5 U packaging and deployment system

The system has been integrated into the CATSAT 6U bus and TVAC tested as shown in figure 8 and 8. The system uses compressed nitrogen to inflate the reflector. An automated pressure control system has been designed to regulate pressure inside the inflatable during operation.

Spherical line feed system

The line feed system consists of a geometry inspired from a slotted cylindrical waveguide used in the Arecibo observatory. Flight ready feeds optimized for 10.5 GHz operations have been near-field tested. Figure 7 shows processed near field measurements with an estimated peak gain of 26.7 dB at 10.5 GHz.

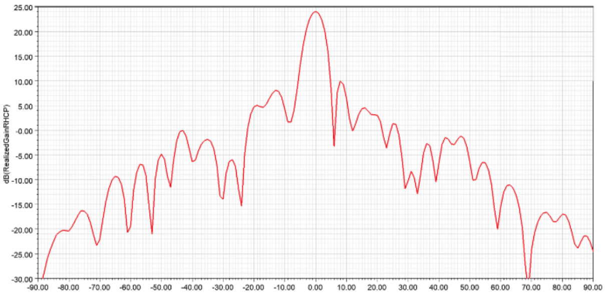

Figure 7: Expected Far-field pattern

Figure 8: Inflatable antenna TVAC testing

Estimating the lifetime of the inflatable system has been a central focus of the systems development. From an environmental point of view, lifetime assessments have been made with respect to drag effects of the inflatable in LEO and its endurance in the event of micrometeoroid impact damage. The next two sections describe our efforts towards these.

Orbit Drag Lifetime Assessment

The NRLMSISE2000 atmospheric model was used to estimate induced drag on a deployed 0.5 m inflatable antenna on board CubeSat buses of varying sizes. These studies were conducted as a function of orbit inclination, launch date, altitude, and inflatable deployment configurations. Table 1 shows estimated LEO lifetime of a 0.5 m spherical inflatable with a drag-coefficient of about 2.2 for a 30-degree orbit inclination. As shown, these effects reduce to negligible above an altitude of about 650 km.

Further analysis using a computational fluid dynamic model is underway to improve drag coefficient estimations in the expected flight regimes.

Table 1: Estimated LEO lifetime

Platform	Lifetime in years			
	500 km	**550 km**	**600 km**	**650 km**
6U	2.00	3.75	11.94	24.48
12U	2.45	4.56	14.52	28.98
16U	3.07	6.53	17.24	

Orbital Debris Impact Assessment

A second and more critical performance aspect studied has been a micrometeoroid impact threat assessment. This study has been necessary to arrive at a design to a carry enough make up gas in the event of damage. NASA's ORDEM 3.1 debris flux model was used to estimate damage probability and expected leak rates due to damage.

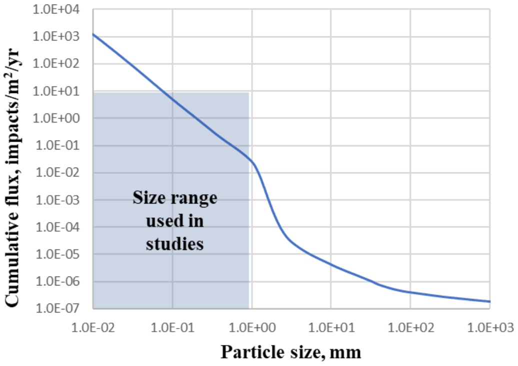

Figure 9: Orbital debris flux at 550 km orbit, 30-degree inclination

A damage assessment model has been developed with the ability to estimate lifetimes as a function of LEO altitude and inclination, launch time, inflation gas composition, inflatable membrane material and membrane thickness. A simulated puncture experiment as shown in figure 10 was conducted in a TVAC chamber to validate the model. A deflectometry based metrology system was developed to measure inflated surface shapes and repeatability.

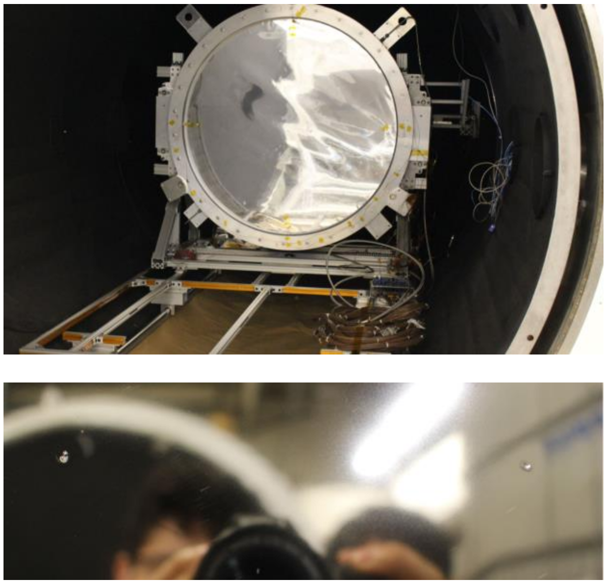

Figure 10: TVAC Impact damage analysis test

Scalability over frequencies

The developed inflatable antenna system is unique in the scalability of its architecture. From an RF and mechanical deployment point of view, this designed can be scaled to much larger aperture sizes and higher frequencies without major re-design of its subsystems. Figure 11 shows the basic structure of the architecture and table 2 shows RF performance specifications over higher frequencies.

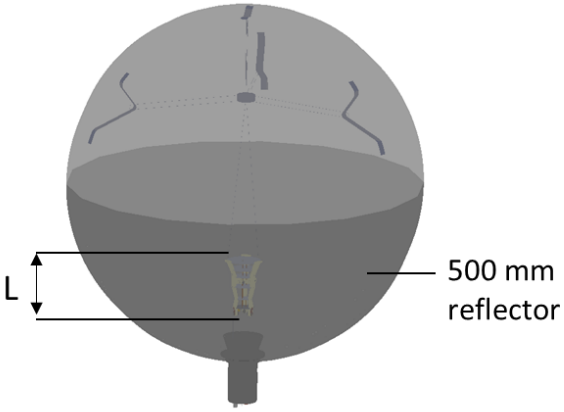

Figure 11: 500 mm reflector system

Table 2: Expected antenna performance at varying frequencies

Frequency (GHz)	Peak Gain (dB)	Beam-width (degrees)	Side-lobe level (dB)	L (mm)
10.5	26.7	5	-17.3	67.4
12	32.0	4	-18.7	79.6
27	38.1	1.6	-16.3	56.7

Future work

Improving the survivability and reliability of inflatable antenna technology necessitates the need for rigidization of the membrane. FreeFall Aerospace is developing on command (ROC) technologies using composite structures that can be packaged, deployed and rigidized on orbit from a CubeSat payload form factor.

Conclusion

The CATSAT mission serves as a pathfinder to determine the feasibility of inflatable antenna technology in space. Data from the flight shall be used to validate lifetime assessment models and the spherical inflatable reflector RF architecture.

Acknowledgments

This work has been in the works for a few years and has been the result of collaboration between the University of Arizona, FreeFall Aerospace, Rincon Research Corporation, Arizona State University, NASA Jet Propulsion Laboratory, US Air Force and Northrop Grumman.

References

List and number all bibliographical references at the end of the paper. When referring to references in the text, type the corresponding reference number in superscript form as shown at the end of this sentence.**Error! Reference source not found.** Use the **References** style for formatting citations, as shown in the following examples:

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