Inflatable antenna for CubeSat: Extension of the previously developed S-Band design to the X-Band

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The inflatable antenna for CubeSat is a 1 meter antenna reflector designed with one side reflective Mylar, another side clear Mylar with a patch antenna at the focus. The development of this technology responds to the increasing need for more capable communication systems to allow CubeSats to operate autonomously in interplanetary missions. An initial version of the antenna for the S-Band was developed and tested in both anechoic chamber and vacuum chamber. Recent developments in transceivers and amplifiers for CubeSat at X-band motivated the extension from the S-Band to the X-Band. This paper describes the process of extending the design of the antenna to the X-Band focusing on patch antenna redesign, new manufacturing challenges and initial results of experimental tests.

I. Introduction

CUBESATS[7] are now providing innovative means to explore space. They are made mostly of COTS products, they are designed and prototyped very quickly and they allow a fast turnaround from proposal to launch and operation. As a result, there is an increasing interest in the aerospace community (academia, industries and space agencies) in using CubeSat for deep space/ interplanetary missions. However, CubeSats were originally conceived mainly with the goal of operating in Low Earth Orbit (LEO) and technological advancements are required to move Cubesats from LEO to deep space. Specifically, one of the areas of research in the field of interplanetary CubeSats is communication: as Cubesats move farther in the solar system new solutions need to be developed to allow the small satellites to close the link.

Current work in this area includes developments in antenna design (deployable as in Ref. 1, reflectarray as in Ref. 2 and 3, inflatables as in Ref. 4), amplifiers and transceiver designs (Ref. 5, 6, and 7), coding (Ref. 8), CDMA (Ref. 9 and 10), multiple spacecraft per antenna (Ref. 11), optical communication (Ref. 12), and collaborative communication (Ref. 13).

This paper focuses on the inflatable antenna technology. The antenna is an inflatable parabolic reflector made of one side reflective Mylar, another side clear Mylar with a patch antenna at the focus. An initial version of the antenna for the S-Band was developed and tested in both anechoic chamber and vacuum chamber in Ref. 14. The simulated and experimental results in Ref. 15 showed that the antenna can achieve a considerable gain (16-20 dB) for a CubeSat and it can be packaged in less than 0.5 U. In addition, the inflation mechanism is performed using sublimating powder (benzoic acid) which eliminates any need for carrying pressure vessels on board. This lightweight, efficiently packaged high gain antenna can be very promising for future interplanetary CubeSat communication, especially for its unique stowing efficiency (20:1), which differentiate the antenna from deployables and reflectarrays antennas currently in development in Ref. 1 and 2.

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However, one very recent trend in interplanetary exploration with small satellites is the transition towards higher frequencies than S-Band and specifically X-Band. As a result, the design of the inflatable antenna has been revised and extended to the X-Band.

This paper is organized as follows: Section 2 summarizes the original S-band design, Section 3 described the redesign process at X-Band, and Section 4 describes the experimental results for the preliminary tests. Section 5 describes the currently ongoing effort to study the different sublimating powder compound and Section 6 is dedicated to the conclusion and to future work.

II. Overview of the S-band design

The inflatable antenna design at S-Band is detailed in Ref. 14. This section is just a summary of the design to facilitate the comprehension of the following sections dedicated to the extension to the X-Band.

The inflatable antenna is a parabolic antenna composed of two Mylar surfaces (a transparent surface and a reflector surface) bounded together. The transparent Mylar surface can be designed in different shapes, while the reflective surface, which is the reflector, has to be parabolic. A patch antenna, designed to fit on a 1U CubeSat side, is used as the feed. When connected to a power source, the patch antenna radiates, the radiation pass through the clear Mylar and it reflects on the parabolic reflective Mylar surface. Two concept shapes for the inflatable antenna were initially studied and developed: a cylindrical and a conical shape, shown in Figure 1. These two shapes were extensively analyzed and compared at the S-Band frequency because they produce very different radiation pattern (peak gain for the conical at S-band is 16 dBi, while peak gain for the cylindrical is 21 dBi). However, at the X-Band the difference in the radiation characteristics are mostly negligible, hence only one shape (the conical) has been manufactured at the X-band (see next section).

The inflatable antenna technology is unique for its low mass (less than 0.5 Kg), volume (less than 0.5 U for a 1 m reflector), and inflation mechanism. The inflation mechanism uses sublimating powder (benzoic acid) which eliminates any need for pressure vessels on the spacecraft, hence making this solution especially appealing for CubeSats launched as auxiliary payloads. In addition, sublimating powder acts as a makeup gas: in case of micrometeoroid perforations, excessive sublimating powder could be used to extend the life of the antenna and to increase its reliability.

The S-Band version of the antenna was tested for mechanical deployment, vacuum chamber inflation and anechoic chamber in Ref. 15. The mechanical deployment tests showed that the antenna can be packaged and deployed successfully using a simple canister mechanism. The vacuum chamber tests showed the correct functioning of the sublimating powder mechanism. The anechoic chamber tests did not allow for a clear quantification of the antenna efficiency, although they identified issues with the polycarbonate plate interface used to inflate the antenna. The lessons learned from manufacturing and testing the S-Band antenna were intensively used in the design, manufacturing and testing of the X-Band version.

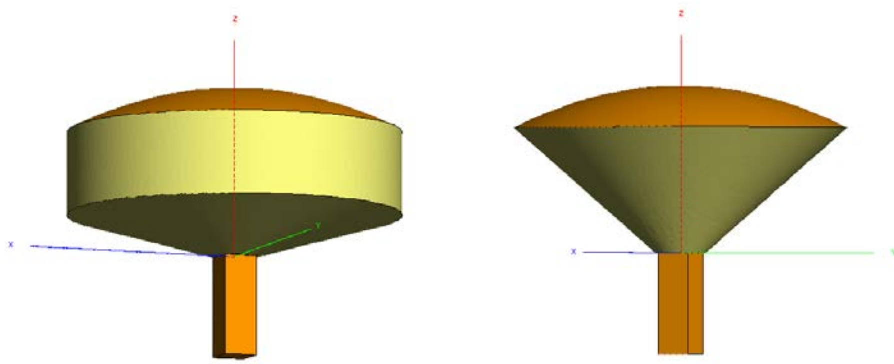

Figure 1. CAD of the inflatable antenna with CubeSat attached. The cylindrical shape is on the left and the conical shape is on the right.

III. X-band design

The extension of the antenna design to the X-Band required three steps. Initially, a new patch antenna to resonate at the new frequency was designed, analyzed and then fabricated. After the patch antenna design was completed, the inflatable antenna design was simulated using a suite of EM software tools to quantify the projected gain. Then, the new X-band reflector was manufactured through the help of a professional Mylar company (Ref. 16). The following sub-sections describe in details each of these steps.

A. Patch antenna design and radiation simulation

The new patch antenna needed to be designed to resonate at the central frequency of 8.4 GHz. The design approach was focused on maximizing the heritage with respect to the S-Band design in terms of material, choice of dielectric and internal impedance. As a result, the main change in the X-Band patch design was the size of the conductive plate which became smaller. The characteristics of the patch antenna are summarized in Table 1.

Table 1. Key parameters of the patch antenna feed (Frequency: 8.4 GHz, Impedance: 50 Ohm).

Component	Material	Parameters
Conductive plate	Copper	11.3 x 7.4 mm
Dielectric	Rogers RT/duroid 5880 ™	90 x 90 x 1.57 mm
Ground	Copper	90 x 90 mm
Probe	PEC	Offset – 3.4261 mm Radius - 0.1 mm

HFSS was used to analyze the antenna. Figure 2 shows a polar diagram of the antenna. A peak gain of 7.39 dBi was estimated.

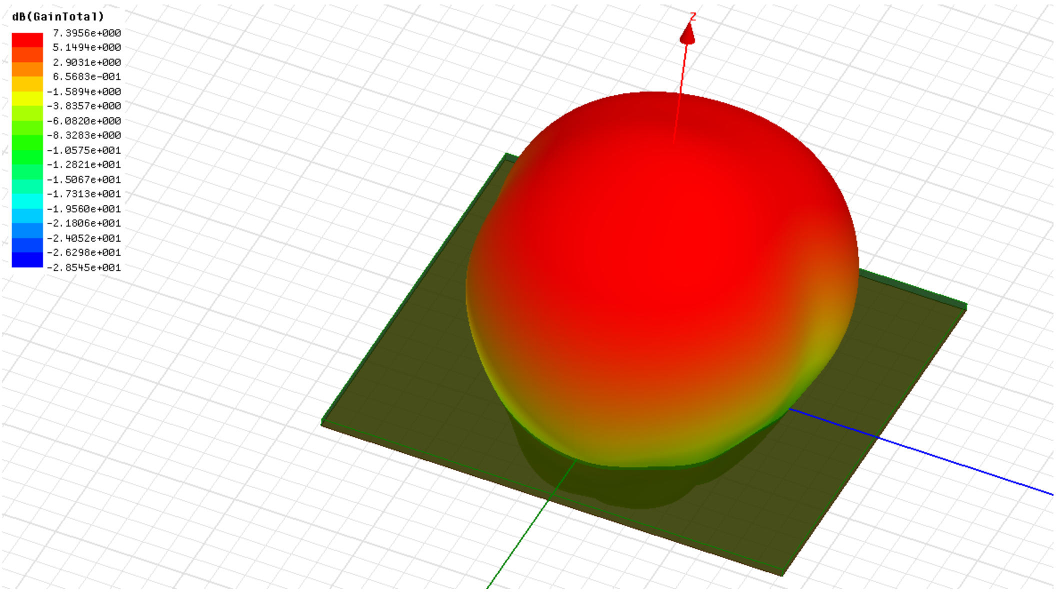

Figure 2. Radiation diagram (3D) of the patch antenna. The peak gain at 8.4 GHz is 7.3 dBi.

Finally, a Gerber file was generated using HFSS and a manufacturer was subcontracted to produce the antenna. Figure 3 shows the antenna manufactured.

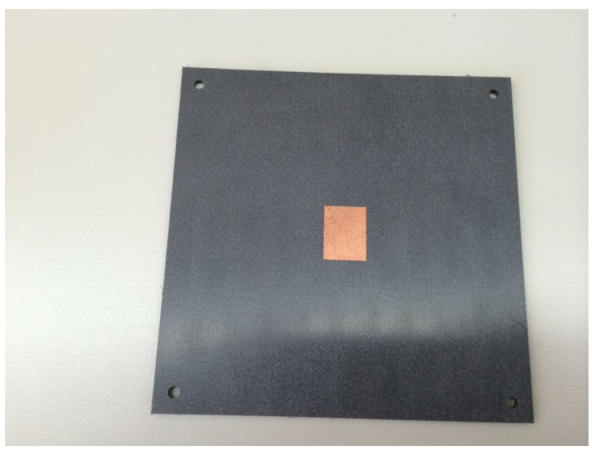

Figure 3. Patch antenna.

B. Inflatable antenna design and simulation

HFSS was used to simulate the entire inflatable antenna at the X-band. The CAD model used in the simulation is shown in Figure 1. The polar diagrams of the radiation (horizontal plane) for both the cylindrical and conical antenna are shown in Figure 4. It is possible to notice that the antenna can achieve a simulated peak gain of 34.4 dBi. It is also interesting to observe that there is not a strong difference in the radiation pattern between the cylindrical and the conical antenna which is very different from the simulation results obtained at the S-Band shown in Ref. 14. An explanation for this fact may be the different behavior of the dielectric Mylar membrane at X-Band than S-Band. Finally, side lobes can be observed in the polar diagram: they are mostly due to the obstruction posed by the CubeSat body. Future studies are focused on minimizing side lobes.

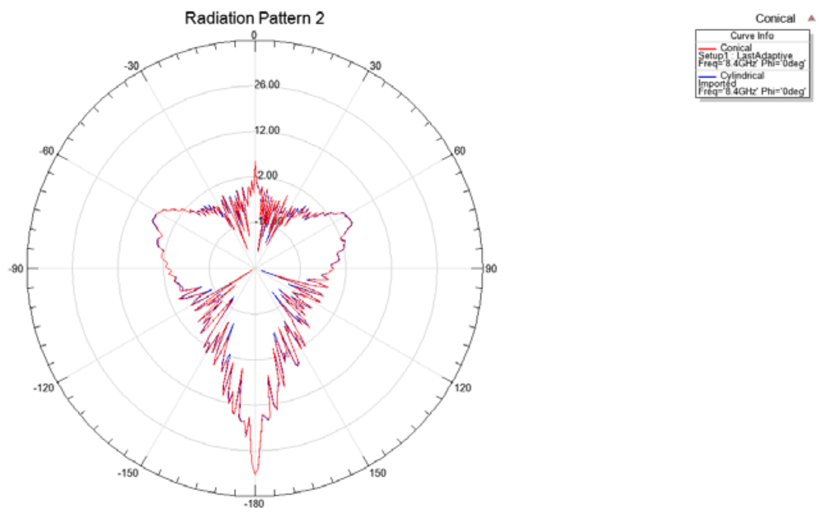

Figure 4: Polar diagram of the inflatable antenna at the X-Band. The peak gain for both the cylindrical (blue) and the conical (red) configurations is approximately 34.3 dBi (8.4 GHz).

The 34.34 dBi gain is very promising because it opens new opportunities for Cubesat to relay data from very far locations in the solar system. Additionally, a very significant result of the simulations is the discovery that the transparent Mylar configuration (cylindrical or conical) does not affect the radiation pattern at the X-band, as it allowed to eliminate the option of the cylindrical configuration from the design trade space. In this way, the research team could concentrate the efforts on only one design: the conical shape which is chosen because it occupies less volume than the cylindrical shape when folded (0.3 U against the 0.5 U).

C. Inflatable antenna manufacturing

A Mylar manufacturer was subcontracted to provide the Mylar dish according to the design. Two versions of the Mylar dish were sent by the manufacturer to JPL to perform preliminary leakage tests: the first membrane was made of a thicker (54 micron) Mylar, while the second membrane was made of a thinner (6 micron) Mylar. The two versions were tested (see results section) and the company manufactured a final version following the suggestions from the engineering team that performed the leakage tests.

The choice of involving a Mylar manufacturer for the X-Band case (differently from the S-band case in which the antenna was prototyped by students) allowed the team to obtain an antenna with a better resistance to leakage and a better attachment for the inflation pump. This is critical for the success of the antenna experiment, especially in the case of X-Band where a higher precision than S-Band is required.

However, even with the involvement of the Mylar manufacturer some issues with maintaining the parabolic shape when inflated where identified during the anechoic chamber tests. The issues are discussed in the next section.

IV. Preliminary experimental tests for the X-band design

This section of the paper discusses the experimental tests performed and it is divided into three subsections: test stand setup, leakage test and anechoic chamber tests. However, anechoic chamber tests were severly compromised by a thermal issue of the membrane in the chamber. Hence, these results are considered only preliminary. New tests with an improved prototype are currently in development and will be reported in a follow up article.

A. Test stand and setup

The test stand (Figure 5) used for the S-Band tests was modified to perform the X-band tests.

Figure 5. Test stand originally used to perform the first radiation tests at the S-Band. The polycarbonate originally placed on the top of the polycarbonate rod was eliminated and substituted with the new plate shown in Figure 6 (Ref. 17).

Specifically, one of the most significant issues in the S-Band anechoic chamber tests (Ref. 15) was the presence of a polycarbonate plate in front of the antenna which caused strong attenuation. The presence of the plate was a necessity for the S-Band test since the plate was used as an interface for the antenna inflation. In the new design for the X-Band, the inflation valve was placed on the side of the cone and attached to the Mylar directly, hence eliminating the need for the plate. However, a plate was still required to attach the reflector to the patch antenna feed. In the flight prototype, the plate will not be necessary as the membrane will be glued directly to the patch antenna feed. However, for testing purposes, a plate is important as it allows the switching between different antenna feeds, when needed. To allow for this flexibility, a new interface plate was designed. The plate needed to be large enough to allow for tape attaching of the Mylar membrane, while at the same time it needed to minimize the attenuation impact caused by the plastic material itself. As a result, a design with a circular hole was developed. The hole allows for complete visibility of the radiating patch element, eliminating the attenuation issue, while the edges of the plate are large enough to allow a proper attachment of the membrane. The plate was fabricated using 3D printing technology, and it is shown in Figure 6.

Figure 6. The adaptive plate designed to hold the patch antenna in position, to attach the inflatable membrane and to connect with the MIT stand.

B. Leakage test

A preliminary leakage test was performed at JPL to check if the design and the attachments were accurate enough for the tests in the anechoic chamber. Specifically, the antenna (Figure 7) was placed on the stand, inflated with helium (used in alternative to the benzoic acid for non-vacuum tests) and tied to the base of the stand using fishing lines. The precise distance from the center of the reflector to the ground was measured at the beginning of the test and the measurement was repeated at intervals of 15 minutes each to identify whether leakage was present and causing the antenna to sink and move from its initial position. Both the antenna prototypes (the thicker and the thinner antennas) did not present leakage problems with the exception of the attachment piece at the connection with the helium pump. This problem was corrected at the delivery of the final product. Additionally, it was observed that the thicker Mylar was more stable and less sensitive to air movements. Hence, since for the test in the anechoic chamber is required to have a very stable inflatable antenna to maintain a certain position with respect to the patch antenna, a recommendation was made to the manufacturer to fabricate the final version of the antenna using the thicker Mylar.

Although the leakage test went very smoothly, it was all performed in the same room and no strong temperature differential was present. Hence, the team did not realize the impact that the temperature difference would have had on the antenna during the test. This phenomenon was observed at the anechoic chamber facility and it caused the antenna to not inflate properly. More details on this aspect of the test are described in the next section of this paper.

Figure 7. The antenna was mounted on the stand and a leakage test was conducted to measure how much the antenna would have sunk due to the loss of helium. The antenna did not sink for more than 6 hours (time required to perform the test at the anechoic chamber) which shows that the antenna does not have significant leakage issues.

C. Anechoic chamber test

The radiation test was performed at the anechoic chamber at the NASA Jet Propulsion Laboratory. Initially, the radiation of the standard gain horn was characterized to provide a reference for the gain quantification (Figure 8).

At that point, the inflatable antenna was inflated using helium and prepared for testing. An initial issue with the inflation pump caused the first prototype to be damaged, and it was substituted with a second prototype. This second prototype was prepared for the testing, inflated with helium, mounted on the stand and tied to prevent floating. The entire structure was mounted on a test stand specifically designed and manufactured for this experiment. After the setup procedure (the antenna mounted on the stand shown in Figure 5), the measurement of the inflatable antenna radiation was taken. Unfortunately, the temperature differential between the outside of the chamber (where the helium pump was located) and the inside of the chamber, caused a partially deflation of the antenna which did not allow for a perfect inflation of the membrane (Figure 9).

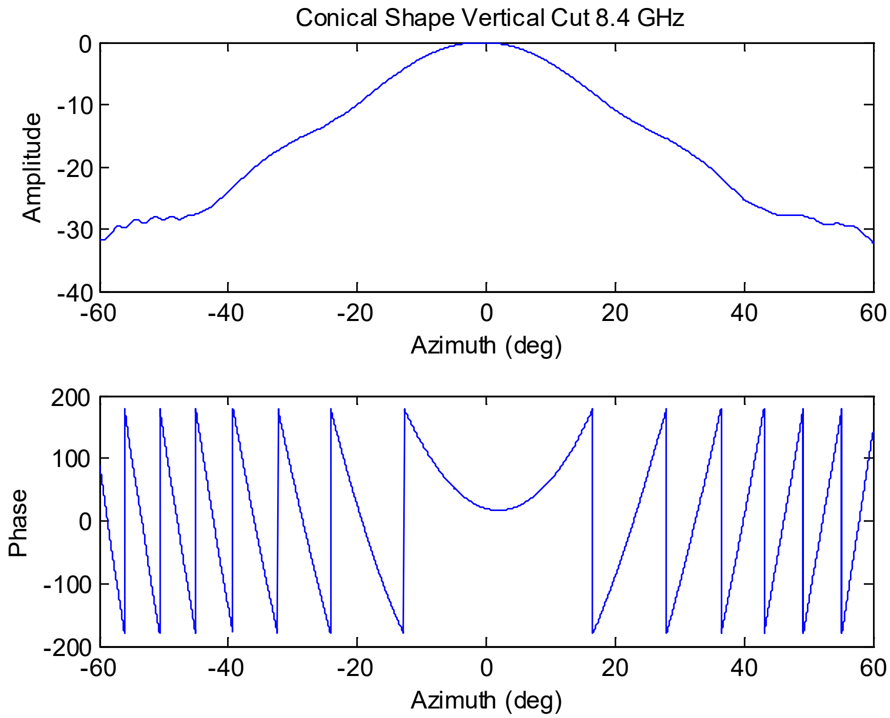

Figure 8. Amplitude and phase profile for the standard gain horn antenna, vertical cut measured at 8.4 GHz.

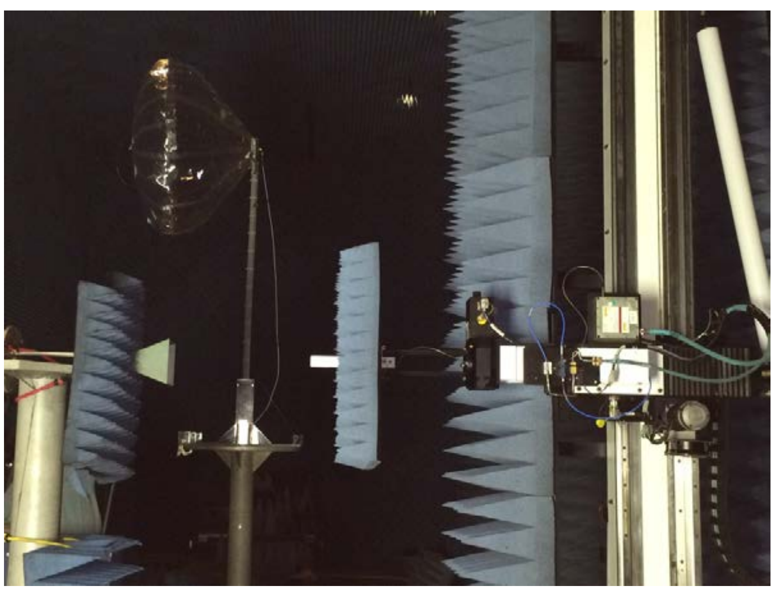

Figure 9. Test setup of the antenna in the anechoic chamber. It is possible to observe some deflation in the corners of the Mylar attachment surface.

The test was run 2 times in an effort of minimizing the impact of the temperature differential, although a visible level of deflation could be observed. As a result, the gain achieved by the antenna was less than what expected from the simulation due to leakage issues in the Mylar plastic. Specifically, a gain in the order of 12-14 dB for the 8.4 GHz frequency was detected and the leakage in the plastic did not allow the antenna to form a complete main beam pattern as it can be seen in Figure 10.

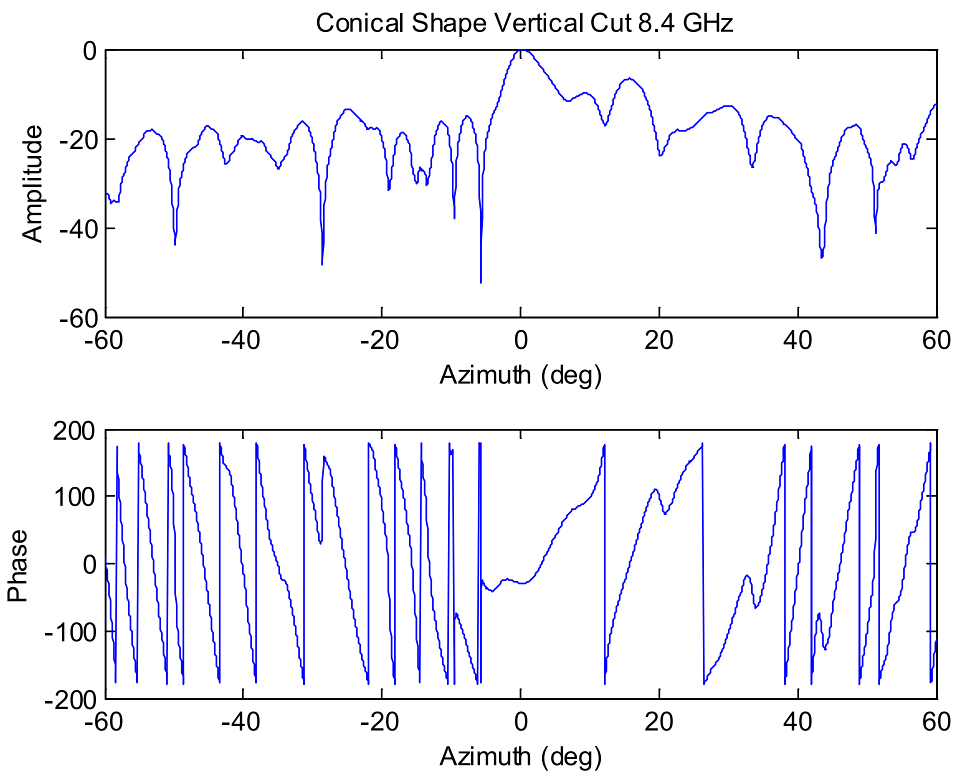

Figure 10. Radiation pattern experimentally measured at 8.4 GHz. It can be noticed the absence of the main beam.

To verify whether the leakage issues/ lack of inflation were the main cause in the loss of gain, a comparison with an HFSS simulation was performed. In this simulation, a flat surface was substituted with respect to the parabolic shape. This choice was motivated by the fact that the deflation produced mainly a flat surface on the back of the reflector. Hence, a flat surface represented a simple and yet reasonable approximation to reproduce in simulation what happened in the experimental test. A CAD model of the simulated surface is shown in Figure 11. The results of the simulation showed a loss of gain up to 12 dB which matches the experimental results. Figure 12 shows the polar plot of the antenna obtained by the simulation.

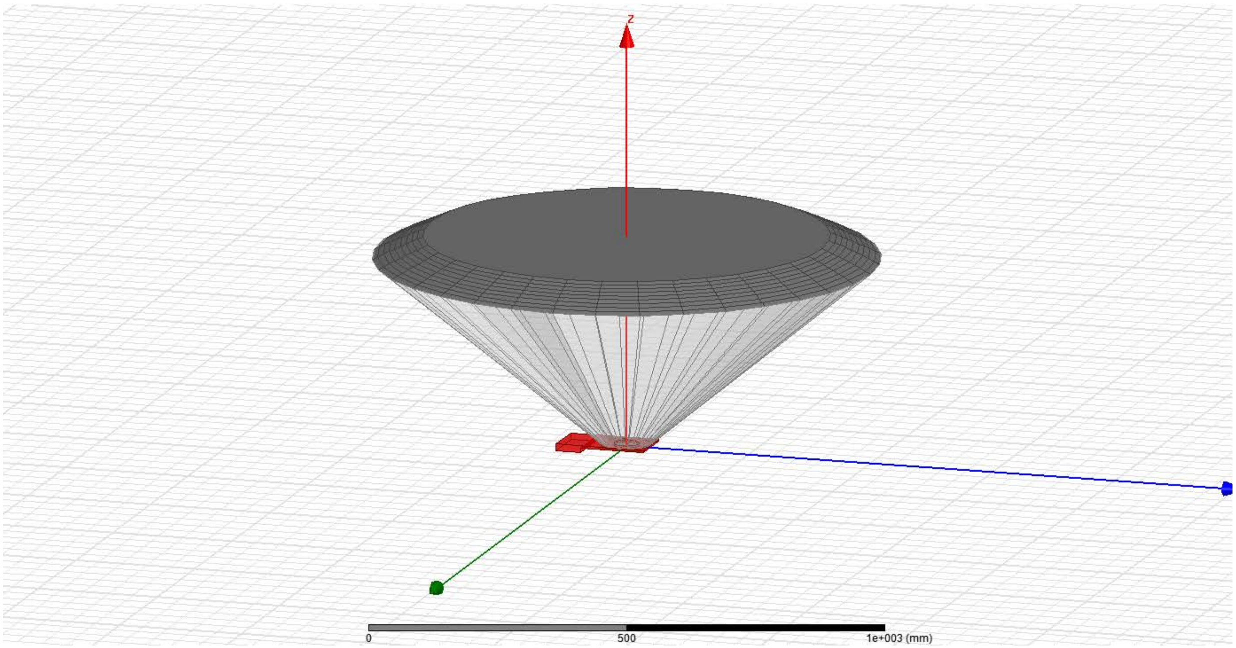

Figure 11. Flat surface simulation CAD model.

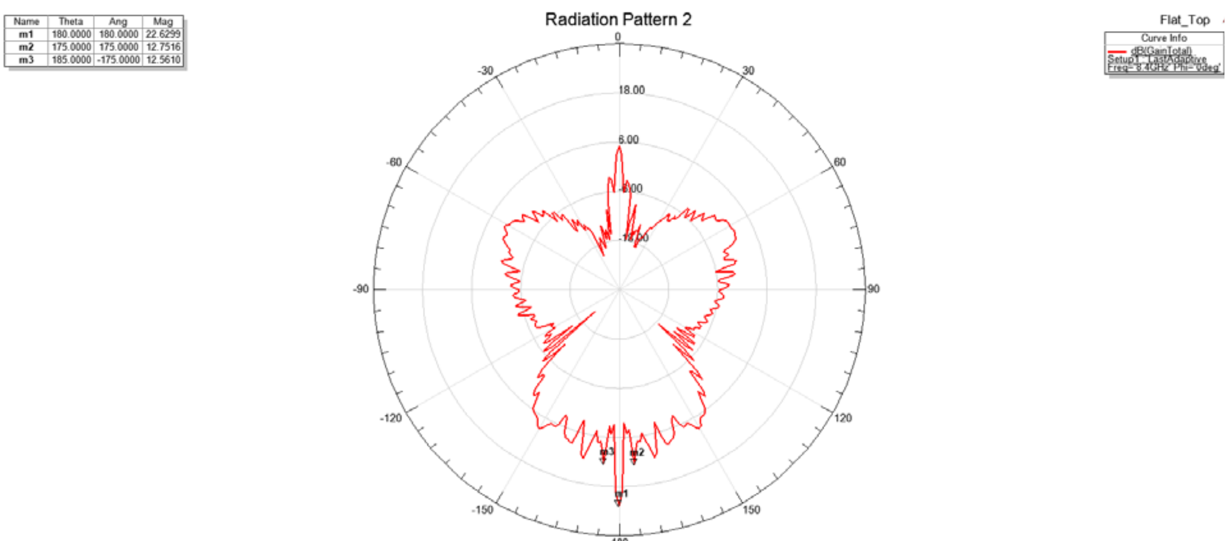

Figure 12. Radiation pattern obtained by simulating a flat surface (effect of leakage and deflation). It can be notice the drop in gain as compared to the original simulated results.

The comparison of the experimental results with the ones derived by simulating a flat surface antenna in HFSS showed that the deflation caused by the thermal differential has to be considered the main cause for the degradation of the gain of the antenna.

To solve this issue, a new version of the antenna is currently being developed. The new antenna is slightly diferent in design and it will be initially measured using photogrammetry to characterize eventual irregularities of the shape prior to radiation testing. This new antenna will be measured at the anechoic chamber in a stable thermal environment and inflated in the same chamber using a pressure sensor and control system to maintain the antenna at a given shape for all the duration of the test. This test is currently (July 2015) in progress and results will be described in a follow-up paper.

V. Inflation System: Analysis of Sublimating Powders

The sublimating powder is the preferred technique to achieve space inflation. With respect to other possible inflation technologies, the sublimating powder is prefereed for three main reasons.

- Volume and mass: sublimating powders are generally very efficient. Few grams can be enough to inflate the entire balloon.
- Absence of pressure vessels on board: the mechanism is completely passive and it does not require the presence of pressure vessels.
- Make up gas: one of the most interesting aspects of this technology is the possibility of using additional powder as a make up gas. The antenna should inflate and use only enough powder to reach the designed volume. The rest of the powder should maintain itself in its powder state until a leakage triggers loss of volume and hence needs for inflation.

While inflating with sublimating powder seems undoutably a promising technique, a lot needs to be done to understand better how the chemical process works and what are the limitations/issues that need to be overcome to make this system reliable for the use in space. To accomplish this result, the inflatable antenna team at JPL is partnering with the research group led by Prof. Thangavelautham at Arizona State University. The group has performed a review of the possible sublimating powders compounds (around 10) to use and has performed preliminary experiments in the vacuum chamber. Regarding the possible sublimating powders to use, many chemical were compared on the basis of their operating temperature (which has to be very close to the one in space), and of the mass required to inflate the balloon. Results show that the benzoic acid is actually the compound which achieves the best compromise between molecular mass, and operating temperature.

Table 2: List of sublimating powders.

Powder	Mass to inflate the antenna (g)	Lowest Operating Temperature (K)
Urea	0.44	346.15
Butyramide	0.64	354.15
Diformylhydrazine	0.65	371.15
Oxalic Acid	0.66	335.15
Benzoic Acid	0.9	334.15
Salicylic Acid	1.02	369.15
Mthoxybenzoic Acid	1.12	369.15
Pyrene	1.49	409.15
Hexachloroethane	1.76	356.15
Enanthamide	2.56	424.7

In addition to review and compare different options for sublimating powders, a set of vacuum chamber tests to assess the feasibility of this inflation mechanism were performed. Specifically, a replica of the same antenna measured in the anechoic chamber was placed in the vacuum chamber and the inflation wih sublimating powder was tested. Initial leakage in the antenna did not allow for a complete inflation with the powder. As a result, the experiment was repeated with a different membrane, without leakage, in order to be able to verify and test the inflation. This second experiment was successful and showed that it is possible to use the sublimating powder as a mechanism to inflate the antenna. However, more challenges needs to be addressed including identifying the amount of powder needed to ensure inflation and to allow for make up gas inflation. Another challenge is how to perform rigidization of the membrane once in space.

Figure 13: Sequence of inflation.

VI. Conclusions

The paper describes the effort in designing, analyzing, manufacturing and testing of an inflatable antenna for CubeSat at the X-Band. The main characteristics of the antenna are described and the steps required to extend the previously developed S-Band design to the X-Band are presented. The experimental tests results are given and they show how the thermal differential between the room where the helium pump was located and the anechoic chamber compromised the correct inflation, causing a significant drop in the measured gain. A simulation to corroborate this conclusion is presented. Efforts in analyzing the mechanism of inflation using the sublimating powder are also described. Future work is ongoing and it is focused on improving the test condition of the antenna by possibly introducing a pressure regulator in the anechoic chamber for the duration of the test and by developing a structural support to ensure the maintenance of the parabolic shape of the reflector. A new antenna has actually been manufactured together with the pressure regulation system. The results of the test performed with this new antenna will be described in a follow up paper.

Finally, it is important to identify how to properly rigidize the antenna in space to ensure additional reliability of the membrane. A preliminary study is in development at Arizona State University and tests are expected to be performed in the next year.

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