Inflatable Antenna for CubeSats: Development of the X-band Prototype

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- Inflation and rigidization
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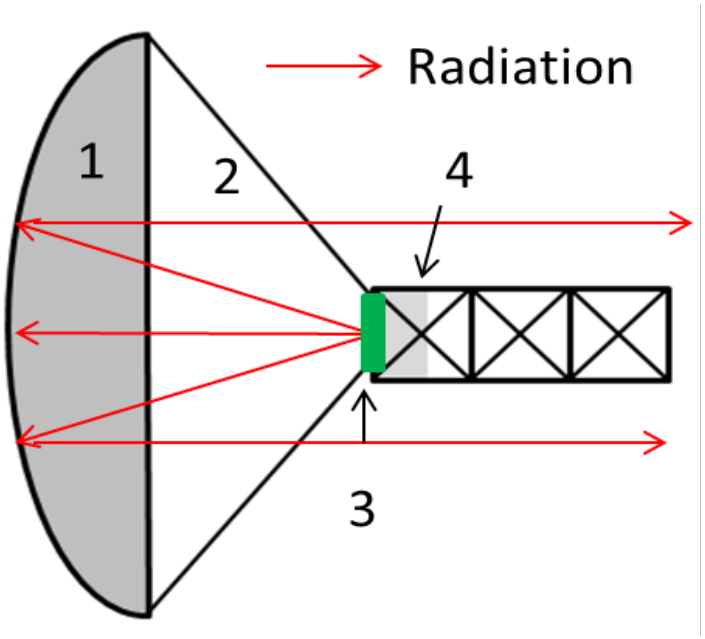
  - Vacuum Chamber
  - UV curing rigidization
- Conclusion and future work

Introduction

- Cubesats are now becoming a new way to explore space. They are designed to be smaller, with high stowing efficiency, and they are fabricated at a lower cost and faster development schedule than traditional spacecraft.
- CubeSats have now been widely tested at Low Earth Orbit by academia, industries and space agencies. Applications include testing new technologies, Earth imaging, Earth science and education.
- Recently a new trend emerged: the concept of "interplanetary CubeSats" (INSPIRE, MarCO, NEAScout, LunarFlashlight, LunarIceCube, LunaH-Map)
- As CubeSats are becoming a way to explore deep space in a more affordable way than traditional spacecraft, new needs emerge: propulsion systems, thermal and radiation protection and telecommunication systems that can sustain a severly increased path loss.
- Different communication technologies are in development to approach this problem and to support interplanetary exploration with CubeSats and small satellites. Examples are: the IRIS radio, reflectarray antennas, deployable antennas , CDMA techniques, optical communication, MSPA (Multiple Spacecraft Per Antenna), and the inflatable antenna.
- The inflatable antenna is unique as it provides an extremely high stowing efficiency (20: 1), low mass (<0.5 Kg), scalability and inflation with sublimating powder. The first inflatable antenna for CubeSats was designed at the S-Band [14] [15].
- This paper describes the development of the inflatable antenna for CubeSats at the X-Band.

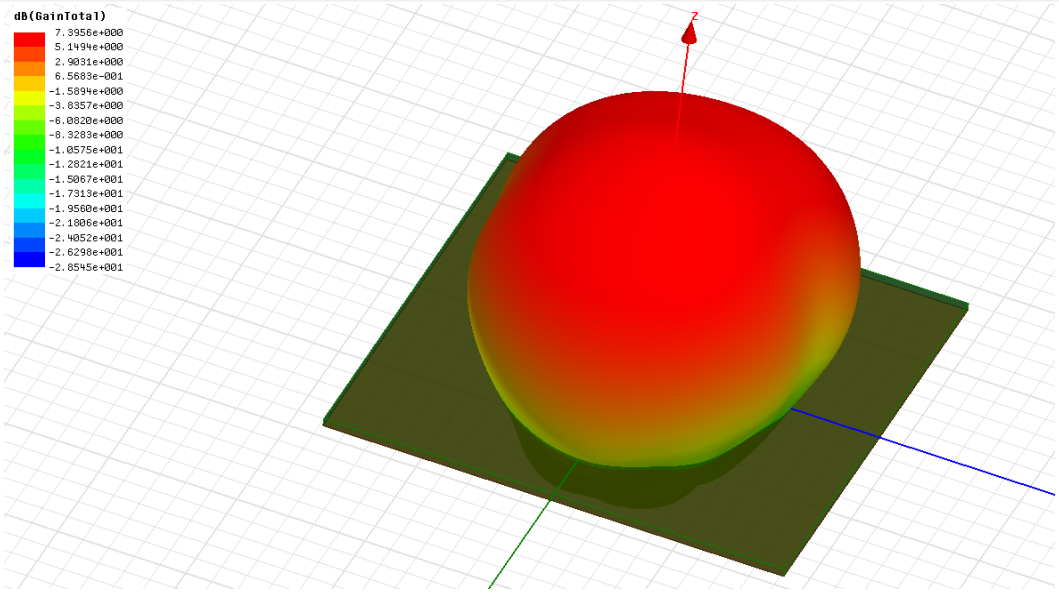
Inflatable Antenna Concept

- The inflatable antenna is a parabolic dish reflector made of one side metalized mylar, one side clear mylar, and with a patch antenna as the feed.
- The inflatable antenna is unique as it provides
  - extremely high stowing efficiency (20: 1)
  - low mass (<0.5 Kg)
  - Scalability
  - inflation with sublimating powder.

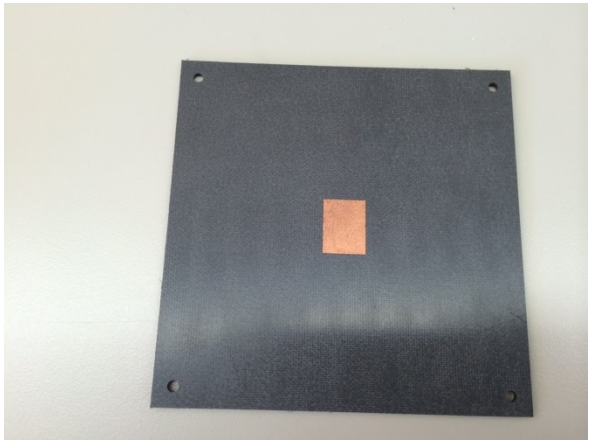


Patch antenna design

- 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.

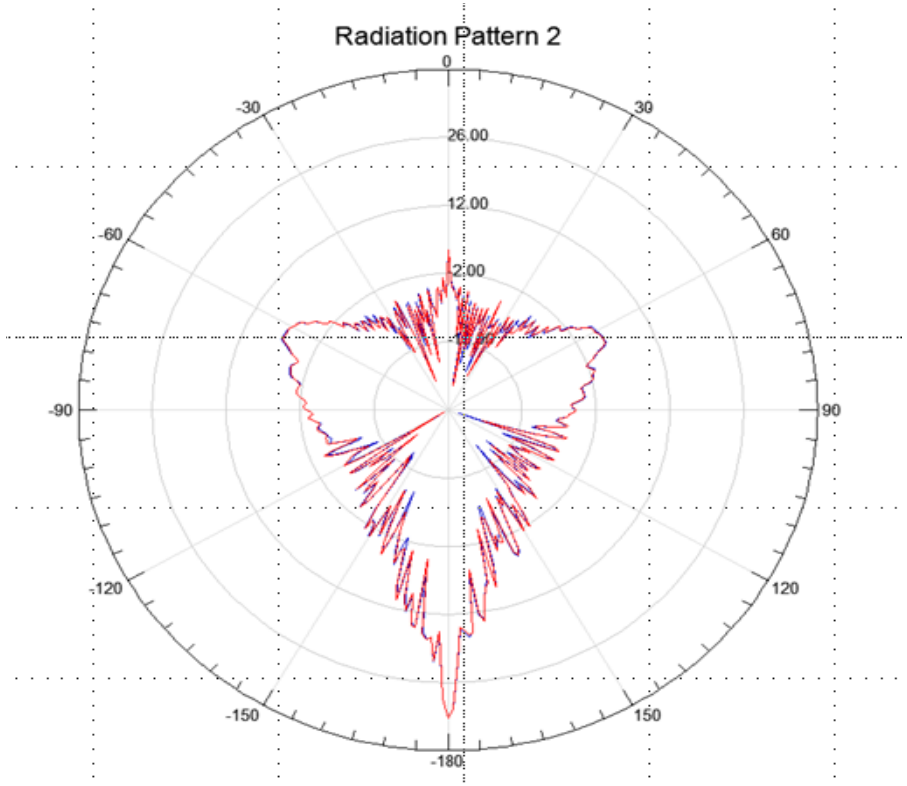


Parameter	Value
Antenna size	9 x 9 cm
Antenna conductive plate size	1.2 x 1.8 cm
Impedance	50 Ohm
Dielectric	RT Duroid 5880 (perm=2.2)
Frequency	8.4 GHz
Peak gain	7.3 dBi



Reflector simulation

- HFSS was used to simulate the radiation of the inflatable antenna at the X-Band. A peak gain of 34 dBi was estimated.

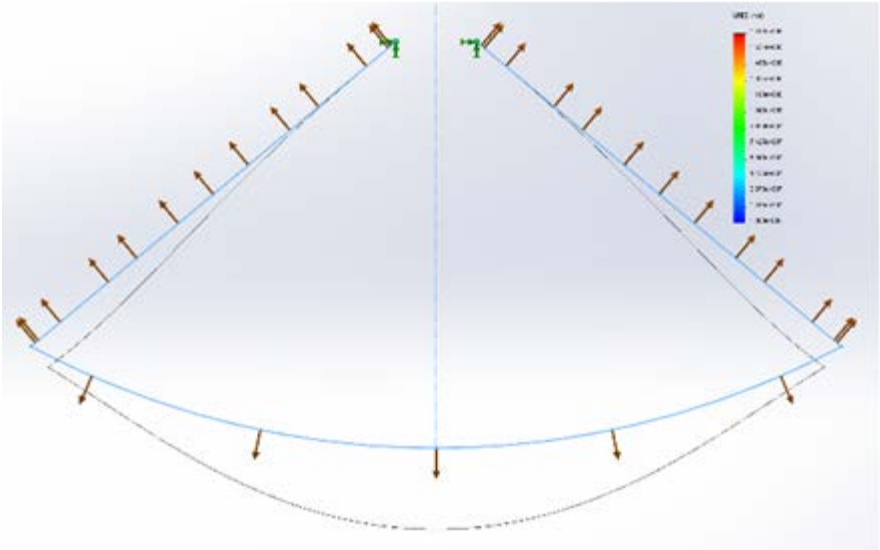


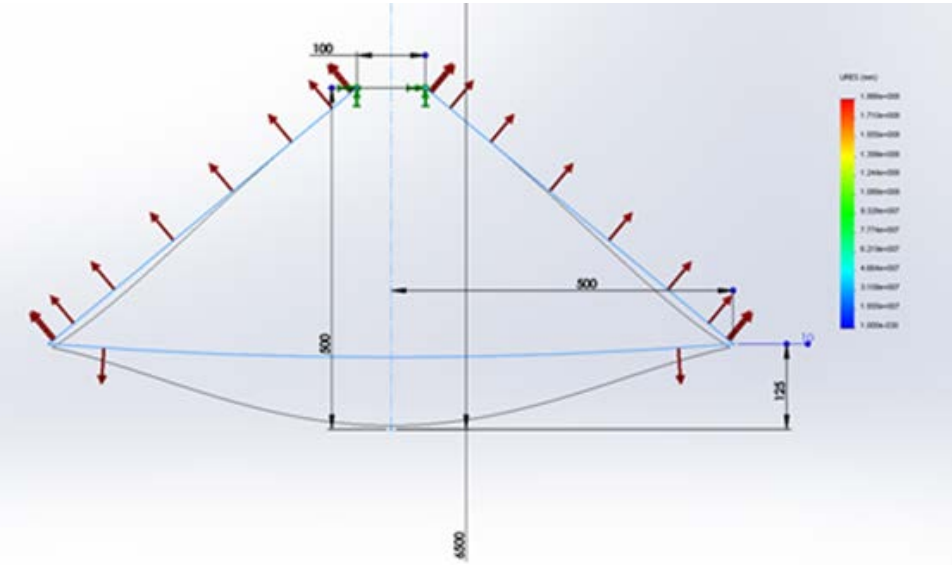
Structural model: pressure vs. shape

- On the macro scale, the antenna geometry changes as any pressurized membrane will deform to a more spherical shape as pressure increases
- While an initial goal was to simulate a pressure of 0.2 psi, the solutions failed to converge.
- This was due to challenges with the software in simulating thin membranes, and the locations where the thin membranes joined each other quickly experience failure.
- To solve this problem, it was found if the simulations were run at pressures of 0.001 psi, the solution would converge, and show a 2.5mm displacement at the center of the 1 meter antenna.
- However, the pressure of 0.001 psi was not realistic to achieve, and it would be impossible to regulate pressure at this level
- Therefore, it was determined that they best approach forward would be to empirically test the antennas.
- The simulations were used only to determine the shape to manufacture

Inflatable antenna structural desin

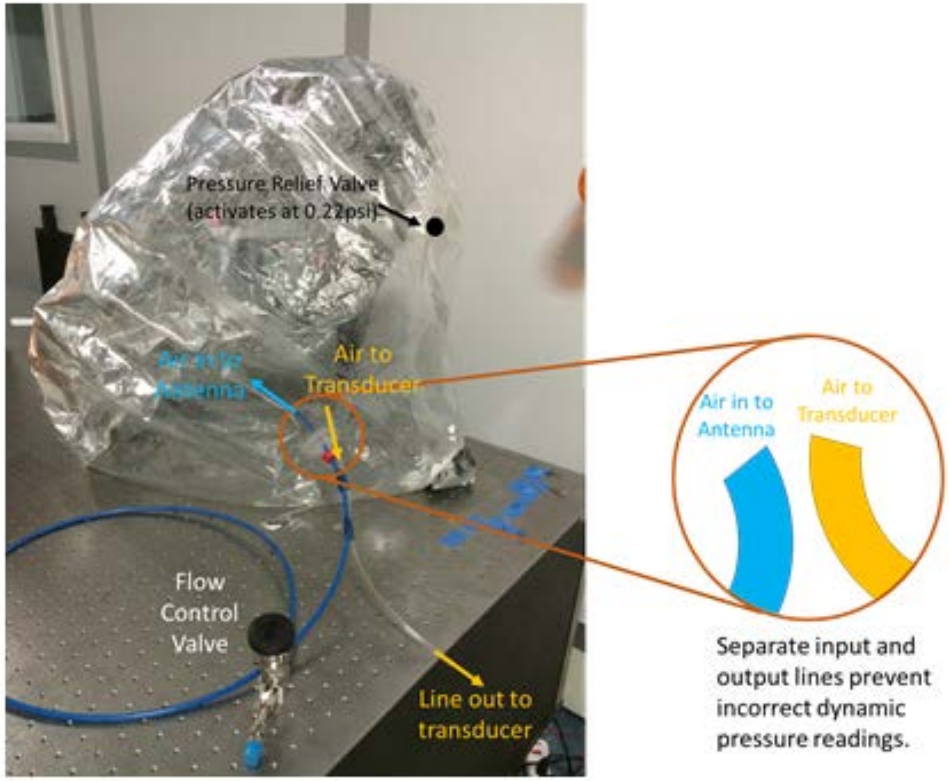
- Two designs were chosen for manufacturing from the simulation results.
- An undersized curved paraboloid surface→ after pressurization it would deform to the spherical shape which approximated a parabola.
- An entirely flat shape→ would be deformed by pressurization into a spherical surface which closed approximated a parabola. .





Antenna manufacturing

- The inflatable antenna membrane was manufactured by Meteorological Product Inc.
- A pressure input and pressure measurement couplings which connected to ¼" flex tubing were built into the antenna, along with a pressure relief valve to prevent over pressurizing the antenna.
- The pressure relief valve was designed to activate at 0.22 psi.

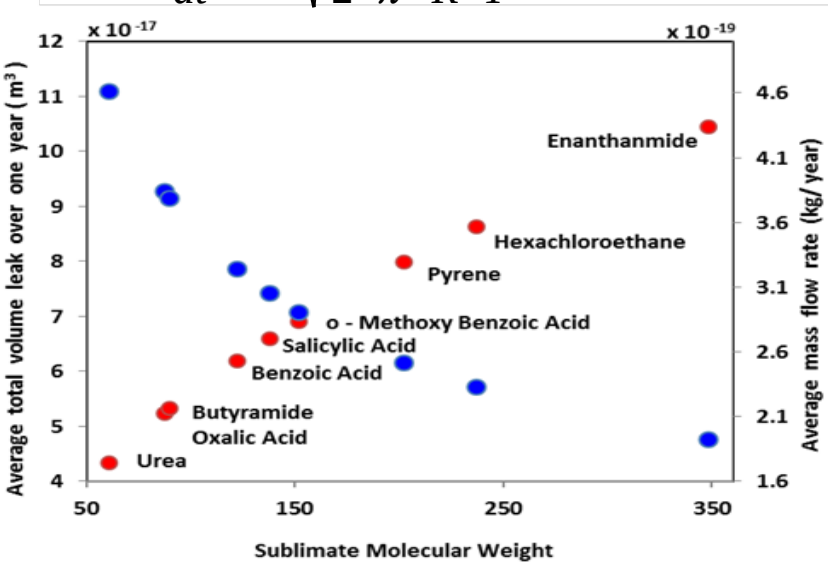


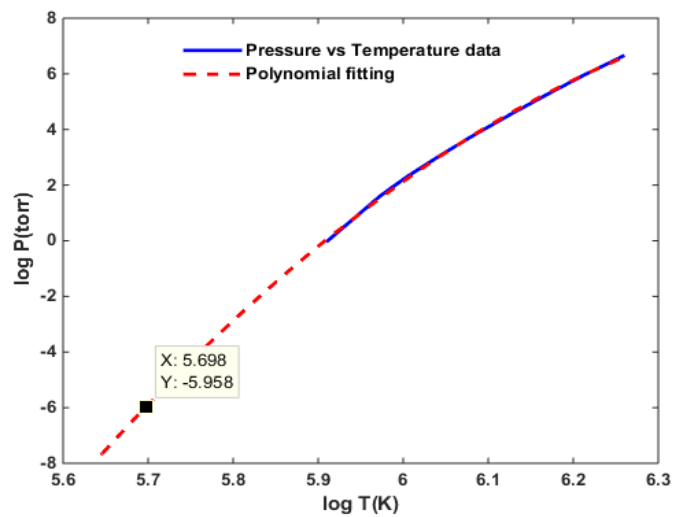
Inflation

- Possible powders were reviewed for factors
  - stability in high vacuum conditions
  - high molecular diffusivity
  - large gas vapor volume to mass ratio.
- Our study shows benzoic acid, salicylic acid and o-methoxy benzoic acid closest to the region of highest feasibility.
- Due to ease of availability and low cost, benzoic acid was chosen as our candidate sublimate.

$$\frac{dm}{dt} = \alpha\sqrt{\frac{M}{2\cdot\pi\cdot R\cdot T}}\cdot\left(p_{eq} - p\right)$$

$$p_{eq} = \beta\sqrt{\frac{2\pi R}{M}}Te^{-\frac{\lambda}{RT}}$$





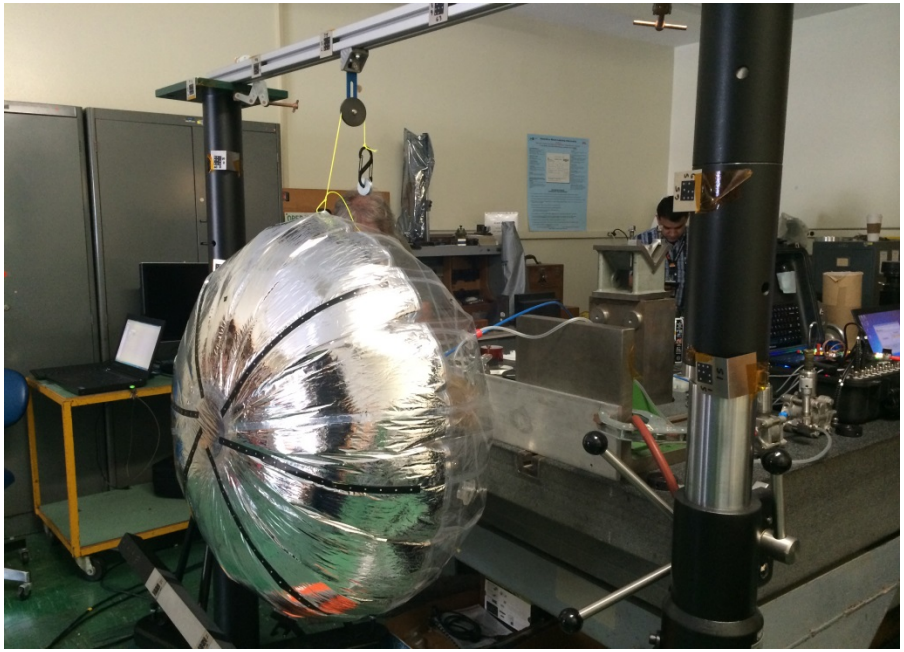
For benzoic acid, this was found to be as 0.002585 torr at 25° C.

Rigidization

- Vapor pressures exerted by sublimates drop dramatically with temperature.
- For reliable retention of inflated shape, rigidizable support structures are required.
- For this we use a UV radiation cured resin: it consists of a photo-initiator group that causes curing upon exposure to radiation
- A study of curing duration and vacuum stability revealed P600 ROC to be feasible.

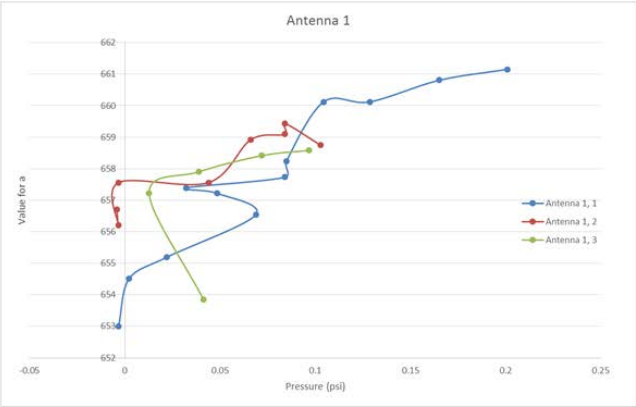
Photogrammetry

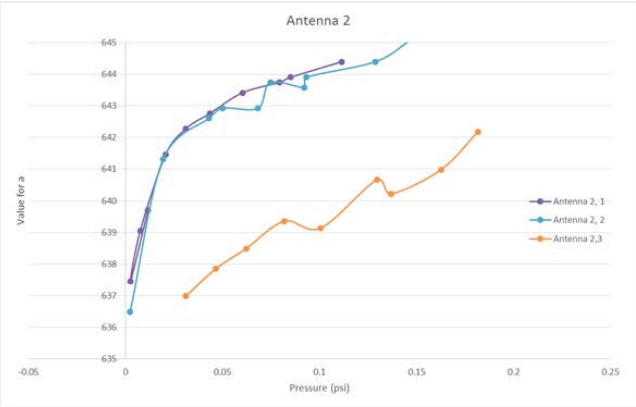
- The photogrammetry test was designed to test the impact of different pressure ranges on the curvature of the antenna.
- Pressure input was controlled manually, by a high sensitive valve, and pressure readings were made by using an Omega pressure transducer.
- A set of 3 photogrammetry cameras were used to determine the position of various photogrammetry targets, which were attached to the face of the reflector

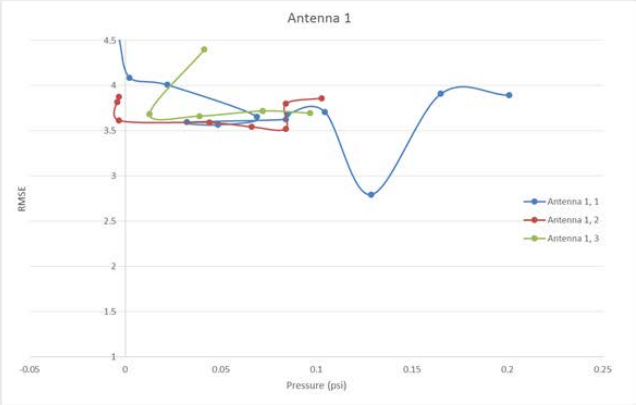


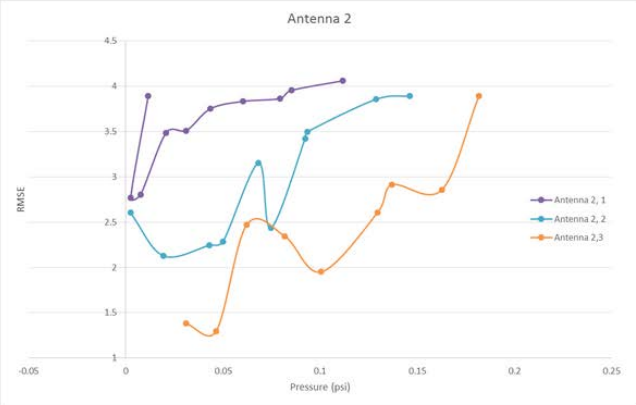
Photogrammetry: Results

- Both the antennas were tested
- Two key values were tracked
  - RMSE error from a best fit parabola
  - focal length, given by the value "a".
- While the data was quite noisy, the flat antenna (antenna 2) was found to have the most predictable pressure vs. displacement curves
- Even further, as the flat antenna was found to have far less micro scale deformations (wrinkles) than the curved antenna.

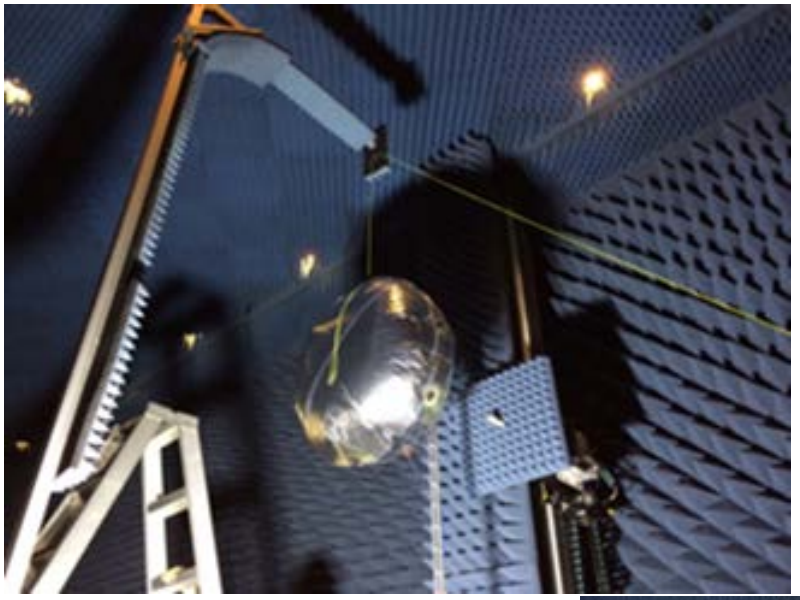


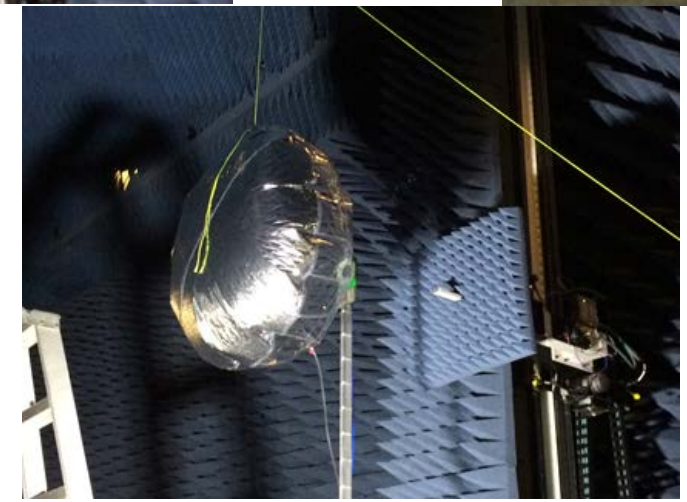






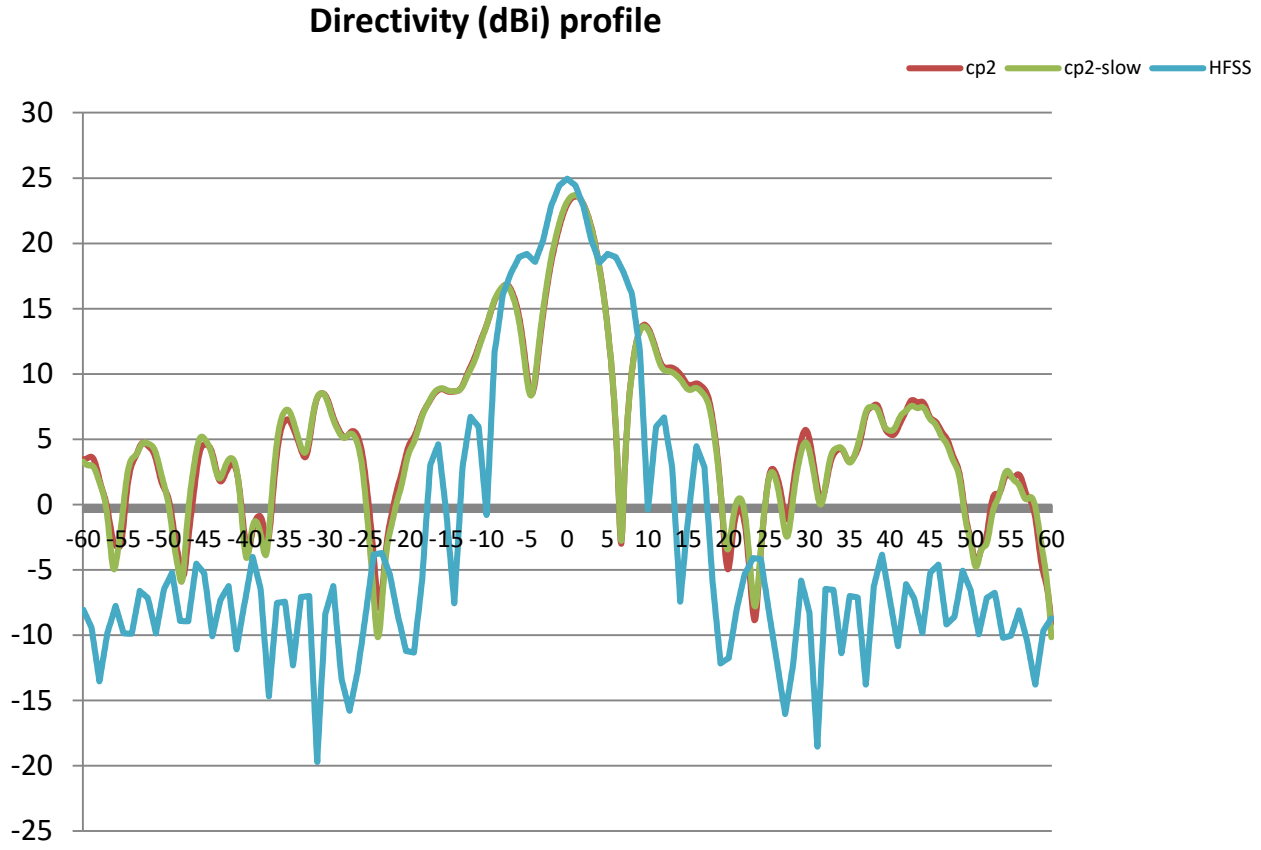
Anechoic Chamber Test: Setup



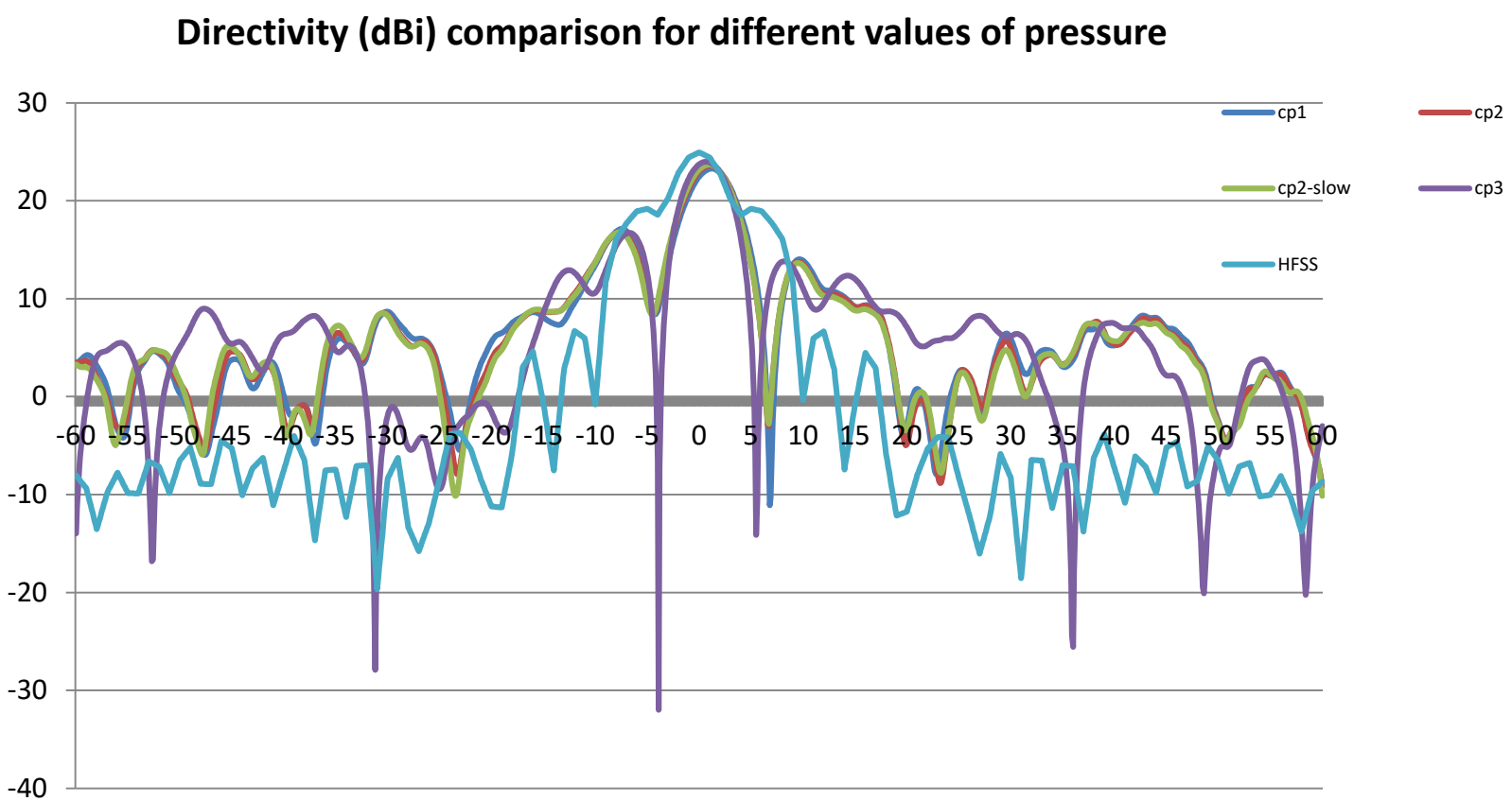


Anechoic Chamber Test: Results

- The scan were taken at 0.197 psi.
- The predicted peak directivity was 24.9
- The measured peak was 24.2 dBi
- Gain was approx. 3 dB lower due to return losses in the patch



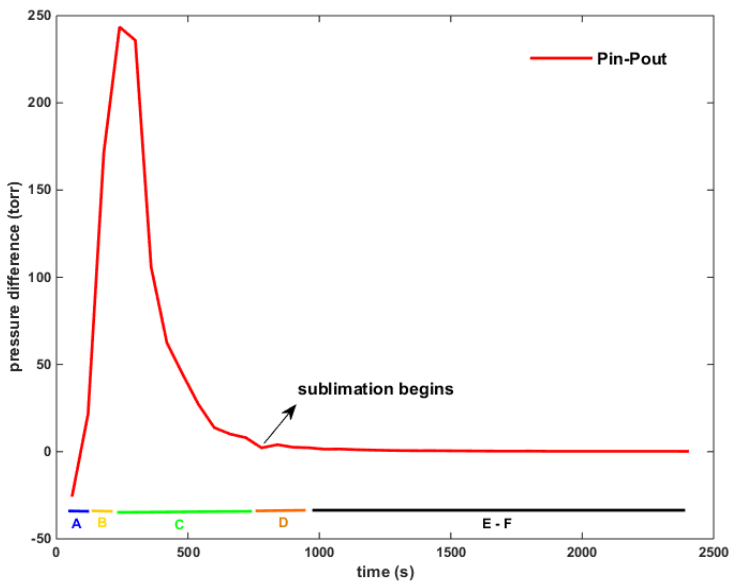
Anechoic Chamber Test: Different Pressure



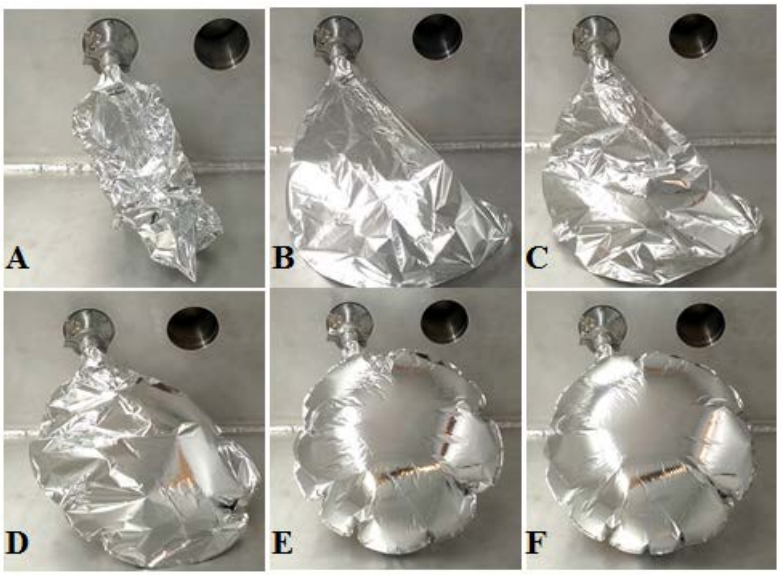
Directivity for different values of pressure (cp1=0.177 psi, cp2=0.197 psi, cp3=0.05 psi)

Vacuum Chamber Test

- Test steps:
  - The inflatable is evacuated of residual air at atmospheric pressure
  - The inflatable is sealed and the vacuum chamber is then evacuated
  - The chamber is held at a pressure of 10^{-5} torr.
- Phases:
  - A→ air evacuation
  - B→ peak due to redistribution of air locked pockets formed in Phase A
  - C→ progressively pressure lowering
  - D→ sublimation begins
  - E-F→ equilibrium is reached (0.0026 Torr)



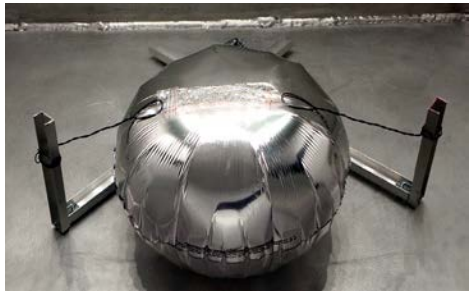
Pressure difference over time (external – internal)



UV Rigidization

- Clear Mylar envelope (15 cm x 3cm) injected with UV resin P 600.
- The envelope was stretched and placed over a sublimate containing inflatable.
- Upon reaching vacuum and completing inflation, the envelope takes the curved shape and it is exposed to UV radiation.
- UV radiation takes up the induced curvature and forms a rigid glass like structure in approx. 2.5 hours.

Before inflation



After inflation

Before UV curing

After UV curing

Conclusions and Future Work

- This paper describes the effort in developing an X-Band inflatable antenna for CubeSat.
- HFSS simulations show a projected gain of 34 dBi.
- The structural analysis looked at the correlation between pressure and shape, discovering that only a very minimal pressure is necessary to inflate the antenna.
- The reflective part of the surface was designed as something less than parabolic.
- Two shapes were manufactured and tested at the photogrammetry laboratory
- The flat shape presented fewer wrinkles due to the differences in the manufacturing.
- The flat reflector was further tested in the anechoic chamber were a directivity of 24.1 dBi was measured (very close to the simulated value of 24.9 dBi). The measured gain was less than the simulated one due to return losses in the patch antenna.
- Regarding inflation, a review of the powders was performed to identify the most appropriate sublimate compound for the antenna and benzoic acid was chosen.
- Test in the vacuum showed that it is possible to inflate the antenna using sublimating powder and provided measurements of the pressure differential.
- The UV rigidization experiment is a preliminary effort in the process of rigidizing the antenna.
- Future work is focused on
  - Improving the EM characteristics of the antenna: an array of patch antennas will be used as the feed to compensate for the lack of a perfect parabolic curvature on the reflector.
  - More studies and experiments on the rigidization process
  - A dynamic test to identify the effect of rotation and translation on the antenna structure

Thank you!

Questions?

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