Deployment Mechanisms for High Packing Efficiency One-Meter Reflectarray Antenna (OMERA)

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While the capabilities of CubeSats have greatly increased in the past years, large, deployable high frequency apertures remain a limitation. The goal of this work was to develop a large 1 meter antenna operating at 35.75 Ghz for RADAR applications. A reflectarray design was selected, as the flat panels were compatible with the CubeSat form factor. A center-fed, Cassegrain configuration was selected for the feed, to minimize deployed height. The flat panel configuration and Cassegrain feed allowed the entire 1 meter antenna to be compatible with a 6U bus, leaving a little under 4U of volume for remaining instrument and spacecraft components. Several iterations of the design have been built and tested, with an RF test of a fully deployed assembly being completed most recently. The goal is to have the antenna flight ready before 2020.

I. Introduction

The opportunties for CubeSats seem endless, as technology and launch opportunities for CubeSats have greatly increased in the past years. This enables a greater variety of missions, including opportunities for missions beyond low earth orbit. As operational distances between CubeSats and earth increases and instruments become more advanced data rates and instrument aperture become limiting factors. The need to improve these capabilities can be witnessed by programs like the CubeQuest Centennial Challenge[1], in which NASA is seeking innovative solutions to improve data rates. Currently, many CubeSats communicate on UHF bands, with those that are viewed as having high data rate abilities using S-band or X-band patch antennas. Some instruments often focus on arrays of patch antennas. However, this will not achieve the high data rates or large apertures/high frequencies required for more advanced instrumetns. A compelling solution can be found by designing a deployable antennas operating at the high, Ka-band frequency.

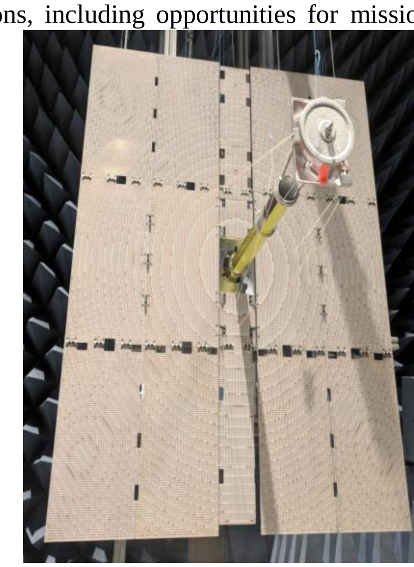

Figure 1: OMERA As Built

II. Background

Deployable antenna concepts can be organized by architecture, each of which have strengths and weaknesses in meeting CubeSat communication needs. Architectures include solid deploying reflectors, shape memory reflectors, inflatables, reflectarrays, and mesh reflectors.

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Solid deploying reflectors have great surface accuracy, but do not stow well in small spaces and can be heavy (e.g. Hughes spring-back antenna[2]). Shape memory reflectors may work at lower frequencies, but much development is still required as at Ka-band the surface is not accurate enough[3]. Inflatable reflectors[4] stow well and are lightweight but have issues with maintaining inflation and shape.

The remaining two architectures, parabolic antennas and reflectarrays are the most attractive for the high frequency, large aperture antennas on a CubeSat. Parabolic reflectors consist of a parabolic shape, to focus RF energy to a focal point. Parabolic reflectors developed for CubeSats have included goer-wrap composite reflector[5], the Aeneas 0.5 meter S-band antenna[6], a very thin ribbed, wrap rib design[6], the 0.5 meter Ka-band Parabolic Deployable Antenna (KaPDA)[7], and the 1.0 meter Ka-band KaTENna. While parabolic antennas work well at a number of frequencies, they generally present a more challenging approach for deployment, as a curved parabolic surface is required.

The reflectarray operates by using individual patches, arranged to provide a progressive reflection phase shift across the antenna surface, to generate a plane wavefront. This enables a flat surface to behave, at least from an RF point of view, like a parabolic surface. The key disadvantage of reflectarrays is that they can only work at their designed frequencies. However, this is often offset by its advantages, that a flat surface is easier to deploy and packs more efficiently when stowed.

The first reflectarray to fly in space was on the CubeSat ISARA (Integrated Solar Array and Reflectarray Antenna). This was a 0.3 meter by 0.3 meter Ka-band antenna. One of the key advantages of using a reflectarray on the CubeSat, is that the reflectarray can be stored in the "bonus" space on a CubeSat, allocated for the solar panels, minimizing the impact the antenna has on usable volume. The next reflectarray design to be developed for the CubeSat form factor was Mars Cube One (MarCO), which doubled the size of the deployed reflectarray to 0.3 meters by 0.6 meters. The frequency however dropped from Ka-band to X-band, as it was being used as a telecommunications relay for the Insight lander.

OMERA takes the MarCO concept to the extreme, by quadrupling the size, increasing the frequency and order of magnitude form X-band to Ka-band. This has profound implications on the design, as it means the surface accuracy requirements increase by the same amount. However, the larger size means there are many additional hinges and deployment mechanisms.

III. RF Design

The RF optical design drives the rest of the antenna design, as well as the requirements on the mechanical shape. For a deployable antenna occurs as part of a close collaboration between RF and mechanical engineers, to ensure the design is realistic from both perspectives. The first RF trade to be completed was determining if a center fed design or an offset fed design would be used. The offset fed design would be similar to the ISARA and MarCO reflectarrays, and the feed would be located on one side of the CubeSat, with the reflectarray panels on the other. The offset fed design is advantageous as the feed does not need to deploy as far, and multiple feeds can use the same reflector if desired. However, there are disadvantages due to blockage of the refelctarray by the CubeSat body and deployment errors would have been more challenging to control, as an offset design would have resulted in a greater number of hinge lines for the CubeSat base structure.

The other alternative, a center fed design, places the feed in the middle of the reflectarray. The key advantage is that it minimizes RF losses. However, the feed must be deployed a significant distance in the center of the reflectarray antenna. The configuration is shown in Figure 1.

To minimize the requirements on deployed height of the feed, a Cassegrain configuration was used, as it places the secondary reflector for the feed below the focal point of the antenna. Even this reduced distance requires the sub-reflector to deploy 0.62 meters, and the horn to deploy 0.48 meters out of the CubeSat body. Once the depth inside the CubeSat body to store the feed is considered, the total deployment distance is 0.82 meters. Utilizing a Cassegrain design also enabled the reuse of a similar design to the Ka-band Parbolic Deployable Antenna feed[8], which enabled quicker development of the concept. A similar telescopic approach was taken to the waveguide. But now, instead of just the horn telescoping around the waveguide, two sections of waveguide and the horn telescoped, resulting in a 3 element telescopic design.

Because of this new multi-element telescoping design, and because of the novel nature of reflectarrays, it was critical to test a non-deployable antenna to verify the RF design early. A non-deploying reflectarray, along with a non-deploying feed (but with variations in diameter of the wavguide to simulate the telescoping nature of the waveguide) was test to verify RF performance, and found to achieve 48.1 dBi of gain. As the performance aligned with the simulations, this enable continuation into the mechanical design of the antenna. Mechanical design of the antenna is divided into two main sections, the deployable feed and the hinges.

IV. Mechanical Design: Deployable Feed

The mechanical requirements on the feed were to stow in a 2U height, consume less than a 2U volume, deploy with an accuracy of 0.4 mm in any direction, and finally accommodate a 3 part telescoping waveguide, with transitions located as specific points along that waveguide to ensure integrity of the RF signal.

To fit within the compact volume, the best approach to control feed height was cables. The cables could be precisely adjusted to length, holding the feed in the correct location. The feed would be preloaded against the cables with a spring. While originally the focus was to keep the cables in the center, 2U height and deployed area, it was quickly realized while this controlled height of the feed precisely, it did not control position in the plane of the reflectarray to the stated requirement. It was necessary to provide the cable with a longer moment arm, which was accomplished by moving the attachment points out to the edge of the CubeSat Body. This provided much more precise position of the feed in both height, and in and out of plane.

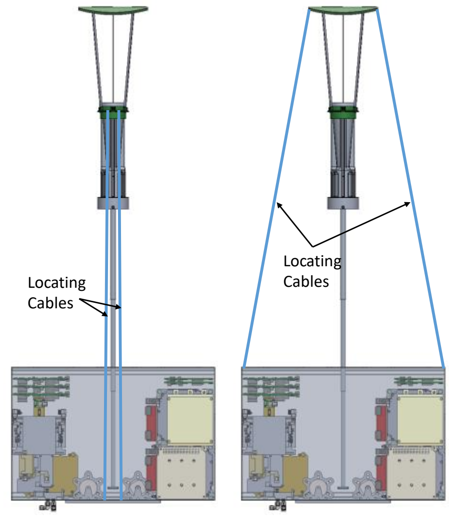

Figure 2: Center (left) vs. edge (right) attached locating cables

A. Initial Dynamic Deployment Design

To deploy the feed, initially a design utilizing long compressions springs was attempted. Two compression springs were used, one which deployed the sub-reflector, telescoping it along the feed, and another which deployed the feed horn. This design was essentially and extension of the KaPDA deployment for the sub-reflector. While the long spring designed to deploy the feed was buckled when fully deployed due to its long length, this was deemed as acceptable as the waveguide prevented the spring from buckling too far. By using two springs, this increased the amount of preload that could be obtained, and decreased the amount of kinetic energy which had to be dissipated at the end of deployment. Further, to assist with energy dissipation, the cables setting the height of the feed were attached to stiff, preloaded springs, essentially creating “shocks”.

However, despite breaking the design into two springs and the energy absorbing “shocks”, deploying 0.82 meters under the power of a compression spring resulted in an extremely dynamic deployment with very low preload at the end. This initial design had enough energy at the end of deployment that it caused the entire CubeSat chassis, and GSE, to leap into the air by several inches, and thus required the addition of two 45 lbs weights to keep the chassis fixed during deployment. At the same time the preload and tension in the cables was so low when deployed, that the deployed feed was in constant motion due to the air conditioning. It was realized that a new configuration would be required for the feed. This prototype helped to inform the location of the cables, as it was noticed the stiffness of the deployed structure greatly increased by moving the cables from the center of the CubeSat bus, to the outer edges.

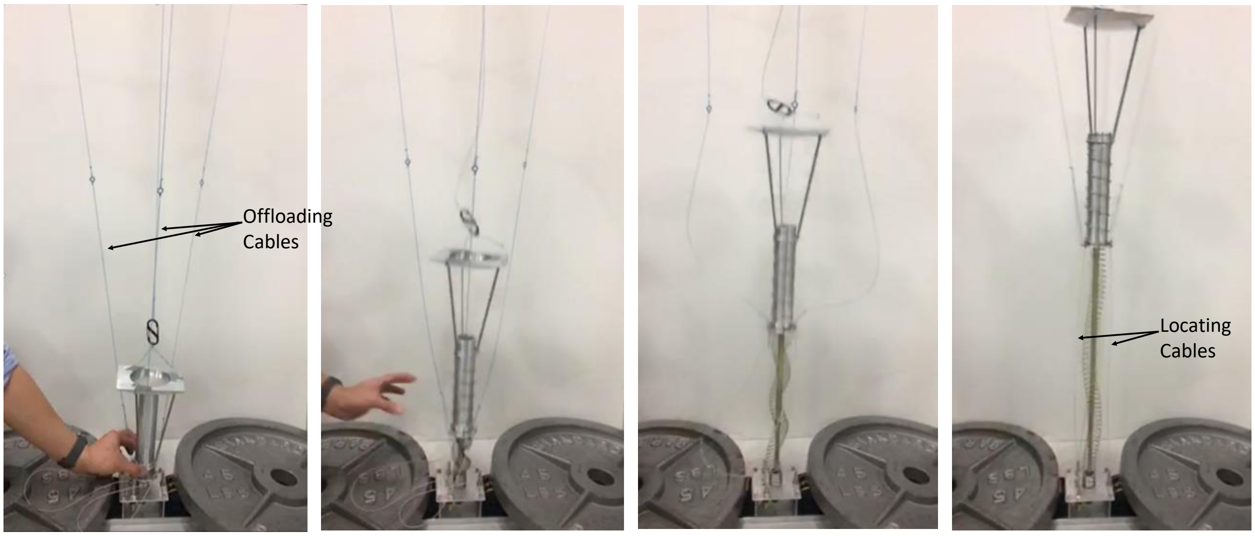

Figure 3: Deployment with a Spring Powered Design

B. Controlled, Deterministic Deployment

To increase the amount of preload in the deployed state, and to decrease the amount of energy in the deployment, alternate deployment methods were explored. Initially, a telescoping structure, powered by a looped cable running through a series of pulleys was investigated. However, due to the tight volume constraints within the CubeSat, the “large” size of the telescoping structure, and the required cable pulley minimum diameter, this configuration was abandoned.

The second configuration explored, and then eventually implemented, was a deployment mechanism using tape measures. Two tape measures were attached to the sub-reflector collar. As the tape measures were unrolled, they would push up the sub-reflector collar causing the sub-reflector to telescope along the horn, and then the horn to telescope along the waveguide. The end deployed positon of the feed was controlled by cables.

This configuration worked much better, resulted in a much more deterministic deployment, and achieved adequate stiffness. The design was explored with both center mounted cables, and cables mounted at the end of the CubeSat bus, and it was found the only way to achieve the surface accuracy of 0.4 mm in position, was by using cables mounted to the edge of the CubeSat bus.

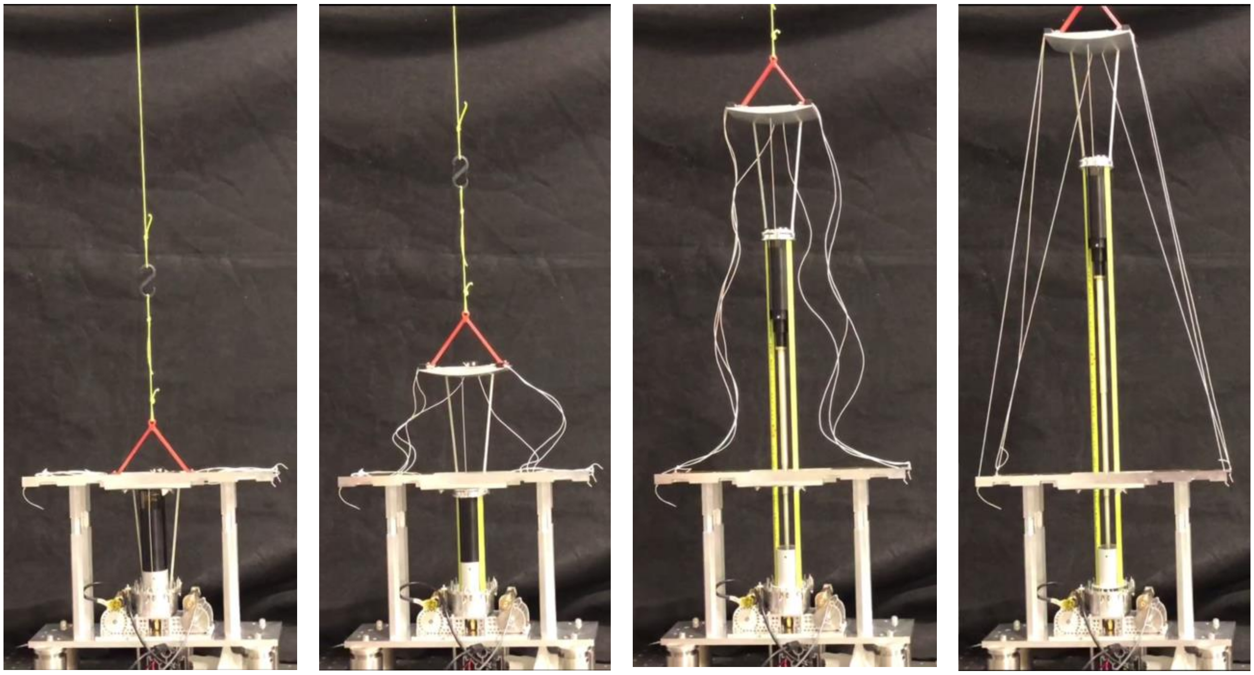

Figure 4: Tape Actuation Provided a more Deterministic Deployment

V. Mechanical Design: Deployable Panels

Figure 5 shows the deployed OMERA reflectarray. It consists of 16 individual panels, connected by 14 hinge lines. Deployed, the array measures 0.91 m × 1.05 m, with an area of approximately 0.96 m^2. . The choice of RF frequency and wavelength (35.75 GHz and 8.39 mm, respectively), dictates the desired surface flatness, which is roughly wavelength/20, or about 0.42 mm RMS surface error.

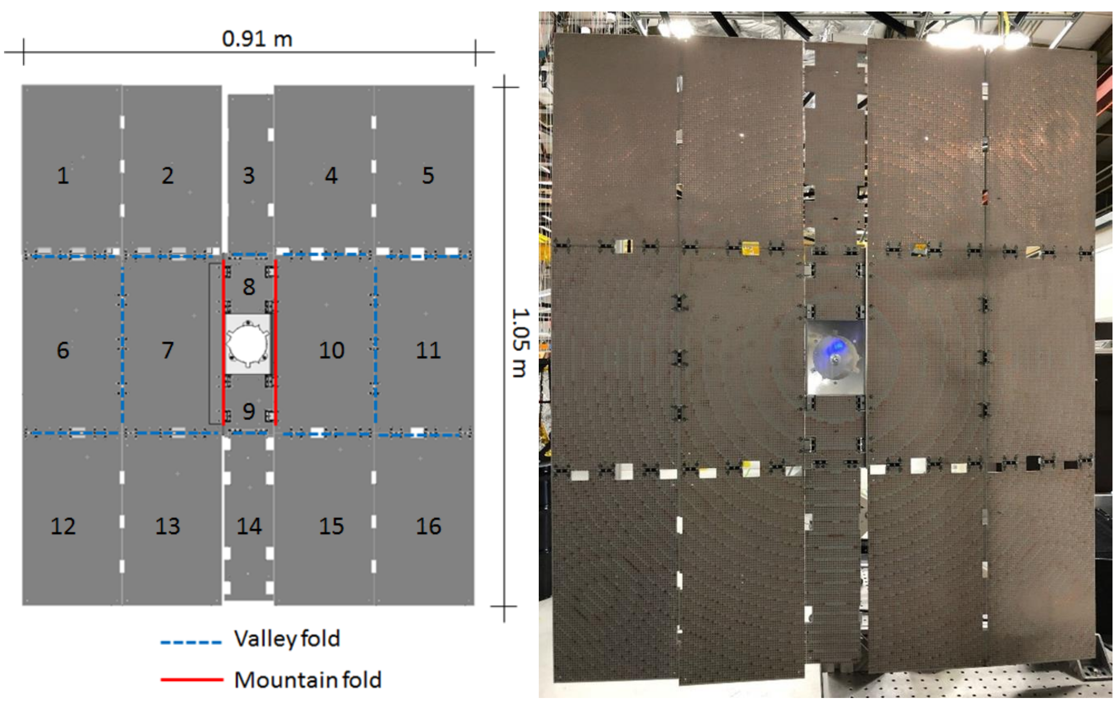

Figure 5: Reflectarray as designed (left) and as built (right)

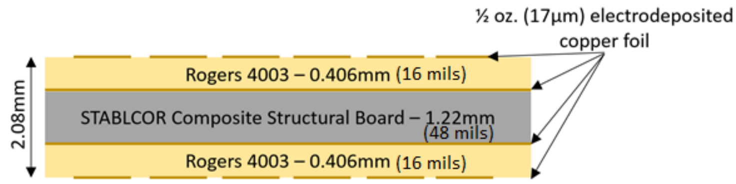

Figure 7: Panel Cross Section

The 16 panels can be divided into two wings (each consisting of six panels; the left wing consisting of panels 1, 2, 6, 7, 12, 13, and the right wing consisting of panels 4, 5, 10, 11, 15, 16), two side panels (panels 3 and 14), and two body-mounted fixed panels (panels 8 and 9).

The two wings each fold into a stack of six panels against the side of the CubeSat. The two side panels fold atop the stowed feed assembly and fixed panels. The folded configuration of the array is shown in Figure 6. Folded, each wing occupies a volume that is approximately 13 mm × 201 mm × 358 mm on either side of the CubeSat bus, and the folded side panels occupy a volume that is approximately 4 mm × 93 mm × 346 mm atop the CubeSat bus.

Each panel is 2.08 mm thick, consisting of a 1.22 mm (48 mil)-thick STABLCOR composite structural board core, surrounded on both the top and the bottom by a 0.41 mm (16 mil)-thick Rogers 4003 panel, as shown in Figure 7. Each Rogers panels has 17 um of electrodeposited copper on either side, with the outer copper layer etched to form the reflectarray patches. Only the top Rogers panel is the RF-active reflectarray; the bottom Rogers panel solely provides thermal balance to the panel plate structure.

To achieve the desired surface flatness, this folding architecture required the hinge lines to unfold to a precision of about 0.03 degrees for the body hinges lines (that connect panels 7 and 10 to the CubeSat body), and about 0.1 degrees for the other fold lines. To meet these tolerances, the adjustment capability was designed into the hinges, to allow for the post-assembly measurement and subsequent corrective adjustment of each of the unfolded hinge angles. This decision was made based on experiments with non-adjustable hinge lines that were unable to meet the needed unfolded angle tolerances.

Most of the hinge lines consist of three separate sprung hinges, with the central hinge having a fine-threaded set screw that allows for the adjustment of the deployed angle of the hinge line. The exceptions are the body hinge lines (that connect panels 7 and 10 to the body of the CubeSat), which comprise four separate hinges, with the two central hinges being adjustable in the manner described above; and the side-panel-hinges (that connect panels 3 and 14 to the CubeSat body), which comprise two separate hinges, both of which are adjustable.

The adjustable hinge is illustrated in Figure 8. In the unfolded configuration, a fine-threaded ball-end set screw (with a 200 µm pitch) is pressed against a hard steel insert in the paired hinge leaf (illustrated in green in Figure 8 right). This set screw controls the unfolded angle of this hinge; this angle can be easily and finely adjusted. This allows for the assembly and the bonding of the hinges to the panels to occur with loose tolerances; fine alignment of the array takes place after bonding, by using precision non-contact metrology to measure and then adjust the hinge angles accordingly

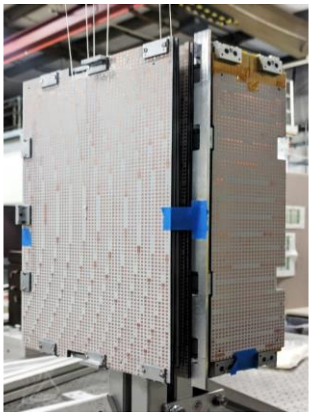

Figure 6: The folded reflectarray. A six-panel-wing is shown folded to the side of the CubeSat body, and the two side panels are shown folded above the CubeSat body.

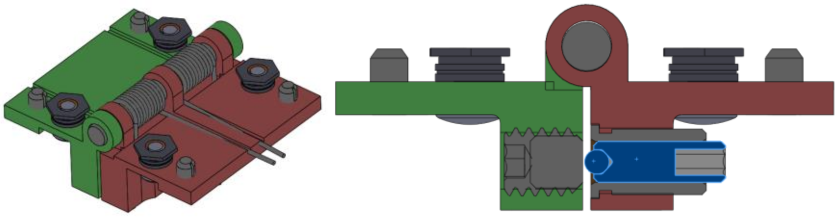

Figure 8: Adjustable hinge design, side view (left) and cross-sectional view (right). The fine-thread set screw is highlighted in blue. Its position can be adjusted with respect to the red hinge to set deployed angle of the hinge

This alignment procedure was used to prepare the deployed reflectarray for RF testing. Figure 5 shows the as-tested surface profile of the reflectarray. The RMS error of 0.345 mm, as tested, was below the typical λ/20 requirement of 0.42 mm.

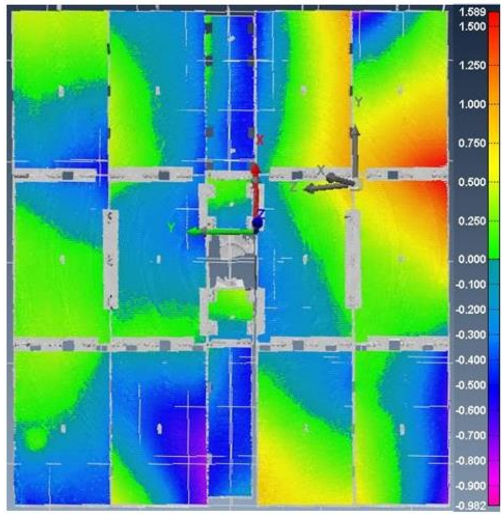

Figure 9: The final adjusted reflectarray surface profile as RF tested. The units on the colorbar are millimeters. The RMS error was 0.345 mm.

VI. Testing: Deployment and RF

Initial deployment testing as been completed, and the panel and feed have been shown to meet deployment requirements. After both met their requirements individually, the two systems were combined, and tested in an RF test. RF testing was completed in the past week, with results pending. More details about testing and the results will be included in the full paper, beyond this extended abstract.

VII. Preliminary Conclusion

An initial feasibe antenna architecture was achieved. The antenna deployed to within its required tolerances, and fit within the volume constraints. The full paper will speak to the results of the RF test, and the changes after this test enabling the antenna configuration. OMERA stands to be a breakthrough innovation for enabling a highly compact, high frequency reflectarray in the Cubsat form factor.

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