Lessons Learned from a Deployment Mechanism for a Ka-band Deployable Antenna for CubeSats

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Abstract

The Ka-band parabolic deployable antenna (KaPDA) is a 0.5-meter-diameter antenna that fits in a tiny, CubeSat compatible 10 cm by 10 cm by 16 cm volume. The design evolved from a rough concept in an R&D proposal to a fully flight-qualified design, scheduled for launch in May of 2018, in a timeframe of just 4 years. This paper focuses on key lessons learned on maintaining precision through structural depth, the use of fixtures, additive manufacturing for fabrication, the design of robust, deterministic mechanisms, and the dangers of friction and press fits.

Introduction

CubeSats have undergone an exciting evolution over the past decade. From being considered an academic exercise, they have grown to the point of obtaining real science data and are providing commercially viable business opportunities [1]. As the technology has increased in capability, so have the needs in the areas of power, propulsion, and communications. One critical need in the area of communications is high gain antennas, and specifically deployable antennas given the CubeSat's small size. Deployable antennas would enable communication at much higher data rates and radar instruments in small packages. Operating at a high frequency, like Ka-band, further increases the amount of data that can be transmitted. However, a deployable Ka-band parabolic antenna makes for a very challenging mechanism design problem. While there have been individual aspects of the mechanical design published in a series of AIAA conference papers [2], [3], and details on the radio-frequency design in a series of journal articles [4], [5], this paper focuses on key mechanism lessons learned from the KaPDA development.

The seed inspiring this concept started with the Aneas parabolic deployable antenna (APDA) folding rib parabolic mesh antenna used on the University of Southern California's Information Sciences Institute (USC/ISI) Aneas spacecraft [6]. The Aneas was launched in 2012, and the folding rib geometry illustrated a robust deployment sequence that has been used on larger antennas, like some of Harris's Unfurlable Antennas [7]. However, the APDA was designed to operate at S-band, whereas Ka-band brings an entirely new set of requirements. Therefore, while a similar general architecture was used, the RF design and each the mechanisms were completely re-engineered.

Requirements for KaPDA and Design Overview

Requirements

The goal of KaPDA was to create a new capability for CubeSats, to enable high-speed data rates from deep space. Data rates in a communications link budget depends on a number of things, including power of the transmitter, receiver sensitivity, ground antenna configuration, frequency of operation, and satellite antenna configuration. The goal for this task was to improve data rates through the satellite antenna, specifically to achieve a gain of 42 dBi. The three ways of accomplishing this are to 1) have a high frequency antenna 2) operate with high efficiency and 3) a large diameter.

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The antenna was chosen to be optimized for Ka-band, specifically the frequency range from 32 to 35 GHz, as this is a frequency used by the Deep Space Network for communications and is also a frequency for precipitations radars. To ensure high efficiency at this frequency, the antenna had to deploy to a surface accuracy of 0.4-mm RMS or greater. A trade study on antenna diameters revealed a 0.5-meter antenna would be large enough to offer a major advancement in capabilities. Combining these three aspects into one antenna would multiply data rates by 100 times what the APDA antenna would have achieved.

Because this system was targeted for a CubeSat, it had several key dimensional constraints. CubeSats are modular satellites, built on around a 1-unit (U) system. One "U" is 10 cm by 10 cm by 10 cm. CubeSats have been launched in sizes of 1U, 1.5U, 2U, 3U, 6U, and 12U. (6U systems are approximately 10 cm by 20 cm by 30 cm, whereas 12U systems are 20 cm by 20 cm by 30 cm). To accommodate the CubeSat unit system, the antenna had to stow in a 10 cm by 10 cm cross-sectional square, with a goal of keeping the height as short as possible, at approximately 15 cm. This would allow the antenna to consume only half of a 3U spacecraft or a quarter of a 6U spacecraft.

Key Subsystems and Components

An overview of the key subsystems and components is beneficial before discussing the development of the KaPDA antenna. The subsystems are illustrated in Figure 1. The canister and hub make up the primary *deployment actuation* sub-system. The canister encircles the antenna when stowed. Near the bottom of the canister is the hub, to which the ribs and the horn mount. The ribs are divided into two parts, the *root ribs*, which attach to the hub and are the closest to the center of the antenna, and the *tip ribs*, which are the outermost ribs when the antenna is deployed. The tip ribs are attached to the root ribs via the *mid-rib hinge*. The *horn* is primarily an RF component, but the exterior walls serve to guide and position the *sub-reflector* and position the ribs when stowed.

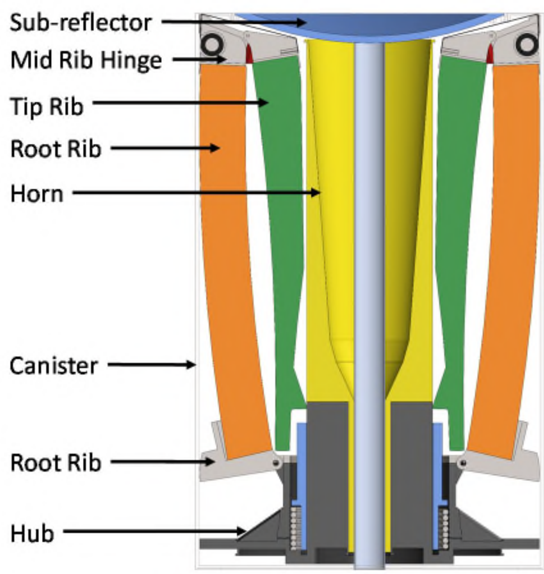

Figure 1. Key KaPDA Components

Overview of the KaPDA Development Sequence

To deploy, the hub is first driven upwards. (Figure 2, A-B). As the hub nears the top of the canister, the root ribs begin to bloom, opening (B-C). When the tip ribs reach the point where they become free of the horn interference, they are free to actuate at the mid-rib hinge (Image C). The hub continues to travel upwards until the root ribs fully deploy (image D). After the ribs are mostly deployed, the sub-reflector is allowed to telescope along the horn, and reach its final fully deployed location (C to D).

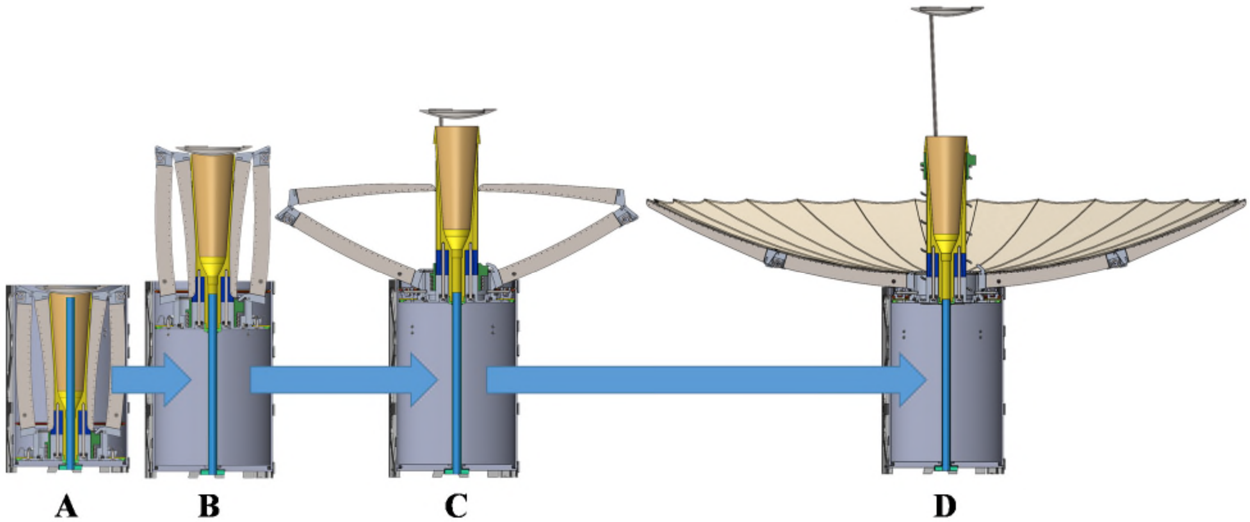

Figure 2. KaPDA Deployment Sequence

Early Development of KaPDA

<u>Characterization of the Aneas Antenna</u>

The development of KaPDA began by researching the Aneas antenna. The team first met with the Aneas team at USC/ISI to capture lessons learned, and was able to borrow the antenna from USC/ISI for metrology. A theodolite measured the accuracy of the deployed shape of APDA and found that the surface error was an average of 2.4-mm RMS. While this is perfectly adequate for an S-band antenna, requirements for a Ka-band antenna are tighter, at 0.4-mm RMS maximum error. APDA was designed with thin ribs, which helps to reduce storage space, but also impacted the surface accuracy possible. Torsion springs actuated the hinges and setscrews adjusted the position. These were key elements requiring redesign to improve accuracy.

A second issue when going from an S-band design to a Ka-band design is the mesh. At S-band, 10 opening per inch (OPI) mesh is adequate, which also requires a low amount of tension to achieve its shape. The 40 OPI Ka-band mesh requires a much greater tension of 17.5 N/m. This means the antenna must be designed to achieve greater values of preload upon deployment; approximately 250 N. The APDA deployment architecture only achieved a fraction of this, and therefore the deployment approach needed to be completely redesigned.

The third and most significant issue is the RF design. The Aeneas antenna used a splash plate feed connected to a co-ax cable. At Ka-band this would create far too much loss, removing any gains achieved through surface accuracy. As a result, an entirely new RF design was required for the antenna to operate at Ka-band with minimal loss.

<u>RF Design Effort</u>

The first approach to create a system that would operate at Ka-band was to develop the RF design. While the idea of using a parabolic dish to reflect RF energy remains the same as APDA, the rest of the system had to be completely redesigned, to the point which the KaPDA RF design and the Aeneas RF design share no heritage. In order to achieve high frequency communications with low loss, the RF energy must be kept in the electro-magnetic wave form all the way through exiting the antenna. Three subsystems were used to achieve this: the secondary reflector, horn and waveguide. The secondary reflector collects the RF energy from the parabolic dish, and reflects it into the horn. It also has a critical feature where it corrects for the geometric errors in the mesh which occur because of the finite number of ribs. The horn concentrates RF energy and transitions it from the sub-reflector to the waveguide. The waveguide transports RF energy out of the antenna in electro-magnetic wave form.

Multiple types of secondary reflectors were considered including Gregorian, Displaced Axis, Cassegrain, and “Hat” style feeds. One of the key challenges was finding a feed that did not have to be placed far from the vertex of the parabolic reflector. If the feed was located far away from the parabola, it would be difficult to stow it in the short 15-cm height. While the “hat” style feed provided the most RF gain, they also had to be deployed the furthest. The Cassegrain secondary reflector, while not providing the best gain performance, would actually fit within the stowed volume as its geometry allowed the secondary reflector to be deployed below the focal point. Therefore, the Cassegrain secondary reflector was selected.

As already noted the horn takes the RF energy from the sub-reflector and concentrates it into the waveguide. While the horn is a very technical complex piece of RF design (discussed at length in [4]), from a mechanical perspective, it is a highly toleranced conical shape.

The waveguide presented a greater mechanical challenge. The waveguide must be connected to the fixed base of the antenna and also to the horn, which starts near the base of the canister, but then deploys to the top of the canister. While “flexible” waveguides exist, they are actually mostly rigid and would not work. Therefore, the only solution was to allow the horn to telescope around a fixed waveguide. This was a new RF innovation demanding tight mechanical tolerances. It was also risky, as a number of RF engineers did not think it would work. However, early prototyping of the concept with non-deploying hardware proved the concept would work form an RF point of view.

Detailed Mechanical Design of KaPDA

Design of the Ribs

The design of the ribs is crucial for defining the antenna’s parabolic shape, and therefore was the first place to start. The prior RF analysis indicated that 30 ribs were required to avoid significant losses, due to the “flat facets” which occur in between the ribs. To fit a 0.5-meter antenna in a 15-cm-tall canister, the ribs had to be folded in half when stowed. Therefore, each rib would have 2 hinges. While designs were also investigated to fold the ribs three times, it was determined this would result in an overly complex deployment sequence.

The next step was to determine how to enable the ribs to achieve a surface accuracy of 0.4-mm RMS. This was first accomplished by making the ribs deep, increasing the area moment of inertia, so they would be stiff against the tension of the mesh. To maximize the amount of depth where it is most needed (where bending moments are the highest), the rib was deepest at the base. It can be observed that the tip rib steadily gets less deep the further it is from the center of the antenna as less moment is applied to it. This design provides an approximately equal distribution of bending stress across the entire length and results in less material where it is not required.

The second key features to achieve accurate deployment were the hinges. The depth of the ribs was carried into the hinges to minimize the effect manufacturing tolerances could have on the hinges. The hinges had a hard stop located 12.7 mm on the opposite side of the hinge pin, compared to the approximately 3 mm which the Aeneas antenna had between its hinge pin and the position setting set-screw. This one architectural change increased the deployment accuracy of the hinges by at least 4 times. Further, using flat hard stops instead of setscrews prevented the position from changing with each deployment as set screws can move. The tips of the setscrews would dig into the aluminum hinge on deployment, whereas a flat hard stop prevents the deformation with better distribution of the load.

Rib Fabrication Process

As the hinges did not use setscrews, this also meant that the hinges were not adjustable. Therefore, it was very important that the ribs and hinges were placed relative to each other with a high degree of accuracy. While this could be achieved with extremely tight manufacturing tolerances, this was deemed too expensive, especially on a quantity of 30 ribs. A better solution was found by using a bonding fixture to precisely set the position for the root and tip rib, and then insert and bond the hinges in place. This fixture also ensured all the ribs were identical to each other.

Design of the Antenna Deployment

A number of concepts were initially brainstormed for deploying the antenna, which included using springs, cable and pulley systems, springs combined with cable and pulley systems, and gas-powered piston systems. A major aid to developing the concept was creating a CAD drawing showing an outline of the canister and folded ribs, and printing it out to scale. Deployment mechanisms could then be sketched on this paper, as shown in Figure 3.

Figure 3. Original CAD template (left) and sketches made at scale on the template (center to right)

One of the major issues when working in CAD software is an unrealistic understanding of scale. By printing out drawings of the constraints, and sketching deployment systems to scale, it was quickly realized that any type of cable and pulley system fitting in the volume would require very small components. In addition, it would be hard to route cables in the small volume while also preventing tangling.

Springs alone were not a realistic system either because of the preload required to tension the mesh. While the total preload needed was calculated to be 250 N at the end of deployment, this would result in a force of at least 500 N when the spring was stowed prior to deployment. This means there would be a lot of excess energy in the spring which would go into accelerating the antenna, resulting in a dynamic impact. Therefore, the most reasonable system appeared to be a gas driven canister as the primary mode of actuating the deployment. As the entire system is stowed in a canister, it was convenient to also use the hub as a piston. Pumping gas between the piston and the base would cause it to expand in the cylinder, pushing the antenna out and deploying it. If the gas could be properly metered, the antenna would be allowed to slowly deploy, and then pressure could be increased only at the end when the additional preload was required. Given the 10-cm-diameter piston, operating in the vacuum of space, only 32 kPa (about 1/3rd of atmospheric pressure) would be required to achieve the 250-N load. Further, no miniature parts were required by such a pressurized system. To ensure the antenna would stay in the deployed state after the gas-powered deployment, the fully deployed antenna would be latched in place

When considering the deployment system, beyond pushing the antenna out of the canister, the antenna ribs also required deployment from their initial state. While originally multiple cable systems for rib actuation were explored, and even tested, these were dropped for the same reasons they were not used for actuating the antenna out of the canister; lack of space. It was determined the best approach was to have the root ribs catch on the edge of the canister, leveraging them out to deploy. This ensured the root ribs, which react a majority of the moment, could have a high preload when deployed. Each rib has two springs attached to either side of it. These springs are all attached to one ring, which ensures all 30 ribs are synced together.

When the antenna reaches the top of the canister, the ring hits an internal stop in the canister, which prevents it from moving while the hub continues to travel up. This causes the root ribs to deploy as they are pulled by the springs attached to the ring. The springs also add compliance to the system accommodating for any small deviations in deployment of the root ribs.

The tip ribs are each deployed by a constant force spring in the mid-rib hinge. The tip rib spring actuates once the root ribs have deployed far enough such that the tip ribs are clear of the horn.

Use of Additive Manufacturing

When fabricating the spring ring, which coordinates all 30 springs to the ribs, it was found additive manufacturing was the most cost-effective approach and gave the best result for building this part. The spring ring consists of multiple small holes through which extension spring hooks attach. Traditional manufacturing would have been challenging as the spring holes would be at an angle, and thus hard to drill with a small diameter drill bit. Further, the holes would have sharp edges, which would catch on the hooks of the extension springs. However, by additively manufacturing this part, a full annular hole was created in the spring ring, perfectly fitting the geometry of the extension spring (Figure 4). This made it function better than a traditionally fabricated part.

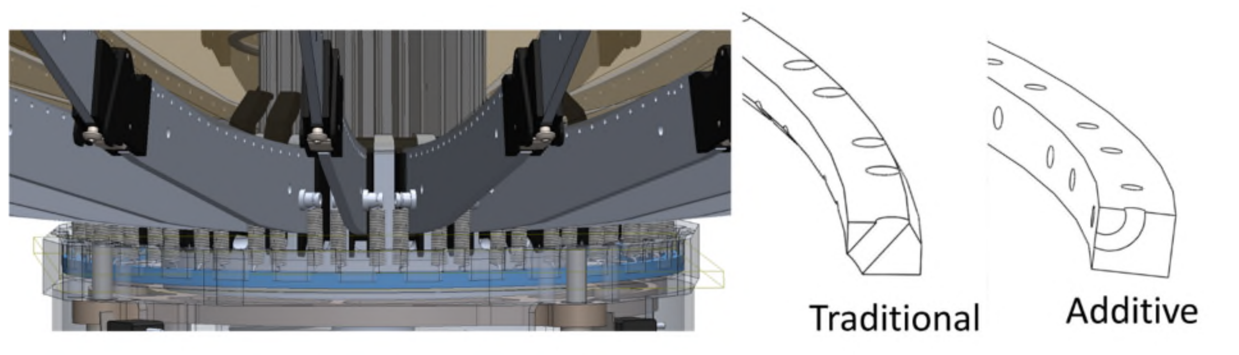

Figure 4. An Additively Manufactured Spring Ring Allows for Unique Features

The component was printed of 304 stainless steel, and as additive manufacturing has been known to have variable material properties, a stress analysis was performed and found the part had a factor of safety of greater than 10. Therefore, material property variance was deemed to be low risk enough to not require testing of the additively manufactured parts. Perhaps the most exciting part about additively manufacturing this component was that it was cheaper than machining the part traditionally. As material volume is the key cost in additive manufacturing, and complexity is not a driver, this part required minimal material and could thus be built inexpensively. This also provided a good example of using additive manufacturing for its strengths in creating complex features which would be hard to machine otherwise. While additive manufacturing is not the best option for many parts, for this one component, it had significant advantages.

Construction and Testing of the KaPDA Antenna

Three versions of the KaPDA antenna were constructed in series. First a prototype, then an engineering model, and finally a flight unit was constructed.

Prototype

The first prototype of KaPDA was constructed to primarily verify the accuracy with which the antenna could be built and test the gas-powered deployment system. The prototype was a full fidelity prototype, which used flight like materials.

To construct the antenna, first the 30 ribs and hinges were assembled. The ribs were then attached to the hub. Mesh was stretched and tensioned over a parabolic mold, and then the hub with ribs were set on top of the mesh. The mesh was attached to the ribs through a series of holes in the ribs, with nearly 2,000 hand stitches attaching the two. The antenna then came off the mold in the fully deployed state.

The antenna was first RF tested to check the as-built tolerances prior to deployment, and found to achieve 42.5 dBi of gain, outperforming the gain requirement of 42 dBi. This indicated the RF design had adequate margin and the antenna was built to better than required tolerances.

After the RF test, the antenna was stowed by carefully folding the ribs and sliding the hub down into the canister. Then pressurized gas was inserted through the base plate, actuating the deployment, which appeared to be successful as illustrated in Figure 5.

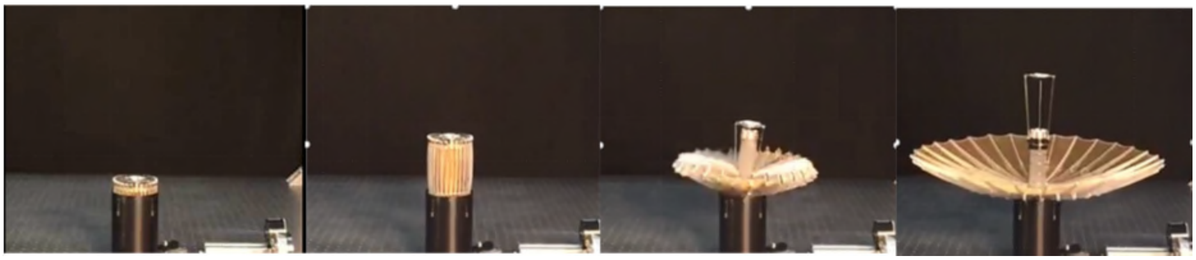
A B C D

Figure 5. Antenna Deployment Via Gas Power

After deployment, the antenna was taken to the range for RF testing. When mounting the antenna horizontally, it was noted some of the ribs were folding closed. Further investigation showed that the inflation powered deployment had never latched the antenna. While the antenna was able to be manually latched in place, and the RF test could be finished, in orbit this would have been a requirement critical failure as the ribs would not be in the right location to achieve high gain. RF testing also revealed after being manually latched in place, the antenna only achieved 42.0 dBi of gain, just meeting the requirement.

Further investigation of the deployment video revealed that the spring ring and hub tilted to one side near the top of the deployment (Figure 5C). This angle prevented the ribs from properly latching in place. Because gas was just pushing on the antenna during deployment, nothing was constraining the antenna to ensure it deployed straight and vertical. The piston consisted of a thin plate attached to the hub, and therefore was free to rotate like a coin spinning its way down a pipe of similar diameter. While height could have been added to the plate, there was not enough room to add as much length as the cylinder diameter, which would mean the L/D for a sliding contact would be less than one, putting the design at risk for jamming.

While this was the first indicator that a gas-powered deployment would not be suitable for this space deployable, several other complications arose. First, when looking for a gas system to operate in orbit, the only commercially available parts that would fit in the system were small cold gas generators. Unfortunately, these release pressure relatively quickly, and would result in an explosive deployment. Secondly, even if the deployment could be controlled by a gas-powered system, there was the added complication of a canister of gas sitting in space. If it began to leak, even a small jet of gas would behave like a propulsion system, and could potentially cause the spacecraft to lose control. Finally, residual pressure and launch locks to resist residual pressure added further complications to the design. Because of this series of issues, it was determined an alternate approach for the primary deployment system had to be found.

Development of the Engineering Model

The engineering model began with a design process investigating alternatives to provide the main deployment of the antenna out of the canister. After going back to the drawing board, a motor-powered deployment with lead screws was investigated. This deployment approach was initially rejected during the early trades because the most intuitive place to locate a lead screw was in the middle of the antenna, conflicting with the waveguide. However, through further brainstorming, realization dawned: the antenna fit into a canister, but a CubeSat is a square. As such, there were four corners not being utilized. Four lead screws could be located in the corners, driven by a motor (Figure 6). The main challenge: synchronization of all four lead screws to ensure a steady deployment.

To synchronize, each lead screw was attached to a “planet” gear. Each “planet” gear interfaced with the “sun” gear in the center of the antenna which kept all four lead screws in sync. While this is not a traditional planetary gearbox, it is easiest to reference the design in these terms. Because of the waveguide in the center of the antenna, the sun gear was mounted to a large diameter thin section bearing. A pinion attached to the motor would drive one of the planet gears, in turn driving the sun gear, and then the other three planet gears. While initially there was discussion of using two motors for redundancy in the system, if one of two motors failed, extra torque would be required to back drive the non-functioning motor. Therefore, the antenna was maintained with a single motor.

The lead screws attached to a brass threaded feature on the hub which would drive the antenna up and down. A further advantage of the motorized system was realized when investigating adding launch locks to the design. The lead screws could also be used to hold the hub down, in addition to deploying it. Therefore, one system provided the launch lock and deployment capabilities.

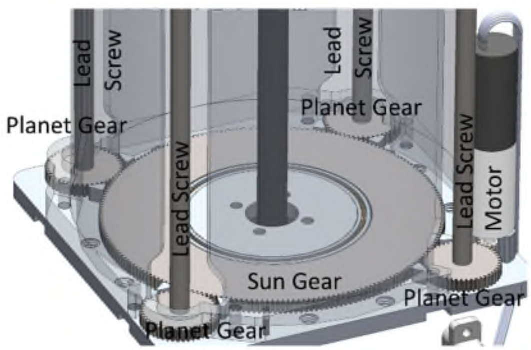

Figure 6. Motorized Deployment System Components

The prototype antenna was retrofitted with the motorized system. The same mesh, horn, and secondary reflector were used. This meant only the canister, base, and some components on the hub needed to be replaced, along with the additional motorized drive system. This retrofitted designed was referred to as the engineering model.

<u>Engineering Model Testing</u>

The antenna was then deployed with the motorized deployment system, where all systems behaved nominally. The antenna was taken to the RF range for testing after deployment to check the deployed shape. It was found the motorized system could apply more preload to the system in the deployed state, which resulted in a better surface accuracy, and thus a gain of 42.7 dBi, once again exceeding requirements.

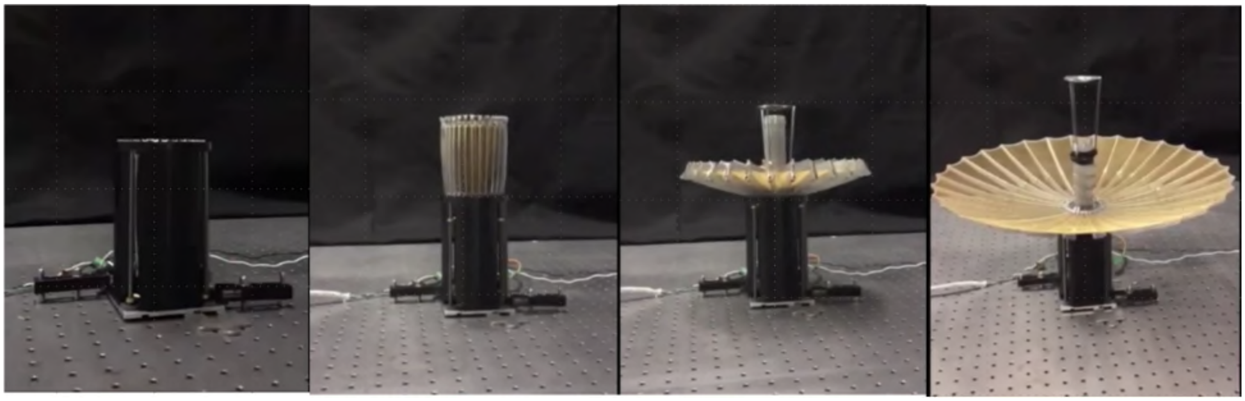

Figure 7. Antenna Deployment with Motorized System

After the deployment system demonstrated successfully, the next key challenge was to prove the design through vibration testing. The antenna was vibed at 14.1 G_{RMS} in three axis, which is the General Environmental Verification Spectrum qualification level, as no launch had been determined at that point. After the vibration in the first axis, the antenna was deployed to ensure everything worked as planned. However, the deployment revealed a problem with the design. The mid-rib hinges, actuated by the constant force spring did not deploy. This resulted in the deployed antenna stopping in position illustrated in Figure 7C. While it was known the mid-rib hinges had a low torque margin, prior deployments had never failed to deploy the antenna. The root cause was found to be a combination of friction and gravity from a number of test runs with an extra hinge. When the antenna was stowed, the constant force spring is unrolled and pulled across the root portion of the mid-hinge. The friction on the spring prevents it from fully relaxing, resulting in tension. But vibration shifted the spring into lowest energy state, resulting in friction that was originally providing additional tension, now resisting the deployment. In addition, in the configuration the antenna was deployed, the mid rib hinges had to deploy against gravity. The combination of gravity and additional friction resulted in a negative torque margin.

After the failed deployment, kick-off springs were added under the constant force springs to ensure the antenna deployed. Vibration test proceeded in the remaining two axes, and afterward the antenna deployed successfully. Once, again, the antenna was taken to the RF range for testing, and found to achieve a gain of 42.7 dBi.

One final note on the engineering model antenna: during a subsequent deployment, after the RF test, one of the kick off springs became jammed in a closed rib which prevented the antenna from fully deploying. Thus, a more permanent solution was required.

Flight Model

After the completion of vibration testing on the engineering model, construction of the flight model began for the RainCube Spacecraft, a 6U CubeSat. RainCube is a precipitation radar and will be the first active instrument in the CubeSat form factor. Some redesign efforts were required, the first and foremost being changing the rib mid-hinge geometry to allow the constant force spring to generate more torque. Other changes included features to better hold the ribs in the stowed position, switches for deployment verification, and vacuum-compatible grease in all components. During construction of the flight model, the torque margin was checked on the mid-rib hinges, and found to be more than adequate when compared to the engineering model design.

After construction of the flight model, it was first deployed and then tested on the RF range, once again achieving a gain of 42.6 dBi. Next it was stowed and then deployed in thermal vacuum (TVAC) at a temperature of 65°C. In general, antennas are not fully deployed in thermal vacuum due to size, but because KaPDA was intended for a CubeSat, it was easy to find a chamber which could accommodate a full deployment of the antenna. While initially the deployment went as planned, the antenna suddenly stalled about 2/3rds though the deployment. After trouble shooting, it was found the motor controller, which had a poorly design thermal path to the chassis, was overheating. The motor controller had a thermal limit of 85°C, but without adequate heat conduction, the heat generated by running the antenna caused it to overheat at just 65°C. Deploying the antenna at 55°C eliminated this problem. While the initial thermal range from deployment was 10°C to 50°C, the range was decreased to 10 to 40°C.

After TVAC testing, the antenna was taken to the RF range for further testing, and no changes were observed to antenna gain. However, another problem occurred when stowing the antenna. When driving the antenna down, an odd noise was coming from the sun and planet gears. Investigation revealed the sun gear was running at a slight angle. It appeared that during thermal vacuum tests, because the gear was a 300 series, or austenitic stainless steel, and the bearing was a 400 series, or matristic stainless steel, the coefficient of thermal expansion was different enough to cause the press fit to become loose. As the antenna was deployed with the loose press-fit at the high temperature, the sun gear worked its way off the thin section bearing. Further detailed analysis revealed, depending on the tolerances of manufacturing, when going cold the sun gear would likely crush the thin section bearing. The end solution was to increase the diameter for the hole in the sun gear, and then bond the sun gear to the bearing, providing compliance at the thermal interface. Further, a 0.4-mm bond line with EA9360 epoxy helped to athermalize the joint, resulting in less stress on the gear and bearing.

After re-installing the sun gear bearing, the antenna was installed on the RADAR instrument assembly. The RADAR instrument then went through a 6.1 G_{RMS} workmanship vibe, which was the minimum required as actual launch loads for RainCube are expected to be much lower, closer to 2 G_{RMS} (given it is being stowed with soft cargo to the International Space Station). After vibe, the antenna went through a second thermal vacuum test, this time where it was deployed at 0°C. The antenna behaved exactly as expected through both tests.

However, about 3 months prior to installation of the antenna on the spacecraft, it was realized the spacecraft (built by a vendor, Tyvak) would be supplying 12 V to the antenna, where previously the antenna operated at 5.5 V during testing. This change warranted investigation, and revealed the antenna would be performing fundamentally differently than before, and could generate a higher stall torque than observed in the prior test. As such, a current limiting feature was programmed in the motor controller to ensure the performance on orbit was similar to the performance in the number of environmental and deployment tests on the ground.

The KaPDA antenna and RainCube instrument has been integrated into the RainCube spacecraft at Tyvak, the spacecraft bus vendor. Assembly and EMI/EMC testing have been completed.

Current Status

The RainCube spacecraft assembly is about to undergo environmental testing for a 3rd time at the spacecraft level, although this testing is much more benign than the level to which the Instrument Assembly with the antenna was qualified. After environmental testing, the antenna will be deployed one last time to verify operation before it is stowed. RainCube is scheduled to launch in May 2018 from Kennedy Space Center and fly as soft cargo to the International Space Station. Once there, it will be deployed from the station via the NanoRacks CubeSat deployer. After approximately one month of bus checkout tests, the antenna will be deployed for a final time, in low earth orbit. The mission and antenna are designed to operate for approximately 1.5 years, before it reenters Earth's atmosphere and disintegrates.

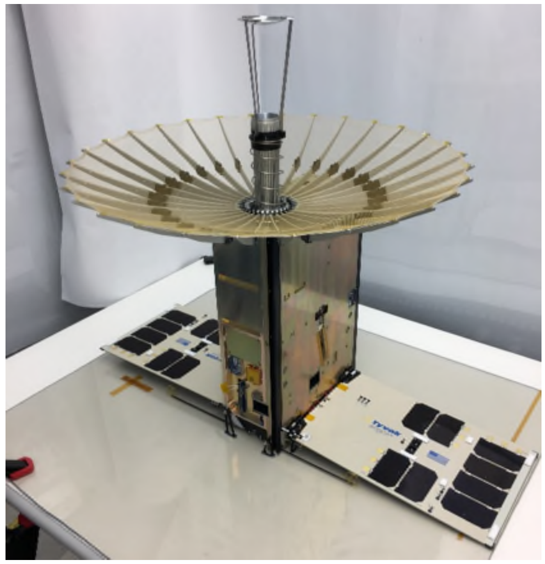

Figure 8. Flight KaPDA Installed with the Tyvak Spacecraft

Conclusions / Lessons Learned

KaPDA has provided a number of great lessons learned with regards to mechanism design, given it combines motors, gear trains, lead screws, springs, and at one point pneumatics. There are a number of separate actuating features, each of which have generated key lessons learned, detailed below.

Add as much Depth in a Deployable as Possible
It is common knowledge increasing the area moment of inertia improves cross section performance. While this seems like a minor change, it was a key instrumental factor in achieving the surface accuracy and deployed stiffness. While it is often challenging to add deep sections to a deployable because of stowed size constraints, the KaPDA design achieved additional depth by placing it where the bending moment was the highest and reducing it where the bending moment was lower. The additional depth also made the hinges less sensitive to manufacturing tolerances by allowing hard stops to be placed far away from the hinge pins.

Use Fixtures to Prevent Tolerance Stack up Issues
A key design decision in the assembly process was to use fixtures to assemble components, and bond them in place thereby achieving very accurate and consistent ribs. This effectively removed the effects of tolerance stack-up from assembly, such that the fixture was the key driver in achieving the appropriate geometry. This allowed both versions of the antenna to be extremely precise and provide high RF performance.

When to use Additive Manufacturing
Additive manufacturing was found to have advantages for building small, complex components. This allowed lower cost approaches than traditional machining for a part that had better function. However, most parts used in the antenna were still best implemented through traditional machining, and additive should not be considered a replacement for traditional methods. Rather, it becomes an alternate method in the designer's toolbox.

Use Deployment Methods Provide Control Authority
The original deployment method, using a gas powered pneumatic approach provided almost no control authority, other than deciding when to start the deployment. Moving to a motorized system allowed specific

control of the motor rate, and the encoder could even be used to monitor the deployment status. Therefore, a deterministic deployment was much preferred.

Friction on Sliding Components

Be very wary of any effects friction may have, as was learned in the constant force springs in the mid-rib hinges. When deploying, ensure all components have relaxed to their lowest strain energy state prior to deploying, to ensure there are no surprises later in the program.

Press fits

Beware of press fits. Even if the type of material is the same (i.e. stainless steel), ensure the microstructure and details of the alloys are understood, especially when it comes to CTE effects. We were able to use a thicker bond line to compensate for the dimension changes.

General Lessons Learned

While lessons learned above were quite specific, there were also two key general lessons learned. First, ensure understanding of all the variations of performance of a system, especially when dealing with a complex system like an electrical system. This was learned when working with the motor controller. Second, while we do our best to understand our mechanisms through environmental testing, one really is not done learning the ins and outs of a mechanism until the mechanism is fully qualified, or likely even operational in orbit. While we are not in orbit yet, given what we continue to learn about this mechanism design, we expect to continue to glean lessons learned throughout orbit.

Conclusions

Despite the challenges, lessons learned (many of which may be obvious to the experienced designer), it is truly exciting to have KaPDA functioning as expected, and slated to launch in the next several months. It will be even more exciting to see what KaPDA does for small satellites, as it is a new capability which will dramatically increase satellite gain, whether it be radar instruments, or high data rate communications. The design has also been licensed to a company for commercialization, so beyond just changing capabilities for future NASA missions, KaPDA may very well be a ground-breaking technology for a much broader array of missions.

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