From Prototype to Flight: Qualifying a Ka-band Parabolic Deployable Antenna (KaPDA) for CubeSats

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CubeSats have experienced a number of exciting technological advancements in the past several years. However, until recently, there has been very limited development in the area of high gain CubeSat antennas, which are critical for both high data rate communications and radar science. A Ka-band high gain antenna would provide a 10,000 times increase in data communication rates over an X-band patch antenna and a 100 times increase over state-of-the-art S-band parabolic antennas. Because of this, three years ago the Jet Propulsion Laboratory (JPL) initiated a research and technology development effort to advance CubeSat communication capabilities, with one of the key thrusts being the Ka-band parabolic deployable antenna (KaPDA). This antenna started with the ambitious goal of fitting a 42 dB, 0.5 meter, 35 Ghz antenna in a 1.5U (10 cm x 10 cm x 17 cm) canister. This paper discusses the process of taking the antenna from a first prototype to the flight design, which is flying on the RainCube mission, and earth science CubeSat. The prototype antenna was constructed in early 2015, and then upgraded to an engineering model at the end of 2016 to compensate for lessons learned. The flight version is currently under construction, and scheduled to be finished in 2016. KaPDA is the second deployable parabolic antenna to fly on a CubeSat, and the first of its kind to operate at Ka-band enabling a number of opportunities for high rate deep space antenna communications and radar science.

I. Introduction

CubeSats have recently seen a large increase in technical capabilties and launch opportunties, including potential missions beyond low earth orbit. As instruments become more advanced and operational distances between CubeSats and earth increases, data rates become a mission limiting factor. Improving CubeSat data rates has become critical enough for NASA to establish the CubeQuest Centennial Challenge[1] where one of the key metrics is transmitting as much data as possible from the moon and beyond. 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. The CubeSat ANEAS, which was launched in September 2012, pushed the envelope with a half-meter S-band dish which could achieve 100x the data rate of patch antennas. A half-meter parabolic antenna operating at

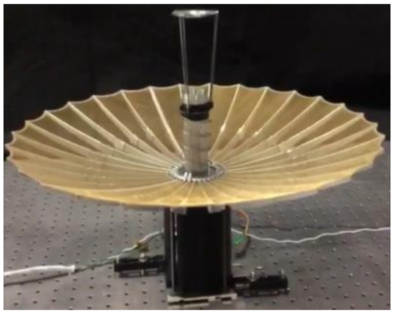

Figure 1. KaPDA Engineering Model

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Ka-band would increase data rates by over 100x that of the ANEAS antenna and 10,000x that of X-band patch antennas. Further, various radar missions are enable by large aperture high frequency parabolic antennas. This would be particularly useful for Earth monitoring CubeSat constellations.

II. Background

A number of deployable parabolic and parabolic like antennas have been developed in the past for CubeSats. Concepts have included a goer-wrap composite reflector[2], a reflector transformed from the CubeSat body[3], an inflatable parabolic reflector with reflecting material on one side and transparent material on the other[4], a mesh reflector supported by ribs[5,6], and a reflectarray[7]. While these designs provide unique solutions, they are all designed to operate at S-band (with the exception of the reflectarray, which is also currently under development at the Jet Propulsion Laboratory). A Ka-band antenna would have much greater gain, which translates to greater data rate, but requires a much higher surface accuracy than S-band. The lack of high gain antennas motivated JPL to launch a research and development effort for high frequency deployable antennas for CubeSats three years ago.

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. 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[8]). Shape memory reflectors may work at lower frequencies, but much development is still required as at Ka-band the surface is not accurate enough[9]. Inflatable reflectors stow well and are lightweight but have issues with maintaining inflation and shape. This is especially problematic on interplanetary CubeSat missions which will likely last much longer than LEO CubeSat missions. Reflectarray antennas provide a relatively high gain and stow well in large flat spaces (i.e. areas for solar panels on a CubeSat), but have very limited operational frequency range, thus requiring two separate antennas, one to transmit and the other to receive. Therefore, the most attractive high gain deployable antenna design for JPL to pursue was the mesh reflector architecture.

There are many concepts for mesh parabolic deployable antennas at much larger scales than CubeSats. In the 1970's Lockheed Martin developed the Wrap-Rib reflector, which uses a mechanism to wrap the ribs and mesh like a tape measure[10]. However, the design does not fit well in the CubeSat form factor, as the mechanism that deploys and stows the ribs is quite large. There are also a number of knit mesh reflectors, the most popular of which are Harris's Unfurlable Antenna and Northrop Grumman's AstroMesh[9]. However, these two designs consist of many small, detailed components, which are challenging to scale down without the antenna becoming prohibitively expensive. It should be noted that about two years after the start of JPL's initiative, others began developing CubeSat antenna designs inspired by the AstroMesh and Unfurlable Antenna configurations, but both have larger apertures and are likely to consume more volume than the antenna discussed in this paper[11,12].

At the point the Ka-band antenna effort began three years ago, two knit mesh antennas had been developed for CubeSats, but both were designed for S-band operation. They were a spiral stowed rib design[6] and the ANEAS parabolic deployable antenna (APDA) folding rib design that was used on USC/ISI's ANEAS spacecraft[5]. The spiral stowed rib design, while very compact, would be challenging to extend to Ka-band as the ribs could not apply adequate force required to stretch Ka-band mesh to achieve the required surface accuracy. The APDA architecture would work well for Ka-band, as it used straight folding ribs, which can apply more force and allow for greater surface accuracy. In addition, the APDA is the only CubeSat parabolic deployable antenna to have flown. Therefore, it was decided to use the APDA as a starting point for the Ka-band parabolic deployable antenna (KaPDA) design[13,14].

III. Design of the Mechanical Prototype

The first design task was to analyze the influence of antenna configurations on stowed space and gain. A number of designs were explored including Cassegrainian, Gregorian, and several hat-style feeds[15]. The Cassegrainian configuration was selected as it best balanced performance and stowed size, as the dimensions for the sub-reflector were such that it could be stowed within 1.5U.

The number of ribs supporting the mesh structure is a key factor for achieve surface accuracy, which is critical at Ka-Band. More ribs result in a more ideal dish, and thus greater RF gain. However, as the number of ribs increase, the clearance between each rib when stowed decreases. Packing ribs too tightly could result in snagging during deployment. The best compromise between rib clearance and RF loss due to a non-ideal shape was found to be 30 ribs.

Each rib was divided into two components, the root rib and tip rib, which were connected by a hinge. The mesh forces and resulting moments determined the geometry of the rib. As the root ribs experienced the greatest bending moment, they are deeper. The tip rib had a tapered design to conserve space and eliminate material where it was not required for rigidity. The taper was designed to create an even stress profile throughout the rib. To improve both stowing efficiency and surface accuracy, the ribs were much deeper (by over 10 times) but slightly thinner than those used on APDA. The deep rib design also was advantageous for precisely controlling the rib's deployed position.

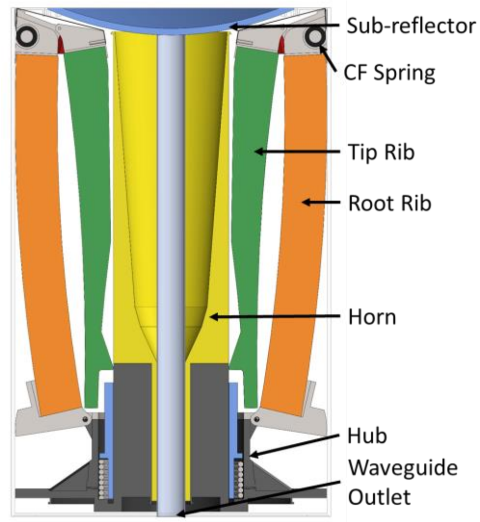

Figure 2. Key KaPDA Components

Perhaps the greatest design challenge was developing a deployment mechanism that stowed in 1.5U with the antenna. The deployment mechanism must first push the hub out of the CubeSat and then unfold the ribs. The APDA was deployed entirely using springs, with all the components unfolding quickly. However, Ka-band requires 40 opening per inch (OPI) mesh which is stiffer and required greater deployment forces (APDA only used 10 OPI mesh). A preload of approximately 250N was required at the end of the spring's displacement, which means any stowed spring would likely be compressed to well over 500 N resulting in a violent deployment. Therefore, other concepts for deploying the hub and ribs had to be explored.

To deploy the hub, a number of concepts were explored including motors driving threaded rods, a scissors lift, low force springs (if hub deployment was decoupled from rib deployment), cables and pulleys driven by motors, and a gas driven piston. Many concepts were eliminated because of complexity (e.g. cables and pulleys driven by motors), they were challenging to implement within the highly constrained space (e.g. scissors lift), or they didn't work (e.g. low force springs). Initially, the most attractive deployment mechanism was the gas driven piston, as it stowed well in a small space. To actuate the antenna, two micro CGG's, built by CGG technologies, would provide enough gas to deploy the antenna to the required pressure in the vacuum of space [16]. After deployment, a latch was used to lock the hub in place to ensure if the gas escaped the antenna would remain fully deployed.

To deploy, the hub was first driven upwards by compressed gas pushing on a piston (Figure 3, A-B). As the hub neared the top of the canister, the root rib base hinges caught on a snap ring and the ribs began to deploy (B-C). The tip ribs reached a point where they became free of the horn interference, and the constant force springs deployed them (Image C). The hub continued to travel upwards until the root ribs fully deployed (image D). As the ribs folded outwards, the sub-reflector was released by the root rib hinges and telescoped along the horn, pushed upward and held in place by a spring (C to D). After the hub was fully deployed, it was locked into place by spring-loaded latches.

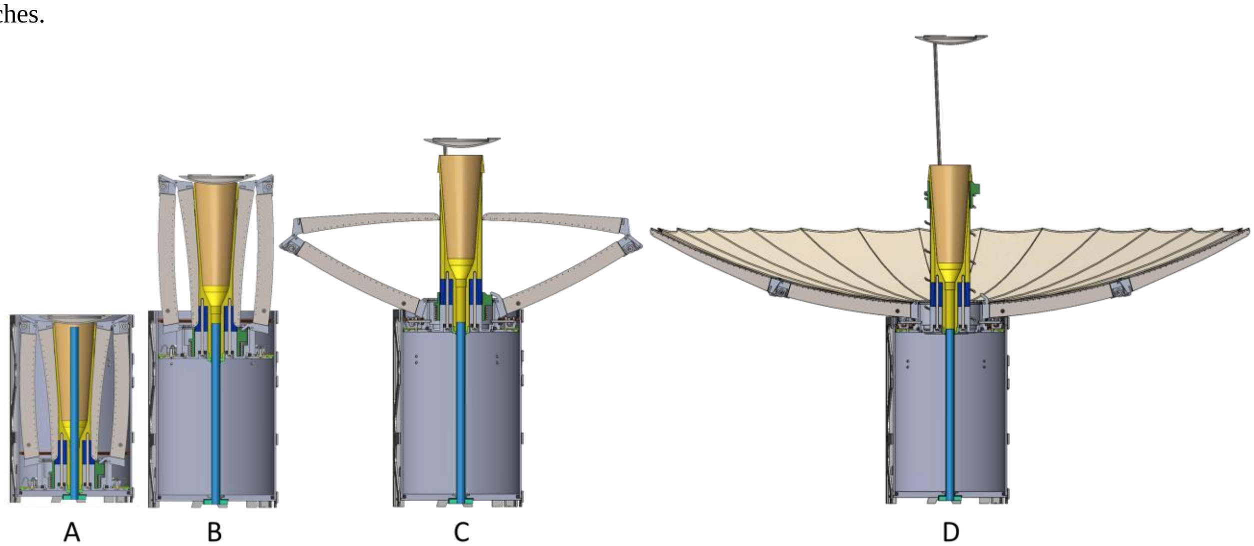

Figure 3. KaPDA Deployment Sequence

IV. Antenna Modifications from Prototype

The mechanical prototype was tested for deployment using an air supply and adjustable valve. While deployment initially appeared successful, when the antenna was taken to the RF range for testing, it was found some of the ribs were not latched in the deployed state. Detailed investigation into the slow motion videos of the deployment revealed that during deployment the antenna hub tilted to one side, as it neared the top of the canister, only straightening itself after the ribs began to deploy. This tilt prevented some of the ribs from latching into place on the hub. After manually latching the hub, the antenna assumed its shape and it was possible to RF test the antenna. However, there was a degradation in RF performance (Table 1) and manual adjustment is not possible on orbit, therefore it was necessary to explore other deployment solutions.

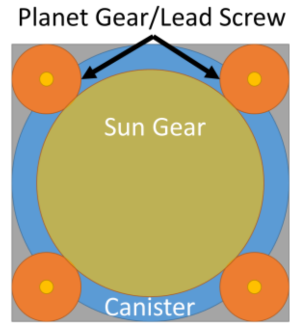

Figure 4. Four Lead Screws Provide a Level, Controlled Deployment

The primary problem with the air powered design was that there was nothing keep the hub axially aligned with the waveguide near the end of deployment. While the waveguide preliminarily kept the hub aligned, as it neared the top of the canister in Figure 3C, there was not adequate length over diameter to ensure the two stayed axial until full deployment. Unlike springs or other actuator concepts, air does not provide any stabilization or centering capabilities. Further investigations into the CGG's revealed actuation occurred quite suddenly, on the order of 10ths of a second, which would result in a deployment with comparative violence to that of springs. Therefore, another deployment approach was required.

About this time, serendipitously one of the authors observed a small 10 mm motor with a 1024:1 gearbox. Investigation revealed the motor and gearbox combination could produce the required torque when applied through a lead screw. A properly designed lead screw would also keep the hub aligned axially with the waveguide. A key design challenge with this architecture was connecting the lead screw to the hub, as the most intuitive design would place it at the center of the antenna. However, the telescoping Ka-band waveguide was located at the center of the antenna, and there was no room to place a lead screw without interfering with the RF design, which is why this design was not considered earlier.

A solution was found by utilizing four lead screws instead of one, located in the four unused corners of the canister (Figure 4). The four lead screws kept the hub axial to the waveguide at all times. However, to ensure a smooth deployment, all four lead screws had to deploy synchronously. To maintain synchronization, all four lead screws were attached to "planet" gears which mated with one "sun" gear. A single motor drove one of the planet gears, which was then transferred to the other planet gears through the "sun" gear. The deployment sequence occurs in the same fashion as illustrated in Figure 3, except now the hub is moved upwards in the canister by the lead screws.

The motorized design provided a number of other advantages, beyond a controlled deployment and keeping the hub axially aligned with the waveguide. It also eliminated the need for all latches and a launchlock, as preload from the lead screws were used to secure the antenna in the stowed position and retain it in the fully deployed position. Given the low pitch of the lead screws, it is virtually impossible for launch or deployment loads to back drive the screws, thus providing a secure latch. Using a motorized deployment provides a controllable deployment sequence, as a motor controller governs motor rate and position of the antenna and the encoder provides feedback on the number of shaft revolutions, providing deployment status. Further utilizing a motor decreases deployment test cost, as each CGG costs several thousand dollars, and eliminates the risk of a high pressurized can of gas which could potentially spin up the CubeSat if any leaking occurred after deployment.

Measure	Units	Goal	Simulation	Pre-Deploy	Gas Deploy	Motor Deploy
Stowed Size	U (10x10x11.3cm^3)	1.5	1.36	1.36	1.36	1.43
Deployed Diameter	m	0.5	0.51	0.51	0.51	0.51
Gain	dB	42	42.6	42.5	42.0	42.7
Beam Width	degrees	1.2	1.2	1.2	1.2	1.2
RMS Surface Accuracy	mm	0.40	N/A	0.22	0.25	--
Mass	Kg	3.0	1.9	1.2	1.2	1.2
Thermal	°C	-17 to 35	-26 to 62	--	--	--

Table 1: Comparison of KaPDA Performance

The canister and base of the hub were replaced on the existing prototype to enable the addition of the gear train and motor, upgrading the prototype to an engineering model. The antenna was then deployment tested a second time, with even better results than the deployment via gas powered piston. It is theorized that the motorized deployment may provide more preload than the latches, which may result in a more robust antenna shape. This likely resulted the 0.5 dB increase in gain indicated in Table 1 between the gas and motorized deployments. This meant the antenna performed just as well after deployment, as it performed prior to deployment.

V. Antenna Qualification Testing

The engineering model antenna is currently in the process of undergoing vibration testing. The antenna has been vibrated up to 14.1 Grms (Figure 5), and successfully deployed post vibration. It is awaiting testing on the RF range to verify antenna performance after vibration testing. Details on the results after vibration testing and any lessons learned will provided in the full paper.

Construction of the flight model of the Ka-band Radar Parabolic Deployable Antenna (KaRPDA) for the RainCube mission is currently underway, and completion is anticipated in August. RainCube is a technology demonstration mission, which is anticipated to be the first active radar in a CubeSat. RainCube is designed to track precipitation patterns around the globe. The flight KaRPDA will undergo further qualification testing from August through October, including additional vibration testing and deployment in a thermal vacuum. Results of these upcoming tests will also be included in the full paper submitted in December.

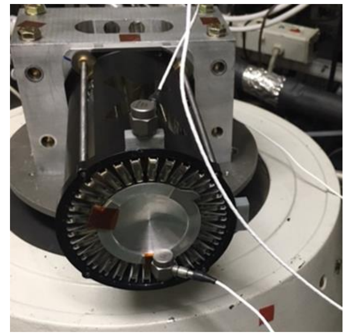

Figure 5. KaPDA Engineering Model on Vibration Shaker

VI. Conclusion

The KaPDA antenna design has been shown to exceed its goals by testing prototype and EM versions of the antenna Table 1). The antenna is lower mass, fits in a smaller volume, provides higher gain, and is a larger diameter than initially anticipated. While it remains to be seen how environmental testing will influence KaPDA's RF performance, its current design provides margin for any environmentally induced degradation.

KaPDA would create opportunities for a host of new CubeSat missions by allowing high data rate communication or high fidelity radar instruments, such as its first opportunity to fly on RainCube. It is thrilling to think about the number of new opportunities KaPDA opens up.

Acknowledgments

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