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Ultra-Compact Ka-Band Parabolic Deployable Antenna for RADAR and Interplanetary CubeSats

Jonathan Sauder, Nacer Chahat, Mark Thomson, Richard Hodges, Eva Peral
Jet Propulsion Laboratory
4800 Oak Grove Dr., Pasadena, CA; 818-669-3590
Jonathan.Sauder@jpl.nasa.gov

Yahya Rahmat-Samii
University of California Los Angeles
420 Westwood Plaza, Los Angeles, CA; 310-206-2275
rahmat@ee.ucla.edu

ABSTRACT

Over the past several years, technology and launch opportunities for CubeSats have exploded, enabling a wide variety of missions. However, as instruments become more complex and CubeSats travel deeper into space, data communication rates become an issue. To solve this challenge, JPL has initiated a research and technology development effort to design a 0.5 meter Ka-band parabolic deployable antenna (KaPDA) which would stow in 1.5U (10 x 10 x 15 cm^3) and provide 42dB of gain (50% efficiency). A folding rib architecture and dual reflector Cassegrainian design was selected as it best balances RF gain and stowed size. The design implements an innovative telescoping waveguide and gas powered deployment. RF simulations show that after losses, the antenna would have over 42 dB gain, supported by preliminary test results. KaPDA would create opportunities for a host of new CubeSat missions by allowing high data rate communication which would enable using high fidelity instruments or venturing further into deep space, including potential interplanetary missions. Additionally KaPDA would provide a solution for RADAR applications and the opportunity to obtain Earth science data. This paper discusses the design challenges encountered, the architecture of the solution, and the antennas expected performance capabilities.

BACKGROUND

SmallSats and CubeSats are becoming more capable than ever, and launch opportunities are rapidly increasing. It is exciting as these experimental spacecraft are beginning to transform into real spacecraft with the ability to do significant missions. However, while many options exist for electronics, bus manufacturers, chassis and orbital deployers, there are two key technology developments required for CubeSats to become successful interplanetary spacecraft: propulsion systems and antennas. This paper focuses on the development of the latter.

Large aperture, high gain, high frequency antennas have been critical for large satellites such as Thuraya, SMAP, and ICO G1 to achieve the data rates or perform radar missions. A number of solutions have been developed for these spacecraft over the past 40 years, including the wrap-rib, taco shell, AstroMesh, and Harris Unfurlable Reflectors[1]. As CubeSats are continually becoming more capable spacecraft, it is no surprise they require high gain deployable antennas as well.

Existing CubeSat Antenna Designs

There are a number of deployable high gain parabolic and parabolic like antennas developed for CubeSats. These antennas include a goer-wrap composite reflector[2], a reflector transformed from the CubeSat body[3], and mesh reflectors supported by ribs[4,5]. The key issue is the antennas developed to date have been designed for S-band performance. By changing the operational frequency from S-band to Ka-band, the gain can be improved, and thus data rate increased by a factor of over 100. However, such an antennas surface accuracy requirements increase by a factor of ten from about half a centimeter to sub-millimeter. This is extremely challenging, but would enable high speed data communications, necessary for interplanetary SmallSats.

New Antenna Research at JPL

In addition to the antennas just mentioned, several high gain deployable antennas for CubeSats are under development at JPL, including an inflatable, reflectarray, and parabolic mesh reflector.

The inflatable antenna, which is being designed for X-band operation, is essentially a balloon shaped like an ice cream cone with a parabolic reflector (made of metalized Mylar) on one side and a transparent cone on the other[6]. The transparent cone is mounted to the spacecraft, where the feed is located. Key advantages of the inflatable antenna are that it consumes less than 1U but deploys to over 1 meter in diameter, making it highly space efficient. The key disadvantages are that an inflatable antenna must maintain inflation at a very precise pressure to keep its shape.

The two versions of deployable reflectarray antennas are being designed for CubeSats, an X-band antenna for the MarCO spacecraft and a Ka-band antenna for the ISARA spacecraft[7]. The reflectarray antenna consists of a series of patches located on a flat sheet to create a simulated parabolic surface. This provides a key advantage, as only flat sheets need to be deployed rather than a shaped surface. This also means the antenna can be mounted in the same place as solar panels, or can even be designed with the solar panels on one side, and the antenna on the other, like the ISARA spacecraft. The two key disadvantages of this antenna is that it operates over a narrow frequency band, and the size is proportionally limited to the surface area of the CubeSat, thereby limiting scalability for small CubeSats.

A parabolic mesh reflector consists of gold plated molybdenum mesh stretched by a support structure into a parabolic shape. On larger spacecraft, the wrap-rib, AstroMesh, and Harris unfurlable antennas are examples of this antenna architecture[1]. The key advantages of this antenna design is that it can operate over a wide range of frequencies and is relatively durable. The key disadvantage is stowing efficiency, as the antenna consumes 1.5U for a 0.5 meter reflector. This antenna architecture is the focus of the rest of the paper.

DESIGNING A HIGH GAIN ANTENNA

USC/ISI Collaboration

To begin designing a high-gain parabolic deployable mesh antenna, existing concepts for CubeSats were first investigated. The two existing designs were a wrap rib reflector and a bi-folding umbrella style reflector, both designed for S-band operation. In comparing these two designs, the bi-fold umbrella style antenna appeared to be the most promising for maintaining surface accuracy when extending the design to Ka-band. The bi-fold umbrella style antenna was originally designed for the Aeneas spacecraft by the University of Southern California Information Sciences Institute (USC/ISI). Aeneas was launched is 2012, and is the only CubeSat to have deployed a parabolic antenna in flight. To begin the design of a Ka-band Parabolic Deployable Antenna (KaPDA), a collaboration with USC/ISI was initiated. The flight spare of their antenna was brought to JPL for characterization, to determine surface accuracy. Unfortunately, characterization of the antenna revealed while the same general architecture could be used, a complete redesign would be required to obtain the surface accuracy required by Ka-band.

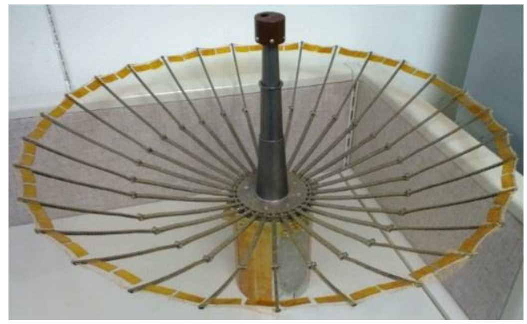

Figure 1: Aneas Spacecraft was the first high gain CubeSat antenna to fly

Feed Design Trades

The second step in designing a Ka-band antenna was to develop the RF prescription. The Aneas design had used a splash plate feed and helix. While this works for S-band, at Ka-band the system would have resulted in large gain loss. Multiple feed options were explored including Displaced Axis, Gregorian, Cassegrain, and corrugated hat feeds, where the feed is a precision machines surfaces mounted on top of a dielectric. Ultimately the Cassegrain feed was decided on as it best balanced RF gain with stowing compactness. The key feature of the Cassegrain feed is that the secondary reflector is located below the focal point, making the secondary reflector and supporting struts the shortest possible dimension and enabling it to stow in 1.5U.

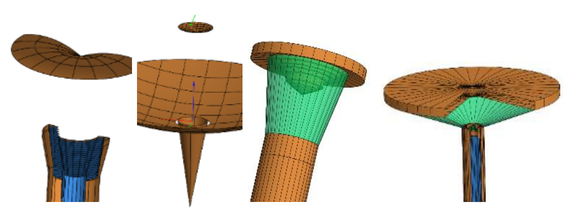

Figure 2: Feed Design Options (right to left): Gregorian, Cassegrain, Small Hat, Large Hat

Key Innovations

After determining the appropriate feed the rest of the mechanical architecture was developed. To enable the highly constrained stowed volume, several innovations were required.

One of the biggest challenges in in deploying the antenna were the connections from the antenna to the radio. The minimize RF losses, it is desirable to use a waveguide. However, the waveguide must remain connected to a static radio, while the antenna is deployed. The solution was to use a telescoping waveguide. Additionally, to fit into the packaging requirements, a telescoping secondary reflector was also required. These two innovations were a risk as it was not known how a telescoping transition may impact RF performance, but later testing mitigated this risk.

A second key innovation was the gas powered deployment. Traditionally, the simplest deployment mechanisms would be to use a large spring. However, to adequately tension the mesh required for Ka-band operation over 450 newton's of spring force would be produced when the antenna was stowed. This would result in thousands of G's of shock on deployment, destroying the antenna. Therefore, the best approach found was to use compressed gas to power the deployment. This gas could be applied at a metered rate, to ensure a steady deployment. Also, in the vacuum of space gas is highly effective, and given the large surface area of the antenna's hub, minimal gas is required to deploy the antenna.

RESULTING ARCHITECTURE

The final design for KaPDA is shown in Figure 3. The antenna consists of deep ribs which provide structural rigidity to hold a precise parabolic shape. The deep ribs also provide a second advantage, as the hinges have precision stops which are located almost a half inch from the pivot point. Having a stop located this far from the pivot reduces the influence of manufacturing tolerances. The tip ribs taper off near the end, where stiffness is not require and the additional space is needed. The ribs are connected to a center hub, which also supports the horn and secondary reflector. The hub also serves as a piston for the gas to push against.

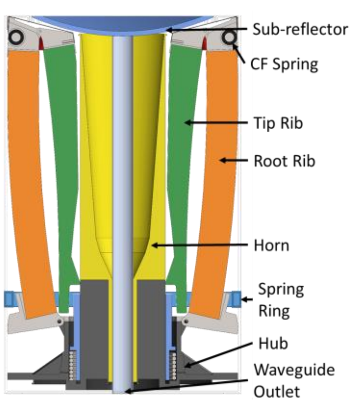

Figure 3: Key KaPDA Components

To deploy, the hub is driven upwards by compressed gas pushing on a piston (images A to B). As the hub starts to get close to the top, the root rib base hinges catch on a snap ring in the top of the CubeSat canister, and the ribs begin to deploy (B-C). The tip ribs reach a point where they become free of the horn interference, and the constant force springs deploy them (Image C). The hub continues to travel upwards until the root ribs have fully deployed (image D). As the ribs fold outwards, the sub-reflector is released by the root rib hinges and telescopes along the horn, pushed upward and held in place by a spring (C to D). After the hub is fully deployed, it is locked into place by spring loaded latches.

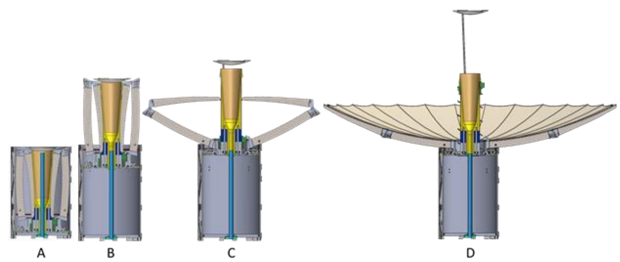

Figure 4: KaPDA Deployment Sequence

ANTENNA TESTING

The design of the antenna is complete, and construction of the first full fidelity prototype began recently. There were actually two prototypes under constructed. One is a mechanical prototype to test the deployment mechanics and the second is a solid, non-deploying RF prototype which is used to verify RF models. Preliminary tests on the prototypes demonstrated that the antenna met or exceeded its performance goals as shown in table 1. Particularly exciting were the results of the test on RF gain, which resulted in over 1dB of additional gain above the initial goal. The mechanical test demonstrated successful deployment to the required surface accuracy.

Table 1: KaPDA Performance Requirements

Measure	Units	Goal	Analytical	Tested
Stowed Size	U (10x10x10cm^3)	1.5	1.54	1.54*
Deployed Diameter	m	0.5	0.51	0.51*
Gain	dB	42	43.3	43.2
Beam Width	degrees	1.2	1.2	N/A
RMS Surface Accuracy	mm	0.40	N/A	0.37*
Mass	Kg	3.0	1.9	2.1*
Thermal	°C	-17 to 35	-26 to 62	N/A

*Preliminary test results.

The next step in the development process is to test the mechanical prototype on the RF range, as it has a gold plated molybdenum mesh instead of a solid metal surface. Its performance will be compared to the non-deploying RF reflector performance, to understand how mesh and small surface imperfections due to deployment influence surface accuracy. Next, lessons learned from these two prototypes will be incorporated into an engineering model, which is slated for completion in December of 2015.

APPLICATIONS

The two key applications for KaPDA are radar and communications. What is unique about this particular parabolic antenna, is with just a few small changes to the secondary reflector height and the waveguide outlet, the same antenna can be used for radar or telecommunications. The radar operational frequencies would focus around 35.7 GHz, whereas communication frequencies would be focused at 32 to 34 GHz. Having the same geometry of antenna enabling both applications is truly valuable for CubeSats, as there is virtually no additional non-recurring engineering costs to switch the purpose of KaPDA from communications to radar.

The need for KaPDA as a communications antenna was made very evident at a recent Mars CubeSat workshop, as many CubeSat missions to Mars baselined using one of the existing Mars assets, like the Mars Reconnaissance Orbiter, to communicate with earth. Of course, as multiple CubeSats and other missions arrive at Mars, there will not be enough bandwidth through the existing communications spacecraft. Therefore, it will be required that CubeSats have their own antenna or that a dedicated CubeSat telecom relay is built.

Another groundbreaking opportunity is to perform radar science using CubeSats. One can imagine how a constellation of earth monitoring CubeSats could provide new data on weather, atmospheric, or other earth science phenomena by covering the same area of ground with repeated flybys from multiple CubeSats over very short time periods. Such is the concept behind the RainCube spacecraft, that by flying multiple identical spacecraft over the same geographic location within an hour or less of each other, new precipitation patterns would be observed. KaPDA is a key enabling technology for such a CubeSat based radar, and is slated to fly on the first technology demonstration of RainCube.

CONCLUSION

KaPDA is a novel, game changing technology with cross-cutting applications, ranging from radar to communications. It improves data rates by 10,000 times that of an X-band patch antenna, and improves on the Aneas antenna by over 100 times. Additionally, the antenna is a “plug-and-play” unit, where all required systems are included in a single package and it provides a standard waveguide outlet which can be attached to a radio or instrument of choice.

Acknowledgments

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