

A Novel Approach for a Low-Cost Deployable Antenna

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Abstract

The Naval Research Laboratory (NRL) has designed, built, and fully qualified a low cost, low Passive Intermodulation (PIM) 12-foot (3.66-m) diameter deployable ultra high frequency (UHF) antenna for the Tacsat-4 program. The design utilized novel approaches in reflector material and capacitive coupling techniques. This paper discusses major design trades, unique design characteristics, and lessons learned from the development of the Tacsat-4 deployable antenna. This antenna development was sponsored by the Office of Naval Research.

Introduction

The Tacsat-4 satellite is part of a series of fast-paced, low-cost missions for the Operational Responsive Space (ORS) initiative. The spacecraft bus, funded by the Office of the Secretary of Defense, was designed, built and tested by a team consisting of both NRL and Johns Hopkins University Applied Physics Laboratory. The payload, Comm-X, is funded by the Office of Naval Research and will provide Communications-on-the-Move (COTM), Blue Force Tracking (BFT), and Data Exfiltration to the user community. The COTM capability provides UHF legacy radio support and a Mobile User Objective System (MUOS) like channel bit (but not MUOS-like capability) for early testing. The BFT capability collects existing UHF devices with tasking priority expected for underserved areas. The Data Exfiltration capability focuses on data collection from Navy buoys, which are typically remotely located on the seas and in littorals. The Tacsat-4 payload operates in a bent pipe fashion, working directly with legacy radios and/or sensors and ground terminals. Tacsat-4 has several ORS system-level objectives including using a prototype bus to mature spacecraft bus standards for acquisition and to fly in a "low" highly elliptical orbit (HEO), enabling a new set of ORS missions that require dwell, such as communications. The deployable antenna on the CommX payload was designed to provide UHF capability from the HEO orbit to the ground such that no active pointing was required by any ground assets.

Design Requirements

The Comm-X UHF antenna is a parabolic reflector with an f/D of 0.425 and operates over a frequency range of 240 MHz to 420 MHz. The reflector surface accuracy of the antenna was designed such that the root mean square (RMS) of the surface was within 6.35 mm (0.25 inch) of the ideal parabola. This RMS requirement, very loose compared to many industry standard reflectors, is sufficient because of the wavelength/frequency that the payload operates at. The antenna was designed to fit within the stowed envelope of the Minotaur IV launch vehicle. The antenna mass allocation was 27 kg (60 lb) with a stowed first mode of >60 Hz and deployed first mode >5 Hz. The Comm-X antenna was designed as a Class D mission, and scheduled to be completed within 12 months for $< \$4M$.

The selected orbit of the TacSat-4 satellite is 700 km x 12,050 km with an inclination of 63.4 degrees. The UHF antenna is unshielded and is required to withstand 100 MRad of total ionized dose radiation in this orbit. Additionally, the antenna will be required to withstand the thermal environments imposed by the HEO orbit (-150 deg C to +150 deg C).

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The mission required that the antenna would be capable of transmitting and receiving multiple carriers simultaneously. In order to meet this requirement, the antenna is designed to be low PIM. PIM effectively raises the noise floor of the receiver system, reducing the sensitivity of the system.



Figure 1: Stowed TacSat-4 UHF Antenna



Figure 2: Deployed TacSat-4 UHF Reflector on Comm-X Payload

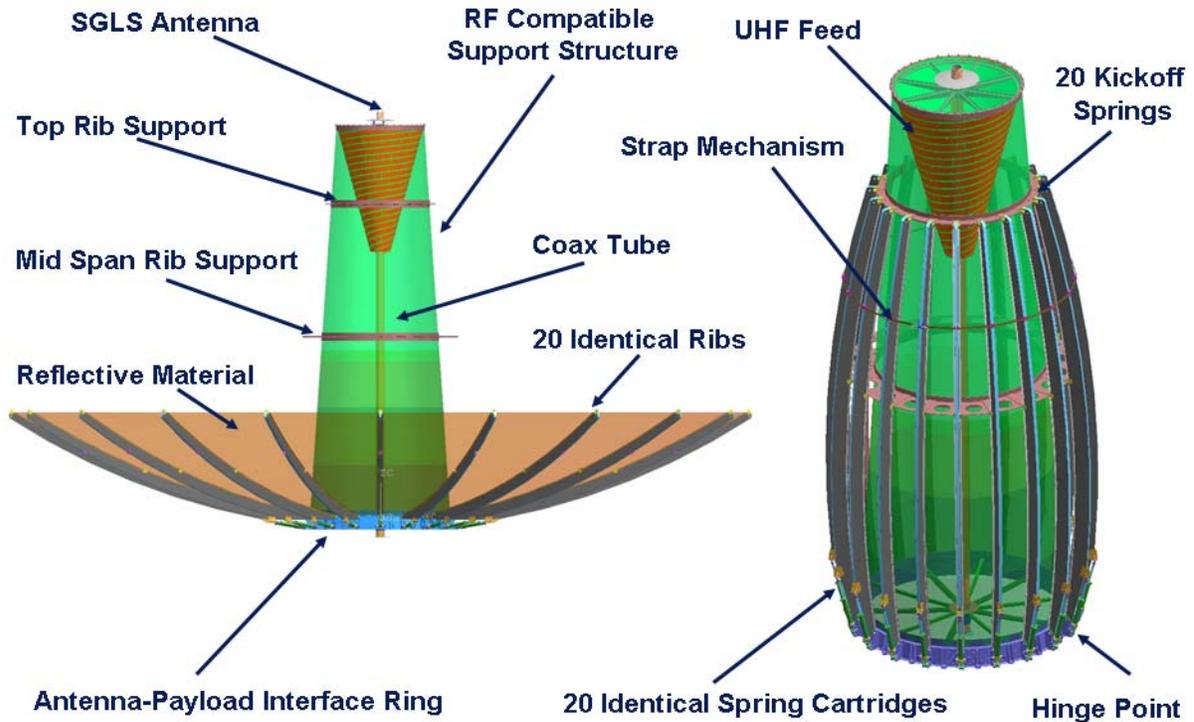


Figure 3: Tacsat-4 UHF Antenna Design

Major Design Trades

Make vs. Buy

The initial design trade of the antenna was a make versus buy decision. Several of the recognized private industry providers of space qualified reflectors were approached and provided ROM estimates for meeting the TacSat-4 antenna design requirements. Several companies provided estimates for building an antenna; however, no vendor could meet the design requirements within the schedule and budget constraints of the program. The industry estimates were approximately two to five times the available schedule and budget. Additionally, because of the extremely aggressive schedule of the program, most necessary derived requirements were determined in parallel, not serially, with the antenna development. It was therefore decided that the UHF antenna would be built in house at the NRL to meet the program's budgeted cost and schedule.

Deployment Schemes

Several deployment schemes were initially traded for the antenna. The two best options were a tensioning band around the deployable ribs and a top release "pie plate" approach which would release the ribs from the tips. It became apparent that the deployment approach would affect the relative sizing of the fixed and deployable portions of the reflector.

The "pie plate" approach required that the deployable ribs would need to reach above the UHF feed of the reflector to meet RF and PIM requirements (no metal in RF field). This meant that either the fixed portion of the reflector would be smaller than structurally desired or the ribs would need to be unnecessarily long to reach the top of the UHF feed. The release band approach allowed flexibility of fixed and deployable reflector sizing enabling the design to be optimized for mass and stiffness. The band design also did not require any additional metal in the RF field once deployed. For these reasons a release band design was used for the antenna.

Further analysis proved that a band located at a midpoint between two circumferential rings with v-block interfaces provided the highest stiffness and least complex design. These rings and v-blocks were fabricated from Ultem 2300[®] to provide necessary strength and tribology for reliable release while meeting RF requirements.

The release device selection and band design was a complex and essential part of the antenna development. Thermal knives and other flight-qualified separation mechanisms were traded for the release device. Program requirements did not allow the use of any pyrotechnic devices and therefore were not included in the trade space. A low-mass release device was needed to minimize deployment dynamics differences between all ribs. Furthermore, because of the length of the band (~2.5 m or 100 inches) and the kinematics of the deployment, it was decided to deploy the band in two halves rather than one long piece (shown in Figure 4 and Figure 5). This was done to minimize possible snagging and friction forces. A TiNi Aerospace Frangibolt[®] device was selected for the release of the band. A single device was selected to release both band halves over two devices because of complexity and risk implications on the antenna design. Early full-scale breadboard testing of the release concept ensured confidence in the release design approach for proper function as well as working out band tightening techniques.

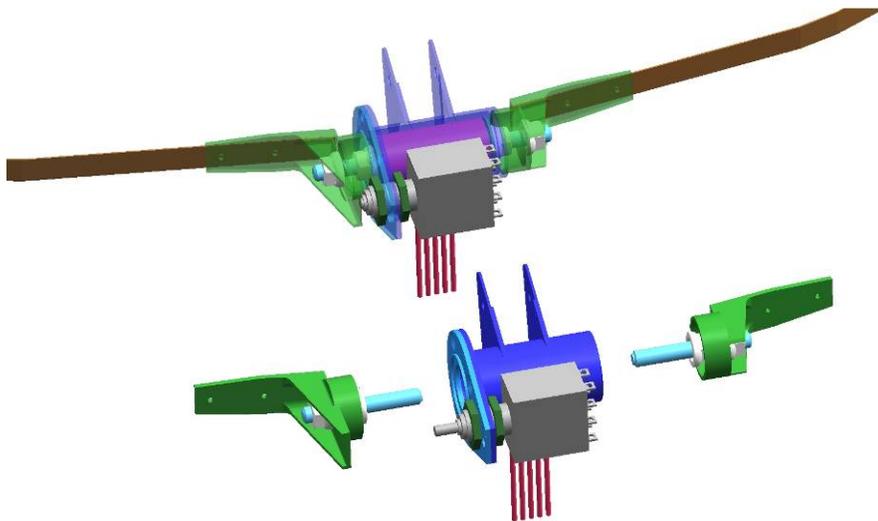


Figure 4: Release Device Assembly



Figure 5: Deployment Band Breadboard Fixture

Reflective Material

The reflective material for the antenna was a major design driver and yielded a novel design approach. The low PIM requirement, required surface accuracy, survival temperature, radiation environment, and stowed packaging all factored into the material selection trade space. PIM is generated by loose or “dirty” metal to metal contacts in the RF field. A low-PIM reflector required that any metal to metal contacts would need to be avoided if possible and closely analyzed where necessary.

There are many proven deployable reflector designs which use a woven metallic mesh material and achieve much tighter surface accuracies. In this type of design, the material must be managed very carefully to maintain the tension of the mesh in order to maintain low PIM. This is accomplished through an intricate design adjusted through a labor intensive process to meet RF performance requirements. The material is also expensive and is not readily available for purchase. For TacSat-4, the cost and schedule ROMs showed that this design approach would not be feasible, nor was it required to meet the looser UHF tolerances for surface accuracy.

The goal of the TacSat-4 antenna design was to take advantage of the very loose RMS requirements in order to lower the complexity, and in turn cost of the antenna. A gore approach was selected using several smaller reflector pieces that were joined together using capacitive coupling into a single reflector while avoiding any metal to metal contacts. The novel approach used Kapton[®]-Copper flex circuit material. Each gore is made of a sandwich material with Kapton on the outside and a soft copper grid in the middle. The copper thickness was selected so that it was three skin depths over the frequency range of the antenna; so the gores acted as a RF reflector. It was important to minimize the amount of copper used in the design in order to achieve the required mechanical performance of the gore material as well as minimize the mass of the reflector. The flex circuit material has been used in space applications previously but not in this manner. To gain confidence and qualify the material, several small material samples were thermally cycled in vacuum and exposed to expected radiation levels. Additionally, Kapton[®] material was fit on a scaled antenna model to evaluate the behavior of the stowing and deploying process necessary for the deployable reflector. As a result of this testing, small through-holes were added to the gore design with the intent to better allow out of plane bending and relieve stress concentrations when stowing the reflector. It was thought that the holes would also have the secondary benefits of both reducing the part mass and reducing air drag during deployments in air. The grid selection and hole size were limited by RF requirements on the reflector. The EDU gore design is shown in Figure 6. The part size was driven by available raw material and manufacturability of the part which in turn drove the number of deployable ribs. Flex circuits are readily available in standard panel sizes, but not in the length and

width of the antenna gores. An industry survey showed there were a limited number of vendors that were capable of processing parts of this size. There was a learning curve for handling and tooling the antenna gores mostly due to the cover-lay process in the part manufacturing.

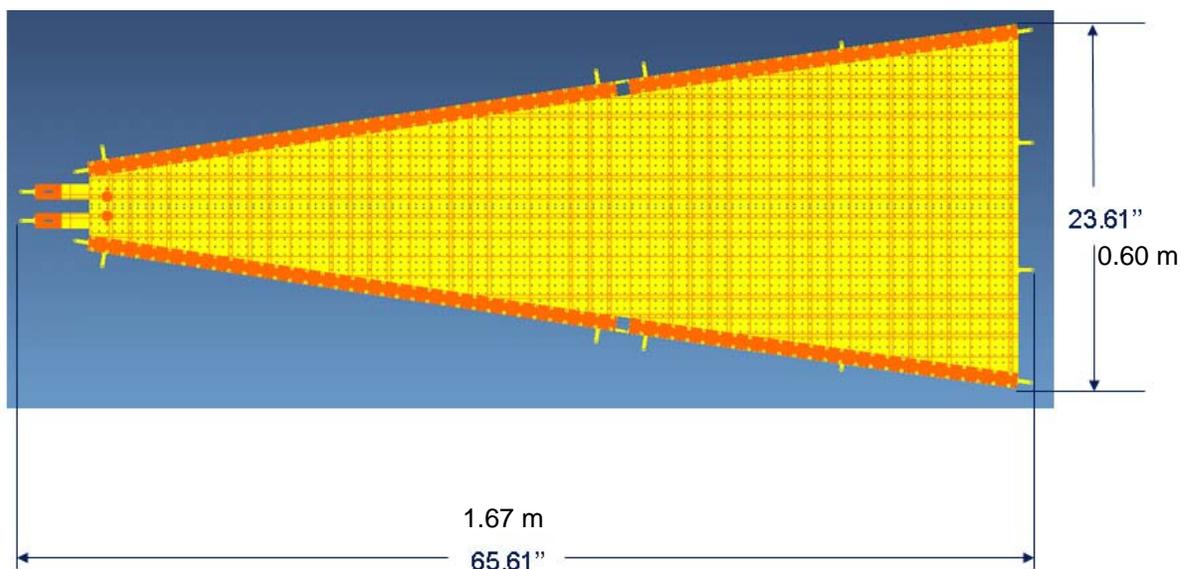


Figure 6: EDU Gore Layout

Gore Fasteners

As previously stated, the low PIM requirements on the antenna forced a capacitive coupling approach throughout the antenna design. This capacitive coupling relies on an even preload to be maintained on all RF joints, which includes the joints between individual gores. Many fasteners were used to maintain the equal preload required across the entire joint. These fasteners hold the reflector gores to each other and to the ribs.

There are over 2000 fasteners used to hold the reflector gores both together and to the individual antenna ribs. Standard metallic fasteners were not an option because of the mass and RF implications. Several non-metallic space-qualified materials were traded to find a suitable substitute for metal in the fasteners. Additionally both socket and pan head screws were evaluated. Pull testing and radiation testing were done on the top two choices of the trade. After testing, socket head Ultem 2300[®] was selected for the material of the fasteners, washers, and nuts for attaching gores. The screws needed to be fabricated in a special run, and the end cost was roughly \$4 per fastener. The fasteners were not as strong as metal fasteners so free running nuts were used to keep the running torque as low as possible. A torquing technique was developed and each fastener was staked for backout prevention.

Gravity Offloading

The 60-Hz stiffness and 27-kg (60-lb) mass requirements for the antenna meant that materials and parts would need to be light weighted and optimized for on orbit deployment loads. However, because of the ground testing requirements and program budget, a highly complex gravity offloading scheme was equally unfeasible. It was critical to show sufficient deployment force and energy margin to qualify the new design using as relatively simple ground testing fixtures to meet cost and schedule goals. As a result the antenna was designed to withstand ± 0.3 g deployment forces. This required that a gravity offloading fixture be designed in order to test both positive and negative deployment force and energy margins. Testing was performed in both air and thermal vacuum (TVAC).

The final gravity offloader design was a single plate with individual mechanisms interfacing with each of the deployable ribs of the antenna. Each rib offloader had a cam profile fit to match the theoretical gravity

forces of the deploying geometry of the antenna that was calculated by kinematic modeling. The offloading force was provided by compression springs that were interchangeable, allowing offloading forces to be varied quickly and different equivalent offloading to be tested easily. This offloader design was straightforward and adjustable; however it interfaced to the base ring of the antenna and was incapable of being used once the antenna was integrated to the rest of the satellite. This meant that the antenna would need to be completely qualified before delivery to the system. "Pop and catch" deployment tests instead of full deployments were done for all system level antenna deployment testing.



Figure 7: Gravity Offloading Fixture

EDU Antenna

An engineering development unit (EDU) was fabricated and fully tested in order to gain confidence in the antenna design. The EDU antenna was the full scale flight design and was completed in February of 2007. Testing included in air deployment testing, baseline RF patterns and PIM measurement, surface RMS measurements, three axis quasi static and random vibration, TVAC cycling and deployment testing, and finally post environmental RF pattern and PIM measurements. In total, the EDU antenna had a total of 22 open/close cycles including 4 in air and 3 TVAC deployment tests.

The EDU antenna passed all tests, however there were several noteworthy lessons learned:

Spring Cartridge Lock Pins

Initial deployment testing and surface mapping revealed that the locking mechanisms in the spring cartridge design did not function as intended. The design did not adequately take out the end of travel slop of the rib. The problem was found to be a combination of both tolerance stack-up of all of the rotating surfaces and the large moment arm of the deployed rib. This issue needed to be fixed in order to meet the deployed frequency (>5-Hz first mode) requirement. To fix the problem, it was decided to remove the

latch feature on all of the spring cartridges allowing the spring travel to bottom out on an existing secondary impact spring. This design change utilized existing parts and also removed the complexity and potential single point failures of the antenna's latch features. The new spring cartridge design solved the issue, met surface tolerance requirements, and was implemented as the baseline for the remaining testing and subsequent antenna builds.

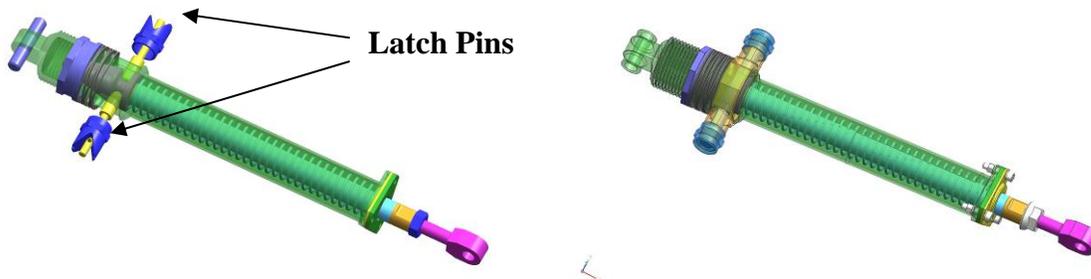


Figure 8: Spring Cartridge With (Left) and Without (Right) Latch

Reflector cracking

The EDU reflector gore material developed cracks. These cracks were caused through the folding of the reflector associated with stowing. The cracks initiated at the edge of the through holes in the gores and once initiated ran from one hole to another. All cracking was similar in location and type on all gores of the reflector and worse in areas that were required to package tighter for stowing. This cracking was reproduced with sub-scale material samples and was shown to be worse once exposed to thermal cycling.

The through holes were put into the gores using a drilling process that is standard in the flex circuit and printed circuit board industry. Testing of samples without holes proved to largely solve the cracking issue. Additionally, there was no compelling requirement (air drag, easier to fold, lighter) to keep the holes. For these reasons the holes were removed for the FM antenna. The copper trace width was also reduced in an effort to improve material compliance and lower the mass of the gores. This was a low risk change given the RF data from the EDU testing.

Release Strap Development

A test fixture, shown in Figure 5, was developed early on in the development to address a number of deployment strap concerns. There were concerns that special attention would need to be taken to control the band tensioning to avoid destruction of the ribs and/or feed support through twisting or excessive and/or uneven loading. A prototype deployment strap was heavily instrumented with strain gauges between every rib to examine the band tension uniformity and how easily the band slid on the Ultem band guides. A process was developed to step the band tension up gradually and work the loading around the ribs by lifting the band off the Ultem blocks for a uniform distribution. A flight band tensioning procedure was developed with expected torque values and correlating band tensions. This early testing enabled removal of the strain gauges for the flight unit eliminating multiple snag hazards. The strain gauges were also initially required to verify and correlate the structural analysis of band behavior and performance of the stowed antenna during launch. Testing showed that uniform rib gapping force was the critical parameter affected by band tension. This uniform rib gapping force could be maintained by controlling the band tension to ± 13 N (3 lbf). Instead of using the strain gauges, a handheld force gauge was used to apply the theoretical gapping force. If the rib did not gap under that load, the band was sufficiently tensioned.

Upon actuation, energy stored in the Frangibolt fastener and strap tension is released into the bands. Initial prototype testing revealed there was sufficient energy for the two band end fittings to contact on the opposite side of the structure and possibly tangle, thus possibly preventing a full deployment. If the bands

did not contact, they would spring back into the deploying antenna. A damping method was required to absorb some of the energy to prevent the ends from striking the gores or payload and becoming entangled. The ultimate solution was to attach two welding rods to the Elgiloy band with heat shrink tubing as a damper/stiffener. The solution was tested with a 1G gravity assist to prove the end fittings would never come into contact.

Reflector CTE

During TVAC testing of the EDU antenna, a cold spike test was conducted to demonstrate survivability and performance at the coldest predicted temperatures. During the test, the antenna was taken cold (~ -50 deg C) and deployed with ~ 0.3 g offload giving a worst case energy deployment. After the deployment was completed, the shrouds of the chamber were set to -150 deg C and the antenna was allowed to be exposed to a cold spike. The reflector has very low thermal mass and quickly moves with the shrouds of the chamber while the rest of the antenna remains within survival temperature limits. The purpose of the test is to show that the EDU gores were properly designed for on orbit coefficient of thermal expansion (CTE) effects. The reflector material is made primarily of Kapton[®] which has a fairly high CTE. This is a potential issue because if the reflector material shrinks too much it would go taut and would exert force on the deployable ribs. This force would act to move the ribs back towards the stowed condition, altering the deployed shape of the antenna. Without a latch, the ribs could move enough to change the shape and/or pointing of the antenna as a function of temperature. The advertised CTE of the reflector material is 25 ppm/degC and the gore was sized such that the extreme cold temperature would not allow the gores to go tight while meeting RMS requirements at the predicted hot condition. During the cold spike test, it was visually observed that the deployed ribs did move in the stowing direction indicating that the reflective material did get tight. More slack gore was added to solve this issue. This in turn adversely affected the RMS of the reflector surface at hotter temperatures. The solution to this problem was to loosen the RMS requirement of the reflector to 12.7 mm (0.50 in) RMS, resulting in a link margin reduction of ~ 0.2 dB, which was deemed acceptable by the program. The flight gores added 6.35 mm (0.25 in) additional material from rib to rib which proved to solve the CTE issue.

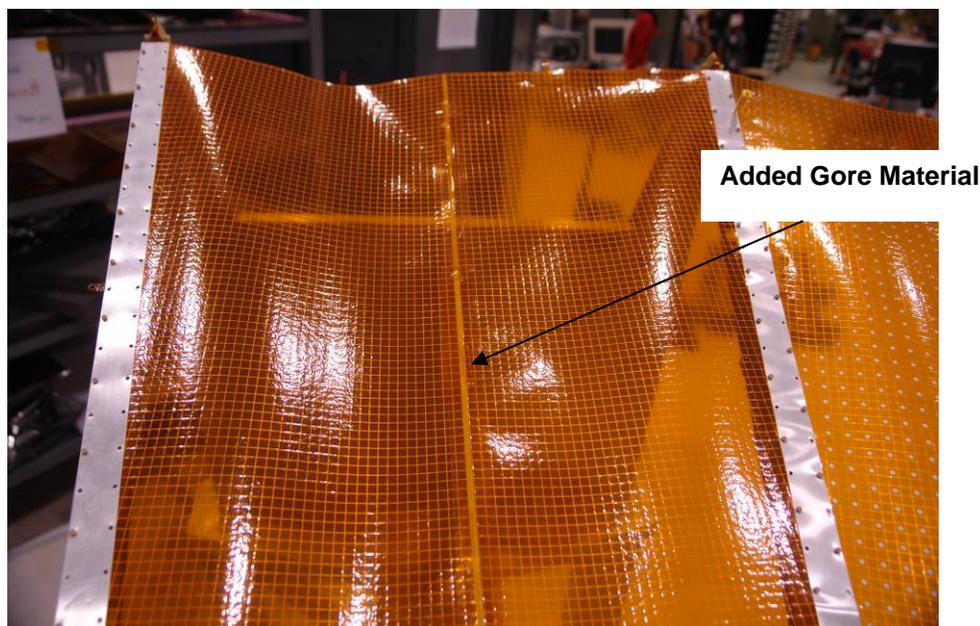


Figure 9: Mockup FM Gore with Added Material

Gravity Offloading Issues

Deployment testing showed that the gravity offloading was not acting as intended. This problem presented itself as the antenna stopping short of the fully open position. The deployment force required to

gap the gravity offloader in the deployed position was measured and compared to the theoretical model. These measurements showed a discrepancy between predicted and as-built gravity offloading forces at the open position. Further analysis showed that the as-built gravity offloader force profile was offset which resulted in both under-offloading in some positions and over-offloading in other positions over the antenna deployment. The issue was traced to a small link chain that was used to transfer the offloading spring force over the cam profile and onto the antenna rib. The chain restricted movement along the profile of the offloading cam. The “as-built” offloader design was capable of testing either energy margin or force at fully deployed position but not both simultaneously. The offloader was used in the “as-built” configuration for all remaining testing and was adjusted accordingly to get the desired energy or force offload.

Surface Mapping

The reflector was mapped using laser scanning photogrammetry; a technique which is often used in reverse engineering applications. Because of cost limitations the antenna was mapped at room temperature in a “cup sideways” orientation only; that is the boresight of the antenna is parallel to the ground. The loose RMS accuracy required of this antenna allowed this simplified measurement setup to be used. The surface accuracy of the antenna was loose enough that the antenna met the requirement even with the 1g sag of the reflector. Several setups were used to record the shape of the reflector and the data was processed to find the RMS deviation of the antenna from the ideal parabola. The antenna RMS deviation was measured to be 6.35 mm (0.25 in) from the theoretical surface. The measurement technique worked well, however it was necessary to find a laser scanner that was capable of imaging a surface with optical properties of both the Kapton used for the EDU antenna and the germanium sputtered Kapton[®] used for flight model (FM) antenna. The laser scanner that was found to be adequate was a Cyrax 2500.

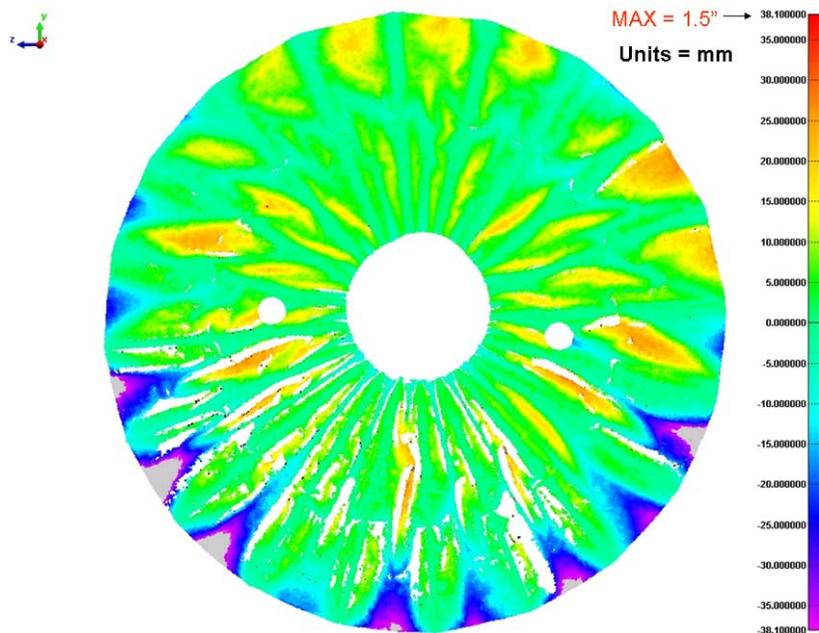


Figure 10: Surface Mapping Results

FM Antenna

The FM antenna was built following the completion of all EDU testing. The flight antenna incorporated the lessons learned on the EDU antenna discussed in this paper including changes to the spring cartridges, gores, and deployment strap. The FM antenna went through identical mechanical and RF and PIM testing as the EDU antenna. This included in-air deployments, surface mapping, RF and PIM performance

testing, quasi static and random vibration testing, TVAC (thermal cycling, deployment testing, cold spike) testing, final surface mapping, and post environmental RF performance testing. The antenna passed all tests and was delivered for system integration and testing. All of the design changes made from the EDU antenna did improve the performance of the antenna. The FM antenna has a measured surface accuracy of 8.1 mm (0.32 in) RMS and has seen a total of ~30 open/close cycles, including 3 TVAC deployments and 6 in air deployments.

There were additional lessons learned through the build and testing of the FM antenna:

Gore Cracking

In total the gores on the FM antenna behaved much better than the EDU gores. The additional material added solved the CTE issue that was found on the EDU antenna. Secondly removing the through holes substantially improved the cracking issue that was seen on the EDU antenna. However, as expected, the FM gores were stiffer and proved to be slightly more difficult to stow. After ~20 open/close cycles some minor gore cracks have developed. These cracks were very small (pin holes to 1.6-mm (1/16-in) long), and developed in areas where the reflective material was forced to bend in multiple planes creating “kinks” through the stowing action. This phenomenon can be observed by bending a piece of paper in a similar fashion. The effect is that a stress point develops and this point has a very tight bend radius. These stress points are worked over time from opening and stowing the antenna and eventually a small pin hole develops in the material. When left unchecked the pin hole developed into a small crack/tear in order to relieve the stress in the material. To combat this issue, a patching procedure was developed and tested. Small (25 mm x 25 mm) germanium sputtered black Kapton tape was placed over the problem areas on both sides of the reflector. This method proved to stop the propagation of the crack without adversely affecting the RF performance or the material behavior during the stowing process. In some cases preventative patches were placed in areas showing beginning signs of crack development.

Several design changes were considered to solve the cracking problem. These potential changes included changing the gore geometry to give the localized stress areas additional material, using thinner Kapton in the flex circuit to lower the gore bending stiffness, using a different type of Kapton that could have better resistance to this type of stress, and increasing the f/D of the reflector. In the end these changes were not necessary because the patches proved adequate to meet the mission requirements.

Overall the flex circuit gore material proved to be fairly robust to work with. The material did work very well in order to meet the low PIM requirements and was easy to handle and manipulate in order to stow the antenna while meeting the surface accuracy requirement of the reflector.

Conclusions

The Naval Research Laboratory has developed a novel design approach for a low-cost, low-PIM, deployable UHF antenna. The design has been fully qualified and will launch as part of the Tacsat-4 satellite in 2010. This new technology is directly applicable to other sub four-meter deployable antennas at UHF and may have application for other missions at higher frequencies.