Deployable Reflectors for Small Satellites

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ABSTRACT

A key limitation for future Small Satellite communications and radar missions will be available antenna reflector aperture. Two types of reflectors are dominant for satellite RF systems today, rigid, single-piece reflectors and deployable mesh reflectors. Single-piece reflectors are limited to the aperture that fits inside a launch vehicle without packaging the reflective surface. Mesh reflectors have become the workhorse of the deployable reflector market, however these reflectors are expensive because they require complex mechanisms and have substantial labor cost for fabrication. The recurring cost for a 4m mesh reflector of sufficient surface precision for a radar mission is on the order \$10M. This historically high cost for deployable reflectors will limit small satellites to missions and performance that can be achieved with the relatively small aperture of a single-piece reflector unless a low-cost deployable reflector can be developed.

This paper will discuss a deployable solid surface reflector that can be packaged into small, low-cost launch vehicles, such as the Taurus and Falcon 1e, while also minimizing cost with a simple, low-part-count design. This technology is being developed by Composite Technology Development (CTD) using TEMBO[®] Elastic Memory Composites (EMC).

LOW-COST, SOLID-SURFACE DEPLOYABLE REFLECTOR

Current communications and radar missions for small satellites are limited by the performance that can be achieved with small, low-cost antenna systems. A wide range of small satellite mission objectives could be met with 2m to 4m diameter deployable reflectors that package into a nominally 1.5 meter diameter fairing. Since no current reflector designs fall into this category and simultaneously meet the \$1M-\$3M cost goal of small satellite payload budgets, innovative is required.

To respond to this need, CTD has developed a high frequency solid-surface deployable reflector that incorporates substantially fewer parts and involves greatly reduced fabrication time than current deployable reflectors. This reflector uses a graphite composite reflective surface which is pleated and closed upward like an umbrella. Performance metrics for the CTD solid-surface reflector versus deployable mesh and onepiece reflectors for a small satellite are given in Figure 1. A 4m-diameter version of this reflector design is shown packaged in a Falcon 1e launch fairing in Figure 1 and deployed in Figure 2. These figures demonstrate

he	impressive	packaging	performance	of	the	new
desi	gn.					

Table 1:	Reflector Performance Metric	S

Metric	CTD Solid- Surface	Deployable Mesh	One-piece	
Aperture	4m	4m	1.5m	
Accuracy 0.020"		0.050"	0.005"	
Freq. Band	Ku (~15GHz)	Ku (~15GHz)	Ka (~30GHz)	
Cost/m2	\$200k	\$400k-\$800k	\$300k	
Mass/m2	~0.75kg/m2	~3 kg/m2	>2 kg/m2	
Total Cost ~\$2.5 million		\$5-10 million	\$500k	
Total Mass	~10 kg	0 kg ~30 kg 3.5 kg		



Figure 1: Solid-Surface Reflector Stowed in 1.4m Falcon 1e Launch Vehicle Fairing with Satellite



Figure2: Solid-Surface Reflector Deployed

Enabling Technology

A key element of the deployable solid surface reflector system is a TEMBO® (EMC) stiffener around the outer diameter of the furlable composite reflector surface. TEMBO® is the registered name for CTD's family of EMC materials. EMC materials are fully cured composites that consist of traditional fiber reinforcements (carbon, glass, etc.) and a thermoset shape-memory polymer resin. In other terms, TEMBO® EMC materials are CTD's proprietary line of shape-memory composites. The typical packaging cycle for an EMC component is as follows: cure the structure in its desired deployed shape; heat the structure above the resin glass transition temperature (Tg) to allow deformation into the stowed launch configuration, cool below Tg to freeze the structure into this stowed configuration; then once on orbit reheat the structure to gradually deploy back to the as-manufactured shape. Packaging EMC in the softresin state (i.e., above Tg) enables much higher packaging strains than is possible with traditional hardresin composites, and EMC deployments are slow and predictable.

The EMC stiffener in the solid-surface deployable reflector provides deployment force and post-deployed stiffness. Meanwhile, a simple mechanical backing structure guides and synchronizes the deployment and adds depth and global stiffness to the deployed reflector. Furthermore, due to the high-strain capability inherent in TEMBO® EMC materials, the stiffeners are designed to dramatically reduce the required packaging volume, as compared to a traditional composite design. Finally, deployment of the reflector is guaranteed to be well-controlled, as the TEMBO® EMC stiffeners are designed to gradually return to their deployed shape upon heating on-orbit.

LIMITATIONS OF CURRENT ANTENNA DESIGNS

Radio frequency (RF) reflector technologies can be categorized in one of three groups: ¹

- One-piece rigid (not deployable) reflectors capable of fitting inside existing launch vehicle shrouds while fully formed.
- Moderate-precision reflectors, which are launched in a packaged configuration, deployed on orbit, and are intended to operate at frequencies below 40 GHz.²g This group includes deployable mesh reflectors and "Springback" Reflectors.
- High-precision reflectors, which are launched in a packaged configuration, deployed on orbit, and are, intended for operation at frequencies over 40 GHz.

The first category, one-piece reflectors, meets the cost requirements but a small launch vehicle limits the available aperture of a single-piece reflector so severely that many missions are not achievable. The third category of rigid-surface deployables is well beyond the cost and mass limitations for small satellites. Therefore, small satellites must be provided with a reflector that falls into the middle category. Current deployable reflector designs for moderate-precision space-based antennas and radars can be divided into two categories: mesh antennas and elastically folded composite antennas. Neither of these design architectures provides the combination of simplicity (i.e., low cost) and packaging efficiency that is necessary to meet future small satellite needs. Table 2 summarizes how the three most common reflector types, one-piece reflectors, mesh deployables, and "Springback" reflectors compare to the requirements for a small satellite reflector.

Parameter	One-Piece	Mesh	"Springback"
	Reflectors	Reflectors	Reflectors
Frequency/ Surface Accuracy	Meets Requirements	Meets Requirements	Meets Requirements
Aperture/	Does not meet	Meets	Meets
Diameter	Requirements	Requirements	Requirements
Packaged	Does not meet	Meets	Does not meet
Volume	Requirements	Requirements	Requirements
Cost	Meets	Does not meet	Meets
	Requirements	Requirements	Requirements
Mass	Meets	Meets	Meets
	Requirements	Requirements	Requirements
Comments	Aperture limited by size of existing launch vehicle shrouds.	Mechanical complexity of deployment mechanisms results in high cost.	Packaged volume limited by single-fold stowed shape.

Table 2:	Comparison of Reflector Characteristics
	to Small Satellite Requirements

Mesh Reflectors

Deployable mesh reflectors, distinguished by a lightweight pliable mesh making up their reflective surface, have taken the majority of the deployable reflector market. This mesh surface has allowed the industry to develop highly mass efficient deployable reflectors, which have been flown with much success. An example of this type of reflector is shown in Figure 3. The compliancy of the mesh allows stowage in a small volume for launch, and results in system designs with minimal stored strain energy, and minimal resistance to deployment. However, these reflectors require complex back structures with numerous "drop ties" to shape the mesh, which necessitate substantial "touch-labor" time and cost during fabrication and checkout. Different approaches to design and surface optimization of mesh reflectors have been taken to attempt to reduce cost, but the inherent complexity in controlling the surface contour of the mesh and keeping the mesh in tension for RF reflectivity keeps the cost high.



(Courtesy Harris Corporation) Figure 3: Five-meter TDRS Mesh Reflector

Springback Reflectors

A much simpler class of deployable moderate-precision reflectors is the taco shell or "Springback" reflector (see Figure 4). The surface of this reflector is a thin, openweave carbon fiber/epoxy laminate that has a secondary lattice of ribs and struts that provide deployed stiffness and precision. For launch, the reflector is furled by pulling the opposite sides into a cylindrical shape, and then launch-restraint devices are used to constrain the strain energy of the system. Once the satellite is onorbit, the launch restraints are released, and the reflector self-deploys. The system is mechanically simple with no moving parts or assemblies. However, this design suffers from a low packaging efficiency as compared to mesh reflectors. The aperture available for a small satellite in a typical small launch vehicle fairing would only be slightly greater than a one-piece reflector.



(Courtesy The Boeing Company) Figure 4: 6m MSAT "Springback" Reflector OPERATIONALLY RESPONSIVE SPACE NEEDS

Operation Responsive Space (ORS) is a US military program to meet theatre spacecraft requirements with small, inexpensive satellites. This program represents a significant growth area for small satellites. However, many future ORS missions for RF communication and radar applications will be limited by available antenna reflector aperture. For example, the two primary functions of a radar system are search and track. The amount of surface area searched per unit time is set by the product of radiated power and antenna aperture area. While search capability is set by the poweraperture (PA) product, for a tracking radar PA2 is the appropriate metric to determine how many individual tracking beams can be supported. This, in turn, implies that there is an extra benefit to increasing antenna size rather than power-doubling the antenna size quadruples tracking capability. For example, the improved resolution, accuracy, and clutter suppression of a larger antenna yield synergistic improvements in all tracking performance metrics; indeed, bigger is better.³

Similarly, larger aperture antennas that give higher data-rate, cross-link, and downlink capability are becoming an important requirement for many future ORS tactical communications missions.⁴ Indeed, NRL's TacSat-4 mission, which includes Comms-on-the-Move (COTM), Blue Force Tracking (BFT), and Data-X, is currently baselined to include a 3.5m aperture, deployable RF antenna. The TacSat-4 reflector is a purpose-built in-house design by the NRL intended only for RF communications in the UHF bands below 1 GHz. The reflective surface for the TacSat-4 reflector is a copper-Kapton printed circuit with a backing structure and construction similar to mesh reflectors.

A vision for ORS is to keep total spacecraft costs below \$20M, which means that primary payload costs must be on the order of \$10M and individual payload subsystems must be on the order of \$1-4M. For example, the low-precision, 3.5m-diameter deployable reflector for the TacSat-4 mission would ideally have a recurring cost of \$1-2M, and a higher-precision, largerdiameter reflector for a SAR mission would ideally have a recurring cost of \$2M-\$4M. Unfortunately, the current deployable-antenna products in the market cost at least twice the target figures. As an example, the TacSat-4 reflector budget allocation was \$1M. The current in-house design is limited to low frequency and does not appear likely to meet the budget allocation. This design also does not contribute technology which will provide inherently lower cost than mesh reflectors.

Clearly, new design paradigms for deployable reflectors are necessary if the aggressive cost goals of ORS are to be met. At the same time, to be successful a lower cost reflector must have sufficient surface accuracy to meet a number of RF missions.

DETAILED DESCRIPTION OF 4m SOLID-SURFACE REFLECTOR DESIGN

Another view of the 4m version of the solid-surface deployable reflector is shown in Figure 5. The deployed reflector is a 4m parabolic dish with a focal length of 2.4m for a f/D ratio of 0.6. The reflector is divided into two sections: a rigid center section that is 1.0m in diameter with a 0.5m hole in the center, and a deployable outer section that has a 1.0m inner diameter and 4.0m outer diameter. The deployable outer section is connected to the rigid section with a ring of 18 TEMBO® EMC hinges. The deployable outer section is also supported by six deployable struts. The outer section is composed of a thin, thermally stable graphite composite membrane and a thicker, 5 cm wide outer ring that forms the TEMBO® EMC outer stiffener. The outer stiffener stabilizes the pleated shape in the stowed condition and stiffens the reflector edge in the deployed condition.





The graphite composite reflective surface is stabilized by a simplified deployable backing structure. The backing structure is launch locked to the feed tower to provide additional horizontal stiffness to the packaged reflector during launch. Each deployable arm would be a single degree-of freedom mechanism and would be fabricated from graphite composite honeycomb panels. The six deployable arms would be synchronized by the slow deployment of the reflector shell, as constrained by the outer EMC stiffening ring of the shell. In the deployed state, each arm will lock into position to stabilize the reflector with a deep cross-section structure.

To furl the reflector, the deployable section is pleated into 18 folds and rotated upward at the outer edge, much like the pleats in a coffee filter allow the filter to fold upward. Once packaged, the deployable backing structure attaches to the feed tower with six bolt ejectors located on the feed tower above the feed or sub-reflector. The stowed volume of the 4m reflector is shown in Figure 6. This volume is compatible with the payload fairings for the Falcon 1e, Minotaur II, Taurus 63" payload fairing, or larger launch vehicles such as the Minotaur IV.



Figure 6: 4m Solid-Surface Reflector Envelope

Deployment of the reflector requires only heating the TEMBO® Hinges and TEMBO® EMC outer stiffener with 200W for ~2 hours using integral heaters until the material reaches the activation temperature of ~100°C, and the reflector gradually returns to its natural parabolic shape. This deployed antenna will be capable of operating at Ku band with a surface accuracy goal of

0.050cm (0.020") RMS. The deployable backing structure follows the deployment of the TEMBO® elements and provides sufficient stiffness for an agile spacecraft

Family of Antenna reflectors for use on Small Satellites

In the example shown above, the point design is a deployed reflector with a 4m parabolic dish that has a focal length of 2.4m, resulting in a f/D ratio of 0.6. However, the solid-surface deployable reflector design can be scaled for practical small satellite reflectors from 2m to 4m aperture. The depth of the parabolic surface can also be increased for focal length ratios of f/D = 0.3 to f/D = 0.6. The design could also be modified to accommodate shallow off-axis parabolic or mild shaped-reflector surfaces.

The range of apertures and focal lengths is necessary to meet a variety of small satellite missions. Broadcast or two-way communications to a modest area, such as the theatre military requirement of TacSat-4, requires a shallow aperture to efficiently spread the radiated power over a defined field-of-view. Coverage area, mission altitude, and feed type can change the optimum f/D from 0.35 to 0.45. Radar applications from L to Ku band would also require a focal length ratio in the same range. Point-to-satellite communications generally require a higher gain to maximize data rate, usually requiring a deeper reflector in the f/D ratio in the 0.25 to 0.35 range.

PERFORMANCE ESTIMATES FOR LARGER APERTURE REFLECTORS

Of all these missions, it is perhaps simplest to compare relative performance for a point-to-satellite communications where the data rate is proportional to the gain of the antennas on either end. Assuming the gain of the ground station or remote point is constant for different frequencies; the effect on antenna performance from changing the aperture at different frequencies can be assessed. The change in data rate for different apertures is plotted in Figure 7 on a relative basis with the data rate for a 1m Ka band (35 GHz) assumed as 1.0. This graph shows the significant performance impact that can be gained by increasing the aperture of the antenna. Similar gains could be expected from any RF system.



Figure 7: 4m Solid-Surface Reflector Envelope

The relative cost of a larger aperture can also be assessed using the plot in Figure 7 and the baseline point-to-satellite mission. The satellite cost for an ORS mission is targeted at \$20M as discussed earlier. By increasing the overall cost from \$20M to \$22M, a program could go from a 1m single-piece Ka band reflector that costs \$235k to a 3m solid-surface deployable reflector that costs \$1.4M. The data rate for the 3m deployable reflector would be 10 times greater and would only have cost the program 10% more than the single-piece reflector.

CONCLUSION

Many of the inherent limitations in small spacecraft can be overcome by miniaturizing electronics and creating more efficient and compact sensors. However, for RF missions the performance of the satellite is dependent upon the power and aperture available to the antenna. For some missions, like wide-area communications, the performance of single-piece reflectors or phased arrays is sufficient. For other small satellite missions, such as radar, one-piece reflectors can't achieve sufficient signal-to-noise ratio to accomplish the mission. Power is limited for small satellites; therefore the only route to better RF performance is with a larger deployable reflector. The increased performance can allow small satellites to increase service for existing missions or achieve missions that were previously beyond their reach. To meet these needs, CTD has developed the deployable, solid surface, reflector that can achieve both the performance and cost targets.

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