Packaging and Deployment Strategies for Synthetic Aperture Radar Membrane Antenna Arrays

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Abstract

The performance of spaceborne synthetic aperture radar (SAR) is limited by the size and therefore the areal density of the antenna array. Conventional arrays consist of radiating elements mounted on hinged panels that are relatively heavy. In order to produce larger arrays capable of operating at higher altitudes, or to support comparable SAR payloads on smaller spacecraft, a lighter structure such as one using membranes must be used. Membrane antenna arrays have been developed, but deployment remains a challenge. This paper describes possible techniques to package and deploy membrane structures that can support these antenna arrays.

1. Introduction

Space-borne synthetic aperture radar (SAR) has numerous applications including environment monitoring, planetary science, and navigation. Earth observation using SAR has the potential to enable earthquake forecasting and improved disaster response, but this requires larger area antenna arrays at higher altitudes than existing systems – on the order of 700 m^2 for a platform at geosynchronous Earth orbit (GEO) [1]. Current SAR payloads use antennas deployed on rigid, hinged panels. These systems are not scalable to GEO antenna requirements, because the overall system mass would exceed available launch capability. For example, RADARSAT-2's 1.5 x 15 m antenna had a mass of 784 kg [2], resulting in an areal density of almost 35 kg/m^2. Conservatively assuming a linear scaling, a 700 m^2 array would require over 24,000 kg for only the antenna, already several times greater than the existing launch capability of modern EELV rockets to GEO. In order to achieve the lower areal densities required for large antenna arrays, an alternative structure must be used. One possibility is to use a membrane structure to support the antenna array. Membrane structures are challenging to package and to deploy, but recent advances in solar sail and other membrane-based technologies have provided a new impetus for overcoming these difficulties. In Section 2, we describe an existing membrane antenna array design that serves as a reference configuration for the following discussion. Sections 3 and 4 discuss the challenges associated with membrane packaging and deployment, respectively. In Section 5, we discuss possible compromises between RF and structural performance in order to establish a trade space for design. Finally, we summarize and conclude in Section 6.

2. Background

One membrane antenna array design that has been tested on the ground is an L-band (1.26 GHz) patch array designed to be supported by two parallel membrane layers [3]. The membranes are composed of a polyimide substrate with laminated copper foil layers on each side. The patch elements are 8.89 cm (3.5") squares spaced every 15.24 cm (6") in a rectangular array on one membrane surface with all copper removed on the opposite surface. The ground plane is on a second parallel membrane held at a distance of 1.27 cm (0.5") from the patches. The feed network is on the opposite surface of the membrane to the ground plane, and radiatively coupled to the patches through slots. A prototype of this antenna configuration has been constructed with an array of 16 x 16 elements [4] using membrane-compatible transmit/receive (T/R) modules for electronic beam steering. However, it is supported by a rigid framework and has not been designed to be packaged or deployed. A smaller (3 m^2) version of this antenna design, using three membrane layers but no active electronics for steering, was deployed using inflatable booms [5].

3. Membrane Packaging

In order to fit a large array into a spacecraft for launch, it must be smaller than the rocket fairing and be able to survive the acoustic environment during launch. Membrane structures are inherently flexible, and can be folded or rolled. However, with electronics, care must be taken to avoid affecting the RF performance. In this section, we discuss possibilities for packaging a membrane antenna into a more compact geometry such that it can be deployed once it is spaceborne.

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3.1 Membrane Folding and Creasing

We define a fold to be a local bending in the membrane with radius of curvature much less than the planar dimensions of the membrane. When a membrane is folded tightly (with small radius of curvature), plastic deformation can occur, which we refer to as a crease. This plastic deformation can include material yield, delamination between layers, and crack formation. If a crease is formed, the material around the fold will not unfold completely. This can lead to loss of electrical continuity or changes in impedance, which would degrade RF performance. Because of this, the ideal solution is to position crease lines such that they do not cross over sensitive RF geometry, such as the radiating elements. However, concerns still remain regarding the possiblity of damage to feedlines or a ground plane, as well as overall loss of geometric precision of the array.

One possible solution to avoid the detrimental effect of creases is to avoid folding entirely, e.g., by rolling the membrane instead. However, this only enables compaction of one dimension of the antenna array. If the array can be physically partitioned into strips, these can be independently rolled, and then deployed in parallel. Alternatively, folding a membrane can be done elastically, if the membrane curvature over the fold does not result in material strain beyond the yield point. Using a thinner membrane substrate allows for tighter folding without introducing plasticity. However, this is much more difficult with a metal layer because of its more ductile material properties. Another challenge is that two elastic folds in different directions will still cause plastic deformation at the point of intersection. This can be avoided by removing enough material around this point, leaving a hole that accomodates the presence of the two folds [6].

3.2 Folding Patterns

A basic folding pattern that can be used even for rigid hinged panels is the Miura-ori pattern [7], as shown in Figure 1. Compared to a double accordion fold, where all the creases are perpendicular, the Miura-ori shifts the crease vertices so that they do not stack on top of each other. This reduces the strain introduced in the folds and enables larger membranes to be folded. This pattern is particularly well suited for rectangular arrays of antenna elements, because of the regular spacing of the crease lines. However, the dimensions of the antenna elements constrain the slant angle ψ in the folding pattern. For the array described in Section 2, ψ must be greater than 54° to fit between a single row of patches, but approaches 90° for larger arrays containing more patches per folded panel. As the angle increases, the packaging efficiency of the Miura-ori pattern diminishes.

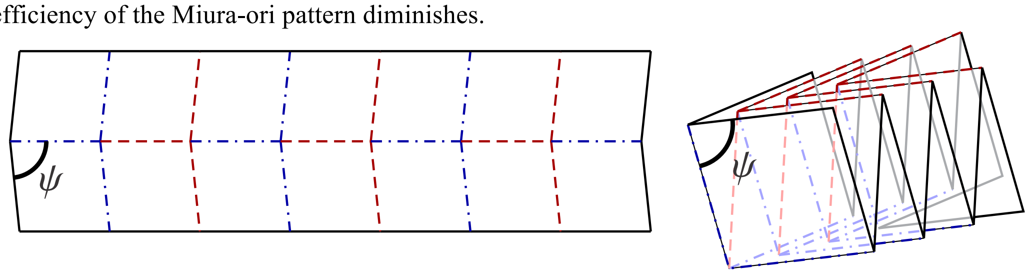

Figure 1. Unfolded (left) and folded (right) Miura-ori pattern, showing the slant angle ψ.

As mentioned in the previous section, an alternative is to roll the membrane, with the advantage of not forming any creases, but this only allows for one-dimensional deployment. A combination of these two approaches is to wrap a folded membrane around a spool. For membranes with significant thickness, this requires the fold pattern to be composed of curved, rather than straight lines [8]. A curved folding pattern, however, is more difficult to fit in between the radiating patches in a rectangular array, and cannot be folded elastically as described in the previous section.

Another family of folding patterns involves wrapping a membrane around a central hub. In contrast to Miura-ori-type patterns, wrapping patterns have major folds (where the membrane is folded close to 180°) in a mostly radial direction, and less acute folds in other directions [9]. By wrapping around a polygonal rather than circular cylindrical hub, a folding pattern can be composed of straight line segments instead of curves. This allows for elastic folding as described above.

4. Membrane Deployment

Deploying membrane structures is challenging and prone to failure, as has been experienced on many previous space missions. Deployment dynamics are more complex than for structures composed of rigid elements, and the low areal density of membranes leaves them more susceptable to disturbance forces. The large size of many membrane structures also makes it difficult to test and characterize deployment on the ground in a suitable environment. In this section, we discuss the force profiles required to unfold a membrane, and the supporting structure that is required to deploy and maintain the membrane's geometry.

4.1 Unfolding

The force profiles of unfolding membranes are strongly dependent on the geometric constraints around the deployment system [10], as well as on the thickness of the membrane [11]. In particular, many folding patterns such as the Miura-ori pattern are designed to unfold as a single mechanism. However, the presence of a hub, housing, or other component of a deployment system can impose forces on some parts of the membrane, preventing it from unfolding all at once. These constraints can induce severe bending or even unintentional creasing in the membrane as it deploys. Even with a bare membrane, these effects can result in significantly higher deployment forces required and could result in jamming or stalled deployment, but in a membrane supporting RF elements in an active array, this is especially a concern because of the presence of rigid electrical components on the membrane, which might be pulled or scraped off as the the membrane unfolds. An example of a membrane deployment force profile (from a measurement in a laboratory setting) is shown in Figure 2, for a single-layered polyimide membrane. The membarne is 60 cm by 30 cm in area, and 50 μm thick. This profile highlights some of the dominant characteristics of deployment force profiles in general. First, the high frequency variation in the force profile, especially evident between 0.1 and 0.2 m deployed length, is indicative of friction as the membrane is deploying. Second, the larger periodic peaks in the profile between 0.2 and 0.5 m deployed length are a result of the geometric constraints forcing the membrane panels to unfold sequentially rather than simultaneously. Finally, the force profile increases drastically at the end of deployment, as the structure transitions from unfolding to membrane stretching.

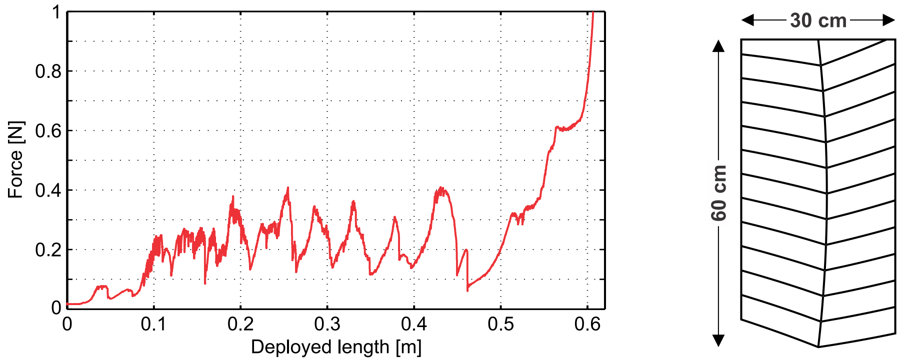

Figure 2. Deployment force profile (left) for a membrane wrapped around a spool and enclosed in a housing. The membrane (right) was folded using a curved crease pattern to wrap around a spool.

4.2 Structural Support

In order to provide the deployment force to unfold or otherwise unfurl a membrane, one or more stiff structural elements are often required. A typical geometry is to have a square array supported by four booms along the diagonals, extending from a central hub. These booms provide the force to pull the membrane out of its housing as well as to tension the deployed structure so that it remains flat. Because of the boom configuration, these membrane structures tend to be cut into quadrants, with a gap between quadrants where the boom is positioned. Centrifugal deployment without any booms is also possible and allows for a continuous membrane surface. However, given a deployment driven by an initial spin rate and no external torques, the centrifugal force is greatest at the start of deployment and lowest at the end. As a result, the required initial spin is determined by the force necessary to achieve and maintain adequate flatness at the end of deployment, and will provide more force than necessary at during the earlier stages of unfolding. This excess force could potentially damage the membrane as it deploys. Additionally, a centrifugally deployed membrane will require continued spin throughout its lifetime to provide the tension that maintains the array's geometry.

5. RF and Structural Performance Tradeoff

In the previous two sections, we discussed factors that must be considered when designing a membrane antenna array. Creasing and fold locations may affect the antenna positions as well as the geometry of the array feed network, in order to minimize folds over the transmission lines. For some fold patterns, it will not be possible to maintain a regular antenna spacing as well as avoid folding or creasing over the radiating elements. However, it may be possible to simultaneously optimize fold geometry and antenna locations in order to minimize the amplitude of grating or side lobes. A nonuniform antenna spacing could very well improve the array performance by reducing the largest lobes [12]. The structure supporting a membrane array could also influence the RF design by partitioning the membrane into discrete segments. This would affect the topology of the RF feed network, and might require a more complex design than the parallel corporate feed used in the existing membrane antenna prototype. Finally, the overall geometry of a membrane structure will not be as precise as an equivalent panel structure. This could lead to the choice of a lower operating frequency than would otherwise be desired.

6. Conclusion

In order for large SAR missions to be realized in GEO, membrane-supported antenna arrays must replace traditional rigid hinged panel structures. However, the challenges associated with both packaging and deployment of these membrane arrays are significant. A radar system using a membrane antenna array must account for these challenges and allow for flexibility (literally and figuratively) in the RF design in order to best leverage the mass savings that come with a membrane structure.

7. Acknowledgments

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8. References

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