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Tape Spring Large Deployable Antenna

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This paper presents a novel concept for a low-mass 50 m^2 deployable P-Band dual polarisation antenna that can measure terrestrial biomass levels from a spacecraft in a low-Earth orbit. A monolithic array of feed and radiating patches is bonded to a transversally curved structure consisting of two Kevlar sheets. The first sheet supports the array and the other sheet supports a ground plane. The two sheets are connected by a compliant Kevlar core that allows the whole structure to be folded elastically and to spring back to its original, undamaged shape on release. This structural concept has been given the acronym of FLATS (Folding Large Antenna Tape Spring). Test-pieces have been made to demonstrate both the RF and mechanical aspects of the design, particularly the RF performance before and after folding the structure. It is concluded that the proposed concept is the design with the highest potential for large low frequency antennas for low-cost missions.

I. Introduction

One of the biggest challenges of the 21st century is that of maintaining the environmental balance of the planet. A key concern for environmental scientists is the balance between CO_2 emissions and the capability of terrestrial vegetation to extract CO_2 from the atmosphere. Measuring or estimating the emissions is only half of the equation; we also need to have an accurate measure of the global biomass level, a major element of which is that associated with tropical rain forests and boreal forests.

To achieve global monitoring of the planet, scientists have looked to satellite instruments to provide the appropriate data on a recurring basis. Existing optical or radar instruments can provide accurate measurements of the area of vegetation on the planet but none can penetrate the forest canopy to determine the actual density of the biomass. The average boreal forest density is estimated to be 50 tons/ha, with maximum densities of 120 tons/ha. Existing space based Synthetic Aperture Radar (SAR) systems, such as ASAR, ERS-2 and Radarsat-1, operate at too high a frequency (C-Band) and literally bounce off the canopy of these forests. Figure 1 shows that only with radars operating at or below P-Band can adequate penetration of these forests be achieved, thus allowing provision of an accurate classification of the world's biomass. Note that, once the reflected signal level flattens out there is no signal differentiation between biomass densities; hence a saturation point is reached for that frequency.

The difficulty facing the SAR system designer is that existing instruments at C-Band (5.3 GHz) are already over 10 m^2 and to maintain the same SAR performance the antenna area needs to increase linearly as the frequency decreases. Thus, at P-Band (0.435 GHz) an antenna of 100 m^2 is required to be launched

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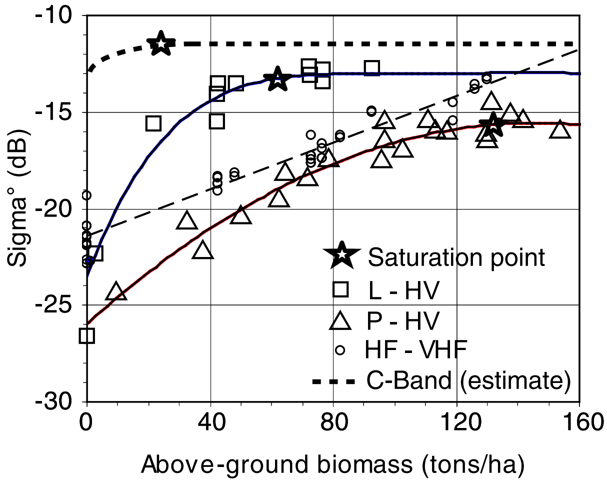


Figure 1. Strength of signal reflected off vegetation of different density.

and deployed in space. It is this packaging and structural problem and its unique solution that are the subject of this paper.

II. Antenna Requirements and Proposed Approach

The science requirements and the resulting RF design and analysis indicated that a 50 m^2 antenna at P-Band in a LEO of approx. 630 km could provide the data needed to measure terrestrial biomass levels. This antenna would only be able to electronically scan between 20 and 30 degrees off Nadir, instead of the usual 20 to 40 degrees achievable with a 100 m^2 antenna. However, this only affects the time taken to achieve global access by a few days (from 11-days to 20-days) and not the quality of the data, hence was deemed acceptable. The antenna requirements affecting the mechanical design are listed below;

- P-Band antenna operating at 0.435 GHz.
- Quad Polar operation, transmitting and receiving on both H- and V- polarisations, hence requiring two independent feed systems.
- 50 m^2 with a height of 2.82 m and a length of 17.29 m.
- Deployed frequency of at least 0.5 Hz, but ideally around 1 Hz.
- Deployed antenna planarity better than 40 mm.
- Stowed packaging to allow launch on a low cost launch vehicle (Rockot, Vega or Soyuz).
- Low mass design, in order to be compatible with the launch vehicles, hence a mass target of less than 1 kg/m^2.

RF design options already in use for higher frequency SAR antennas include slotted waveguide (ERS-1 and 2 and Radarsat-1) and active phased arrays (ASAR and Radarsat-2). A trade-off looked at the packaging (stowing and deploying) of these types of RF solution to see what was viable and realistic for low frequency SAR applications. The slotted waveguide solutions were ruled out due to the size of the P-Band waveguide even though collapsible options were reviewed, see Figure 2. Phased array antenna designs have relied on splitting the antenna length into separate panels which are then folded onto each other in order to produce a smaller panel stack, though adding deployment complications, mass and cost, see Figure 3.

The design solution with the highest score from the trade-off exercise was that of a monolithic array with 5-rows of 28 radiating elements per row, see Figure 4, based on a Folding Large Antenna Tape Spring (FLATS) structure. It is this FLATS technology that is presented in this paper. The design solution is shown stowed and deployed on a satellite in Figure 5.

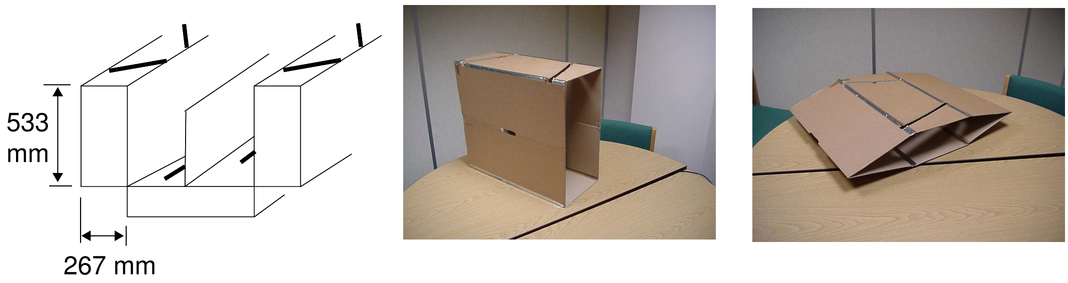


Figure 2. P-Band waveguide solutions.

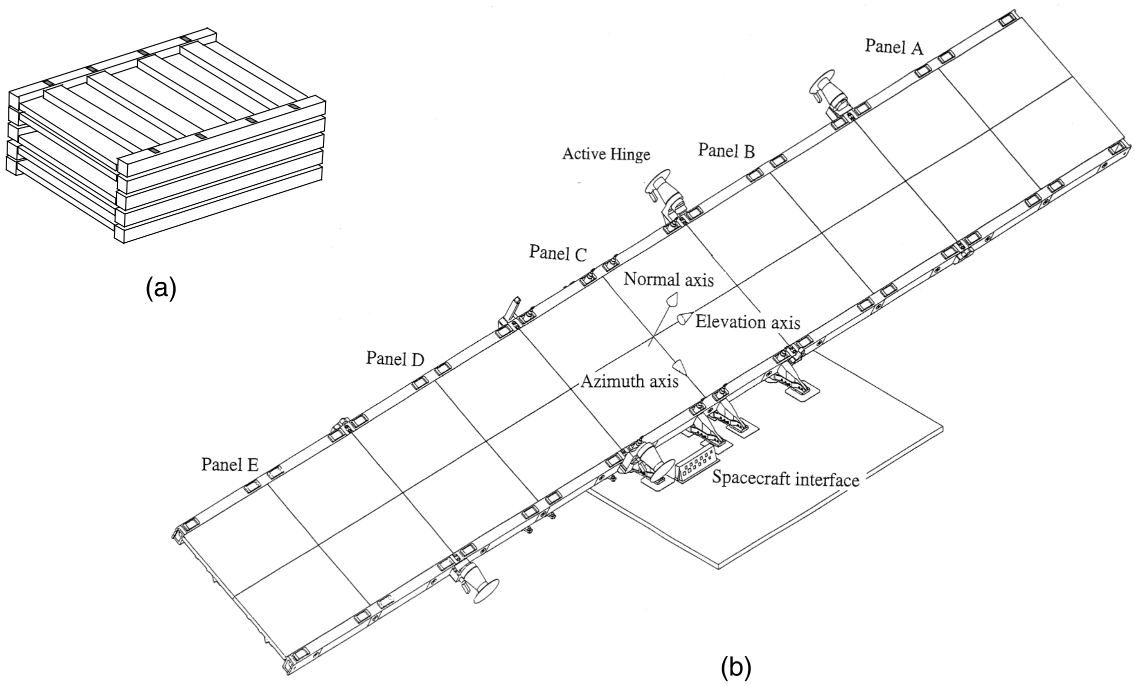


Figure 3. Active array antenna (ASAR) (a) packaged and (b) deployed (Courtesy of Ref.[1]).

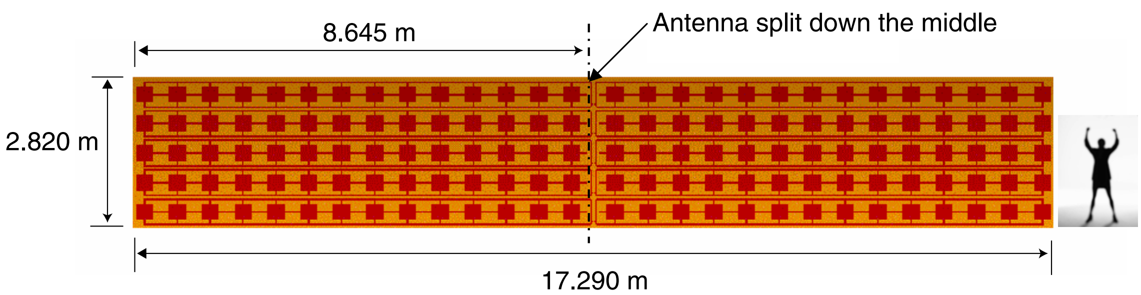


Figure 4. Monolithic P-band antenna.

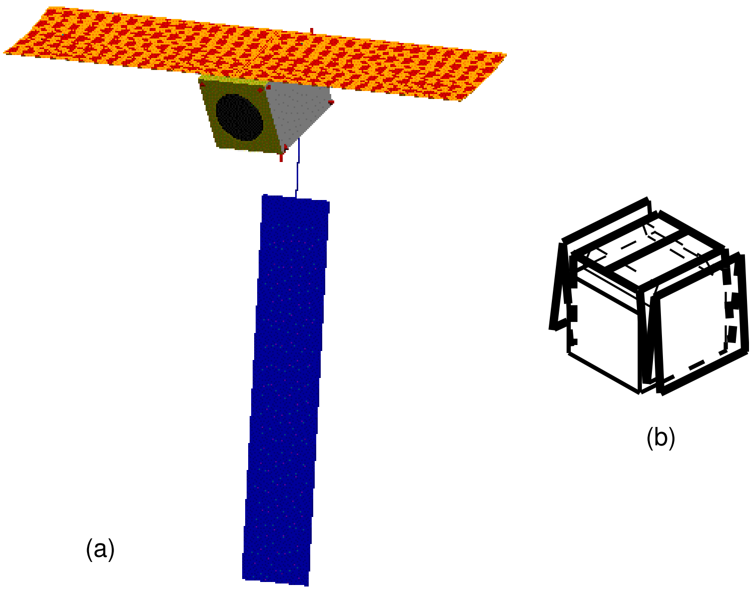


Figure 5. (a) Arrangement on spacecraft of monolithic array antenna and (b) packaging scheme.

This paper summarises the mechanical design of the full 50 m^2 P-band antenna as well as the design, manufacturing and testing of a test-piece.

III. Mechanical Design

A. Monolithic design based on a FLATS Curved Surface

The basic concept, shown in Figure 6, is a transversally curved sandwich plate structure forming a giant tape-spring. Tape springs are well known in the field of deployable structures.[2,3] They have the unique feature that their curved shape provides a significant increase in stiffness compared to a flat plate, yet once the transverse curvature has been removed, a tape-spring can be easily folded.

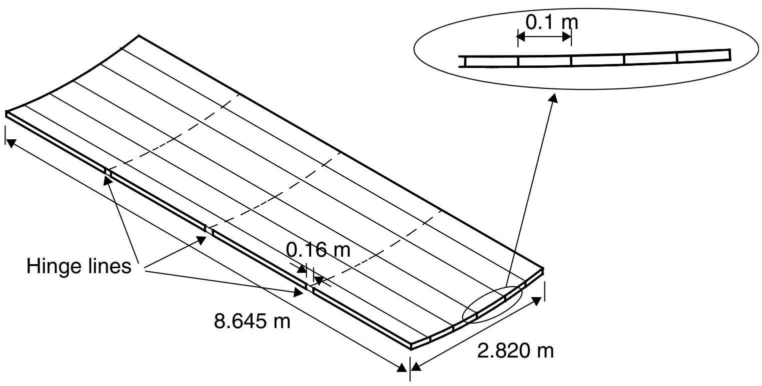


Figure 6. FLATS concept (single wing).

A single sheet tape-spring with dimensions of 2.82 m by 8.64 m would never be stiff enough, however, the RF design requires two sheets 20 mm apart, the ground plane being the second sheet. By joining together the two sheets with a core structure an efficient structural design is obtained. Of course, a standard sandwich plate with this shape would be very stiff, and hence it would not be possible to fold it. To overcome this, the core of the proposed structure consists of longitudinal ribs, but no transverse ribs.

Note that this structural concept provides a curved array rather than a planar array, however, a planar RF beam can be obtained by phase correction for each row power source. The transverse curvature of the array is not detrimental to the planarity specification, which, given the curved nature of the proposed solutions, really ought to be termed a *surface accuracy requirement*, not a planarity requirement.

Thus, the structure consists of two curved cylindrical face-sheets 20 mm apart, with internal unidirectional ribbing, strengthening the longitudinal direction of the antenna. The structure can be folded at hinge-lines where the internal ribs have been removed, while the face-sheets bend to a compliant hinge similar to that seen in a steel tape measure. The structure is stress free when deployed, hence the stowing (flattening and folding) of the structure stores potential energy to create a self deploying structure.

The curved nature of the deployed structure allows it to lock into the desired shape on deployment. Designed as a Monolithic SAR, one skin acts as the ground plane and the other skin as the feed and radiating patches. The nature of the structure allows continuous RF paths, even across the hinge-lines. The radiating rows run in straight lines down the cylindrical shape. The material between the patches and the ground-plane must be RF transparent, hence Kevlar has been chosen.

B. Structural Analysis

One wing of the deployed structure was analysed using a finite element model consisting of thin shell elements. The analysis showed that with a 4-ply plain-weave Kevlar lay-up for each skin and unidirectional ribs spaced approximately every 100 mm, the deployed fundamental natural frequency of vibration was about 0.9 Hz, see Figure 7(a), which is above the 0.5 Hz minimum requirement and acceptably close to the 1 Hz goal. The model was constrained at 4 points, at the ends of the external support ribs that attach the antenna to the platform.

The predicted mass of the structure was 1 kg/m^2, while the load required to flatten one wing was predicted to be 160 N applied along the edges of the antenna. This results in stresses of only 12 MPa (with 500 MPa at a strain of 1.4% being the ultimate strength, 120 MPa at a strain of 0.3% the tensile yield and 60 MPa at a strain of 0.2% the compressive yield).

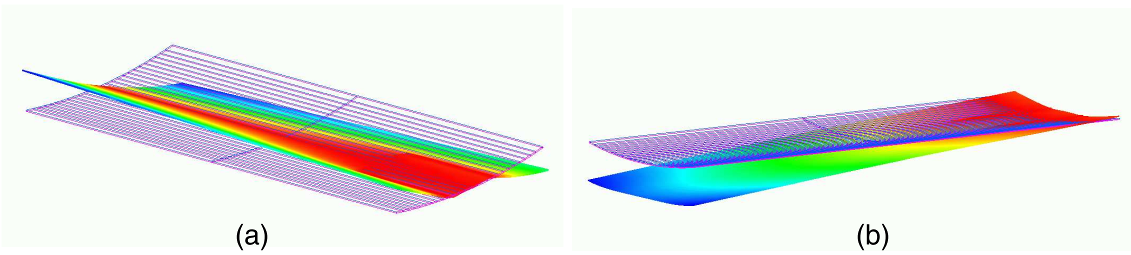


Figure 7. Natural modes of deployed half wing: (a) twisting mode at 0.9 Hz; (b) bending mode at 0.94 Hz.

Structural analysis has been performed to predict the fundamental natural frequency of vibration of the stowed panels and from this the maximum panel displacement during launch. The analysis predicted a frequency of 10 Hz for the fully stowed antenna and, assuming typical design accelerations of 20 'g', the maximum panel deflection would be 50 mm assuming linear behaviour. However, at this low frequency non-linear effects take over and so the maximum displacement is expected to be less than 10 mm.

An analysis of a test-piece using a finer mesh was carried out with the ABAQUS finite-element package,[4] again concentrating on the hinge-line folding process. The process is in two steps: flattening and "Z" folding. Flattening is simulated by fixing one longitudinal edge of the structure and pulling the other edge away from it. At this point the structure is not completely flat, but it is sufficiently flat for the next stage of the simulation, which involves longitudinal folding, to be conducted successfully. The strain levels after flattening are insignificant. The formation of a longitudinal fold involves contact between the two skins in the hinge line region: frictionless hard-contact with finite sliding is assumed. The simulation of longitudinal folding is in two stages. First, one part of the structure is rotated 180° while the other end is not allowed to move. Second, the moving part is pushed down against the fixed part, to tighten the fold region and so package the structure more compactly.

Figures 8(a-c) show contour plots of the maximum in-plane principal strains during the first stage. The maximum strain is 0.74%, and occurs in a region of the inner skin, just at the inner end of the ribs. Figure 9 shows a contour plot of the maximum in-plane principal strains for the tightly packaged structure, when the folded part is almost touching the other. The maximum principal strain has increased to 0.94%.

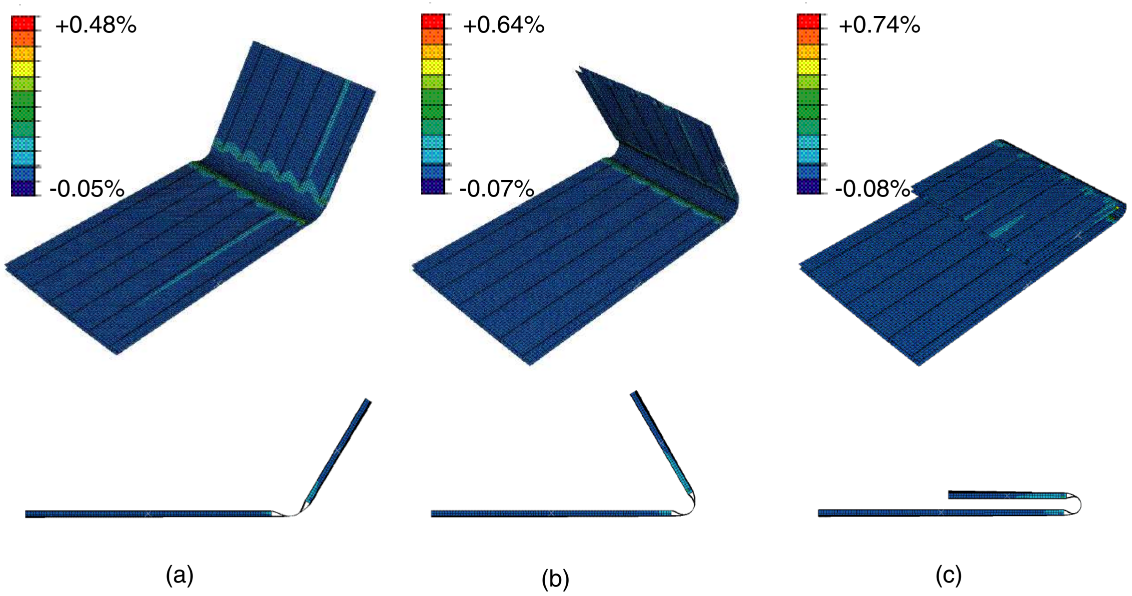


Figure 8. Perspective and side views of folding simulation: (a) 60 deg. folded; (b) 120 deg. folded; (c) 180 deg. folded.

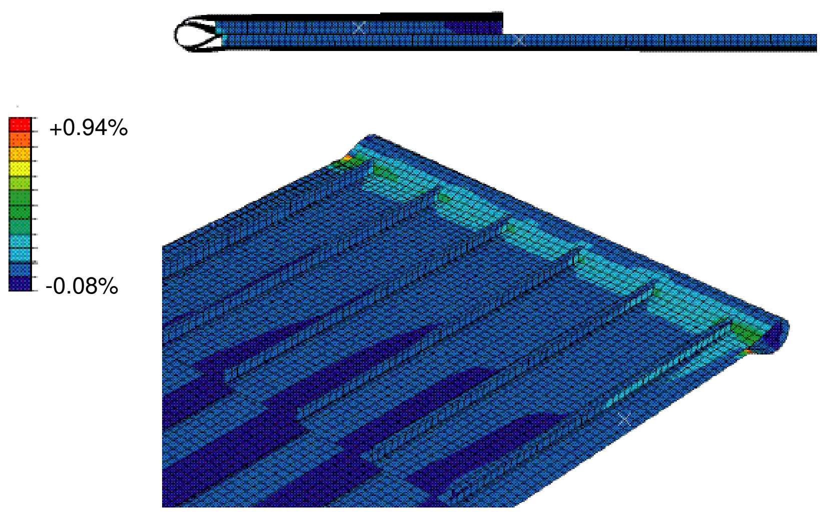


Figure 9. Flattening process, bringing panels together.

IV. Manufacture

A. Test pieces

Two test pieces of one row each were manufactured as shown in Figures 10 and 11.

In addition to these large test pieces some sample hinge-lines were made. Two hinge-line models were

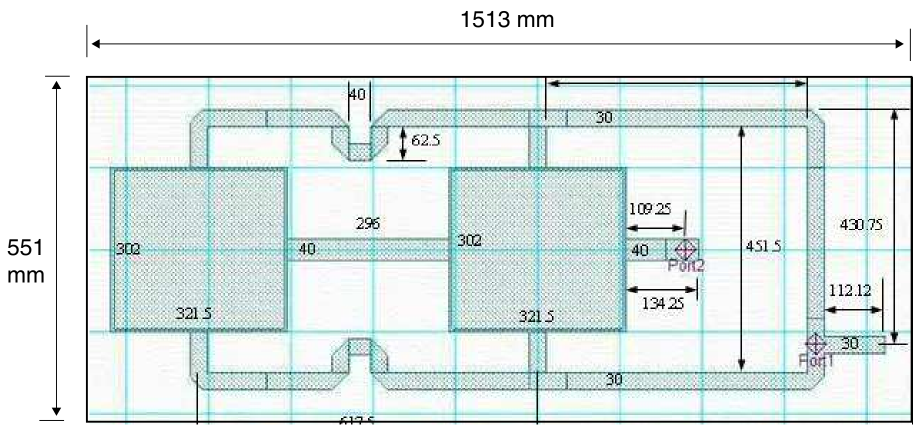


Figure 10. Test piece.

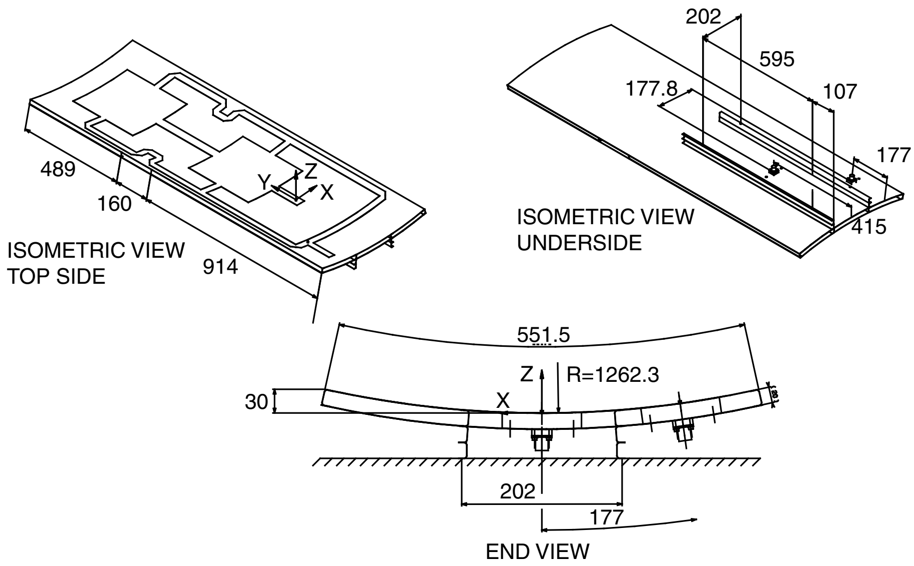
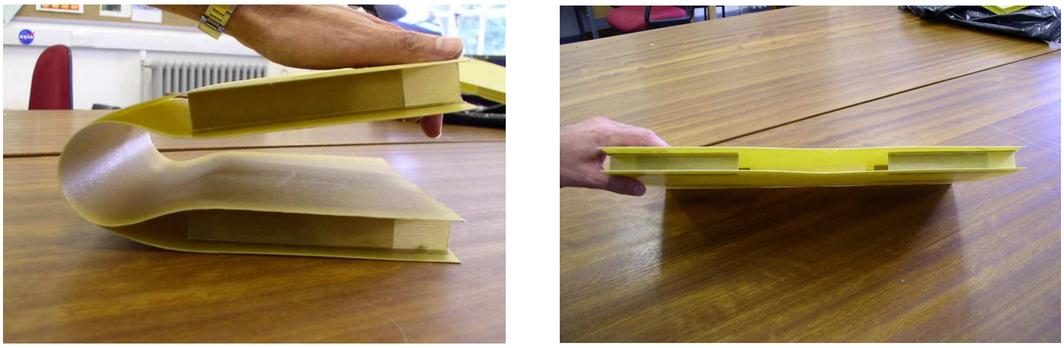


Figure 11. Test piece drawing (dimensions in mm).

made from 3-ply and 4-ply layups respectively. These models had different ply thicknesses in order to investigate which was best for the main test-pieces. The 4-ply required more force to bend the hinge, thus creating more pressure on the internal ribs. The 3-ply design naturally is less stiff, requiring less force to bend the hinge, thus applies less pressure to the internal ribs.

After bending the 4-ply sample 180 deg. to a radius of approximately 30 mm, and then straightening, the deformation of the material was not fully recovered, Figure 12. It was concluded that the Kevlar had been taken beyond its compressive yield limit. This was subsequently confirmed by an analysis of the stresses involved in the bending of a hinge, using the limiting values quoted in Section III-B. The solution was to reduce the stresses in the skin during bending by reducing the skin thickness to the 3-ply design and limit the bend radii, by using spacers, to 40 mm.



(a) (b)

Figure 12. Hinge-line model with 4-ply layup showing residual deformation after bending.

B. Mould Tool

The main test-pieces require curved skins to produce the tape-spring effect. Initially, a flat sheet of stainless steel under 3-point bending was used as the mould tool, but this was later replaced with a 4-point bending configuration using two tubes. The improved tool is shown in Figure 13.

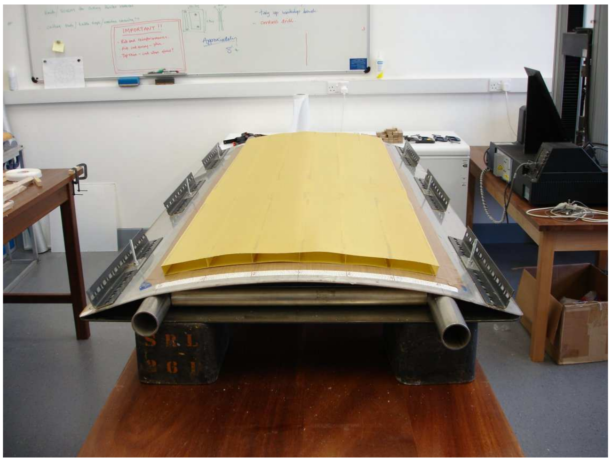


Figure 13. Mould tool used for the second structure.

C. First Test Piece

The first test piece was manufactured on the initial mould tool and had only 4 internal ribs, to avoid them interfering with the RF connections. However, the unsupported span was too great, leading to poor control of the gap between the skins.

This structure has been folded and unfolded 6 times and Figure 14 shows the hinge-line when the structure is folded into its stowed state. Note that whereas the curved structure flattens, the ribs do not.

Figure 14. Hinge-line when antenna stowed.

The structural analysis described in Section III-B has shown that using Kevlar the rigid panel sections on either side of the hinge-line should not be brought into contact, otherwise the bend radii will be too tight and the skin material will permanently deform. Therefore, spacers should be used to maintain the appropriate gap and bend radii. These spacers can be used as hard points to hold the stowed structure. An initial design is for 4 cup and cone standoffs with 50 mm diameter and 40 mm height. This not only provides the required radii but also provides dynamic clearance for the launch loads.

This first structure was used in the assembly of the first test-piece, see Figure 15. This assembly was range tested for antenna pattern, gain, and cross polar isolation. The antenna was then folded and unfolded and retested.

(a) (b)

Figure 15. First test-piece (a) hung for display (b) showing connectors at the back.

D. Second Test Piece

A number of design improvements were made for the second structure;

- The mould tool was improved by going to a 4-point bending scheme.
- The structure skins were reduced to 3-ply to avoid yield during bending of the hinges.

- The number of longitudinal ribs was increased from 4 to 7 in order to provide improved gap control.
- A 50 mm section of each rib either side of the hinge-line was strengthened in order to prevent buckling of these ribs during the folding process.

The resulting second structure shown in Figure 16 was far superior to the first structure in that it maintained its curvature better and held the 20 mm gap between the skins more accurately. In fact 95% of the structure was well within specification for this size of test-piece (± 1 mm). The only area out of tolerance was the free edges (extreme ends and edges of the hinge-line).

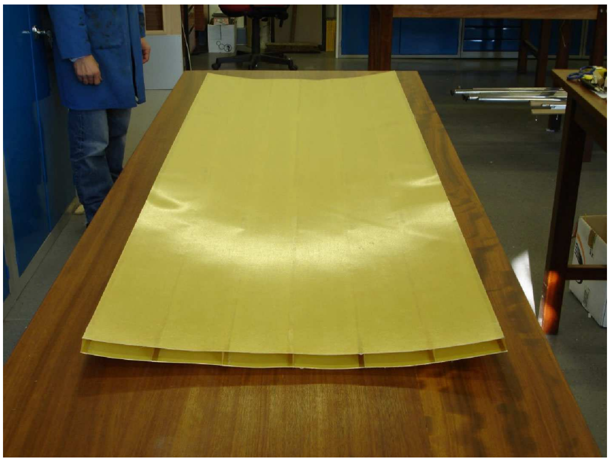
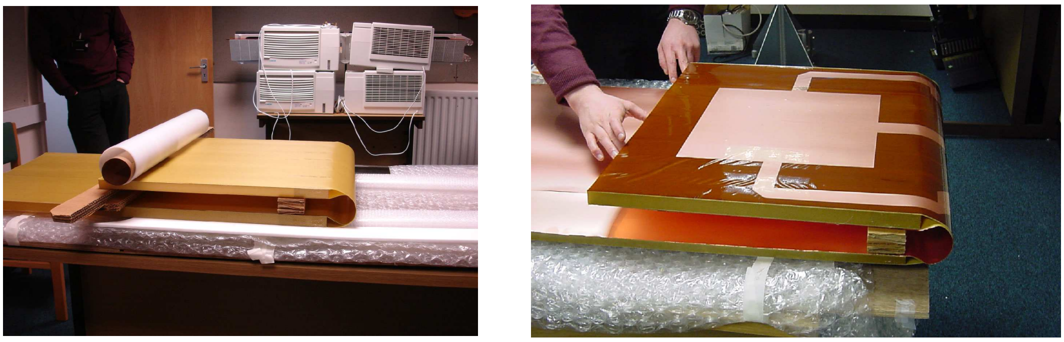


Figure 16. Completed second structure.

The second structure has been folded and unfolded 5 times, see Figure 17, in both directions. The 3-ply skins, ensuring the bend radii remain greater than 40 mm by the use of spacers, the increase in internal ribs and the stiffening of the ribs around the hinge-line meant that the folding process was far more robust than that of the first structure. Furthermore, no permanent distortion was found after folding.



(a) (b)

Figure 17. Folding of second test piece (a) 180 deg. inwards (b) 180 deg. outwards.

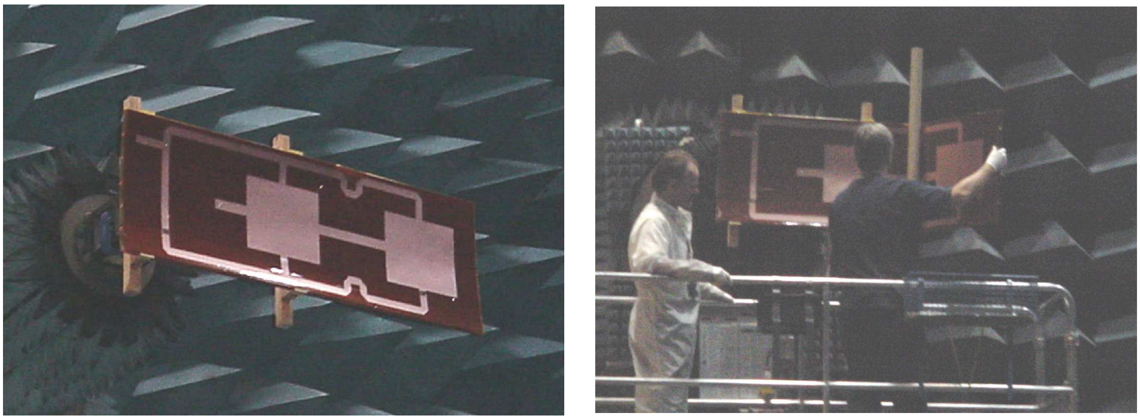
E. RF Feed and Radiating Patches

The RF feed and radiating patch has been manufactured by Printech using an etching process. The base material is copper coated Polyimide film from Sheldahl. The film consists of 50 microns of Polyimide (e.g. Kapton) coated on both sides with 5 microns of copper. The circuit was attached to the structure using double sided sticky tape, however, for a flight programme this product could be co-cured onto the Kevlar skin.

V. Testing

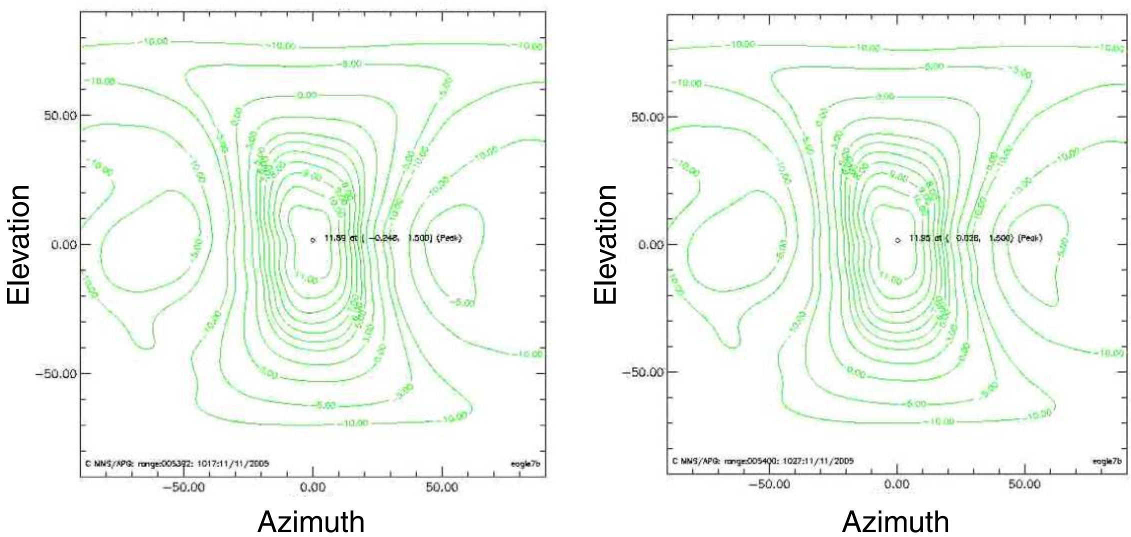
The first test piece was RF tested. Initially the test-piece was 'bench' tested for input return losses and isolation between ports. The assembly was folded and unfolded, and retested. No significant change in RF performance was seen.

The test-piece was then mounted in an antenna range for further RF testing (antenna pattern, gain and cross-polar isolation measurements), see Figure 18. Again the antenna was folded, unfolded and retested. The RF performance did not change. Examples of typical results are presented in Figure 19 and show good correlation between measurements of beam profile before and after deployment.



(a) (b)

Figure 18. Antenna range testing of first test piece; (b) shows the test piece being folded.



(a) (b)

Figure 19. Typical results from the first test piece; (a) pre-fold pattern: Directivity = 12.61 dB i, Gain = 11.89 dB i±0.25 dB (error); (b) post-fold pattern: Directivity = 12.63 dB i, Gain = 11.95 dB i ± 0.25 dB (error).

VI. Discussion

The design concept of this antenna structure is based on the shape and properties of a tape-spring. The key structural aspects are to achieve the required stiffness and structural stability while being flexible enough to be able to fold the structure without damage or change in the RF performance. The design feature of the unidirectional ribs being interrupted at the hinge-lines is key to achieving both the stiffness and the folding.

Future mechanical work should look at the choices of material, particularly the rear face sheet that doesn't need to be RF transparent if the metallised layer is on the top. A deployment scheme will need to be selected and demonstrated.

VII. Conclusion

A monolithic array using a Folding Large Antenna Tape-Spring (FLATS) structure has been identified as the design with the highest potential for large low frequency antennas. The overall antenna design has 5 rows with 28 elements per row, covering an area of 2.82 m by 17.29 m (approx. 50 m^2), split into two equal wings of 5 rows by 14 elements. The continuity of the proposed monolithic antenna design is a very desirable feature, as it avoids the complexity and expense of providing RF transmission across the gap of a more traditional hinge.

The design uses a curved FLATS structure which follows the basic principle of a tape spring that can be folded flat and Z-folded, yet it springs back to its original, undamaged shape on release. The energy required to fold the structure is stored as elastic strain energy in the structure and is used as the deployment energy. A deployment control system is yet to be designed.

Test pieces have been made to demonstrate both the RF and mechanical aspects of the design, particularly the RF performance before and after folding the structure.

This study has investigated different technologies that might be considered for use in a large, low frequency SAR antenna. The potential for a low mass, low cost, simple and reliable design offered by the FLATS design was recognised in the trade-off study. The design itself has been investigated both analytically and via test-pieces and has been shown to be a viable solution to the problems posed by such large antennas.

Acknowledgments

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