LARGE SAR MEMBRANE ANTENNAS WITH LIGHTWEIGHT DEPLOYABLE BOOMS

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ABSTRACT

At the DLR Institute for Composite Structures and Adaptive Systems and the company Kayser-Threde extremely lightweight and stiff deployable carbon fibre reinforced plastics (CFRP) booms and deployment mechanisms have been developed. The main target application is to develop an ultra-light weight solar sail for deep space satellite propulsion. Based on the successful development and ground-testing of a 20m x 20m deployable solar sail structure the in-orbit verification of the deployment principle and mechanisms is now being planned for launch in 2007. Kayser-Threde in collaboration with DLR has most recently completed a phase-B study of the solar sail project under ESA/ESTEC contract. In addition, mission and design studies have been performed at Kayser-Threde for ultra-light weight structures which can reach 100m x 100m in free space where a reflective, thin polyimide membrane is unfolded using DLR's advanced CFRP booms.

Synthetic Aperture Radar (SAR) satellites require large and long antennas which in turn require a large satellite bus as well as a launcher with a large fairing. This is especially true for lower frequency SARs such as L-Band, where antenna sizes of typically 12m x 3m are required. The cost for such a SAR mission could be reduced significantly if the antenna and its deployment and support structure would be lightweight and could be folded during launch. The membrane antenna concept has been demonstrated in Canada by the CSA and EMS Technologies, and in the US by JPL. Receive only antennas are of interest for micro satellites which fly in a formation with a large active SAR satellite in order to perform SAR interferometry in a "Cartwheel" configuration. However, research has also been done for active phased array membrane antennas. In order to achieve good electrical performance the flatness of the membrane should be in the order of 1/30 of the free space radar wavelength. In the case of L-Band this would be plus or minus 1cm. The paper provides a first concept for a deployment and support structure for an L-band SAR membrane antenna. Estimates for the mass and the achievable stiffness are provided. It is planned to extend the assessment to the concept of a P-band SAR membrane antenna for sounding of the Arctic and Antarctic ice shields. The concept could allow accommodation of the SAR membrane antenna aboard a small satellite mission.

1. FROM THE SOLAR SAIL TO MEMBRANE ANTENNAS

Although the basic idea behind solar sailing is simple, challenging engineering problems have to be solved. Since the propulsion efficiency depends on a very low ratio of overall spacecraft mass to solar sail area, technological solutions for in-orbit deployable, ultra-lightweight sail surfaces are required. The main technical challenges are to manufacture sails using thin, ultra lightweight film membranes and to manufacture deployable ultra lightweight booms, to pack the sail membranes and the undeployed booms into a small volume which fits into the fairing of the launcher, and to deploy these ultra lightweight, photon reflecting structures in space. Based on results of system studies, a joint effort for the development and demonstration of several critical technologies was initiated by ESA and DLR. As a first milestone in terms of demonstration, a 20m x 20m breadboard model was developed, manufactured and ground-tested in 1999 under simulated zero-g conditions.

Following the successful ground demonstration, a low-cost technology demonstration mission to validate sail deployment in Low Earth Orbit is currently being implemented. Under contract to ESA, Kayser-Threde GmbH will be the Prime Contractor for this mission. An ultra-light weight solar sail structure will be manufactured, stowed in a compact deployment module for launch on a low-cost, submarine-based Russian VOLNA rocket, and will be deployed in a 450km circular orbit.

First analysis revealed that many design aspects and technological solutions of the on-going solar sail development effort can be transferred to the completely different application of large microwave membrane antennas.

2. REVIEW OF THE EXISTING SOLAR SAIL DEPLOYMENT TECHNOLOGY

2.1 20 x 20m Breadboard Model Development

During the first on-ground deployment of the Solar Sail breadboard model in 1999, four CFRP booms with a length of 14m each were unrolled from the central Deployment Module and subsequently the four folded, triangular sail film segments were released from Sail Containers. The breadboard model is shown in Fig. 1 in its stowed (launch) configuration prior to deployment. The stowed volume of the Deployment Module is only 60cm x 60cm x 60cm. The total mass of the Deployment Module, including booms and the sail membranes, is 35kg [1,2,3]. The main structural elements of the Deployment Module are made of CFRP parts to minimize mass.

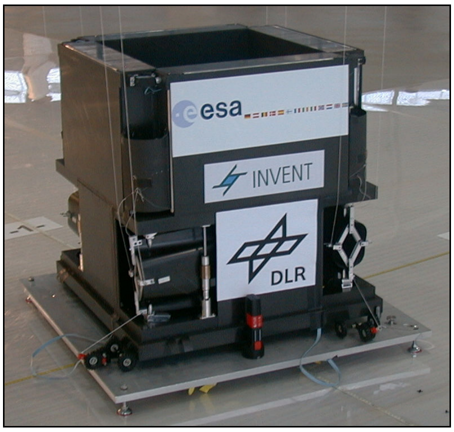

Fig. 1: Solar Sail Deployment Module

The deployment was carried out under simulated 0-g and ambient environmental conditions within ca. 30 minutes (15min for Boom deployment, 15min for Sail deployment) at the European Astronaut Center at DLR Cologne. Fig 2 shows the status where the booms were fully deployed to a length of 14m, providing the rigid structure for the subsequent sail membrane deployment.

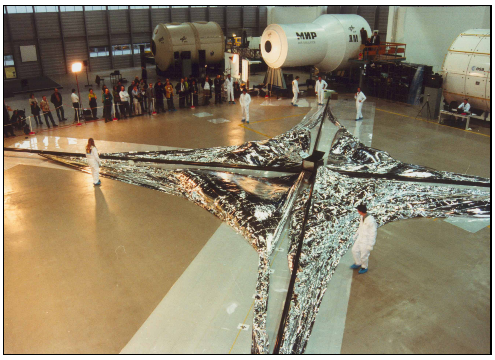

Fig. 2: CFRP Booms fully deployed (14m length) and Sails partially deployed

After the deployment of booms and sails, using a gravity compensation system with Helium balloons attached to the Booms, the four sail segments were fully deployed to approximately 20m x 20m (see Fig. 3).

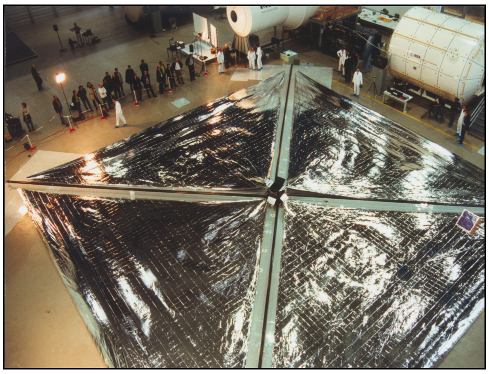

Fig. 3: Solar Sail fully deployed (approx. 20m x 20m)

Each sail segment is a right isosceles triangle providing an area of 82.6 m². The sizing of the segments was based on the triangular space provided between each of two 14m CFRP booms with consideration of clearance and connection requirements. Three different film materials were used for the sail segments:

- 12.0 µm Mylar, Al-coated on one side
- 7.5 µm Kapton, Al-coated on both sides
- 4.0 µm PEN (Polyethylen-naphthalate), Al-coated on both sides.

The main objective for using different materials was to assess the film handling and processing, and to evaluate the material behavior for seaming, folding, as well as for sail deployment.

As a compromise between secured transportation into space, controlled deployment and the performance in deployed configuration deployable booms (uncoiled from a roll), made of carbon fibre reinforced plastics (CFRP), were chosen for the baseline ESA/DLR Solar Sail design. The booms consist of two laminated flexible Ω-shaped sheets which are bonded at the edges to form a tubular shape (see Fig. 4) [4,5,6]. They combine strength and stiffness with low density and, pressed flat and coiled around a central hub for storage within a tight volume, they can be uncoiled from the central hub for deployment.

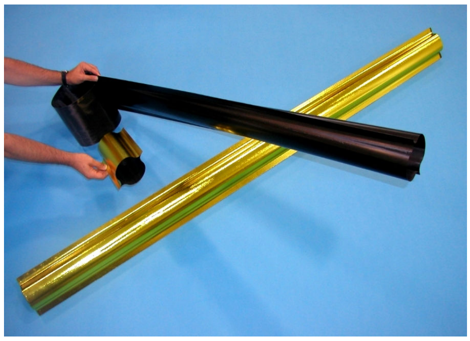

Fig. 4: Deployable DLR Boom (uncoated and coated)

Ultra-thin prepregs (pre-impregnated composite of fibres embedded into a resin system) are used for the manufacture of the booms. They are cured to two half cross-sections and subsequently bonded together at the even bonding flanges. The DLR CFRP booms are similar in their design concept to the Collapsible Tube Mast (CTM) developed by SENER in the 80s [7,8], but provide improved structural performance parameters, i.e. superior bending stiffness for the same specific mass in terms of grams per meter. In addition, in the DLR-Kayser-Threde concept all four booms can be co-coiled on a single, central drum, whereas the CTM would require four individual deployment mechanisms.

In order to improve the thermal properties of the booms and extend the application rage, CFRP booms with embedded Kapton coating have recently been developed (see Fig. 4). A layer of Kapton is included in the pre-preg lay-up during boom manufacturing.

In contrast to inflatable structures, the deployment concept applies a slow-speed (about 1m/min) and controlled deployment of four CFRP booms. Due to the stored elastic energy, the boom deployment is controlled by additional actuators and brakes.

2.2 In-Orbit Deployment Demonstration

Under contract to ESA a Phase B effort for an in-orbit deployment demonstration mission was carried out by Kayser-Threde, with contributions of DLR.

The top-level objective of the mission is to conduct a successful in-orbit deployment demonstration of a Solar Sail of approximately 20m x 20m size, i.e. full extension of the four supporting CFRP booms and the four sails, and to produce positive evidence of the accomplished task.

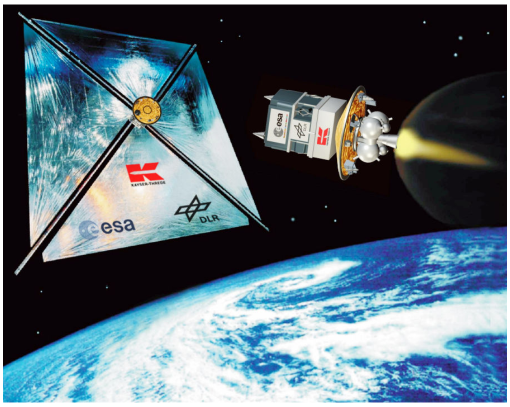

Fig. 5: Planned In-Orbit Deployment Demonstration of a 20m x 20m Solar Sail Membrane

The mission profile comprises the following main mission phases:

- VOLNA launch from submarine and orbit insertion
- Pre-deployment Phase incl. attitude stabilization
- Deployment Phase consisting of boom deployment and sail deployment
- Post-Deployment Phase until reentry in the Earth's atmosphere.

The mission scenario is shown in Fig. 6. The baseline orbit is defined by an altitude of 450km, with an orbital inclination of 78°. The orbital plane will be selected to allow the spacecraft to remain in permanent sunlight for the first days of the experiment, avoiding passage of the Earth's shadow.

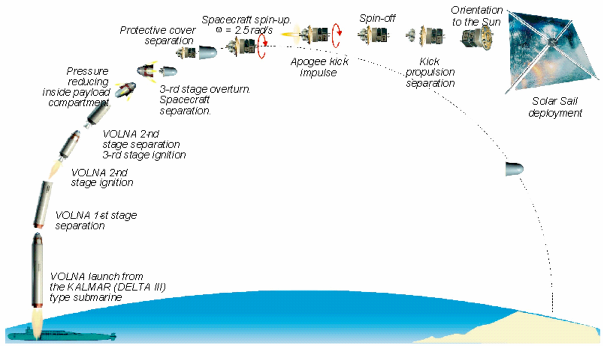

Fig. 6: Scenario for In-Orbit Deployment Demonstration

The Sailcraft is fixed to the fourth stage of the VOLNA rocket which will perform the orbit insertion burn (see Fig. 7).

During the deployment of the booms the sail containers are still closed, while actuators are used to unwind deployment ropes along all four booms.

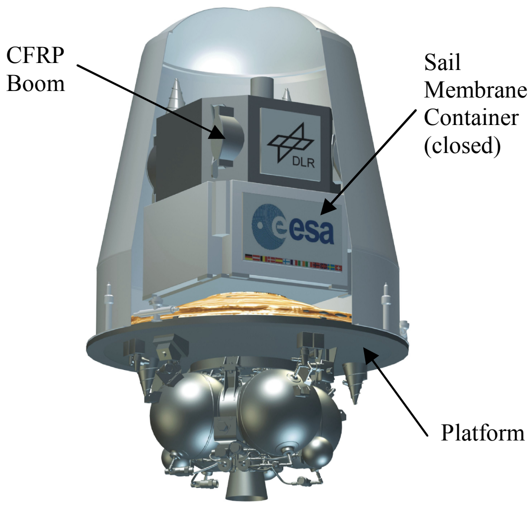

Fig. 7: Sail Payload attached to Orbital Platform

After full boom deployment the four sail containers are opened to allow sail membrane unfurling with the sail deployment mechanisms using the deployment rope system. The deployment is observed with a suite of on-board sensors which monitor the deployment process. This includes a color camera which will deliver visual evidence of the deployed booms and sails.

For deep space science missions several studies have been performed which involved the design of sails with size requirements of 60m x 60m up to more than 150m x 150m [9,10,11].

3. THE NEED FOR SAR MEMBRANE ANTENNAS

Membrane antennas are micro-strip antennas on a flexible lightweight substrate like Kapton. It consists of three separated layers, where the middle one is a ground plane of a copper film. For launch they can be folded together or rolled up and therefore they can significantly reduce the SAR satellite mass and launch volume.

Typical SAR antennas are made from planar microwave radiators with slotted waveguides. Tiles are connected with hinges and folded together for launch. They still require considerable space in the launcher fairing and their weight prevents a cost effective launch like with the Dnepr. Also the satellite bus could become cheaper if the mass of the antenna could be decreased. For example the Radarsat-1 antenna with an unfolded size of 15m x 1,5m weighs 339 kg [12]. The Canadian Space Agency (CSA) has therefore started already in 1996 to develop the so called membrane antennas [13].

Very lightweight SAR antennas are also of great interest for passive receive only SAR mini-satellites which shall fly in formation with an existing standard SAR satellite. Such proposals have been made for Envisat [14], ALOS [15] and TerraSAR-L [16]. These configurations allow for several interesting applications in bi-static SAR and SAR interferometry [17]. Since these passive satellites have no large power consumption the bus can be rather small and light. However, such kind of micro- or mini-satellite bus is not compatible with a large conventional SAR antenna.

Another application of membrane antennas are SAR systems to be placed in Medium or Geosynchronous Earth Orbits (MEO or GEO). Due to the much larger distance between sensor and ground huge antenna sizes are required. However, the big advantage of these orbits is the drastically improved field of view which would lead to much shorter revisit times in comparison to satellites in a Low Earth Orbit (LEO). Several applications could greatly benefit from this advantage like repeat pass SAR interferometry for the measurement of surface displacements due to seismic activity, volcanism or glacier flow [18]. If the antenna offers an electronic beam steering also in along track, furthermore very high geometric resolution can be achieved by spotlight techniques and the system can multiplex between several sites of high interest (like seismic hot spots). In this case the revisit time can again be drastically reduced. The forerunner in this field of research is JPL where a membrane antenna demonstrator has been build which had a specific mass of 2kg/m^2 (including support structure). This is an order-of-magnitude reduction in comparison with the SRTM phased array antenna of 20 kg/m^2 [19].

A fourth application which requires large and lightweight antennas is P-band (wavelength: 0.77 – 1.07m) SAR which is proposed for sounding of the Arctic and Antarctic ice shields [20]. Since the requirement for the flatness of the antenna aperture drops with the radar wavelength, this band will have the most relaxed requirements to the membrane support structure.

This paper does not address the electrical problems related to membrane antennas like the feed network with centralised T/R modules or integration of the T/R modules with the membrane. We focus on the deployment mechanism which has been adapted from a space-borne solar sail project.

4. CONCEPT AND DEPLOYMENT TECHNOLOGY

Based on the deployable structure technology which has been developed for the Solar Sail application, the concept was adapted to a lightweight SAR membrane antenna concept. This concept bears the potential for accommodation on a relatively small SAR satellite. Fig. 8 shows a conceptual design of a 12m x 3m membrane antenna (tip to tip dimensions of 16m x 4.5m) which is supported by a X-configuration of deployable CFRP booms.

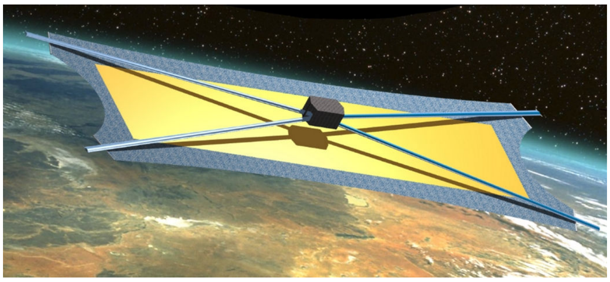

Fig. 8: Deployable 12m x 3m lightweight SAR Membrane Antenna

In the design of innovative deployable SAR membrane antennas the mass, the volume in stowed configuration and the production costs shall be significantly reduced. The main requirement, however, arises from the electrical performance. It can be expressed in terms of geometrical accuracy or membrane flatness. The antenna quality of a proposed solution is, therefore, directly linked to the design of a highly stable structure. The nominal geometry can be, for example, influenced by creases which result from the manufacture and the stowage.

Furthermore, wrinkles could occur in the membrane, if the formation of wrinkling patterns has not been considered in the design of the antenna. Since the membrane antenna does not provide any bending stiffness it must be tightened and supported by use of a compression-loaded interface structure, which needs to be deployable and lightweight as well. This interaction between membrane and lightweight support structure is considerably challenging, especially with respect to thermo-elastic deformations, temperature gradients and thermal shocks. To prevent the membrane antenna from thermally induced instabilities (see for example jittering of the first generation flexible solar array blankets of the Hubble space telescope) one could use rigid support structures like solid frames or several stiff telescope booms. These solutions, however, are usually much too heavy to meet the requirement of a lightweight antenna design.

Several concepts exist for the realisation of extremely light but load-bearing deployable support structures. Inflatable space technologies have matured in the past so that they are potential candidates for the antenna application. NASA-JPL/ILC Dover and L'Garde in the US and CSA/EMS Technologies in Canada recently developed SAR membrane antennas on base of inflatable technologies.

However, there are several disadvantages connected to the use of inflatables in the SAR antenna concept. Inflation technologies rely on manufacturing steps in free-space conditions. Flexible materials are sewed together on ground and subsequently, after launch, inflated in space. Different concepts exist to rigidize the inflatable materials in space and to provide a load-bearing deployed structure even if the inflation gas has been vented. In any case it is considerably difficult to predict the geometrical accuracy due to a missing shape-giving mould during the rigidization process in space. For inflatable technologies on base of thermoset materials it is, for example, hardly achievable to care for a homogenous heating if the curing is driven by the absorption of solar flux only. Material shrinkage and the increased outgassing could result in significant distortions which would negatively influence the SAR membrane antenna performance.

Inflatable concepts on base of Aluminium/Kapton laminates aim at the plastic deformation beyond the yielding of the metal by the inflation pressure. Although such concepts are not affected by criticalities of uncured prepreg materials and, therefore, unclear curing conditions, residual stresses between the metal and Kapton layers could result in distortions as well. Another problem arises from the high coefficient of thermal expansion of the aluminium. In combination with thermal loading during the operation of the antenna, thermal stress and deflection could develop.

Another method to provide a lightweight deployable support sub-system counts on readily on-ground manufactured structures, which can be stowed in a highly elastically deformed bi-stable condition. In the framework of a joint ESA/DLR solar sail technology demonstration DLR together with Kayser-Threde GmbH has developed an ultra-light version of deployable STEM booms (Storable Tubular Extendable Member) [4,5,6] together with a deployment mechanism (Fig. 9), as outlined in Chapter 2.

It is obvious that geometrical requirements play a significant role in the solar sail concept as well, because any inaccuracy of the optimal inclination would decrease the effect of solar sail propulsion. The functional requirements of the solar sail boom assembly are therefore generally comparable to a SAR membrane antenna application. Consequently the technologies being used for the solar sail offer potential spin-offs for a SAR antenna design.

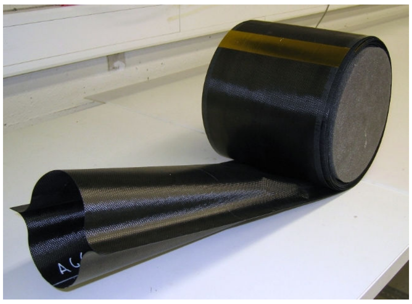

Fig. 9: 14m Deployable CFRP Boom in Stowed Configuration

The choice of the laminate stacking sequence is essentially based on the requirement to minimize the bending that takes place during single-sided thermal loading as it will be expected if the booms are exposed to the radiation environment in space. For this reason, a very low coefficient of thermal expansion in the boom longitudinal direction is an important prerequisite.

To manufacture the CFRP boom half-shells a low-cost prepreg technology has recently been established at DLR. The CF prepregs are laid into a mould and subsequently evacuated and compressed by a vacuum-bag. The curing process is usually carried out inside an autoclave in compliance with the temperature cycles and pressurization required for the necessary laminate quality. However, recent studies have shown that for the curing of the thin-walled boom half-shells an autoclave is not inevitably necessary. A good laminate quality can also be achieved by vacuum bag processing inside a simple oven. For manufacturing studies, training purposes and prototypes a bake-out tent was therefore installed at DLR facilities. Since autoclaves are only available up to a certain length, the modular vacuum bag technology is an important economical alternative to produce very long booms at reduced production costs. The qualification of the production facility and processes is, nevertheless, necessary. Meanwhile, first items of 14m long booms were successful produced with this low-cost technology.

The next process step after curing is the adhesive bonding process. The half-shells are bonded at the even flanges together. At this process step the exact positioning, in particular at large boom length, and the compliance with the process parameters are very important for a high boom quality.

Fig. 10: Full-scale Boom Bending Test.

5. PRELIMINARY ANALYSIS RESULTS

The 16m x 4.5m membrane antenna described above was investigated. In the first analysis loop finite element (FE) computations were used to get information on the structural performance of the deployed antenna configuration. In the mass budget the membrane weighs 50 kg and the deployment module 20 kg (single mass node). The ultra-light solar sail booms contribute less than 5% to the total mass of the sub-system. They have a specific mass of only 100 grams per meter. According to the nominal antenna aperture of 12m to 3m the specific mass results in approximately 2kg/m².

In the analysis procedure the membrane tensioning is conducted by the deflection of each boom's root along its individual longitudinal axis. A simplified wrinkling analysis is performed during the tightening step. The minor principle stress of each membrane element is determined and, in case of being less than zero, the element stiffness in transverse direction is reduced. Although this iterative approach is less computational effective it provides a straightforward method to identify these regions of the membrane which entail a high risk to become partially slack. To counteract drawbacks of the wrinkles due to the electrical performance of the antenna, the X-configuration of the support structure is significantly larger (here: 16m x 4.5m) than the nominal antenna aperture of 12m x 3m, because wrinkling patterns normally develop at the edges of the membrane. After the static solution step of the membrane tensioning was finished a modal analysis was performed to provide information on the system stiffness.

The lowest significant mode amounts to a natural frequency of only 0.29 Hz (Fig. 11). The corresponding mode shape and the related relative deflections are pictured in Fig. 11. The greatest amplitudes develop at the edges of the membrane which do not take part of the nominal antenna aperture, whereas the aperture itself remains relatively even. However, the very low eigenfrequency makes it clear: low damping rates, long decay times and high amplitudes mean challenging requirements to the attitude & orbit control system when the antenna is operating. A method to counteract such criticalities could be the use of adaptive means. Recent studies at DLR facilities have shown that PZT (=lead-zirconate-titanateas) actuators in combination with a suited controller concept were able to reduce the magnitude of the boom tip oscillation by 15 dB when excited in cantilever configuration (see Fig. 12 and Fig. 13).

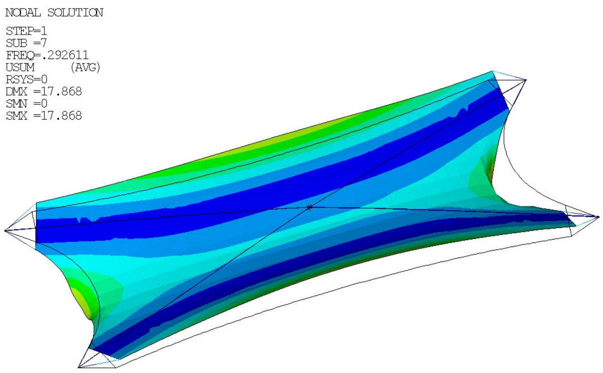

Fig. 11: Modal Analysis of SAR Membrane Antenna, Relative Deflection Sum of Mode Shape

The flatness accuracy of this concept will be studied in follow-on work in order to assess the requirements on membrane stress, which will drive the bending stiffness and detailed design incl. prepreg layer optimization of the CFRP booms.

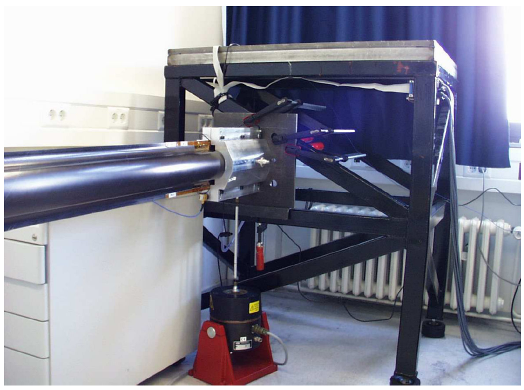

Fig. 12: Test Rig with an Adaptive Boom Segment supported in Cantilever Configuration (length approx. 2m)

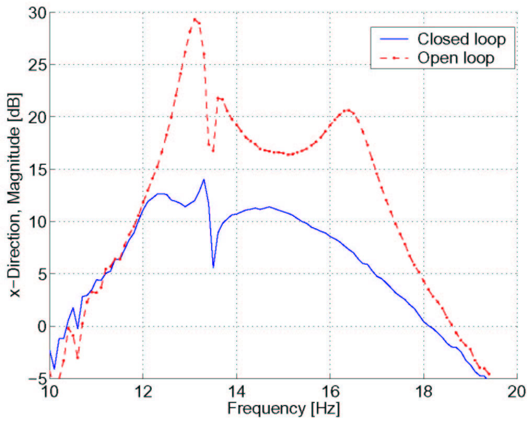

Fig. 13: Frequency Response with Open and Closed Loop

6. FUTURE WORK

Based on this initial assessment of a typical L-band SAR antenna concept it is planned to further investigate the technical performance of antenna deployment mechanisms and booms for small SAR satellites. This will include analyses on the membrane surface flatness which is achievable with the deployable structure using the DLR CFRP booms and the Deployment Mechanism developed at Kayser-Threde.

The design work is planned to be extended to typical membrane sizes on the order of 20m to 30m in length in combination with the assessment of a P-band SAR membrane antenna. Accommodation options aboard small sat missions shall also be included in the scenarios in order to identify the cost saving potential of this concept vs. a more conventional approach.

It is also planned to investigate the application of Fiber Optic Sensors (FOS) technology embedded into the deployable booms for measurements of the deflection status of the booms (see Fig. 14). Space qualified hardware for such a system is already existing at Kayser-Threde.

Fig. 14: Kayser-Threde Fiber Optic Sensor (FOS) mounted to DLR CFRP Boom

7. CONCLUSIONS

The initial assessment of the potential to adapt the solar sail deployment technology currently being developed jointly by ESA, the German Aerospace Center DLR and the company Kayser-Threde resulted in a first concept for an L-band SAR membrane antenna. It was found that the deployment concept using four co-coiled light-weight CFRP booms and a central deployment mechanism can be adapted to such an antenna. Based on the successful ground testing of this technology under simulated zero-g conditions, the in-orbit verification of this technology is currently being defined by ESA and DLR. Such a membrane antenna, due to its very small stowage volume bears the potential for accommodation on a small satellite mission, avoiding use of a large launch vehicle. The membrane size studied so far is about 16m x 5m, but it is planned to investigate also larger membrane areas of 20m typical size. This could be enabled by solar sail deployment technology in a X-configuration of the four booms. The application range is envisioned to be extended to a P-band SAR membrane antenna, which could be an enabling technology for sounding of the Arctic and Antarctic ice shields.

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