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ENABLING TECHNOLOGIES AND ARCHITECTURES AT LSS GMBH FOR EUROPEAN LARGE DEPLOYABLE AND RECONFIGURABLE REFLECTOR ANTENNAS

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Abstract

Large Deployable Reflectors (LDRs) and in orbit reconfigurable reflectors are requested by the telecommunication market more and more. High frequency applications including Ka-Band missions are required. Ka-band 5 m reflectors are requested for (very) high throughput telecommunication satellites demanding special highly stable and precise technologies. LSS GmbH is a European leader in the development of large deployable and reconfigurable antenna reflectors. LSS has demonstrated two types of LDR technologies based on its own architectures with metal mesh and shell-membrane RF surface types. In both cases, 5 m demonstrators have been designed, manufactured and tested by LSS, with some contributions from SMEs and universities, resulting into an ESA declaration of TRL 5. In addition to conventional LDR technologies, LSS is working on shaped large deployable reflectors as well as in-orbit reconfigurable reflectors enabling a full coverage of the currently requested antenna reflector types. Mechanically reconfigurable reflectors can replace the typical configuration of several shaped reflectors and satellites with a single reflector and thereby allow covering newly requested coverage areas on the Earth during a single lifetime in orbit. Thus, their application promises huge cost savings. Further on, within an ESA project, LSS has developed a mechanical concept that can significantly reduce grating lobes for faceted surfaces of large deployable reflectors.

Keywords

Large Deployable Reflector; LDR; Shell-Membrane; Metal Mesh; Enabling Technology; CFRS; FlexRS; LSS

1. INTRODUCTION

Large deployable reflectors (LDRs), including small deployable reflectors [1], are intensively considered for high radio frequency (RF) applications including Ka-band missions. A 5 m Ka-band reflector is requested for (very) high throughput telecommunication satellites demanding highly stable and precise enabling technologies.

Two different directions of enabling LDR technologies are being developed at LSS, which are named as a family of **FlexRS®** technology (**FlexRS** is a registered trademark of LSS standing for **Flex**ible **R**eflecting **S**urface technologies for antenna reflectors). These are LDRs based on membrane surfaces, e.g. knitted metal meshes, thin films, etc., and LDRs based on shell-membrane and flexible shell (Figure 1) reflecting surfaces. The flexible shell and shell-membrane types of RF surface materials [1] - [4]

FlexRS Technology of LSS Refelctors

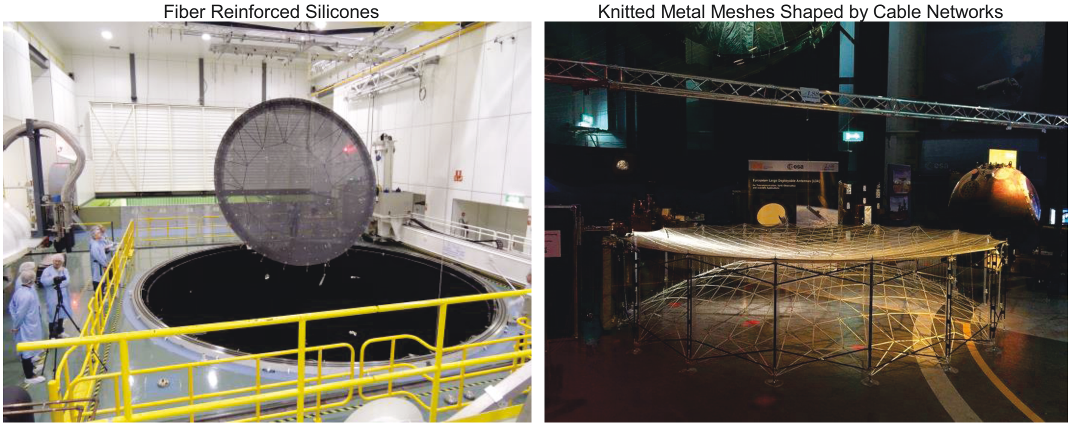
Fiber Reinforced Silicones
Knitted Metal Meshes Shaped by Cable Networks

Figure 1. 5m LDR demonstrators: ESA projects LABUM (left) and SCALABLE (right) with FlexRS technologies

give the possibility of realizing surfaces in doubly curved shapes free of the so-called pillow effect [1]. The pillow effect is an inherent characteristic of tensioned knitted metal meshes. Major differences between these two types of enabling RF surface technologies are pre-defined by that fact. The shell-membrane types of surfaces need neither pre-stressing nor a high number of supports for shaping and reaching high accuracy, while metal knitted meshes require tensioning and need to be densely supported for high frequency applications (see also section 3.3). However, the mesh type surfaces can be stowed in a much smaller transport package than the shell-membrane types.

2. ENABLING TECHNOLOGIES AND BUILDING BLOCKS OF LDRs

The current development level of LDRs in Europe corresponds to TRL 5 (6), taking into account readiness levels of the most critical, so called enabling technologies, and has been achieved by leadership and significant participation of LSS and its staff within the ESA projects for more than 20 years [5] - [18]. From a structural point of view, these critical technologies are LDR deployment architectures and shape provisioning of reflecting surfaces (in particular for high RF frequencies), and, from a material development point of view, reflecting surface functional materials. LSS has been working in both directions and is offering several different concepts / architectures and RF reflecting surface technologies on the market. There are a number of other input technologies, which are readily available in Europe, even with the highest TRL 9. These are, e.g.

- highly stable CFRP tubes
- curved CFRP beams
- end-fittings' bonding technology including metal, or full-CFRP versions
- metal joints and mechanisms
- satellite interface deployable arm with CFRP limbs and mechanisms

The selection of the input technology supplier depends on their cost effectiveness. Metal mesh for lower frequencies being offered within Europe is also at TRL 9 meaning that LDRs of P-band to X-band (Ku-band) missions, of sizes up to 18 and 8 meters, respectively, can already be offered using existing technologies available at LSS and its partners. The research effort at LSS is currently focused on the creation of high frequency reflecting surfaces of the FlexRS family in both membrane (e.g. knitted metal meshes) and shell-membrane directions for large reflectors. FlexRS for small size deployable, fixed, shaped and reconfigurable reflectors are already being offered by LSS up to Ka-band radio frequencies.

The enabling technologies being developed at LSS are associated to different building blocks of LDRs. Depending on the types (Figure 2), building blocks of mesh and shell-membrane deployable reflectors (Figure 3 and Figure 4) include

- peripheral deployable truss (ring) support structures
- radial / meridional deployable stiff ribs
- hold down, release and deployment mechanisms
- different structures for interfacing to the satellites
- cable networks, and last but not least
- reflecting surface materials / structures like
    - shell-membranes and
    - knitted metal meshes

One may add also the foldable solid RF surface, which combine a number of RF and structural functionalities. In this paper though, the focus is on the enabling flexible reflecting surfaces, as well as on their deployable support structures.

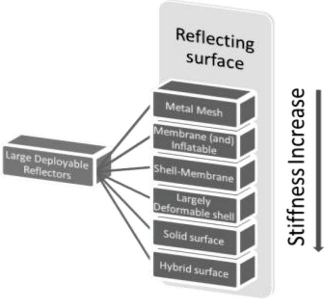

Figure 2. LDR groups according to the reflecting surface types

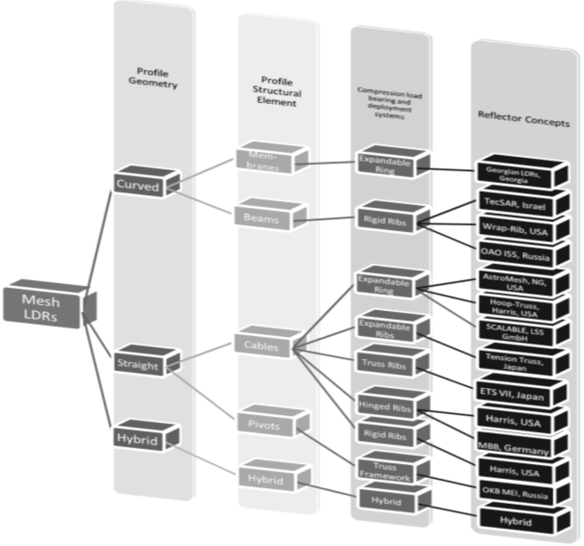

Figure 3. Building blocks and concepts of Mesh LDRs

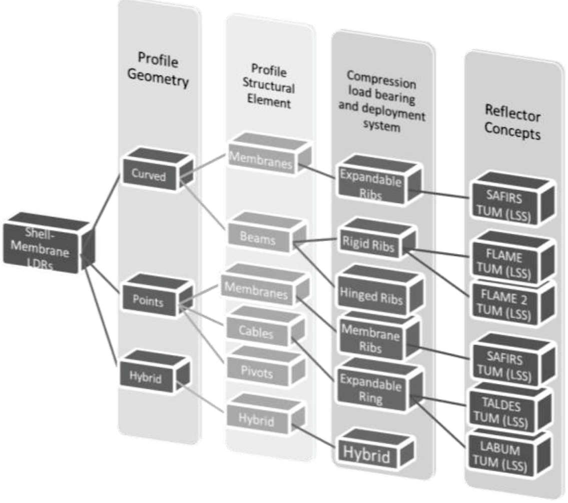

Figure 4. Building blocks and concepts of Shell-Membrane LDRs

Any parabolic antenna includes a reflecting surface, which shall be considered as a combination of several different materials and components. For example, in mesh LDRs, the reflecting surface is realized by a knitted metal mesh of various patterns. The mesh itself needs other structural elements for acquiring the RF functionality through provision of a parabolic or any other needed shape. Therefore, it is convenient to consider the mesh and its shaping cable network as the reflecting surface technology. On the contrary, in case of rib-supported mesh surfaces, the mesh and ribs are better considered separately. This is especially true if considering different radio frequency bands, e.g. low frequency bands, will require simpler RF surface technology with a simpler and cheaper metal mesh, cable network and their joining technology. These are much more complex and time consuming for high (e.g. Ka-band) frequencies. Challenges of high RF reflecting surface technologies are addressed in the following.

3. THE FlexRS® TECHNOLOGY

3.1. Fibre Reinforced Elastomers

The first group of the FlexRS material technology discussed hereafter contains fiber reinforced elastomer (e.g. silicone) composite materials that can be used to fabricate foldable reflecting surfaces for deployable and reconfigurable reflectors. These materials form a foldable shell-membrane and reconfigurable/foldable flexible shell reflecting surfaces respectively. Compared to metal mesh surfaces, this type of material does not require pre-tensioning, thus reducing the stiffness requirements for a support structure in case of LDRs and allowing the in-orbit reconfiguration of the RF surface via only predefined control (support) points without any other support structure. The shell-membrane and flexible shell reflecting surfaces are manufactured on high accuracy molds with the desired shapes, thus allowing to reproduce the mold shape without the aid of a supporting cable network and eliminating the faceting and pillowing errors known from metal mesh surfaces. In this way, high accuracies are achieved, which allow high frequency applications.

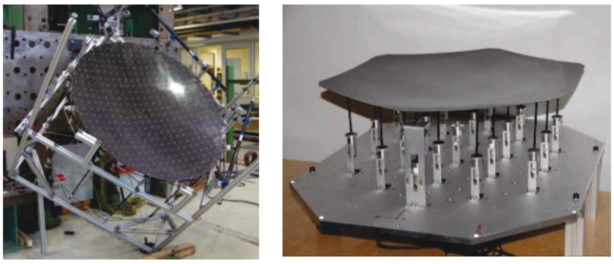

Figure 5. FlexRS technologies: a shell-membrane LDR demonstrator (left) and a reconfigurable flexible shell surface reflector.

The FlexRS fiber reinforced elastomer materials are based on the CFRS shell-membrane technology developed by LSS and its staff at TU München [1], [2], [4], [12]. They utilize woven carbon fiber fabrics and a silicone elastomer matrix material to achieve the desired multifunctionality, foldability, stiffness and reflectivity of the surface, and, at the same time, satisfying the requirements for high surface accuracy and dimensional stability. LSS has made an effort to enhance this technology within the last years, so that by now a wide range of fiber reinforced elastomer materials is available for diverse requirements, applications and frequency ranges within the family of the FlexRS technology. These materials, which include unidirectional, multi-directional, quasi-isotropic, biaxially and triaxially woven fabrics made from different fiber grades and elastomers, have been tailored to meet the diverse accuracy and RF-requirements of an application. While these materials are primarily used for the RF surface of LDRs, LSS has also created flexible hybrid (e.g. dual) matrix materials [3], which are well suitable as structural parts of space structures. In some other cases FlexRS materials are supplied with RF active surface layers to further enhance the RF performance or even reaching (non-imaging) optical flexible mirror application requirements.

The fiber reinforced silicone FlexRS materials that have been used by LSS within a number of ESA projects, e.g. [16]−[18] have been subjected to a wide range of screening and qualification tests. Figure 6 shows the results of the RF-measurements on two different materials of the shell-membrane FlexRS technology as an example.

It can be seen that the reflection losses up to a frequency of 30 GHz are less than 0.3 dB for the first example, whereas 0.5 dB are acceptable in many practical cases. The second example shows a shell-membrane material of the FlexRS family with even lower losses of less than 0.15 dB. Currently LSS investigates enhancement possibilities for the RF performance with the previously mentioned material combinations and hybrid materials: characterization and/or qualification tests are ongoing.

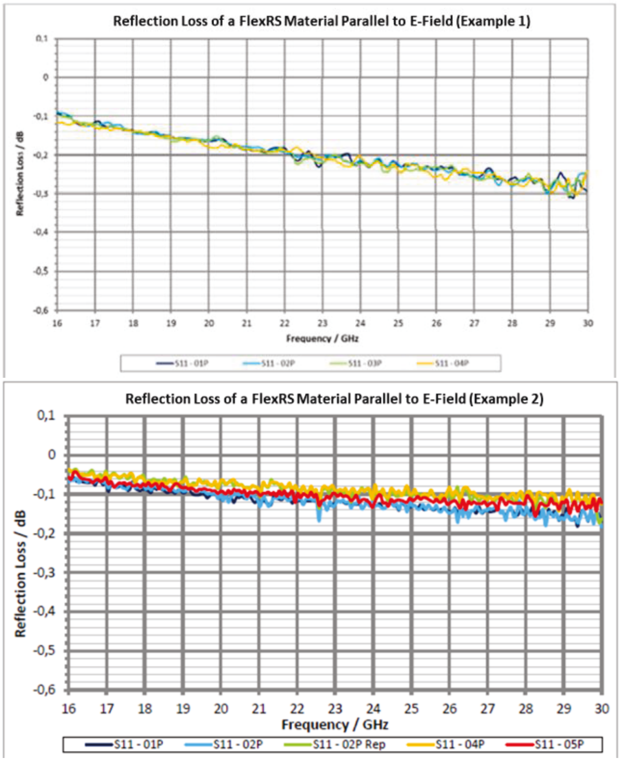

Figure 6. Reflection losses of two different FlexRS materials for frequencies of 16 to 30 GHz.

The excellent thermal stability of the shell-membrane FlexRS surfaces has been proved during the LABUM 5 m reflector thermal vacuum tests in the Large Space Simulator at ESA / ESTEC (Figure 1). Within the test campaign, the reflecting surface of the demonstrator has been subjected to a minimum temperature of −157 °C and a local temperature raise on the otherwise cold surface. Tests with elevated temperatures have also been performed outside the vacuum chamber. The resulting best fit surface RMS change for the tests inside the thermal vacuum chamber is given in Figure 7 for average temperatures.

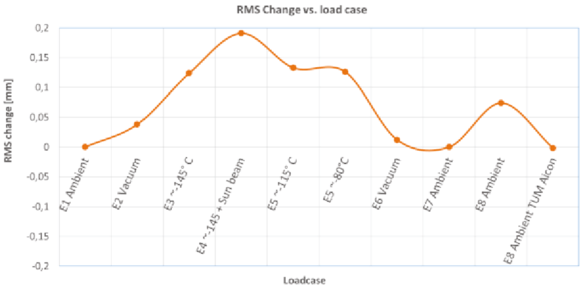

Figure 7. RMS of the 5m LABUM demonstrator w.r.t. the different load cases during the thermal vacuum test at ESTEC (best fitting of the deformed shape with a fixed focal length *f*)

As it can be observed from the figure, the RMS change is insignificant, even for an artificial load case of a central part of about 3 m diameter illuminated by the sun-beam with the rest of the surface and the ring being at lowest temperatures. For the other quasi-uniform load cases, the RMS change equals to 0.13 mm. Note that the best fitting has been performed with a fixed focal length.

3.2. Metal Meshes Supported by Cable Networks

The second group of FlexRS technology contains knitted metal meshes that are supported by a cable network architecture to achieve the desired shape of the reflecting surface. Depending on the applicable frequency range, different types of metal meshes can be used and the material for the supporting cable network is adapted to satisfy the required surface accuracy and dimensional stability while keeping the mass minimal.

The cable network technology developed by LSS according to conventional tension truss networks (Figure 8) is well suitable for LDRs with diameters up to 18 m. Conventional tension truss networks are characterized by very large heights of the peripheral support ring structures for reflectors with large aperture diameters and smaller focal lengths to diameter ratios [8]. To overcome the problem for larger diameters, LSS has developed innovative network architectures with front and rear networks interconnected by tension ties and compression members (Figure 8, see also the right photo in Figure 1). This design allows for high scalability, as the network height does not anymore determine the peripheral ring height [9].

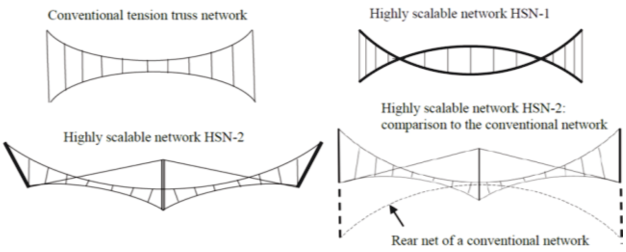

Figure 8. LSS highly scalable network architectures and comparison with conventional networks [9]

Furthermore, the described FlexRS technology also gives the possibility to shape the reflective surface for a contoured radiation pattern by introducing additional compression members. LSS is currently developing another network architecture that will enable the shaping of the reflective metal mesh surface with only tension ties (within a running project of ESA / LSS).

Within the same project, together with TICRA of Denmark, LSS has developed a methodology to minimize the grating lobes that occur due to the approximation of a parabolic surface with quasi-flat surface facets arranged within a regular network. An example of the improvement achieved with the LSS network optimization is shown in Figure 9.

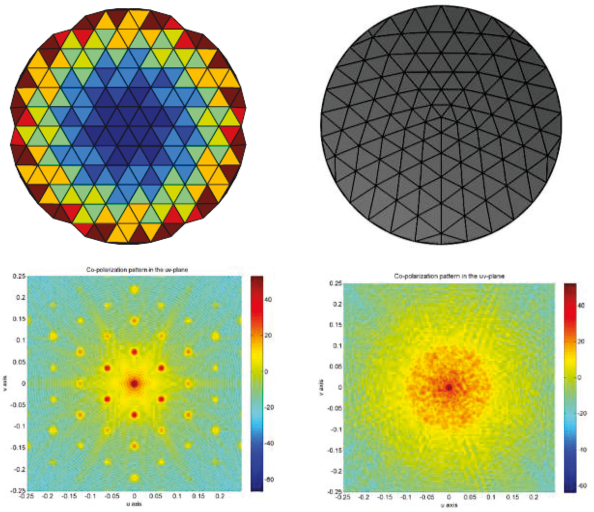

Figure 9. An example of a mesh reflector surface with non-regular triangular facets before (top left) and after LSS optimization for grating lobes reduction (top right) and the respective co-polar patterns for both versions (bottom) [10]

3.3. FlexRS Capabilities and Comparison

The FlexRS technology is suitable to produce high accuracy reflecting surfaces for use up to Ka-band frequencies including shaped surfaces and is available in different variations for different RF and LDR classes. Table 1 gives a summary of the FlexRS technology for shell-membrane and metal mesh reflecting surfaces.

LSS FlexRS Technology Capability Matrix				
Freq. Range	LDR Classes	FlexRS-I: Shell-membranes	FlexRS-II: Mesh & related	FlexRS-III: Flexible shells
Up to S-Band	Small (up to 4 m)	Y	Y	Y
	Medium (4 to 8 m)	Y	Y	N
	Large (8 to 18 m)	Y (<=12m, tbc)	Y	N
	Very large (> 18 m)	N	Y	N
Up to X-Band	Small (up to 4 m)	Y	Y	Y
	Medium (4 to 8 m)	Y	Y	N
	Large (8 to 18 m)	Y (<=12m, tbc)	Y (<=12m, tbc)	N
Up to Ka-band & +	Small (up to 4 m)	Y	Y	Y
	Medium (4 to 8 m)	Y	Y	N

Table 1. Application capabilities of the FlexRS technology

Observing the table, it is obvious that the mesh RF surface technology can be used in all the possible ranges of the frequencies and size classes. But then, what makes the shell-membrane technology still attractive? To answer this question let's estimate the number of ribs required for the mesh surface to compensate for the pillow effect in case of X and Ka-bands. The number of the ribs estimated according to [19] are plotted in Figure 10 for umbrella type mesh reflectors depending on the reflector diameter D and the respective curvature (*f*/D).

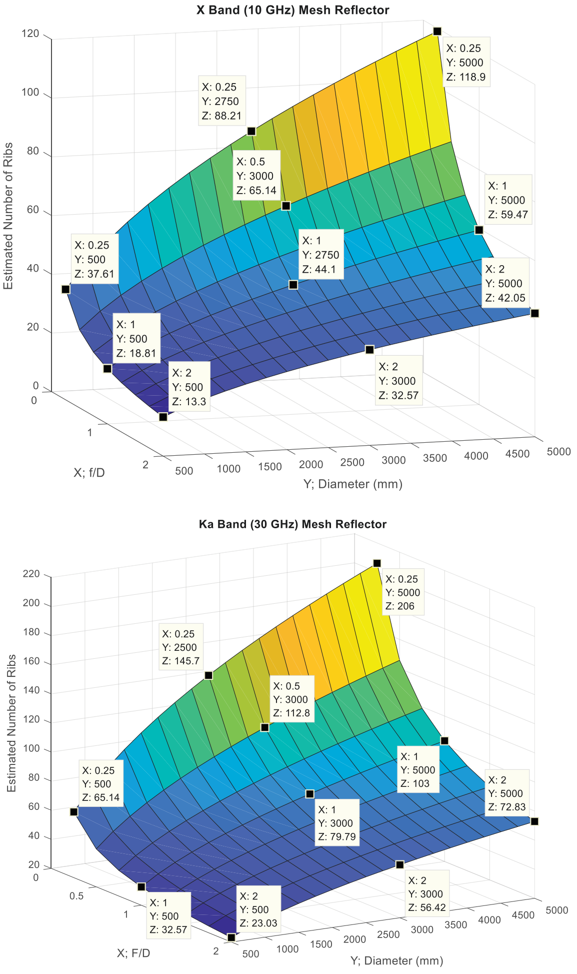

Figure 10. Estimation of required number of ribs for mesh surfaces of umbrella type reflectors for compensation of pillow effect

It is obvious that with increasing frequency and curvature (decreasing f/D), a higher number of ribs is required. For example, a small reflector of 0.5 m diameter would need 18 ribs for X-band and 32 ribs for Ka band for the metal mesh. The shell-membrane FlexRS technology would require only 6 ribs in either case of RF. Similar effects can be observed for larger diameters: 5 m metal mesh X-band reflector would need ~120 ribs, while the shell-membrane FlexRS provides high accuracy and RF functionality with only 24 ribs.

The advantages of the shell-membrane FlexRS reflecting surface technology are obvious. As compared to the metal mesh, the shell-membrane FlexRS surface gives increased deployment reliability and mass reduction in small and medium class reflector cases.

4. LDR ARCHITECTURES

LDR architectures of LSS [1]-[9], which have been created to functionalize shell-membrane and metal mesh FlexRS surfaces by providing reliable deployment and accurate support, have been investigated and demonstrated within a number of ESA projects [14]-[18]. In this point of view, the most important building block (section 2) predefining the LDR architecture is a deployable support structure, a peripheral ring and radial ribs for reflecting surfaces of FlexRS-I and FlexRS-II.

The most mature deployable ring architecture of LSS is based on the innovative shifted double pantograph ring concept according to [5] and [6], as shown in Figure 11. The total mass of the reflector equals to 15.6 kg with a package volume of 420 mm diameter and 1 m height being very competitive and superior on the market.

Figure 11. 5 m diameter reflector demonstrator with FlexRS-II technology for medium and large sizes and up to X-band of frequencies

Further evolutions of the ring concepts shown in [9] give mass savings of up to 25 % and are currently in investigation and breadboarding phases. High thermal stability and low deformability of the LSS ring concepts allow up to medium size designs for up to Ka band frequencies with adaptations of FlexRS mesh and cable network technologies (in progress).

A similar ring based concept for the shell-membrane FlexRS technology is demonstrated in Figure 12 and is suitable for up to Ka-band frequencies and up to medium size antenna reflectors.

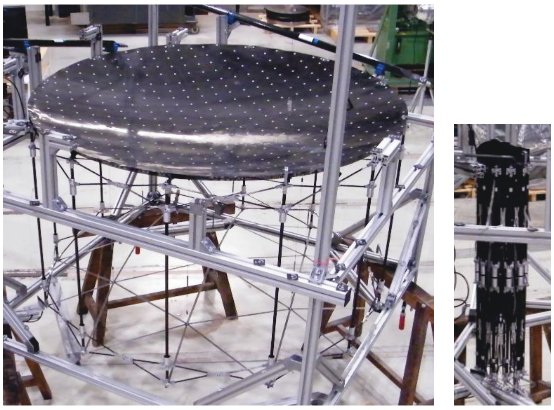

Figure 12. 1.6 m diameter demonstrator (deployed and folded) of the shell-membrane FlexRS suitable for small and medium deployable reflectors for up to Ka-band frequencies

Another type of deployment building blocks of LDRs is shown in Figure 13 and Figure 14.These are suitable for small and medium size reflectors (0.5 m to 8 m) for high RF frequencies up to Ka-band.

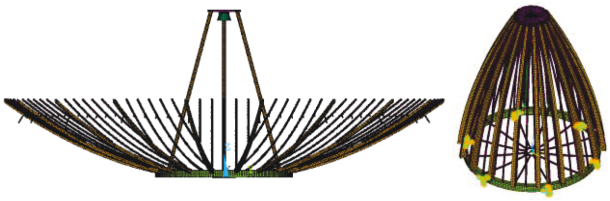

Figure 13. CAD model of a 5-m diameter centre fed reflector with FlexRS-II suitable for small and medium deployable reflectors designed for X-band (deployed and folded).

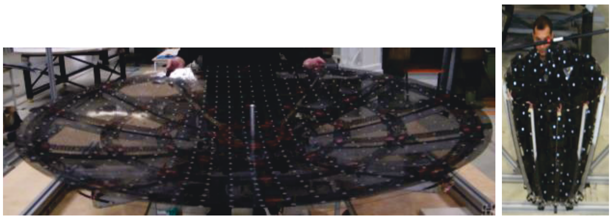

Figure 14. 1.6 m diameter centre fed reflector (deployed and folded) with FlexRS-I technology suitable for small and medium deployable reflectors for up to Ka-band frequencies

The mesh reflector in Figure 13 has 108 ribs for X-band with a pillowing RMS of 0.4 mm, while the shell-membrane reflector in Figure 14 functions at Ka-band with only 12 ribs and 0.22 mm RMS under gravity loads with no pillowing errors. It can reach manufacturing RMS accuracies far below 0.1 mm.

Another conceptual direction of the FlexRS support structure being investigated and developed at LSS are flexible shell reflectors based on the FlexRS-III technology (Table 1). These are not supported by any deployment structure but based on the FlexRS inherent properties tailored for independent functionality, they can be folded / reshaped and deployed just by its own stored elastic energy. This technology is suitable for small antennas only and requires special folding patterns.

One more very attractive and challenging direction of LSS research is related to FlexRS technology for shaped reflectors. It has already been proved within ESA projects that first two options of FlexRS technologies can be designed for large shaped deployable reflectors. A 2.6 m demonstrator design with shaped FlexRS-II surface is in progress, which will be tested also for RF in early 2018.

5. CONCLUSIONS

Multidisciplinary research carried out by the staff of LSS at the Technische Universität München, Germany and at LSS resulted in the development of expertise in the following but not limited to:

- Lightweight and dimensionally stable structural concepts with innovations for deployment and support structures of LDRs
- Mechanical Design and Analysis with highly parametrized CAD and FEM models of LDRs
- Micro-mechanical and thermo-elastic homogenization analysis tools for textile composites and related multi-scale analysis methodology
- Shell-membrane FlexRS manufacturing and assembly technology with step-by-step procedure and folding techniques
- Metal mesh and cable network FlexRS manufacturing and assembly technology with step-by-step procedure (for high RF, e.g. Ka-band, still under development)
- Equilibrium cable network design and optimization tools of form finding, including techniques of the cable network design for shaped surfaces and with reduced grating lobes, manufacturing and assembly procedures – under development
- Nonlinear accuracy analysis of pillow effect and faceting of mesh / membrane surfaces
- Unique expertise of deployment testing and thermo-elastic deformation testing of LDR in the Large Space Simulator of ESA
- MGSE systems, especially gravity compensation systems for deployment and accuracy measurements
- 3D printing and topology optimization routines for lightweight junctions' design and manufacturing, in particular for deployable structures
- Innovation and know-how at every step of the development

And last but not least, to mention a unique heritage accumulated at LSS of long-term research and development of LDRs of up to 30 m size with a successful in-orbit deployment demonstration of the 6-m Georgian Mesh Reflector on-board of the MIR station in 1999 [20].

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