



Review and evaluation of warp-knitted patterns for metal-based large deployable reflector surfaces

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Abstract

A large deployable reflector antenna (LDA) is comprised of numerous components. One of the key components of this reflector antenna is the reflector surface. Several types of reflector surfaces have been developed and used, namely, metal mesh-based reflector surfaces, membrane-based reflector surfaces, etc. The benefits presented by warp-knitted metal mesh-based reflector surfaces are their foldability and light weight structural characteristics. Typical metal mesh-based reflector surfaces are produced using a warp knitting textile manufacturing process. A warp-knitted metal mesh reflecting surface is an elastic, open structured knit with a low bending stiffness produced on a high gauge knitting machine (E26 or higher gauge) consisting of a compatible metal yarn (typically tungsten or molybdenum). This paper gives an overview about the requirements for mesh reflector surfaces stated in the literature. Afterwards, an overview of different patterns currently investigated by the LDA community is given. The names given to the various types of patterns in the literature often differ. The construction of the various patterns is therefore first optical analysed and compared. Subsequently, the different patterns are evaluated on the basis of the requirements. Based on the requirements and the possibilities of the warp knitting machine, new possible patterns are identified and evaluated. For the development of a new reflector surface, the identified patterns are developed as a warp-knitted spacer fabric. This decision increases the stiffness of the knitted fabric. This new concept for an advanced reflector surfaces is introduced by Large Space Structures GmbH (LSS) (concept) and ITA (production technology).

Keywords Large deployable reflector antenna · LDA · Metal mesh · Warp knitting · Reflecting surface

1 Introduction

The need for large deployable reflector antennas (LDA) has been addressed since the start of space communication and is still an active area of research given ever-developing communication requirements. A key component for metal mesh-based LDA is the warp-knitted reflector surface. For several years, the Institut für Textiltechnik of RWTH Aachen University, Aachen (ITA) is systematically working towards increasing the technology readiness level for warp-knitted reflector surfaces for commercialisation in the European market [1–4]. Large Space Structures GmbH, Eching (LSS)

is focused on the creation of large deployable space reflectors and other large space lightweight structures, as well as in-orbit mechanically reconfigurable reflectors [5].

Both knitting methods, weft and warp knitting, are currently investigated to produce mesh reflector surfaces [2]. Unlike warp-knitted fabrics, weft knitted fabrics are susceptible to ladder and the formation of holes. Laddering should generally be avoided due to the risk of crack propagation after local damage, e.g. due to micro-meteoroids.

Some of the key benefits presented by warp-knitted reflector surfaces include their foldability and light weight structural characteristics. Even though a commercial warp knitting machine can produce a large variety of different patterns, at the moment, four different patterns are being investigated. As shown in this paper, warp-knitted reflector surfaces are made of metal wires such as molybdenum or tungsten. Processing this type of wire on warp knitting machines is very complicated and work intensive. For this reason, it is not surprising that so far four different patterns

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have been investigated in detail for use as reflector surfaces. The authors, owing to their textile engineering background, have identified critical mislabelling in the nomenclature for warp-knitted meshes currently used by the aerospace community. Considering the varying nomenclature used by the aerospace community the authors have reason to limit the number of currently used patterns down to four. There is a possibility of certain nomenclature being used multiple times for defining a given mesh pattern. This paper aims at providing a benchmark for the nomenclature to be used and referenced for all forthcoming mesh-related research activities and publications. The authors encourage the commencement of an open discussion and research aimed towards an exploration of more options for possible warp-knitted patterns.

To provide the opportunity to examine a larger set of possible patterns, a two-step pattern selection process is presented. In this paper, the requirements for warp-knitted reflector surfaces are discussed from a textile engineering point of view. Based on the requirements, a large set of new patterns are developed and evaluated. Based on this, a current product development of a novel reflector surface is presented. A recommendation for future developments is made.

2 Basic principles of warp knitting

The subject of this paper is an analysis of knitted mesh patterns. To understand the requirements for warp-knitted reflector surfaces, first, a clear understanding of the construction of knitted fabrics and knitting machines, the stitch formation process, warp-knitted patterns and general information on the processing of metal wires on knitting machines is required.

2.1 General terms and principles of knitting technology

According to the German Industrial Standard DIN 60,000, knits are “fabrics, made of one or several threads or one or several thread systems by stitch formation”. Two specific knitted methods exist namely, warp knits and weft knits (Fig. 1). On first glance, warp knits look similar to weft knits, commonly referred to as conventional knits. Warp knits are produced by parallel threads fed from warp beams. In weft knitting, the yarn can be fed from a single spool [6–9]. In the following, only warp knits will be discussed.

Warp-knitted fabrics are textile structures consisting of so-called stitches (Fig. 1). Knitted fabrics are mainly used for technical applications such as nets, seat covers or swimwear. Additional fields of application are lace fabrics such as in ladies' underwear or curtains. In warp knitting technology, each stitch in a row is formed from a separate yarn, the

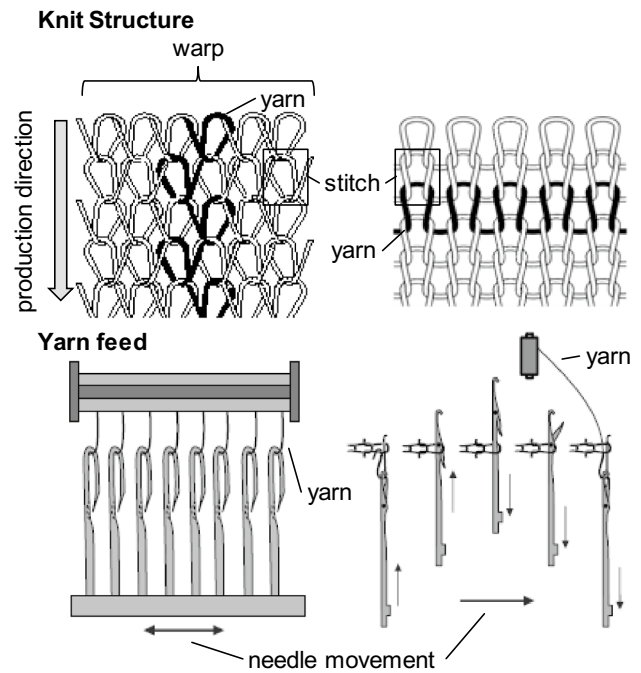


Fig. 1 Top: schematic drawing of warp-knitted (left) and weft-knitted (right) fabrics. Yarn course is marked in black. Bottom: schematic drawing of warp-knitted (left) and weft-knitted (right) yarn feed. In warp knitting parallel threads are fed from warp beams, in weft knitting the yarn is fed from a single spool [6]

warp thread. Knitted fabrics are produced in the longitudinal direction of the textile. The most characteristic feature of warp-knitted fabrics is that adjacent stitches in a wale are not formed from the same yarn. The warp threads of knitted fabrics have an approximately perpendicular path through the textile structure. Using different stitch arrangements (patterns), both dimensionally stable and highly elastic knitted fabrics can be produced without having to change the yarn type. In summary, warp knitting produces fault-tolerant textiles and has sufficient degrees of freedom to produce knitted fabrics with specific properties according to requirements [7].

Warp-knitted fabrics can be produced with two different types of warp-knitting machines: Raschel machines and tricot machines. Figure 2 illustrates the construction of a raschel knitting machine. The main differences to a tricot machine are take-off direction (angle between warp thread and cloth take-off), number of guide bars and machine speed.

Warp knitting is a multi-thread production process. The warp is prepared as a collection of yarns. The yarns of the warp all have the same length and yarn tension. The warp is guided from the warp beam to the knitting elements via the yarn feed. The stitch is formed in the knitting elements. The finished textile is evenly drawn off via the fabric take-off.

The stitches are formed within the warp knitting elements (Fig. 3) by the movement of the eye needles around the latch

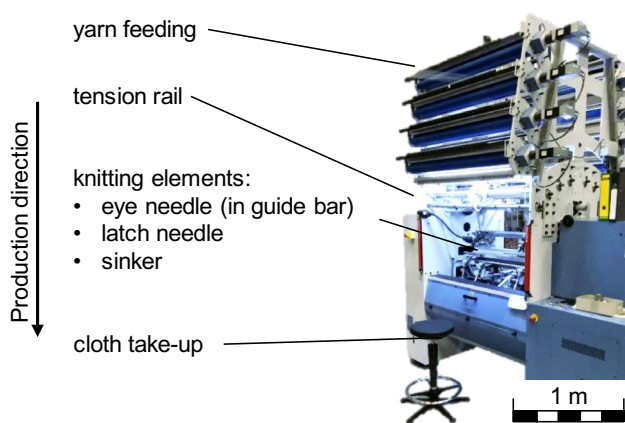


Fig. 2 Construction of a raschel warp knitting machine; shown machine: Rius Mini-Tronic from RIUS Comatex, Barcelona

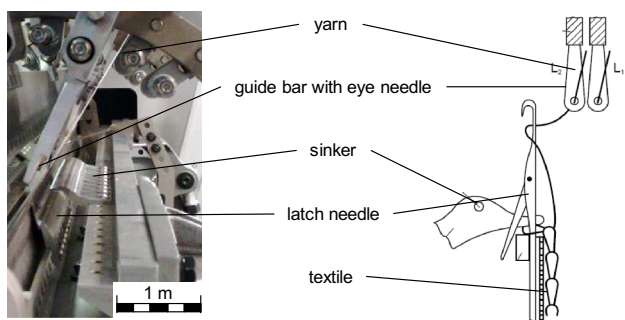


Fig. 3 Left: photo of the warp knitting elements. Right: schematic drawing according to [6, 7]

needles and by the subsequent knocking off of the stitches by the up and down movement of the latch needles. The movement of the guide bars during the stitch formation process consists of four phases. First, the underlap takes place, during which the guide bars perform a lateral offset behind

the latch needles. Then, the latch needles of the guide bars swing through the needle spaces of the latch needles. In the overlap, a lateral offset of the guide bars takes place in front of the latch needles. In the last step, the return swing, the eye needles of the guide bars swing behind the latch needles. During stitch formation, several guide bars can feed a thread to the respective latch needle. This creates more complex patterns with special characteristics.

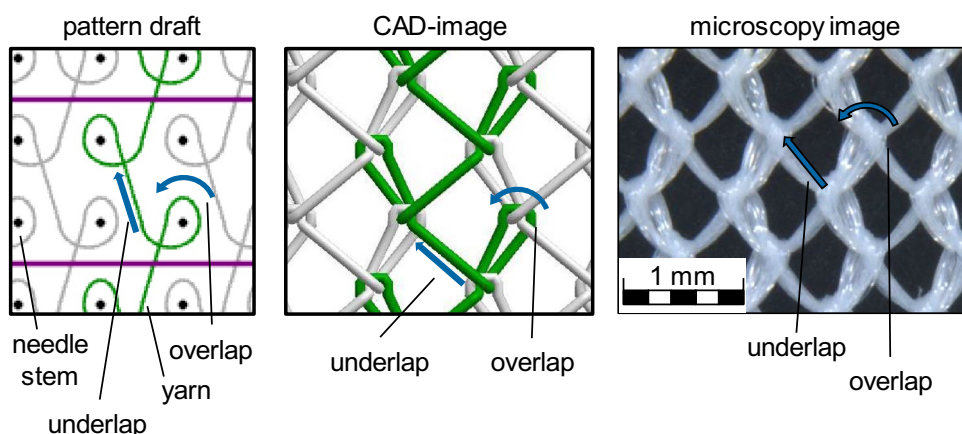
2.2 Design possibilities of knitted fabrics

The type of interlacing of the threads in a warp-knitted fabric is known as pattern. In addition to the yarn material, the pattern is decisive for the elasticity of the warp-knitted fabric. Patterning in warp knitting is done via the length and direction of the underlap (Fig. 4), i.e. the connecting element between the stitches of the different rows of stitches. In addition, underlaps without loop formation can be carried out via laying-in (Fig. 8; second picture from above, yarn in blue). It is also possible to completely remove underlaps and overlaps, thus creating standing threads. Depending on the type of machine, several yarn systems with different patterns can be fed in and the pattern repeats are also variable in length, making the warp knitting technique one of the textile production methods with the most extensive patterning possibilities. Assuming three guide bars and a repeat of length 24 alone, there are over 40 million patterning possibilities.¹

There are several possibilities to create different patterns in warp knitting as a very versatile fabric production system. There are basic patterns which can be combined with each other or can be connected with other construction elements. The basic types of pattern include (Fig. 5):

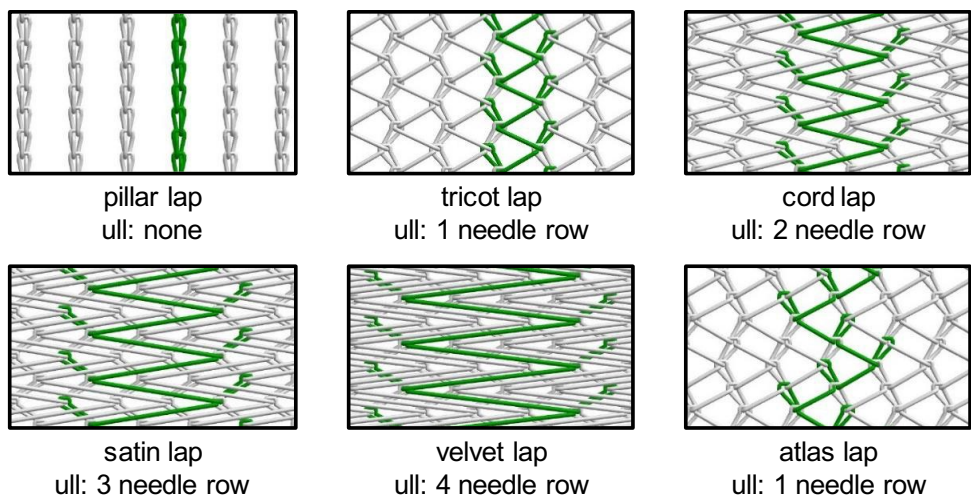
- Pillar lap.

Fig. 4 Structure of a pattern as pattern draft, CAD image and microscopy image (fltr) using the example of tricot pattern



¹ Jung, S.: Expert talk with Stephan Jung; online, 27. May 2021.

Fig. 5 Basic types of pattern incl. the respective underlap length (ull)



- Tricot lap (Fig. 4).
- Cord lap.
- Satin lap.
- Velvet lap.
- Atlas lap.

The difference from pillar stich to velvet lap is, that the underlaps is each one needle row longer. An increase underlap makes the structure stronger, more opaque and heavier. Also with an increased underlap, the fabric as a more horizontal appearance [9].

In addition, each of the basic patterns can be made with open or closed laps (Fig. 6). The difference of the laps opening can be summarized, that fabrics with closed laps are:

- Heavier,
- More compact,
- More opaque, and,
- Less extensible

Compared to fabrics with open laps [9].

As another design element, each guide bar can produce a different pattern at the same time. Thus there are complex patterns possible e.g. for lace underwear, tablecloths or curtains. For mesh reflector surfaces, often a mesh pattern (also called filet pattern), such as the atlas mesh is used (Fig. 7). For a mesh, at least two guide bars are required. The guide bars are part threaded and the lapping is in opposite direction (Fig. 7, top). Both the microscopic images from Fig. 7, bottom use are made from tungsten yarn with an atlas mesh pattern. However, different yarn-feeding and different fabric take-up speed as well as different fabric tension, while taking the microscopic picture result in a different in appearance.

Combining different patterns, warp-knitted fabrics can be produced to have elastic or rigid behavior as well with an

open or closed structure. Figure 8 represents a summary of different structures and which pattern elements lead to the given structures.

2.3 Warp-knitted spacer fabrics

Warp-knitted spacer fabrics consist of two parallel cover surfaces, which are connected to each other in the z-direction by so-called pile yarns (Fig. 9). The basic structure of the cover surfaces consists of knitted fabrics, so that a fundamentally high elongation and thus drapability is achieved. The pile yarns integrated in the z-direction give the overall structure stiffness. As a semi-finished textile product, warp-knitted spacer fabrics can be (temporarily) deformed or folded without destroying the structure [6]. Both cover surfaces can be designed independently of each other with the patterns described in Sect. 2.2. Thus, spacer fabrics with two closed cover surfaces, two cover surfaces with net structures or, as

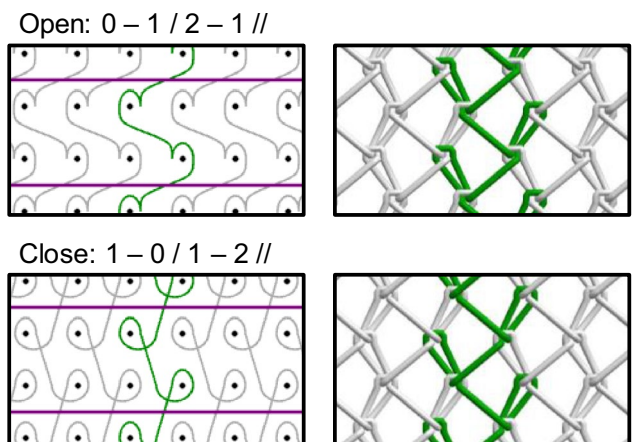
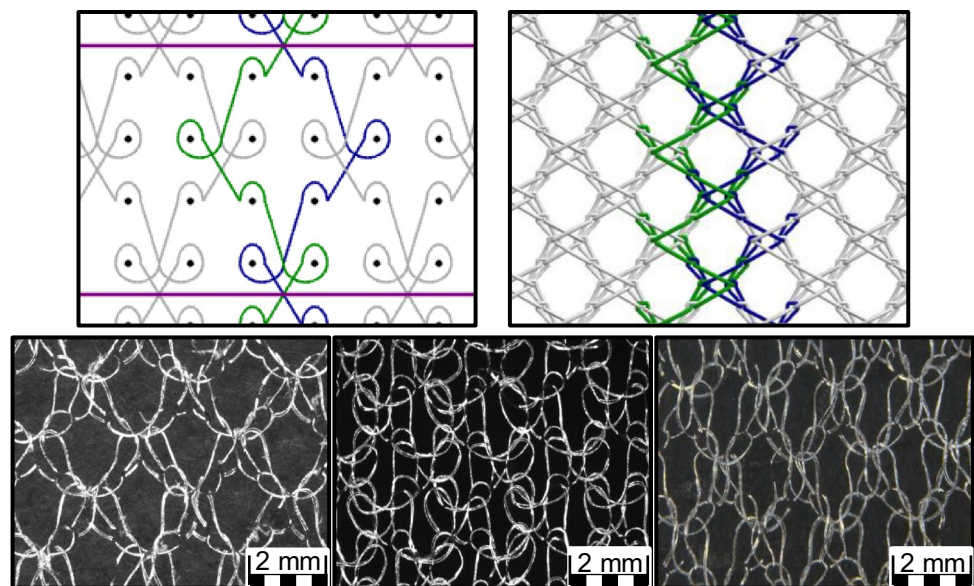


Fig. 6 Top: tricot pattern with open laps. Bottom: tricot pattern with close laps. Left: pattern draft. Right: CAD image

Fig. 7 Top: pattern draft (left) and CAD image (right) of an atlas mesh Bottom: microscopy images of tungsten atlas meshes with different yarn feeding and take up speed



in Fig. 9, one closed cover surface and one cover surface with a net structure are possible.

Applications for warp-knitted spacer fabrics can be found wherever increased air circulation or a comfort effect due to the cushioning structure is desired [40]. They are used in medical textiles (e.g. orthoses), in automobiles (e.g. climate comfort layer), in home textiles (e.g. chair cover), in clothing (e.g. bras) as well as in protective and sports gear. Warp-knitted spacer fabrics are produced on spacer warp knitting machines. Spacer warp knitting machines are raschel machines with two needle beds facing each other. The construction of a spacer warp knitting machine is shown schematically in Fig. 10. Warp-knitted spacer fabrics are not a new technology, but have been used for the above-mentioned textile applications since the 70ths [41]. The use of a spacer fabric as a reflector surface is currently taking place for the first time in a research project, of which this paper is a part.

2.4 Processing of metal yarns on knitting machines

Polymer yarns are processed on traditional warp knitting machines. When compared to metallic yarns, materials like polyester multifilaments offer a higher elasticity. Yarn guiding elements, in particular, have been optimized to handle polymer yarns. Processing metallic wire or yarn is doable using weaving. However, unlike weaving, warp knitting requires curved wires to create the loop structure of the stitch. Due to the non-ductile nature of materials like tungsten or molybdenum, processing them on warp knitting machines is difficult. As mentioned by [3] while producing a warp-knitted antenna reflector surface plastic deformation of the wire must be avoided in all processing steps [1].

To enable a warp knitting process despite the very fine (mostly 30 μm diameter or smaller) and inelastic yarn material, various modification measures are necessary on a conventional warp knitting machine. Yarn monitoring is an important element, as the brittle yarns can easily break in this production processes [2]. In addition, a large part of the yarn guiding elements must be replaced or changed, as otherwise metal-to-metal friction occurs between the yarn and the yarn guiding element. The yarn guiding elements designed for polymer yarns are not designed for this type of friction. Especially on the influence of metal-metal friction during the processing of metal yarns on warp knitting machines, there have been some studies [1, 42]. Due to the non-elastic yarn material, the springs of tension rail are modified or converted. Another measure that is necessary to process fine metallic yarns on knitting machines is the yarn preparation of the metallic yarn. Here, for example, protective wrapping yarns [2] or twisting of the yarns can be used.

3 Review of warp-knitted patterns used for mesh reflector surfaces

There are many different warp-knitted pattern names discussed and used, sometimes erroneously, by the antenna community. Unfortunately, most of times, the pattern name presented and the corresponding picture do not match up in a textile engineering context. The lack of credible information available has restricted the technical advancement of the European satellite reflector engineering and manufacturing development. This paper aims at creating a consolidated list of existing mesh patterns currently being used in the large reflector mesh community.

Fig. 8 Summary of different structures and which pattern elements lead to the given structures [9]

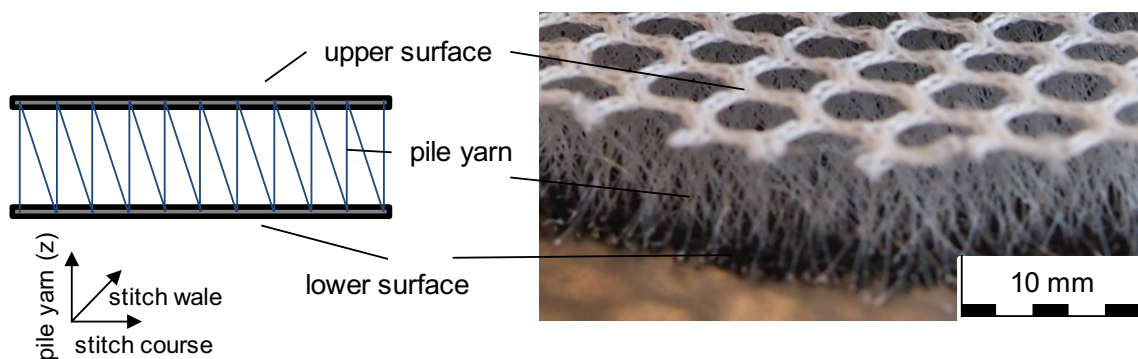
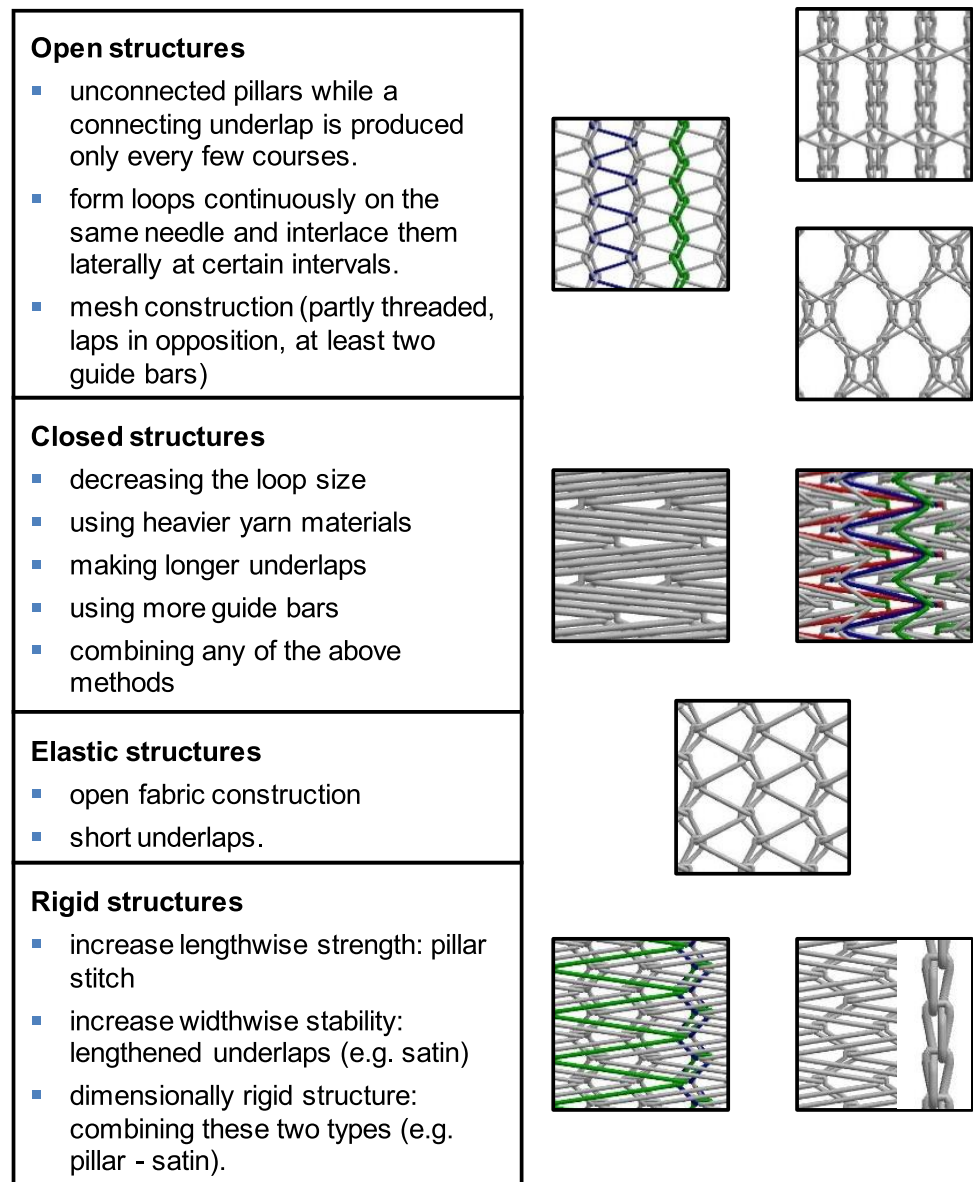


Fig. 9 Structure of a warp-knitted spacer fabric

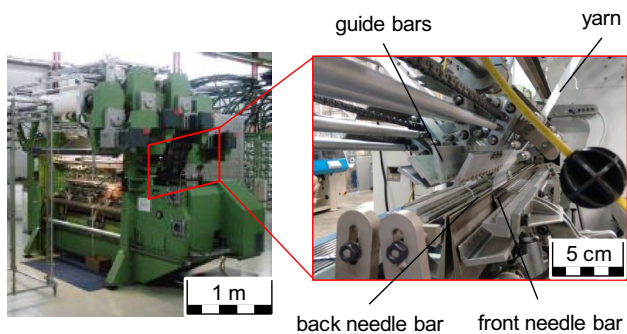


Fig. 10 Construction of a spacer warp knitting machine

Close Atlas Mesh

- 1. Guide Bar: 0 -1 / 2 -1 / 3 -2 / 1 -2 //
- 2. Guide Bar: 3 -2 / 1 -2 / 0 -1 / 2 -1 //

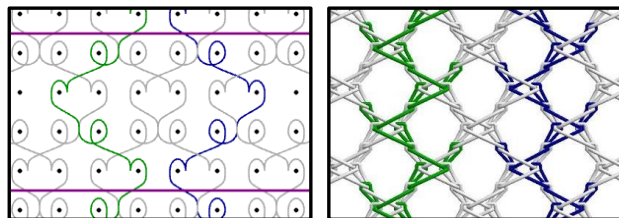
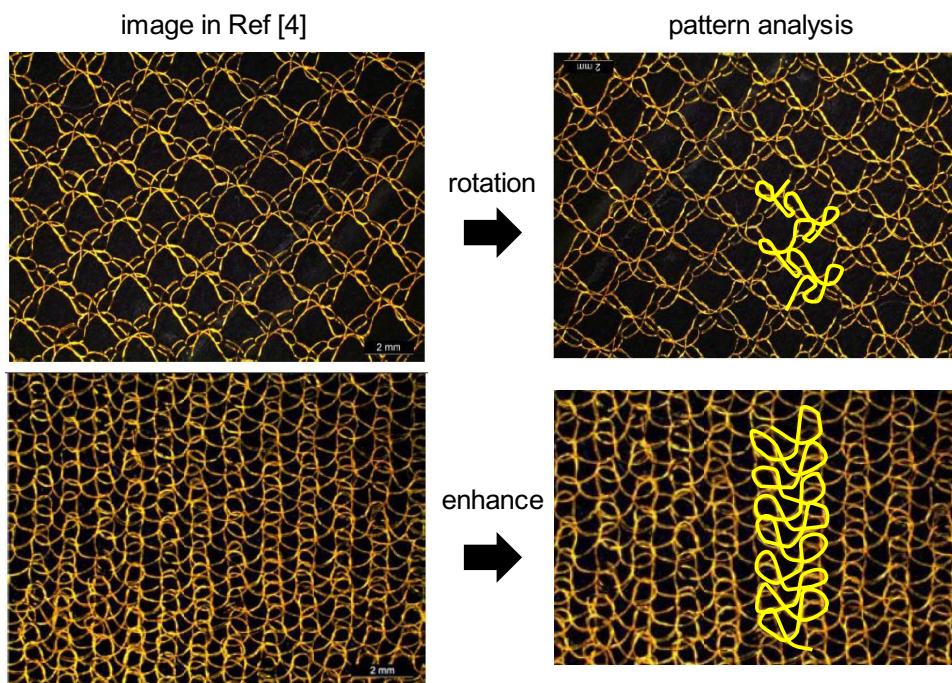


Fig. 12 Atlas mesh, the most common used pattern for mesh reflector surfaces. Pattern draft (left) and CAD image (right) of an atlas mesh

Fig. 11 Example of pattern analysis using Ref. [4]



Following different patterns and corresponding pictures presented by various authors in previous work are analysed, resulting in a list of existing patterns used for mesh reflector development.

Following, only papers showing photographs or drawings of the reflector surface are considered in this list. As will be demonstrated in the following, the name of the pattern often does not correspond to the corresponding

photo or drawing in the respective publication. Therefore, any given pattern name without a picture must be taken with grain of salt. For this analysis, the figures are all rotated in the direction of production of the fabric. Figure 11 shows an example of the analysis. By aligning the image frame and drawing in the course of the yarn, the pattern can be identified.

Table 1 Analysis of mesh pattern images used by [11–17] with their respective names used there

Image used in Ref	in Ref. given name
[11–13]	Tricot type [12], tricot [11, 13]
[14–17]	Two-bar tricot [14–16], atlas-atlas [17]
Both pattern depicting an open atlas mesh	

Table 2 Analysis of mesh pattern images used by [2–4, 19] with their respective names used there

Image used in Ref	in Ref. given name
[2, 3]	Atlas–Atlas [3], Atlas–mesh [2]
[4]	Atlas–Atlas
[4, 19]	American mesh

The first pattern is an atlas mesh pattern in which all four laps are close; the second and third pattern are both open atlas mesh

3.1 Atlas mesh

The pattern atlas mesh (Fig. 12) is the most common used pattern for mesh reflector surfaces. Atlas Mesh is a symmetrical net and is produced by two opposite working guide bars, both of which have a one full one empty intake. An atlas is laid on both bars. The atlas pattern on both guide bars represents a zigzag course of the yarn (see Sect. 1.2). The opposing underlaps improve the strength of the knitted fabric [9]. Nets like the Atlas Mesh are used in textile industry for various applications. Examples of applications are nets for sportswear, linings, blouses and shirts, shade nets or fishnets [9, 10].

The name of this pattern differs much in mesh reflector focus literature. Names such as atlas–atlas, atlas or even tricot are commonly used. In English textile literature, the name Sandfly net is also used for this pattern [9]. In the following, 11 distinct different images of Atlas mesh and the corresponding papers are analysed.

There are a few US patents that describe the mesh reflector surface by Northrop Grumman Corporation, West Falls Church, United States and Harris Corporation, Melbourne, United States [11–13]. It seems like the patents use the same image, just at a different rotation. In the patents, the pattern is described as a tricot but the corresponding pictures are, respectively, of an atlas mesh. A third patent by Hughes Electronics Corp., United States, defunct in 2003 describes the mesh tensioning [14]. The mesh is described both as a soft tricot mesh and two-bar tricot mesh. The corresponding pictures seems to be an atlas mesh. Therefore, it is unclear to the authors if these patents describe either a tricot, a two bar tricot, an atlas mesh or something else. The image depicted

Table 3 Analysis of mesh pattern images used by [16, 20–22, 25–29] with their respective names used there

Image used in Ref	in Ref. given name
[20]	Atlas
[16, 25–27]	Two-bar tricot
[21, 22, 28, 29]	Tricot knit mesh

The depicted pattern is an open atlas mesh

in [14] is often used in antenna focus literature. There it is usual named two bar tricot or tricot. The authors assume this patent is the origin of the pattern name confusion within the antenna community. The result of the image analysis is shown in Table 1. Both knits are so-called open atlas mesh, since the middle loop has an open lapping and the side loops are close laps.

In previous work provided by ITA under the ESA funded project “Ultralight Reflector Mesh Material for Very Large Reflector Antennas”, an atlas mesh is successfully manufactured using both a three wire bare tungsten and gold plated tungsten [3, 4]. The aim of the research was to develop a mesh for Large Deployable Reflectors to a technology Readiness level 5 in Europe. In [3] and [4], the pattern is called atlas–atlas. Within the same study the atlas mesh patterned mesh has been RF characterized and a low RF loss was evidenced up to 10 GHz [4, 18]. The result of the image analysis is shown in Table 2. The pattern of the first warp knit is an atlas mesh pattern in which all four laps are close. The other two warp knits are open atlas mesh.

Reference [20] describe the investigations in the MESNET (ESA) and LEA (EC-H2020) projects regarding the optimization of the mesh configuration and design and the refinement of processes for combining several segments of mesh to form a larger reflector [20]. investigated warp-knitted fabrics using the atlas mesh pattern. Reference [20] describes the production of a five-rowed atlas. The corresponding sketch shows a double-breasted lodged atlas and on the corresponding photograph an atlas mesh is shown (Table 3). Mechanical, RF tests as well as PIM (Passive Intermodulation) tests are done to the atlas mesh in a closed and so-called open/closed configuration. Their study [20] concludes that the best performance is shown by their atlas mesh-patterned mesh in their so called open/closed configuration. In a next step, they will investigate the resistance against crack propagation at the operative tension level.

In [15] different wire mesh patterns for mesh reflectors regarding their electrical properties are analysed. It is important to note that only theoretical findings are discussed in [15]. The authors of [15] concluded that the electrical properties of the mesh structures depend on the pattern but no suggestion for future mesh patterns was made. The same group of researchers analyse in [16] wire meshes for mesh

Table 4 Analysis of mesh pattern images used by [19, 30–32] with their respective names used there

Image used in Ref	in Ref. given name
[30]	Two-bar, half-set, with diamond-shaped openings
[19, 31]	Alenia/EGS LDR mesh
[32]	Two-bar satin

The first image/pattern is an open atlas mesh; the second and third image/pattern are both atlas mesh pattern in which all four laps are close

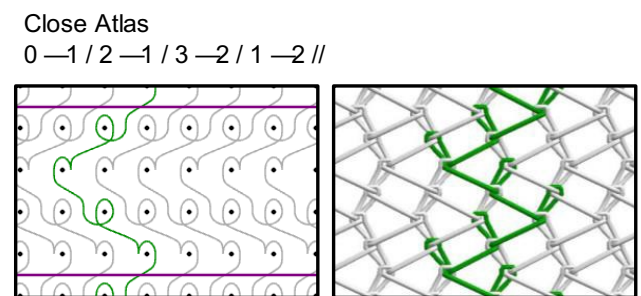


Fig. 13 Atlas lap. Pattern draft (left) and CAD image (right)

reflectors using fractal mechanics. For their study, they use a two-bar tricot mesh as an example, but it appears to be actually an atlas mesh. Reference [15] lists atlas, tricot, satin and two bar tricot as warp-knitted reflector surface patterns. These have been called single atlas, back half tricot, single satin, and two-bar tricot in the study. The corresponding sketches are not easy to recognize. One is the so-called two bar tricot, which seems to be an atlas mesh (Tables 1 and 3).

There are several papers about analysis model and numerical diffraction analyses of meshes for reflector antennas funded by NASA (e.g. [21–24]). In reference [21, 22] sketches of atlas mesh are given (Table 3), the pattern is called two bar tricot.

[30] is a NASA report from 1976 which describe the development of a 5 m diameter durable reflector antenna. The paper describes the design analysis and testing of the antenna. The photograph of the mesh shows an atlas mesh pattern (Table 4). In the report, the pattern is called “two-bar, half-set, with diamond-shaped openings”.

In [31], mesh reflector antennas are numerically analysed by using extended physical optics technique [31] uses for their development the mesh described in Table 4. In [31], the pattern of the mesh is not named. It appears to be an atlas mesh. The same picture is also used in [19], here, it is called Alenia/EGS LDR mesh. The pattern is an atlas mesh in which all four laps are close.

Table 5 Analysis of mesh pattern images used by [15, 24, 29, 32–36] with their respective names used there

Image used in Ref	in Ref. given name
[15, 24, 29, 32–36]	Single atlas

The depicted pattern is an open atlas lap

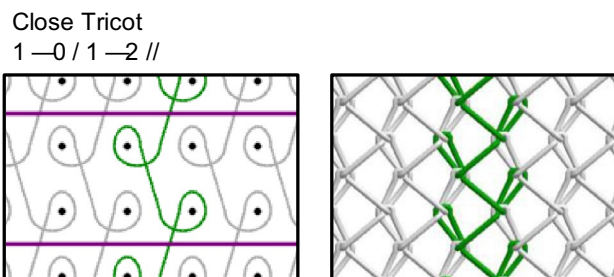


Fig. 14 Tricot lap. Pattern draft (left) and CAD image (right)

Table 6 Analysis of mesh pattern images used by [4] with their respective names used there

Image used in Ref	in Ref. given name
[4]	1 × 1

The depicted pattern is a close tricot lap

Another paper about modelling the mesh of mesh reflector surfaces is [32]. It uses similar sketches as the previous modelling papers such as [15]. In addition, a photograph is shown which is the papers’ main resources on its modelling. The depicted mesh has an atlas mesh pattern. In the paper the pattern is called two-bar satin (Table 4).

3.2 Atlas lap

The atlas lap pattern (Fig. 13) is one of warp knitting basic pattern (see Sect. 2.2). A warp-knitted fabric from an atlas lap is produced with a guide bar that is fully drawn in. The movement of the yarn follows a zigzag path. The change of the direction of the yarn reflects light to produce a faint, transverse shadow, stripe effect [9]. Atlas is the base for many simplex and all Milanese fabrics [9].

Unlike the Atlas Mesh, the Atlas Lap does not create a net structure but a closed knitted fabric. Due to the fact that only one guide bar is used, there are fewer thread intersections with the Atlas Lap than with the Atlas Mesh.

In mesh reflector focus literature, it is both referred to as atlas or single atlas. In another study, the authors of [21, 22] about analysis model and numerical diffraction analyses of meshes for reflector antennas, satin and atlas pattern are

Close Cord lap
1—0 / 2—3 //

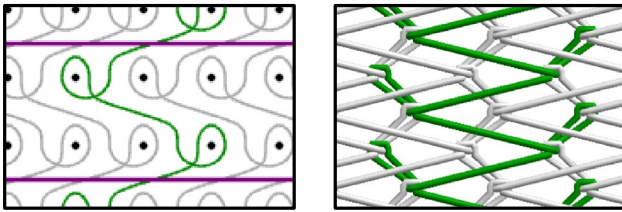


Fig. 15 Cord lap. Pattern draft (left) and CAD image (right)

Table 7 Analysis of mesh pattern images used by [20, 37] with their respective names used there

Image used in Ref	in Ref. given name
[20]	Pin net
[37]	—

The depicted pattern is an open cord lap in [20] and a close cord lap in [37]

investigated for the numerical analyses (which are called Single Satin and single atlas in the papers) [23, 24]. In the corresponding sketches, only the atlas lap is identifiable (Table 5).

3.3 Tricot lap

Tricot lap (Fig. 14) is one of the simplest and most used warp-knitted patterns in a textile and clothing oriented context. It is a very simple way to form a surface on a warp knitting machine. The knitted fabric is formed with a guide bar and the underlap has a length of one needle row. Usually the tricot lap is used in combination with other patterns to get special properties. Tricot fabrics in the sports sector, for example, are produced by two tricot lap bars working in opposite directions and fully drawn in. A velour is obtained by combining a satin lap on the first guide bar and a tricot lap on the second guide bar [7].

In the work provided by ITA under the ESA funded project “Ultralight Reflector Mesh Material for Very Large Reflector Antennas” a tricot lap pattern is successfully manufactured [3, 4] (Table 6). In [3, 4], the pattern is called 1×1 , which is also a common English name for this pattern.

3.4 Cord lap

Cord lap (Fig. 15) is one underlap longer than tricot lap. It is also formed with a single guide bar that is fully threaded in. Similar to tricot lap, it is often used in home textiles and

Close Satin lap
1—0 / 2—3 //

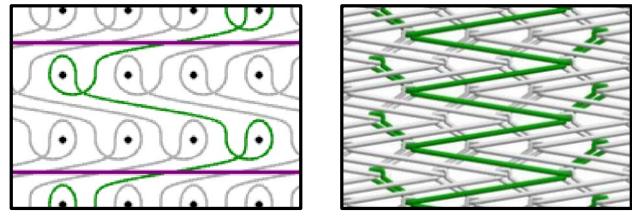


Fig. 16 Satin lap. Pattern draft (left) and CAD image (right)

Table 8 Analysis of mesh pattern images used by [38] with its respective name used there

Image used in Ref	in Ref. given name
[38]	Single satin

The depicted pattern is a close satin lap

clothing. Cord lap pattern can also be called 2×1 or fabric in English textile literature.

In reference [20], the investigations in the MESNET (ESA) and LEA (EC-H2020) projects, also a cord lap pattern is investigated. In the paper, the cord lap pattern is named as a pin net. In the study, open and closed lap cord laps knits are produced (Table 7). Similar to the atlas mesh, mechanical, RF tests as well as PIM tests are done on the produced cord lap knit in open and closed configuration. In a next step, they will investigate the resistant against crack propagation at the operative tension level. Depending on these results, the authors of [20] suspect that the cord lap knit will be used in the next research steps.

In Reference [37], the design as well as the deployment of a mesh reflector is describe. A photograph of a mesh is included. The mesh is not specified in the corresponding text, but a cord lap pattern is clearly visible (Table 7).

3.5 Satin lap

Satin lap (Fig. 16) is one underlap longer than cord lap and two underlaps longer than tricot lap. Similar to tricot lap and cord lap it is often used in home textiles and clothing. Satin lap pattern can also be called 3×1 in English textile literature.

In [38], an apparatus is developed to measure the reflection coefficient, transmission coefficient, and radiative coefficient of reflector mesh surfaces. To develop and test the apparatus, a gold-plated $30 \mu\text{m}$ diameter molybdenum wire mesh is used. The mesh pattern is called single satin in the paper (Table 8).

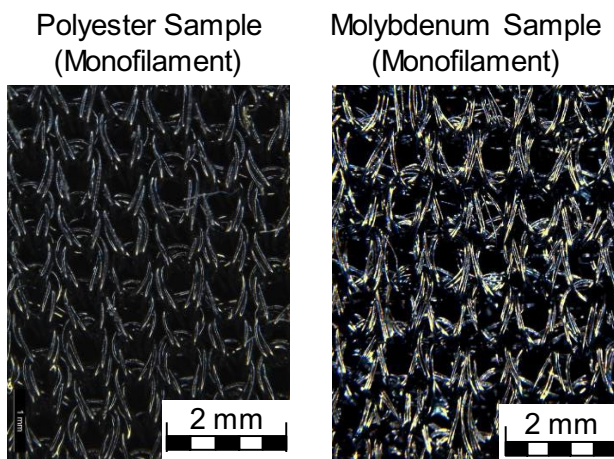


Fig. 17 Optical comparison of a polyester sample (left) and a molybdenum sample (right) with the same pattern

3.6 Conclusion

In conclusion, in the literature, there are many different names for warp-knitted reflector surface patterns. Currently, four different basic patterns are investigated:

- Atlas mesh,
- Tricot lap,
- Cord lap, and,
- Satin lap.

In addition, atlas lap meshes are investigated. The authors assume that these investigations are on a theoretical basis since no photograph of an atlas lap mesh could be found.

Except for [4] and [20], the patterns are not compared in terms of textiles but instead they are compared theoretically. This is due to the focus of the various papers in terms of modelling and the background of the various authors within aerospace. At this time, it is noted that the atlas mesh is the most commonly used pattern for use as a mesh reflector surface. A statement whether the atlas mesh is additionally the best pattern for the application is not yet given at the current state.

Additionally, it can be seen that the same drawings of the different patterns are used by different authors. This creates a repetition of ambiguous naming.

4 Development of an innovative new pattern for warp-knitted mesh reflector

Since the reason for choosing the pattern of the warp-knitted reflector surface is not clear in the literature, the pattern question is approached openly in the development of the novel reflector surface presented in this paper. First, the requirements for a warp-knitted reflector surface are collected from the literature. Then the product development of a new reflector surface proceeds in two phases. In the first phase, a comparatively large patterning experimental space is set up based on the requirements. Testing the entire experimental space with metal yarns would be both too much avoidable wear for the machines used and an irresponsible cost. Instead, the different samples are made with polyester yarns (Fig. 17, left) and then compared with each other in mechanical tests. As the mechanical tests are carried out with warp-knitted polyester fabrics, the results of the tests do not give absolute values about the properties of the respective pattern with a metal yarn. However, the results of the mechanical tests of the polyester knits allow to compare the patterns with each other. If pattern A with polyester has more elongation than pattern B, pattern A will also have more elongation than pattern B with a metal yarn. In the second phase of product development, the three most promising patterns are made from molybdenum yarn (Fig. 17, right) and then also compared mechanically. The mechanical comparison of the second phase of product development is not part of this paper.

4.1 Requirements for warp-knitted mesh reflector

A warp-knitted mesh used as a reflector surface is made of electrically conductive metal yarns arranged to provide an elastic surface, which can be stretched to achieve the required parabolic profile. Most of the requirements for the reflector surface influence the choice of material as well as the warp-knitted pattern. As presented by [4], the material choice is mainly constrained by in-orbit space environment requirements such as temperature application from $-190\text{ }^{\circ}\text{C}$ to $+140\text{ }^{\circ}\text{C}$. For yarn materials, gold-plated molybdenum or gold-plated tungsten is mainly used either in a single or multiple wire configuration [19]. Compiled from [30, 39] the requirements for warp-knitted mesh reflectors are succinctly presented as followed in Table 9.

Of these requirements, requirements (5) to (8) relate to the pattern of the reflector surface. Requirement (5) requires isotropic bending stiffness. This can be achieved by an

Table 9 Requirements for warp-knitted mesh reflectors

Yarn material requirement



Textile / pattern requirement

	Requirement	Comment	
1	stiffness of the mesh has to be minimized	in correspondence to wire diameter and modulus and warp knitted pattern	
2	low coefficient of thermal expansion is required	emerges from the wide thermal variation during the operation	
3	high conductivity of the yarn	to improve RF performance	
5	mesh should have isotropic behaviour	to improve both RF (reflectivity) and mechanical (elasticity) performance.	
6	intermodulation products (PIM) performance of the mesh has to be within the acceptable level.	in corresponding to overlaying threads	
7	size of openings in the mesh has to be reduced and the openings per inch (OPI) has to be increased	to achieve the reflecting of high frequencies	
8	mesh should have good drapability properties	to achieve a parabolic reflector shape.	

isotropic patterning, e.g. mesh pattern or combination of large underlay and fringe laying.

Regarding requirement (6), it is known that with more overlaying threads the PIM will increase² and the production will be more difficult. Nevertheless, a knit with two guide bar (atlas mesh) has already been successfully produced and had good PIM values for low frequencies [4].

Requirement (7) for a high OPI can be solved with a high needle fineness, thick yarn material or a closed lapping. It is important to note, that a net-like mesh pattern made from two counter-operating guide bars with one full one empty draw-in is not addressing requirement (7).

Requirement (8) for good drapability means good elastic elongation behaviour. For this, pillar lapping should not be considered as well as laying-ins and miss-lapping. However, the textile must also be stable enough to hold the parabolic reflector shape.

In addition, as stated in Sect. 2.4 while producing a warp-knitted antenna reflector surface plastic deformation of the wire must be avoided in all processing steps [3]. Permanent deformation of the stitches is undesirable, as such deformation would destroy the functional properties of the reflector.

From a textile engineering point of view, many of the requirements are mutually exclusive. For example, should the mesh be as closed structured as possible (requirement (7)) but the diameter of the yarn should be as thin as possible (requirement (1)). Compared to woven fabrics, the drapability of warp-knitted fabrics to achieve a parabolic reflector shape (requirement (8)) is usually given. On the other hand, the textile has to be stable enough to hold the parabolic form. That is because with a more stable textile less accumulators or cable net structure is required, thus making the reflector lighter. Also the systematic error known as pillow-effect is lower with a stiffer textile [43, 44]. A fabric using more guide bars will be closed structures and have a higher OPI. But with more overlaying threads the PIM will increase and the production will be more difficult.

² L. Datashvili: Expert talk with Leri Datashvili. Eching, 08.03.2019.

Table 10 Design space

No.	Pattern	GB1	GB2
	name		
1	Two bar tricot—closed	1-0/1-2//	1-2/1-0//
2	Two bar cord	1-0/2-3//	2-3/1-0//
3	Two bar satin	1-0/3-4//	3-4/1-0//
4	Two bar velvet	1-0/4-5//	4-5/1-0//
5	Two bar tricot—open	0-1/2-1//	2-1/0-1//
6	Tricot/pillar—open	1-0/1-2/	1-0/0-1//
7	Cord/pillar	1-0/2-3//	1-0/0-1//
8	Satin/pillar	1-0/3-4//	1-0/0-1//
9	Velvet/pillar	1-0/4-5//	1-0/0-1//
10	Tricot/pillar—closed	1-0/1-2//	1-0//
11	Fr1Tr1	0-1/2-1/3-2/1-2//	3-2/1-2/0-1/2-1//
12	Fr1Tr2	0-1/2-1/0-1/2-1/3-2/1-2/3-2/1-2//	3-2/1-2/3-2/1-2/0-1/2-1/0-1/2-1//
13	Fr2Tr2	0-1/2-1/0-1/2-1/2-1/3-2/2-1/3-2/1-2/1-2//	3-2/2-1/3-2/1-2/1-2/0-1/2-1/0-1/2-1/2-1//
14	Fr3Tr1	0-1/2-1/2-1/2-1/3-2/1-2/1-2/1-2//	3-2/1-2/1-2/1-2/0-1/2-1/2-1/2-1//

GB guide bar; pattern is notated for raschel machines, in tricot machines GB1 and GB 2 has to be switched

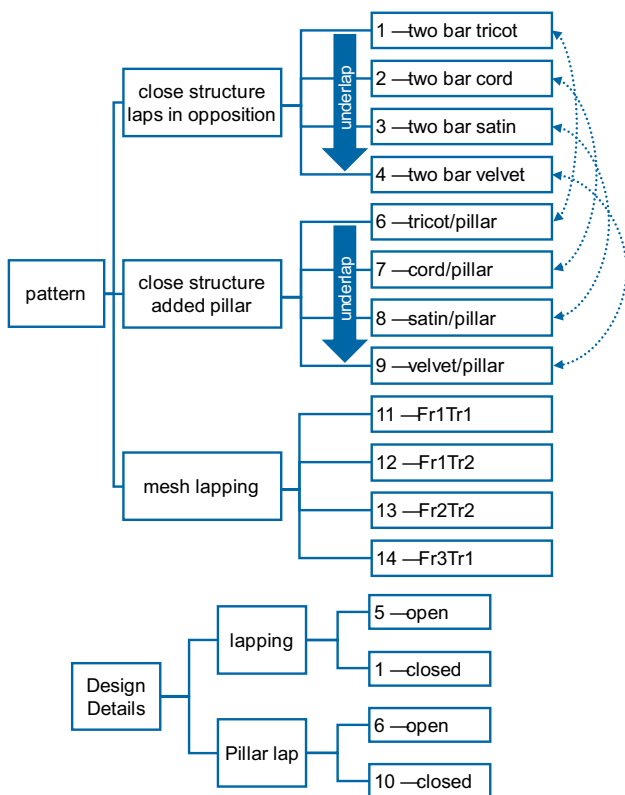


Fig. 18 Explanation of the design space

The main reason for the current desired atlas mesh is historical success and good isotropic behaviour of the mesh (requirement (5)). Since atlas mesh meshes are only partial

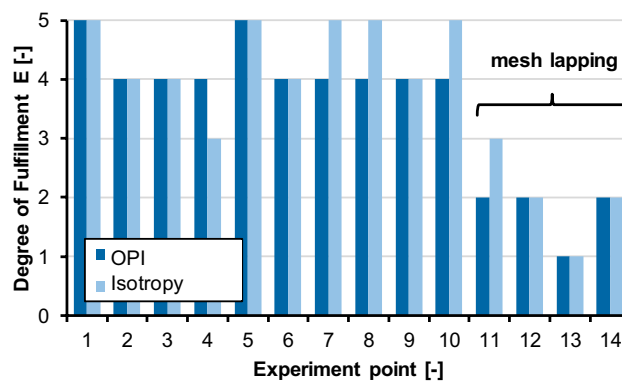


Fig. 19 Results of the OPI measurement

threaded in, the desire of higher frequencies (requirement (7)) is in direct contrast to this mesh construction.

4.2 Design of the experimental space

Based on the pattern requirements, a design space (Table 10) with 14 design points is set up, which reflects the individual requirements to varying degrees. The constraints on the design space are that no mixed patterns are used and no connecting underlap patterns are used. Single guide bar patterns are not considered but only two guide bar patterns with lapping in opposite direction. These sort of pattern have the advantage that the underlap in opposition balance the tension at the needle head and, therefore, the loop head. This results in a more upright formed loop. Also, the opposition underlaps improve the strength of the structure [9]. The design space includes mesh patterns and both open and closed laps.

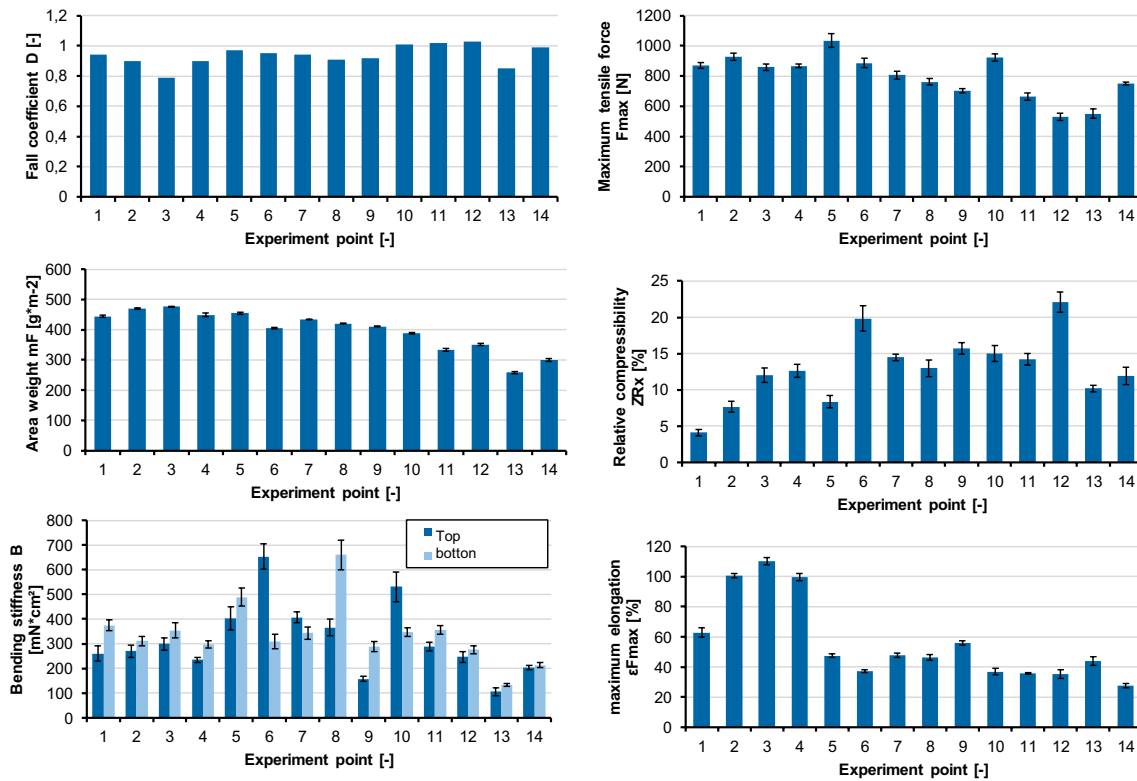
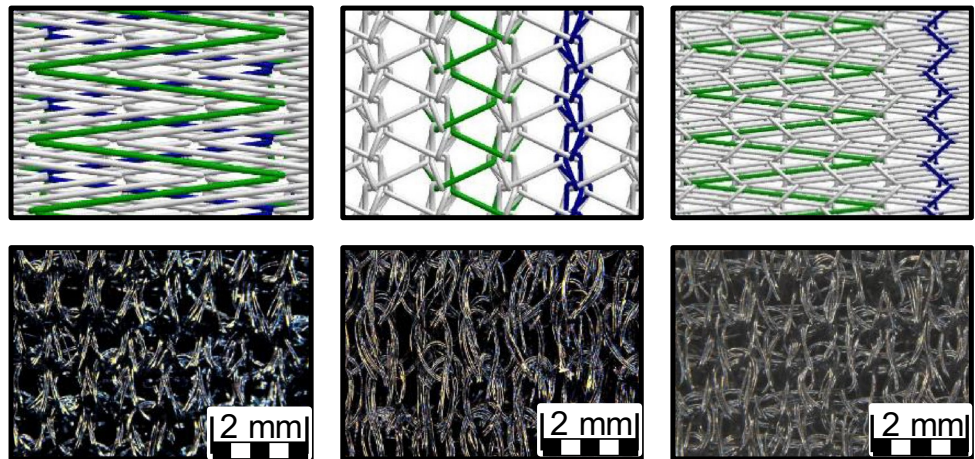


Fig. 20 Results of the evaluation of mechanical isotropy

Fig. 21 Top: CAD image on the three chosen patterns. Bottom: microscopy images of corresponding molybdenum meshes



In addition, the design space includes patterns with high and low underlaps and combinations of patterns with pillar stitch reinforcement.

The structure of the design space is shown as a flowchart in Fig. 18. The aim of this study is to represent the different design options in as small a space as possible and then to draw a recommendation from the sum of the design options.

4.3 Experimental analysis of the different patterns

In the first phase of the product development of a novel reflector surface, the patterns are produced with a polyester yarn as a substitute material and compared in a panel of experts from the textile and antenna community. In addition, to increase the stability of the reflector surface in the

z-direction, the knitted fabric is produced as a warp-knitted spacer fabric (see Sect. 1.3) [5]. Nevertheless, these investigations are also valid for classical two-dimensional mesh reflector surfaces. For the optical evaluation, photographs of the knitted fabrics and the respective CAD files of the knitted fabrics are used. Optically both the OPI and the optical isotropy are evaluated (Fig. 19). The OPI is determined by tensioning the knitted fabric in a specially made tensioning frame under defined and equal force. Microscopy images are then taken of the tensioned knitted fabric. The OPI is based on the analysis of the microscopic images. The results of the OPI measurement clearly show that the OPI is much larger for a closed structure design.

For the evaluation of mechanical isotropy, the following mechanical tests are performed on the fabrics (Fig. 20):

- Bending stiffness.
- Compressibility.
- Drapability.
- Area weight.
- Tensile/elongation behaviour.

The analysis of the mechanical behaviour of the different patterns serves to compare the patterns with each other. Due to the yarn material used, the absolute results of the individual tests cannot be compared with the absolute results of mechanical tests of molybdenum or tungsten knitted samples. From the optical and mechanical investigations, it is clear that a closed lapping of the meshes in the structural bond is preferred (comparing point 1–5). This agrees with the assessment of previous studies.³ For the reinforcing pillar lapping, open pillar laps are chosen based on the bending stiffness properties. Open pillar laps have the additional advantage that the yarn is not additionally twisted and thus less internal stress is created in the yarn. Due to the large pore openings, it is decided not to use mesh lapping such as the atlas mesh (no 11). No preference is found with regard to close structure with laps in opposition or close structures with added pillar. Based on the optical and mechanical values, the design structures 3, 6 and 9 are chosen (Fig. 21, top). Structure 3 is a two bar satin, which has a medium long underlay. The tricot/pillar pattern (open) is test point 6, which supports a small underlay with reinforcement in the production direction. Test point 9 is the velvet/pillar pattern which is also known as Queenscord. The pattern has both a high underlap and thus strengthening against the direction of production, and a high strengthening in the direction of production due to the pillar lap. In the course of the investigation, these three patterns were fabricated with triple-folded molybdenum wire (30 µm diameter) at a reduced

scale (10 cm × 10 cm) (Fig. 21, bottom) and tested. In a next step, the then chosen set-up will be produced for a 0.5 m diameter support structure.

The authors are aware that gold-coated molybdenum or tungsten have better RF and PIM behaviour than bare wires [45]. However, as the present research is the first attempt to produce a warp-knitted spacer fabric with metal yarn on both surfaces and in the pile yarn, as well as the first attempt to produce a reflector surface from a warp-knitted spacer fabric, the current research is at a TRL (Technology Readiness Level) where experiments with gold-coated yarn material are deliberately avoided. In summary, it must first be proven that the basic hypothesis of structure and patterning for a reflector surface is possible. It is recognised that for higher TRL or missions, gold plating of the wire yarn material is necessary.

5 Conclusion

An overview of current warp-knitted reflector surfaces was given. Currently, four different basic patterns are investigated by the antenna community:

- Atlas mesh,
- Tricot lap,
- Cord lap, and.
- Satin lap.

Even though the pattern atlas mesh does not meet today's requirement for high frequencies, it is historically still the most used pattern for reflector antenna surfaces. It is shown, that naming of different patterns is not consistent within the antenna community and it is not always easy to identify the respective pattern. A guideline for consistent nomenclature is given. This review should also help understand why seemingly similar patterns might result in different results during antenna testing.

An overview about the requirements for a mesh reflector surface was given. The requirements were then translated in a textile machinery context. Based on the requirements, a new investigation is started investigating 14 different patterns. The patterns are analysed both optically and mechanically. Based on the results of the analysis three patterns are further investigated and one of the three will be placed on a 0.5 m diameter support structure.

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³ L. Datashvili: Expert talk with Leri Datashvili. Eching, 08.03.2019.

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Declarations

Conflict of interest Authors Bettermann, Löcken, Greb, and Gries declare they have no financial interests. Authors Oses, Pauw, Maghaldadze, and Datashvili have received an additional research support from the Company Large Space Structures GmbH.

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