TOLERANCE ANALYSIS OF S-BAND INFLATABLE ANTENNA ARRAYS

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ABSTRACT

The paper is concentrated on tolerance analysis required to develop antennas made with pressurized structures. Inflatable antennas are desired for many applications emerging in modern mobile, rescue and satellite communications and in some portable radar.

1. A NEED FOR INFLATABLE S-BAND ANTENNAS

The further development of space systems depends on the advancements in the storage methods of large antennas onboard the spacecraft, particularly small ones. In line with this direction of development is the specification for the new antennas needed to help develop the many attractive concepts for communication systems. These requirements can be satisfied with lightweight and easy to transport antennas. Since the mid 90s, advancements in material technology and simulation methods have opened many opportunities for electromagnetic and microwave research in the area of inflatable antennas. Inflatable structures are gaining momentum in other spectacular areas. In July of this year, a breakthrough in the field of inflatable structures composed of dielectric membranes has been made. The capsule Genesis I of Bigelow Aerospace has been successfully launched and placed in a low earth orbit (550 km). During the flight, this 1.2 ton capsule was folded to 4-meter block of approximately 1 meter in diameter. After deployment, the capsule was 4.5 meters long and 2.4 meters in diameter. Its shell is made of Kevlar and Vectran.

Inflatable antennas are to have nominal dimensions upon their deployment; and not only in case of necessity for their usage during rescue operations. Deployable structures resistant to shocks during flight can be made from paper-thin foils consisting of pressurized cells, inflated with air or other gases.

2. FOUR GENERIC CONCEPTS

Our gained experiences thus far allow us to summarize the opinions of the main properties of inflatable antennas (Tab. 1).

Table 1. Views on advantages and disadvantages of classic and inflatable antennas

Parameter	**Classic antenna**	**Inflatable antenna**
Input impedance	*****	****
Side-lobe shape and level	****	***
Polarization properties	****	***
Discrimination of the unwanted polarization	****	***
Feeding losses	***	***
Antenna gain	****	****
Shape of the radiating pattern	****	****
Weight of the antenna	***	*****
Transportation possibility	**	*****
Deployment duration	**	****
Mass production possibility	*****	***
Durability of the structure	*****	***

***** - very good, **** - good, *** - sufficient, ** - insufficient, * - bad

2.1. Generic concepts

Current research on inflatable antennas is concentrated on the utilization of four generic concepts:

(i) reflector and reflectarrays [1], [2],
(ii) flat antenna arrays,
(iii) cylindrical antenna arrays,
(iv) with waveguide structure(s), planar and radial.

Wavelengths corresponding to the S-band seem to be convenient for development antennas with all of these generic concepts. In consequence of using paper-thin dielectric membranes and foils, inflatable structures are incapable of maintaining the geometry limited to planar or other basic surfaces; which is why far going changes are required in the research on inflatable antennas.

Inflatable antennas are capable of being used in other techniques outside of the four aforementioned ones. Over the past decade, we have witnessed a growth in the research on spatial power combining techniques. In order to achieve power combing in space, active planar arrays can be used. However, the inflatable techniques seem also to apply to these kind of feeding methods. A general concept of the antenna array with spatial power combing is illustrated in Fig. 1. Rx patch antennas receive a signal radiated from the source (i.e. horn antenna or monopod), which is then amplified by a microwave low noise amplifier (LNA), and further retransmitted by the Tx patches. Circular profiles are

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easy to build with tough tolerances in the inflatable technique. Combined with spatial power combining, it can be a nice approach to develop an inflatable antenna array.

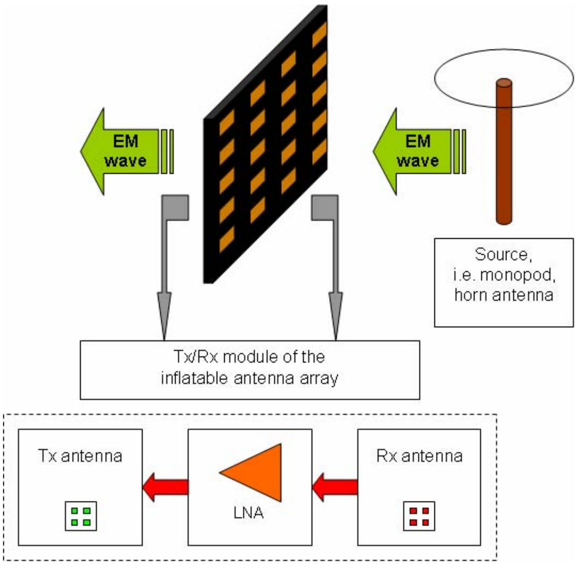

Figure 1. A principle of spatial power combing method, which can be used in inflatable arrays

With inflatable structures, there are presently two related key problems: (i) the development of the structures suitable for manufacturing with metal cladded dielectric foils, and (ii) the mastering of full-wave electromagnetic modeling and simulations of the sophisticated electromagnetic structures. The optimization of the electromagnetic inflated structures with specific deformations of surfaces, the transmission lines, or the waveguides printed on the thin membranes, is becoming the main difficulty in the designing process. Cylindrical inflatable forms are among those, which shape can be accurately achieved in first phases of research, when special engineering techniques are not sufficiently well developed. A cylindrical form of the array has many potential applications and is suited for use with the spatial power combining method (Fig. 2). Then, the central feed waveguide may distribute signals between Tx/Rx modules and the input.

Among the generic concepts, we have used radial line planar antennas in our studies. They can be used in a full range of millimeter-waves and have many in common with reflectarrays. The main advantages of the antennas with wave guiding structures low losses and the broad range of opportunities in beam shaping. A basic structure for an example antenna array is shown in Fig. 3. The feeding network of the array is consisted of a central feeding probe and N coupling probes placed on separate circular rings [3], [4], [5]. The probes are assumed to be identical in rings but can differ between rings. The aperture consists of N identical radiating elements arranged in M circles with radial and circumferential spacing.

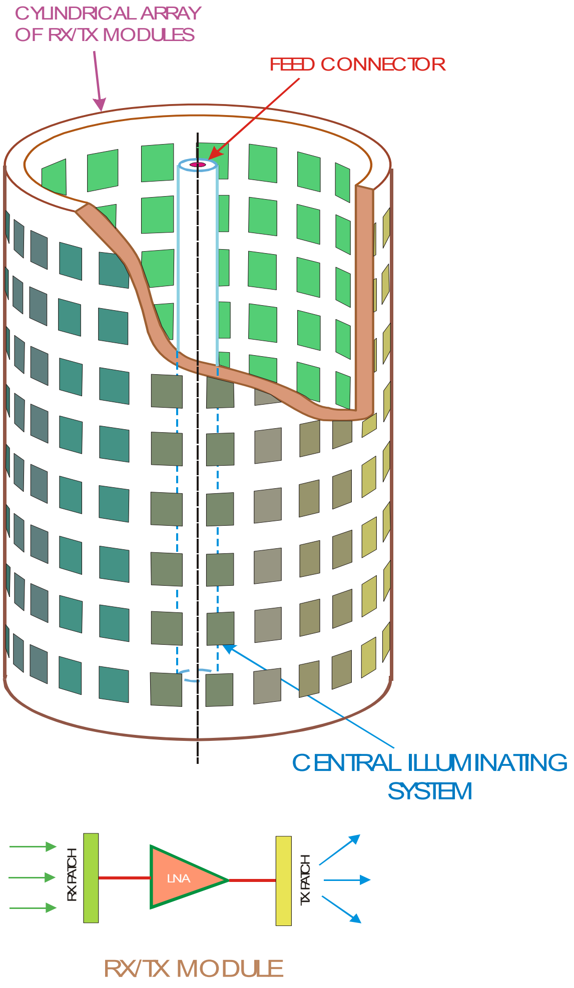

Figure 2. A cylindrical antenna array

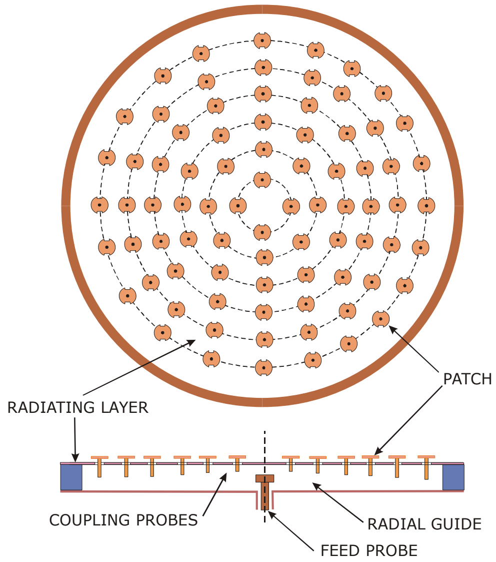

Figure 3. A basic structure of the radial waveguide/line planar antenna array

2.2. Feasibility studies for arrays

In many antenna arrays, transmission lines must be used in feeding. Constraints to the transmission lines made on thin membranes are usually believed to be bottlenecks, which may put all of the antenna concepts in jeopardy. In our studies, we have examined four types of transmission lines (i) microstrip, (ii) suspended microstrip, (iii) centered stripline (sandwich line), (iv) coplanar waveguide (CPW) [6], [7]. All transmission lines have been normalized to a standard impedance of 50 Ω. However, in many cases, lowering the impedance to 40 or less (25 Ω) can improve the performance of the inflatable structures. In our research, we have tested the influence of a number of transmission line parameters such as dielectric foil thickness and permittivity, metallization thickness, port impedance, and gap and line width.

Our analyses have revealed that in the case of simple microstrip lines printed on thin membranes (50 µm and less), obtaining the minimum acceptable width of the transmission line in the S-band have become the main constraint. The range of obtainable widths oscillates between 60 and 360 µm for membranes with a thickness of 20-100 µm (permittivity of the dielectric foil varied between 1.5 and 3.4). In order to improve the parameters, either thicker foil (200 µm and more), or the suspended microstrip line should be applied. Suspension of only 100 µm of the microstrip causes the line widening to about 500-700 µm depending on the dielectric thickness and material permittivity, while for 200 µm, we have achieved approximately 1 mm-wide transmission line. However, in many instances, it becomes indispensable to use more elaborated transmission lines than a simple microstrip.

In further analyses, we have examined the centered striplines and CPW. In the case of striplines, we have to increase the substrate height from the tens to the hundreds of micrometers. As a result, the membrane gets thick and rigid, which puts serious limitations on inflatable structures. However, we believe that bubble foils or honeycomb structures can be adopted to the stripline technique, and may improve the desired line's parameters. CPW does not need thick substrates. We have observed that 25 µm-thick foils are sufficient enough to get the required line widths. The key parameter in the designing of CPW lines process is the gap between the central line and the ground plane. For gaps in the range of 50 to 80 µm, we obtained lines 2 mm-wide that is desired for the manufacturing of paper-thin membranes. The advantage of the CPW line is its ability to permit the use of high permittivity substrates (most of dielectric membranes have permittivity in the range of 2-4).

Another important result has been obtained during the simulations concerning the transmission lines matched to other than the standard 50 Ω impedance. We have analyzed three different impedances: 25, 35 and 40 Ω. As a consequence, there is a possibility to implement standard microstrip lines to inflatable structures. Due to lowering the line impedance, we are able to increase the line width by a factor of 3 from around 200 to approximately 600 µm (for dielectric membranes 50 µm-thick). Similar proportional improvements were achieved for suspended microstrip lines. Finally, we have proposed and designed a novel line concept – rectangular transmission pipeline for use in inflatable structures. A generic concept of this line is depicted in Fig. 4.

The proposed solution is well prepared for the rigidization with gas. Due to the air gap inside the rectangular pipe (ε = 1), we are able to maintain the line width of the manufacturable values, while at the same time, we can use paper-thin dielectric foils. The first analysis has brought line widths in the range of 1-2 mm depending mainly on the air gap height. As far as the air gap height is concerned, we have examined 200 µm to 2 mm-high pipelines. On this basis and from the manufacturing point of view, we think that the reasonable air gap height should be at least 1 mm. Another advantage of this technique is the lower sensitivity to the changes of the main structure geometry parameters.

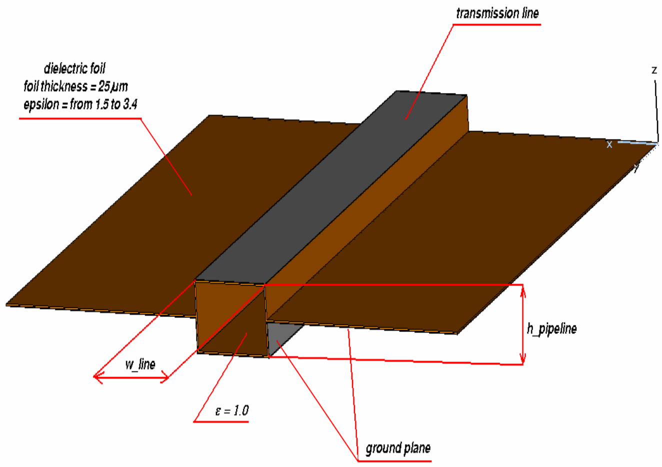

Figure 4. A generic concept of a rectangular transmission made on the walls of a pipeline rigidized with pressurized gas

3. DISTORTION PROBLEMS IN S-BAND INFLATABLE ANTENNA ARRAYS

In the actual structures of inflatable antennas, a major technical constraint is the unavoidable deformations of the pressurized geometry. Other main concerns are the deformations of element surfaces, especially microstrip radiating patches and feeding networks. Due to the adverse effect of such distortions, microwave circuits involving fine details, such as three-strip or multilayer directional couplers should not be considered for use until inflatable techniques gain significant developments. Moreover, coupling slots in the ground plane may also undergo three-dimensional distortion or even offset from the required position. As a consequence, to accomplish the required electrical parameters of such antenna arrays, its concept must be quite immune to geometrical distortions. For the present state-of-the art in inflatable techniques, it seems impossible to compensate most of the deformations, i.e. flattening surfaces distorted by compressed gases. In order to overcome the problems set by geometrical distortions, a detailed analysis has been performed. We have proposed the classification of different deformations and distortions for various antenna elements.

As gas pressure ensures that the inflated structure takes the shape we observe common presence of convex and concave distortions. On the other hand, loss in gas pressure due deployment failures and puncturing are a main cause of concave deformations. Furthermore, we have to deal with the ripples that are a result of the manufacturing inaccuracies and often are remaining of membrane rolling in storage container. Finally, due to platform maneuvers, acceleration forces affect the shape, which may result primarily in bends and twists.

In our research, we have analyzed the distortion problems for the S-band inflatable antenna array of a moderate gain. For the first electromagnetic simulations, we focused on a single inflated circular patch fed with two perpendicular C-shape coupling slots (dual polarized or circularly polarized element).

4. TOLERANCE ANALYSIS

Extensive tolerance analysis is a specific, indispensable feature of the inflatable structure designing process. Prior to the development of models, it is essential to perform systematic and detailed tolerance analysis, assuming not only static shape distortions, but also dynamic fluctuations across large areas. In many instances, it can be presumed that due to forces related to movement or winds, an inflatable structure will undergo moderately fast and dynamic flexures or other deformations observed over large areas. In these circumstances, shapes in rigidized structures are expected to be maintained much better locally than on an overall scale. Fortunately, impedance properties are bounded primarily to local geometries. For this reason, impedance properties should not be so much affected as radiation patterns and gain. Regardless of this observation, the design of inflatable antennas deserves extra efforts for tolerance studies both in terms of impedance and radiating parameters. Due to the ambiguity of what instant geometry the antenna has taken, we apply the Monte Carlo method to investigate the variations of every basic antenna parameter.

4.1. Antenna shape

Needless to mention that each inflatable antenna generic concept has particular strong and weak features when manufacturing inaccuracies are considered. The most vulnerable elements of the arrays are the microstrip radiating patches and their feeding, as their center frequency and bandwidth may vary due to shape deformations. The probe feed can be arranged with flexible strips and this does not affect much of the impedance. Through-aperture coupled feed put strict tolerances onto interlayer offsets. Fortunately, the electrical and physical properties of the substrates are well preserved in a wide range of operational conditions (temperature, humidity). For this reason, our tolerance analysis is focused on geometrical issues. In our research, we applied FDTD and Integral Equations solved by Method of Moments. FDTD is better suited to the electromagnetic modeling of shape deformations. The structures analyzed at the first stage of our research are conical and truncated conical distortions in circular patch elements. Both distortions are illustrated in Fig. 5. As it can be seen, the investigated antennas are fed through a pair of orthogonal slots in a ground.

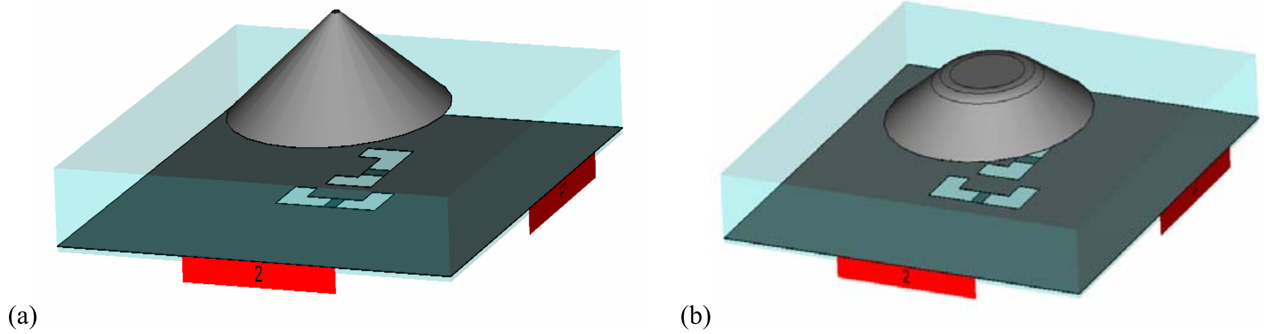

Figure 5. An example of surface deformations of the S-band inflatable antenna element (a) conical and (b) truncated conical deformations

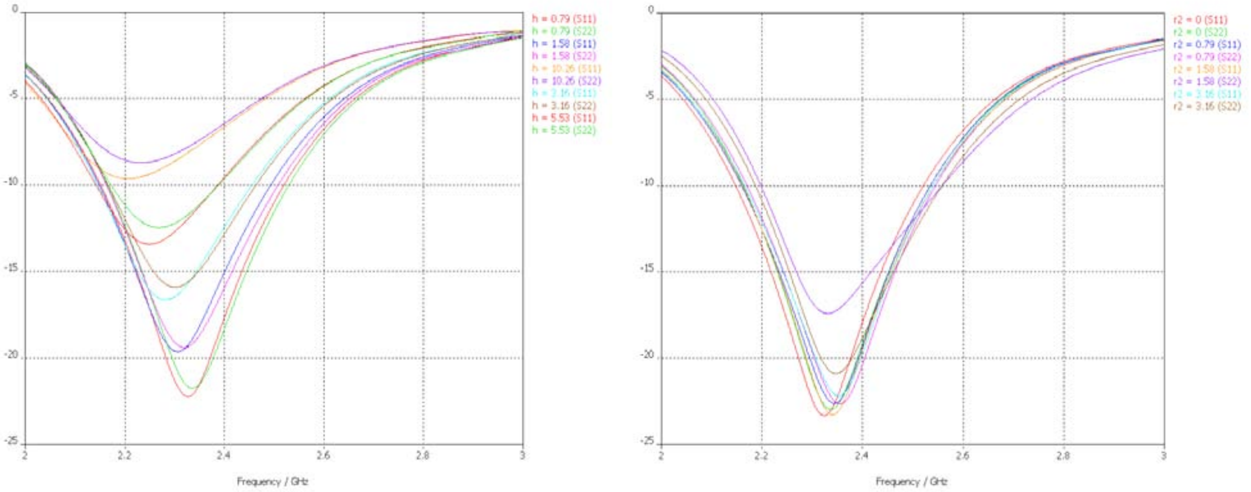

Figure 6. The results of the full-wave electromagnetic simulations of the conical distortion of a single circularly polarized radiating patch. Plots present the influence of the magnitude of the conical distortion (h) and truncated cone diameter (r2)

In the case of conical deformation of the radiating patch, the magnitude of the shape distortion has been parameterized in the tolerance analysis. We have examined how it influences on the return loss of a single S-band inflatable array element. As we can observe in Fig. 6, the return loss of the investigated antenna quickly worsens as the magnitude of the conical distortion increases – from -23 to approximately -10 dB. We may also notice a downward frequency shift. The magnitude of the conical deformation is permitted in reasonable limits for the S-band patch up to 10 mm above the substrate plane.

The second plot in Fig. 6 pertains to the truncated cone shape; truncation diameter was one of the considered parameters. The simulations have been performed for a fixed deformation magnitude (*h*). Contrary to deformation magnitude (*h*), truncation diameter has a minor influence on the antenna return loss for the majority of analyzed cases.

4.2. Transmission lines

Some of the investigated feeding line deformations are explained in the following figures (Figs. 7 and 8). In order to fully understand the effects in antenna patches, the feed lines were analyzed with a wide set of parameter values. A selection of results from the Monte Carlo computations are plotted in Fig. 9 presents the influence of the microstrip line length deviation from its nominal value.

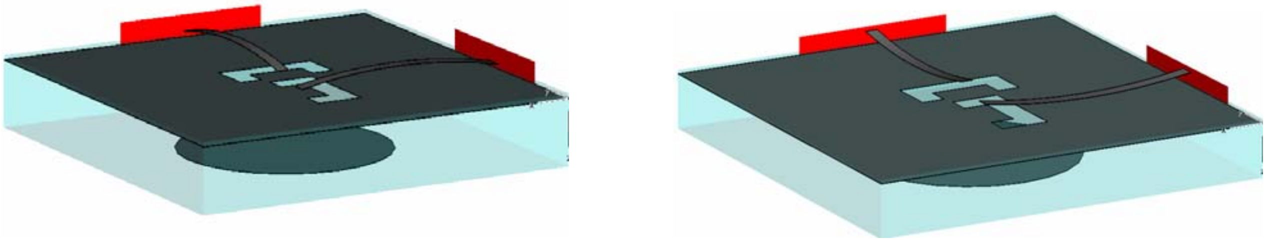

Figure 7. Convex and concave distortions of the microstrip transmission lines

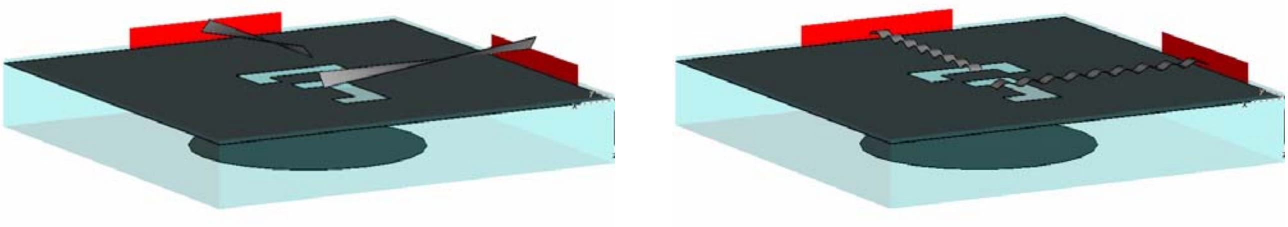

Figure 8. Twists and ripples on the microstrip transmission lines feeding inflatable antenna element

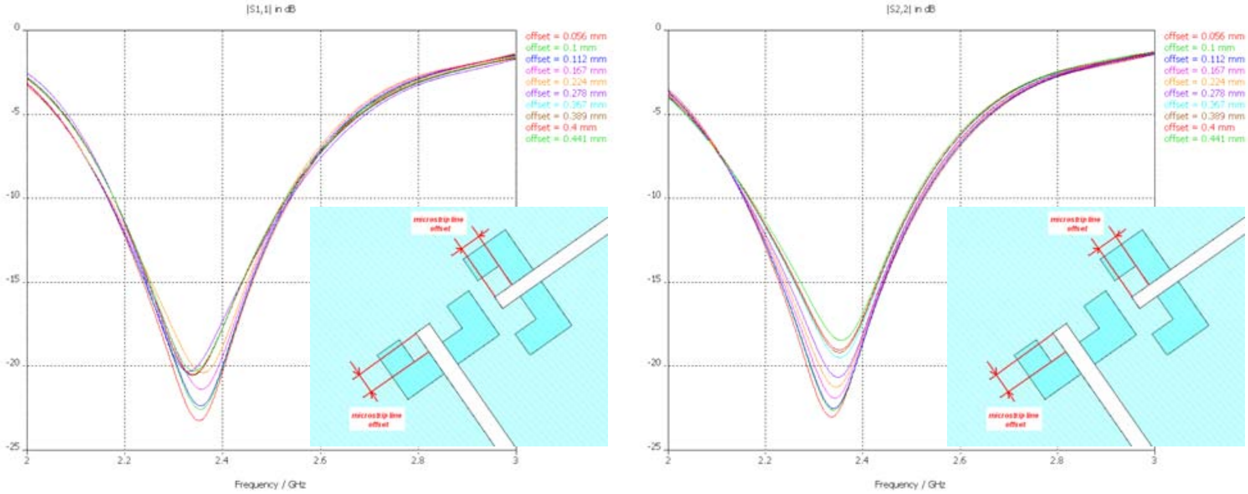

Figure 9. The results of the Monte Carlo tolerance analysis. The influence of the microstrip line elongation from the nominal value

The random deviations of the feed line offset those chosen in the Monte Carlo method, and vary between 0 and 0.5 mm. As shown in Fig. 9, the impact of the examined elongation cannot be neglected. Even a small change in the transmission line length decreases the antenna return loss remarkably. Therefore, full-wave EM simulations of the convex microstrip line deformation have been carried out and the results are given in Fig. 10. The plots reveal that the convex amplitude of 0.5 mm lead to poor impedance properties. Such a value of the convex deformation is quite easy to encounter, unless special engineering efforts are undertaken. The isolation between ports is almost unaffected by the convex distortion of the feed line.

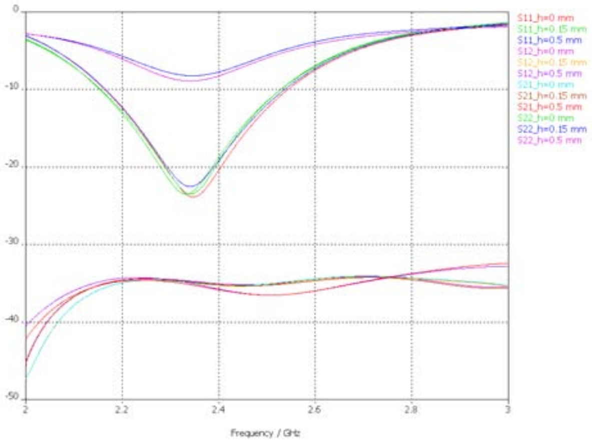

Figure 10. The results of the full-wave electromagnetic simulations of the convex microstrip lines distortion (influence of the line deformation magnitude (h) on the antenna return loss and isolation between ports)

5. CONCLUSIONS

The presented results show that advancements of inflatable antenna uses depend much on availability of modified feed circuits which are capable to operate with a satisfactory properties even though their shape and circuits are reconstructed with significant inaccuracies.

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