Design and Analysis of Microstrip Antenna Arrays for Meteorological Nano-Satellites for UHF Uplink

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***Abstract*—This paper presents the study of microstrip antenna arrays for meteorological nano-satellites that are under development in the frame of UNIESPAÇO programme, which is supported by the Brazilian Space Agency (AEB). The main goal of such satellites is to serve as data relay for transmission of meteorological data collected by stations deployed in remote areas, such as in the rain forest, whereby no wired communication is possible. Arrays composed of linearly and circularly polarized microstrip antennas are investigated. The performance of such arrays is assessed including parameter variations, especially for the case of dielectric constant of the antenna substrate and misalignment in the orientation of the array elements. Such imperfections can occur due to mechanical stress and large temperature variations that are typical to the space environment. The antennas were modeled with the electromagnetic simulator Ansys HFSS. Good results have been observed in terms of the axial ratio, impedance bandwidth and gain for both of the proposed models.**

I. Introduction

The technology of microstrip antennas has been used widely over the last decades and it can be now considered a good choice for several applications, such as wireless communication, mobile radio and aerospace research. Some attractive traits of microstrip technology are compactness, versatility in terms of polarization and input impedance, low aerodinamic profile and light weight [1], [2].

One feature of printed antennas is that the antenna dimensions are dependent on the dielectric constants of the employed microwave laminates. In many cases, miniaturized radiators can be obtained by using substrates with high dielectric constant. However, it is well known that these characteristics have the disadvantage of excitation of surface waves, which can degrade the radiation efficiency of the antenna and deteriorate the shape of the radiation pattern and the polarization. Additionally, another limitation of ordinary microstrip antennas is its narrow band of operation, which tends to be reduced even further if the dielectric constant is increased.

Microstrip antennas have been used already in several nano-satellites. In [3], the design and analysis of an antenna array for telemetry is presented, while [4] discusses on the design of two array composed of triangular patches for a hexagonal nano-satellite. In [5], [6], a method for the construction of microstrip antennas applied to communication systems in the S-band is presented. One interesting approach is described in [7], [8], where the design and analysis of printed quasi-Yagi antennas for WLAN and Wi-Fi applications are shown. The circular polarization is often used in projects as in [9], whereby the design of a microstrip array antennas for spacecraft is discussed. The design of planar microstrip antenna arrays at milimiter-wave frequencies for communication links and detection are presented in [10], [11]. A study of the influence of new nano-composite materials on the performance of antennas is discussed in [12]. In [13], the design of a microstrip antenna with multiple layer substrates is presented.

In this paper, the design of microstrip antenna array for meteorological nano-satellites is presented. Since the nano-satellite should present cubical shape with edges no larger than 20 cm, the main challenge is to design microstrip antennas that are small enough to operate at 401 MHz and still exhibit good performance. The main goal of the proposed nano-satellite is to serve as data relay for transmission of meteorological data collected by stations deployed in remote areas, such as in the rain forest, whereby no wired communication is possible. Section III presents the design of two single patch antennas, one with linear and the other with circular polarization. Section IV shows the results obtained for four 2x2 arrays that are composed of linearly and circularly polarized patches design with two different microwave laminates. The performance of the designed antennas and arrays are assessed by means of numerical simulations. Additionally, since orbiting satellites are subject to large temperature variations, as well as strong mechanical stress during launching, a study of the antenna performance under typical electrical and geometrical imperfections is presented and discussed.

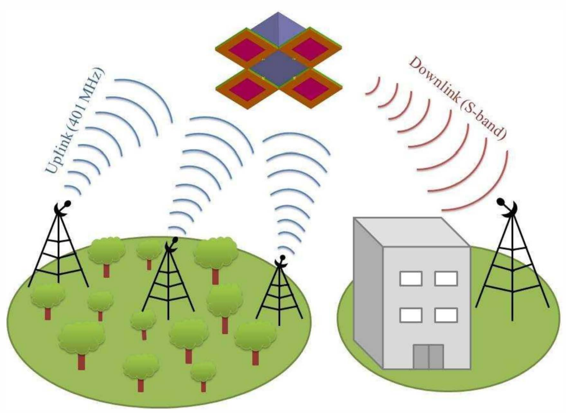

Fig. 1. Transmission system.

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II. Design Specifications

The nano-satellite will operate in a scenario described in Fig. 1. The design specifications given here are focused on the electrical parameters of the receiving chain of the satellite. The uplink signals operate at $f_p = 401$ MHz with right-handed circular polarization (RHCP) and axial ratio lower than 6 dB. Although the uplink data rate of the system is only few kbps, a bandwidth of 5 MHz has been specified for the antennas in order to guarantee correct operation even under moderate variations in the electrical parameters of the employed microwave laminates. Additionally, as previously mentioned, the nano-satellite will have the shape of a cube with edges no larger than 20 cm, which is a small area considering the low frequency of operation.

In order to assess the patch geometry that presents suitable performance, microstrip antennas with linear and circular polarizations have been designed. The antennas that compose the array are installed in the four external lateral faces of the satellite as it is illustrated in Fig. 2. After the satellite is dropped off the launching vehicle, the antennas will be opened out and the array will exhibit the configuration shown in Fig. 3. The gain of the 2x2 array should be larger than 4 dBi.

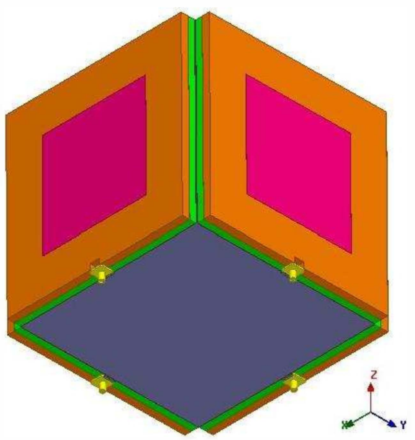

Fig. 2. Microstrip antennas array fully closed.

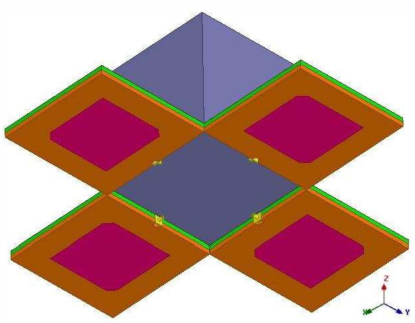

Fig. 3. Microstrip antennas array fully open.

III. Single Antenna Designs

The basic geometry chosen for the design was the square patch fed by electromagnetic coupling. Antennas with this kind of feed are basically formed by two dielectric layers that are used to electrically isolate the patch, the feed line and the ground plane as shown schematically in Fig. 4. Due to the need for space qualification, the dielectric substrate used during the antenna optimization was the Thermoset Microwave Materials (TMM) [14]. In order to obtain the square patch with lateral dimension smaller than 20 cm, antennas on laminates with $\varepsilon_r = 6.0$ (TMM6) and $\varepsilon_r = 9.8$ (TMM10i) have been designed. Two shapes for the patch were considered as described in the following subsections. All the geometries have been modeled in the electromagnetic simulator Ansys HFSS [15].

A. Linearly polarized antenna

To design the linearly polarized (LP) antenna, a simple square patch with side length W and with length of feed line L below the patch has been considered, as it is represented in Fig. 4. This model was designed with both TMM6 and TMM10i materials.

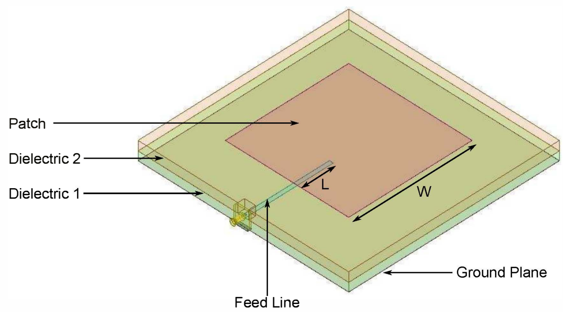

Fig. 4. Dimensions of the antenna with square patch.

After performing the simulations, the following dimensions have been obtained: $W = 14.2075$ cm and $L = 2.47$ cm for TMM6 and $W = 11.1311$ cm and $L = 1.55$ cm for TMM10i. In order to compare the performance obtained with each material, the reflection coefficients were plotted as a function of frequency as shown in Fig. 5. After the analysis of the simulated results, one can see that both antennas present nearly the same performance, whereby the designed with TMM6 exhibits a slightly wider impedance bandwidth. For the single antenna linearly polarized the maximum gain obtained with the TMM6 substrate was 2.74 dBi and the TMM10i substrate was 2.62 dBi.

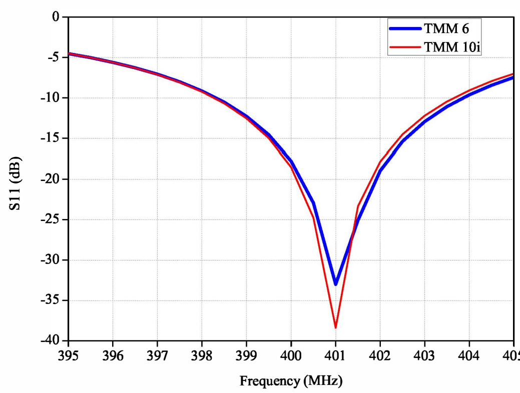

Fig. 5. Reflection coefficient as a function of frequency for single antenna with the square patch for TMM6 and TMM10i substrates, in dB.

B. *Circularly polarized antenna*

The second designed topology was a corners-truncated patch for circular polarization (CP). Similar procedure as for the LP antenna has been used here. In this case, additionally to the dimensions W and L, the other design parameter is the corners truncation represented by A. The geometrical details of the CP patch are exhibited in Fig. 6. After the simulations, the optimized dimensions are $W = 14.51$ cm, $L = 4.0$ cm and $A = 1.4$ cm for the laminate TMM6, and $W = 11.3404$ cm, $L = 3.7229$ cm and $A = 1.0607$ cm for TMM10i. Simulated values for axial ratio (AR) and reflection coefficient for both materials are shown in Figs. 7 and 8, respectively.

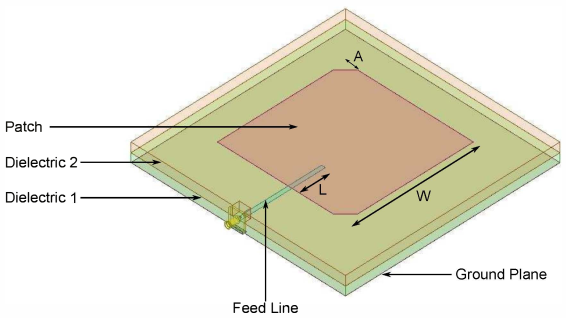

Fig. 6. Dimensions of the antenna with corners-truncated patch.

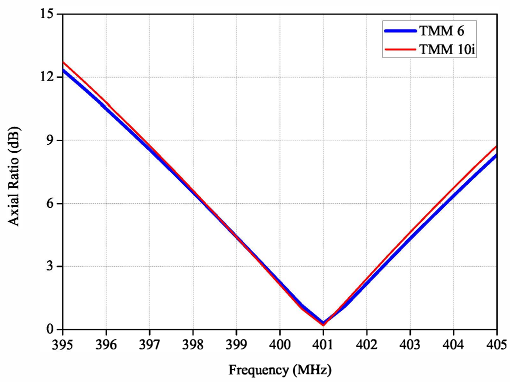

Fig. 7. Axial ratio as a function of frequency for single antenna with the corners-truncated patch for TMM6 and TMM0i substrates, in dB.

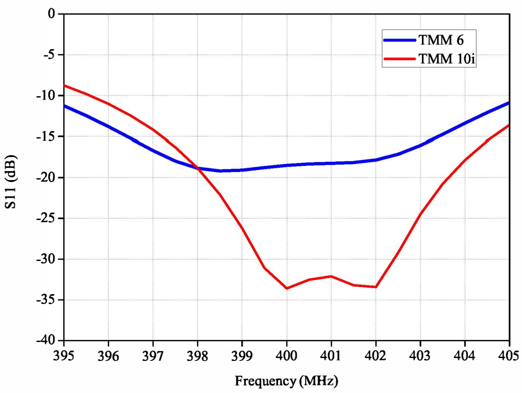

Fig. 8. Reflection coefficient as a function of frequency for single antenna with the corners-truncated patch for TMM6 and TMM10i substrates, in dB.

After the analysis of the simulated results, one can see that both antennas present nearly the same performance. The only advantage of the patch designed with TMM6 is that a slightly wider bandwidth in terms of AR is obtained. For the single antenna circularly polarized the maximum gain obtained with the TMM6 substrate was 2.63 dBi and the TMM10i substrate was 2.57 dBi.

IV. Design of the Antenna Array

A total of 4 single antennas have been designed in and described in section III: two geometries with linear polarization and two with circular polarization. In order to assess which antenna produces the best performance when used to compose the array, a study has been carried out and is described in the following subsections.

A. *Array composed of LP antennas*

Since the uplink operates with RHCP waves, the use of LP antennas demands sequential rotation of the array elements. Additionally to the spatial rotation, circular polarization is obtained by exciting the four antennas with the same amplitude and progressive phase shift of 90 ° [2]. By using this procedure, the resulting radiation patterns are shown in Fig. 9 and 10.

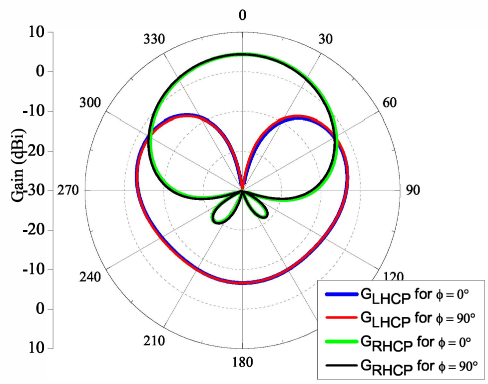

Fig. 9. Gain for antennas array with the square patch for TMM6 substrate, in dBi.

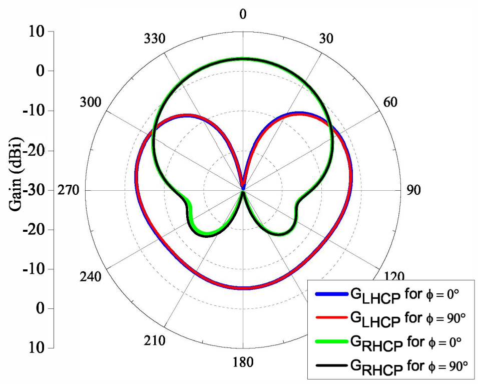

Fig. 10. Gain for antennas array with the square patch for TMM10i substrate, in dBi.

B. Array composed of CP antennas

Although the patches in this case are CP, the 90° progressive phase shift is also needed here. Otherwise, the radiated field will be cancelled out in the boresight. The resulting radiation patterns are shown in Fig. 11 and 12.

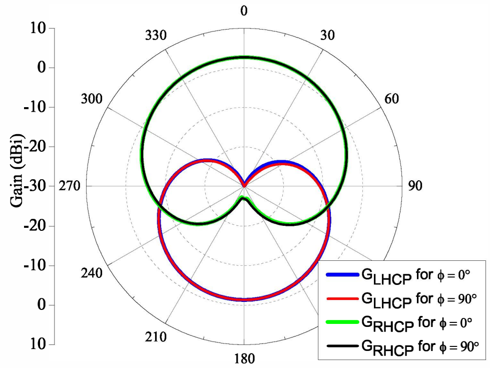

Fig. 11. Gain for antennas array with the corners-truncated patch for TMM6 substrate, in dBi.

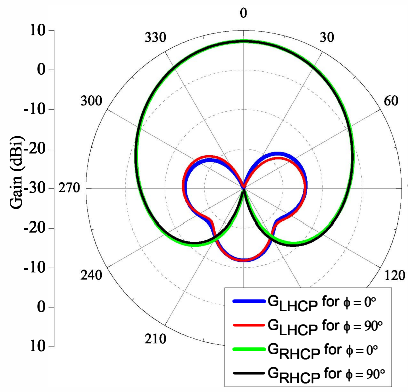

Fig. 12. Gain for antennas array with the corners-truncated patch for TMM10i substrate, in dBi.

After the analysis and comparison of the gain values obtained from the presented results, one can verify that the antenna array with corners-truncated patch designed with TMM10i exhibits the best performance among the analyzed structures, since it results in the larger gain (7.26 dBi) and in the lowest level of cross polarization. Therefore, due to these characteristics, this topology is chosen to be installed onto the nano-satellite.

V. Parametric Study

In order to assess the performance deviation if variations in the dielectric constant and mechanical imperfections of the satellite occur, a parametric study for the geometry chosen in section IV has been carried out. The analysis in terms of dielectric constant is needed, since this parameter may vary with the temperature, which changes strongly in the space environment. The maximum and minimum values analyzed have been taken from the datasheet of TMM10i and were assumed to be $\varepsilon_r = 9.80 \pm 0.25$. The results of the reflection coefficient and gain are shown in Figs. 13, 14 and 15. One can see that the realized gain drops to 5 dBi in the worst case, but this value still fulfills the specification.

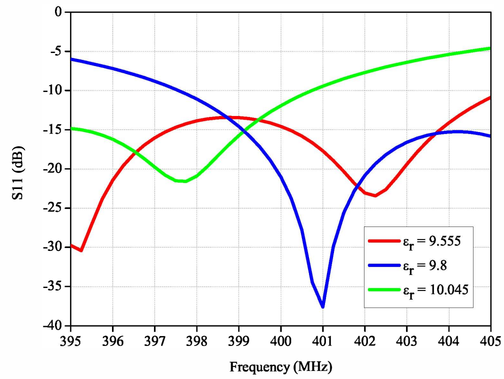

Fig. 13. S11 for antennas array with the corners-truncated patch to range of the dielectric constant of the TMM10i substrate, in dB.

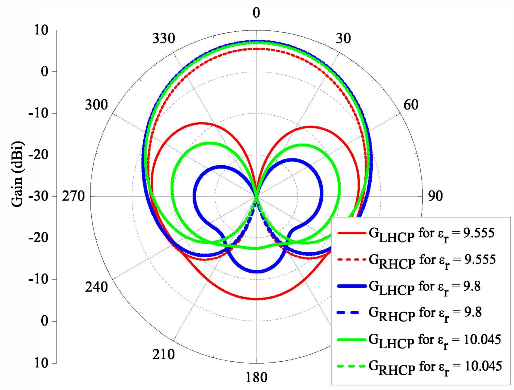

Fig. 14. Gain in $\phi = 0^\circ$ for antennas array with corners-truncated patch to range of the dielectric constant of the TMM10i substrate, in dBi.

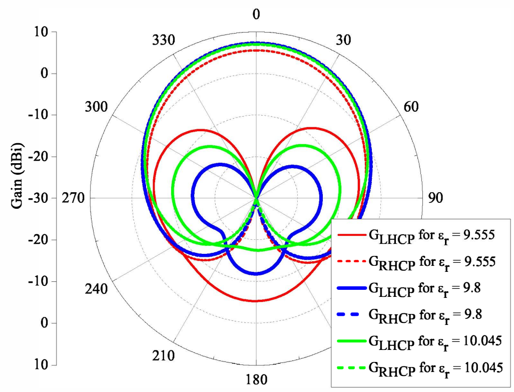

Fig. 15. Gain $\phi = 90^\circ$ for antennas array with corners-truncated patch to range of the dielectric constant of the TMM10i substrate, in dBi.

Finally, simulations were performed for cases of failure during the opening of the antennas. Four cases were tested as illustrated in Fig. 16. The first case stands for the perfect situation, where all the antennas have been perfectly open $\theta_1 = \theta_2 = \theta_3 = \theta_4 = 0°$. The second and the third cases analyzed consider one of the antennas with $\theta_1 = 10°$ and $\theta_1 = 20°$ misalignment, whereas all the other three

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radiators are perfectly positioned. In the fourth case, $\theta_1 = 20\,°$, $\theta_3 = 10\,°$ and $\theta_2 = \theta_4 = 0\,°$. The patterns obtained are plotted in Figs. 17 and 18. One can see that the performance is not strongly deteriorated, since the radiation patterns stay nearly stable with the misalignment values tested.

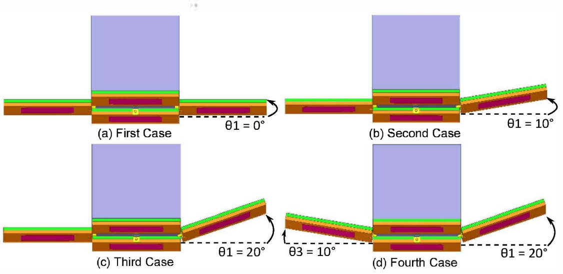

Fig. 16. Four cases of failures in the opening of the antennas.

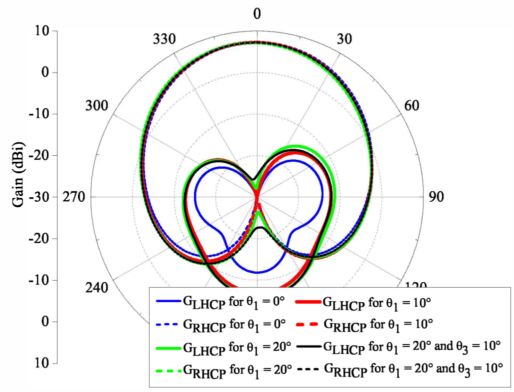

Fig. 17. Gain in $\phi = 0\,°$ for antennas array with the corners-truncated patch to inclinations of the TMM10i substrate, in dBi.

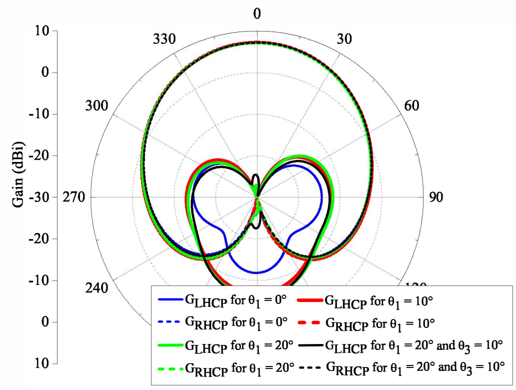

Fig. 18. Gain in $\phi = 90\,°$ for antennas array with the corners-truncated patch to inclinations of the TMM10i substrate, in dBi.

VI. Conclusions

This paper presents the design of a 2x2 microstrip antenna array for a meteorological nano-satellite operating at UHF frequencies. The main design challenge was the development of single microstrip antennas to operate low frequencies whilst keeping the overall antenna size smaller than $20x20$ cm. Simulations showed that good antenna performance could be obtained. Additionally, the designed array exhibits robustness against typical imperfections in the fabrication process and outer space operation, such as variations on the dielectric constant of the dielectric material due to thermal changes and misalignment of the array elements due to mechanical stress during launching.

VII. Acknowledgement

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