C-Band Microstrip Array Antenna for Drone-Based Synthetic Aperture Radar

Felício H. G. Castro; Luciano P. de Oliveira; Valquíria L. B. Castro; Hugo E. Hernández-Figueroa
School of Electrical and Computer Engineering
University of Campinas (UNICAMP)
Campinas, Brazil

***Abstract*—This work presents a microstrip array antenna designed for a synthetic aperture radar to be operated on board a multirotor drone. The array was designed and simulated with a main concern of back-clutter rejection. Lastly, the antenna was manufactured and tested with the radar.**

***Keywords*—antenna; synthetic aperture radar; multirotor drone.**

I. Introduction

Synthetic aperture radar (SAR) imaging has been in use for the past decades in military and civil applications such as reconnaissance, surveillance, target identification, cartography, agriculture, natural disaster assessment and more [1]. SAR systems are usually embedded on satellites and airplanes, but this type of operation is not accessible due to the high costs involved. Recently, small multirotor drones are becoming very popular, specially for aerial photography purposes, but its widespread use and ability to carry small payloads (usually cameras) raised the possibility to use them for SAR imaging [2].

The high density of integrated circuits has made possible for the radar circuit boards to become much smaller and lighter than before and SAR antennas must go in the same direction to enable drones to carry the whole system as its payload. This paper presents a lightweight linearly polarized C-band microstrip array antenna for a synthetic aperture radar to be operated on board a DJI Matrice 600 hexarotor drone.

One of the main concerns in the design of an antenna for a synthetic aperture radar is back-clutter rejection, that is, the ability of the system to differentiate targets in front of the radar (targets of interest) from unwanted targets that are placed in the back. This concept will be explored in the next sections and one of the design goals of the proposed antenna.

The antenna was designed using analytical equations and then simulated and adjusted using the electromagnetic numerical software CST Studio Suite [3]. After the adjustments, the antenna was manufactured, measured and the tests were carried out with the antenna connected to the radar.

II. Antenna Specifications

The desired antenna has a center frequency of 5.45 GHz. At this frequency, which wavelength in free-space λ_0 is 55 mm, a microstrip antenna will have small dimensions and can be easily carried by the drone. The aimed bandwidth ($S_{11} \leq -10\ dB$) is 400 MHz. In radar signal processing the bandwidth is a fundamental parameter because it is used a technique named pulse compression. This technique uses as transmission pulse linearly frequency modulated signals to obtain a fine range resolution. The greater the signal frequency variation, the finer the range resolution that can be accomplished [1]. Although not all the 400 MHz bandwidth will be used by the transmission signal, it is good to have a large bandwidth for center frequency flexibility.

In the azimuth direction (along flight track) the antenna angular 3 dB beamwidth must be around 35°. In satellite and airplane-based SAR systems the azimuth beamwidth is usually smaller, but this is not suitable for a drone-SAR because a lightweight rotary-wing aircraft perform a more unstable flight. Therefore, a larger beamwidth makes the antenna more appropriate to a synthetic aperture radar whose aircraft is more prone to movement error.

The back-clutter rejection is important to a SAR system performance, because it's possible that in some moment the radar is pointed to a region whose targets have reflectivity much lower than the unwanted targets on the back side, in a way that the signal reflected by these interferent targets overcome in amplitude the targets of interest. The operating elevation angular range of a SAR system can be observed in Fig. 1.

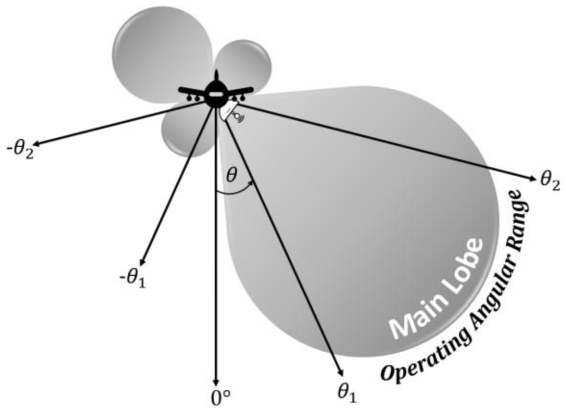


Fig. 1. Operating angular range of a SAR system.

The back-clutter rejection for a specific elevation angle θ can be calculated as a function of the antenna gain (in dB) in the following way:

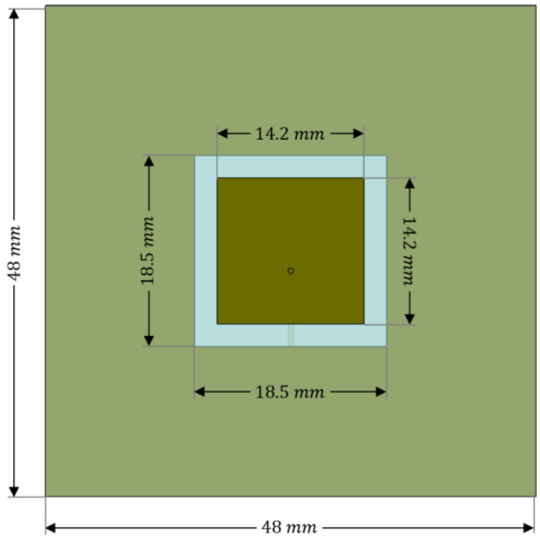
$$Rej(\theta) = G_{dB}(\theta) - G_{dB}(-\theta). \quad (1)$$

To avoid this kind of interference it is desirable for the SAR antenna to have a rejection of at least 20 dB on the operating angular range between θ_1 = 30° e θ_2 = 70°.

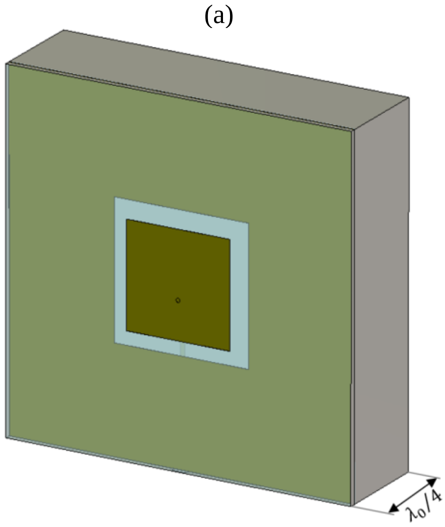
III. Development

The type of antenna chosen for this project was a square microstrip patch due to its linear polarization, lightness, low profile and ease of design and construction. Another advantage of microstrip antennas is the ease of making a coplanar array of antennas and, thereby, controlling the gain and beamwidth.

After choosing the type of antenna, the next step of the development was the making of the theoretical design of a single square patch using analytical formulations provided by [4] and [5]. This resulted in a square patch with a length L = 14.2 mm. A tridimensional model was made in CST for electromagnetic simulation and can be seen in Fig. 2.



(a)



(b)

Fig. 2. Single patch antenna model. (a) Front view. (b) Perspective view.

Note the existence of an 18.5 mm square aperture in the ground plane below the patch. The function of this aperture is to work together with a reflector metallic box to improve the back-clutter rejection by decreasing the back lobes and, therefore, increasing the main lobe gain. The distance from the patch to the box bottom is $\lambda_0/4$ (13.75 mm), so that the waves that leave the patch toward the bottom of the box reflect and travel a total distance of $\lambda_0/2$, when returning at the aperture in the ground plane to add in phase with the waves that are already being radiated to the front.

The single-patch model was fed by a 50 Ω discrete port connected to a 50 Ω microstrip line at the back of the antenna board. The connection between the microstrip line and the patch is made by a cylindrical probe that goes through the board from the feed line to the back of the patch. The connection location among the feed probe and the patch is a impedance matching parameter adjusted at simulation.

The back-clutter rejection of this single-patch antenna, positioned with an inclination of 45° below the horizontal plane, in three frequencies is shown in Fig. 3.

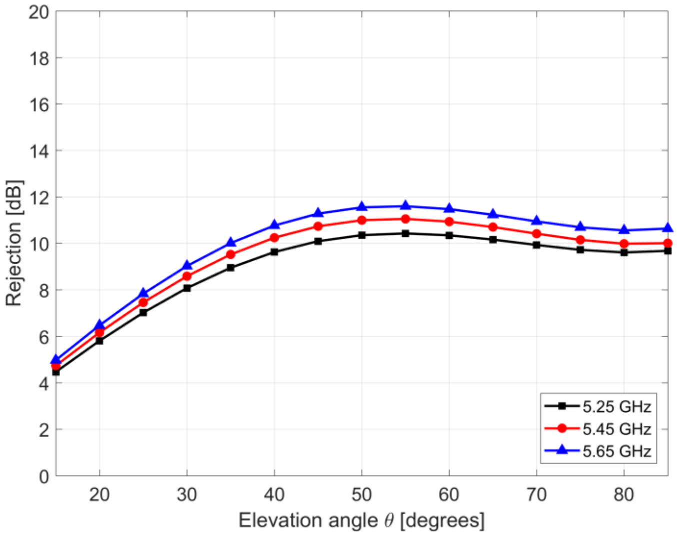


Fig. 3. Back-clutter rejection of the simulated single patch in E-plane.

As we were already expecting, the directivity of a single patch is not enough to have back-clutter rejection of at least 20 dB, but if we combine single antennas to radiate together as a coplanar array the radiation pattern will become more directive. The gain and beamwidth can be controlled by changing the number of patches in the antenna matrix and changing the distance among them. The theory behind antenna arrays can be found in [4] and [6].

Arrays with 2 × 2 antennas were simulated, but the azimuth beamwidth were still larger than desired. The best simulated results were found when using an array with 2 patches in the E-plane direction and 3 patches in the H-plane direction. The final 2 × 3 array dimensions can be seen in Fig. 4. The distance between patches in the E-plane direction is 27.5 mm ($\lambda_0/2$) and the distance between patches in the H-plane direction is 31.5 mm. The length of the antenna array board is 98.9 mm, its width is 63.4 mm, and the reflector box depth remained 13.75 mm ($\lambda_0/4$).

The feeding mechanism is a microstrip line network of quarter-wave transformers [5] in series to match the patches impedances with a 50 Ω source. The feed network at the back of the antenna board can be observed in Fig. 5.

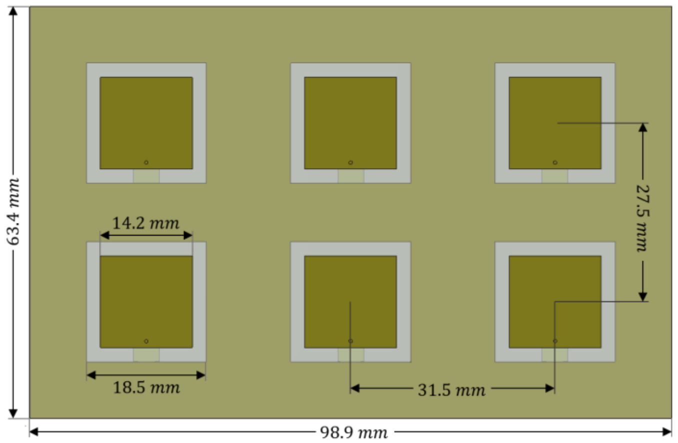


Fig. 4. Designed 2 × 3 microstrip array antenna dimmensions.

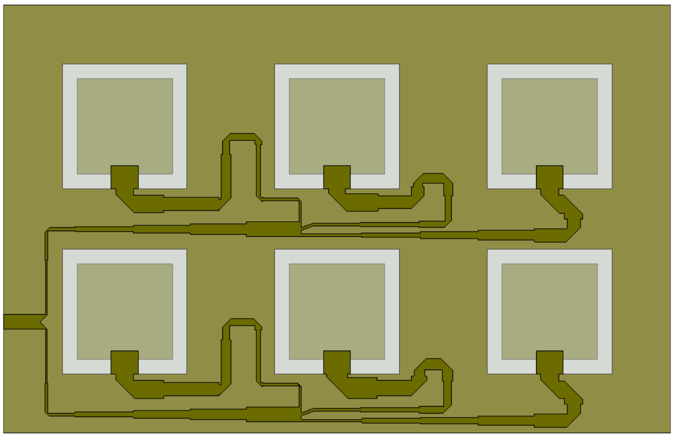


Fig. 5. 2 × 3 microstrip array feeding mechanism.

In Fig. 6 we can see the return loss (S_{11}) of the simulated array.

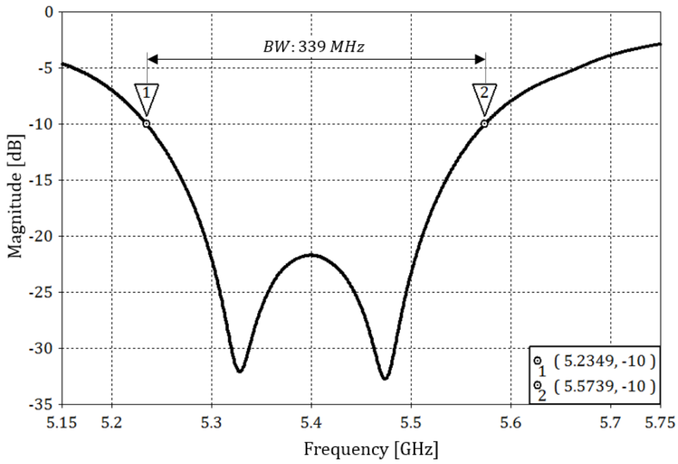
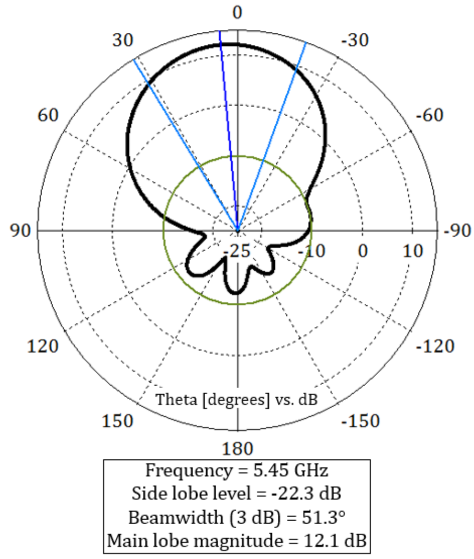


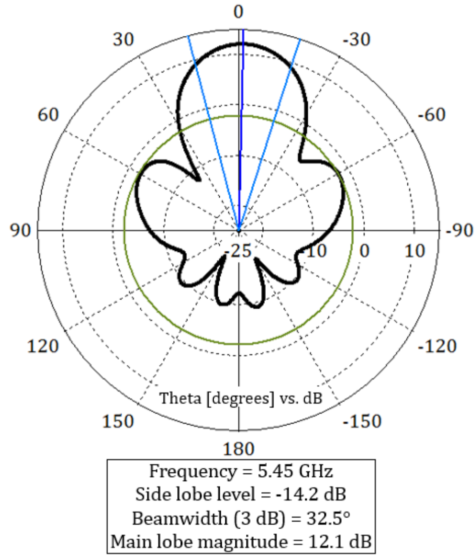
Fig. 6. Return loss (S_{11}) of the simulated 2 × 3 microstrip array antenna.

The bandwidth of the simulated antenna is less than ideal, but it's good enough for a first version of the antenna. Return loss performance is worse at the highest frequencies inside the desired bandwidth.

The simulated antenna radiation pattern in E-plane and H-plane can be observed in Fig. 7. The antenna array has a realized gain of 12.1 dB at 5.45 GHz and an azimuth beamwidth of 32.5°.



(a)



(b)

Fig. 7. Radiation pattern of the simulated 2 × 3 microstrip array antenna. (a) Realized Gain in E-plane. (b) Realized Gain in H-plane.

The back-clutter rejection of this 2 × 3 microstrip array, positioned with an inclination of 45° below the horizontal plane, in three frequencies is shown in Fig. 8 and we can see that this antenna configuration meets the requirement of 20 dB back-clutter rejection.

After the analytical and simulation designs and adjustments, the antenna was manufactured, measured and tested with the radar. The fabricated model and its results are shown in the upcoming section.

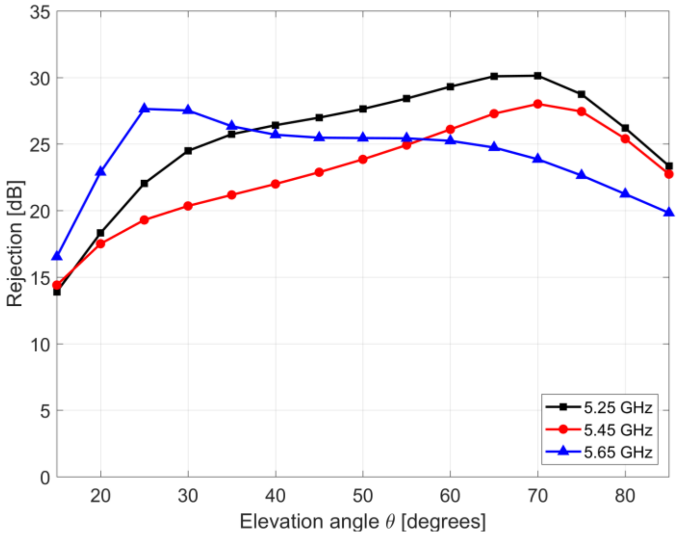


Fig. 8. Back-clutter rejection of of the simulated 2 × 3 microstrip array.

IV. Results

The fabricated 2 × 3 microstrip array can be seen in Fig. 9.

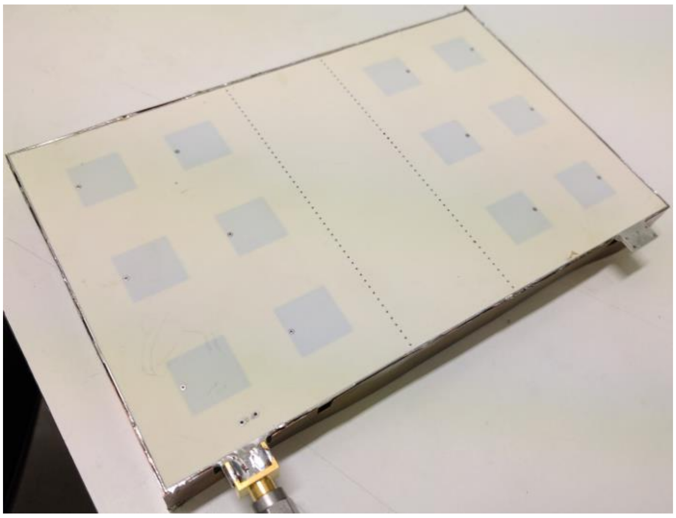


Fig. 9. Two fabricated 2 × 3 microstrip array.

Each manufactured board has two identical antenna arrays, because our SAR system has interferometric capabilities, so the radar transmits with one antenna, but receives with two separated antennas to gather interferometry data.

The antenna was measured with a network analyzer and its return loss can be observed in Fig. 10.

The fabricated antenna has a bandwidth of 414 MHz, but the center frequency is shifted to 5.27 GHz. The reason for this is yet to be investigated and corrected in the antenna's second version. Despite this frequency shift, this antenna is still suitable to be used to test our new radar system that will be used on board the drone.

To test the radar system the antenna was connected to the radar and a corner reflector was used as a target. A corner

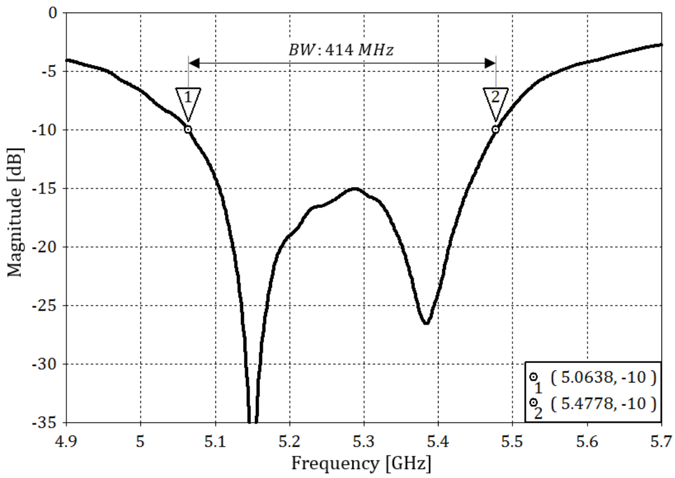


Fig. 10. Return loss (S_{11}) of the manufactured 2 × 3 microstrip array antenna.

reflector was mounted on a vehicle and the car started to move away from the radar with a speed of approximately 6 m/s (as illustrated in Fig. 11), while the radar data was being recorded by the system.

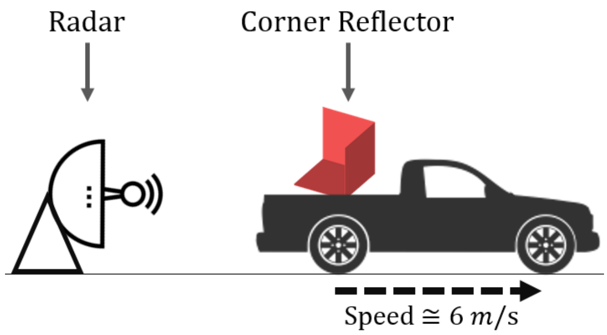


Fig. 11. Radar test illustration.

The recorded data was processed, and a range-doppler image was generated. The corner reflector target be easily found in the image, as we can see in Fig. 12.

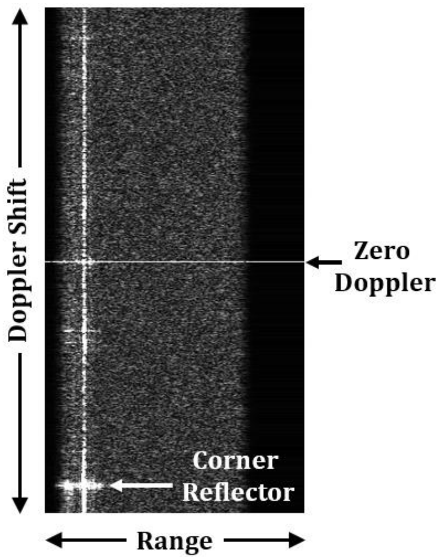


Fig. 12. Range-doppler image from the test.

If we calculate the Doppler shift equivalent speed for the target position, the result is very close to 6 m/s, as we can see by picking the Doppler shift line at the target's range and checking its normalized magnitude in Fig. 13.

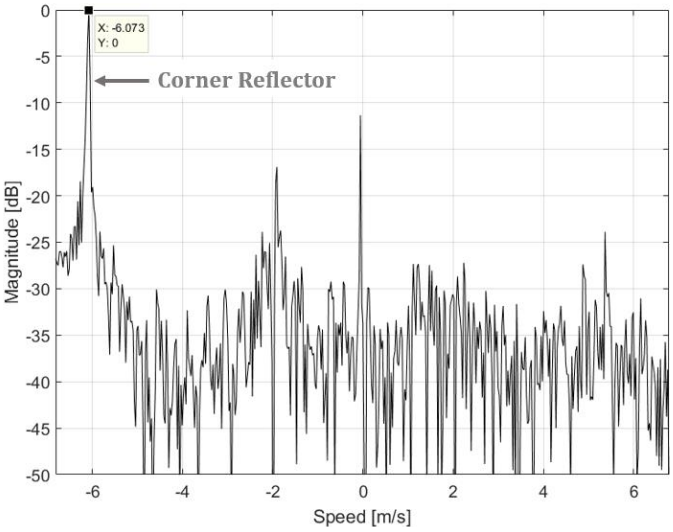


Fig. 13. Target Doppler shift equivalent speed in m/s from the test.

Recently, we started the flight tests with the Drone-SAR system. A picture of the flight test with the radar and two C-band array antennas can be seen in Fig. 14. A few SAR recordings were made, but the data is yet to be processed and the results will only be published in future works.

Fig. 14. Drone-SAR system flyng with the designed antenna.

V. Conclusion

Although the manufactured antenna radiation pattern wasn't measured, the preliminary radar test shown indicates that the antenna is working properly and has a good back-clutter rejection.

We have demonstrated that a microstrip array antenna can be a suitable choice for a drone-based synthetic aperture radar system. An antenna for this system was designed, simulated, manufactured and tested. Upcoming tests will give a better notion on where the antenna can be improved. Future works can use more advanced techniques for secondary-lobe suppression, aiming to suggest another method to achieve a good back-clutter rejection for SAR antennas.

Acknowledgment

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