Journal of Microwaves, Optoelectronics and Electromagnetic Applications, Vol. 21, No. 1, March 2022
DOI: http://dx.doi.org/10.1590/2179-10742022v21i1253618

Radiation Efficiency of an Electrically Small Dual-band UHF Microstrip Patch Antenna Using Wheeler Cap Method

W. G. da Silva[1], A. L. P. S. Campos [1] J. R. F. Guerra [1] I. B. T. da Silva [2]
[1]*Federal University of Rio Grande do Norte, Natal, RN, Brazil, wellington-silva@uol.com.br, alpscampos@gmail.com, juanfguerra@ufrn.edu.br*
[2]*Federal University of the Semi-Arid Region, Mossoro, RN, Brazil, isaac.barros@ufersa.edu.br*

***Abstract*– Determining the radiation efficiency of an antenna is a difficult task that becomes challenging when it is about electrically small antennas. This work investigates the applicability of the Wheeler cap method to measure the radiation efficiency of a UHF dual-band compact microstrip patch antenna. An overview of Wheeler method is presented. An adaptation to the original method is suggested to measure the efficiency of a small slitted microstrip patch antenna operating at two frequencies (400 MHz and 431 MHz). A third-order equivalent RLC circuit has been proposed. The measurements were performed using three metal shields of different sizes and shapes. Measured results agreed with the theoretical model. However, the metallic shield significantly interferes in the fringing fields, reducing the accuracy of the method. Despite the inaccuracy observed in the measurements, the method proved to be attractive due to its low cost and ease of measurement. The contribution of this work is to apply the method to an antenna under test with a high degree of miniaturization, low efficiency, and very narrow band, in addition to using a thick substrate. No previous work with this focus has been found in the literature, up to date.**

Index Terms–Antenna efficiency, dual-band antennas, electrically small antennas, Wheeler cap method.

I. INTRODUCTION

The use of an anechoic chamber is one of the ways to measure radiation efficiency. However, these facilities are expensive and occupy considerable spaces in the laboratories. These disadvantages become more evident in the low UHF band and below that. H. A. Wheeler introduced the first concepts about electrically small antennas (ESA). He has defined the radianlength and the corresponding radiansphere terms. A radiansphere is a hypothetical sphere with a radius of one radianlength ($\lambda/2\pi$), its physical meaning is the boundary between the near field and the far field [1], [2]. Later, in 1959, Wheeler proposed a method to measure the radiation efficiency of small antennas using a metal shield inner to radiansphere surrounding the antenna under test (AUT). This method became known as the Wheeler cap method. The radiation efficiency is calculated by comparing the input impedance of the AUT with and without (measures in free space) the metal shield [3].

In 1975, E. H. Newman et al. have compared two methods to measure radiation efficiency: the Wheeler method, and the Q method. Both methods have been applied to measuring the radiation efficiency of multiturn loop antennas. The authors reported that both methods are suitable and accurate

Brazilian Microwave and Optoelectronics Society-SBMO *received 25 June 2021; for review 6 July 2021; accepted 7 Oct 2021*
Brazilian Society of Electromagnetism-SBMag *ISSN 2179-1074*

for applications in HF and VHF bands. The authors claim found that the size and the geometry of the metal shield were not critical. However, the Wheeler method has some limitations due to the size of the cap in applications in lower frequencies. In addition, the authors found that good electrical contact between the metal shield and the ground plane was important. [4].

Glenn S. Smith has calculated the radiation efficiency of a circular loop using a spherical metal shell. The author studied the influence of the size of the shield and the conductivity of the material. The analysis concluded that the conductivity of the shield has little influence on the measurement. However, electrically small shields can lead to significant measurement errors [5].

Therefore, the authors in [2] suggest that in certain circumstances the Wheeler's original model of a series RLC circuit by itself is not as suitable. Although the results to be quite good. Since then, many authors have proposed modifications to Wheeler's original model.

In 1997, W. E. McKinzie III has proposed to estimate radiation efficiency using the reflection coefficient measures instead of the input impedance. The author presents a method based on the rotation of the reflection coefficient. This technique approximates the input impedance of an antenna with either a series or a parallel RLC circuit model. The results obtained were compared with other methods and presented a good approximation [6].

The ratio between measured Q factors with and without metal shield was used to estimate the radiation efficiency [7]. An analytical function based on the reflection coefficient was proposed to estimate the Q factor. The author considered the effect of feed networks on microstrip antennas. In addition, the impact of the AUT directivity in the determination of the size of the metal shield was analyzed. Measurements on two probe-feed microstrip antennas with circular patches operating at 1.41 GHz and 2.2 GHz were performed.

In [8] the authors reported that the parallel RLC model is a more appropriate model than the series model for a single-resonance, probe-fed microstrip patch antenna on a thin substrate. The work applied the Wheeler method to investigate the efficiency of miniaturized microstrip patch antennas. In addition, the authors reported that a larger metal shield generates interior cavity modes that may interfere with the resonant frequency and to cause a deviation in the input resistance value. A reduction in metal shield height was proposed to decrease the effect of interior cavity modes.

In other work, a modified Wheeler method using a high-order circuit model is proposed to measure the radiation efficiency of patch antennas with multiple resonances. The method was applied to measure the efficiencies of a circularly polarized microstrip patch antenna (frequency range from 880 MHz to 920 MHz) and a triple-band microstrip patch antenna (with resonant peaks at 1.6 GHz, 1.8 GHz, and 2.4 GHz) [9].

Later, in [10], the authors presented a modified Wheeler cap method using a transformer on the equivalent high-order circuit model. The proposed model consists of one series RLC circuit for the input terminal and several series RLC circuits that are connected with the input circuit by mutual coupling. The technique was applied to a circularly polarized microstrip patch antenna and a triple resonance microstrip patch antenna.

As per previous works reviewed, this method is simple, inexpensive, practical, and has excellent accuracy. However, more complex antenna designs require that the method be adapted to the specific properties of each project. The objective of this work is to verify if Wheeler's method is suitable for the case of antennas with a high degree of miniaturization, operating in multiple and very narrow bands.

II. Wheeler cap method

The radiation efficiency is obtained from well know formula as shown in (1), where: η is radiation efficiency; P_{Rad} is radiation power; P_{Loss} is loss power; R_{Rad} is radiation resistance; and R_{Loss} is loss resistance [11].

$$\eta = \frac{P_{Rad}}{P_{Rad} + P_{Loss}} = \frac{R_{Rad}}{R_{Rad} + R_{Loss}} \tag{1}$$

Basically, the determination of the radiation efficiency using the original Wheeler method consists of measuring the antenna input impedance in two situations: with and without the metallic shield. The radiation efficiency is estimated by (2), where, R_{FS} is input resistance at free space operation, and R_{WC} is input resistance using Wheeler cap [3].

$$\eta = \frac{R_{FS} - R_{WC}}{R_{FS}} \tag{2}$$

The Wheeler's theoretical approach assumes that the AUT:

1) behaves like a series RLC circuit;
2) has a single resonance frequency;
3) shows a perfect impedance matching;
4) has null reactance at resonance; and
5) the metal shield does not modify the loss resistance.

However, these considerations are not always true and some authors have proposed adaptations to the original method in order to increase the accuracy of the method. In addition, the original method was developed and verified for wire antennas. Besides, microstrip patch antennas have some specificities and require new adaptations to the method.

David M. Pozar and Barry Kaufman reported that most microstrip patch antennas behave like a parallel RLC circuit. In this case, measurements using the Wheeler method revealed $R_{WC} > R_{FS}$ and the radiation efficiency should be estimated by (3). In addition, the authors reported that the type of feed line can significantly impact the behavior of the input impedance [2].

$$\eta = \frac{R_{WC} - R_{FS}}{R_{WC}} \tag{3}$$

III. Methodology

The authors designed and fabricated a miniaturized slitted microstrip patch antenna to obtain a dual-band antenna operating at 400 MHz and 430 MHz occupying an area as small as 100 mm x 100 mm. This small area must comply with the requirements of the CubeSat standard. The antenna design has been inspired by the design strategies of Huang [12] and Kakoyiannis [13]. The substrate size is 100 mm x 100 mm with a 80 mm x 80 mm patch. The substrate is a 9.8 relative dielectric permittivity (ϵ), 0.002 loss tangent (tan (δ)) and 6.35 mm thickness. Combining a high dielectric constant substrate with slits enabled a high miniaturization degree. Feeding the patch in its diagonal resulted a dual resonance.

Brazilian Microwave and Optoelectronics Society-SBMO received 25 June 2021; for review 6 July 2021; accepted 7 Oct 2021
Brazilian Society of Electromagnetism-SBMag ISSN 2179-1074

The appropriate feeding point was determined for the best S_{11} response at both frequency, using HFSS (High-Frequency Structure Simulator). The final geometry is presented in Fig. 1.

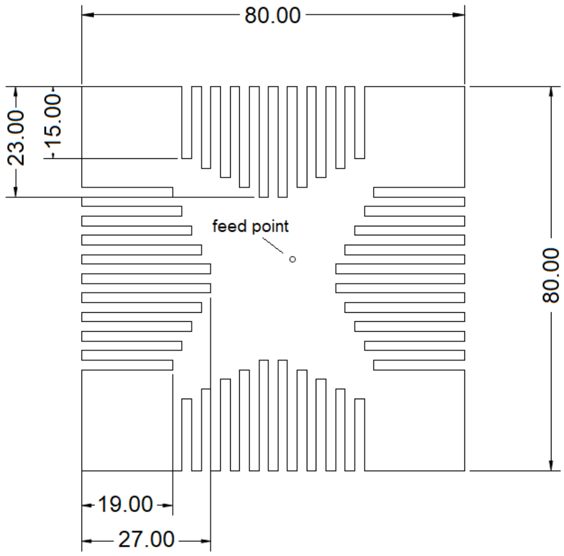

Fig. 1. The final geometry of the proposed microstrip patch antenna, dimensions in mm.

The Fig. 2 shows the prototype of the built antenna, after adjusting the dimensions of the stubs to ensure operation at the desired frequencies.

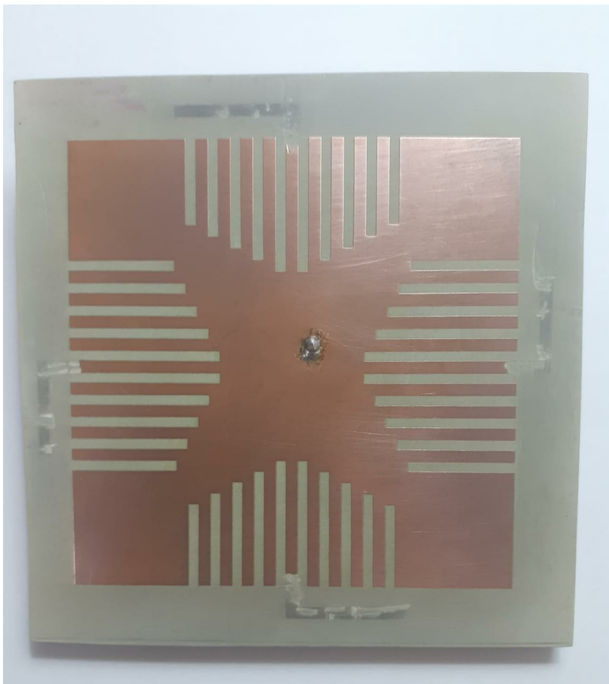

Fig. 2. The prototype of the proposed microstrip patch antenna.

Comparing with Huang [12] and Kakoyiannis [13], in this design, a probe feed was used instead of the microstrip feed, reducing the total area of the antenna. In addition, there are differences between slits dimensions ensuring two operating frequencies.

  ISSN 2179-1074

In order to measure the efficiency of the antenna using the Wheeler cap method, three metallic shields were built in aluminum sheet. The first was a cylindrical shield with a radius of 100 mm and height 150 mm, the second was a rectangular shield with 177 mm x 177 mm x 150 mm, and the third was a cubic shield with 110 mm x 110 mm x 110 mm, see Fig. 3. According to [4], good electrical contact between the shield and the ground plane is important. The shields were fixed to a wooden base coated with an aluminum sheet using screws.

Fig. 3. Rectangular shields.

The high-order equivalent circuit model proposed by [9] was used to measure radiation efficiency. This model is appropriated to microstrip patch antennas with multiple resonances.

IV. Measured Results and Discussions

Fig. 4 illustrates the measurement setup for the cylindrical shield using a Rohde Schwarz Vector Network Analyzer, model ZND (100 kHz - 8.5 GHz), scanning was performed from 390 MHz to 440 MHz.

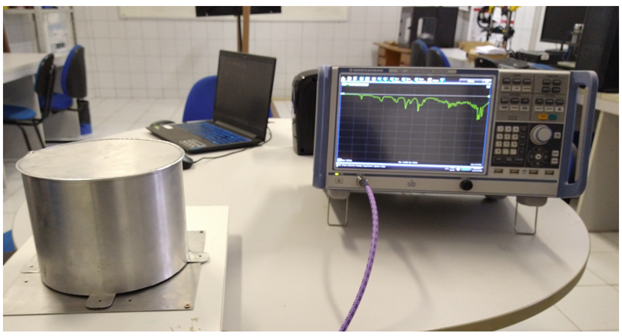

Fig. 4. Antenna under test using VNA and cylindrical shield.

The simulated and measured S_{11} parameter after optimizing process are presented in Fig. 5. The resonance frequency is strongly influenced by the dimensions of the slits. It was also observed that the S_{11} response is very sensitive to the position of the feed point. Thus, variations of millimeter fractions in the length of the slits or at the feeding point have a significant impact on the resonance frequency and S_{11} response, respectively.

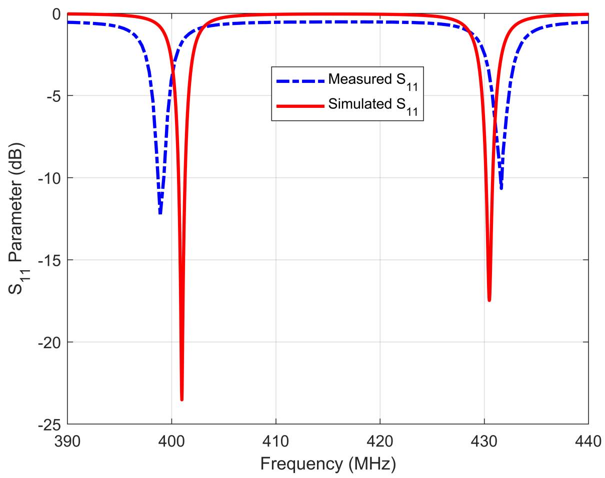

Fig. 5. Simulated and Measured S_{11} parameter after optimizing process.

The measured S_{11} parameter for the four cases: free space, cylindrical shield, larger rectangular shield and smaller rectangular shield are shown in Fig, 6. The cylindrical shield has equivalent dimensions when compared to the larger rectangular shield (same volume). The measurements of these first two cases were extremely close, indicating that the shape of the shield has slight influence. In all cases, it is possible to observe a shift to a higher frequency. In the case of the cylindrical shield and the larger rectangular shield, the observed frequency deviation was 1.55 MHz. In the case of the smaller rectangular shield, the shifting was greater, reaching 2.30 MHz.

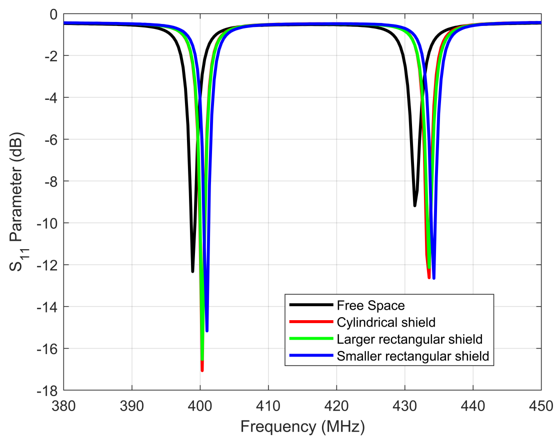

Fig. 6. Measured S_{11} parameter with and without shields.

The deviations observed in the frequencies are attributed to the interference that the metallic shields cause in the fringing field lines, inherent to the radiation process in the microstrips antenna. The shield disrupts the fringing process causing a reduction in the effective length of the microstrip patch antenna and increases the frequency of operation. It should also be noted that as small the shield is, the greater the disturbance is and the greater the shift is. This frequency deviation needs to be compensated for

Brazilian Microwave and Optoelectronics Society-SBMO received 25 June 2021; for review 6 July 2021; accepted 7 Oct 2021

ISSN 2179-1074

when calculating the efficiency. The complex input impedance of the antenna was obtained according to S_{11} parameter, as shown in Fig. 7 and Fig. 8.

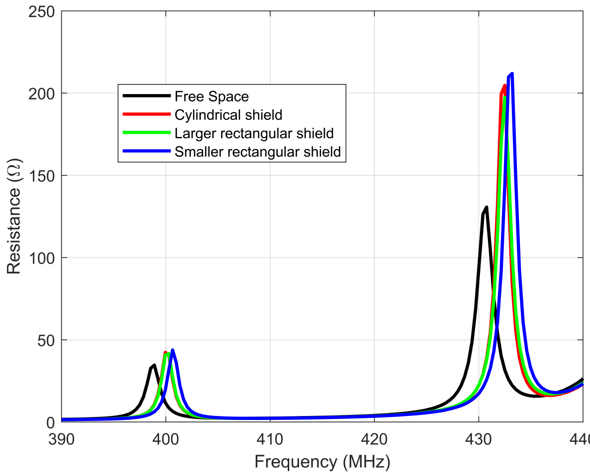

Fig. 7. Measured input resistance for the test antenna for shields with different shapes and sizes.

According to Fig. 7 and Fig. 8, the input impedance increases in the cases using the shield in relation to the free space case. Therefore, the parallel RLC circuit is the one that best represents the behavior of AUT, according to [9].

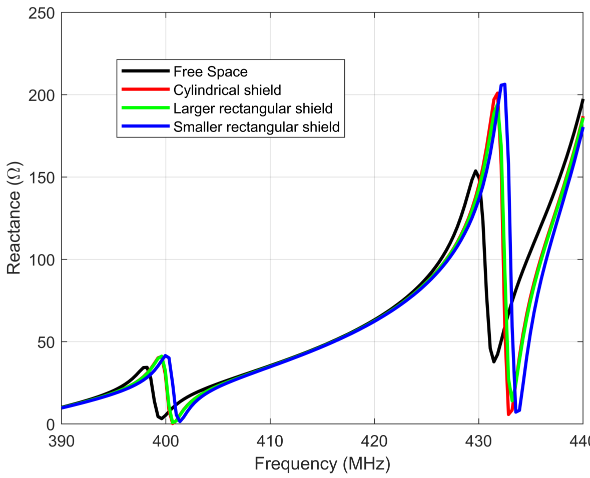

Fig. 8. Measured input reactance for the test antenna for shields with different shapes and sizes.

The lumped element values of the equivalent circuit model must be found, and then the efficiency would be calculated [9]. This approach consider that measured input impedance is influenced by multiple conductances. In this work, the solutions for the lumped element values were obtained by trial and error. Considering that the antenna has two operating frequencies, we initially considered a second order parallel RLC circuit. However, the simulations showed that the best approximation occurs for a third-order equivalent circuit.

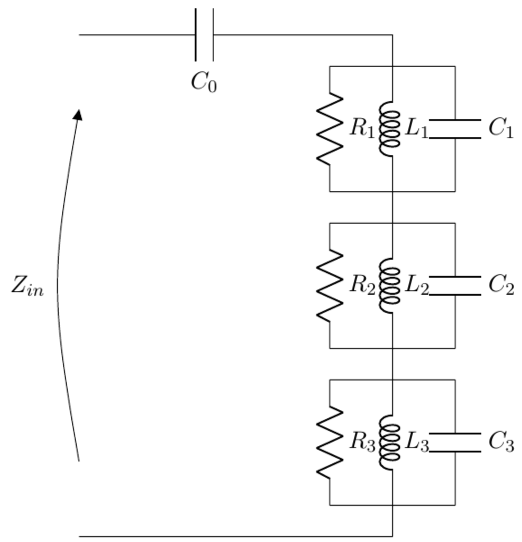

Fig. 9. Proposed equivalent RLC circuit model.

A series capacitor C_0 was added to adjust the reactance of the equivalent circuit, see Fig. 9. The values of the lumped components of the equivalent circuit are shown in Table I.

TABLE I. LUMPED ELEMENT VALUES OF THE EQUIVALENT CIRCUIT MODEL

Lumped Element	**Free Space**	**Cylindrical Shield**	**Larger Rect. Shield**	**Smaller Rec. Shield**
C_0 (pF)	17.50	17.50	17.50	17.50
R_1 (Ω)	34.40	42.36	42.50	42.50
L_1 (pH)	70.20	76.40	86.58	84.25
C_1 (nF)	2.27	2.07	1.83	1.87
R_2 (Ω)	124.50	199.30	198.50	199.00
L_2 (pH)	176.00	21.38	26.61	27.00
C_2 (nF)	775.00	63.33	50.91	50.00
R_3 (Ω)	1889	1889	1889	1889
L_3 (pH)	3.03	3.33	3.01	2.99
C_3 (nF)	41.80	37.82	41.74	41.80

Considering that the antenna behaves like an equivalent parallel RLC circuit, the radiation efficiency was estimated using (2), according to [2]. The results are shown in Fig. 10.

Brazilian Microwave and Optoelectronics Society-SBMO *received 25 June 2021; for review 6 July 2021; accepted 7 Oct 2021*
Brazilian Society of Electromagnetism-SBMag

ISSN 2179-1074

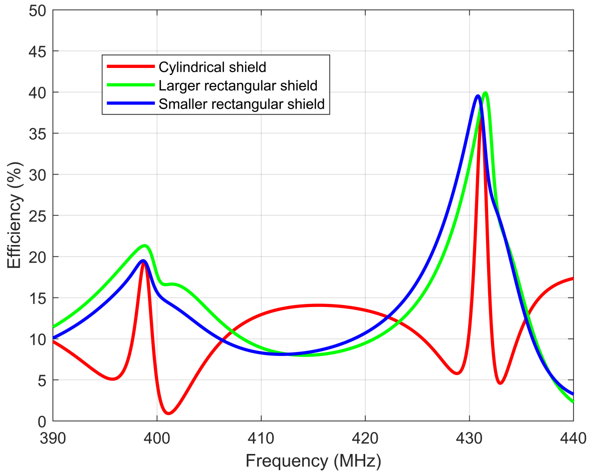

Fig. 10. Calculated efficiencies for the AUT using shields with different shapes and sizes.

The three cases presented an excellent approximation, within the operating band. Outside the operating band, there is divergence between the measurements with the cylindrical shield and the other cases. However, it should be noted that these divergences does not invalidate the method, considering that the efficiency should not be measured out of useful band. The Table II shows the values of the radiation efficiency peaks at the two bands. Using HFSS, the simulated efficiency was calculated from the ratio of simulated gain to simulated directivity. Better efficiency is expected for higher frequencies, this is due to the greater electrical length of the AUT.

TABLE II. RADIATION EFFICIENCY PEAKS

Shield	398-400 MHz	430-432 MHz
Cylindrical	19.33%	36.33%
Larger Rectangular	21.31%	39.87%
Smaller Rectangular	19.33%	39.53%
Free Space (HFSS)	24.33%	31.33%

The results showed mean radiation efficiencies of 19.99% and 38.58% and standard deviations values were 1.14 and 1.95 percentage points for 398-400 MHz and 430-432 MHz bands, respectively.

V. CONCLUSION

In this work, Wheeler's method was applied to measure the radiation efficiency of a dual-band compact microstrip antenna. A third-order equivalent RLC circuit has been proposed. The post-processing of the data was adapted according to the previous approaches. The results showed that the method is valid for this type of antenna. The geometry and size of the shields had a slight influence on the measurements. Shields modify the current distribution in the patch and interferes with the fringing effect, reducing the accuracy of the method and shifting the resonant frequencies.

Within the resonance bands, the method presented coherent results and close to the simulations performed in HFSS. However, the accuracy was lower than those obtained in previous studies. This work differs from previous works by applying the method to an antenna under test with a high degree of miniaturization, low efficiency, and very narrow band, in addition to using a thick substrate. Even with a slight reduction in accuracy, the method is attractive to measure the efficiency of radiation in

Brazilian Microwave and Optoelectronics Society-SBMO *received 25 June 2021; for review 6 July 2021; accepted 7 Oct 2021*
Brazilian Society of Electromagnetism-SBMag *ISSN 2179-1074*

multiband compact microstrip patch antennas with complex geometries, considering the low cost and simplicity of the setup.

REFERENCES

[1] H. A. Wheeler, "Fundamental Limitations of Small Antennas," *Proceedings of the IRE*, vol. 35, no. 12, pp. 1479–1484, 1947.

[2] D. M. Pozar and B. KAUFMAN, "Comparison of three methods for the measurement of printed antenna efficiency," *IEEE Transc. Antennas Propagation*, vol. 36, no. 1, pp. 274–281, January 1988.

[3] H. A. Wheeler, "The Radiansphere Around a Small Antenna," *Proceedings of the IRE*, pp. 1325–1331, August 1959.

[4] E. Newman, P. Bohley, and C. Walter, "Two methods for the measurement of antenna efficiency," *IEEE Transactions on Antennas and Propagation*, vol. 23, no. 4, pp. 457–461, 1975.

[5] G. S. Smith, "An Analysis of the Wheeler Method for Measuring the Radiating Efficiency of Antennas," *IEEE Transc. Antennas Propagation*, vol. 25, no. 4, pp. 552–556, July 1977.

[6] W. E. McKinzie, "A modified wheeler cap method for measuring antenna efficiency," in *IEEE Antennas and Propagation Society International Symposium 1997. Digest*, vol. 1, pp. 542–545, 1997.

[7] Q. Garcıa, "Patch-antenna efficiency based on wheeler cap and measured q factor," *Microwave and Optical Technology Letters*, vol. 40, no. 2, pp. 132–142, 2004.

[8] H. Choo, R. Rogers, and H. Ling, "On the Wheeler Cap Measurement of the Efficiency of Microstrip Antennas," *IEEE Transc. Antennas Propagation*, vol. 53, no. 7, pp. 2328–2332, July 2005.

[9] C. Cho, I. Park, and H. Choo, "A Modified Wheeler Cap Method for Efficiency Measurements of Probe-Fed Patch Antennas With Multiple Resonances," *IEEE Transc. Antennas Propagation*, vol. 58, no. 9, pp. 3074–3078, September 2010.

[10] C. Cho, J.-S. Kang, and H. Choo, "Improved Wheeler Cap Method Based on an Equivalent High-Order Circuit Model," *IEEE Transc. Antennas Propagation*, vol. 62, no. 1, pp. 274–281, January 2014.

[11] C. A. Balanis, *Antenna Theory: Analysis and Design*, 3rd ed. New Jesrsey: John Wiley & Sons, 2005.

[12] J. Huang, "Miniaturized uhf microstrip antenna for a mars mission," in *IEEE Antennas and Propagation Society International Symposium. 2001 Digest. Held in conjunction with: USNC/URSI National Radio Science Meeting (Cat. No.01CH37229)*, vol. 4, pp. 486–489 vol.4, July 2001.

[13] C. Kakoyiannis and P. Constantinou, *Electrically Small Microstrip Antennas Targeting Miniaturized Satellites: the CubeSat Paradigm*. Microstrip Antennas, Prof. Nasimuddin Nasimuddin (Ed.), Vienna, Austria: InTech, 2011, pp. 273–316.