OPEN ACCESS

2nd International
Electronic Conference on
Sensors and Applications
15–30 November 2015

www.mdpi.com/journal/sensors

Conference Proceedings Paper–Sensors and Applications

Experimental Evaluation of Different Algorithms for Permittivity Estimation of Aeronautic Materials Based on Metal-Backed Free-Space Measurements

José David Castaño-Joaqui, David Escot-Bocanegra *, David Poyatos-Martínez and Patricia López-Rodríguez

[1] Detectability and Electronic Warfare Laboratory, National Institute for Aerospace Technology (INTA), Torrejón de Ardoz, 28850 Madrid, Spain; E-mails: castagnojjd.pers_externo@inta.es (D.C.J.); escotbd@inta.es (D.E.B.); poyatosmd@inta.es (D.P.M.); lopezrp@inta.es (P.L.R.)

* Author to whom correspondence should be addressed; E-Mail: escotbd@inta.es;
Tel.: +34-915206357; Fax: +34-915202021.

Published: 5 November 2015

Abstract: Current small unmanned aerial vehicles or target drones used for artillery training are being made of materials other than metallic, such as carbon-fiber or fiberglass composites. From the electromagnetic point of view this fact forces engineers and scientists to assess how these changes may affect the structure in terms of electromagnetic compatibility or radar response. In order to do so, estimations of the constitutive parameters of these new materials has become a need. Several techniques exist to perform this kind of estimations, all of them based on the utilization of different sensors. For this paper, an own implementation of the so-called metal-backed free-space technique, based on the employment of antenna probes, is utilized. Apart from the technique itself, different extraction algorithms can be chosen. In this regard, this paper examines the behavior of several algorithms when applied to extract the complex permittivity from the reflection coefficient of a set of materials. The results are compared with the estimations given by a commercial solution based on another sensor and technique: the open ended coaxial probe. Proper conclusions are extracted regarding the performance of the adopted approach.

Keywords: antenna probes; permittivity; materials characterization; free-space; fiberglass

---

1. Introduction

Current unmanned aerial vehicles (UAV), from the electromagnetic compatibility (EMC) point of view, present particular characteristics and challenges, compared to large aircraft. UAV are mostly made of non-metallic composites unlike typical commercial aircraft which are mainly metallic. Therefore, measurements and properties of commercial aircraft cannot be extrapolated to these platforms. Due to the non-metallic nature of the UAV enclosure, the electronic subsystems are more susceptible to external electromagnetic perturbations and hence, the characterization of the dielectric and magnetic parameters of its materials properties in the frequency range of use is required to achieve the best EMC performance. Along the years, numerous studies have been dedicated to this electromagnetic characterization and the acquired knowledge has been utilized for research and application in many fields such as defense, medicine or engineering [1,2]. Several experimental methods exist to extract the dielectric properties of a material, including: parallel plate capacitor technique, open ended coaxial probe, cavity resonator, transmission line technique and free-space [3–5]. Each method has its own advantages and drawbacks, and the most suitable method for a specific material depends mainly on the specific frequency band, the expected losses, the required accuracy and on the main characteristics and shape of the material. The aim of this paper is to present such characterizations for several samples of fiberglass materials utilized in an actual UAV utilized by INTA, called SCRAB-II. The available sample materials for this research comprise a number of flat sheets of fiberglass with expected low losses, and the frequency range of interest comprises from 8 to 12 GHz. Free-space methods are adequate to characterize flat, parallel-faced samples of materials in a broad frequency range. It is a non-contacting and non-destructive technique and it can be useful to measure materials at high temperatures and hostile environments. INTA owns an anechoic chamber facility suitable for these type of measurements [6]. This facility consists of a dual-axis azimuth turntable and two elevated scanning arms, which establish a bistatic, spherical field scanner. Thanks to its novel design, the antennas on the scanning arms can be situated at any point of an imaginary hemisphere. Therefore, not only this system can measure the reflection parameters at normal incidence but also at given angles, providing capacity to perform improved measurements of material absorption and characterization with the option for bistatic measurements. This paper presents the preliminary results of the characterization of flat sheet materials of the SCRAB-II UAV measured with a free-space technique in a monostatic configuration with the aim of drawing conclusions to extend the methodology for bistatic configuration.

2. Experimental Test Method

2.1. Materials under Test

Material characterization refers to the behaviour of materials under an electromagnetic field. Relative permeability, μ_r, relates to the magnetic field interaction and is equal to unity for non-magnetic materials. On the contrary, every material has a unique set of electrical characteristics that are dependent on its dielectric properties [3]. Note that these can change with frequency, temperature, orientation, mixture, pressure, and molecular structure of the material. Relative permittivity, ϵ_r, describes the interaction of a material with an electric field. It is a complex quantity and is normally expressed relative to the permittivity of free-space ($\epsilon_r = \dfrac{\epsilon}{\epsilon_0} = \epsilon_r' - j\epsilon_r''$). Its real part is a measure of how much energy from an external electric field is stored in a material, while the imaginary part of the permittivity is called the loss factor and is a measure of how dissipative a material is. In this research, for simplicity, we will omit the term "relative" when referring to the complex permittivity relative to ϵ_0.

A set of 2 flat parallel faced samples of fiberglass composite of dimensions 20×20 cm are available. Note that fiberglass is a non-magnetic material ($\mu_r = 1$), therefore, only the complex permittivity is wished to be characterized. Each sample has its own thickness and a different number of composite layers. Additionally, a sample of material with known dieletric properties is also available, Teflon, which will be used as confirmation of results. To further evaluate the validity of the experiment, the samples have been also measured with a commercial kit (DAK from SPEAG [7]) which includes an open-ended coaxial probe (OECP) and a commercial software to estimate ϵ_r. Each material has been measured 12 times with this technique, and from these measurements, after removing the two less representative samples, the mean and standard deviation of their ϵ_r is calculated. Table 1 shows the name of the different samples of fiberglass along with their thickness and the estimated mean complex permittivity obtained with OECP in the measurements frequency range (8-12 GHz).

Table 1. Materials characteristics.

Material	**Thickness (mm)**	ϵ_r' **OECP**	ϵ_r'' **OECP**
SCRAB4	6.3	2.5	0.01
SCRAB9	4	3.25	0.02
TEFLON	10	2.1	0.01

2.2. Metal-Backed Free-Space Methodology

Free-space methods are non-destructive, and they are based on the extraction of the electromagnetic properties of materials from free-space reflection or transmission measurements [8]. Since the materials utilized along this study are non-magnetic, the measurement of the reflected energy is enough to infer ϵ_r. Thus, the reflection coefficients of the aforementioned materials have been measured inside an anechoic chamber at INTA premises. For this test, a monostatic configuration is set, that is, the energy transmission and reception is made by the same antenna. Figure 1 schematically depicts the experimental setup utilized: the material surface is facing the transmitting antenna, while the other face is covered by a metal plate that acts as a short circuit. A Vector Network Analyzer (a four-port Rohde&Schwarz ZVA50) is utilized to extract the S_{11} parameter and with further processing, the reflection coefficient (Γ) of the measured sample is obtained.

Several approaches to infer ϵ_r from a measurement of the reflection coefficient exist. Here, two root-finding and one optimization algorithms have been coded: Newton-Raphson and Müller algorithm (utilized by Ghodgaonkar in [8] and therefore referred here as Müller-Ghodgaonkar), and the Particle Swarm Optimization (PSO) [9]. The starting point of the methodology is the reflection coefficient ($\Gamma_{ref}(\epsilon_r)$) of the materials, measured with the metal-backed free-space technique, their known thickness, d, and the known complex permeability ($\mu_r = 1$) for each frequency. By minimization of a fitness

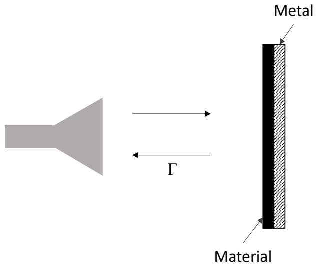


Figure 1. Metal-Backed Free-Space setup

function of the form $f(\epsilon_r) = |\Gamma_{est}(\epsilon_r) - \Gamma_{ref}(\epsilon_r)|$, where $\Gamma_{ref}(\epsilon_r)$ is the measured reflection coefficient and $\Gamma_{est}(\epsilon_r)$ is the estimated one by the algorithms, ϵ_r is estimated with the three aforementioned algorithms given that both reflection coefficients have the form:

$$\Gamma = \frac{\sqrt{\frac{\mu_r}{\epsilon_r}}\tanh(j\frac{2\pi}{\lambda}d\sqrt{\mu_r\epsilon_r}) - 1}{\sqrt{\frac{\mu_r}{\epsilon_r}}\tanh(j\frac{2\pi}{\lambda}d\sqrt{\mu_r\epsilon_r}) + 1} \tag{1}$$

3. Results

First, the method is evaluated with the extracted permittivity of the reference material. The estimated ϵ_r of the 10 mm sheet of Teflon is depicted in Figure 2 for a frequency range from 8 to 12 GHz. Regarding its real part, ϵ_r', there exist good agreement between the theoretic permittivity of Teflon [10] and its estimation from the free-space measurements. As seen, Newton and Müller-Ghodgaonkar algorithm find the same solution for each frequency, while the PSO returns a more fluctuating result. Additionally, the OECP method also returns very good agreement with the theoretic ϵ_r and with the results given by the algorithms. Therefore, at first sight, the metal-backed free-space method along with the extraction of ϵ_r via the proposed algorithms seems to be a proper approach for the problem faced in this study. In the case of the imaginary part, ϵ_r'', Teflon is a low loss material and in this case the results returned by OECP seem more accurate than those provided by Newton and Müller-Ghodgaonkar.

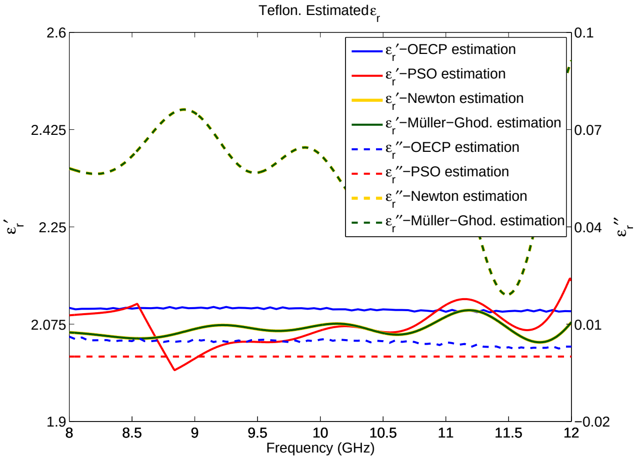
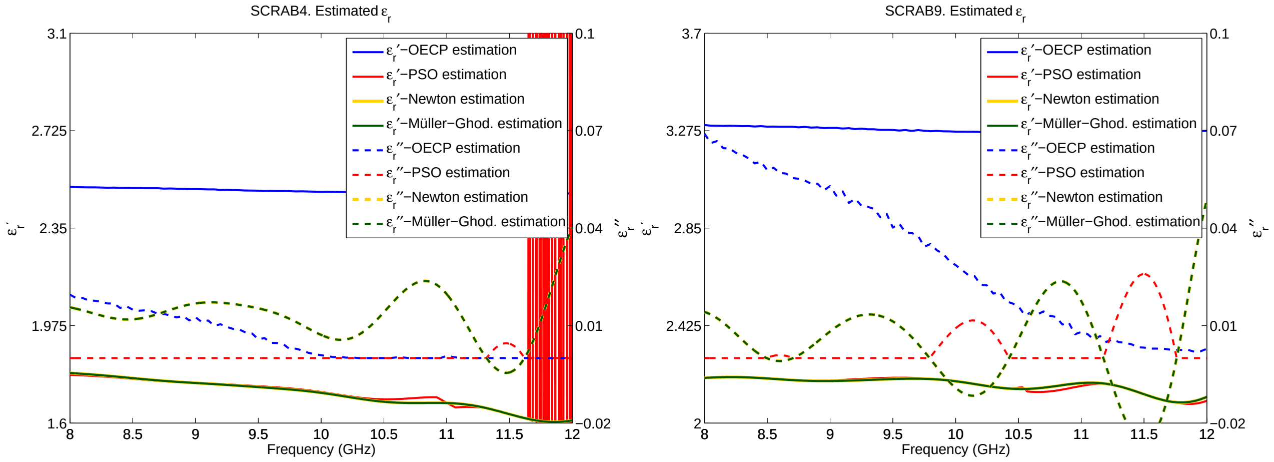


Figure 2. Teflon - Complex permittivity estimation

In Figures 3a and 3b, the extracted ϵ_r of the two sheets of materials are depicted. The extracted ϵ_r' of material SCRAB4 deviates from the one obtained with OECP, however, the three implemented algorithms return the same value for frequencies under 11.5 GHz, where PSO begins to diverge. In the case of ϵ_r'' it is seen that at lower frequencies (<10 GHz), the results given by OECP and the metal-backed free-space with Newton and Müller-Ghodgaonkar methods provide good agreement. At higher frequencies the material seems to get less lossy and the methods are not able to extract this value. The behaviour of material SCRAB9 is quite similar to SCRAB4, the extracted ϵ_r' are quite similar for both methodologies, OECP and metal-backed free-space. Regarding the extraction algorithms utilized with the latter methodology, in this case PSO does not diverge with the increase of frequency. On the other hand, ϵ_r'' has the same behaviour as material SCRAB4 with the frequency, however, here, it seems that Newton and Müller-Ghodgaonkar do not converge from the starting frequency because there is a noticeable fluctuation in the obtained values, especially at frequencies over 10 GHz.



(a) SCRAB4 - Complex permittivity estimation **(b)** SCRAB9 - Complex permittivity estimation

Figure 3. SCRAB-II Materials - Complex permittivity estimation

4. Conclusions

A complete methodology to estimate the complex permittivity of materials utilizing the metal-backed free-space method along with root-finding and optimization algorithms has been provided. To validate the results, the same materials have been measured with an OECP. The agreement between ϵ_r' and the estimated by the metal-backed free-space method is quite good for Newton and Müller-Ghodgaonkar, although the existing little difference may have been caused by possible diffraction effects or by the thickness of the materials. On the other hand, ϵ_r'' does not seem to be accurate in any measurement, either with the OECP or the metal-backed free-space. This is probably due to the fact that we are facing low loss materials and the accuracy of the methods is not enough. Regarding the implemented algorithms, Newton and Müller-Ghodgaonkar present the same converged solution, however to ensure their convergence, starting points near the solution should be provided. On the other hand, PSO is not recommended since as seen, it diverges in some cases and its computation takes longer. Further research is going on in order to deeply analyse the results and to identify the strong and weak points of the methodology. This way, the UAV materials will be accurately characterized and a bistatic scenario could be also studied.

Acknowledgments

This work was funded by the Spanish Ministry of Economy and Competitiveness (MINECO) within the project UAVEMI (TEC2013-48414-C3-2-R).

Conflicts of Interest

The authors declare no conflict of interest.

References

1. Tereshchenko, O.; Buesink, F.; Leferink, F. Measurement of complex permittivity of composite materials using waveguide method. EMC Europe 2011 York. IEEE, 2011, pp. 52–56.
2. Büyüköztürk, O.; Yu, T.Y.; Ortega, J.A. A methodology for determining complex permittivity of construction materials based on transmission-only coherent, wide-bandwidth free-space measurements. *Cement and Concrete Composites* **2006**, *28*, 349 – 359. Non-Destructive Testing.
3. Jilani, M.T.; ur Rehman, M.Z.; Khan, A.M.; Khan, M.T.; Ali, S.M. A Brief Review of Measuring Techniques for Characterization of Dielectric Materials. *International Journal of Information Technology and Electrical Engineering* **2012**, *1*, 1–5.
4. Schultz, J.W. *Focused beam methods. Measuring microwave materials in free space*; CreateSpace Independent Publishing Platform, 2012.
5. Baker-Jarvis, J.; Geyer, R.; Grosvenor, J.H., J.; Janezic, M.; Jones, C.; Riddle, B.; Weil, C.; Krupka, J. Dielectric characterization of low-loss materials a comparison of techniques. *Dielectrics and Electrical Insulation, IEEE Transactions on* **1998**, *5*, 571–577.
6. Escot, D.; Poyatos, D.; Aguilar, J.; Montiel, I.; González, I.; de Adana, F. Indoor 3D Full Polarimetric Bistatic Spherical Facility for Electromagnetic Tests. *Antennas and Propagation Magazine, IEEE* **2010**, *52*, 112–118.
7. http://www.speag.com/products/dak/dielectric-measurements/.
8. Ghodgaonkar, D.; Varadan, V.; Varadan, V.K. A free-space method for measurement of dielectric constants and loss tangents at microwave frequencies. *Instrumentation and Measurement, IEEE Transactions on* **1989**, *38*, 789–793.
9. Robinson, J.; Rahmat-Samii, Y. Particle swarm optimization in electromagnetics. *Antennas and Propagation, IEEE Transactions on* **2004**, *52*, 397–407.
10. von Hippel, A., Ed. *Dielectric Materials and Applications*; Artech House, 1995.