DOI: 10.1478/C1V89S1P038

AAPP | Atti della Accademia Peloritana dei Pericolanti
Classe di Scienze Fisiche, Matematiche e Naturali
ISSN 1825-1242

Vol. 89, Suppl. No. 1, C1V89S1P038 (2011)

SCALED ANALOG MEASUREMENTS OF LIGHT SCATTERING BY AGGREGATES WITH MERGING MONOMERS

J.-M. GEFFRIN,[a*] R. VAILLON,[b*] C. EYRAUD, [a] AND B. LACROIX [b]

ABSTRACT. This work reports on the experimental analysis of light scattering by aggregates with merging monomers. For such complex shape particles, scaled targets can be built using a rapid prototyping technique (stereo lithography). Our microwave scattering device provides the amplitude and phase of elements of the amplitude scattering matrix. Assessment of the approximate codes can thus be carried out on an experimental basis. Sample results for the bi-sphere and a 74 sphere aggregate are presented and discussed.

1. Introduction

Many natural or synthetic particles are irregular in shape and may have complex inhomogeneous interiors. Hence, a lot of efforts are constantly devoted to the setting up of models and computational techniques to simulate light scattering by particles that progressively try to resemble the real ones. Meanwhile, experimental analyses on a single perfectly controlled complex shape particle have suffered from some stagnation, even by applying the principles of the so-called microwave analogy [1]. One of the main limitations was the building of the scaled targets. But the recent advent of prototyping techniques has opened up new possibilities in this field.

For micron-sized aggregates of homogeneous spheres, it is obvious that in reality monomers do not share a single point. There is either some merging between the spheres or some densification of the structure around the joints (sintering) or possibly a combination of these two. As far as simulations of light scattering are concerned, these configurations were recently investigated by means of T-matrix or Volume Integral formulations: the Sh-matrix method for merging spheroids [2, 3] and the Nullfield Method with Discrete Sources [4] or DDSCAT for sintered aggregates [5].

Measurements of light scattering by a single aggregate are possible using microwave scattering facilities. The most known is the University of Florida setup [6] with which a lot of measurements were performed on various aggregates. But until now, the case of aggregates with interconnected spheres could not be analyzed experimentally probably because of difficulties with the building of the scaled targets. With our new microwave scattering device and associated methods [7], it has become possible to deal with targets of increasing shape irregularities such as aggregates with merging monomers. In this paper, we briefly report on special features about the experimental methods and we provide and discuss sample results.

2. Experimental methods: summary and special features

For the sake of brevity, the main features of our microwave analog to light scattering measurement device and associated methods are summarized hereafter. Details can be found in references [7, 8, 9]. The microwave device provides measurements of the amplitude and phase of the total and incident fields (respectively, with and without the studied target), which by careful subtraction [10] yield the scattered field characteristics. By doing so for all polarization combinations, we get the amplitude and the phase of all the elements of the amplitude scattering matrix. As the network analyzer and antennas operate at relatively large wavelengths ([1.5-15] cm corresponding to [2-20] GHz), the analog targets can be large in size (few centimeters). This is quite an asset, but the building of complex shape objects such as aggregates with merging spheres was problematic.
This issue can now be overcome thanks to the use of rapid prototyping techniques. Among several options, stereo lithography was chosen to build aggregates with a partial merging of spheres. The geometry was defined using a computer-aided design (CAD) software which supplies information to the prototyping system with the appropriate file format. A 16 micron layer 3D-printing machine (Objet's EDEN$^{\mathrm{TM}}$350) produced the desired targets by sequential deposit of layers of liquid acrylate resin (here Fullcure®720) which solidifies under UV laser illumination. As an example, Figure 2(a) shows a picture of a 74 sphere fractal aggregate obtained with this technology. The spherical monomers have a diameter d_p of 6 mm and the distance between sphere centers is $0.8\, d_p$ (20% of merging).
If the a priori knowledge of the shape is actually quite satisfactory, the perfect control of all target's characteristics is not achieved yet. First, the material's complex refractive index needs to be determined in the microwave spectral range of interest. To do this, a sphere of 2.5 cm in diameter was produced together with the aggregates (using the same resin). Iterative comparisons of scattering measurements made with the microwave device against Mie theory solutions provided an estimate of the dielectric properties. Here $\varepsilon_r = 2.85+$ i 0.06 was found on the frequency band [16-20] GHz with an estimated uncertainty of 5%. Next, the target has to be precisely positioned within the scattering facility. For this and for each target, an expanded polystyrene support was machined with imprints for the target to be properly set up with respect to reference spheres that only serves for alignment purposes. This support was itself mounted on an expanded polystyrene mast which brings the target at the center of the measurement device. This stage of the overall procedure is crucial as the phase of the total field is measured.
Following these specific and other steps (calibration,drift correction,..), accurate (low noise) measurements of amplitude and phase of fields scattered by aggregates with merging spheres could be accomplished, as shown next.

3. Sample results and analysis

Figures 1 and 2 provide a selection of experimental results for the element S_1 of the amplitude scattering matrix. Simulation data from a Method of Moments (MoM) are given

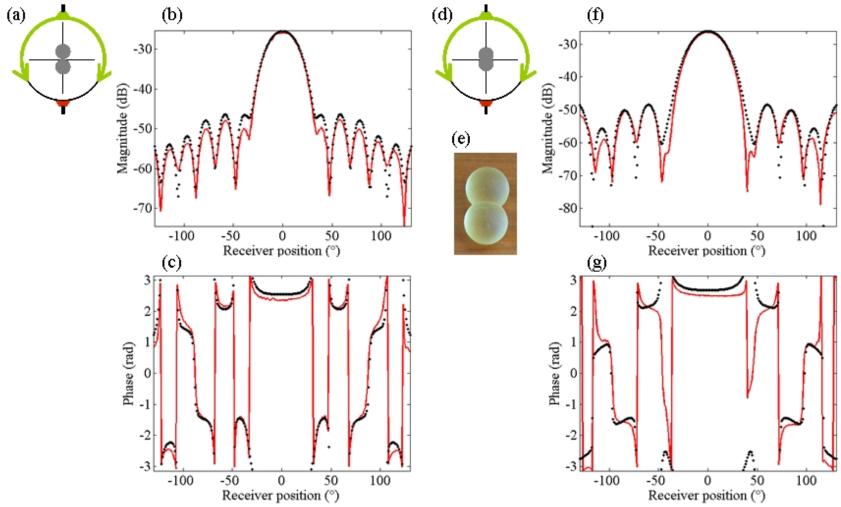

Figure 1. Configuration for measurements on the bi-sphere without merging (a) and with 20% merging (d). Picture of the bi-sphere with merging (e). Measured (red lines) and simulated (black dots) magnitude and phase of element S_1 for the bi-sphere without merging (b,c) and with 20% merging (f,g), at 18 GHz.

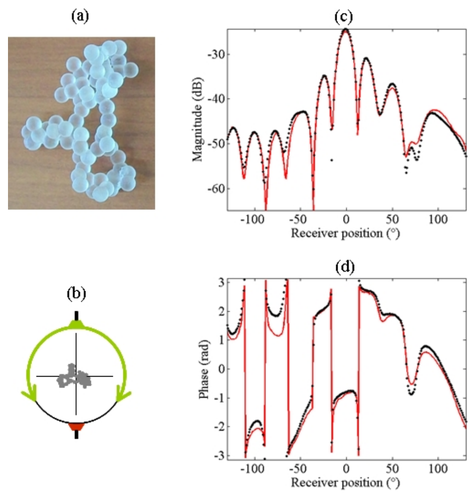

Figure 2. Picture of the 74 sphere aggregate with 20% merging of monomers, built using the stereo lithography (a). Configuration for measurements (b). Measured (red lines) and simulated (black dots) magnitude (c) and phase (d) of element S_1 at 19 GHz.

for comparison purposes. On figure 1, results for the case of two spheres (2.5 cm in diameter) without and with merging (20%) are depicted. Without reading the caption, it is not obvious to guess which are the curves corresponding to the measurements. This demonstrates the high quality of the experimental procedures, as in these cases the smallest magnitude reaches -80 dB, which corresponds to a very weak signal. In any case, the symmetry with respect to the forward scattering direction is nearly perfect. The expected central and secondary lobes are clearly observed but with slight differences between measurements and computations for some of the downward peaks. As for the 74 aggregate with merging spheres, the matching is even more impressive on figure 2 for both the magnitude (c) and the phase (d) of element S_1, for which the symmetry with the $0°$ receiver position is naturally broken. Additional measurements (not shown here) were made on a aggregates with the same characteristics, without merging or with merging but for a smaller monomer radius.

These results are encouraging as they validate the specific parts of the experimental procedures which have been adapted to deal with scaled targets built by stereo lithography. It can then confidently be envisaged to do the same work for the other amplitude scattering matrix elements. In particular, these measurements would open up the possibility to have a non-spherical target at our disposal for the calibration of the cross-polarized elements, which was not achieved to date. We will then complement the analysis to the existing different cases of joints between monomers observed for real aggregates. Afterwards, using the available rapid prototyping techniques, it will be conceivable to make scaled analog measurements of light scattering by other types of particles with even more irregular shapes.

References

[1] B.Å.S. Gustafson, "Scaled analogue experiments in electromagnetic scattering", in *Light scattering reviews 4 - single light scattering and radiative transfer*; A.A. Kokhanovsky Editor; Eds. (Springer, Berlin, 2009); pp. 3-30.

[2] D. Petrov, Y. Shkutarov, and G. Videen, "Analytic light-scattering solution of two merging spheres using Sh-matrices", *Opt. Commun.* **281**, 2411-23 (2008).

[3] D. Petrov, Y. Shkutarov, and G. Videen, "The Sh-matrix method applied to light scattering by two merging spheroids", *J. Quant. Spectrosc. Radiat. Transfer* **111**, 1990-99 (2010).

[4] J. Hellmers, N. Riefler, T. Wriedt, and Y.A. Eremin, "Light scattering simulation for the characterization of sintered silver nanoparticles", *J. Quant. Spectrosc. Radiat. Transfer* **109**, 1363-73 (2008).

[5] T. Wriedt, J. Wilkens, and J. Hellmers, "Differentiating between sintered and non-sintered aggregates", in *Electromagnetic and Light Scattering XII*; Helsinki, Finland, 2010; K. Muinonnen et al., Eds. (Helsinki University Print, Helsinki, 2010), Conference Proceedings; pp. 322-25.

[6] B.Å.S. Gustafson, "Microwave analog to light-scattering measurements", in *Light scattering by nonspherical particles*; M.I. Mishchenko, J.W. Hovenier, and L.D. Travis, Eds. (Academic Press, London, 2000); pp. 367-90.

[7] R. Vaillon, J.-M. Geffrin, C. Eyraud, O. Merchiers, P. Sabouroux, and B. Lacroix, "A new implementation of a microwave analog to light scattering measurement device", *J. Quant. Spectrosc. Radiat. Transfer* **in press**, (2011).

[8] O. Merchiers, C. Eyraud, J.-M. Geffrin, R. Vaillon, B. Stout, P. Sabouroux, and B. Lacroix, "Microwave measurements of the full amplitude scattering matrix of a complex aggregate: a database for the assessment of light scattering codes", *Opt. Express* **18**, 2056-75 (2010).

[9] C. Eyraud, J.-M. Geffrin, P. Sabouroux, P.C. Chaumet, H. Tortel, H. Giovannini, and A. Litman, "Validation of a 3D bistatic microwave scattering measurement setup", *Radio. Sci.* **43**, 4018 (2008).

[10] C. Eyraud, J.-M. Geffrin, A. Litman, P. Sabouroux and H. Giovannini, "Drift correction for scattering measurements", *Appl. Phys. Lett.* **89**, 244104 (2006).

[a] Université Aix-Marseille, Ecole Centrale Marseille, CNRS
Institut Fresnel, UMR6133
Campus de St-Jérôme
Marseille, F-13013, France

[b] Université de Lyon, CNRS, INSA-Lyon, UCBL
CETHIL, UMR5008
20, avenue A. Einstein
Villeurbanne, F-69621, France

* To whom correspondence should be addressed
Email: Jean-Michel.Geffrin@fresnel.fr; rodolphe.vaillon@insa-lyon.fr

Paper presented at the ELS XIII Conference (Taormina, Italy, 2011), held under the APP patronage; published online 15 September 2011.