Analyse expérimentale de la diffusion électromagnétique par des particules complexes via l'analogie micro-ondes

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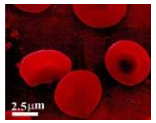
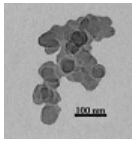
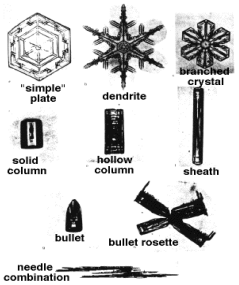
Context and objectives

- **Analysis of light scattering by non-spherical micro-sized particles**
  - interplanetary & interstellar dust
  - biological cells,…
  - ice crystals and aerosols
  - aggregates from incomplete combustion







requires accurate numerical solution of Maxwell equations.

- **Maxwell equation numerical solvers have to be validated**

  in primary variables
  (*amplitude and phase of the electric field*)

  against experimental data.

especially for non-spherical monomers or non-spherical particles

? How to build (sub)-micron-sized (complex shape) particles?

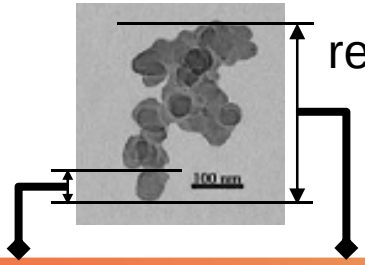
? How to achieve precise control of position and orientation?

! It is not very easy to measure the phase of light waves.

Solution: microwave analogy

Principles

[Greenberg & al., 1961; Gustafson,1996;…]



real soot particle

analog particle

particle size (D)

$\sim 10^{-9}$ $\sim 10^{-6}$ x f ($\sim 10^{4}$) $\sim 10^{-2}$ (m)

wavelength (λ)

light

keep constant
x = πD/λ and electromagnetic properties

micro-waves

Scale Invariance Rule (object embedded in infinite, homogenous, linear, isotropic and non absorbing medium)

Drawbacks are overcome:
better control of the particle and of measurement technique, measurement of amplitude and phase of scattered electric fields

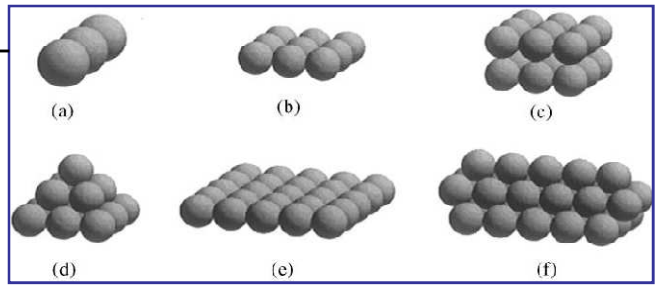
Microwave analog to light scattering measurements: a brief history

- **Principles, bibliography, state-of-the art, measurements by Bo A.S. Gustafson in Chap. 13 of**

  [Mishchenko, Hovenier & Travis, Academic Press, 2000]

- **The facility at the University of Florida: main features**
  - spectral range : **[75 - 110] GHz ; [2.7 - 4] mm**
  - 2D measurements
  - lot of measurement data (mainly intensities)
  - publications and data (1996-1999-2005)

  ex: [Xu & Gustafson, JQSRT, 2001] – for aggregates

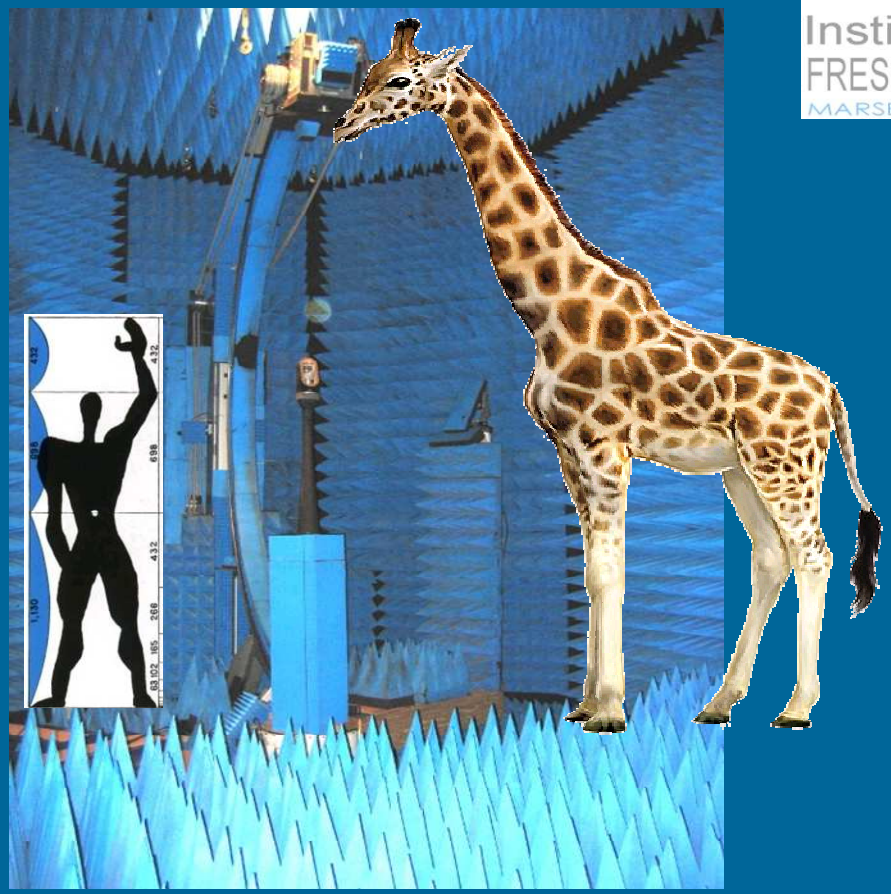


- **Still improvements might be envisaged:**
  - wavelength range (then increase of targets' size)
  - choice of incident and observation angles (''3D measurements'')
  - measurements of the full amplitude scattering matrix (amplitude and phase) for nonspherical particles

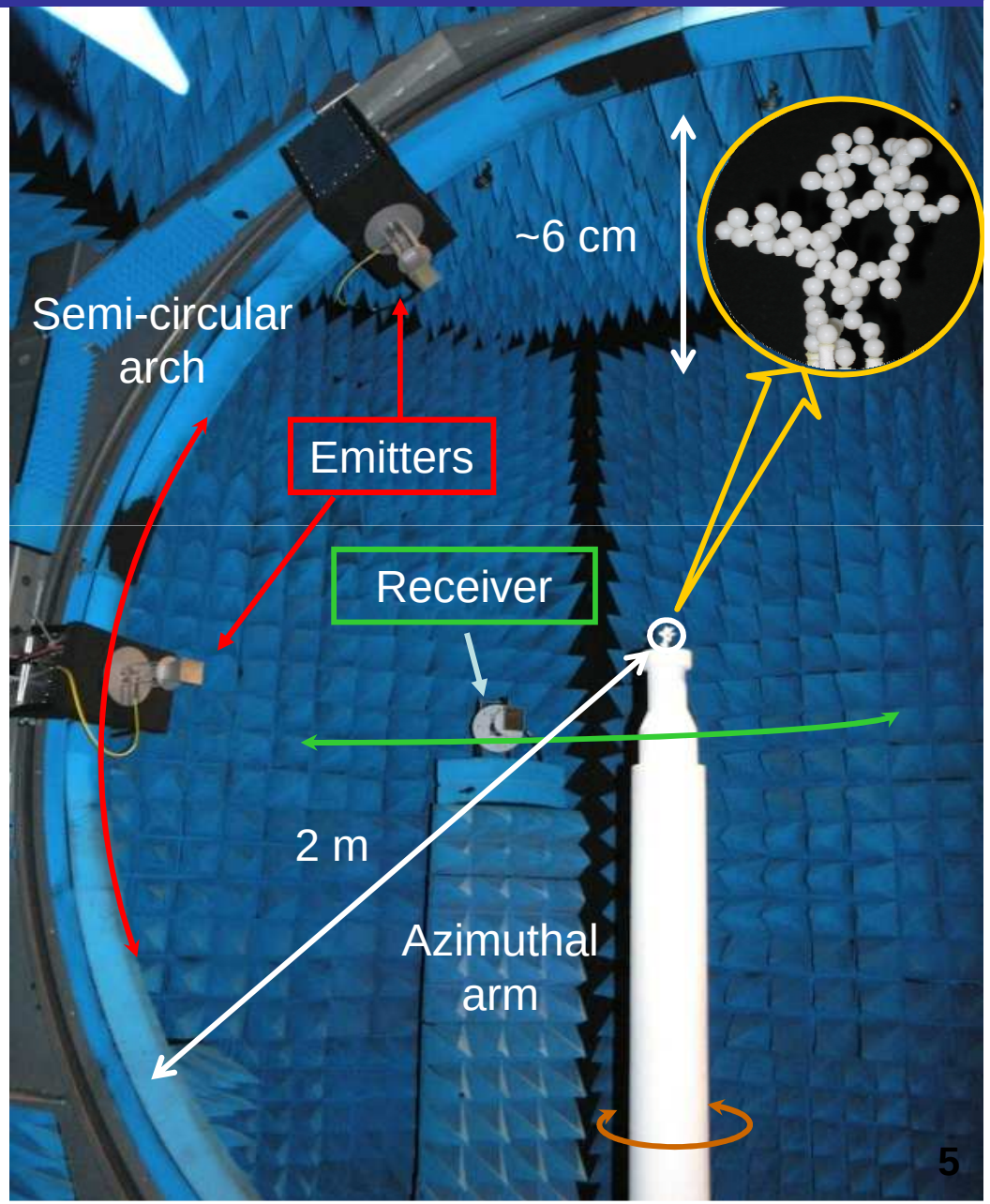
The experimental set-up

Anechoic chamber:

14.2 m x 6.5 m x 6.5 m



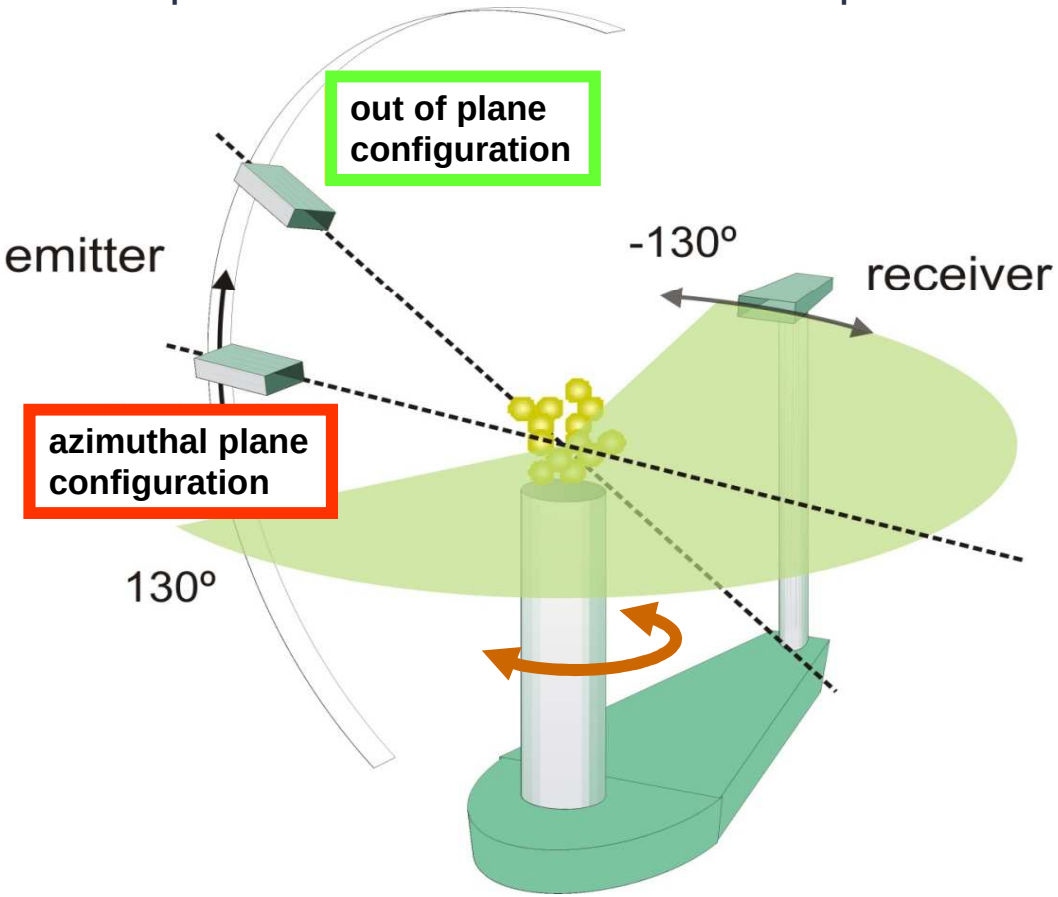
Network Analyzer (HP 8510)
High gain horn antennas (18-26 GHz)



The experimental set-up

Main features

- 3D measurements: emitter can be moved along the vertical arch whereas receiver displacement lies in the azimuthal plane



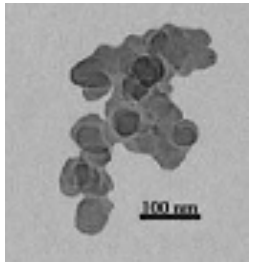
- Broadband measurements
  [2 - 20] GHz ; [15 - 150] mm
- Analysis of all polarization cases (full AS matrix)
- Drift compensation
  [Eyraud et al., APL 89, 2006]
- Noise characterization and reduction to allow cross-polarization measurements
- Investigation of target's orientation (rotation of the vertical axis [mast])

[Vaillon et al., JQSRT 112, 2011] + **www.fresnel.fr/3Ddirect/database.php**

Investigation of a ‘soot-like’ fractal aggregate

Target definition and building

1 Analysis of TEM pictures of real aggregates



TEM picture from **[Xu et al., Combustion and Flame, 2003]**

2 Morphology is satisfactorily represented by a mass fractal law

radius of gyration

fractal dimension

number of spherules in the aggregate

$$N = k_g \left(\frac{R_g}{d_p / 2} \right)^{D_f}$$

prefactor

monomer diameter

Investigation of a ‘soot-like’ fractal aggregate

Target definition and building

3 **Computational generation of an aggregate with pre-specified fractal parameters**

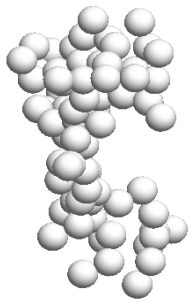
- **the complex aggregate is generated**

by a “growing” algorithm

- **the algorithm allows only combinations**

which satisfy the fractal law

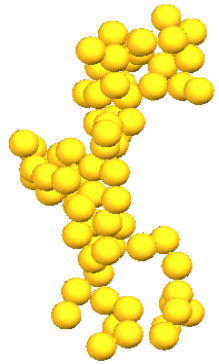
- **chosen parameter values:**



$N = 74$

$k_0 = 2$

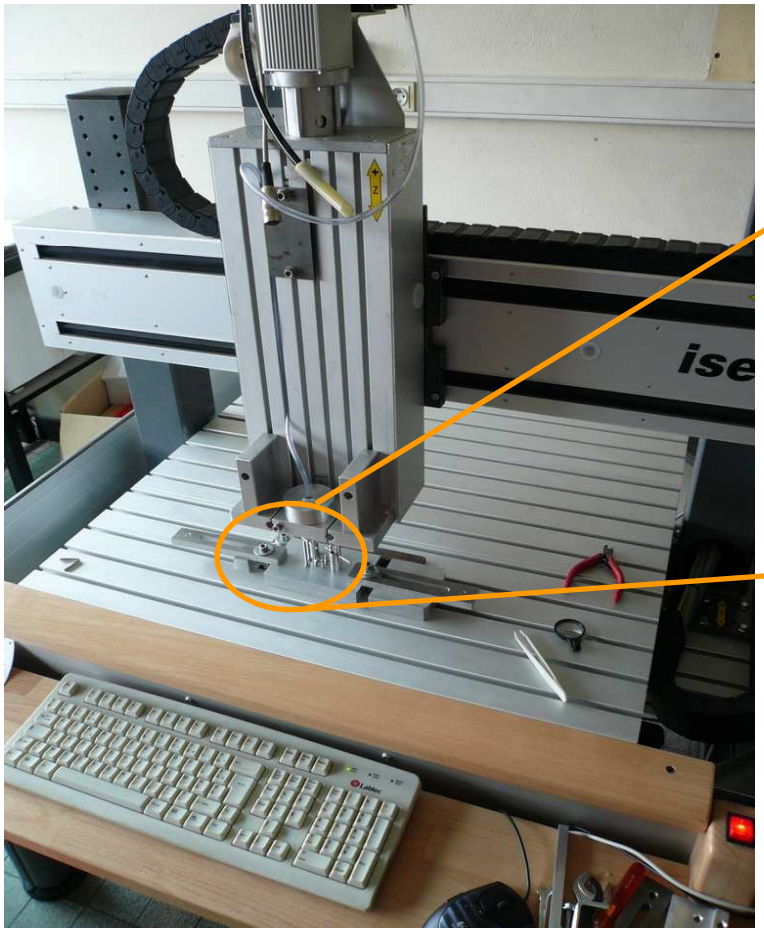
$D_f = 1.7$

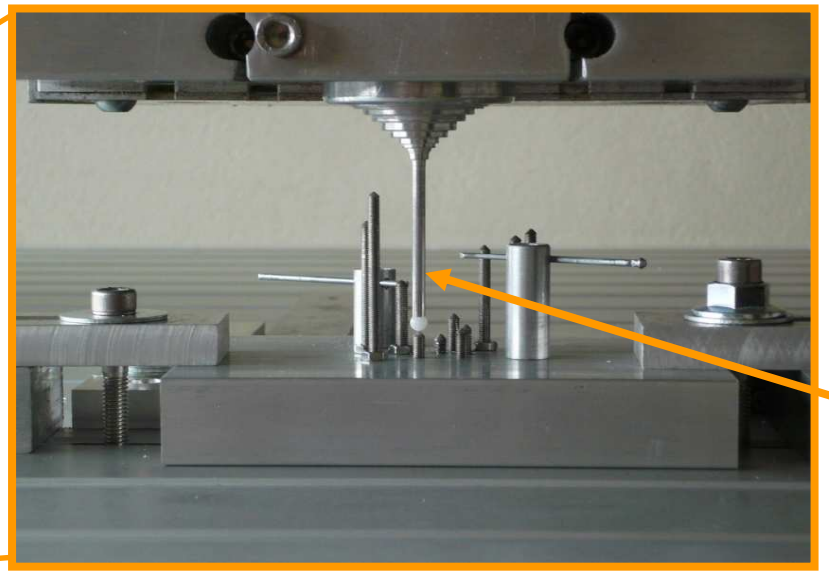


Investigation of a ‘soot-like’ fractal aggregate

Target definition and building

4 **Building of the analog aggregate using a micro-machining apparatus**





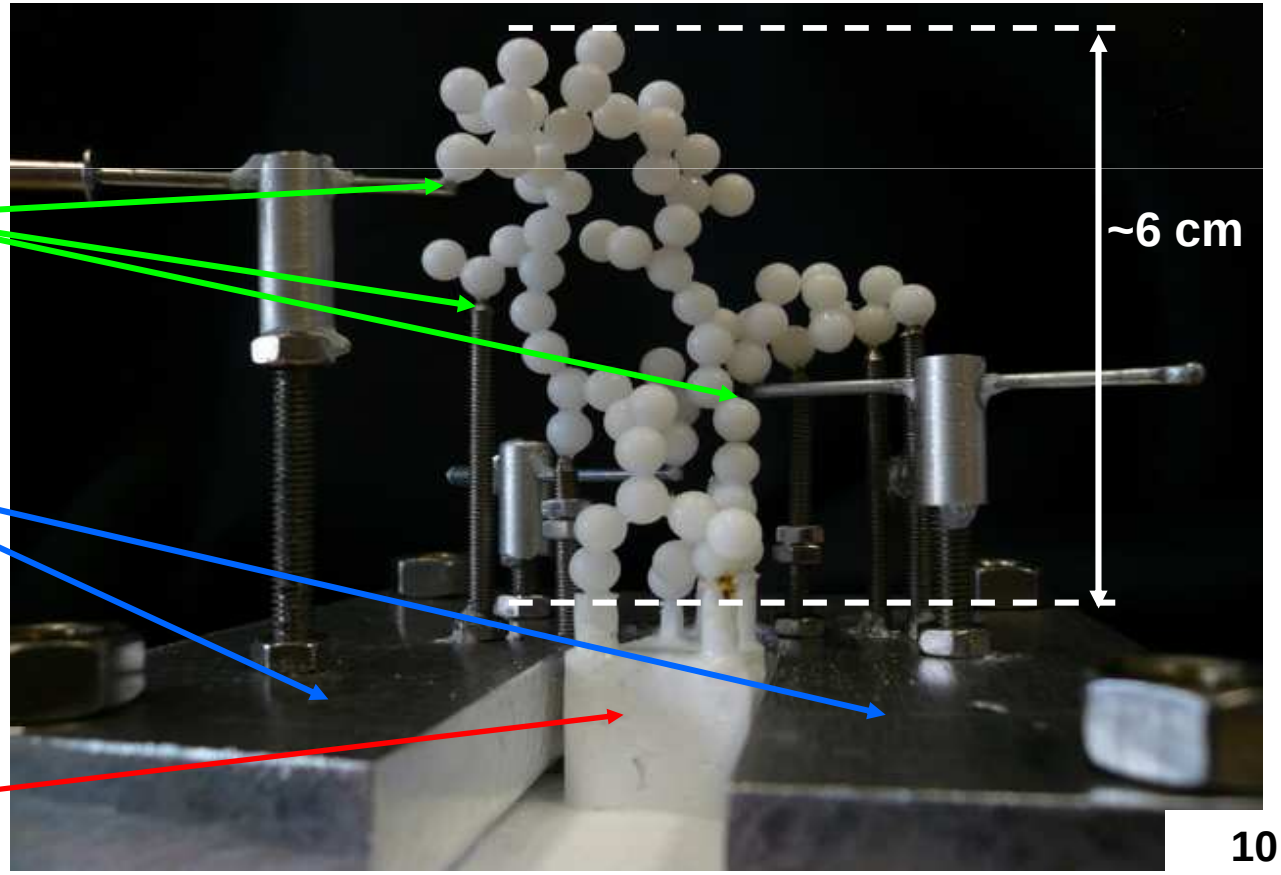
- **3D positioning**
- **Positioning precision 0.001 mm** **<< λ !!**
- **the sphere (diam = 5 mm) is maintained**

using an aspiration system

Investigation of a ‘soot-like’ fractal aggregate

Target definition and building

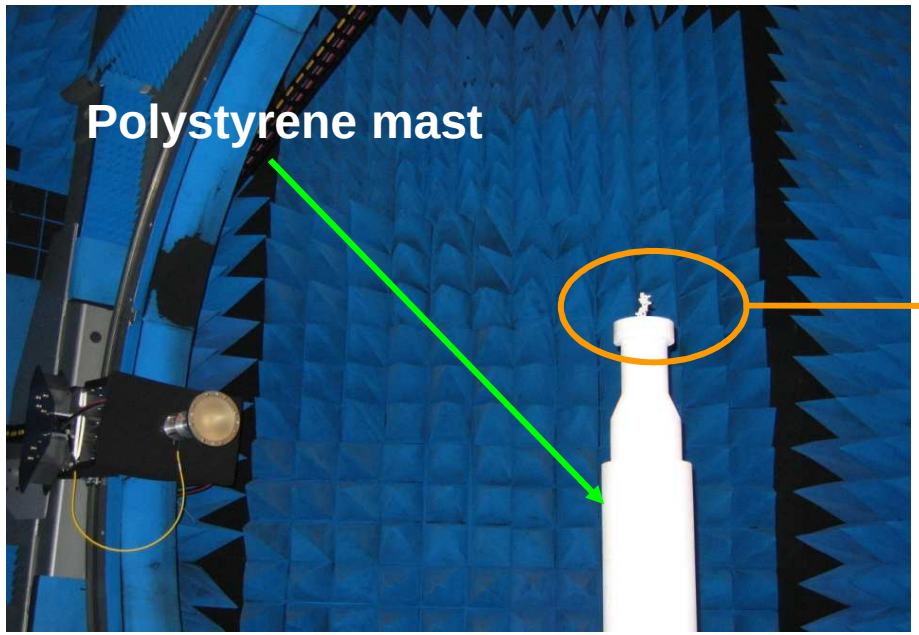
4 **Building of the analog aggregate using a micro-machining apparatus**

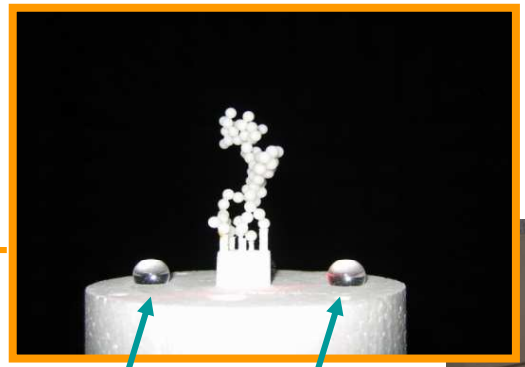


Investigation of a ‘soot-like’ fractal aggregate

Target definition and building

5 **Positioning in the anechoic chamber**





Alignment balls
(removed during measurements)

Empty holder
for measurement of the incident field

6 **Determination of the dielectric properties (complex permittivity) of the aggregate material (polyacetal) using the “*Epsimu*” laboratory facility**

n = 1.668 + *i* 0 on [15-20] GHz

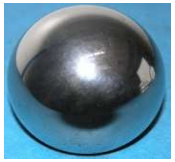
[Sabouroux & Boschi, Rev. Electr. Electron. 10, 2005]

see also www.epsimu.fr

Comparison with light scattering code simulations

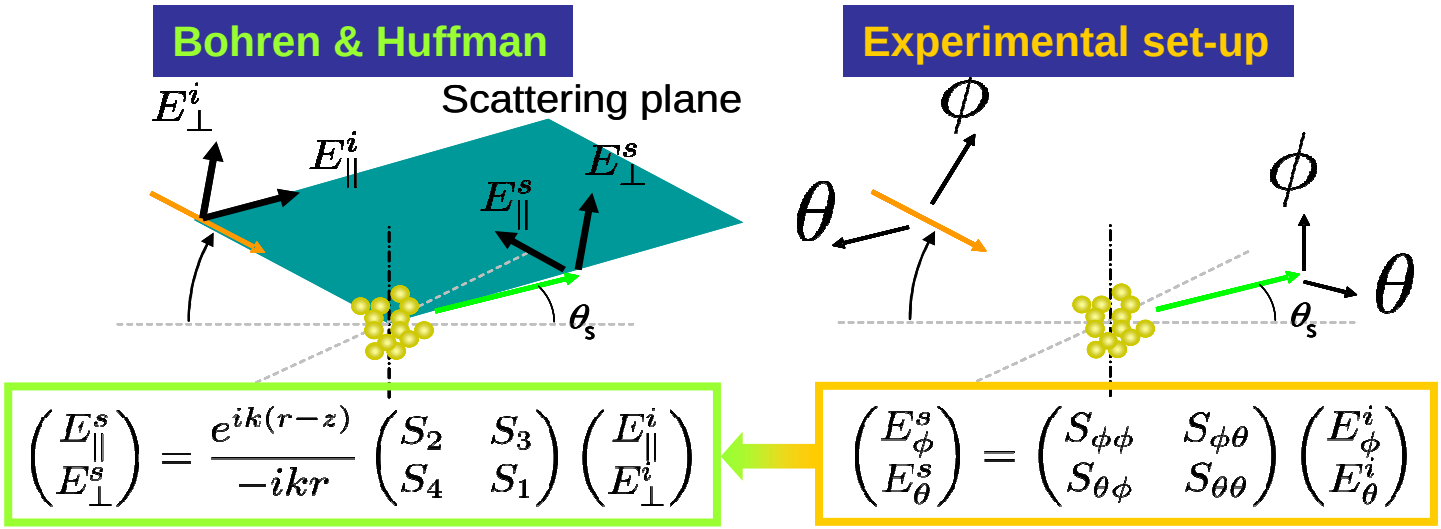
Methodology

- **Calibration**
  - reference target: metallic sphere



  - normalization of measurements for an excitation of amplitude 1 and phase 0 at the center of the sphere
  - a normalization coefficient is obtained for each frequency
  - for other targets, multiplication of the light scattering code data with this coefficient allows performing a proper comparison with experimental data

- **Conventions for polarization components (out of plane configuration)**



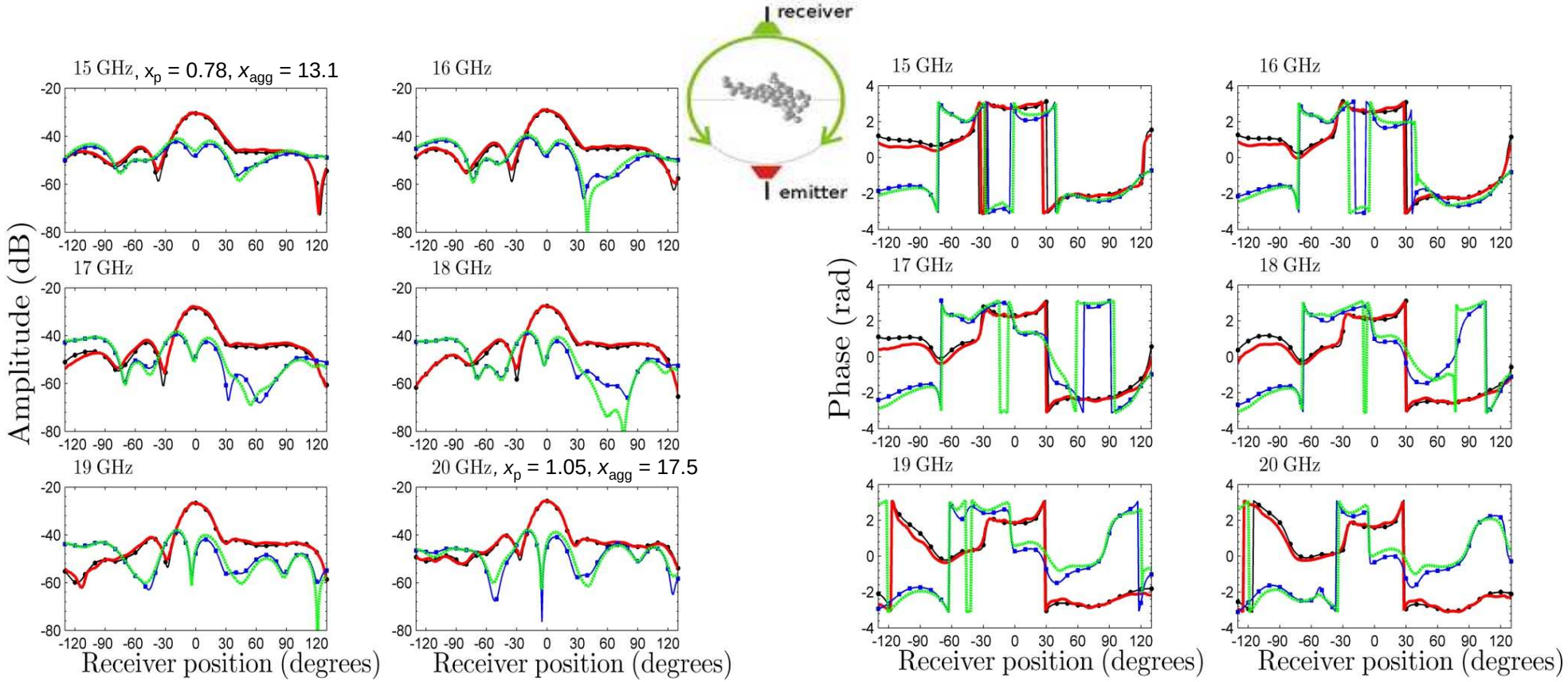
Comparison with light scattering code simulations

Sample results

$$\begin{pmatrix} E_{\parallel}^{s} \\ E_{\perp}^{s} \end{pmatrix} = \frac{e^{ik(r-z)}}{-ikr} \begin{pmatrix} S_2 & S_3 \\ S_4 & S_1 \end{pmatrix} \begin{pmatrix} E_{\parallel}^{i} \\ E_{\perp}^{i} \end{pmatrix}$$

- **Co-polarizations**

[Merchiers et al., Opt. Express 18, 2010]



In plane measurements
Out of plane measurements

In plane calculations
Out of plane calculations

T-matrix code [Mackowski & Mishchenko, JOSA A, 1996]

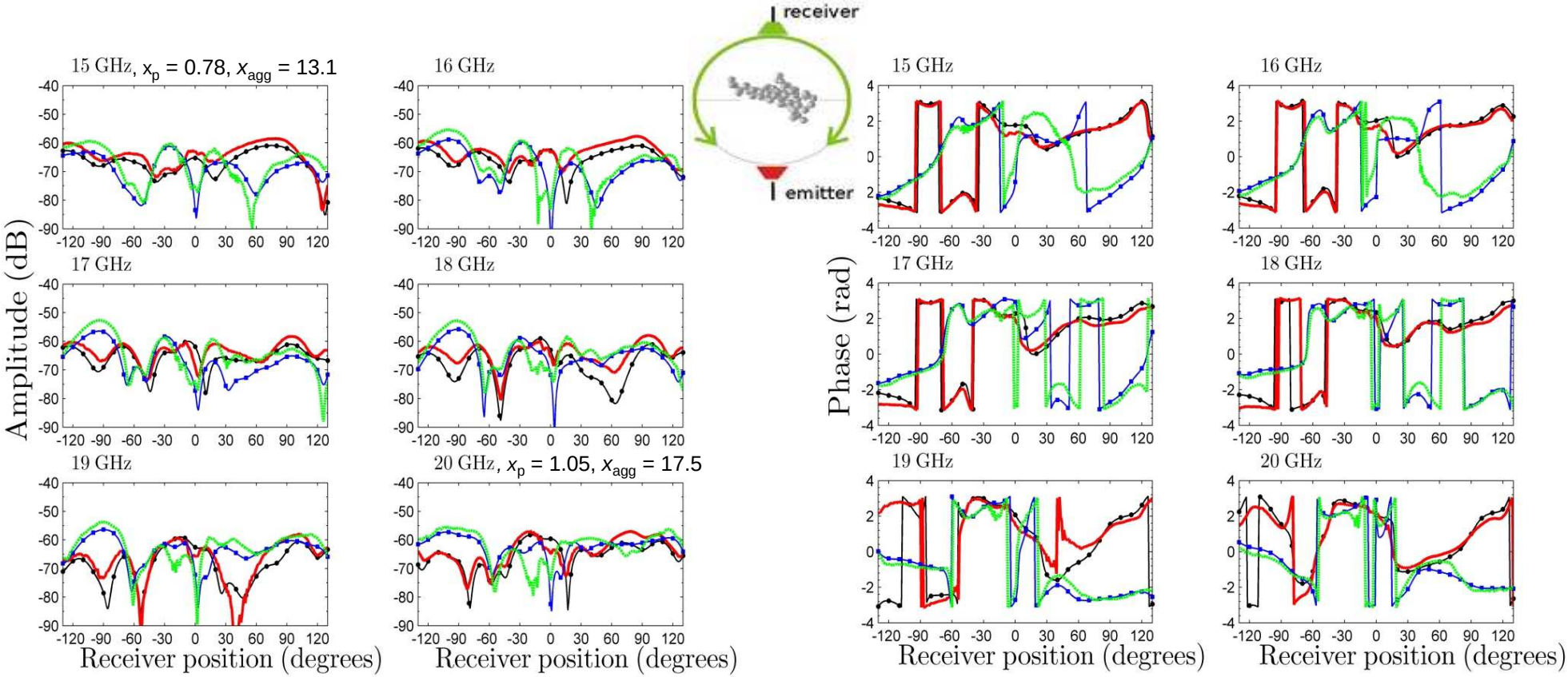
Comparison with light scattering code simulations

Sample results

$$\begin{pmatrix} E_{\parallel}^{s} \\ E_{\perp}^{s} \end{pmatrix} = \frac{e^{ik(r-z)}}{-ikr} \begin{pmatrix} S_2 & S_3 \\ S_4 & S_1 \end{pmatrix} \begin{pmatrix} E_{\parallel}^{i} \\ E_{\perp}^{i} \end{pmatrix}$$

- **Cross-polarizations**

[Merchiers et al., Opt. Express 18, 2010]



In plane measurements
Out of plane measurements

In plane calculations
Out of plane calculations

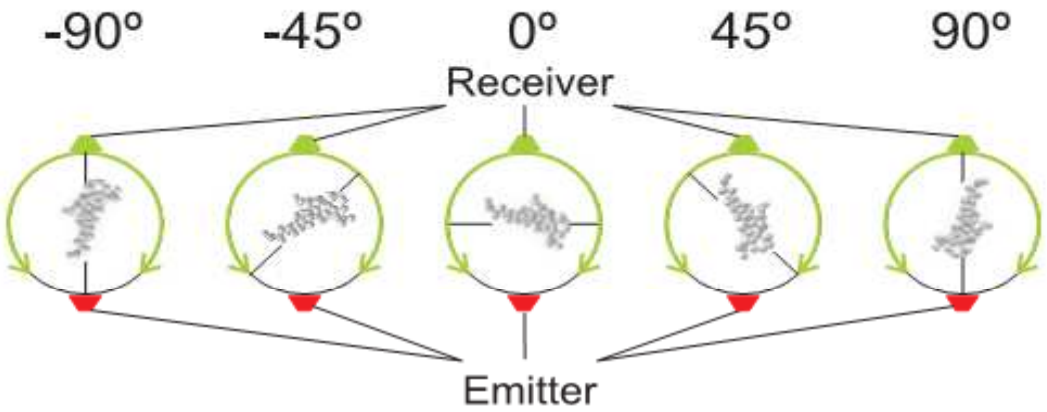
T-matrix code [Mackowski & Mishchenko, JOSA A, 1996]

Comparison with light scattering code simulations

Other results

[Merchiers et al., Opt. Express 18, 2010]

- **Measurements for different orientations of the aggregate**



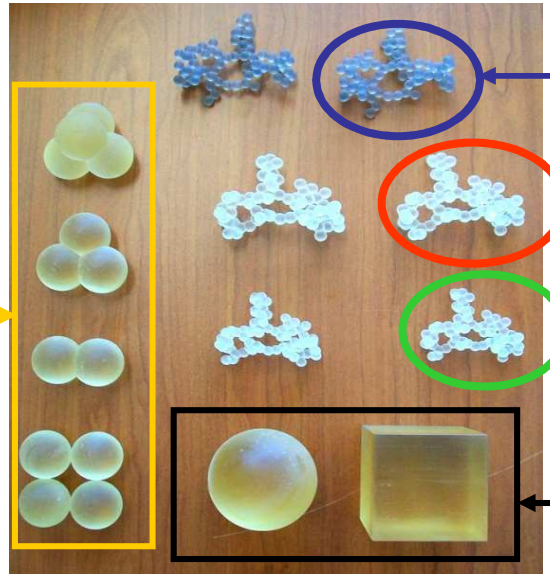
- **Comparisons for several methods and codes**
  - **T-Matrix** [Mackowski & Mishchenko, JOSA A, 1996]
  - **T-Matrix** [Stout et al., JOSA A, 2008]
  - **DDA (ddscat 7.0)** [Draine & Flatau, JOSA A, 1994]
  - **MoM** [Eyraud et al., Inverse Problems, 2009]

Investigation of a ‘soot-like’ fractal aggregate

Targets built by stereo-photolithography

simple aggregates with 2 to 4 spherules (diam = 2.5 cm)

0% or 20% interpenetration

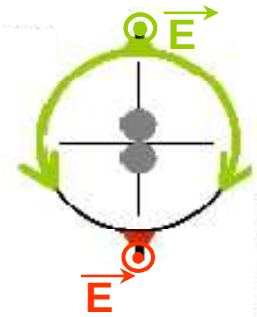


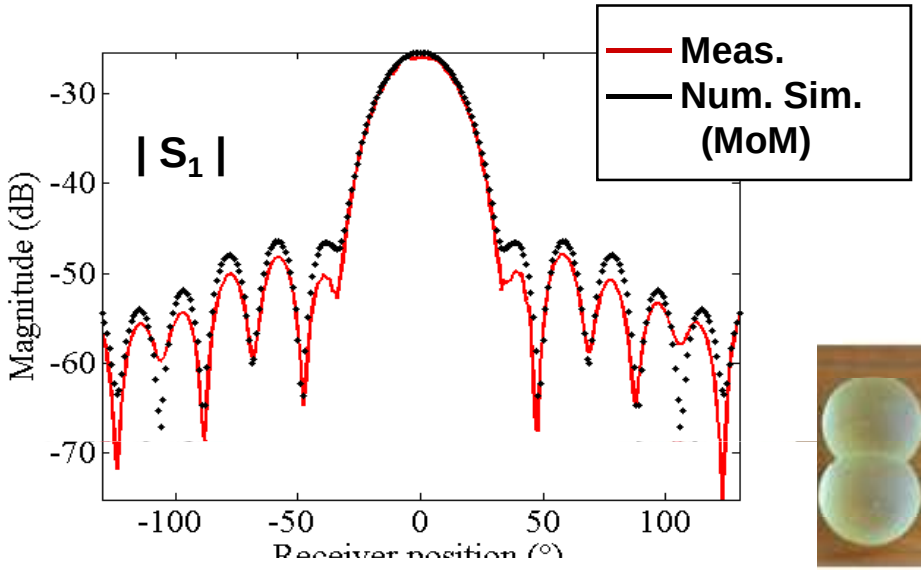
spherule diameter	separation distance	interpenetration coefficient
5 mm	5 mm	0
6 mm	5 mm	0.2
5 mm	4 mm	0.2

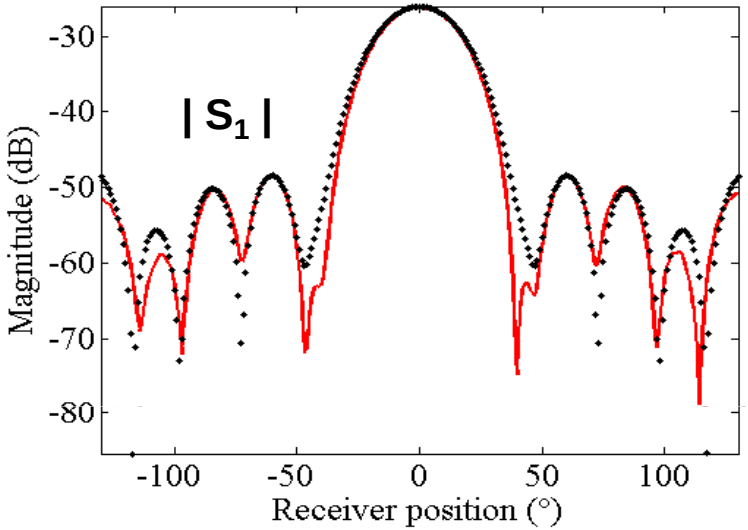
sphere (diam = 5 cm) and cube

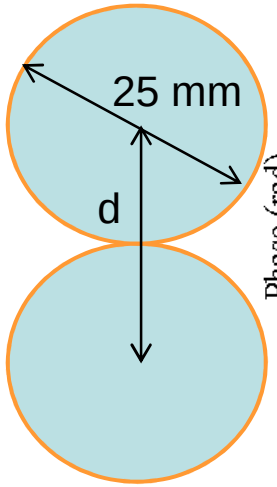
Investigation of two merging spheres

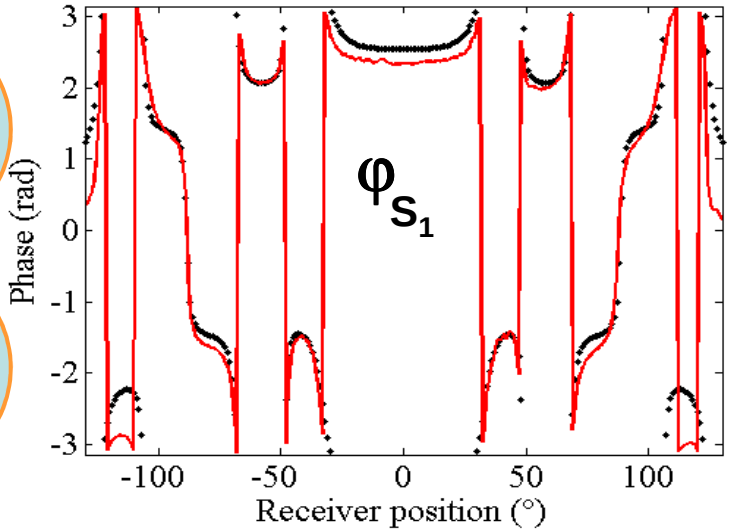
The “big” sphere case

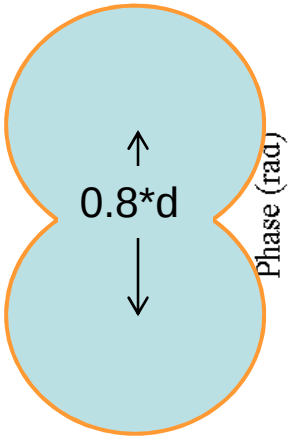




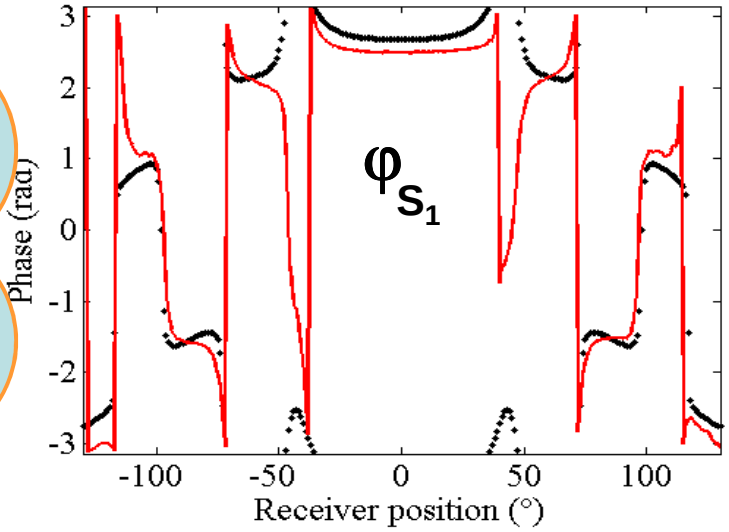








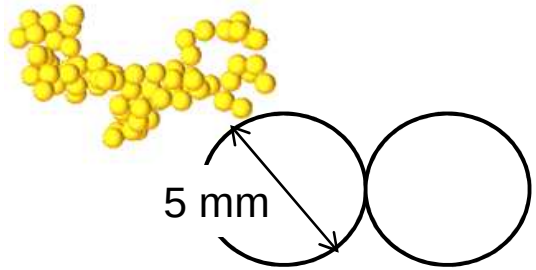
f = 18 GHz
λ = 17 mm



Investigation of the reproducibility of : the measurements, the geometry,…

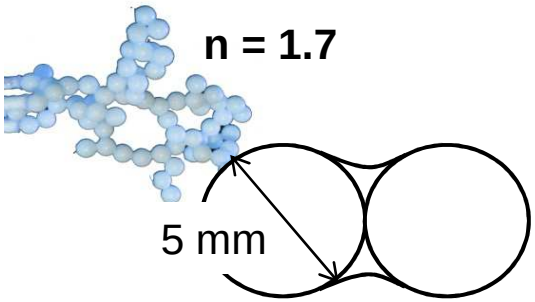
Various aggregates

Numerical simulation



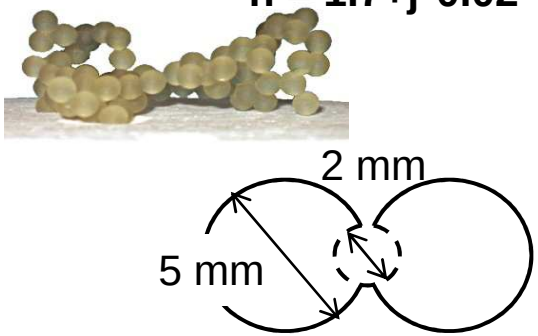
Glued spheres

n = 1.7

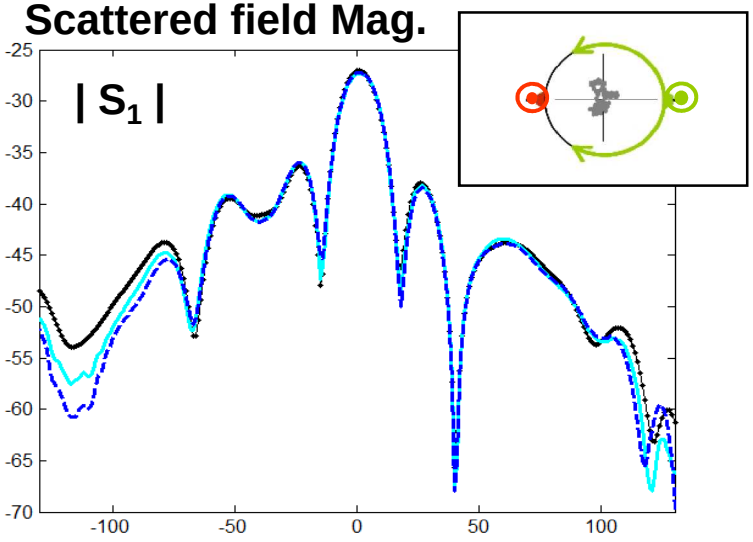


Stereo-photo. reinforced

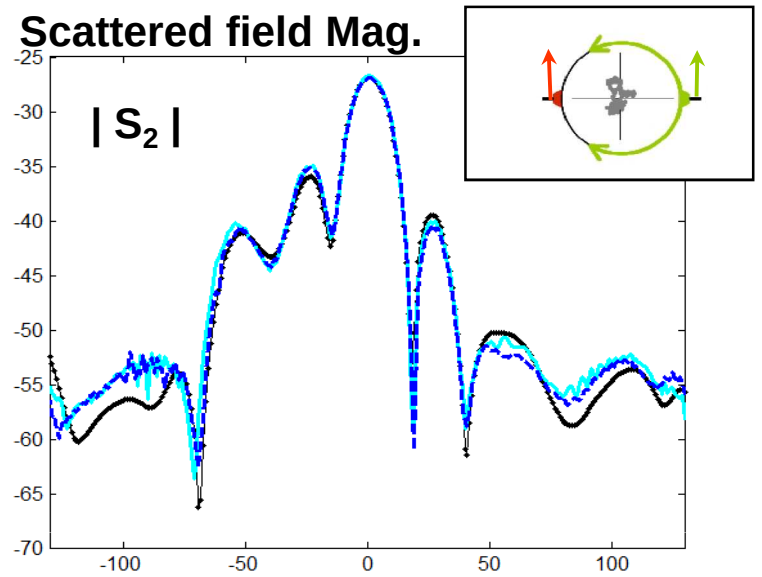
n = 1.7+j*0.02



Scattered field Mag.

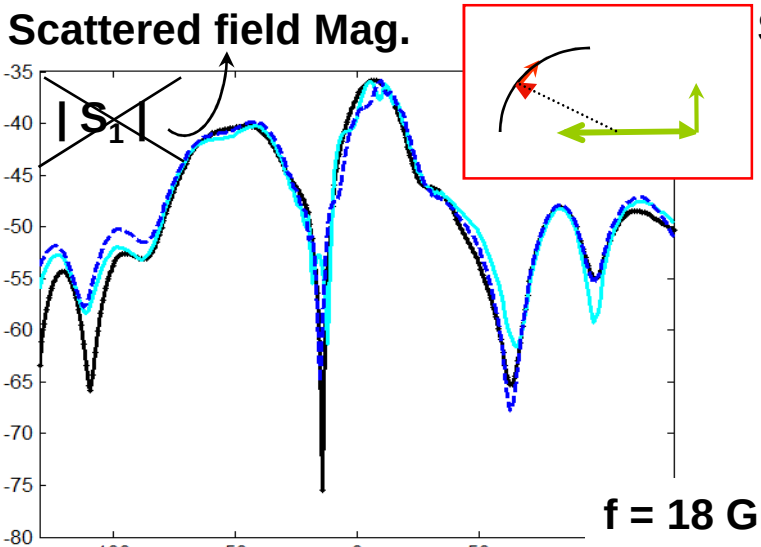


Scattered field Mag.

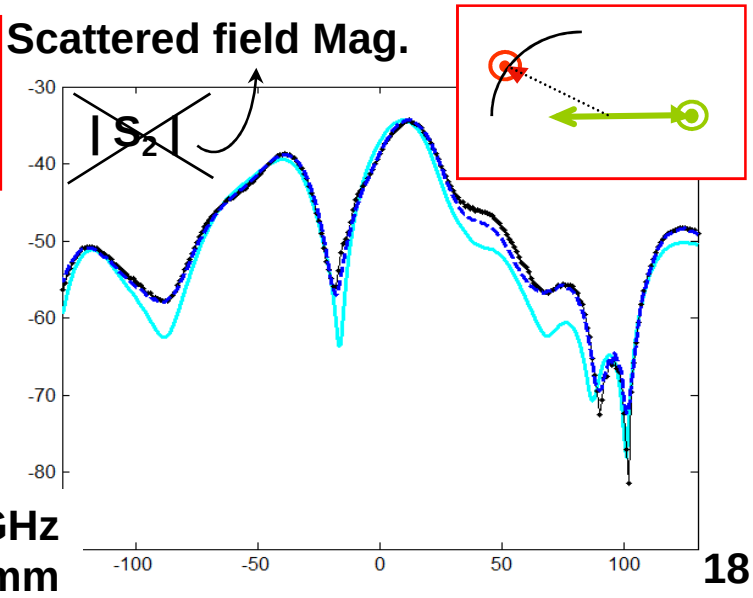


Nunerical simulation (MoM) — Glued spheres — Stereo-photo reinforced

Scattered field Mag.



Scattered field Mag.



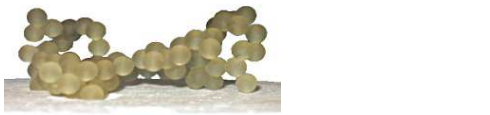
f = 18 GHz

λ = 17 mm

Investigation of the effect of merged spheres in aggregates

Stereo-photolithography

Reinforced



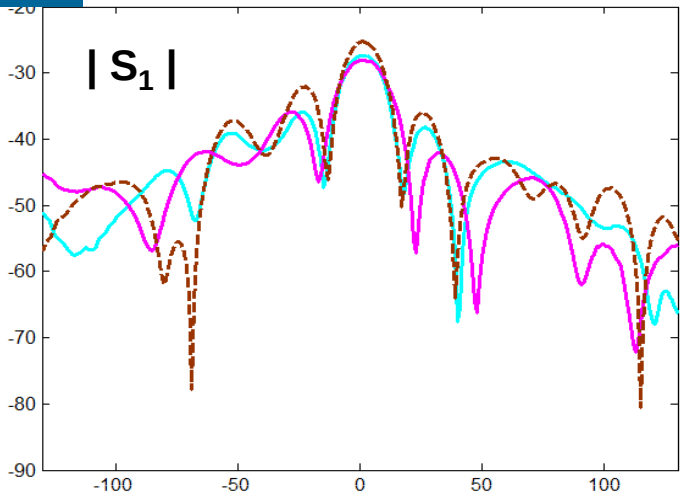
5 mm

Merged

6 mm

5 mm

Scatterd field Mag.

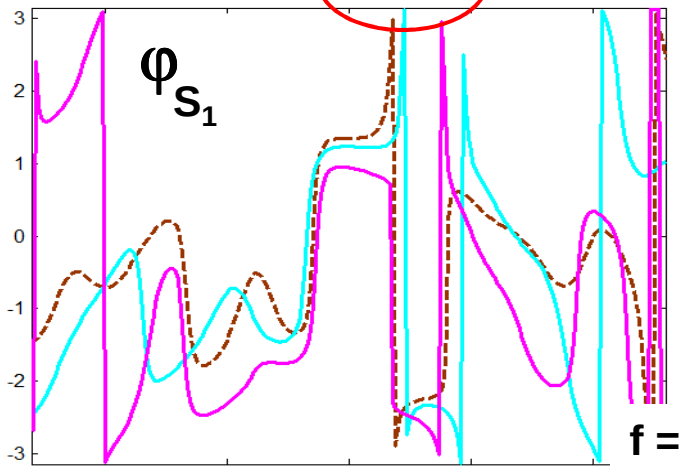


Reinforced

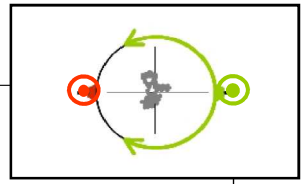
Merged (Φ = 6 mm)

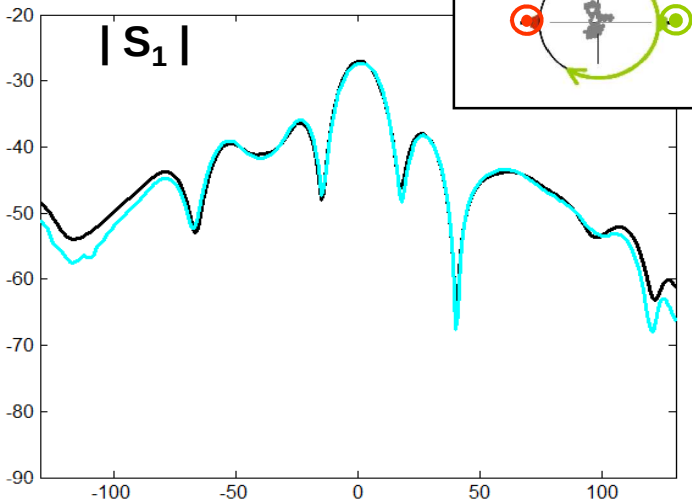
Merged (Φ = 5 mm)

Scattered field Phase



Scattered field Mag.



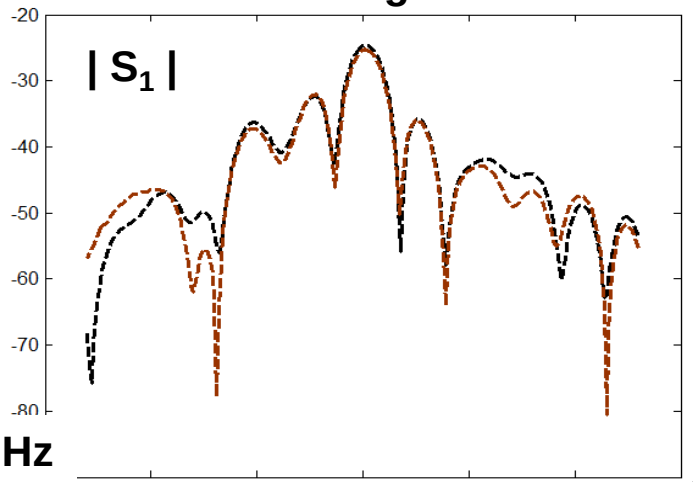


Reinforced

Merged (Φ = 6 mm)

} Num. Sim (MoM)

Scattered field Mag.



f = 18 GHz

λ = 17 mm

Investigation of the effect of merged spheres in aggregates

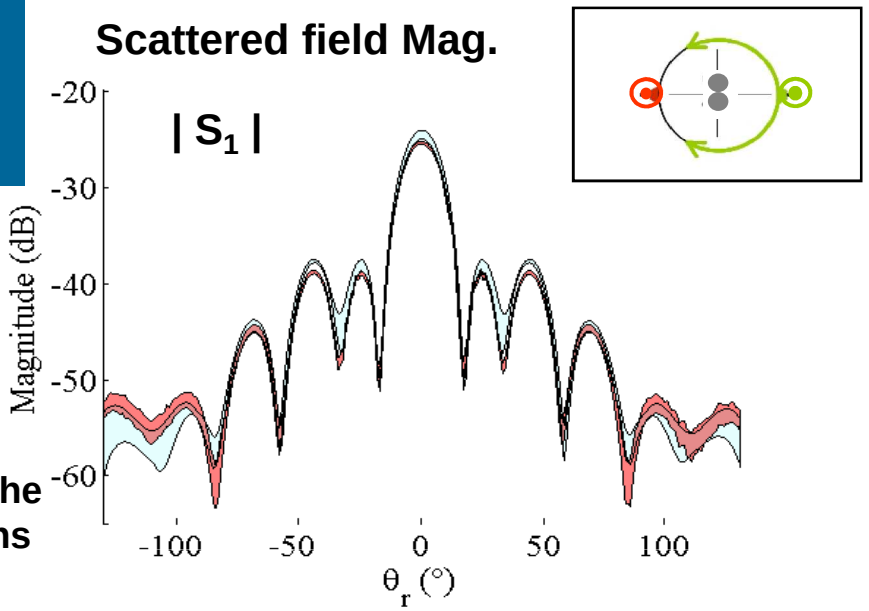
Numerical and experimental errors

Simulations of the uncertainties on the target properties in the numerical simulations
size ±1%
refractive index ±1%

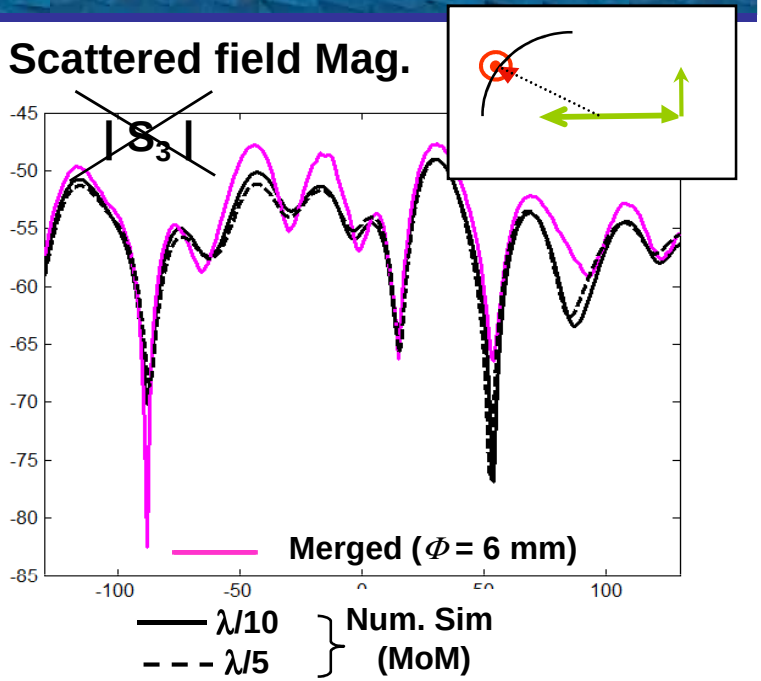
Experimental noise and position uncertainties
position ±0.2 mm

Effect of the cell size on the numerical simulations
λ/5 to λ/10

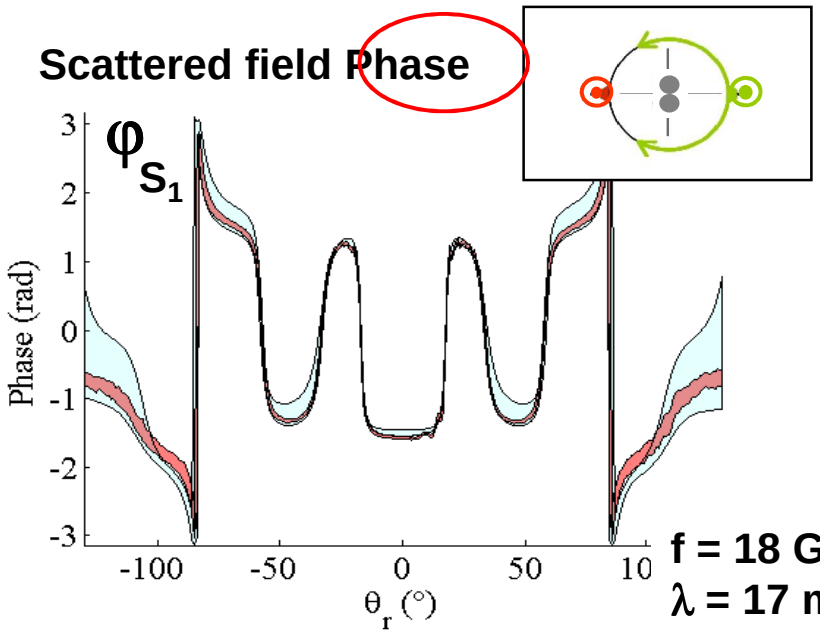
Scattered field Mag.



Scattered field Mag.



Scattered field Phase



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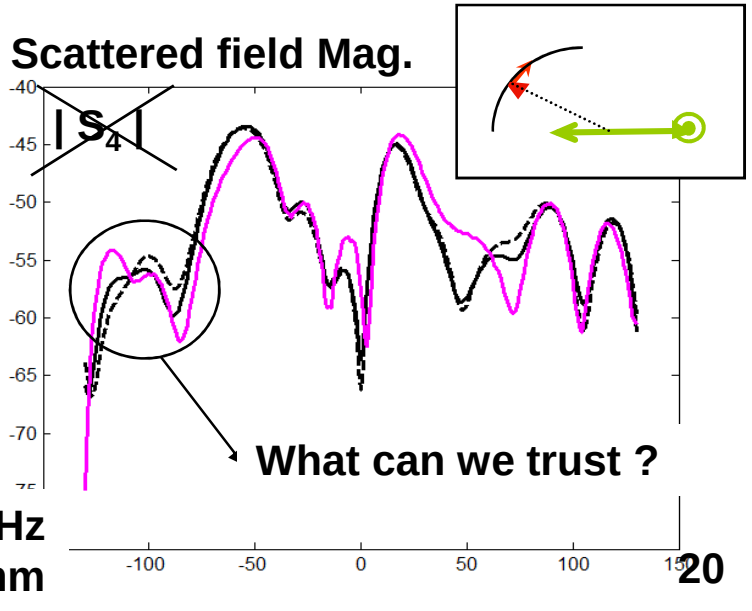


f = 18 GHz
λ = 17 mm

Microwave imaging and inversion…

Quantitative reconstructions of a single aggregate

Measurements made with:

- **11 sources**
- **53 receivers**
- **9 orientations of the aggregate**

+

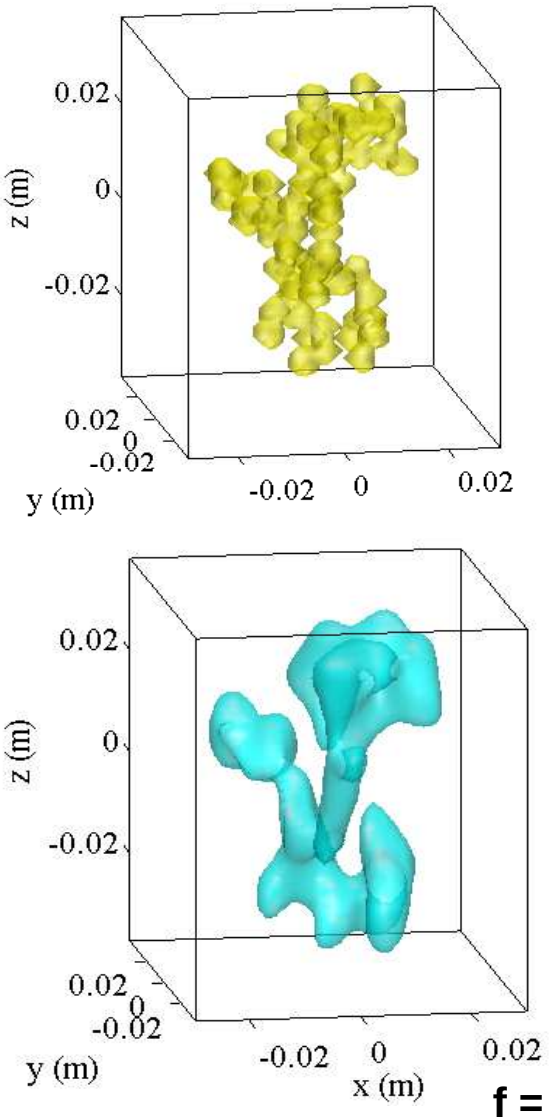
A conjugate gradient minimization algorithm

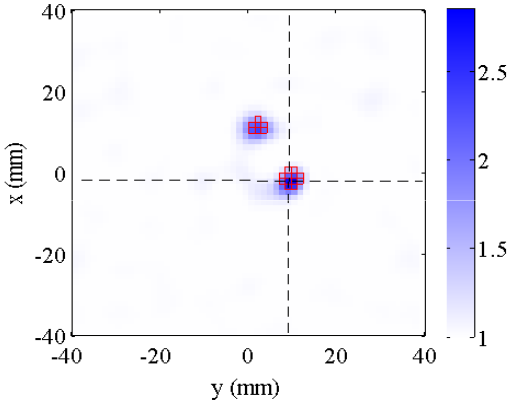
+

The knowledge of the real noise in the measured fields

=

Image of the permittivity inside the test domain using the different polarization cases





Permittivity map
z = -15 mm

f = 18 GHz
λ = 17 mm

[Eyraud et al., IEEE TAP 59, 2011]

Concluding remarks

A novel implementation of a microwave analog to light scattering measurement setup

- large wavelengths **[1.5-15 cm] => larger targets: easier building and better control**
- partial 3D scattering patterns
- full ASM: amplitude and phase
- to assess approximate Maxwell equation solvers

in primary variables

Experimental database: freely accessible at

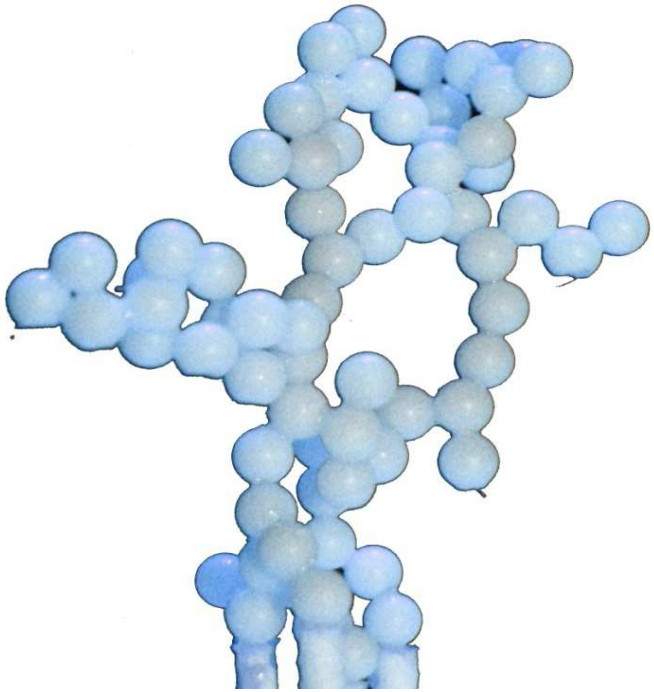
http://www.fresnel.fr/3Ddirect/database.php

Concluding remarks

- **Ongoing and future works**
  - investigation of more realistic aggregates
    - interpenetration
    - ‘’sintered’’ aggregates
    - non spherical monomers?
  - search for an absorbing material in the microwave range with $\varepsilon \sim 3 + i\,3$ to investigate effects of moderate absorption
    - various attempts with polymers charged with carbon particles (CTTM)

  - full 3D measurements by adding a rotation axis
    - total quantities and orientation averaging
  - Other applications:
    - trees, scale reduction UHF-VHF => microwaves (collab. L2E Jussieu)
    - cylinders (collab. The aerospace corporation, USA)
    - holography (collab. U. Mississippi USA)
    - scattering properties of high-refractive-index (n~3.5-4) particles (collab. U. Santander Spain)

Acknowledgements
Some papers, contact persons



Acknowledgements:
Agence Nationale de la Recherche
(project SOOT # ANR-06-BLAN-0349-03)
B. Draine & P. Flatau (DDSCAT)
D. Mackowski & M. Mishchenko, B. Stout (T-Matrix codes)

Some papers:

[Eyraud et al., APL, 2006]
[Sabouroux et al., JQSRT, 2007]
[Merchiers et al., APL, 2009]
[Merchiers et al., Optics Express, 2010]
[Vaillon et al., JQSRT, 2011]

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