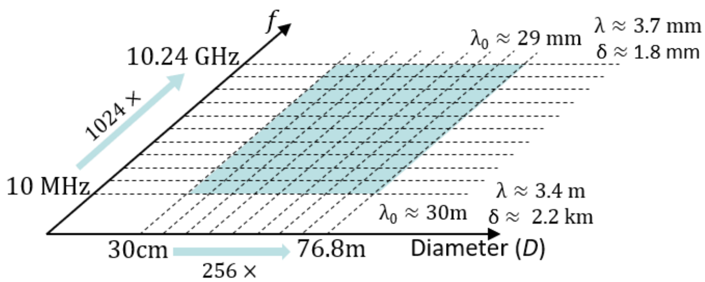
Description of Scattering Object

A water sphere of radius *D*/2 that is assigned distilled-water parameters at room temperature.

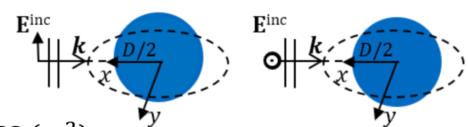
Length Scale and Frequency Range



The problems of interest cover a range of 256x in physical length scale and 1024x in frequency; the ranges are logarithmically sampled to yield 99 unique scattering problems. In these problems, the sphere sizes are in the range $0.01 \leq D/\lambda_0 \leq 2624$ and $0.03 \leq D/\delta \leq 4.27 \times 10^4$, where λ_0 is the free-space wavelength and δ is the penetration depth in the sphere.

Interesting Features

1. Highly accurate, Mie-series analytical solutions are available for Problem Set IC.
2. Frequency-dependent measurement-based material properties are assigned to the sphere.
3. An unusual scattering problem is part of the problem set. Over a narrow bandwidth around 80 MHz, the *D*=60-cm sphere exhibits a more complex RCS pattern than otherwise. Multiple numerical methods were found to require significantly more accurate solutions than usual to find this pattern correctly.
4. Bi-static rather than mono-static RCS is used as the quantity of interest.



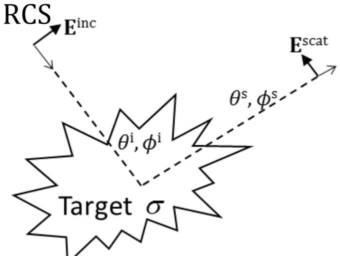
Quantities of Interest

Radar cross section (RCS) definition

$$\sigma_{vu}(\theta^{\mathrm{s}},\phi^{\mathrm{s}},\theta^{\mathrm{i}},\phi^{\mathrm{i}}) = \lim_{R\to\infty} 4\pi R \frac{|\hat{v}(\theta^{\mathrm{s}},\phi^{\mathrm{s}}) \cdot \mathbf{E}^{\mathrm{scat}}(\theta^{\mathrm{s}},\phi^{\mathrm{s}})|^2}{|\hat{u}(\theta^{\mathrm{i}},\phi^{\mathrm{i}}) \cdot \mathbf{E}^{\mathrm{scat}}(\theta^{\mathrm{i}},\phi^{\mathrm{i}})|^2} \quad : \ \mathrm{RCS}\ (\mathrm{m}^2)$$

$$\sigma_{vu,\mathrm{dB}}(\theta^{\mathrm{s}},\phi^{\mathrm{s}},\theta^{\mathrm{i}},\phi^{\mathrm{i}}) = 10\log_{10}\sigma_{vu} \quad : \ \mathrm{RCS\ in\ dB\ (dBsm)}$$

$$\sigma^{TH}_{vu,\mathrm{dB}}(\theta^{\mathrm{s}},\phi^{\mathrm{s}},\theta^{\mathrm{i}},\phi^{\mathrm{i}}) = \max\left(\sigma_{vu,\mathrm{dB}}, TH_{vu,\mathrm{dB}}\right) - TH_{vu,\mathrm{dB}} \quad : \ \mathrm{Thresholded\ RCS}$$



1. Set $\theta^{\mathrm{i}} = 90^{\mathrm{o}}$, $\phi^{\mathrm{i}} = 0^{\mathrm{o}}$, $\theta^{\mathrm{s}} = 90^{\mathrm{o}}$. Vary $0^{\mathrm{o}} \leq \phi^{\mathrm{s}} \leq 360^{\mathrm{o}}$.
2. Compute both $\sigma_{\theta\theta,\mathrm{dB}}$ and $\sigma_{\phi\phi,\mathrm{dB}}$ (the VV- and HH-pol RCS in dB) at $N_\phi = 721$ scattering directions (every 0.5^{o} in the interval $0^{\mathrm{o}} \leq \phi^{\mathrm{s}} \leq 360^{\mathrm{o}}$).

Material Properties

The permeability of distilled water is the same as that of free space. The Debye model in [1], expressed as

$$\epsilon(f,T) = \epsilon_0[\epsilon_r'(f,T) - j\epsilon_r''(f,T)]$$

was used to calculate the complex permittivity of distilled water at the frequencies of interest at temperature $T = 298\ K$. The reference results were found using precisely the permittivity values (i.e., to machine precision) shown in this table:

Frequency f (MHz)	ϵ_r'	ϵ_r''	Frequency f (MHz)	ϵ_r'	ϵ_r''
10	78.44	0.038	640	78.36	2.447
20	78.44	0.077	1280	78.12	4.878
40	78.44	0.153	2560	77.16	9.627
80	78.44	0.306	5120	73.56	18.29
160	78.44	0.612	10240	62.15	30.49
320	78.44	1.225			

Performance Measures

Error Measure: Simulation errors shall be quantified using

$$avg.\,err_{uu,\mathrm{dB}}^{TH} = \frac{1}{2\pi}\int_0^{2\pi}\left|\sigma_{uu,\mathrm{dB}}^{TH}(\phi^s) - \sigma_{uu,\mathrm{dB}}^{\mathrm{ref},TH}(\phi^s)\right| d\phi^s \approx \frac{1}{N_\phi}\sum_{n=1}^{N_\phi}\left|\sigma_{uu,\mathrm{dB}}^{TH}(\phi_n^s) - \sigma_{uu,\mathrm{dB}}^{\mathrm{ref},TH}(\phi_n^s)\right| \ (\mathrm{dB}) \ \text{ for } u \in \{\theta, \phi\}$$

where

$$TH_{uu,\mathrm{dB}} = \max_{\phi^s} \sigma_{uu,\mathrm{dB}}^{\mathrm{ref}} - 80\ (\mathrm{dB})$$

This error measure discounts errors in RCS values smaller than TH.

Cost Measure: Simulation costs shall be quantified using observed wall-clock time and peak memory/ process

$$t^{\mathrm{wall}}\text{(s) and } mem^{\mathrm{maxproc}}\text{(bytes)}$$

as well as the "serialized" CPU time and total memory requirement

$$t^{\mathrm{total}} = N_{\mathrm{proc}} \times t^{\mathrm{wall}}\text{(s) and } mem^{\mathrm{max}} = N_{\mathrm{proc}} \times mem^{\mathrm{maxproc}} \text{ (bytes)}$$

Here, N_{proc} denotes the number of processes used in a parallel simulation. It is expected that results will be reported for at least 2 runs: "Efficient" (small N_{proc}) and "Fast" (large N_{proc}).

Study 1: Error vs. Cost Sweep

Fix frequency and fix sphere diameter. Simulate many error levels (proxy: mesh densities) for 4 cases:

Case 1: *f*=10 MHz, *D*=0.6 m
Case 2: *f*=320 MHz, *D*=0.6 m
Case 3: *f*=10 MHz, *D*=19.2 m
Case 4: *f*=320 MHz, *D*=19.2 m

It's recommended to simulate as many error levels (mesh densities) as possible. 3-5 error levels is typical. A typical error-vs.-cost study will consist of 4x3-5=12-20 simulations.

Study 2: Frequency Sweep

Fix sphere diameter and error level (proxy: mesh density). Simulate many frequencies for 4 cases:

Case 1: *D*=0.6 m, error level 1 (coarsest mesh)
Case 2: *D*=19.2 m, error level 1 (coarsest mesh)
Case 3: *D*=0.6 m, error level 2 (finer mesh)
Case 4: *D*=19.2 m, error level 2 (finer mesh)

Frequencies shall be chosen as $f \in \{10, 20, 40, \ldots, 5120, 10240\}$ MHz. It's recommended to simulate as many frequencies as possible. A full frequency-sweep study will consist of 4x11=44 simulations.

Study 3: Size Sweep

Fix frequency and error level (proxy: mesh density). Simulate many diameters for 4 cases:

Case 1: *f*=10 MHz, error level 1 (coarsest mesh)
Case 2: *f*=320 MHz, error level 1 (coarsest mesh)
Case 3: *f*=10 MHz, error level 2 (finer mesh)
Case 4: *f*=320 MHz, error level 2 (finer mesh)

Diameters shall be chosen as $D \in \{0.3, 0.6, 1.2, \ldots, 38.4, 76.8\}$ m. It's recommended to simulate as many diameters as possible. A full size-sweep study will consist of 4x9=36 simulations.

Study 4: Unusual Scattering Problems

Fix frequency and fix sphere diameter. Simulate many error levels for 2 cases:

Case 1: *f*=80 MHz, *D*=0.6 m using the permittivity values above
Case 2: *f*=80 MHz, *D*=0.6 m using $\epsilon' = 78.98$, ϵ''=0.2

These problems generally require (much) more accurate numerical solutions to yield accurate RCS results.

Reference Quantities of Interest

The following RCS data are made available in the benchmark to enable participants to calibrate their simulators:

4 RCS results corresponding to the cases in study 1 found by using COMPASS-EM code [2].
2 RCS results corresponding to the cases in study 4 found by using COMPASS-EM code [2].

References

[1] U. Kaatz, "Complex permittivity of water as a function of frequency and temperature," *J. Chem. Eng. Data*, vol. 34, no. 4, pp. 371-374, 1989. doi:10.1021/je00058a001.

[2] G. Kaur (2015) COMPASS-EM: Comprehensive program for analytical scattering solutions for electromagnetics. [Online]. Available: http://web.corral.tacc.utexas.edu/BioEM-Benchmarks/COMPASS-EM/index.html