OPUS 3D Benchmarks

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Benchmarking Procedure

- All OPUS 3D results are benchmarked with other methods – both analytical and semi-analytical
- The benchmarks were chosen to cover a broad range of applications (sources, geometries, materials…)
- For all benchmarks there exist well-known reference solutions
- Transparent benchmarking procedure: anybody skilled with Matlab can validate the results

Overview of Benchmark Examples

- Dipole radiation in free space
- Reflection and transmission coefficients for a plane wave impinging on a dielectric material (three-layer problem)
- Reflection and transmission coefficients for a $\lambda/4$ anti-reflection filter
- Scattering from dielectric sphere
- Scattering from metallic sphere
- Plain realistic LED structure

Benchmark 1

Dipole Radiation in Free Space

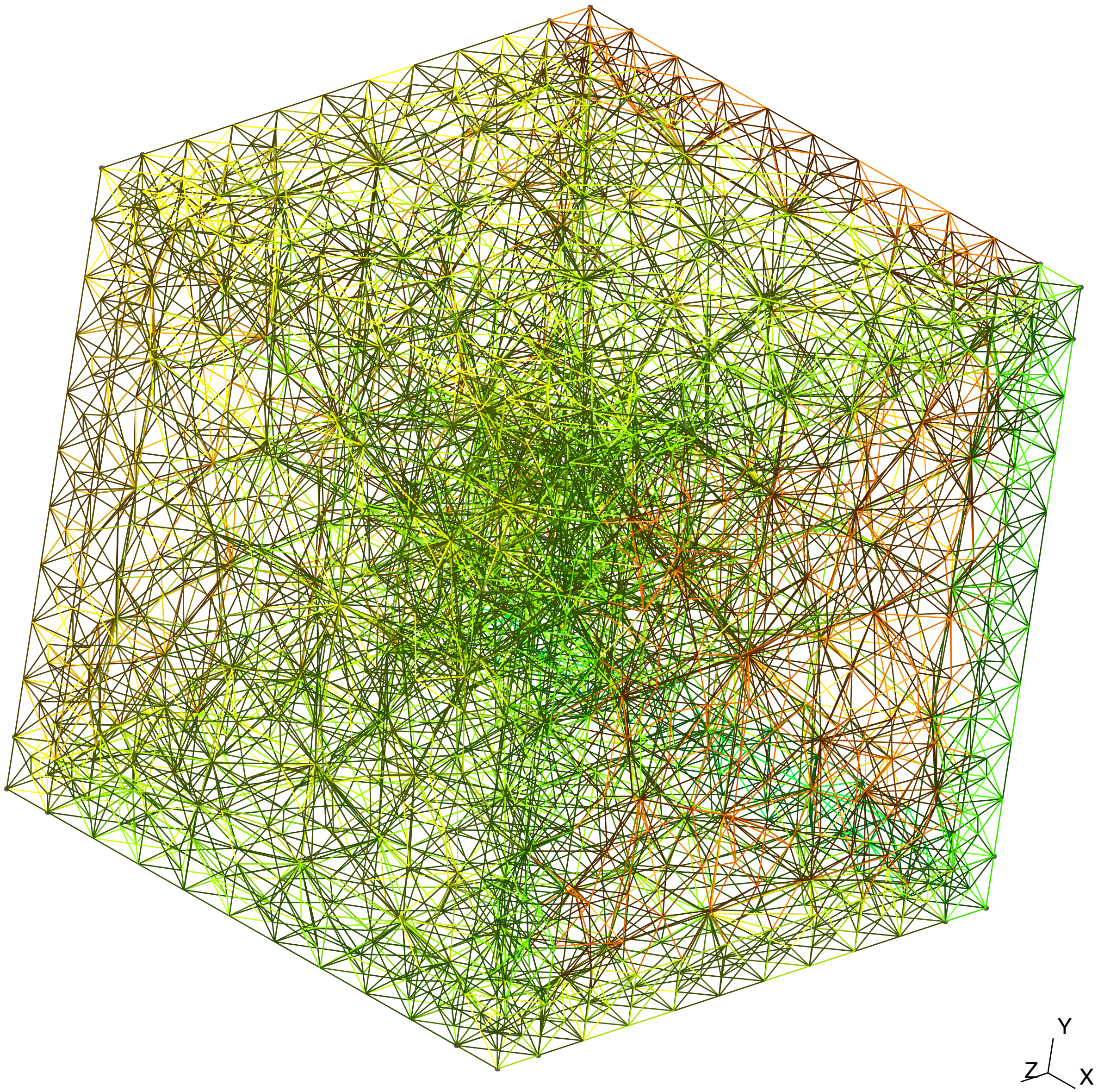
Benchmark 1 – Summary

- **Benchmark:** a dipole radiating into free space
- **Validation:** analytical reference solution taken from Jackson
- **Goals**
  - Show the ability of OPUS 3D to handle large simulation domains ($9\lambda \times 9\lambda \times 9\lambda$)
  - Show the numerical accuracy even close to singularities
  - Focus on all 6 field components (3×E, 3×H)

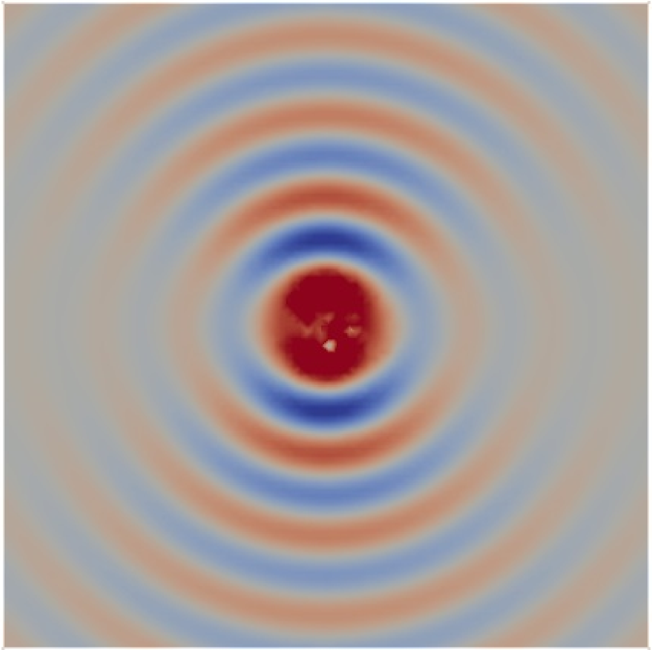
Benchmark 1 – Computational Aspects

- Domain size: $9\lambda \times 9\lambda \times 9\lambda$
- Problem size: 506'000 DoF (Degrees of Freedom)
- Memory Consumption: 6.1 Gbyte
- Computation time (11 CPUs): 394 s

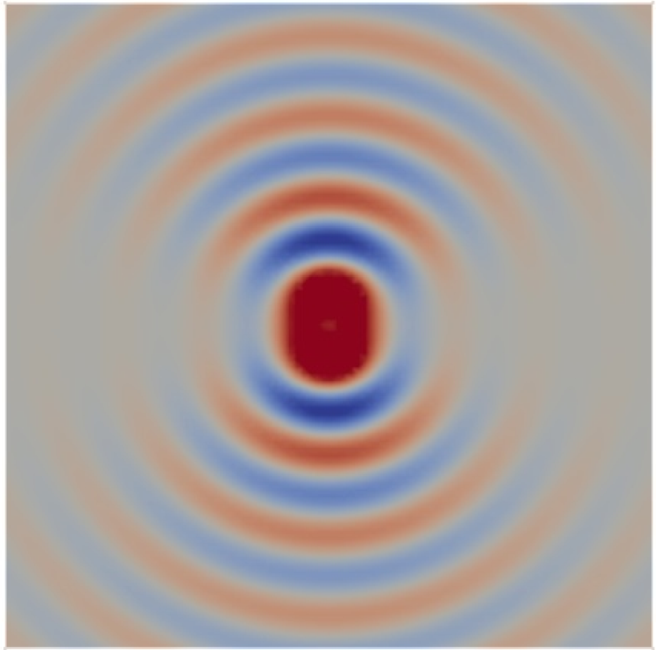
Benchmark 1 – Mesh



Benchmark 1: Results



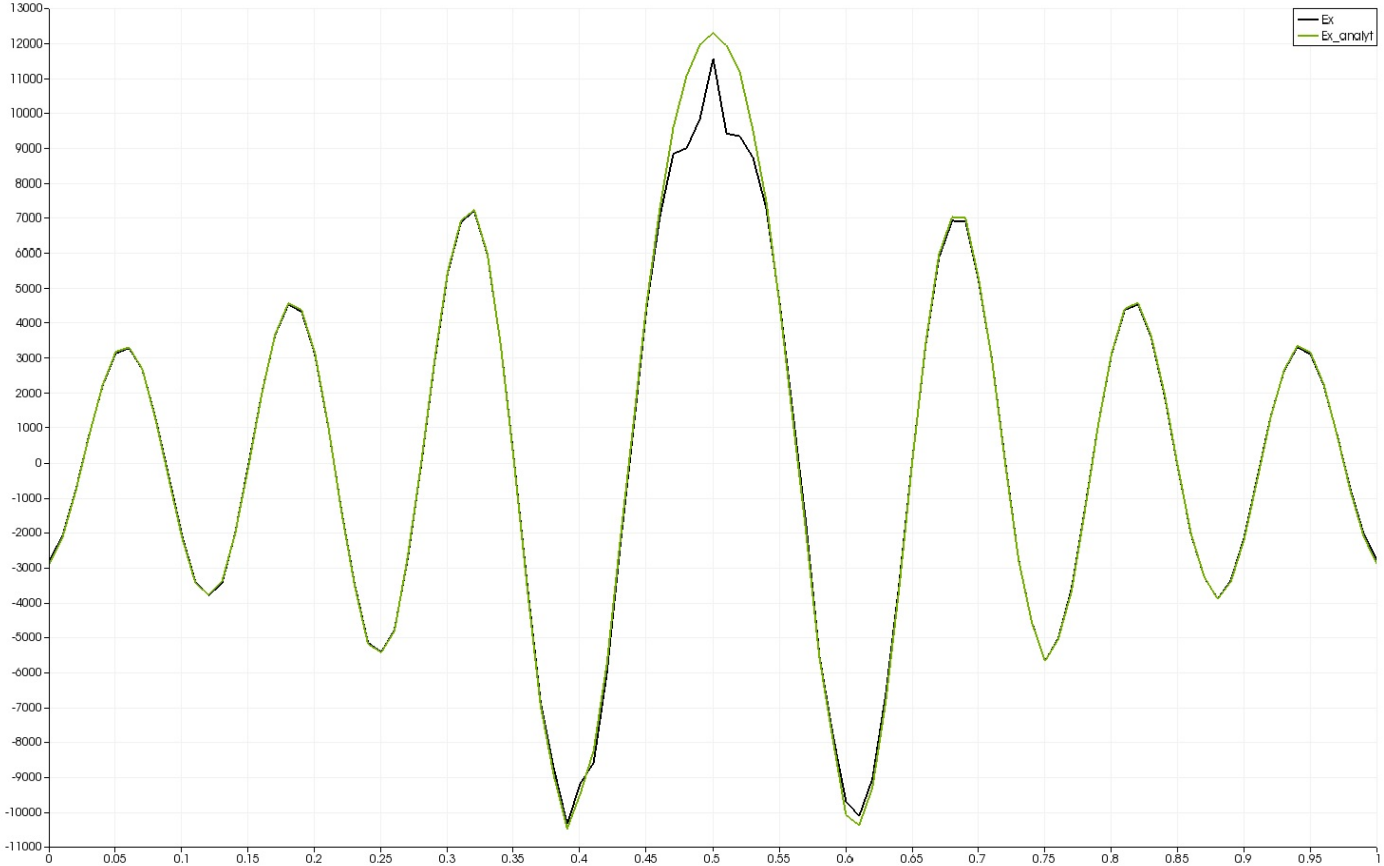
OPUS 3D



Analytical solution

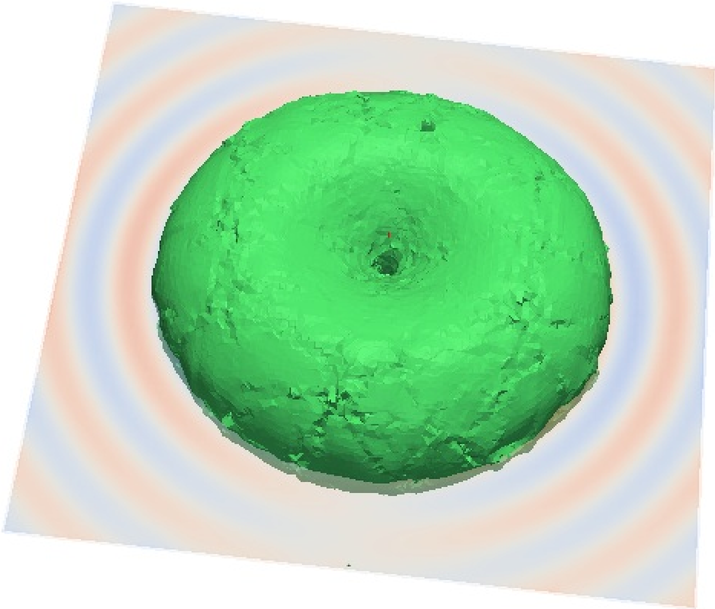
Direct comparison of the computed electric fields in V/m. Both plots feature the same scale. Very good agreement both qualitatively and quantitatively.

Benchmark 1: Results (cont'd)

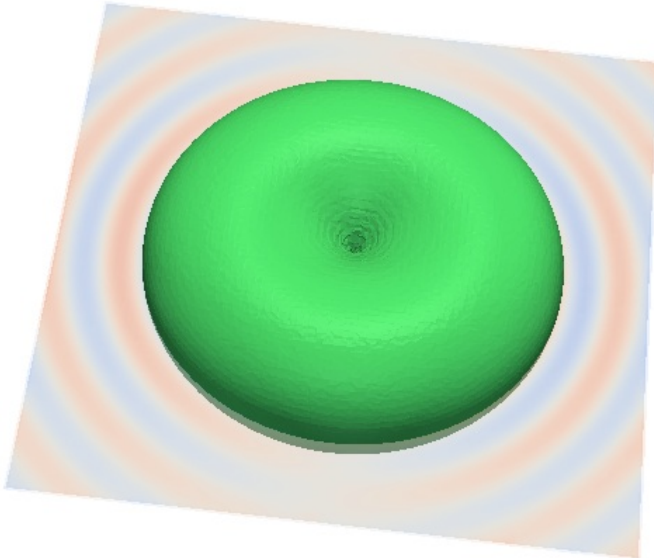


Electric field along an axis; the black curve gives the OPUS 3D result, the green curve is the analytical result.

Benchmark 1: Results (cont'd)



OPUS 3D



Analytical solution

Comparison of the emission beam – it shows how the dipole emits its power. Good results only with efficient Perfectly Matched Layer boundary conditions and correct treatment of both **E** and **H**.

Benchmark 2

Air-Glass-Air Interface
Reflection and Transmission Spectra

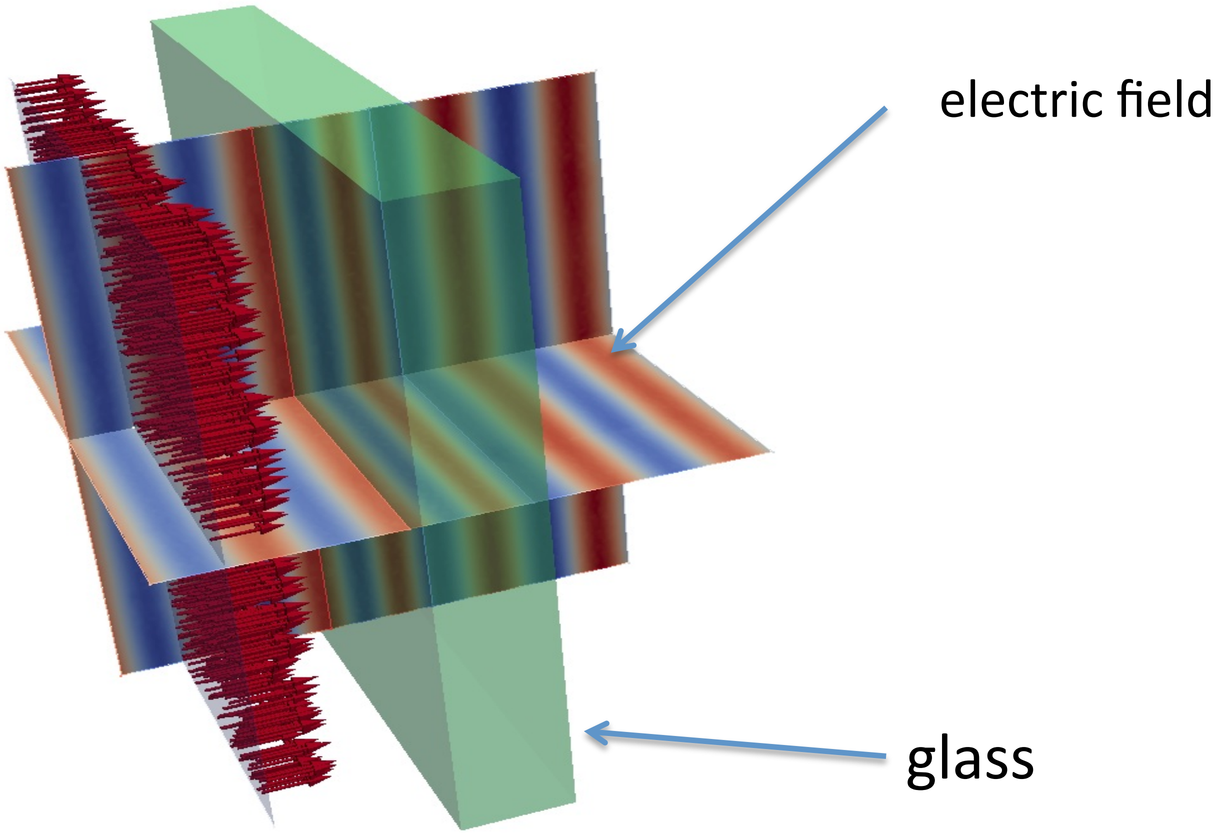
Benchmark 2 – Summary

- **Benchmark:**
  - Plane wave propagation for an air-glass-air structure
  - Computation of R and T
- **Validation:** Transfer-Matrix-Method (TMM)
- **Goals**
  - Show OPUS 3Ds abilities to compute R and T
  - Easy sweep through different wavelengths

Benchmark 2 – Computational Aspects

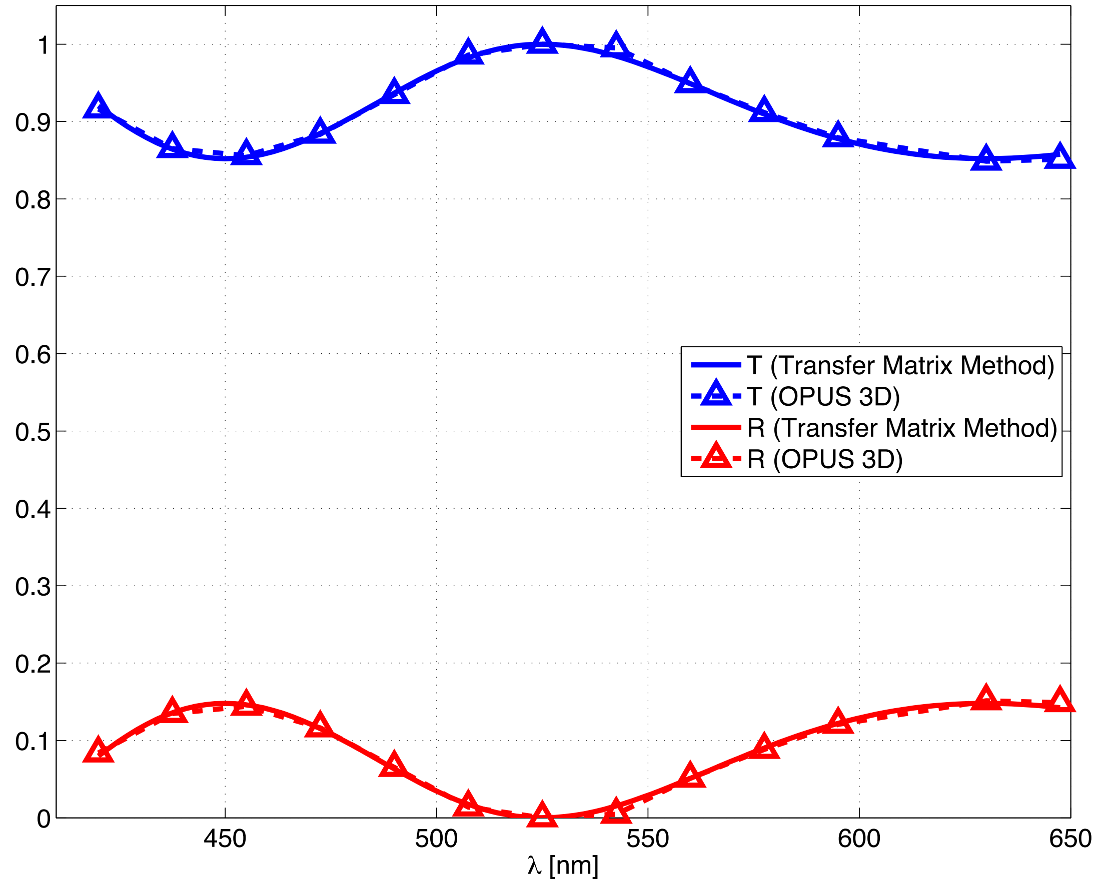
- Domain size: $12\lambda \times 12\lambda \times 5\lambda$
- Problem size: 621’780 DoF (Degrees of Freedom)
- Memory Consumption: 6.4 Gbyte
- Computation time (11 CPUs): 394 s per wavelength

Benchmark 2: Results



Model problem: plane wave (indicated by red arrows) propagates through a dielectric plane with refractive index $n = 1.5$. Plot shows the electric field.

Benchmark 2: Results (cont’d)



Comparison of OPUS 3D (dashed) and TMM (solid) results for various wavelengths. T is the transmission, R the reflection coefficient.

Benchmark 3

$\lambda/4$ Anti-Reflection Filter

Reflection and Transmission Spectra

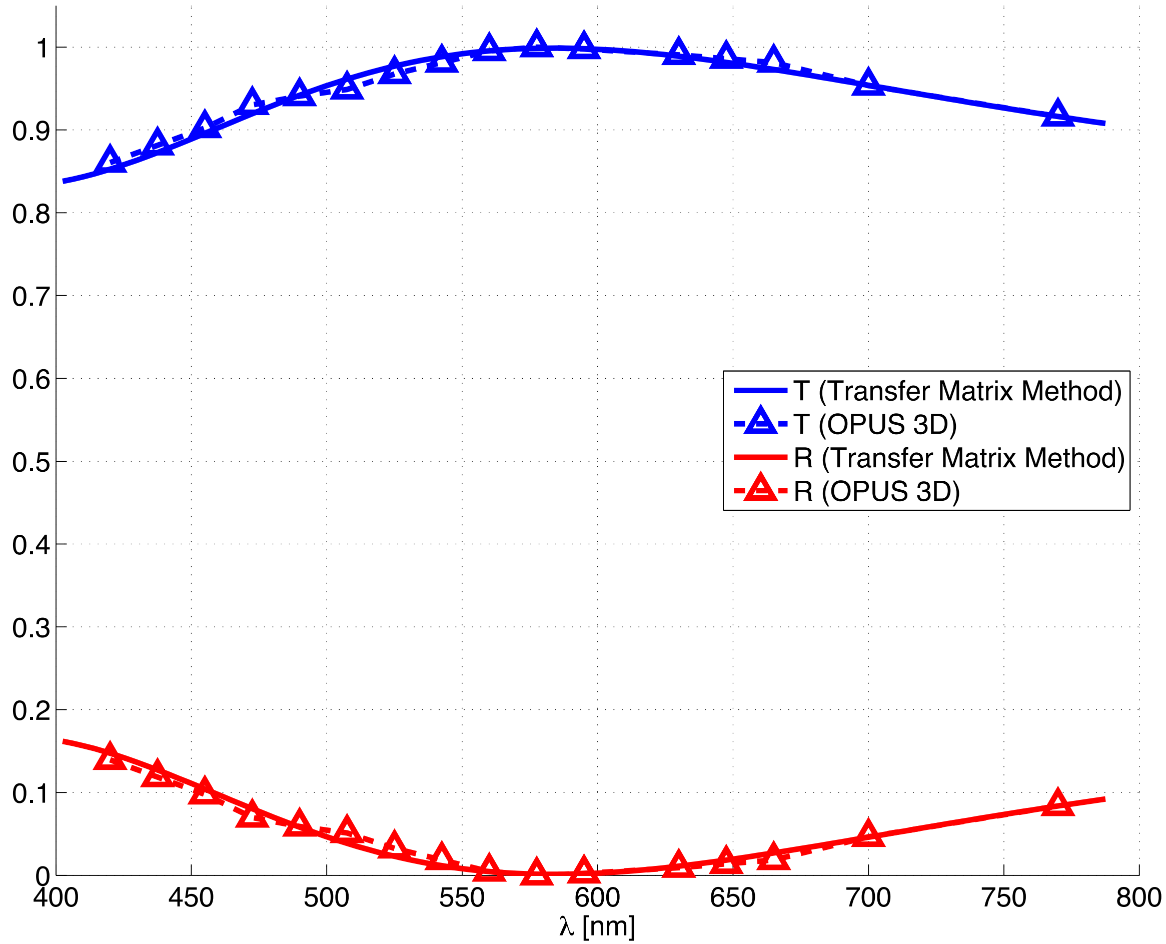
Benchmark 3 – Summary

- **Benchmark:**
  - Plane wave propagation for an $\lambda/4$ anti-reflection filter (4 layer structure)
  - Computation of R and T
- **Validation:** Transfer-Matrix-Method (TMM)
- **Goals**
  - Show OPUS 3Ds abilities to compute R and T
  - Easy sweep through different wavelengths

Benchmark 3 – Computational Aspects

- Domain size: $12\lambda \times 12\lambda \times 5\lambda$
- Problem size: 621’780 DoF (Degrees of Freedom)
- Memory Consumption: 6.4 Gbyte
- Computation time (11 CPUs): 480 s per wavelength

Benchmark 3: Results (cont'd)



Comparison of OPUS 3D (dashed) and TMM (solid) results for various wavelengths. T is the transmission, R the reflection coefficient.

Benchmark 4

Scattering from a Dielectric Sphere

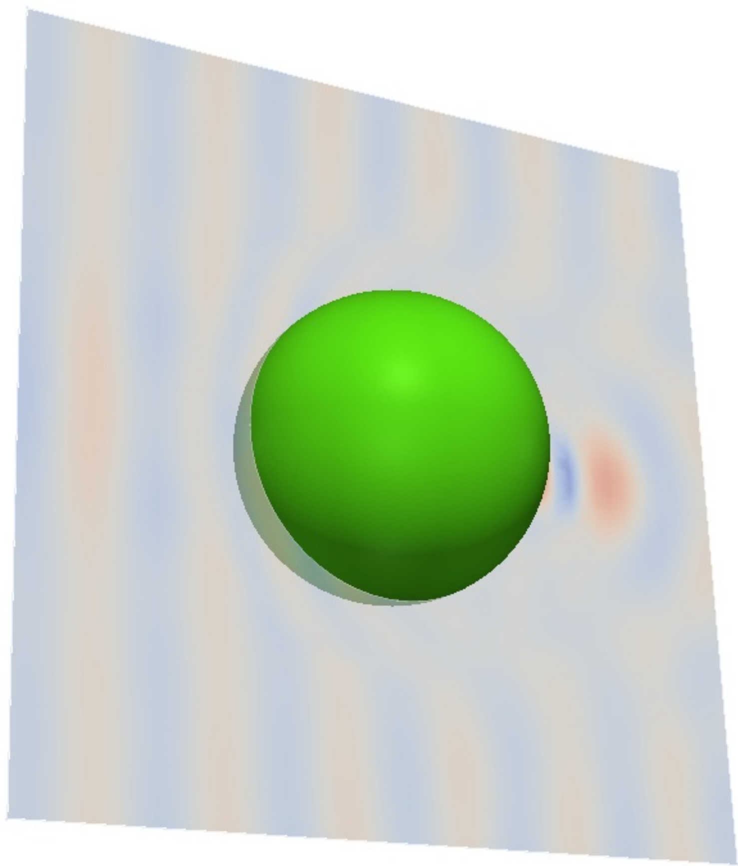
Benchmark 4 – Summary

- **Benchmark:** plane wave impinges on a dielectric sphere; refractive index $n = 2$, sphere radius $r = 1.8\ \lambda$
- **Validation:** Mie series
- **Goals**
  - Show that OPUS 3D can efficiently treat curved surfaces
  - Correct treatment of dielectric materials

Benchmark 4 – Computational Aspects

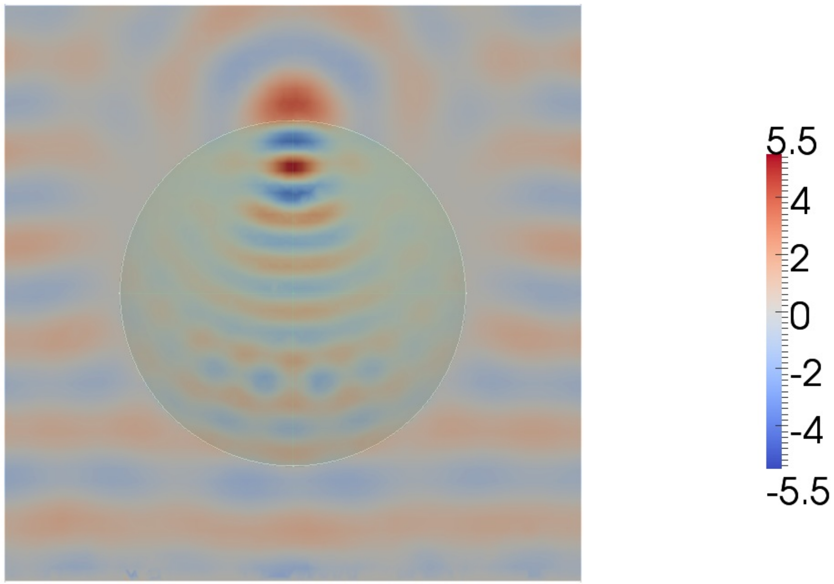
- Domain size: $11\lambda \times 11\lambda \times 11\lambda$
- Very fine mesh around sphere to account for curvature
- Problem size: 1’289’770 DoF
- Memory Consumption: 11 Gbyte
- Computation time (11 CPUs): 875 s

Benchmark 4: Results

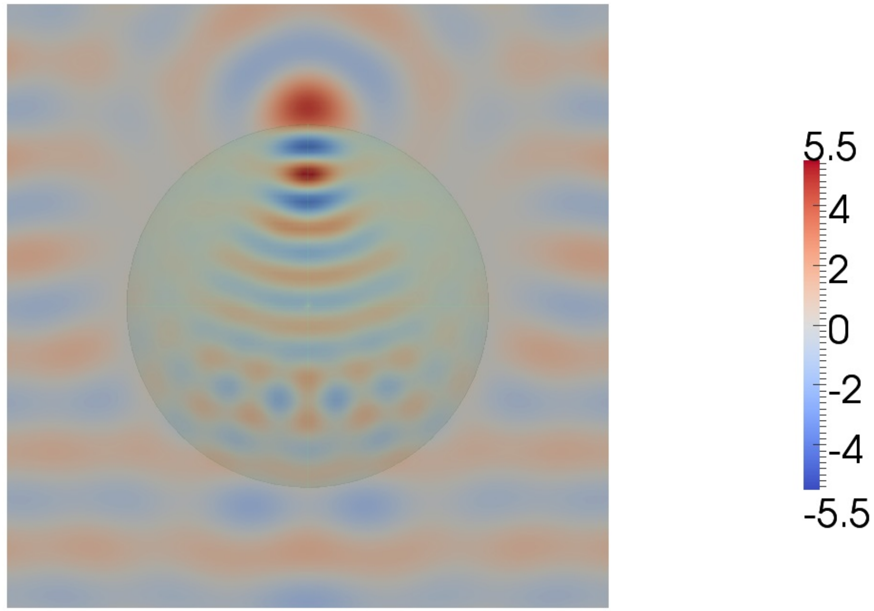


Model problem: plane wave hits a dielectric sphere with refractive index n=2. Plot shows the electric field.

Benchmark 4: Results (cont'd)



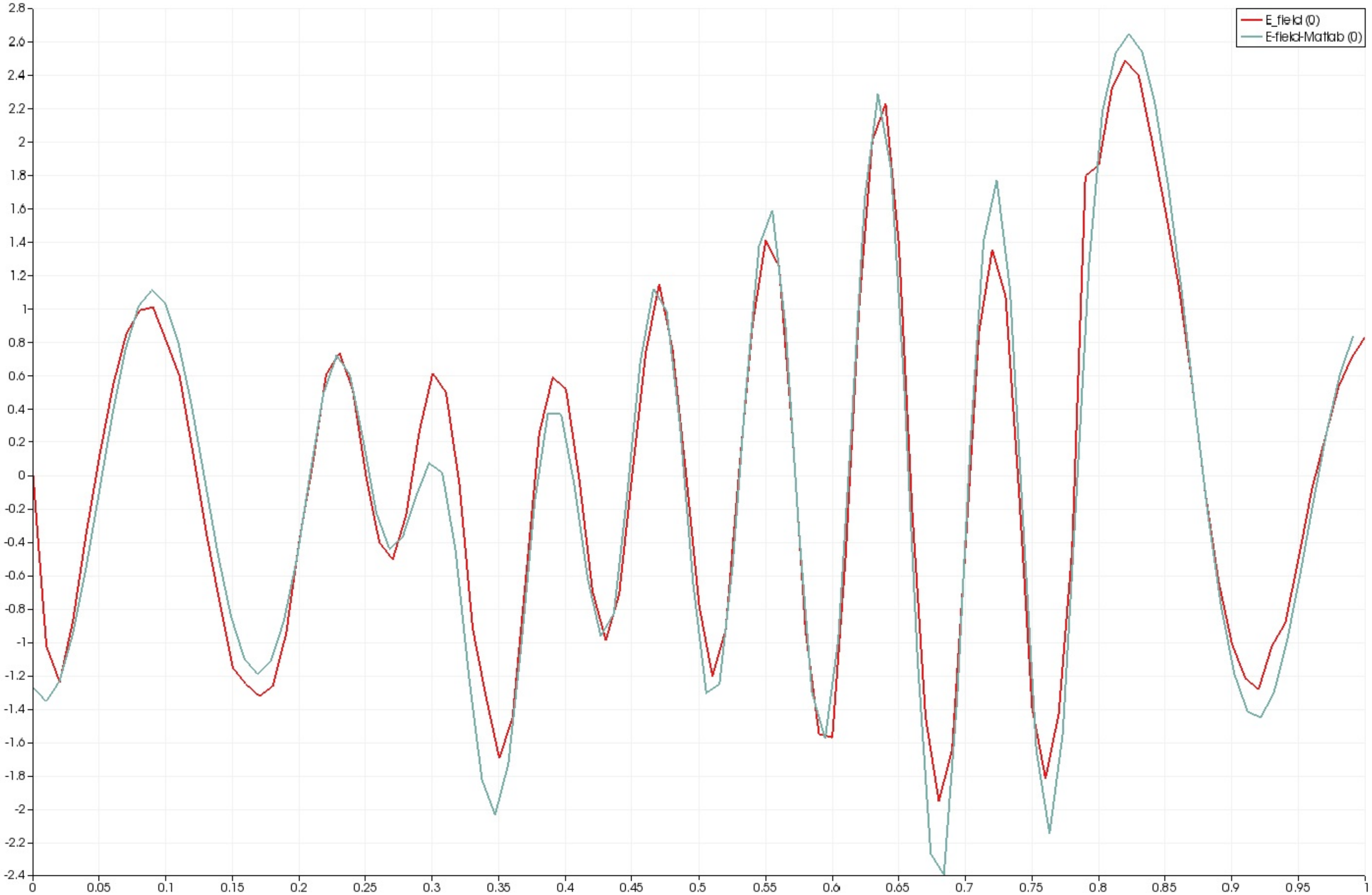
OPUS 3D



Mie series (Matlab)

Direct comparison of the computed electric fields in V/m. Both plots feature the same scale. Very good agreement both qualitatively and quantitatively.

Benchmark 1: Results (cont'd)



Electric field along an axis; the red curve gives the OPUS 3D result, the green curve is the analytical result.

Benchmark 5

Scattering from a Metallic Sphere

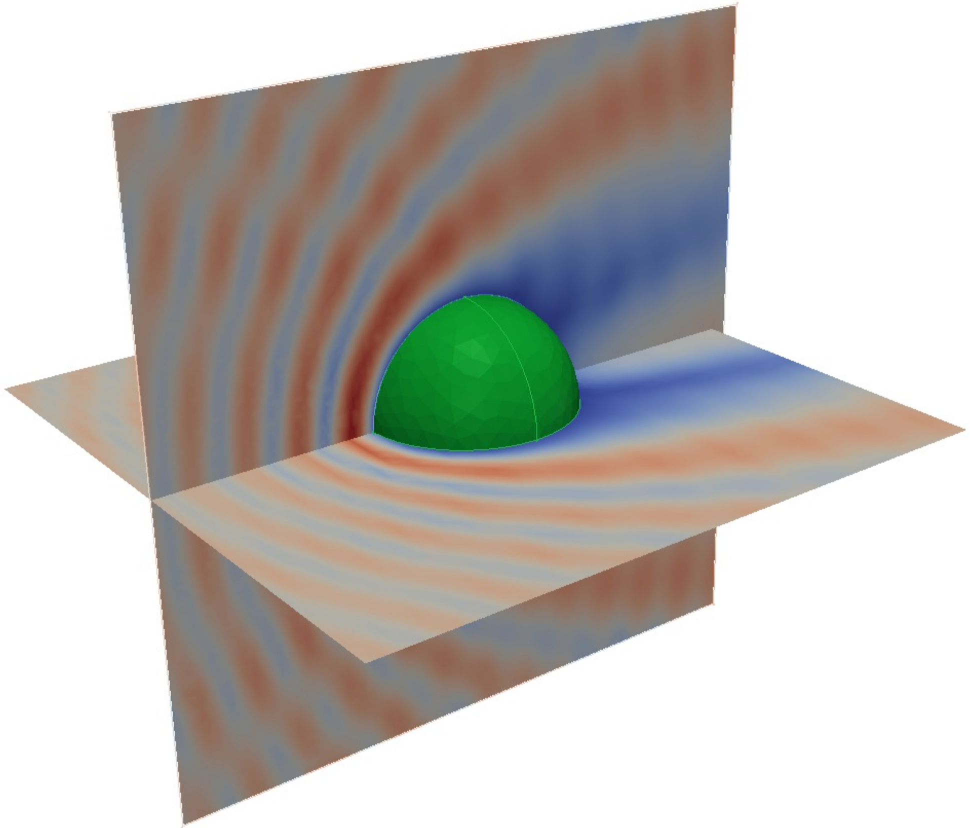
Benchmark 5 – Computational Aspects

Very similar to Benchmark 4

Benchmark 5: Scattering from a Metallic Sphere

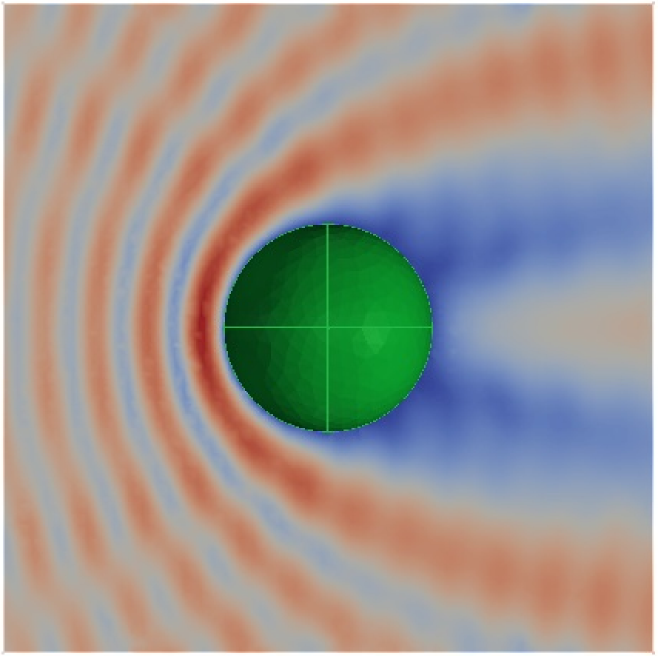
- **Benchmark:** plane wave impinges on a highly conducting sphere; radius $r = 1.0\ \lambda$
- **Validation:** Mie series
- **Goals**
  - Show that OPUS 3D can efficiently treat curved surfaces
  - Correct treatment of highly conductive metals

Benchmark 5: Results

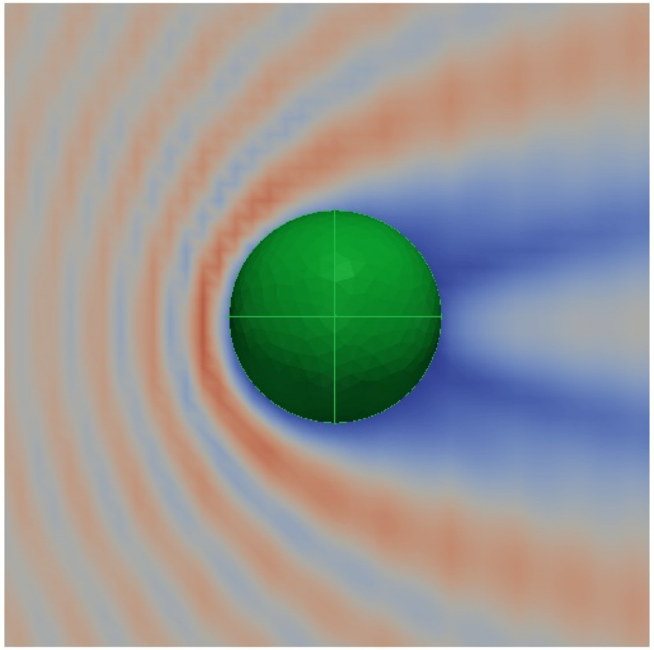


Direct comparison of both solutions. Vertical slice shows the intensity computed with OPUS 3D, horizontal slice shows intensity obtained from Mie series.

Benchmark 5: Results (cont'd)



OPUS 3D

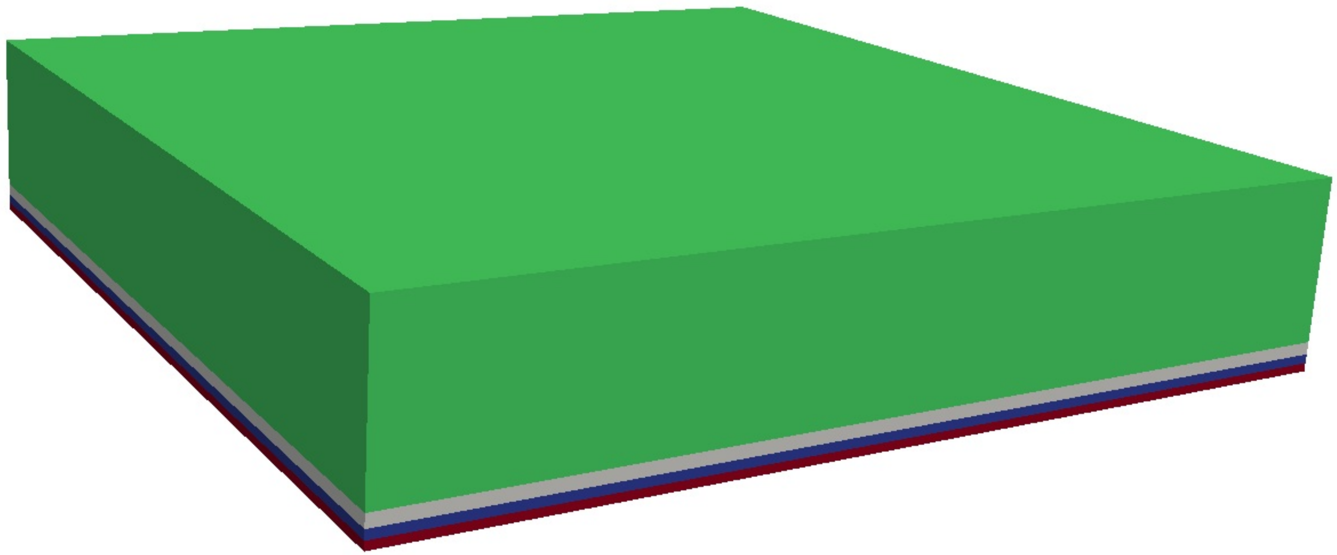


Mie series (Matlab)

Direct comparison of the computed intensities. Very good agreement both qualitatively and quantitatively.

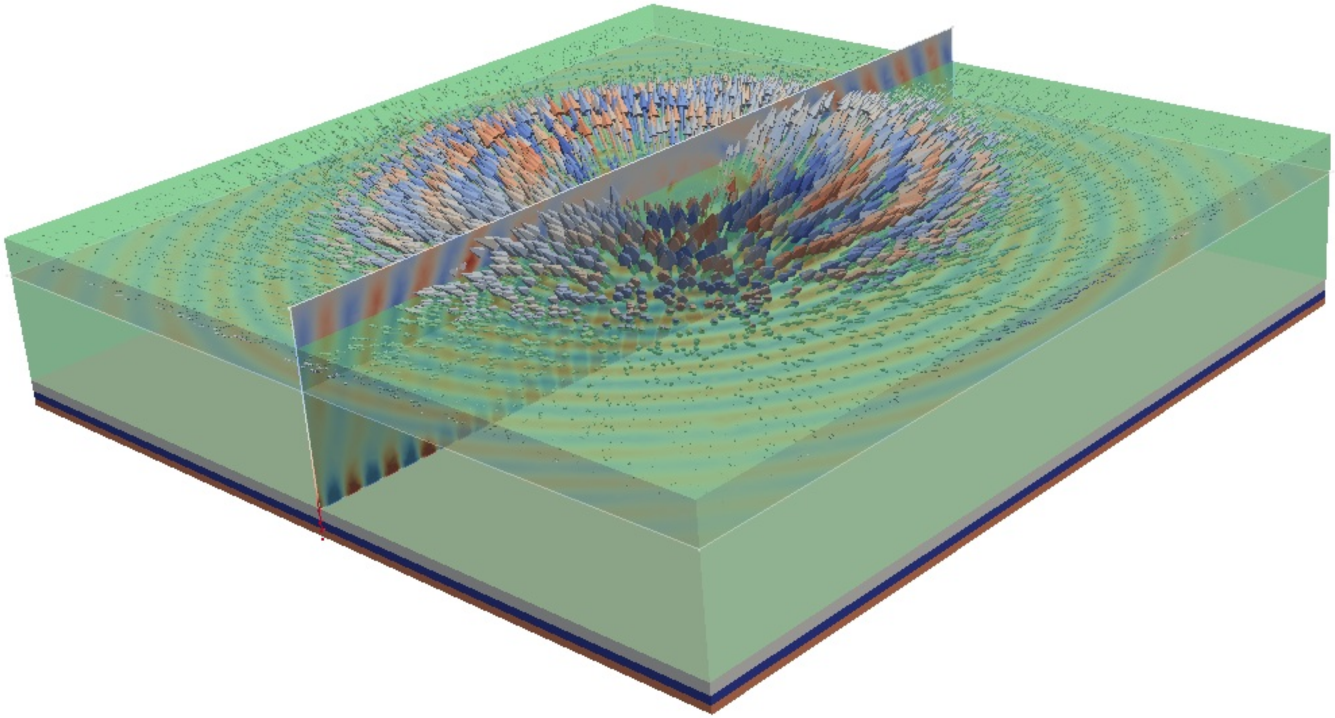
Benchmark 6
Plain LED

Benchmark 6: Geometry



Simulation domain: 6μm × 6μm × 2.5μm
4-layer structure
Layer thickness: between 100nm and 2μm
Computational resources: 11min (10 processors), 17GB RAM

Benchmark 5: Results



Full-wave solution of LED example. The slices show the Ez field component, the arrows indicate the power flow.

Summary

Benchmark Summary

The benchmarks strongly indicate that OPUS 3D

- is computationally efficient on large domains,
- correctly treats dipole sources,
- correctly accounts for plane wave sources,
- is able to deal with both metallic and dielectric material interfaces,
- and can efficiently treat 3-D geometries with curved surfaces.