Adaptive Cross Approximation Solver in the Serenity Radar Cross Section Prediction Code

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Serenity Overview

- **Serenity** is a high-performance, full-wave radar cross section (RCS) solver using the Method of Moments (MoM)
  - Solves surface integral equations (SIE) of scattering
    - Bounding surfaces of conductors and dielectric interfaces are meshed.
  - Objects having conducting (PEC) and bulk dielectric parts with junctions are fully supported.
    - Serenity enforces the EFIE on open conductors, CFIE on closed conductors, and PMCHWT on dielectrics.
- **Choice of linear system solvers**
  - Full matrix with straightforward LU-decomposition
  - Iterative solvers accelerated via Fast Multipole Method (FMM)
  - Block LU-decomposition of matrix in compressed form via Adaptive Cross Approximation (ACA)
    - BLAS Level 3 operations accelerated via Intel Math Kernel Library (CPU version) or NVIDIA cuBLAS (GPU version)
- All routines (matrix fill/solve) are parallelized via threads
- Linux and Windows versions of Serenity are available
Serenity Overview (2)

- Developer: Walton C. Gibson
  - Industry expert in the Method of Moments applied to Electromagnetic Problems
  - Author of *The Method of Moments in Electromagnetics*, 1st and 2nd Edition

- Serenity Version History
  - v. 1.0 (2003): Written in C, supporting conducting objects and full matrix approach.
  - v. 2.0 (2012): Complete re-write in C++, full support for conductors and dielectrics.
ACA Solver Overview

- As the MoM system matrix is dense, a full matrix approach is not tractable for electrically large problems
  - In-core solutions limited to a few tens of thousands of unknowns
  - on current 2015 server-class systems.
- The *Serenity* ACA solver groups basis functions into spatially local groups, breaking up the system matrix into block form.
  - Diagonal blocks due to interactions within a group are computed and stored as usual
  - Rank-deficient off-diagonal blocks are computed and stored in compressed outer-product form on the fly using the ACA algorithm.
    - The ACA algorithm uses only selected rows and columns of each block – a significant portion of the matrix is not computed explicitly.
ACA Solver Overview (2)

• Compression of 98% or more versus the full matrix approach are possible on electrically larger problems.
  • Consider N = 500000, in single precision complex:
    • Full matrix: 1862 GB RAM
    • ACA with 98% compression: 37 GB RAM (solvable in-core!)

• Block matrix can be LU-factored in compressed form directly
  • LU factors also compressible via ACA
  • Can be done very fast using accelerated BLAS Level 3 functions
    • Intel MKL BLAS (SSE/AVX optimized for Intel processors)
    • NVIDIA CUDA BLAS (cuBLAS) on NVIDIA GPUs
  • Direct solve via LU decomposition eliminates problems caused in iterative solvers due to poorly conditioned system matrix

• The thousands of right-hand sides in a scattering problem can be solved simultaneously and efficiently
  • Right-hand side matrix is compressible in block form via ACA
  • Solution (current) matrix also compressible in block form via ACA
  • Nyquist sampled far fields can be computed very quickly
Example: PEC Sphere

- 0.5 m radius
- 81920 triangles \( (N = 122880) \)
- Bistatic RCS at 3.0 GHz
Example: Coated PEC Sphere

- 0.25 m radius PEC sphere
- 0.25 m thick dielectric coating ($\varepsilon = 2.54$)
- 25600 triangles ($N = 69120$)
- Monostatic RCS from 50 MHz to 1.5 GHz
Example: PEC Reentry Vehicle

- RCS at 5 GHz and 9.5 GHz
- 103384 triangles (N = 155076) @ 5 GHz
- 371624 triangles (N = 557436) @ 9.5 GHz
- *Serenity ACA* Solver compared against *Galaxy Body-of-Revolution* MOM Code
- Comparison is excellent at all aspect angles in both wavebands

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**VV RCS (5 GHz)**

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**HH RCS (9.5 GHz)**
Example: Reentry Vehicle With Dielectric Nose Tip

- RCS at 5.0 GHz and 9.5 GHz
- 106696 triangles (N = 166264) @ 5 GHz
- 375980 triangles (N = 585348) @ 9.5 GHz
- *Serenity* ACA Solver compared against *Galaxy* Body-of-Revolution MOM Code
- Comparison is excellent at all aspect angles

\[ R = 0.0375 \text{ m} \]
\[ \varepsilon = 5.0 \]

![Diagram of reentry vehicle with dielectric nose tip](image)

**VV RCS (5 GHz)**

**HH RCS (9.5 GHz)**
CPU vs. GPU-accelerated ACA Solvers

- Comparison executed on a Dell Precision 7500 Workstation
  - 8-core Intel Xeon W5580 CPU + HT (16 threads), 128 GB RAM
- CPU ACA solver uses Intel Math Kernel Library (MKL) v. 11.1.4
- GPU ACA Solver uses NVIDIA CUDA 6.5 and 1 GeForce GTX 770
  - GeForce GTX 770 released in May, 2013
    - Kepler Architecture, 1536 CUDA Cores, 4 GB of Memory
    - Multi-GPU configurations (pictured) are also supported by Serenity
CPU vs. GPU-accelerated ACA Solvers (2)

- Compare run times of PEC sphere, PEC RV and RV With Nose Tip
- ACA matrix fill is executed on CPU in both solvers
- ACA LU factorization and right-hand solve utilizes MKL or GPU
- In monostatic case, all right-hand sides solved for simultaneously
- GTX 770 GPU is 4 to 5 times faster than MKL (16 threads) depending on problem
  - Adding additional GPUs will improve factorization time significantly
    - If the user adds additional GPUs, Serenity can utilize them right away

<table>
<thead>
<tr>
<th>Test Case</th>
<th>N</th>
<th>$T_{\text{Fill}}$</th>
<th>$T_{\text{LU}}\text{ (MKL)}$</th>
<th>$T_{\text{LU}}\text{ (GPU)}$</th>
<th>$T_{\text{RHS}}\text{ (MKL)}$</th>
<th>$T_{\text{RHS}}\text{ (GPU)}$</th>
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<tbody>
<tr>
<td>PEC Sphere</td>
<td>122880</td>
<td>260 s</td>
<td>1551 s</td>
<td>284 s</td>
<td>67 s</td>
<td>67 s</td>
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<td>PEC RV (5.0 GHz)</td>
<td>155076</td>
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<td>2162 s</td>
<td>427 s</td>
<td>64 s</td>
<td>25 s</td>
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<td>PEC RV (9.5 GHz)</td>
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<td>2264 s</td>
<td>12.9 hr</td>
<td>3.01 hr</td>
<td>992 s</td>
<td>286 s</td>
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<td>RV/Nose (5.0 GHz)</td>
<td>166264</td>
<td>441 s</td>
<td>2599 s</td>
<td>531 s</td>
<td>74 s</td>
<td>29 s</td>
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<tr>
<td>RV/Nose (9.5 GHz)</td>
<td>585348</td>
<td>2580 s</td>
<td>14.9 hr</td>
<td>3.5 hr</td>
<td>1162 s</td>
<td>337 s</td>
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</tbody>
</table>
Example: Reentry Vehicle With Dielectric Nose

- Per-frequency run time via ACA is small enough that wide-band runs are possible
  - Previously unattractive in the full-matrix approach as the system matrix must be filled and factored at each frequency
- RV + Dielectric Nose Tip simulated at 64 frequencies between 5 and 6 GHz
- FFT used to convert frequency-domain data to range domain
  - 1 GHz bandwidth yields range resolution of approximately 15 cm
- *Serenity* ACA Solver compared against *Galaxy* Body-of-Revolution MOM Code
- Results are nearly indistinguishable in VV-polarization

![Galaxy (MoM/BOR) 5-6 GHz](image1)

![Serenity (MoM/ACA) 5-6 GHz](image2)