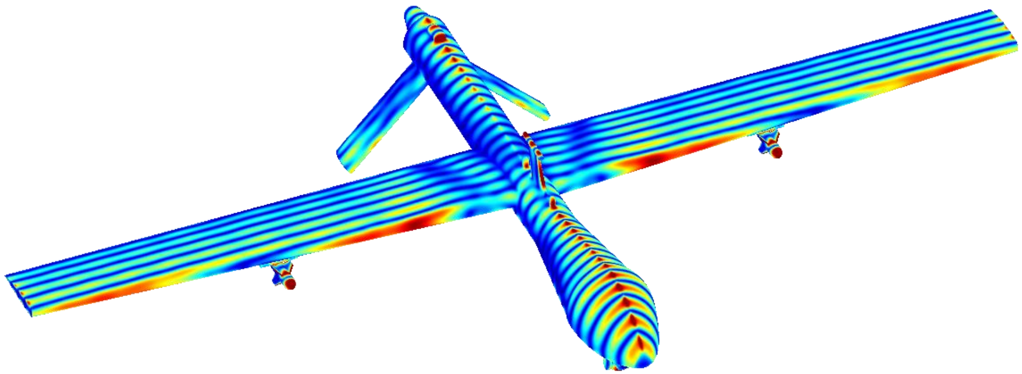
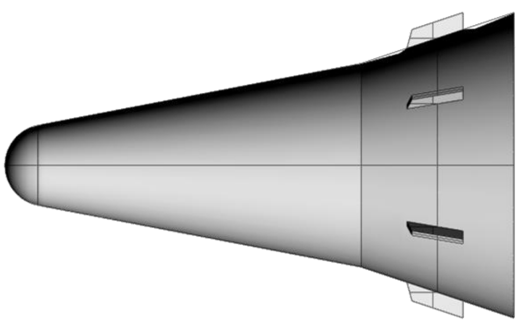
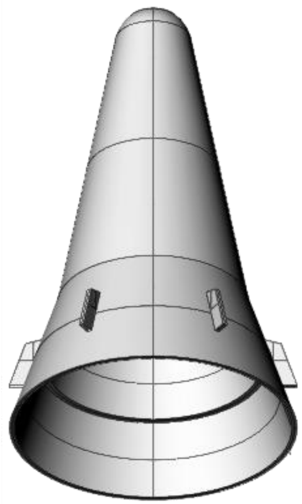
Adaptive Cross ApproximationSolver in the *Serenity* Radar Cross Section Prediction Code

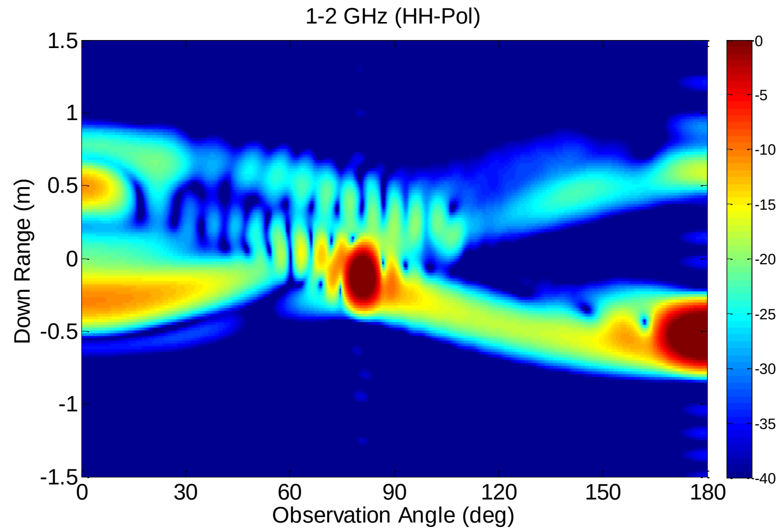
Tripoint Industries, Inc.

May 15, 2015









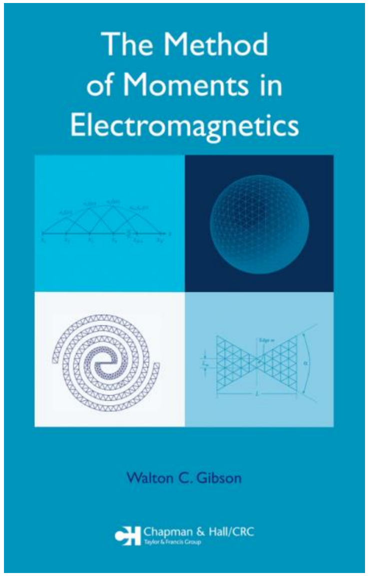
Serenity Overview

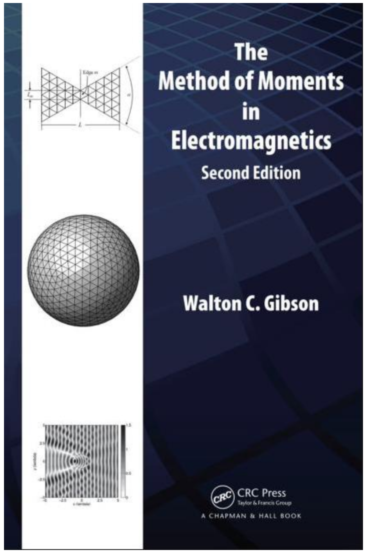
- ***Serenity*** **is a high-performance, full-wave radar cross section (RCS) solver using the Method of Moments (MoM)**
  - **Solves surface integral equations (SIE) of scattering**
    - **Bounding surfaces of conductors and dielectric interfaces are meshed.**
  - **Objects having conducting (PEC) 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**

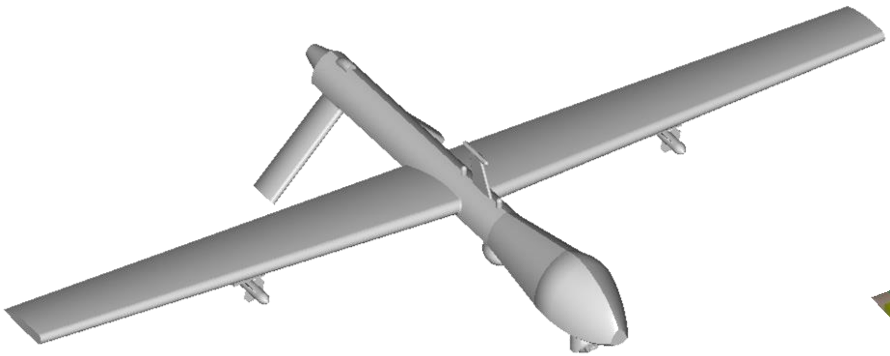
- ***Serenity* Version History**
  - **v. 1.0 (2003): Written in C, supporting conducting objects and full matrix approach.**
  - **v. 1.2 (2005): Added iterative solvers accelerated using the Multilevel Fast Multipole Algorithm (MLFMA). Large problems could be solved.**
  - **v. 2.0 (2012): Complete re-write in C++, full support for conductors and dielectrics.**
  - **v. 2.1 (2015): Added high-performance CPU and GPU-accelerated Adaptive Cross Approximation (ACA) solvers.**

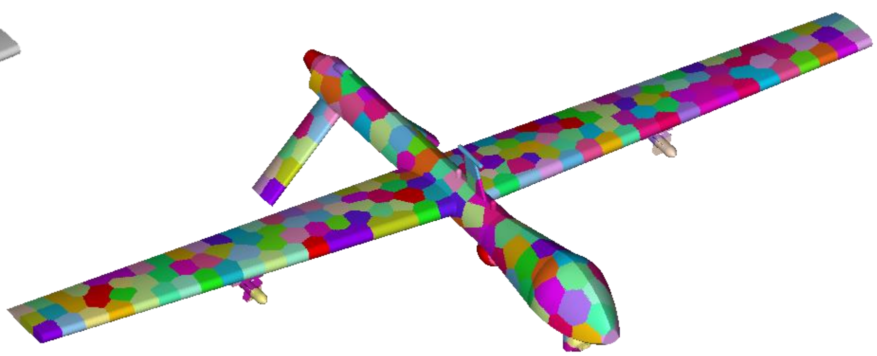




ACA Solver Overview

- **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

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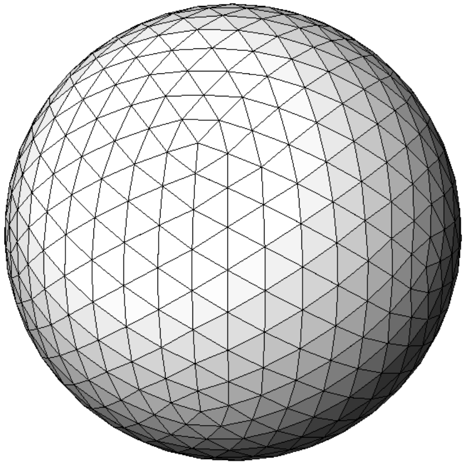
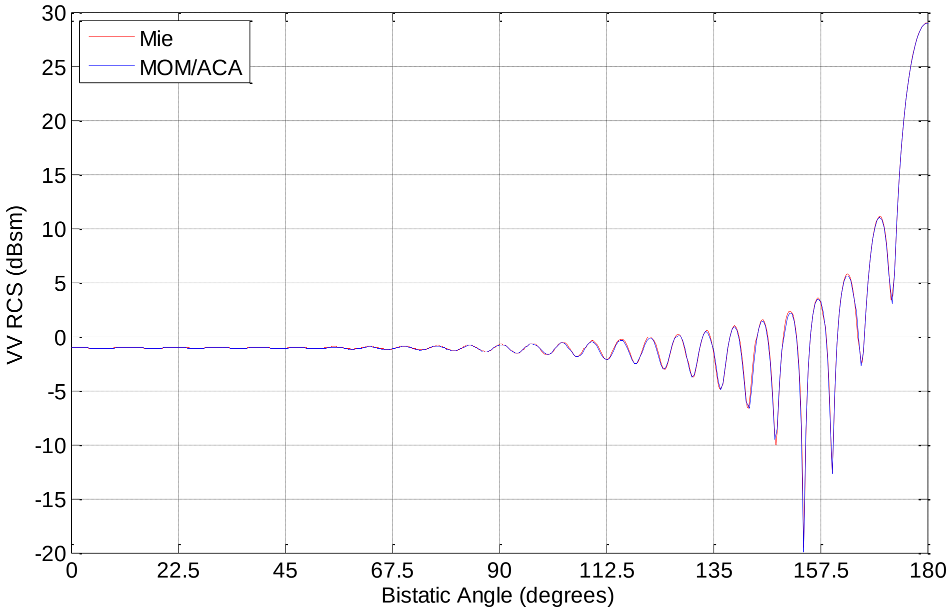
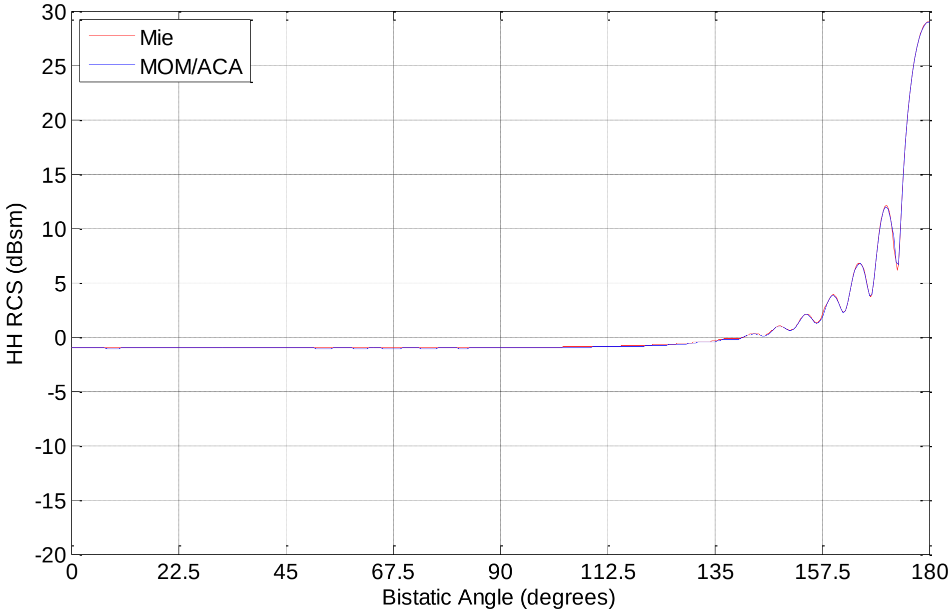
- **0.5 m radius**
- **81920 triangles (N = 122880)**
- **Bistatic RCS at 3.0 GHz**







Example: Coated PEC Sphere

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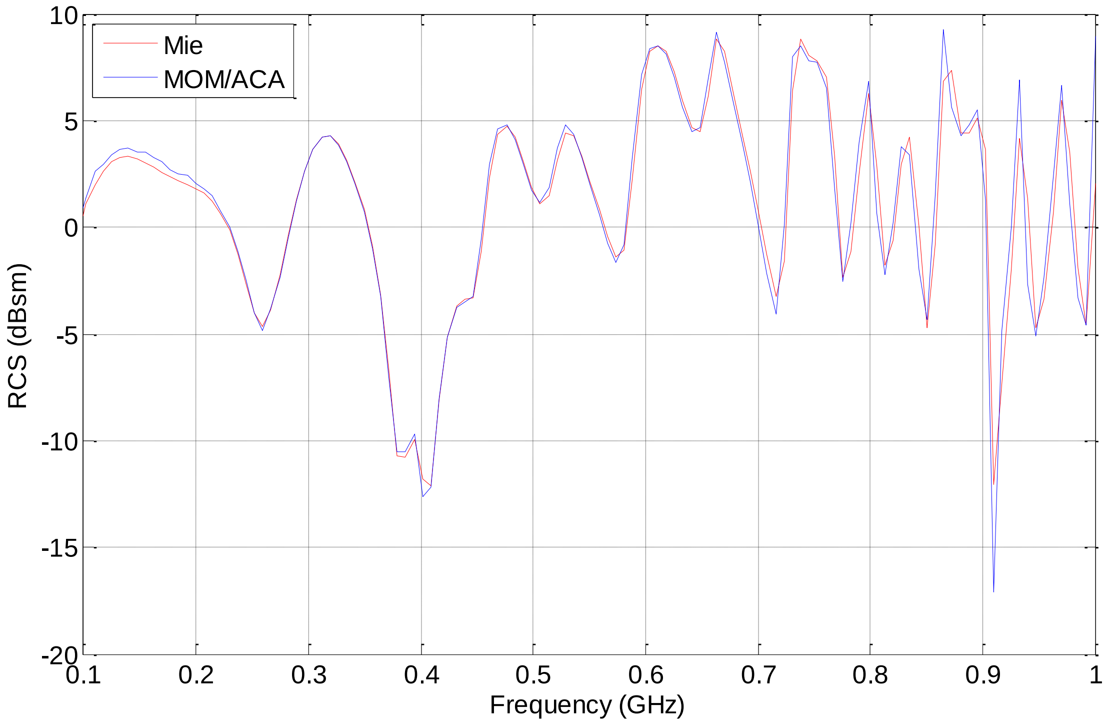
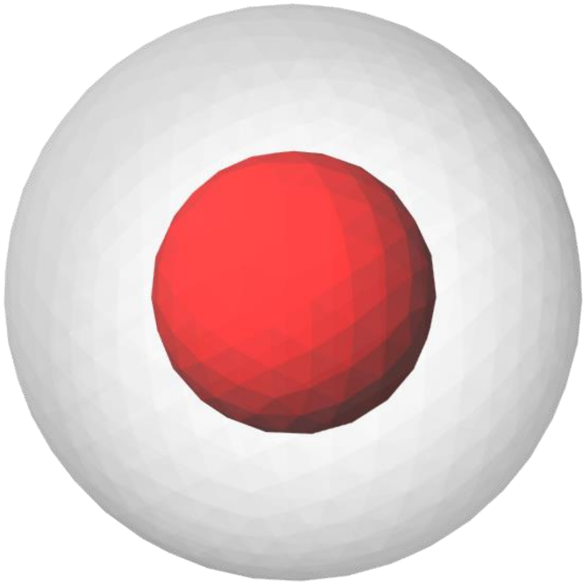
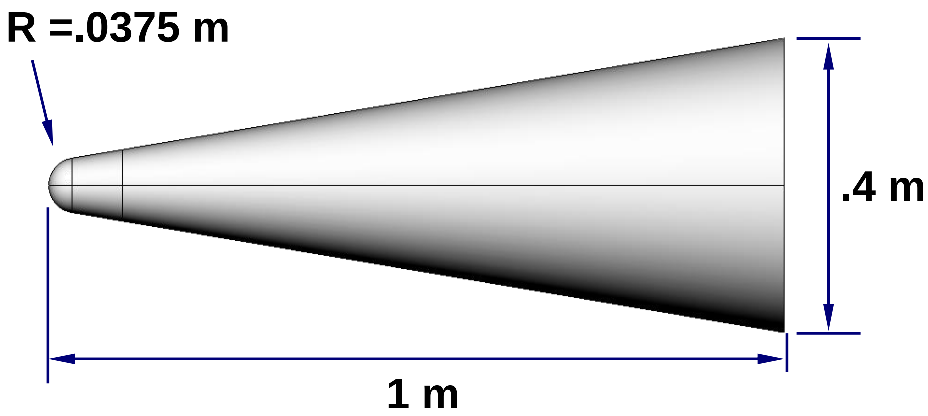
- 0.25 m radius PEC sphere
- 0.25 m thick dielectric coating (ε = 2.54)
- 25600 triangles (N = 69120)
- Monostatic RCS from 50 MHz to 1.5 GHz

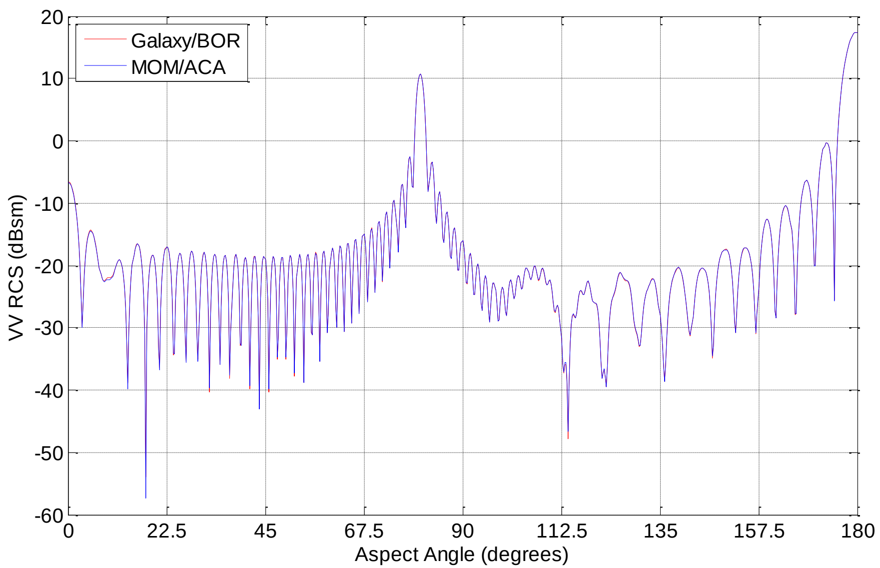




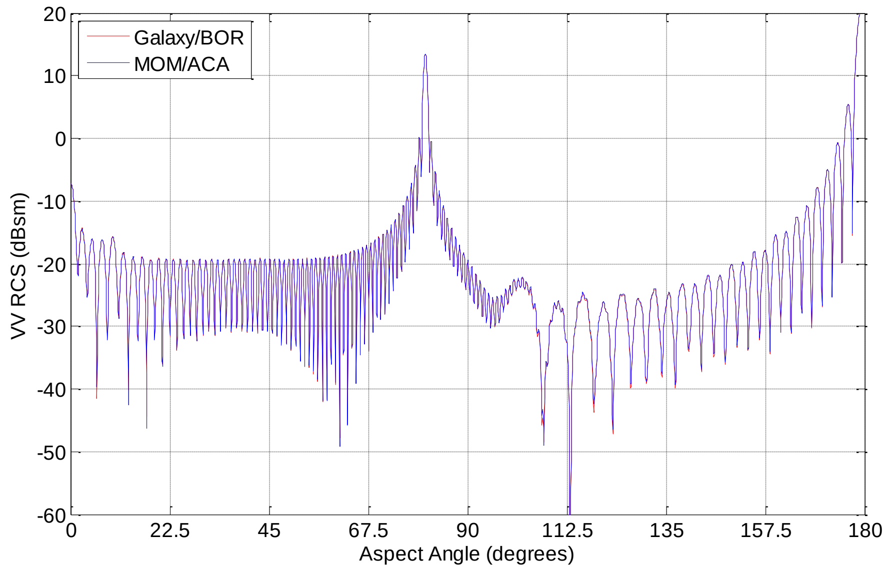
Example: PEC Reentry Vehicle



- 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

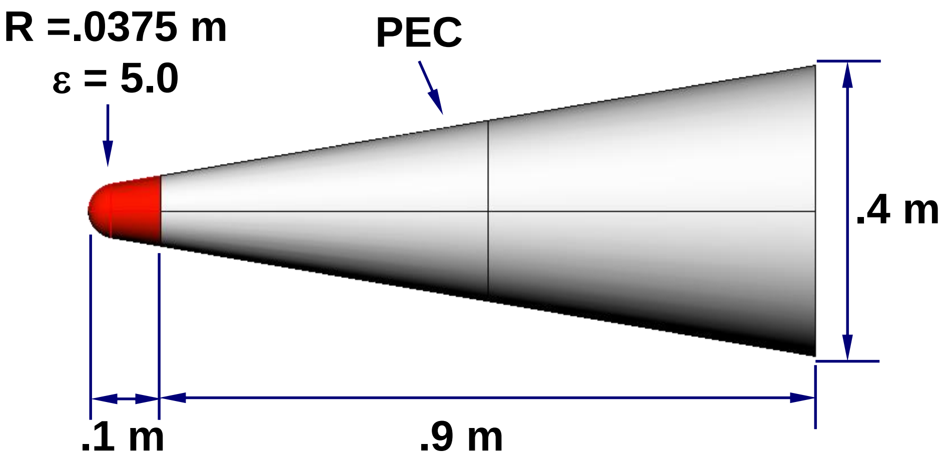


VV RCS (5 GHz)

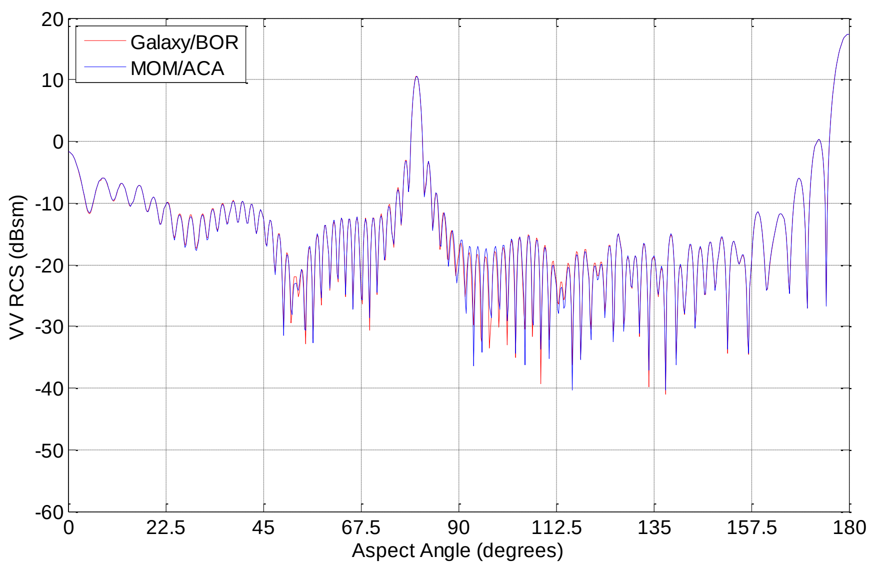


HH RCS (9.5 GHz)

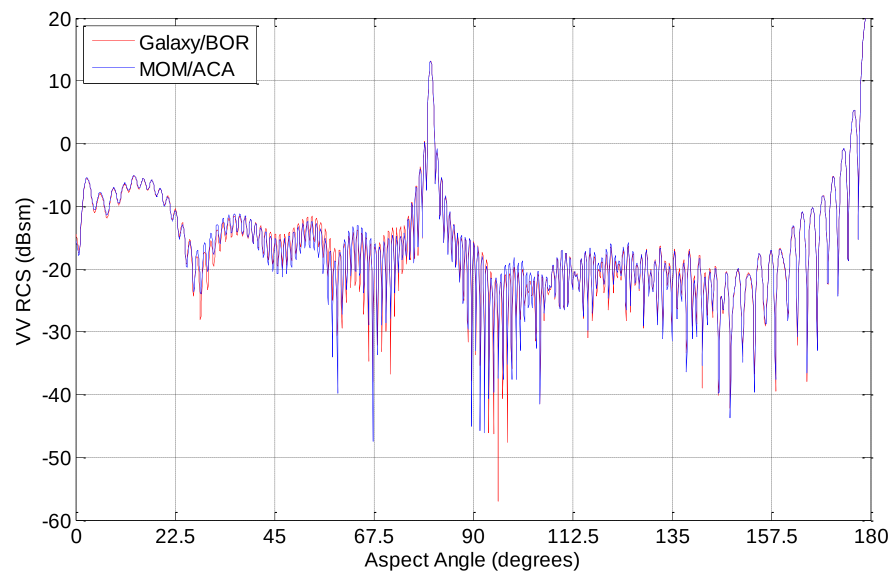
Example: Reentry Vehicle With Dielectric Nose Tip



- 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



VV RCS (5 GHz)

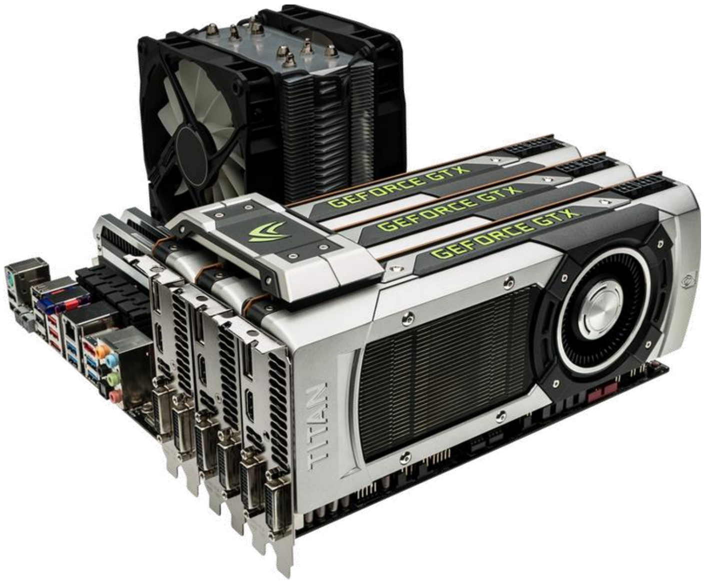


HH RCS (9.5 GHz)

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***

GeForce GTX 770 GPU



Multi-GPU Configuration

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**

Test Case	N	T_{Fill}	T_{LU} (MKL)	T_{LU} (GPU)	T_{RHS} (MKL)	T_{RHS} (GPU)
PEC Sphere	122880	260 s	1551 s	284 s	67 s	67 s
PEC RV (5.0 GHz)	155076	338 s	2162 s	427 s	64 s	25 s
PEC RV (9.5 GHz)	557436	2264 s	12.9 hr	3.01 hr	992 s	286 s
RV/Nose (5.0 GHz)	166264	441 s	2599 s	531 s	74 s	29 s
RV/Nose (9.5 GHz)	585348	2580 s	14.9 hr	3.5 hr	1162 s	337 s

Example: Reentry Vehicle With Dielectric Nose

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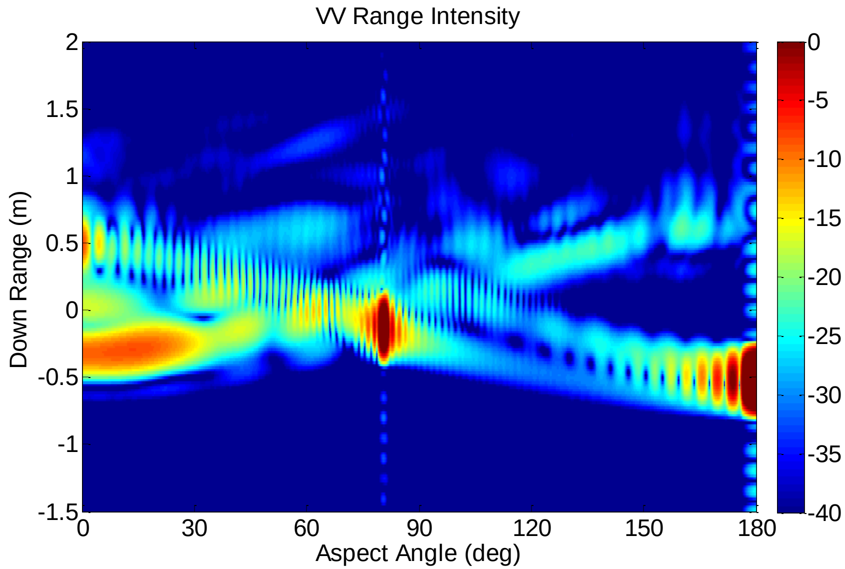
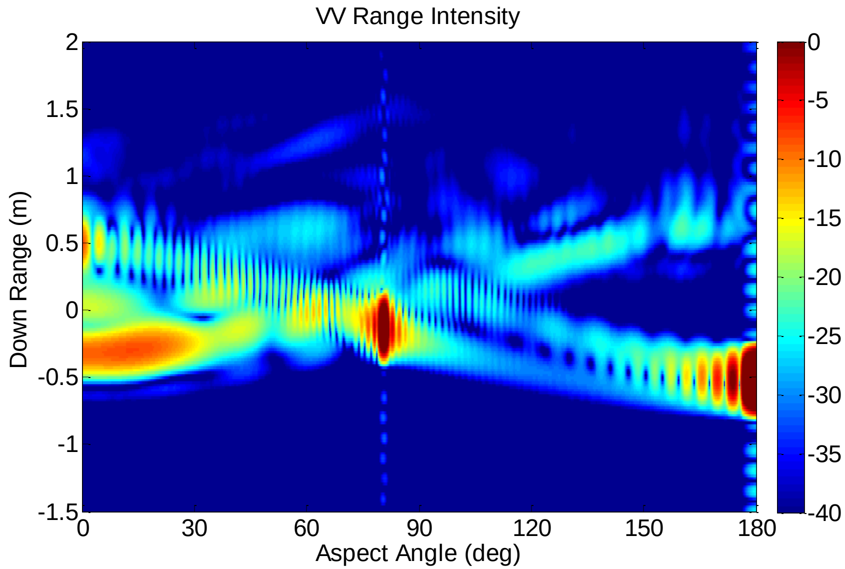
- **Per-frequency run time via ACA is small enough that wide-band runs are possible**
  - **Previously unattractive in the full-matrix approach as the system matrix must be filled and factored at each frequency**
- **RV + Dielectric Nose Tip simulated at 64 frequencies between 5 and 6 GHz**
- **FFT used 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**



***Serenity* (MoM/ACA) 5-6 GHz**