Applying Advanced Computing to Improve High-Fidelity Radar Data Simulations

HPEC 2006 - High Performance Rapid Prototyping

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Outline

- **Introduction**
  - radar system analysis
  - clutter signal model and simulation problem size
- **Implementations**
  - Matlab
  - MEX functions
  - parallel Matlab simulations
  - Standalone code
- **Performance Results**
  - Matlab
  - standalone
- **Summary and Future Work**

Radar System Analysis

- Radar signal modeling has proven valuable in characterizing system performance
- Most performance measures are evaluated over short time intervals
- Other performance measures such as tracking require longer processing intervals
- Simulating enough data for tracking analysis can take weeks or even months on single nodes
- Some signal models reduce fidelity to decrease required simulation run times
- Another approach is to implement high-fidelity models and apply high performance computing resources

Clutter Signal Model

- **A typical clutter signal is**

$$\mathbf{x}_c(t) = \sum_{p=1}^{P} \alpha_p \mathbf{s}_p(t) \circ \mathbf{v}_p \circ \mathbf{u}_p \in C^{NM \times 1}$$

  - α_p is the complex scattering amplitude of the p^{th} patch
  - $\mathbf{s}_p(t)$ is an arbitrary waveform varying for each pulse and channel
  - $\mathbf{v}_p$ is the space-time steering vector for the pth patch
  - $\mathbf{u}_p$ is a unit energy modulation mechanism accounting for temporal and spatial subspace leakage
- **The signal model accounts for real-world effects including**
  - range walk and bandwidth effects
  - environment databases (e.g. terrain and land cover data)
  - platform acceleration during a CPI (e.g. satellite orbits)
- **Since all parameters are independent from patch to patch, this problem is embarrassingly parallel**

Problem Size

- **All terms, except α_p, are M*NxL complex matrices**
  - M is the number of pulses in a CPI
  - N is the number of receive array channels
  - L is the number of range bins in the radar data
- **There are on the order of 4*M*N*L*P floating point multiplications and M*N*L*(P-1) complex additions (P is the number of clutter patches in the problem)**
- **Typical parameter values**
  - M*N = 1000
  - L = 1000
  - P = 35e6
  - 910 TFLOPS
- **Comparatively space-time adaptive processing of a comparably sized data cube is on the order of 5 GFLOPS**

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Implementations

- **Matlab toolbox implementation**
  - serial
  - MEX functions
  - parallel simulations using MatlabMPI/pMatlab
- **Standalone implementation**
  - based on same code as MEX
  - parallel implementations using MPI and OpenMP
- **Implementation summary**

Matlab Implementation

- **The radar simulation code is divided into three Matlab toolboxes**
- **Splatter, Clutter, and Target Signal (SCATS) toolbox**
  – RF phenomenology functions
  – site-specific modeling including terrain and land cover effects
- **Radar simulation toolbox**
  – radar simulation framework including task/parameter initialization and loop over patches
  – uses function handles to run the tasks allowing easy changing of models including of user-written models
  – IQ data and RF phenomenology outputs
- **Space-Based Radar toolbox**
  – space-based scenarios and clutter modeling
  – space-based simulation tools including the clutter signal model described earlier

MEX Function Implementations

- **Even though Matlab is built on many well-optimized libraries, some functions can perform better when written in a compiled language (e.g. C and Fortran)**
- **Matlab recognizes this and provides a convenient API for interfacing code written in C and fortran to Matlab functions**
- **These interfaces are known as MEX functions**
- **Other benefits of MEX functions**
  - can exploit multi-core processors using threads and OpenMP
  - easier transition to Matlab-independent software
  - external code implementations are constantly and thoroughly exercised by analysts using Matlab simulations

VSIPL Library

- **The MEX functions are based on ISL C libraries that use the Vector, Signal, and Image Processing Library (VSIPL) for portable and efficient vector, matrix, and signal processing operations**
- **ISL has optimized parts of the VSIPL library for AMD/Intel architectures**
  - OpenMP parallelization
  - AMD Core Math Library (including the vector math functions)
  - Intel Math Kernel Library
- **Additional optimizations will be implemented based on profile results**
  - more BLAS functions
  - VSIPL FFT functions may use FFTW3 or the AMD/Intel library FFT functions

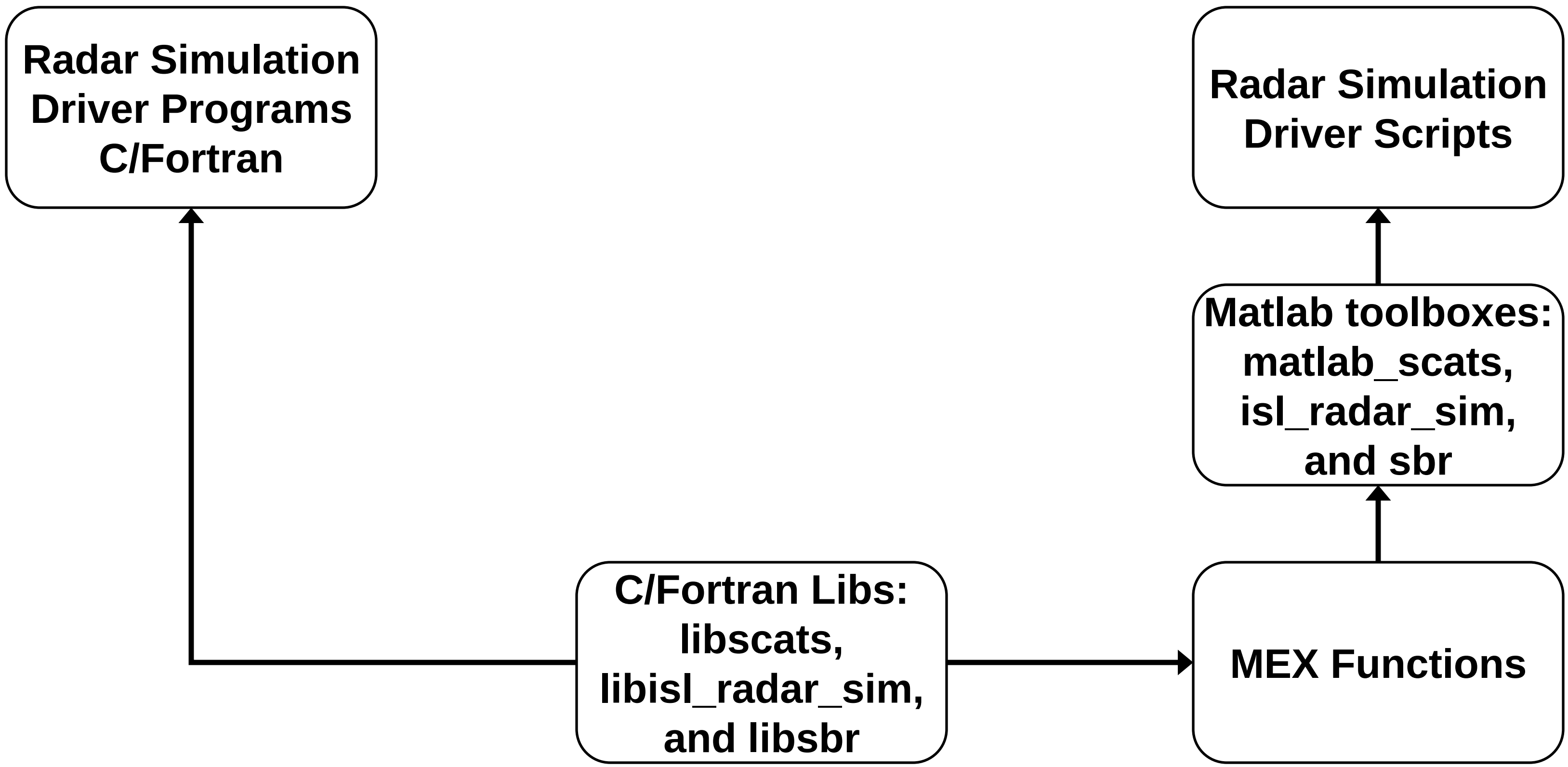
Parallel Radar Simulations

- **MatlabMPI and pMatlab are parallel programming Matlab toolboxes developed at MIT Lincoln Laboratories**
  - http://www.ll.mit.edu/MatlabMPI
  - http://www.ll.mit.edu/pMatlab
- **MatlabMPI is a Matlab toolbox that provides a subset of the Message Passing Interface (MPI)**
- **Launches one or more Matlab instances on multiple nodes**
- **pMatlab is a toolbox based on MatlabMPI**
  - introduces processor maps and data distribution
  - hides most of the details of the parallel communication/coordination
- **The actual underlying parallel code of ISL's toolboxes is abstracted from the user allowing the underlying framework to change without affecting user scripts**

Standalone Simulation Software

- Like the Matlab implementation, the standalone code was divided into three libraries
- These libraries are the same ones the MEX functions are based on
- Uses the same flexible simulation style as the Matlab toolbox by using C function pointers for tasks
- The simulation driver program uses a simple INI style configuration file for parameter inputs
- If a runtime linker is available, simulation functions can be changed without recompiling the driver program
- Includes parallel implementation using MPI
- Outputs can be saved as Matlab data files for easier analysis

Implementation Summary



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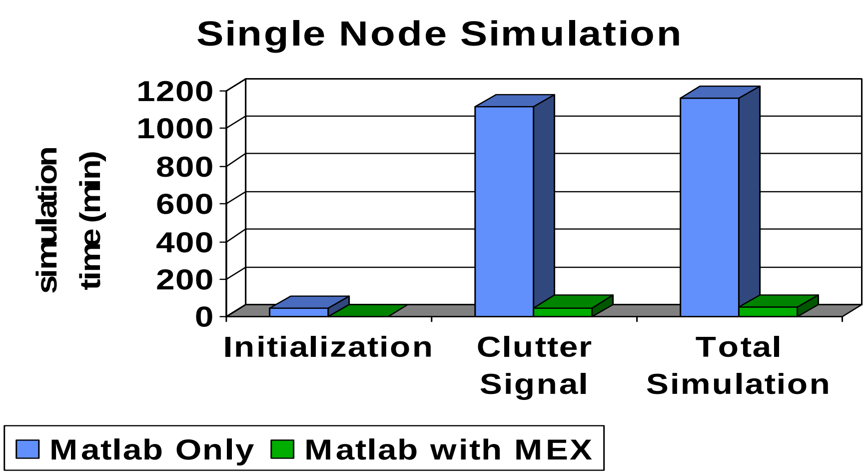
Performance Results

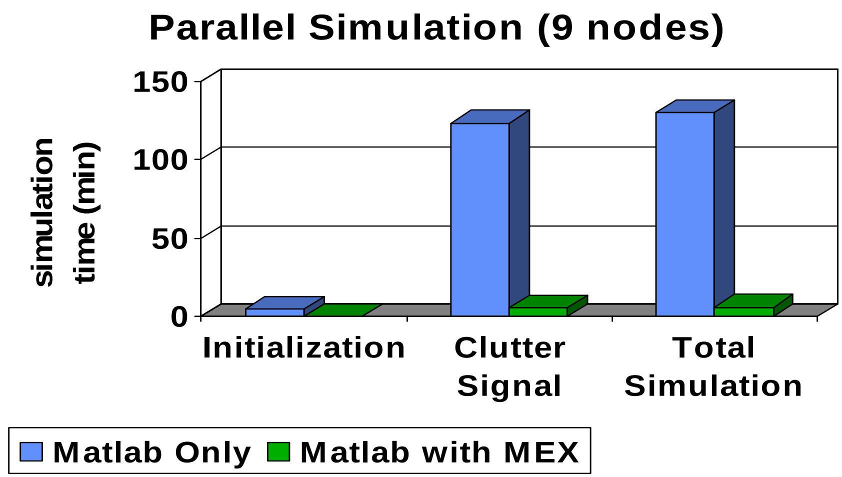
- **Simulation setup**
- **Matlab performance**
  - single node simulation
  - single node with MEX functions
  - parallel simulation
  - parallel simulation with MEX functions
- **Standalone performance**
  - single node
  - distributed memory parallel performance

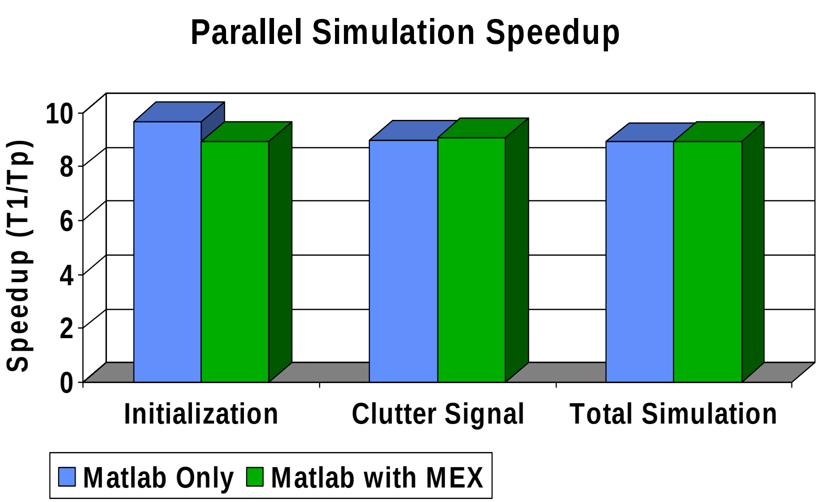
Simulation Setup

- **Low Earth Orbit (LEO) monostatic simulation**
- **Problem Size**
  - 127 pulses, 10 receive subarrays (MN=1270)
  - 121 range bins (L=121)
  - 250,000 clutter patches (P=0.25e6)
  - 192 GFLOP
- **Timing**
  - **Initialization** times the iterative calculation of clutter patches
  - **Clutter Signal** times clutter signal model shown on slide 4 including the generation of the waveform and spatial steering vector
  - **Total Simulation** times the entire simulation including initialization, IQ data calculation, and in the parallel cases collecting data from all the nodes.
- **Architecture (unless noted) is a 9-node cluster of Intel Pentium 4 2.4 GHz systems with 1 Gb SDRAM per node**

Matlab Implementation Performance







- **MEX speedup**
  - 15.9x Initialization speedup
  - 22.1x clutter signal computation speedup
  - 21.6x total simulation speedup
- **As predicted by the problem, speedup is approximately linear**

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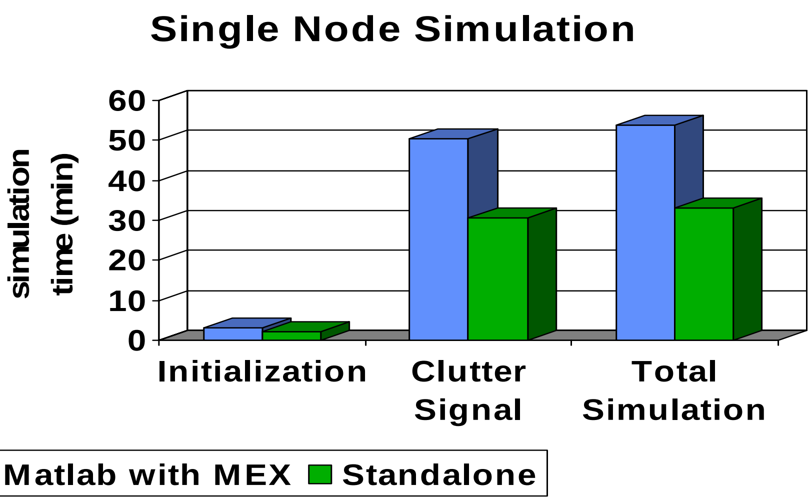
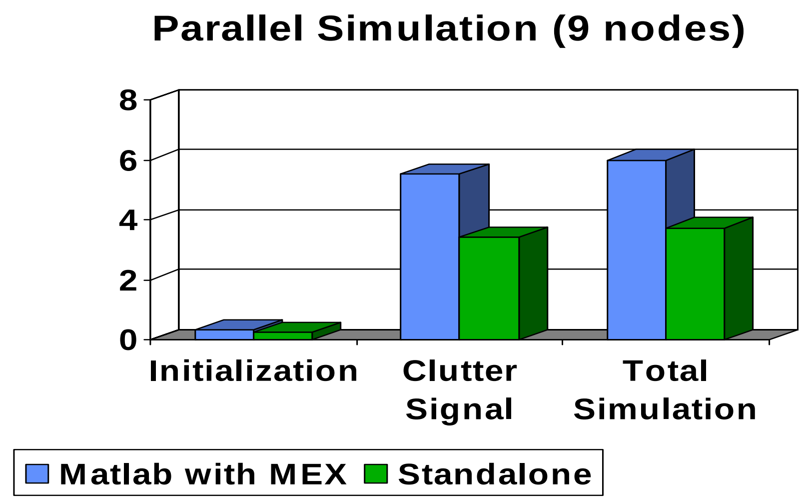
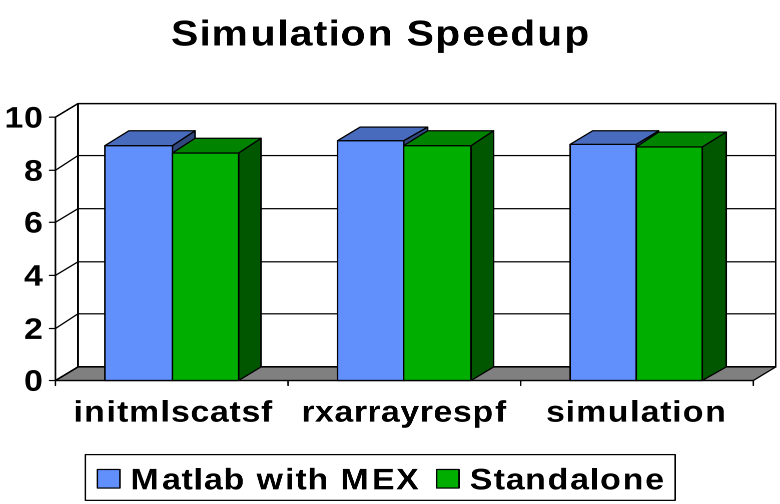
Standalone Implementation Performance







- **Standalone speedup over Matlab with MEX functions**
  - 1.52x initialization
  - 1.65x clutter signal
  - 1.62x total simulation
- **Standalone speedup is also nearly linear**
- **Will the speedup hold as more processing nodes are added?**

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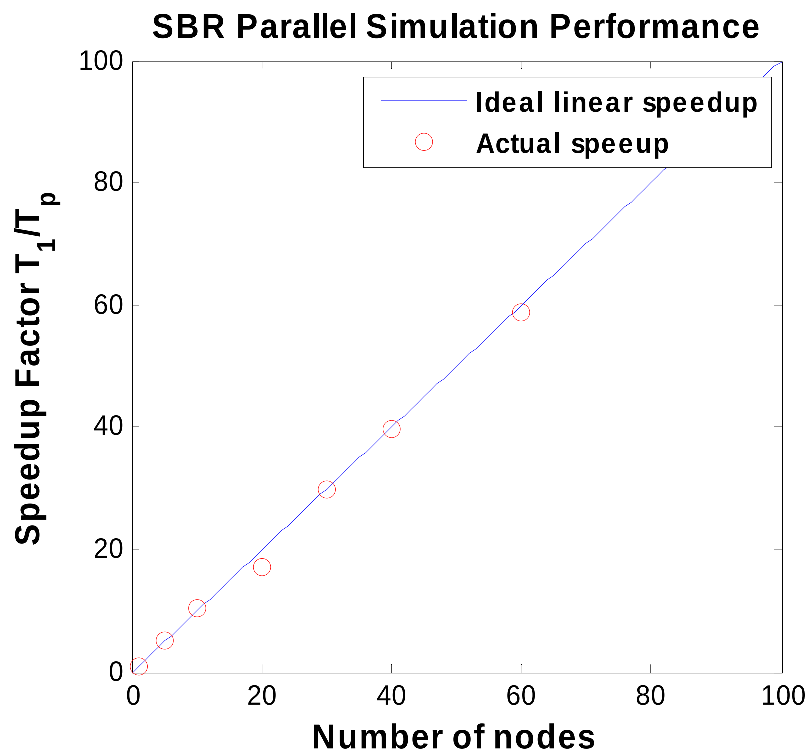
Parallel Standalone (1-60 nodes)

- **Space-based radar simulation**
- **35 million cells in simulated range swath**
- **AFRL Heterogeneous High-Performance Computer cluster**
  - 44 dual processor Intel Xeon 2.2 GHz processors
  - 4 Gb SDRAM per node
  - Gigabit/Myrinet connections
- **Actual performance follows linear speedup**



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Summary

- **Radar simulations are a valuable tool in analyzing radar performance**
- **High-fidelity radar simulations require a large number of operations**
- **The embarrassingly parallel nature of the problem makes parallel simulations simple**
- **Using MEX functions and computing clusters greatly improves simulation performance and allow higher-fidelity models to be implemented**
- **Using VSIPL provides a portable numerical library that can be optimized for various target platforms**

Future Work

- **Analyze task parallelization performance in conjunction with the data parallel implementation**
  - PVL
  - VSIPL++ parallel
- **FPGA**
  - generally have higher memory bandwidth and sustained FLOPS than conventional microprocessors
  - some recent DSP systems employ FPGA coprocessors
  - the AFRL HHPC has a systolic array of 96 FPGA
- **GPU co-processing/clusters**
  - well suited to matrix algebra
  - have high memory bandwidth
  - high FLOP/dollar ratio