

Ray Tracing Simulation Tool for Portal-Based Millimeter-Wave Security Systems using the NVIDIA OptiX Ray Tracing Engine

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Northeastern



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AWARENESS AND LOCALIZATION
OF EXPLOSIVES-RELATED THREATS

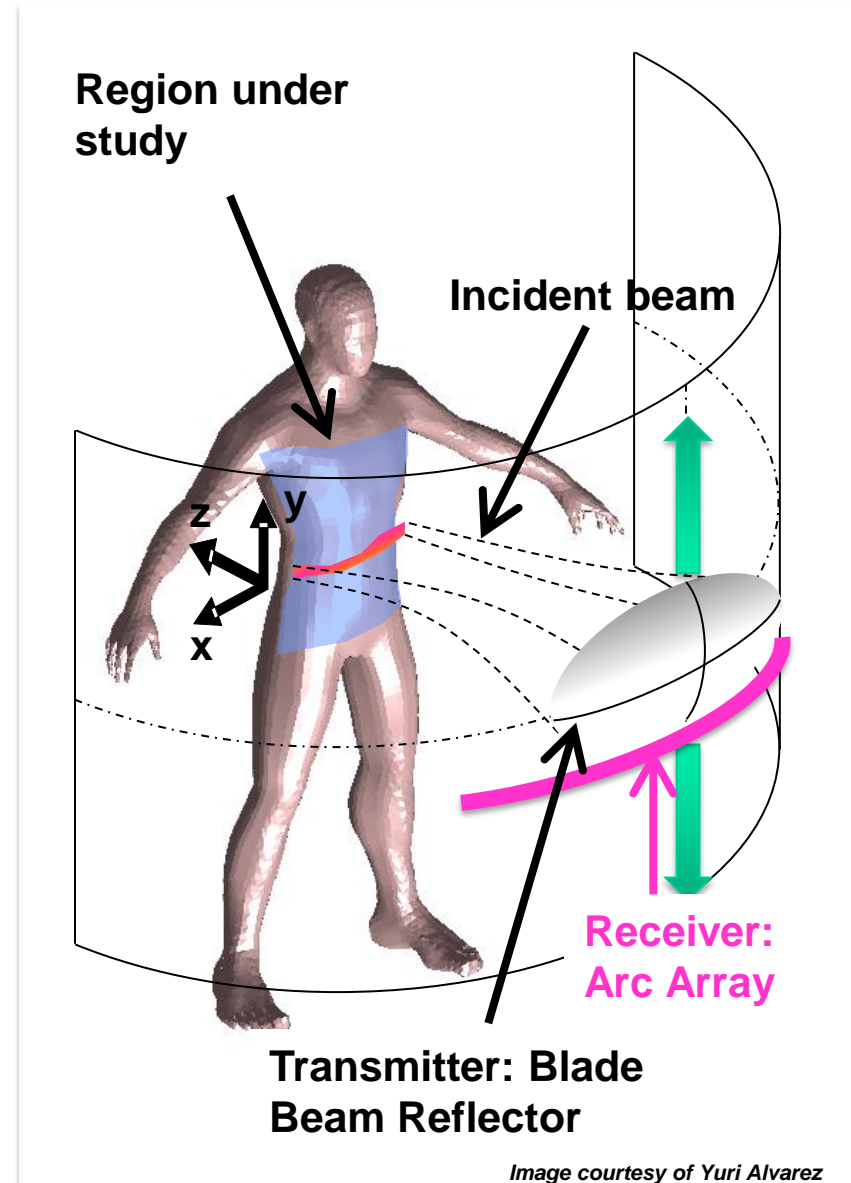
Algorithm Development for Security Applications

October 23, 2013



Project Background

- Create a next generation system to improve detection capabilities of whole-body imaging systems
 - Novel hardware designs
 - Novel algorithms
- This talk: GPU Ray Tracing (RT) Simulation Tool





So what, who cares?

- Why develop computational models?
 - Predict the scattering behavior of objects to mm-waves
 - Model optimal sensor configurations at minimal cost
 - Develop model-based inversion methods
- Why ray tracing?
 - Inherently parallelizable (GPUs!)
 - Can be an effective forward model for inversion



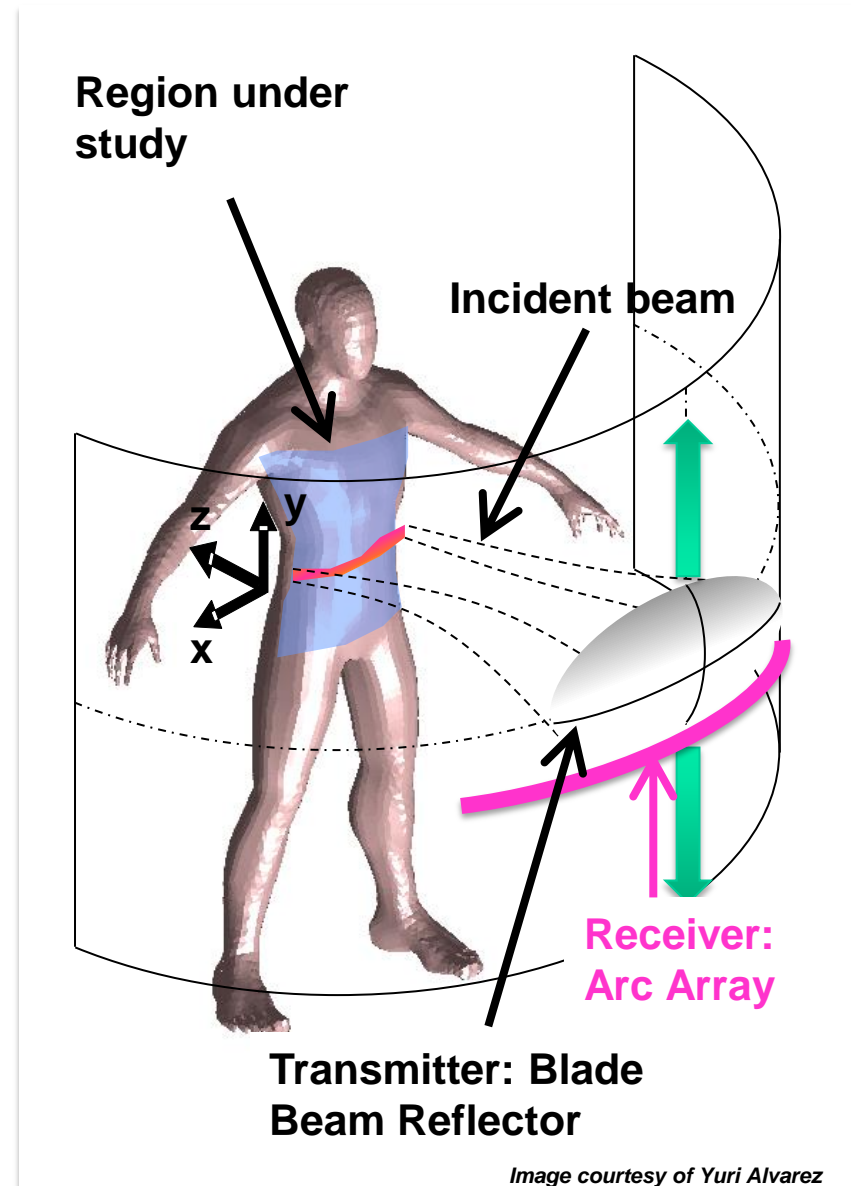
Outline

- **Algorithm development**
 - Modeling of scanner components
 - Implementation
- **Computational Results**
 - Validation
 - Performance



Components to Model

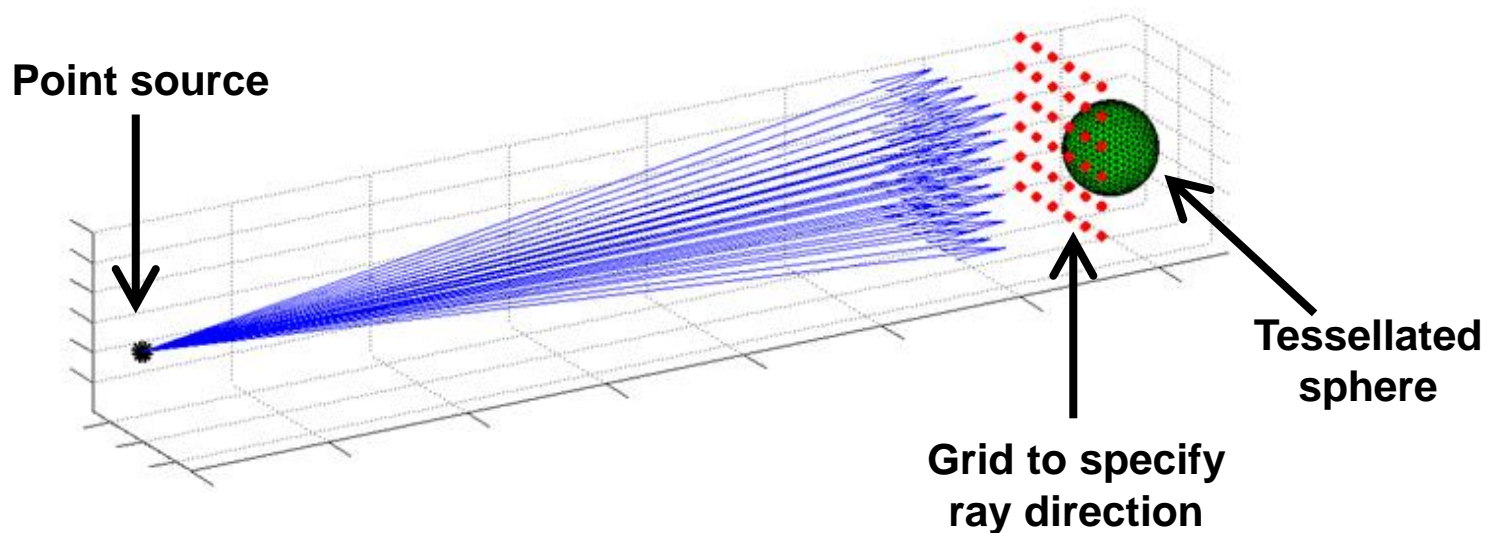
- Transmitter
- Human Body
- Ray-Body Intersection
- Receiver Arc Array





Components to Model

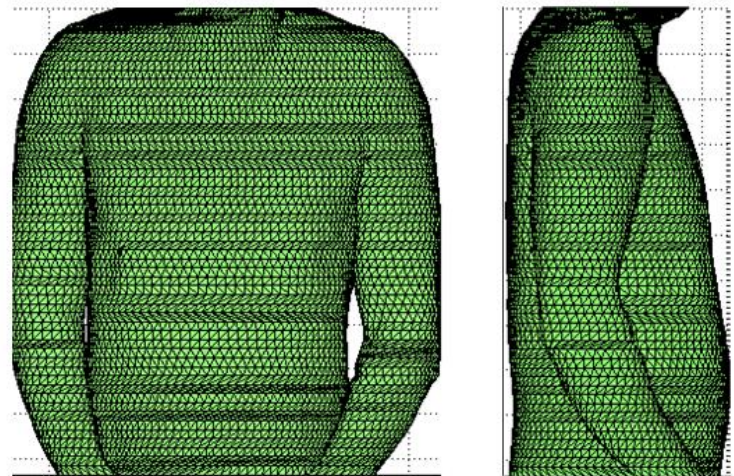
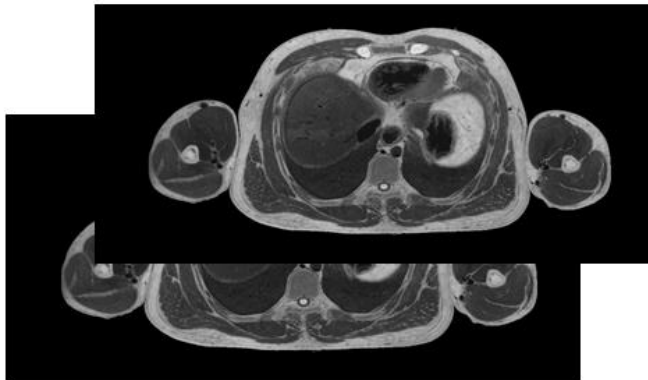
- Transmitter
 - Electromagnetic wavefronts are approximated by a collection of rays
 - Propagation direction of rays governed by a virtual grid
 - Rays are traced from the transmitting source to the mesh (“scene”)





Components to Model

- Human Body
 - Triangular faceted mesh
 - User control over triangle size and uniformity
 - Can extract and correlate 2D slices



Images courtesy of Visible Human Project



Components to Model

- Intersection
 - Perfect electric conductor
 - Interpolation of surface normals
- Acceleration
 - “Scene epsilon”

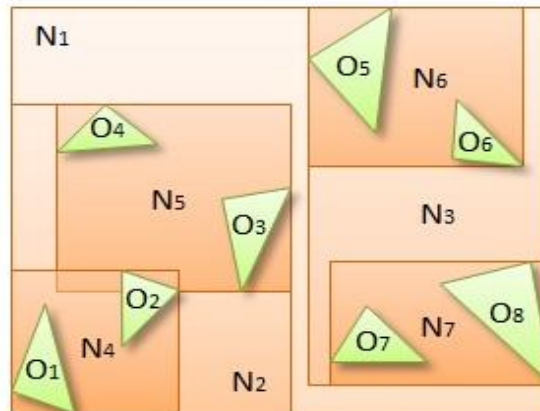
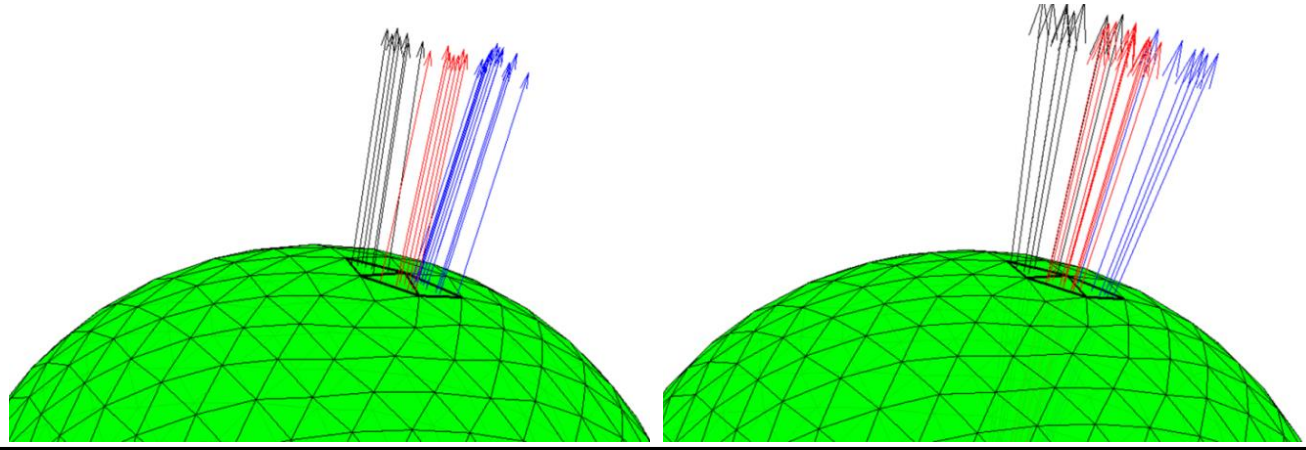


Image courtesy of NVIDIA

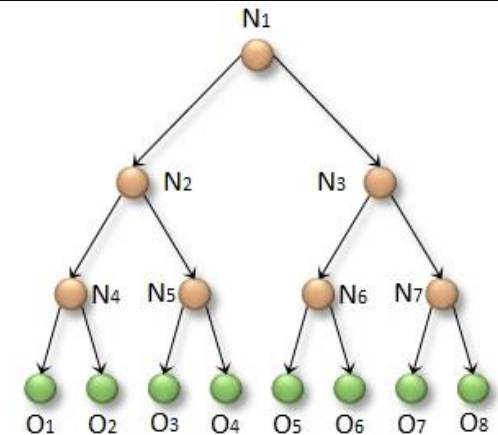
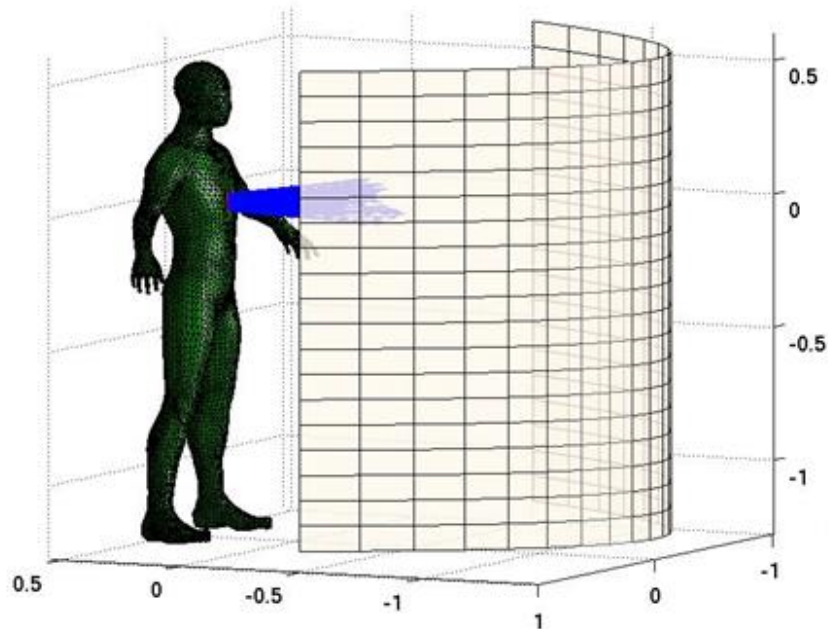


Image courtesy of NVIDIA



Components to Model

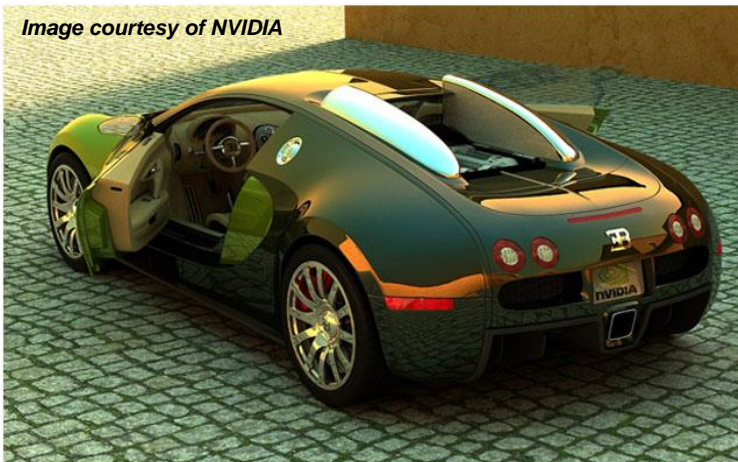
- Receivers
 - Receiver array is discretized into patches (“bins”)
 - Field of each ray is computed, including path length phase: e^{-jkl}
 - If rays land within the same bin, their field values are summed (“ray aggregation”)





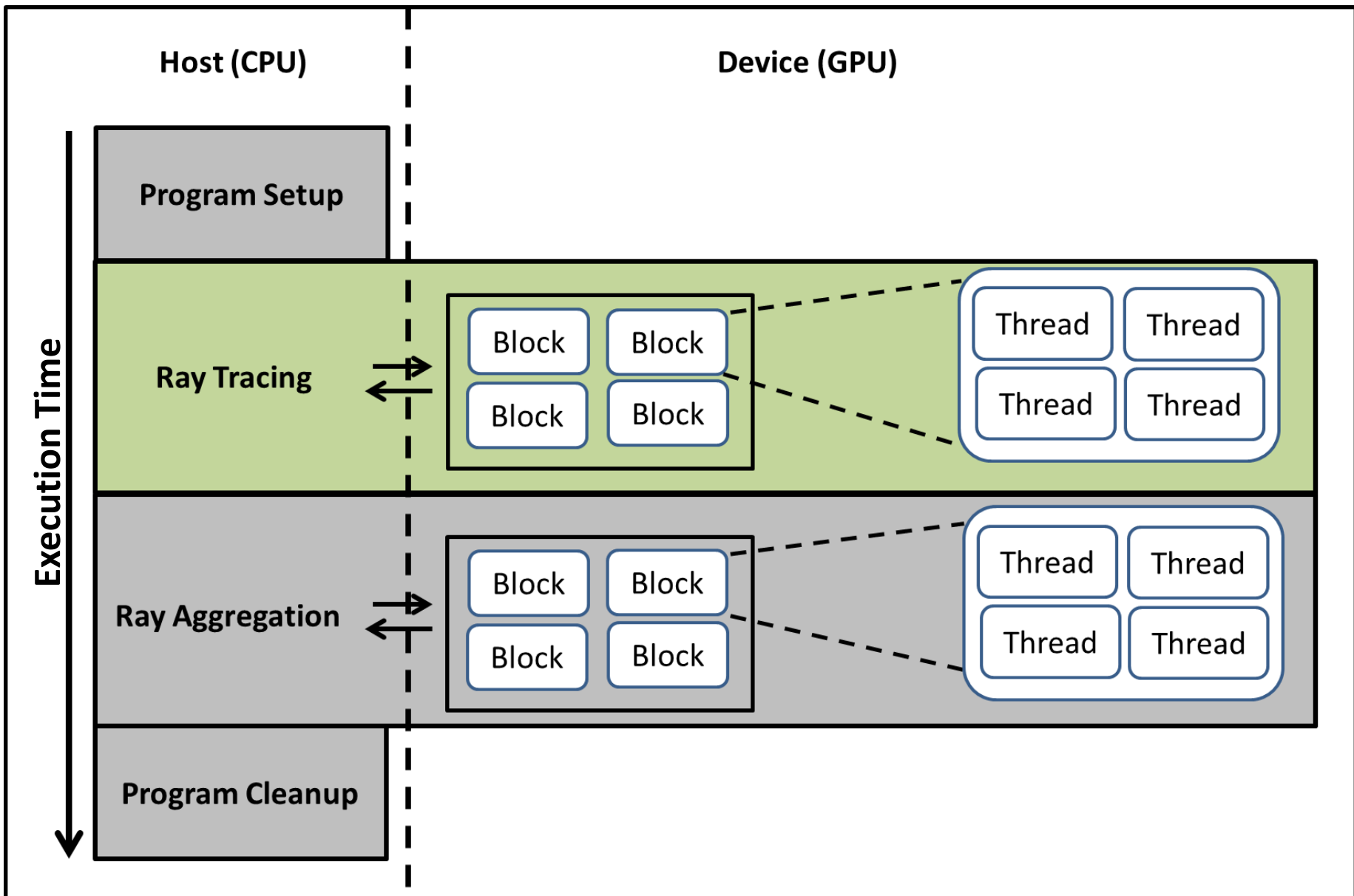
Implementation

- Goal: All rays and all fields (bins) in parallel
- OptiX Ray Tracing Engine
 - Free SDK, released in 2009
 - By NVIDIA for NVIDIA GPUs
 - Uses CUDA C based device (GPU) programs
 - Optimized
 - Used for many applications





High Level Implementation





Implementation

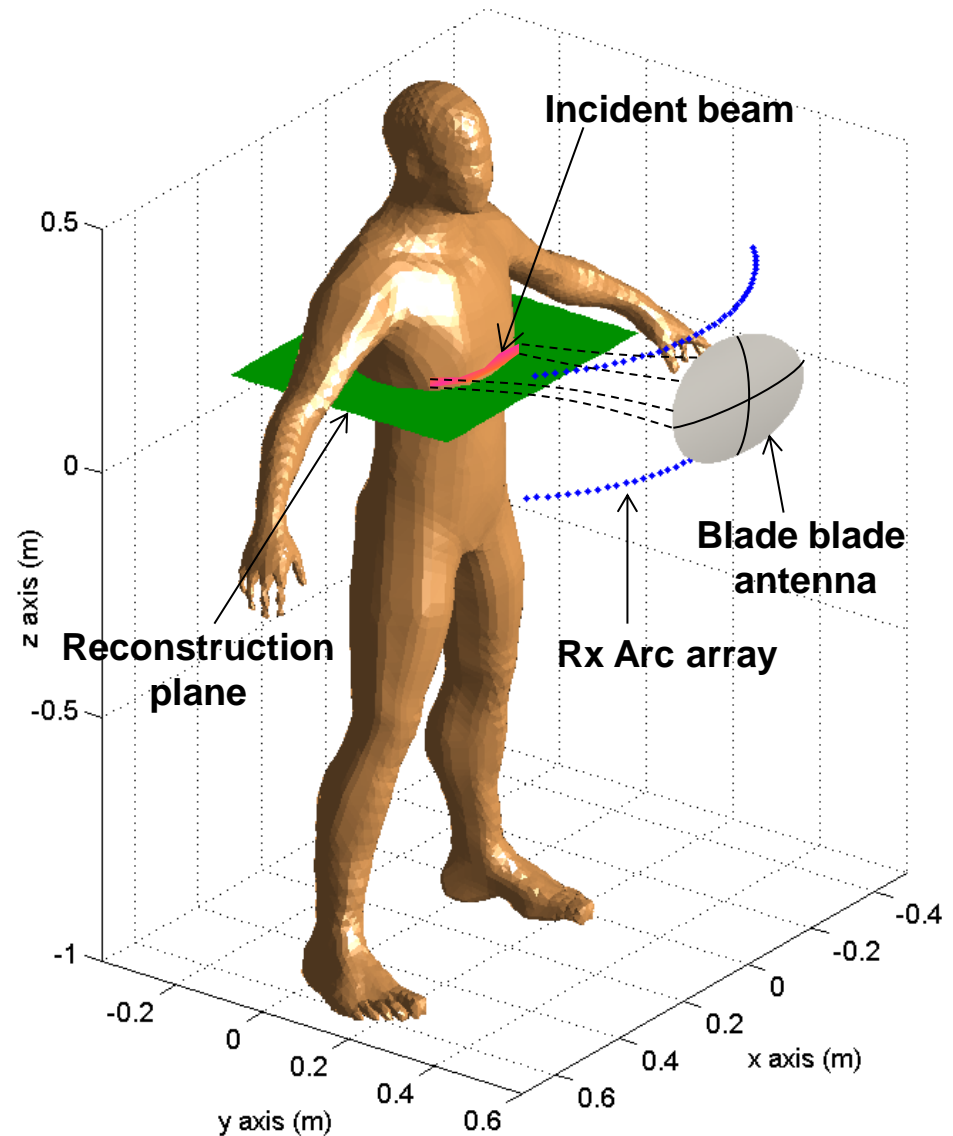
- Platform Configuration
 - OptiX 3.0
 - CUDA 4.2
 - Ubuntu 12.04
 - 3.2 GHz Intel Core i7
 - NVIDIA GTX 670 (1344 CUDA Cores; 2 GB memory)
 - PCI Express 3.0



Computational Results: Validation

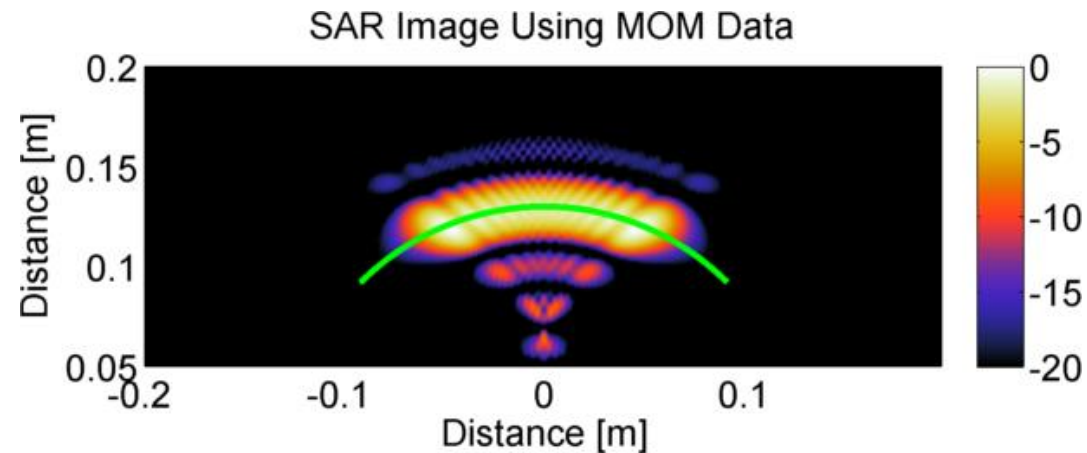
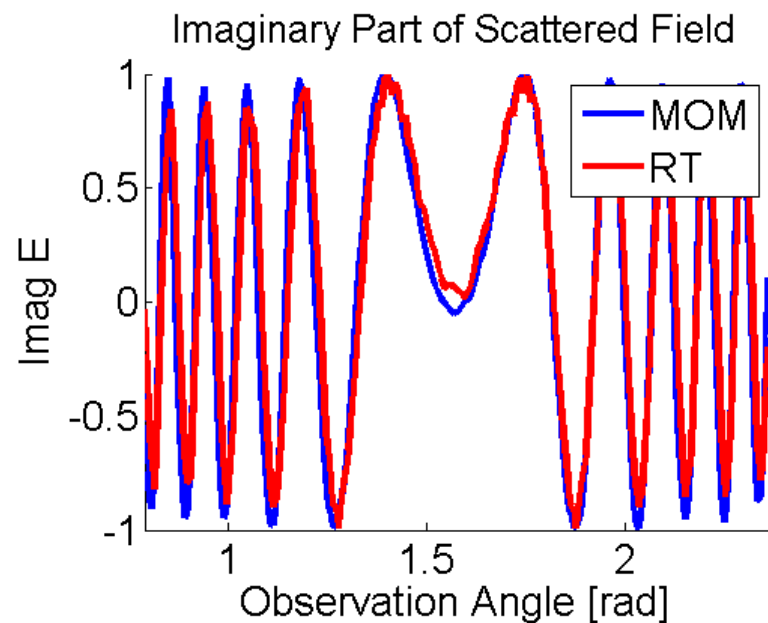
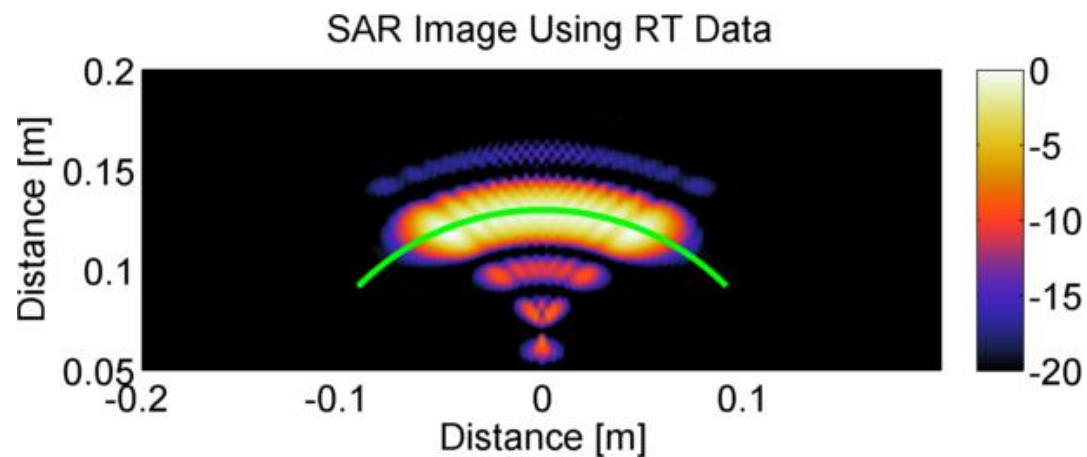
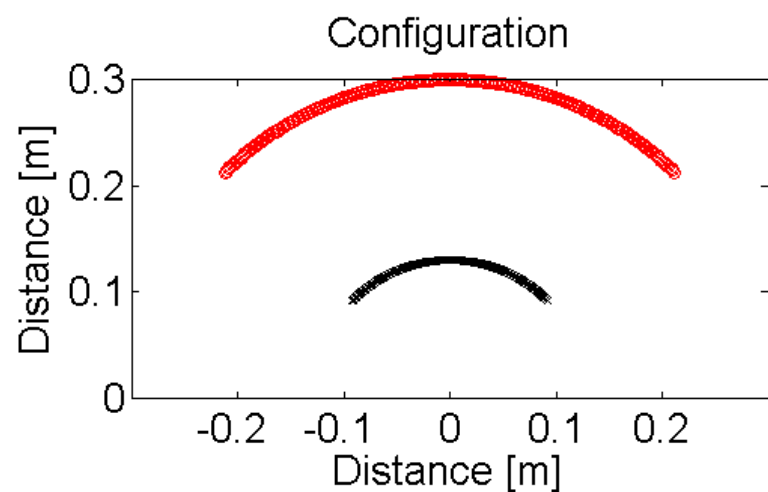
- 4 cases presented here:
 - 2D cylinder to approximate the torso
 - 2D torso with arms
 - 2D torso with arms and pipes
 - 2D torso with realistic features

- RT field values and SAR images are compared with 2D Method of Moments (MOM) solutions





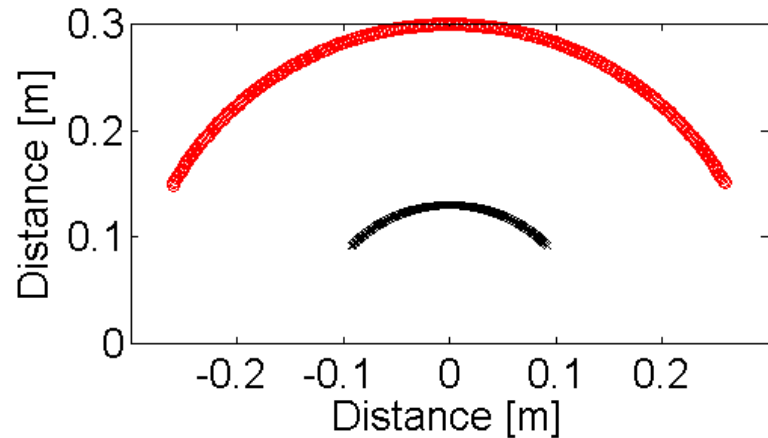
Computational Results: 2D Cylinder



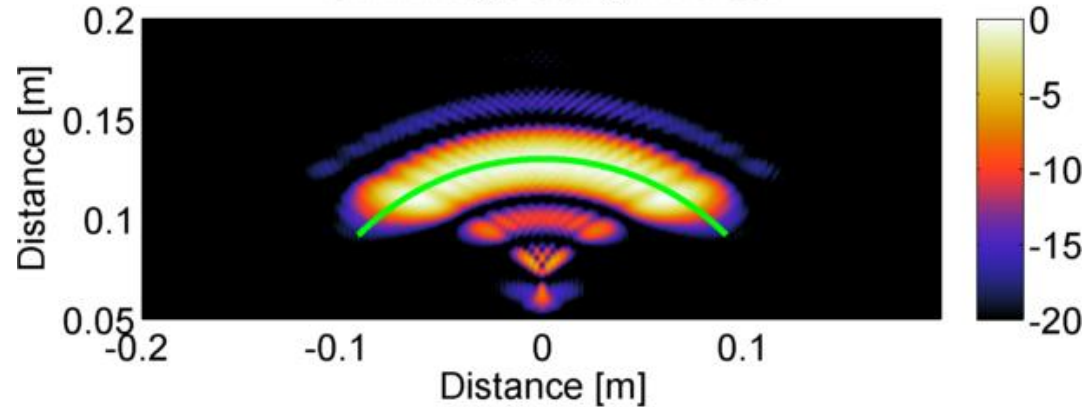


Computational Results: 2D Cylinder

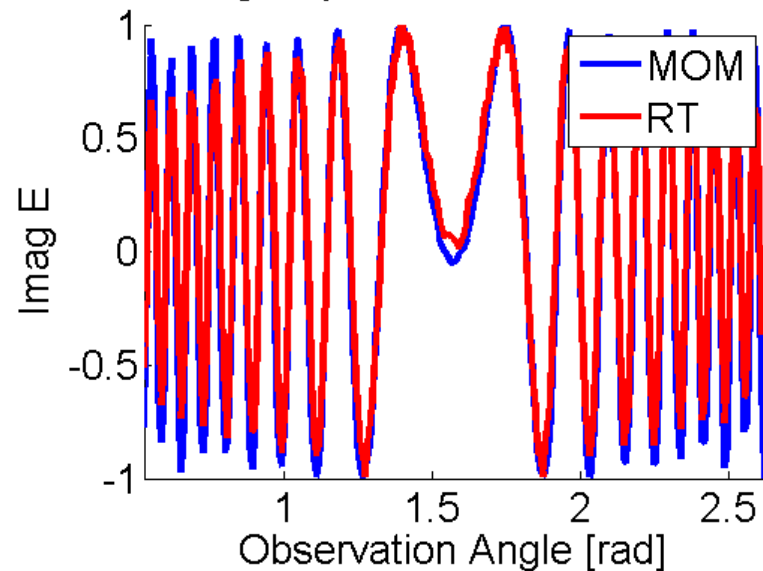
Configuration



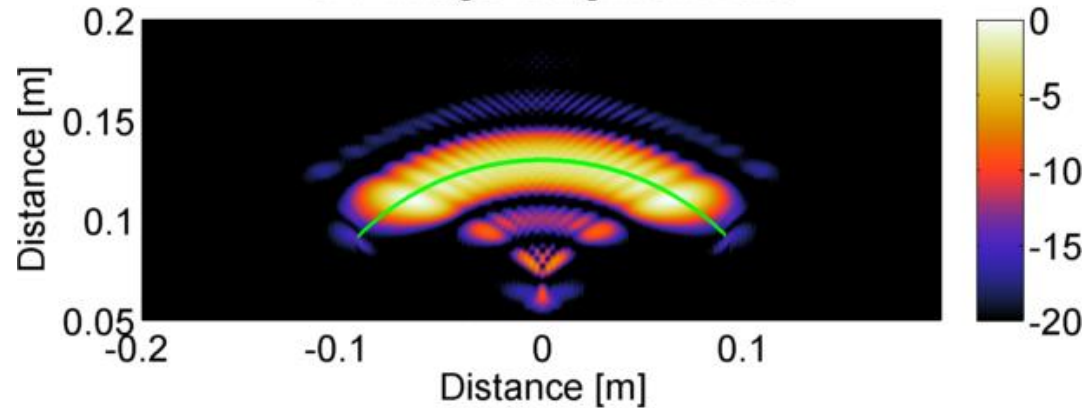
SAR Image Using RT Data



Imaginary Part of Scattered Field

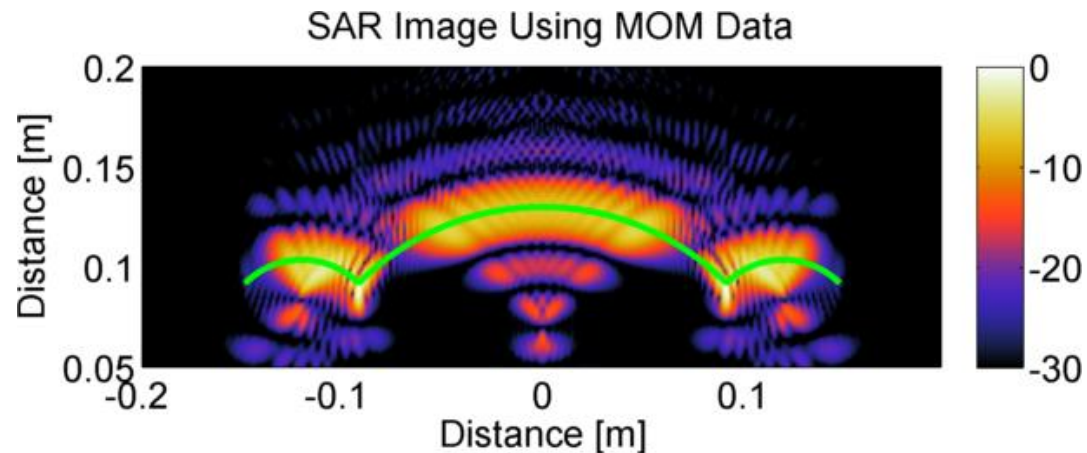
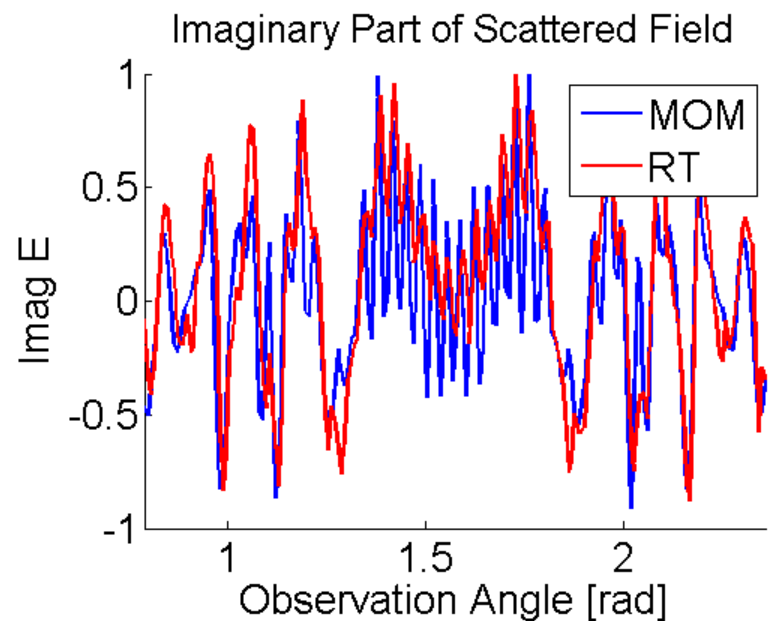
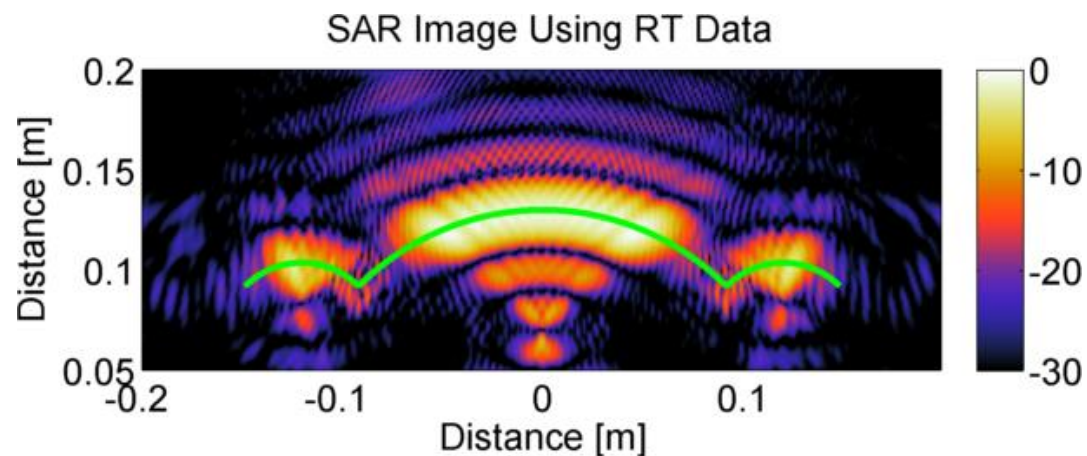
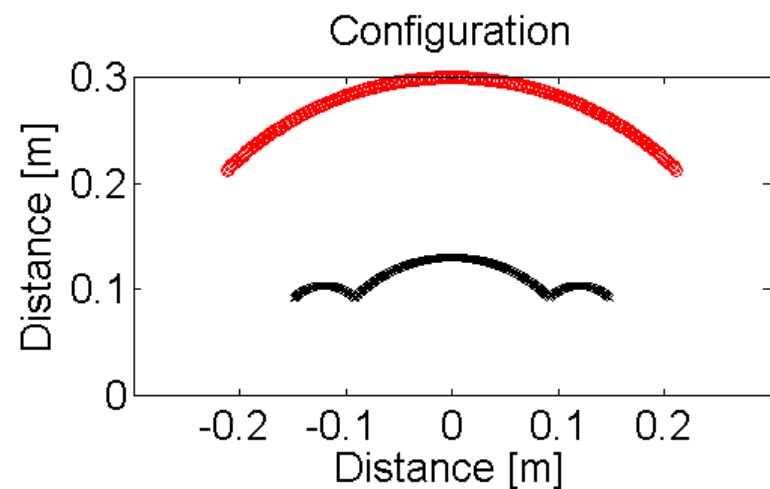


SAR Image Using MOM Data





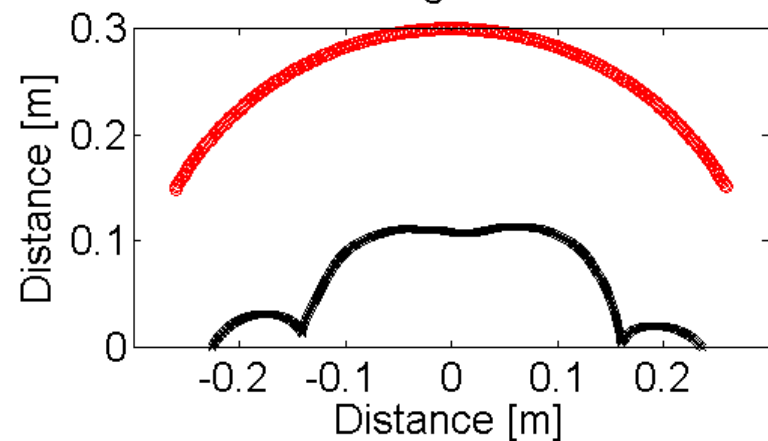
Computational Results: 2D Torso & Arms



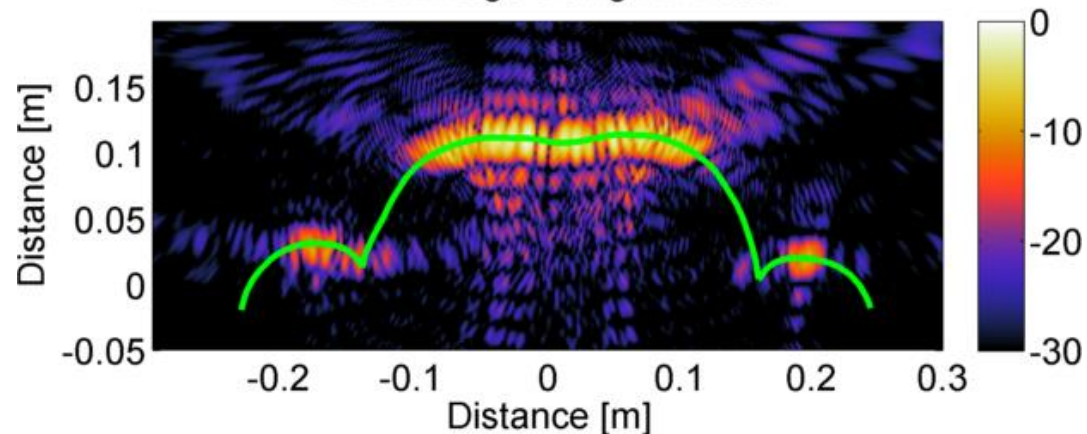


Computational Results: 2D Torso & Arms

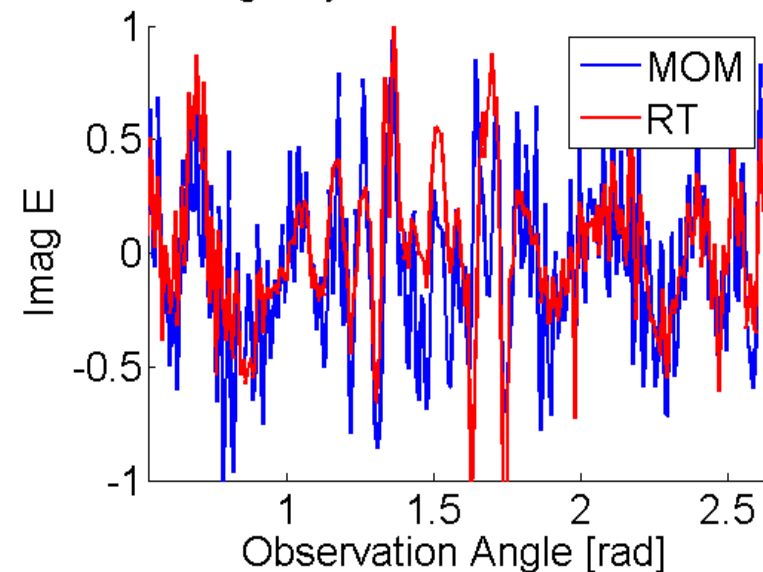
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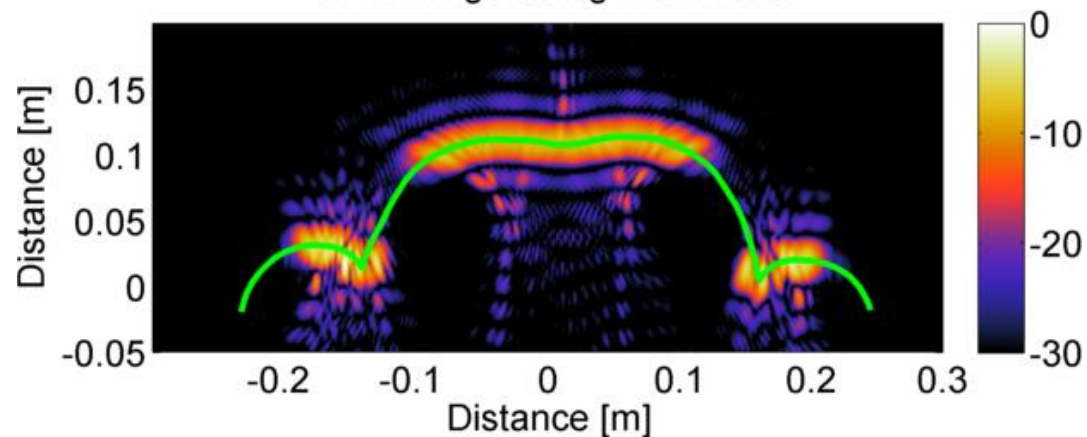
SAR Image Using RT Data



Imaginary Part of Scattered Field



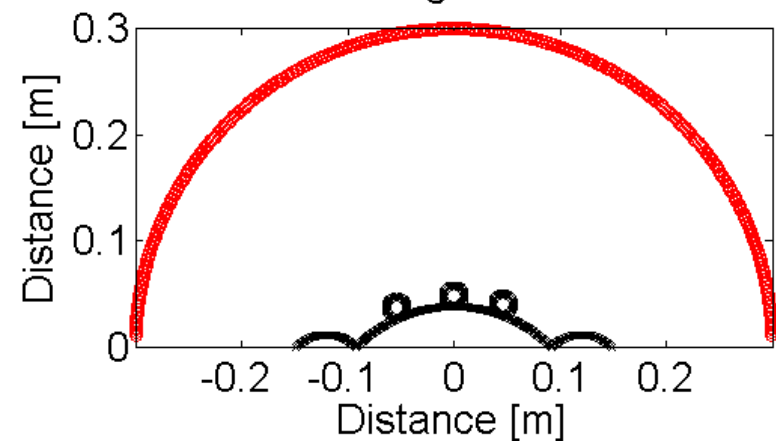
SAR Image Using MOM Data



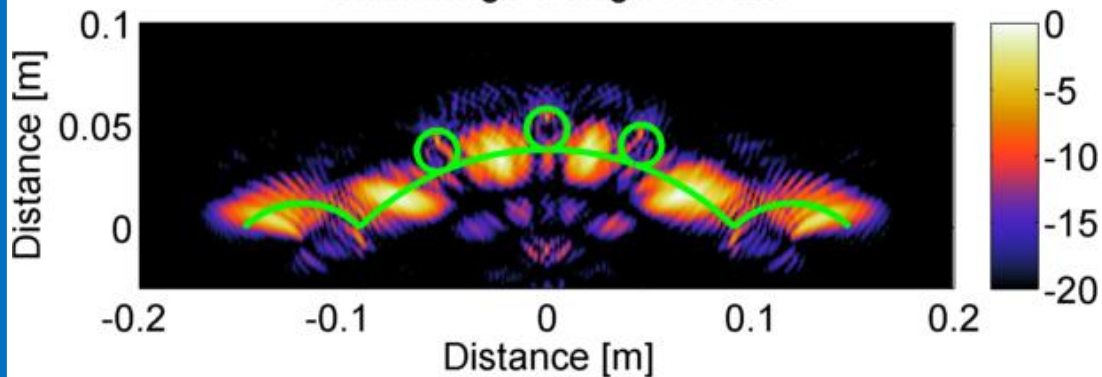


Computational Results: 2D Torso & Pipes

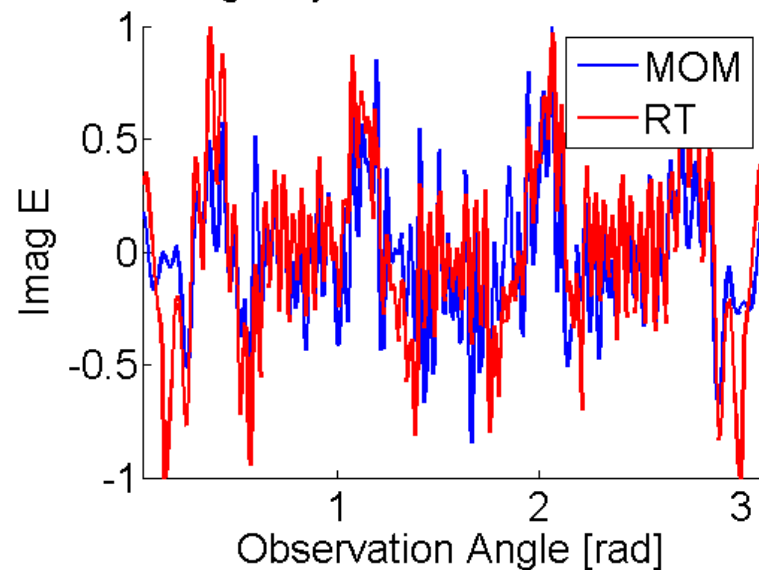
Configuration



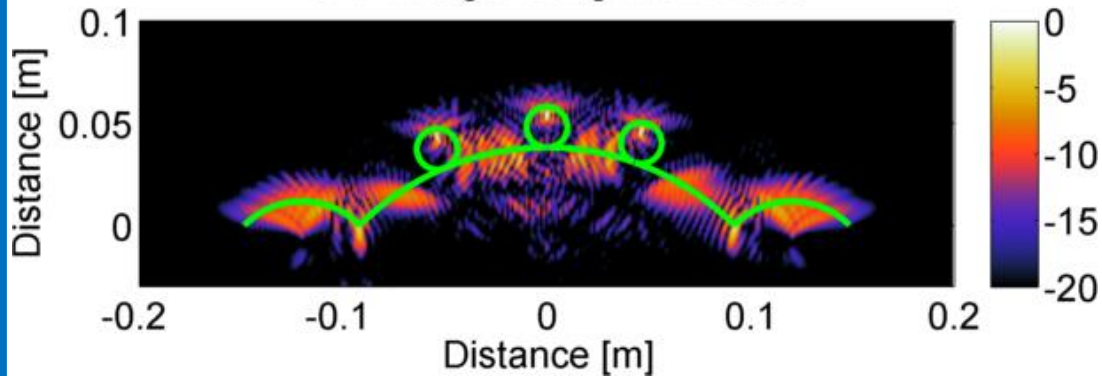
SAR Image Using RT Data



Imaginary Part of Scattered Field



SAR Image Using MOM Data





Computational Results: Performance

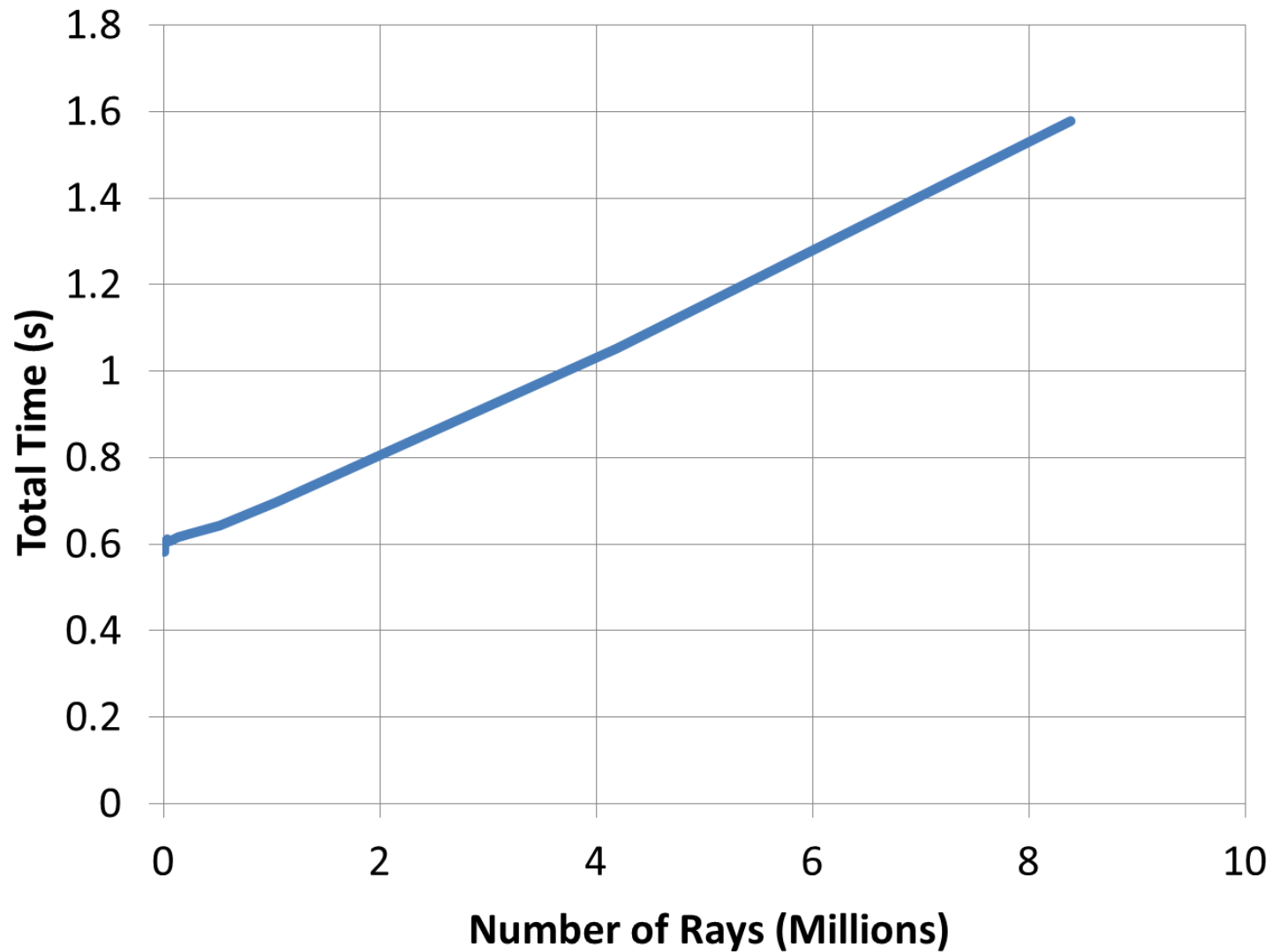
- Factors affecting performance
 - # of rays
 - # facets
 - # receiver bins
 - # of frequencies
- Results performed for a faceted plate
- Computation time is compared, if applicable, with 3D GPU implementation of the Modified Equivalent Current Approximation (MECA) ¹

¹ L. Tirado, . Martinez-Lorenzo, B. Gonzalez-Valdes, C. Rappaport, O. Rubinos-Lopez, H. Gomez-Sousa, "GPU Implementation of the Modified Equivalent Current Approximation," *ACES Journal*, vol 27, pp. 726-733, Sep. 2012.



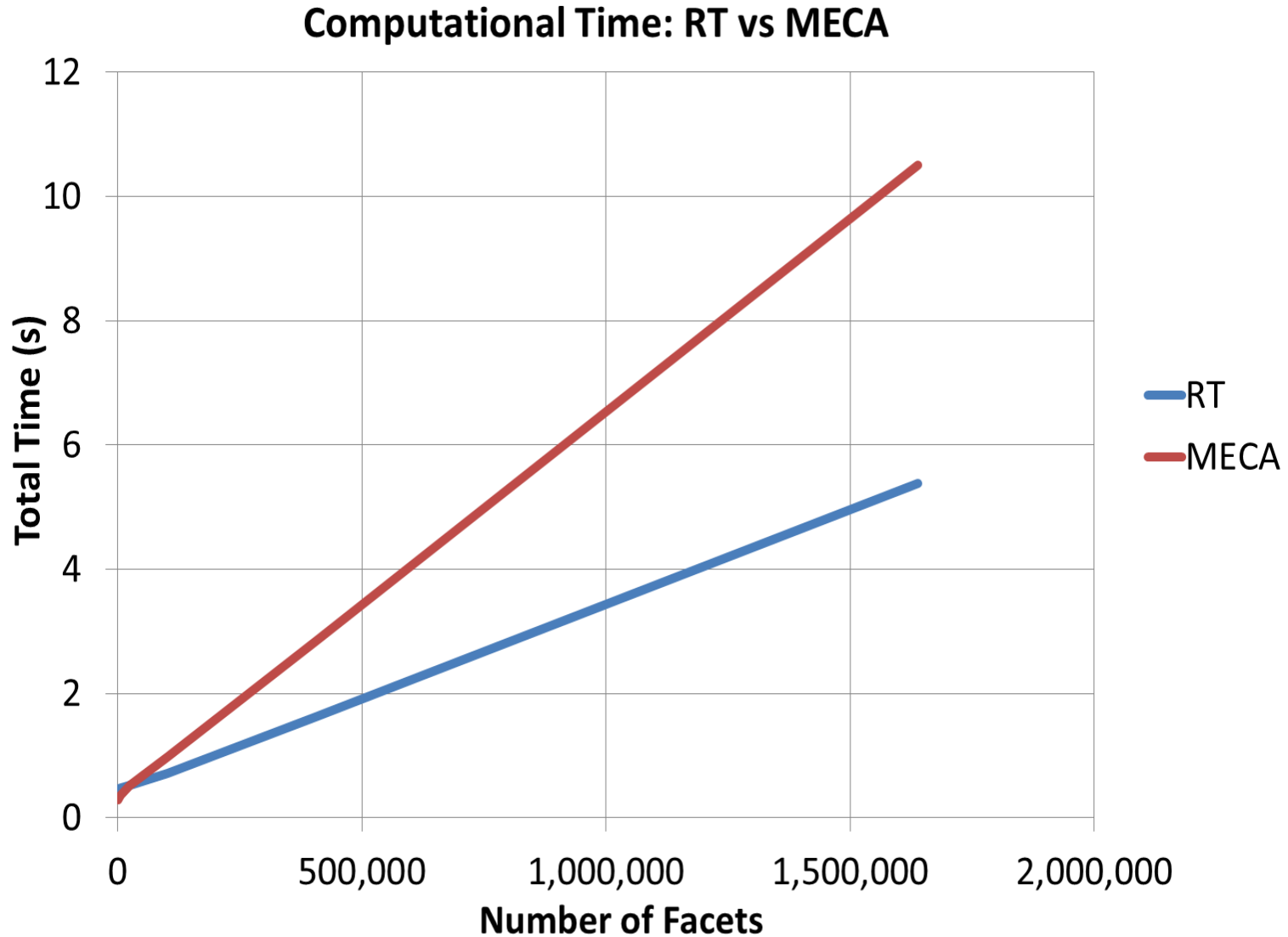
Computational Results

RT Computational Time





Computational Results

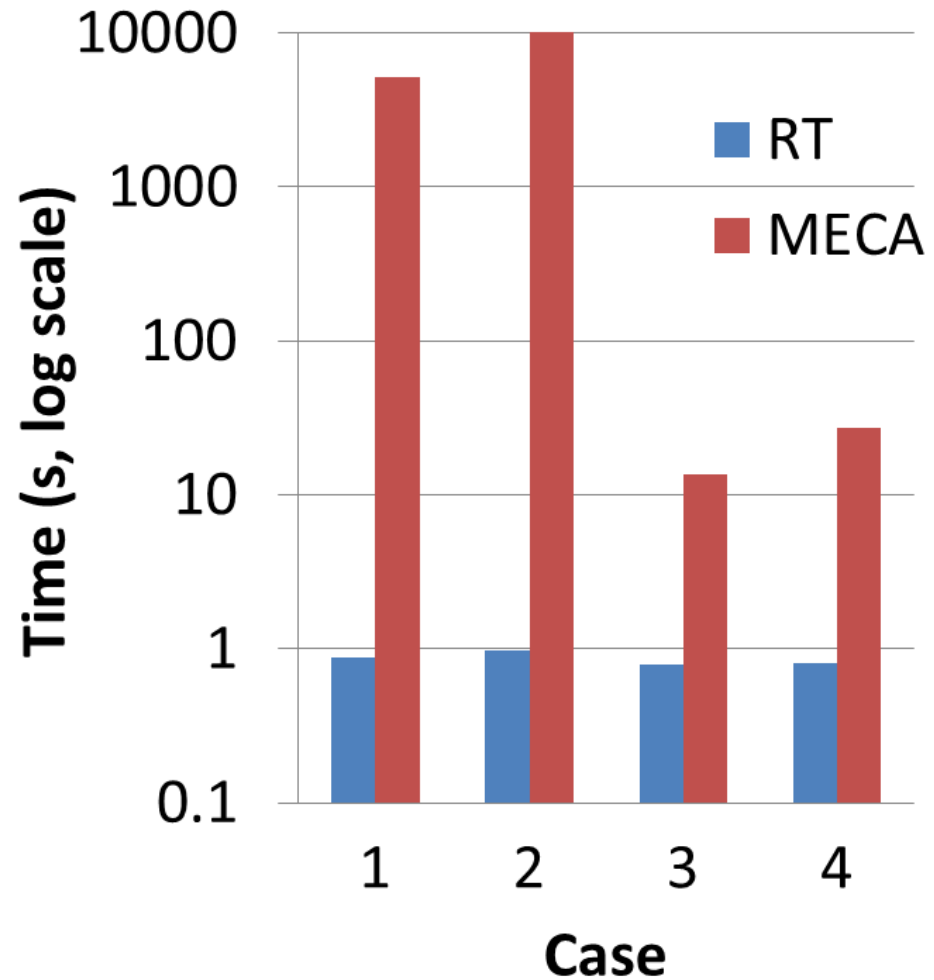




Computational Results

	Parameters			Result
Case	# Freq	# Bins (Azimuth)	# Bins (Height)	Factor Speedup
1	16	654	417	5808
2	32	654	417	10581
3	16	654	1	17
4	32	654	1	33

Computational Time: RT vs MECA





Summary

- Developed ray tracer simulation tool that takes advantage of free software available in the computer graphics community, modified for this application
- Computational modeling leads to better hardware designs, insight into scattering
- Ray tracing produces accurate field values and speed-ups when compared to other methods
- Fast forward models can lead to fast model-based inversion algorithms
- Future work: testing on additional geometries, additional speed-ups, ray tracing-based inversion method



Acknowledgements

**Professor Carey Rappaport, Professor Jose Martinez, Professor Yuri Alvarez,
Borja Gonzalez-Valdes, Luis Tirado, Chen Zhongliang**



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Useful Resources

- CUDA Tutorials
 - [udacity.com](https://www.udacity.com)
 - “CUDA Handbook”, Nicholas Wilt
- GPU Technology Conference On-Demand OptiX Tutorials
 - [gputechconf.com](https://www.gputechconf.com):
 - Online tutorial: “GPU Ray Tracing Exposed: Under the Hood of the NVIDIA OptiX Ray Tracing Engine,” A. Robison, P. Miller, S. Parker
 - Online tutorial: “Advanced OptiX Programming and Optimization”, D. McAllister
 - Online tutorial: “GPU Ray Tracing Using OptiX,” D. McAllister



BACKUPS



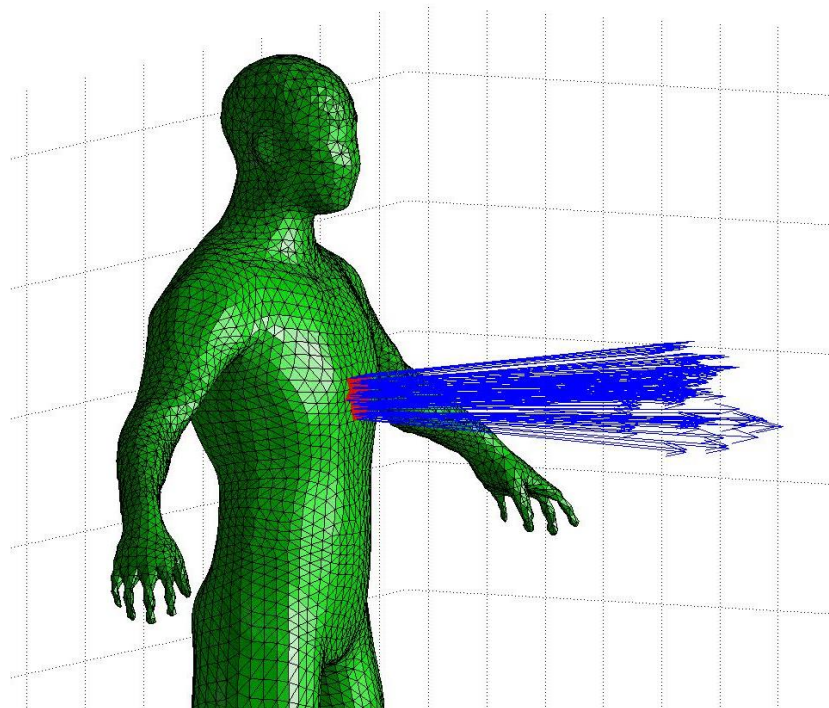
Project Background: Motivation

- Accurate & quick detection of person-borne threats in highly secure areas
- Millimeter-wave portal-based scanning systems are currently used to meet this need
- Millimeter-waves
 - Penetrate clothing, reflect off skin
 - Can detect nonmetal and metal objects
 - Enable high resolution images
 - Multiple views give depth information
 - Non-ionizing radiation
 - More publicly accepted than x-ray



Ray Tracing Basics

- Electromagnetic wavefronts are approximated by a collection of rays
- Rays are traced from a transmitting source to a surface or scene
 - (i.e., a 3D triangle mesh of a human body)
- Rays reflected from a surface are calculated with Snell's law
- Reflected rays are traced until they reach a receiving surface
- All ray contributions, including path length phase, are added at the receiving surface





Advantages of Ray Tracing over Other Methods

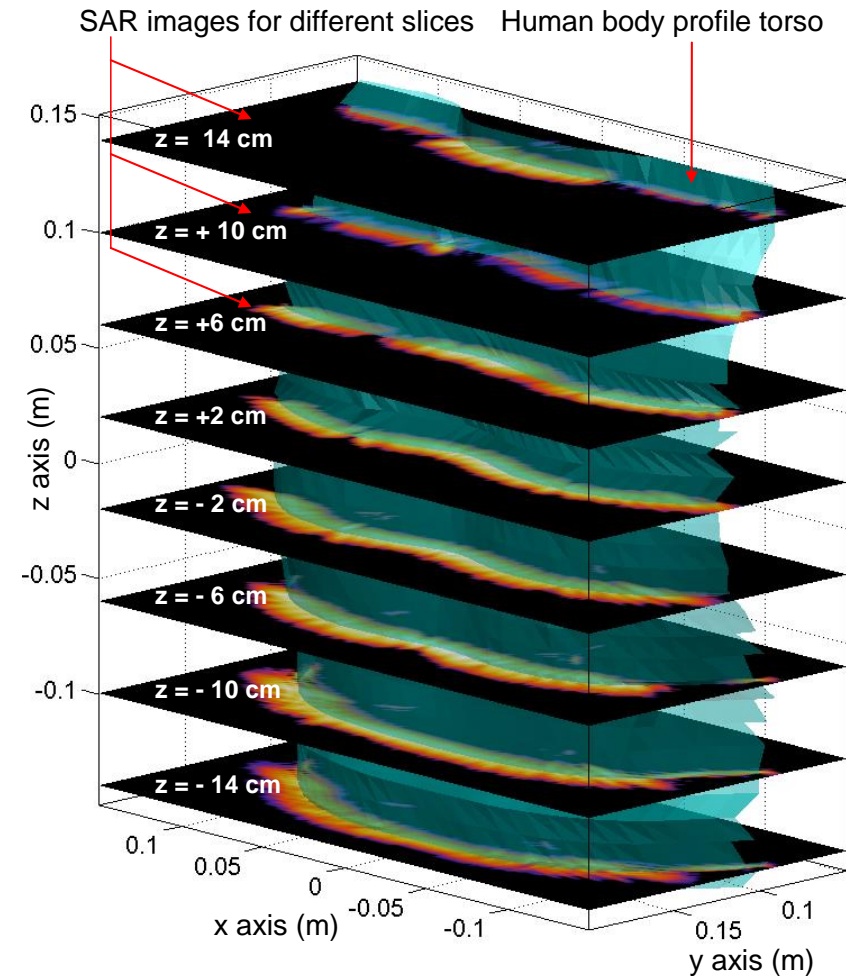
- Simple formulation
- Inherently parallelizable
- Has potential for real-time computation
- Reasonably accurate for mm-waves for objects of interest

- MoM, Finite Difference Frequency Domain (FDFD) are more accurate but slow, and not readily as parallelizable
- Includes mutual interactions (multiple bounces) much more readily than Physical Optics (PO)
- Uses the object 2nd-order normal at every surface point, instead of just the center of each triangular facet for PO



Advantages of Ray Tracing over Other Methods

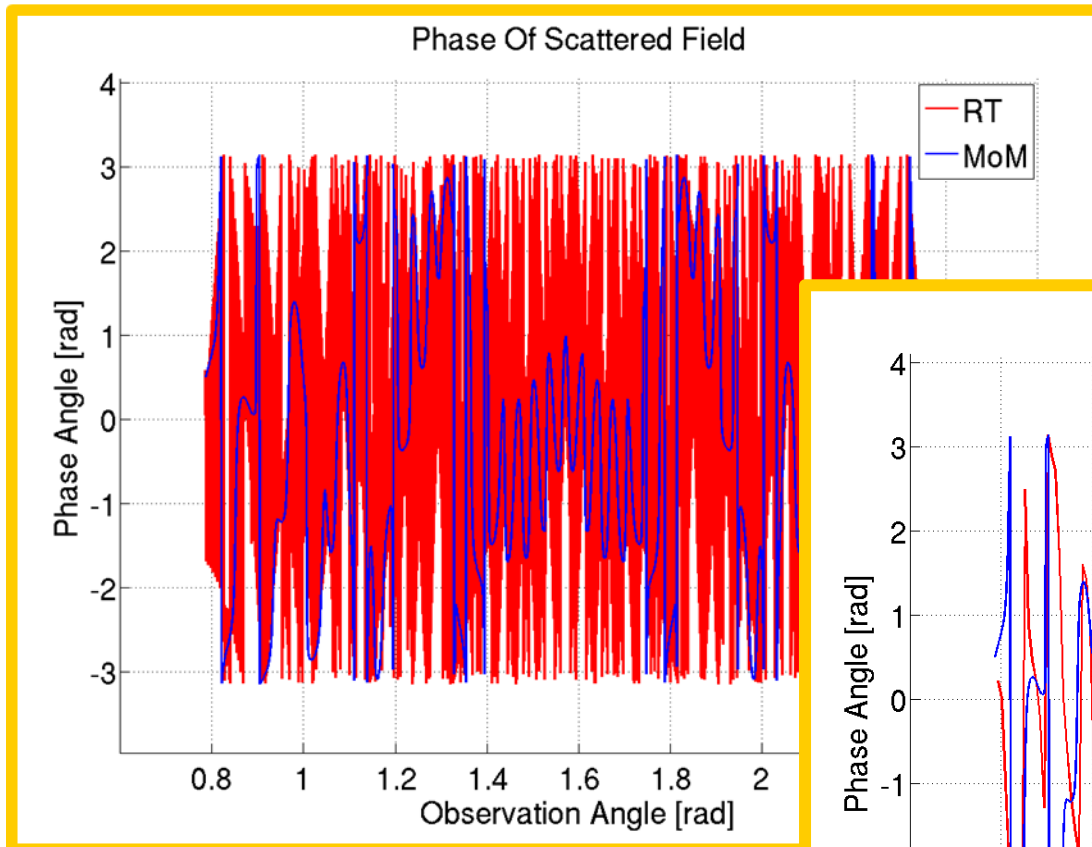
- Can be effective forward model for inversion
 - May give 3D (i.e., height) response to supplement 2D stacked reconstructions
 - May be used for iterative reconstruction
 - May be used as part of a novel multiple bounce SAR inversion scheme
 - May be useful for focusing in on details (i.e., a possible threat)



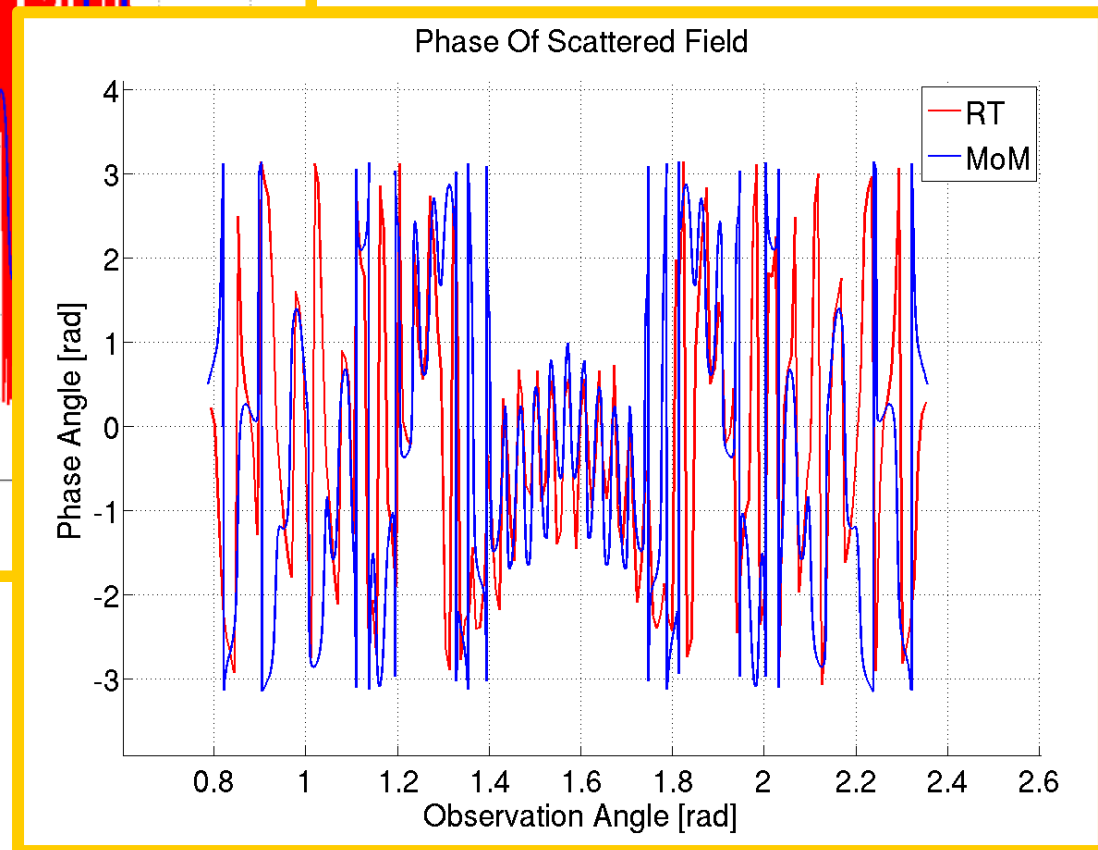


Ray Aggregation: Sample Data

Not aggregated

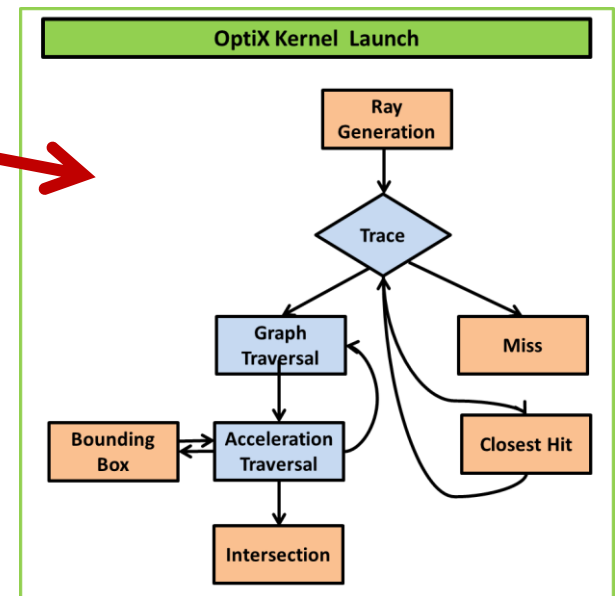
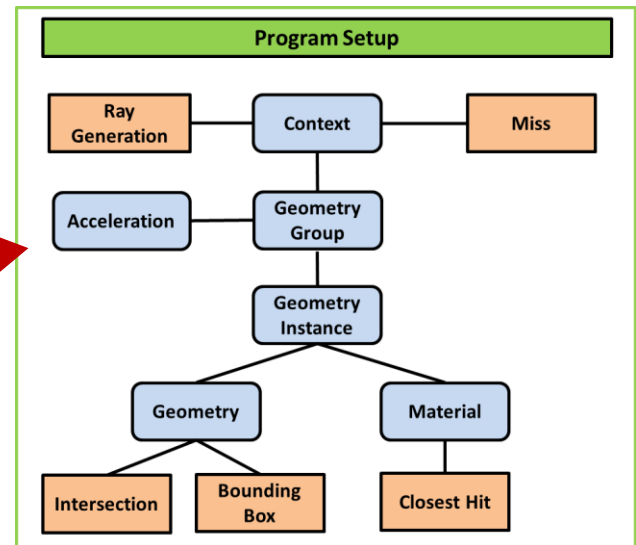
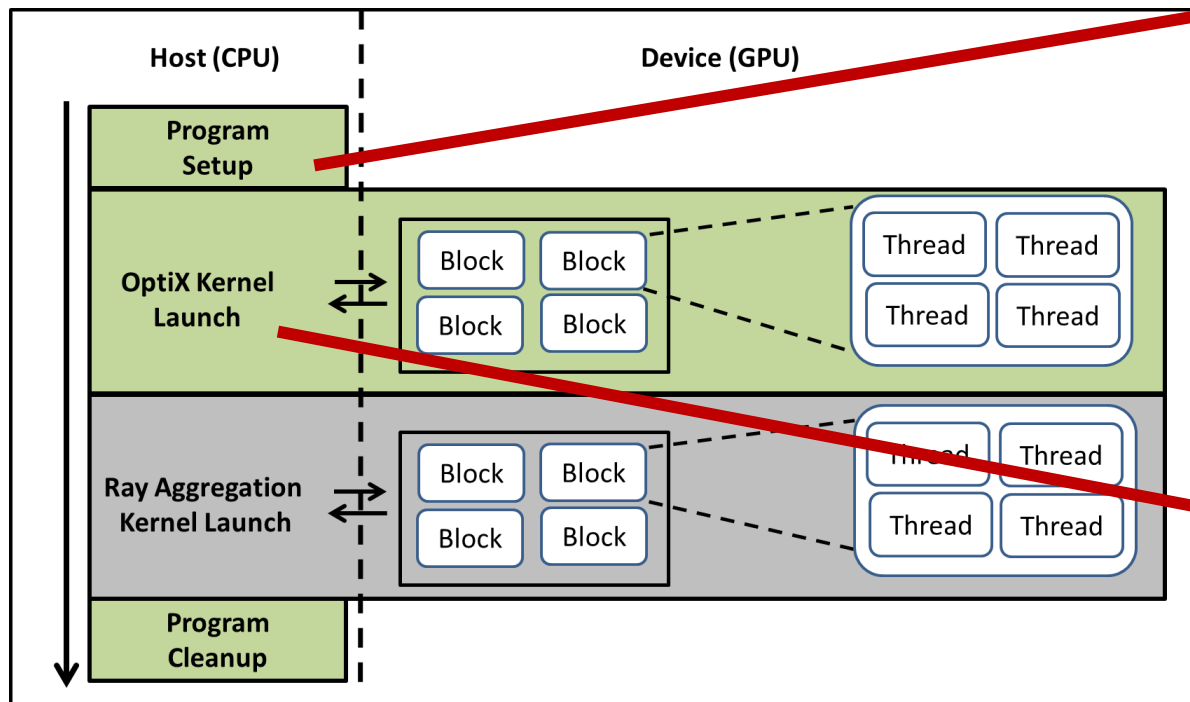


Aggregated





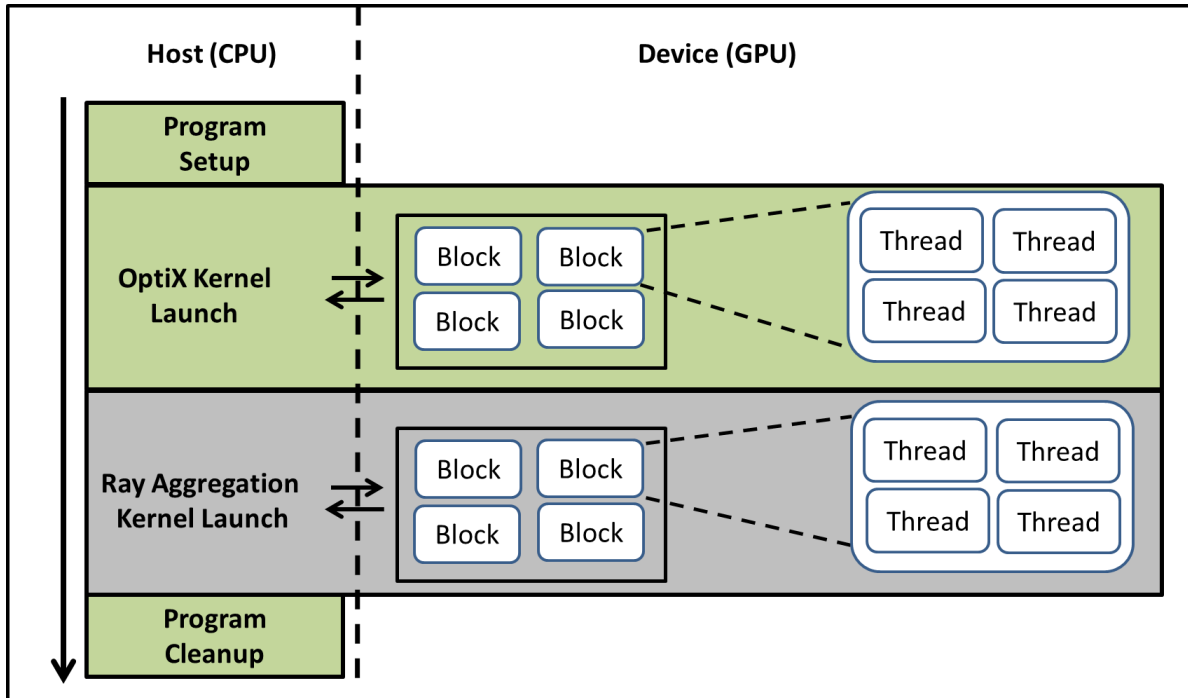
Implementation





Computational Results: Performance

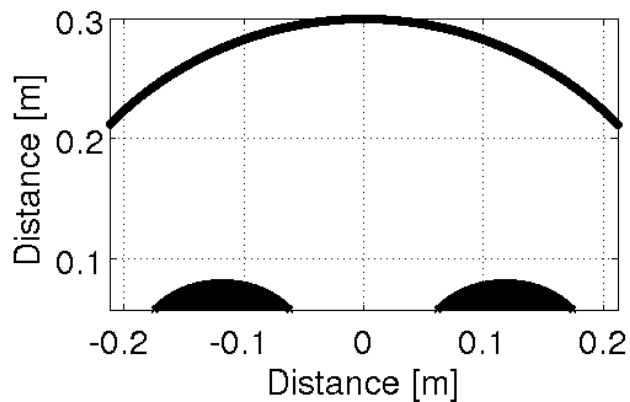
- RT execution time breakdown:
 - Program setup
 - OptiX validation
 - OptiX kernel
 - Ray aggregation
 - Saving fields



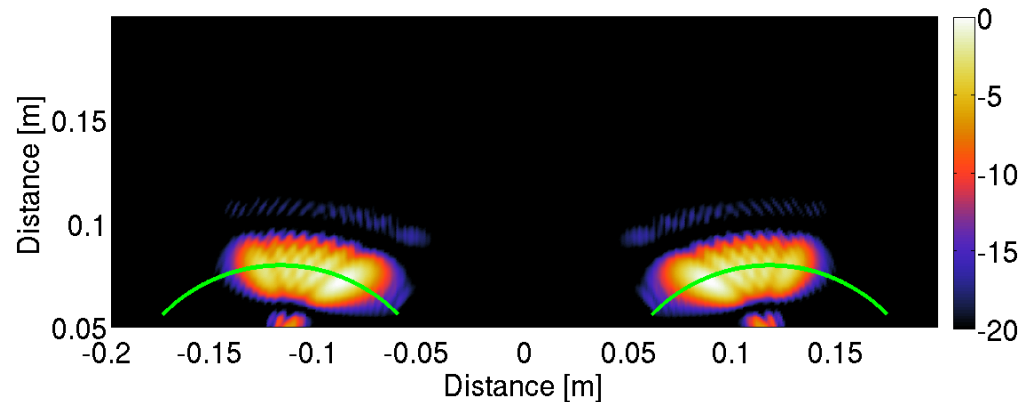


Computational Results: 2D Legs

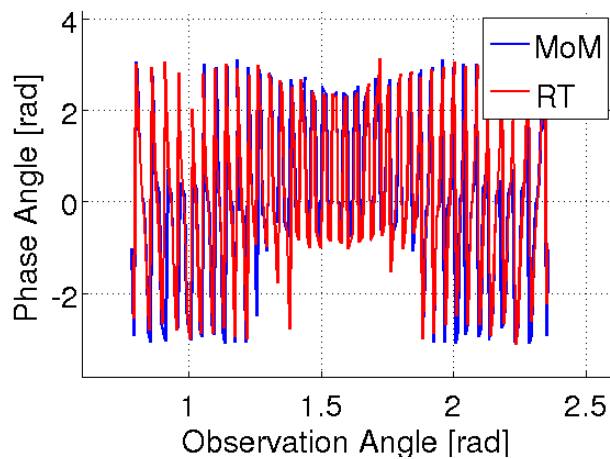
Configuration



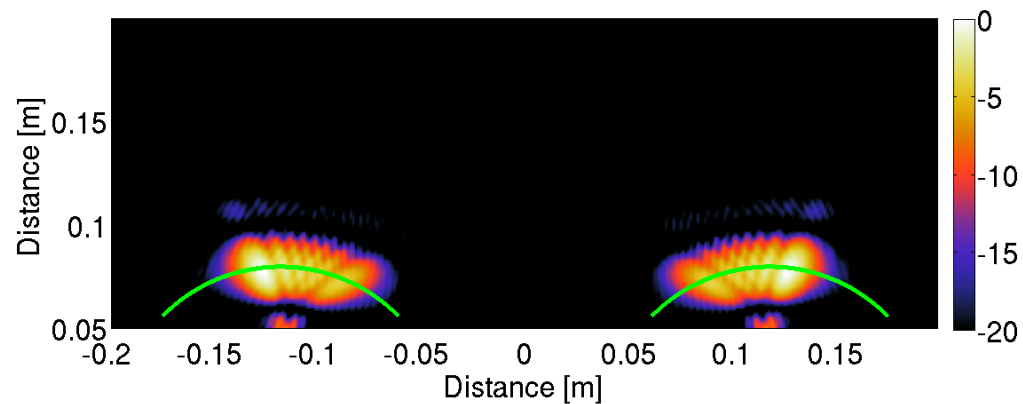
SAR Image Using MoM Data



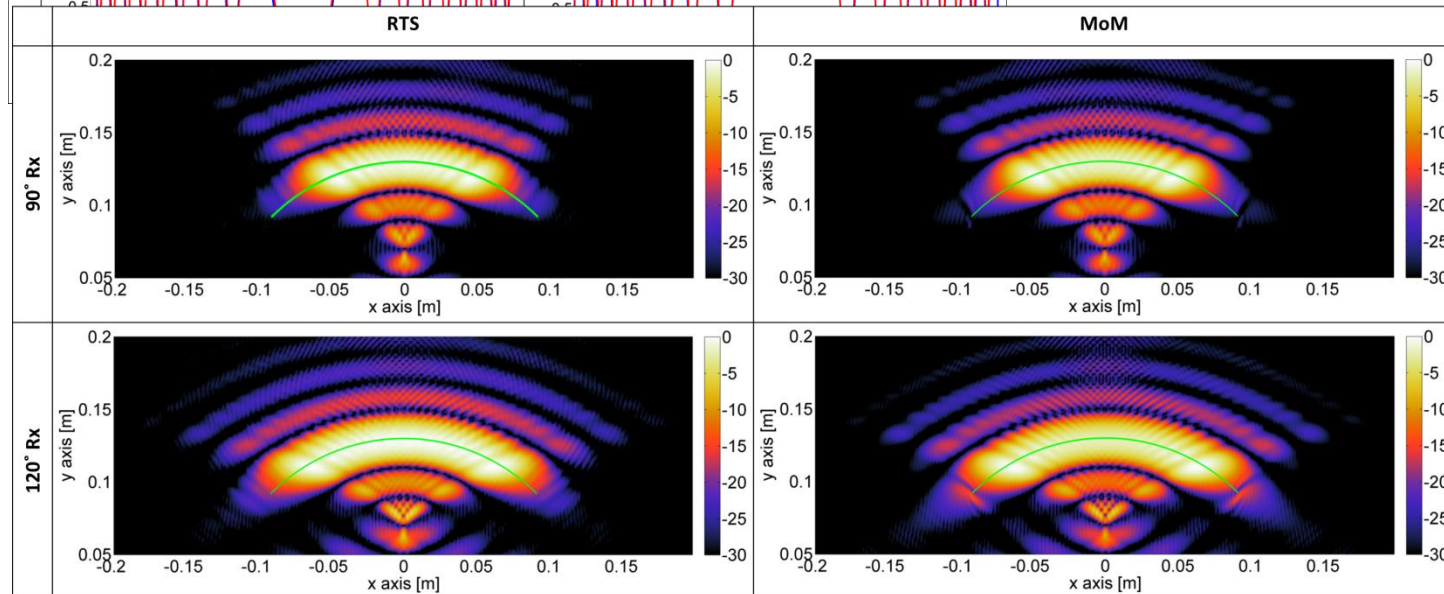
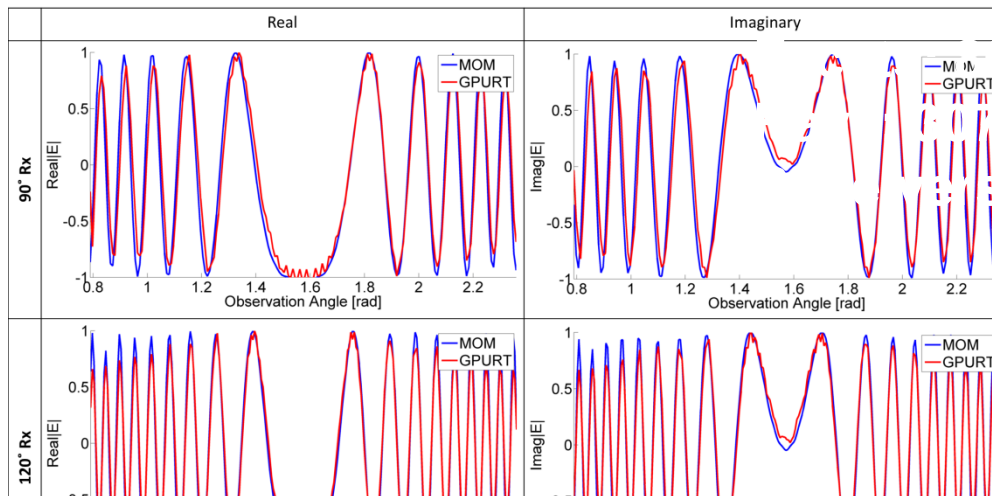
Phase Of Scattered Field



SAR Image Using RT Data

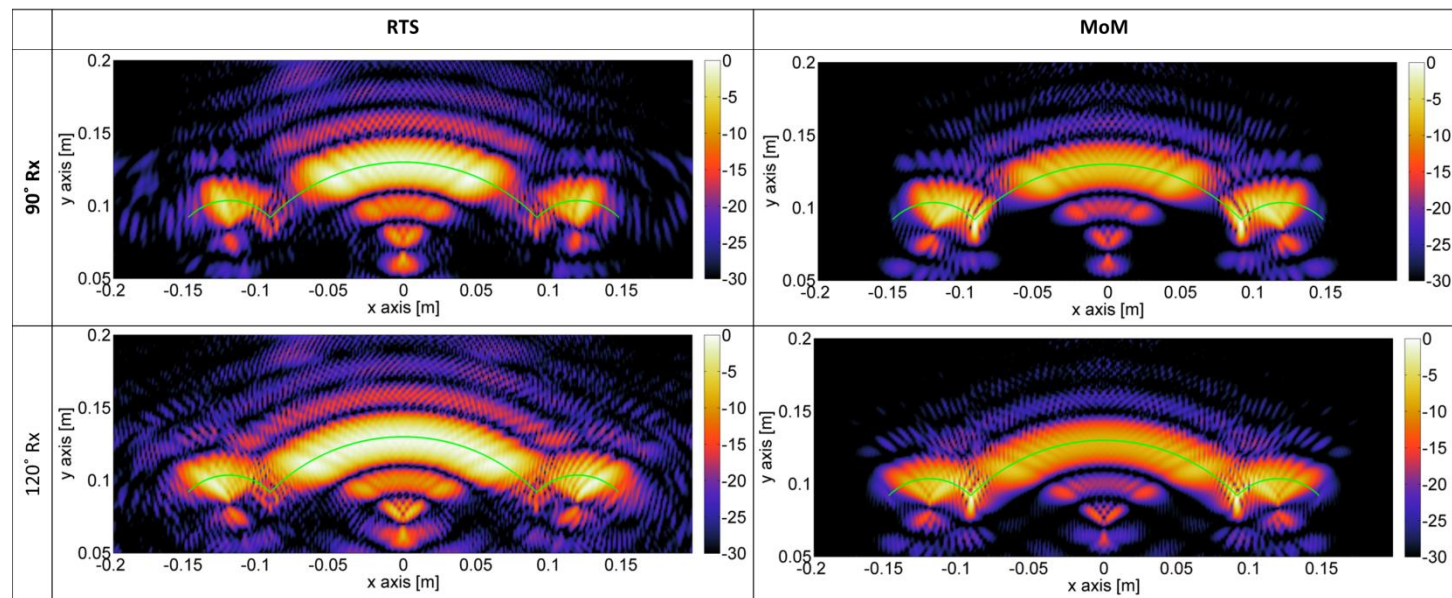
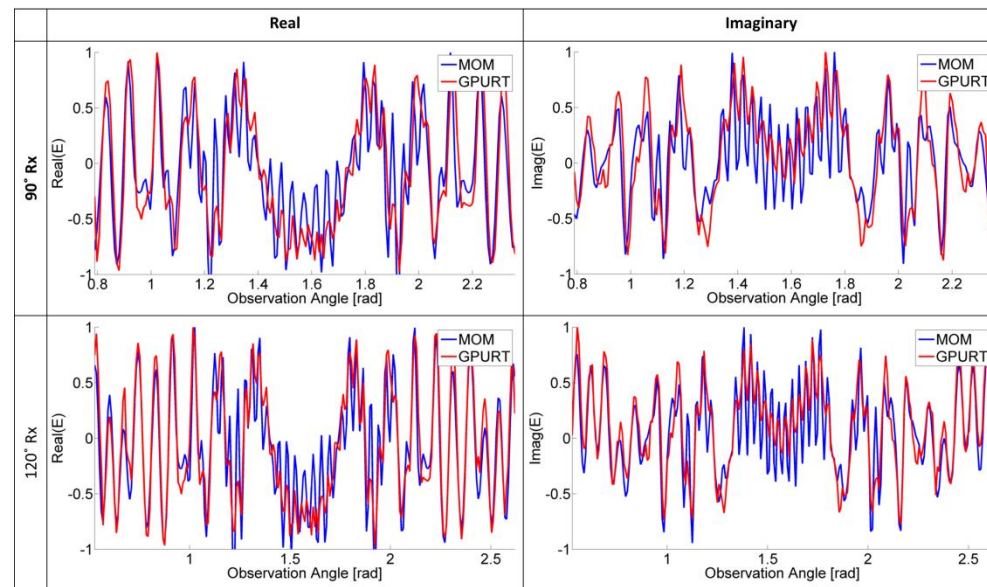


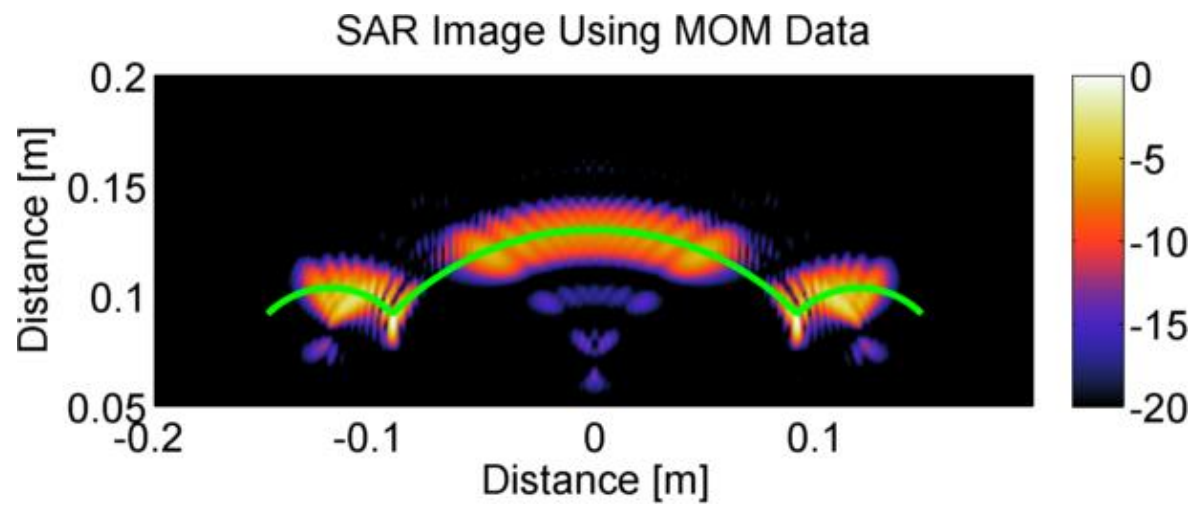
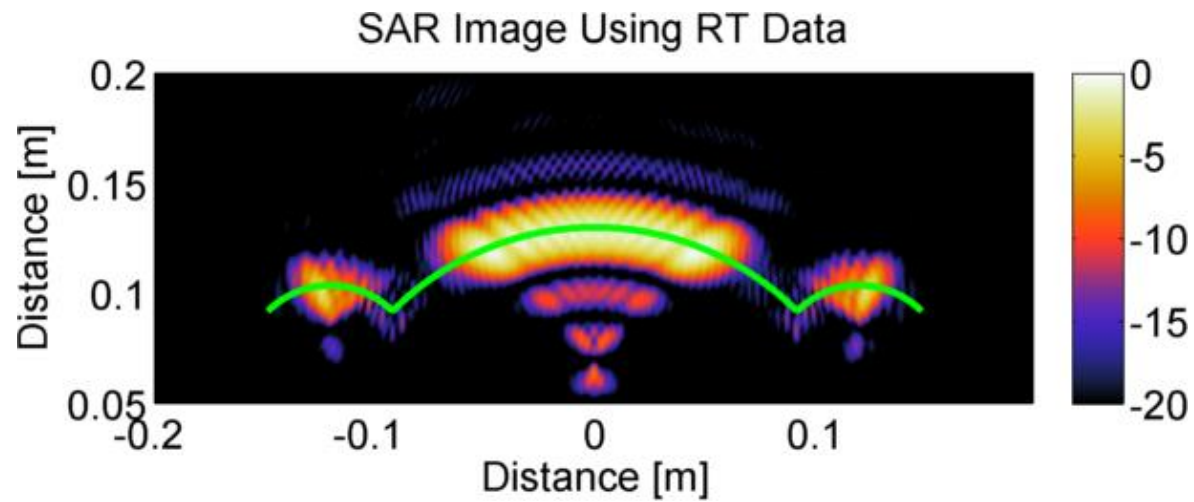
Computational Results





Computational Results

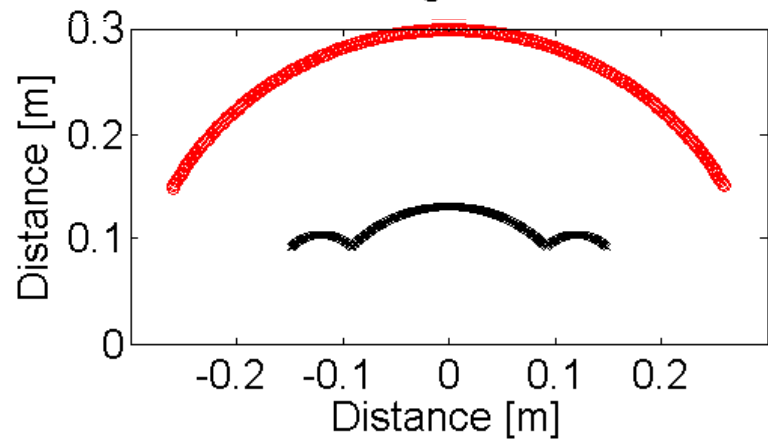




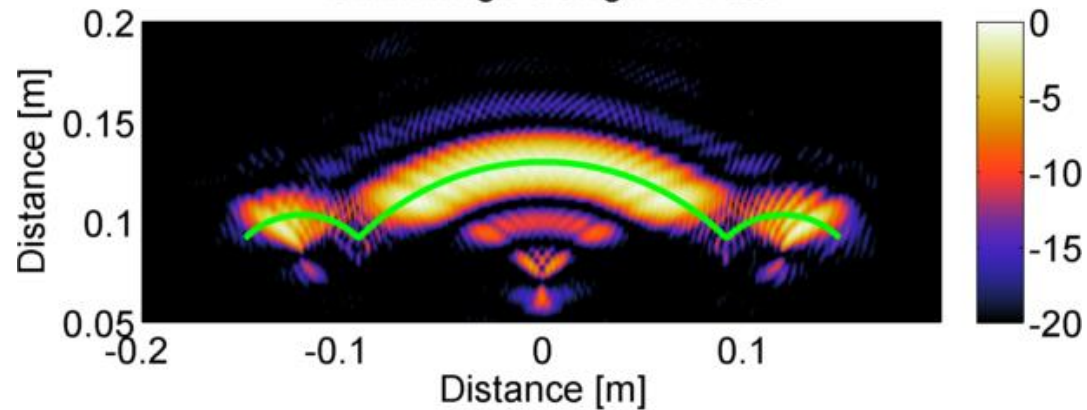


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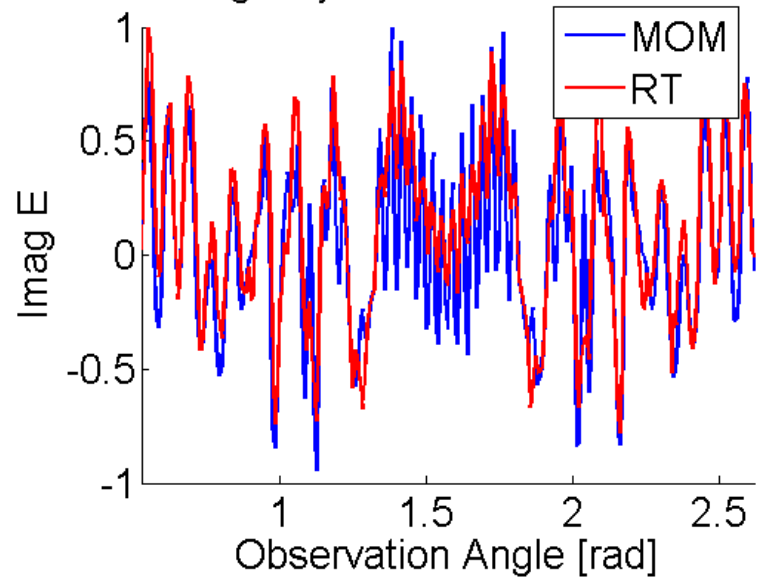
Configuration



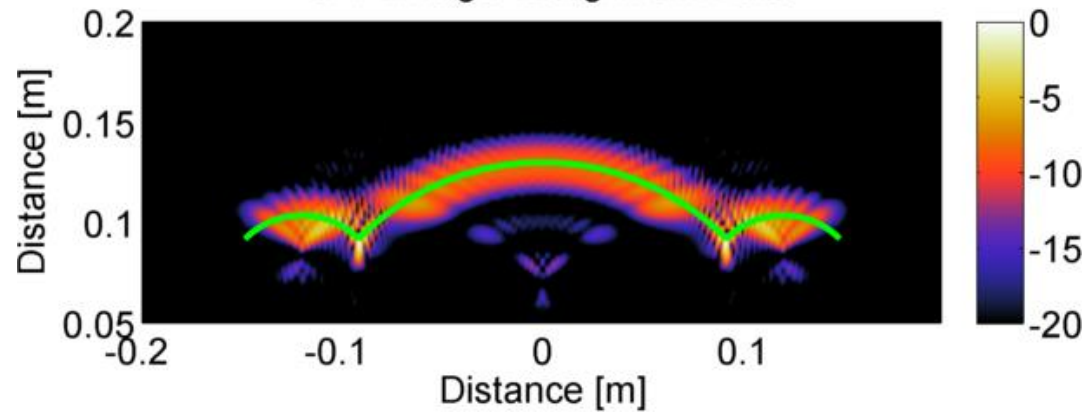
SAR Image Using RT Data



Imaginary Part of Scattered Field

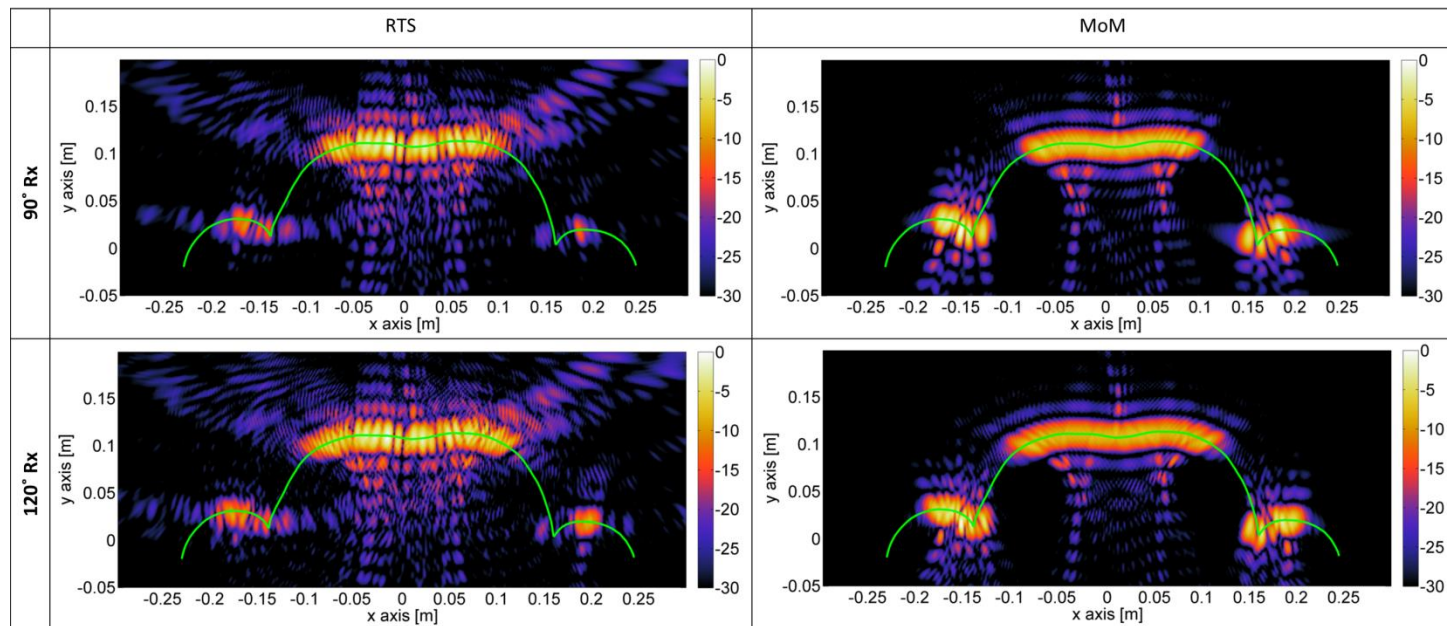
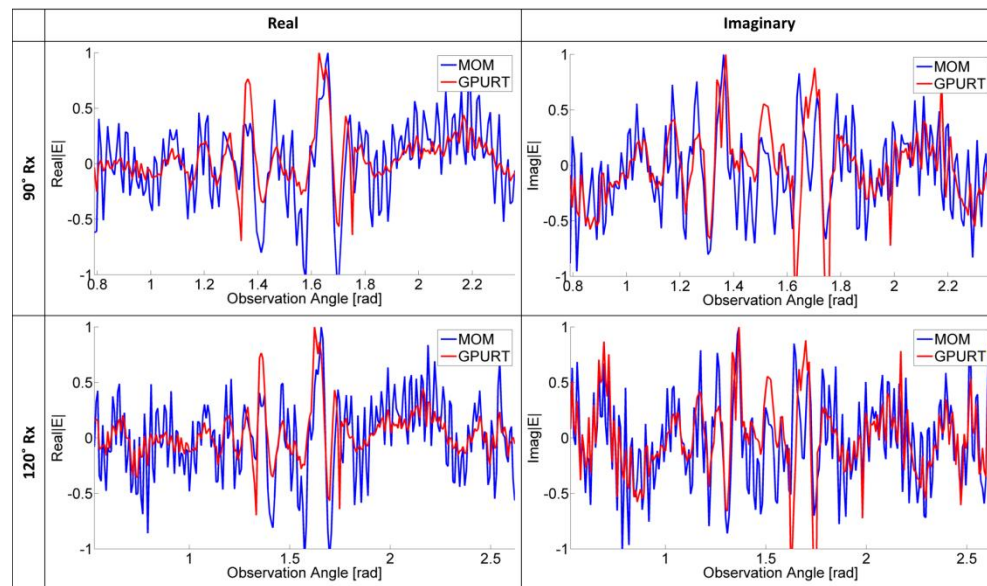


SAR Image Using MOM Data



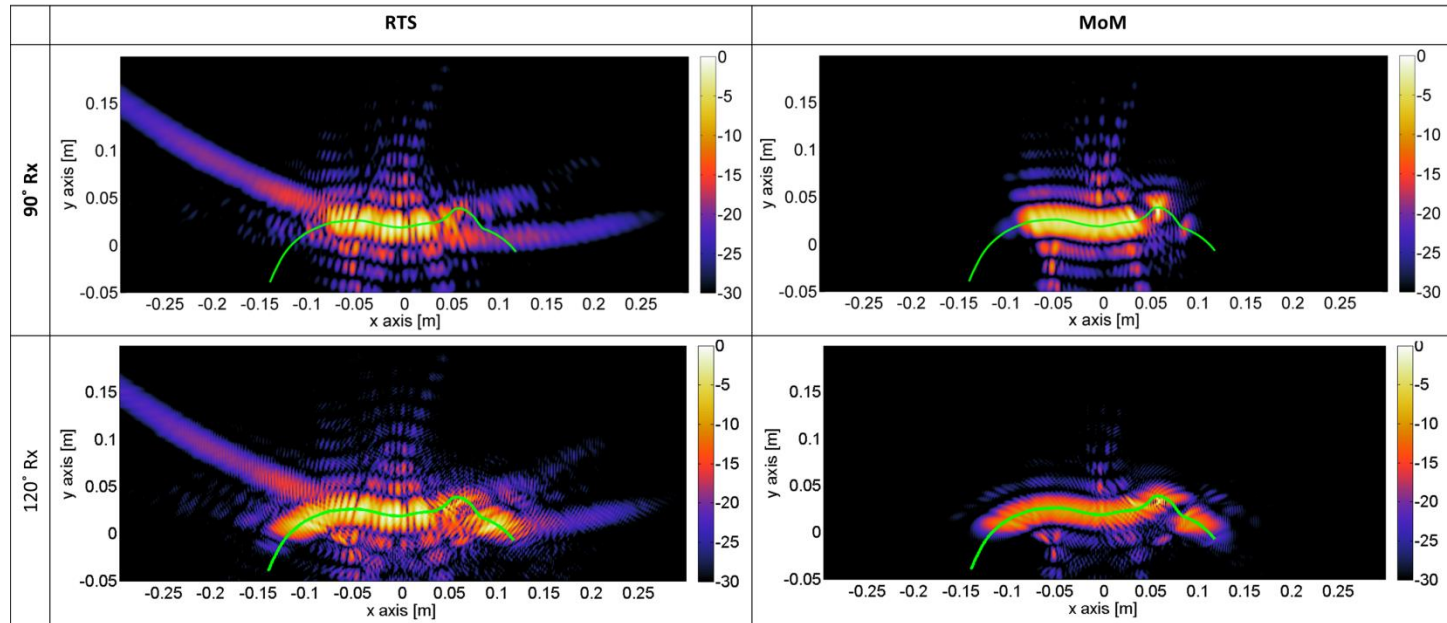
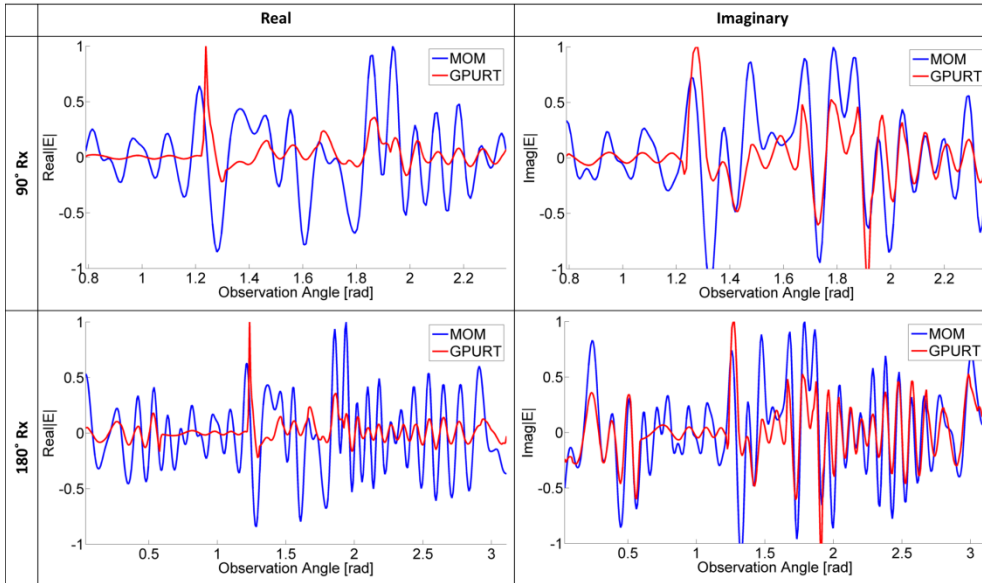


Computational Results





Computational Results





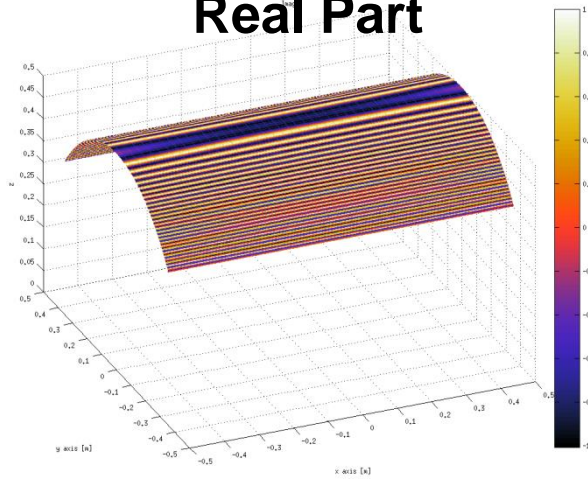
Computational Time

	Parameters			Time		
	# Freq	# Bins in Azimuth	# Bins in Height	RT Time (s)	MECA Time (s)	Factor Speedup (for these case only)
Case A	16	654	417	0.8843	5136	5808
Case B	32	654	417	0.9707	10272	10581
Case C	16	654	1	0.7970	13.68	17
Case D	32	654	1	0.8117	27.36	33

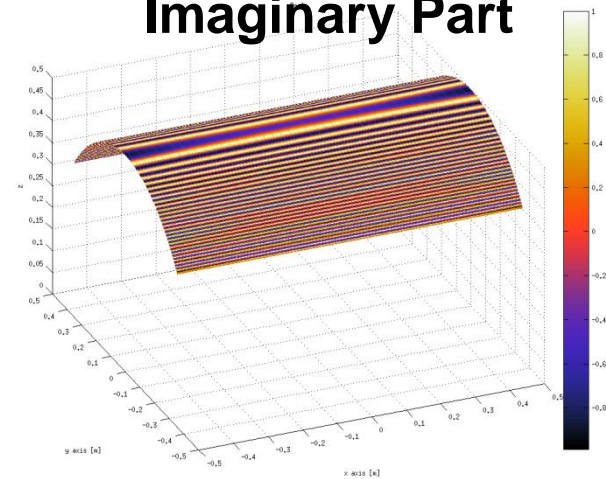


Visualization of Results: 1cm Plate

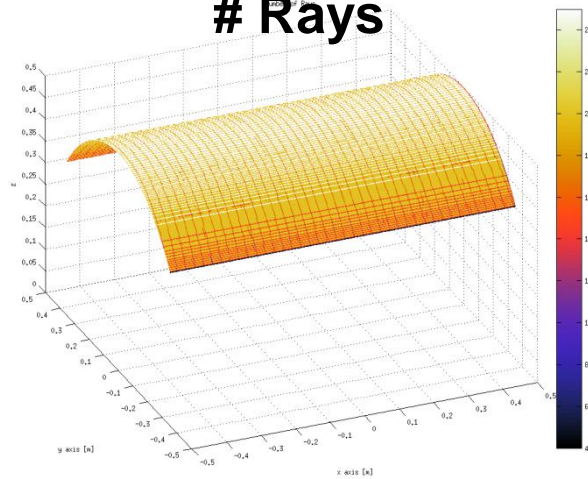
Real Part



Imaginary Part



Rays





Computational Results: Template





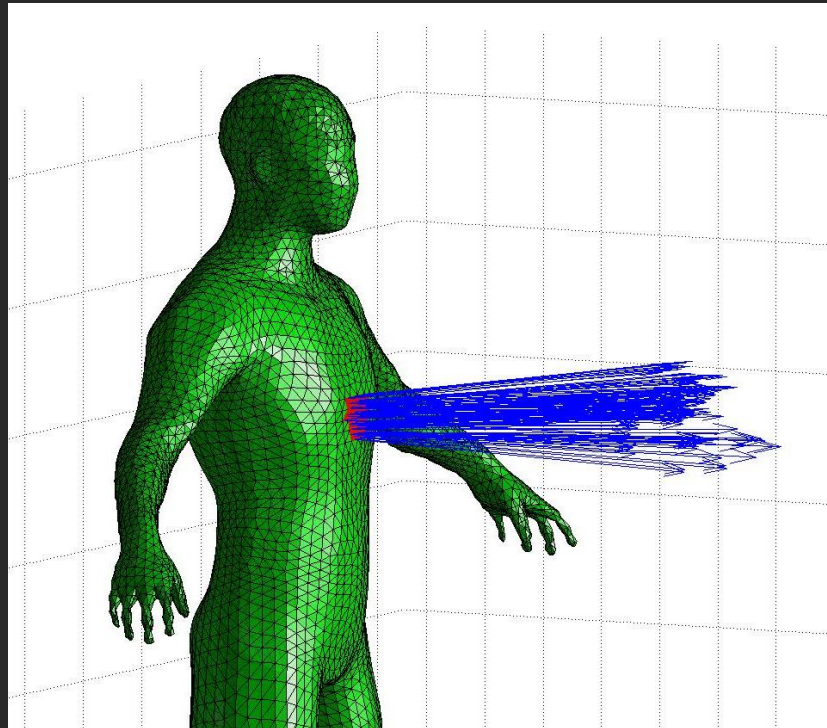
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Advantages of Ray Tracing over Other Methods

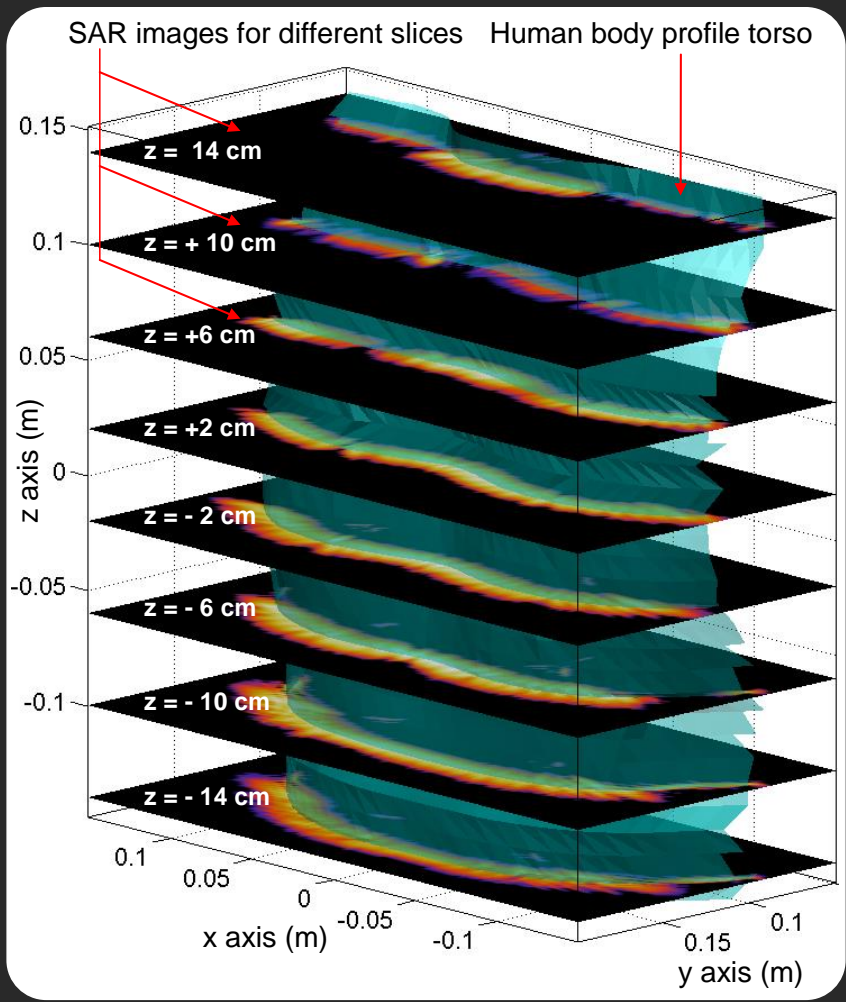
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- Inherently parallelizable
- Has potential for real-time computation
- Reasonably accurate for mm-waves for objects of interest

- MoM, Finite Difference Frequency Domain (FDFD) are more accurate but slow, and not readily as parallelizable
- Includes mutual interactions (multiple bounces) much more readily than Physical Optics (PO)
- Uses the object 2nd-order normal at every surface point, instead of just the center of each triangular facet for PO



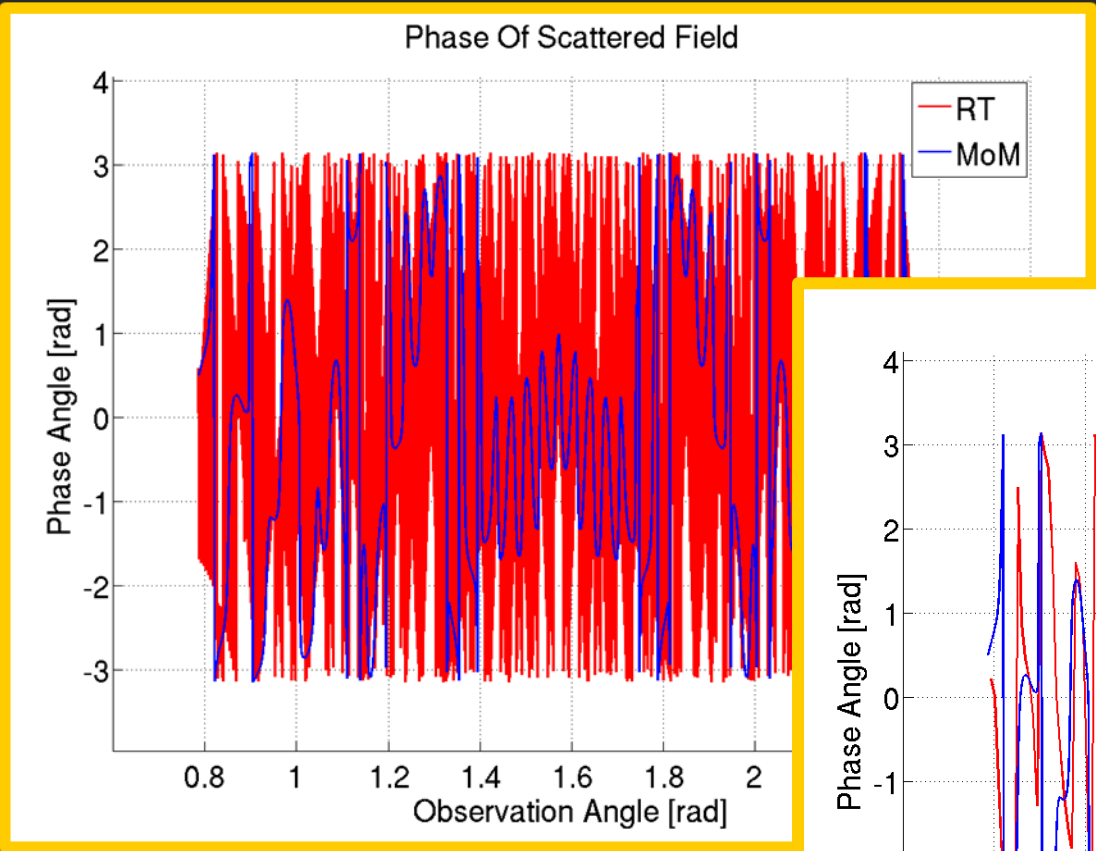
Advantages of Ray Tracing over Other Methods

- Can be effective forward model for inversion
 - May give 3D (i.e., height) response to supplement 2D stacked reconstructions
 - May be used for iterative reconstruction
 - May be used as part of a novel multiple bounce SAR inversion scheme
 - May be useful for focusing in on details (i.e., a possible threat)

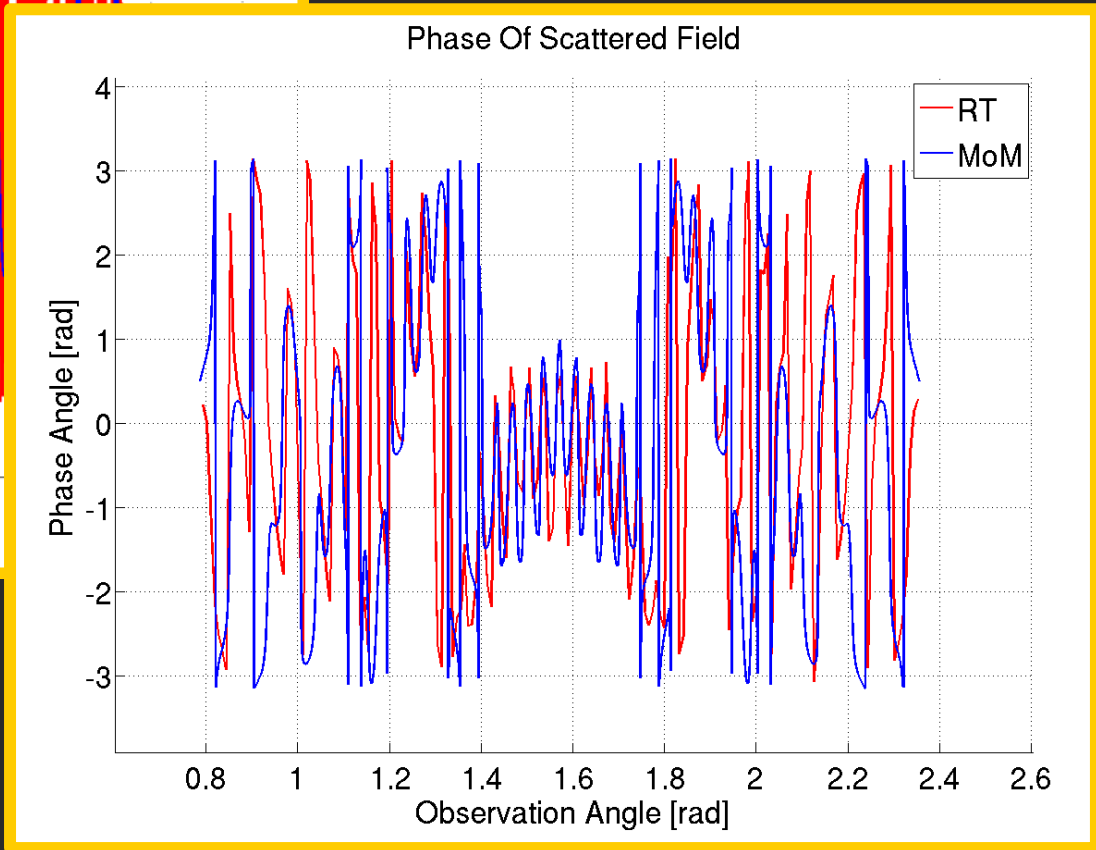


Ray Aggregation: Sample Data

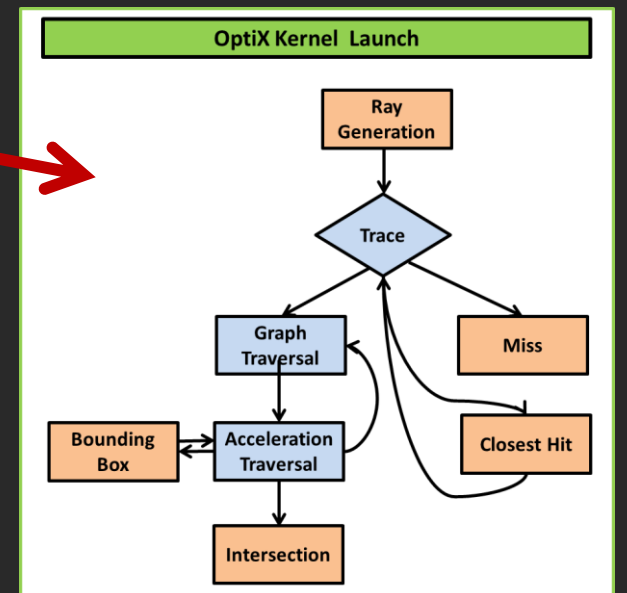
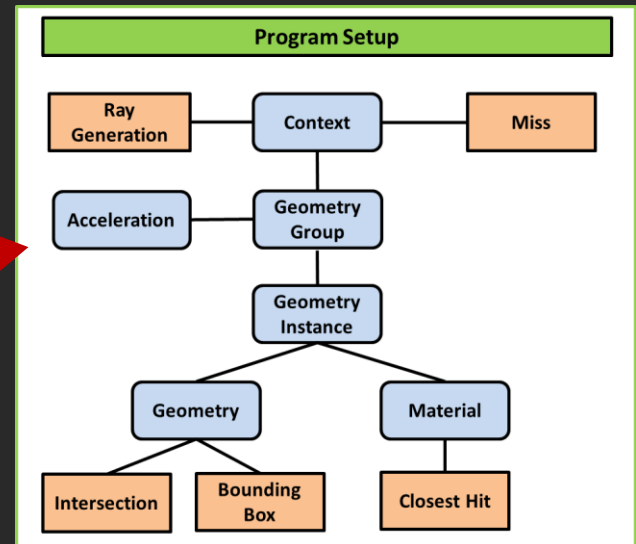
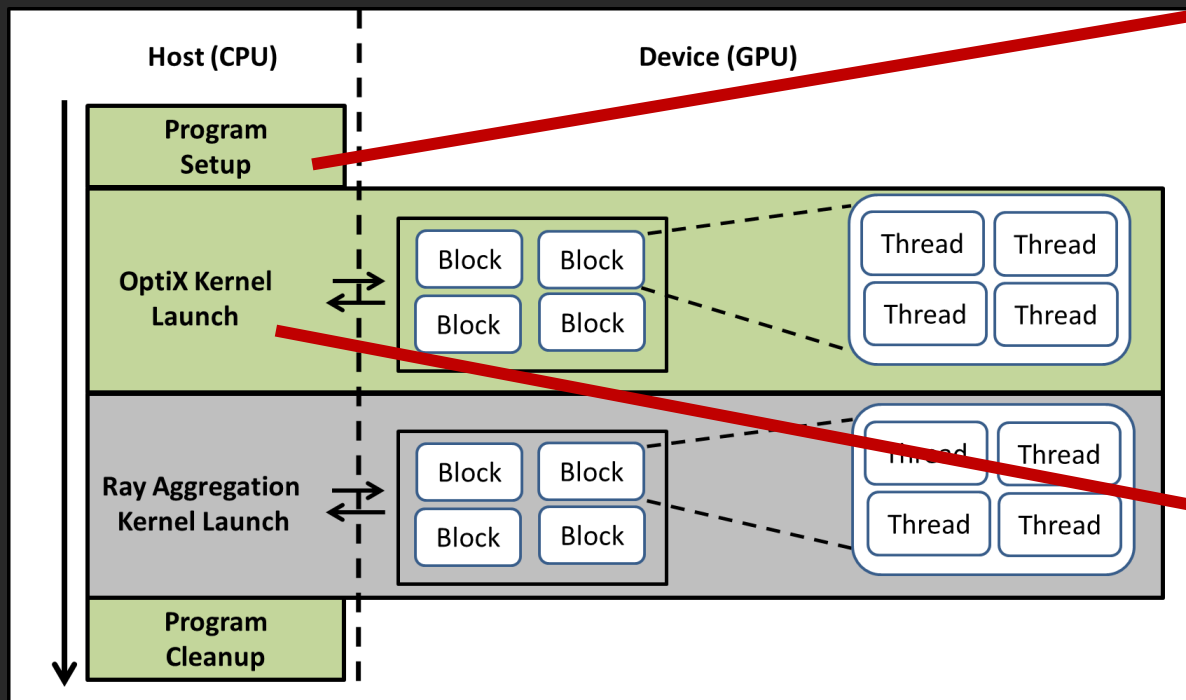
Not aggregated



Aggregated

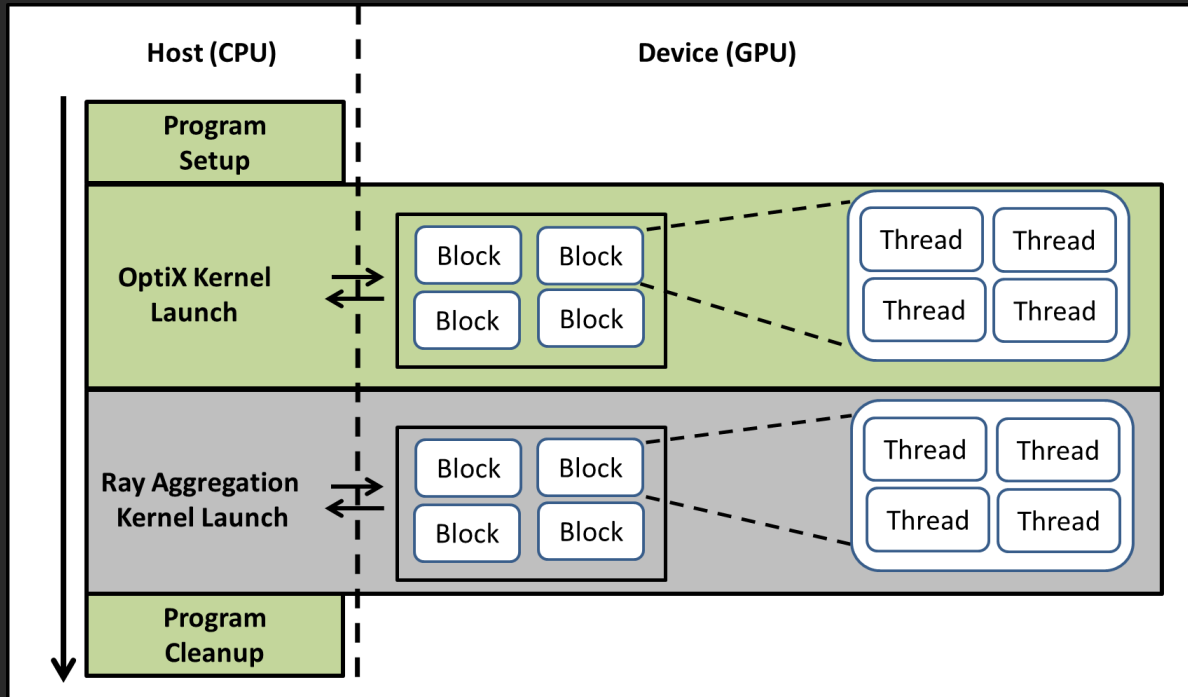


Implementation

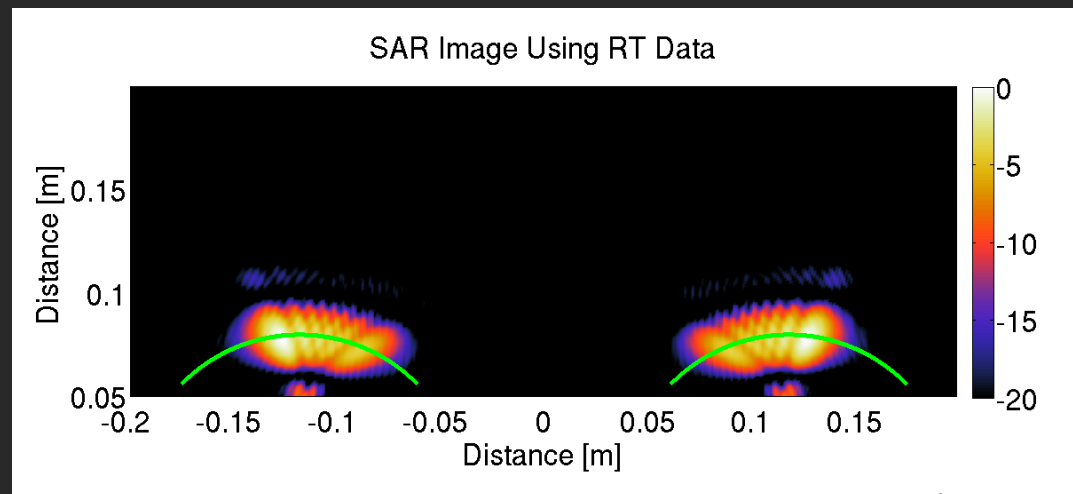
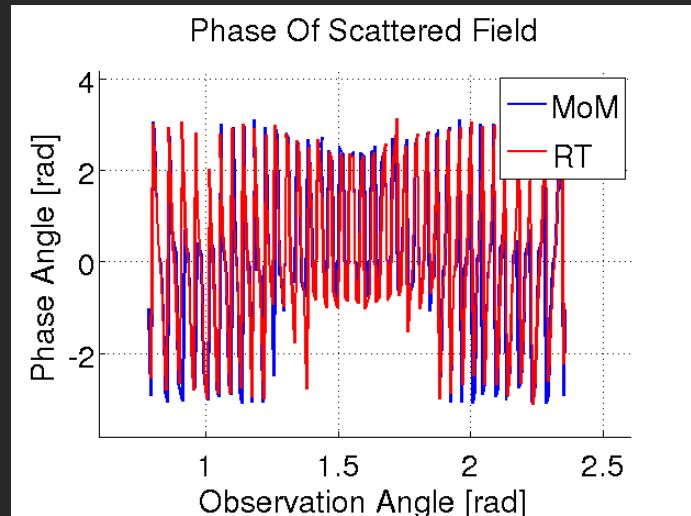
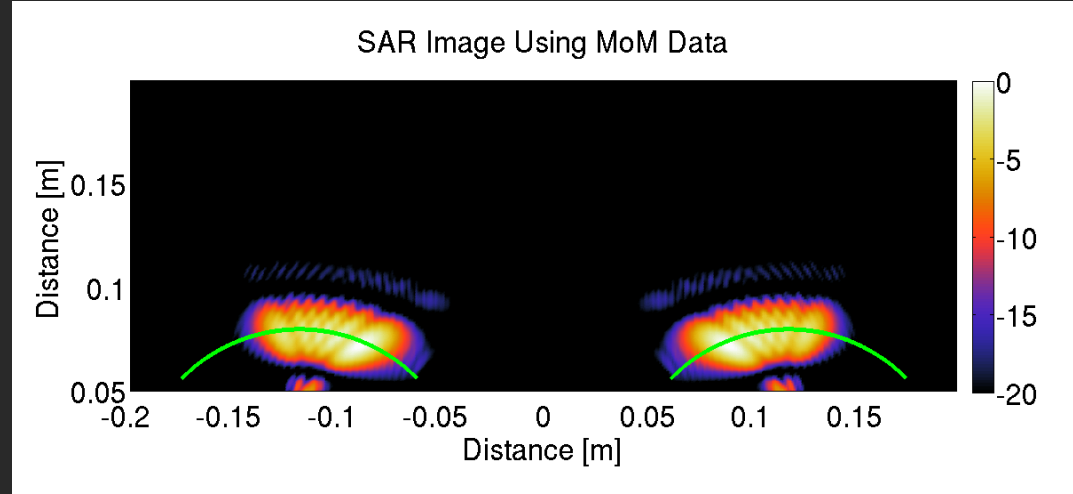
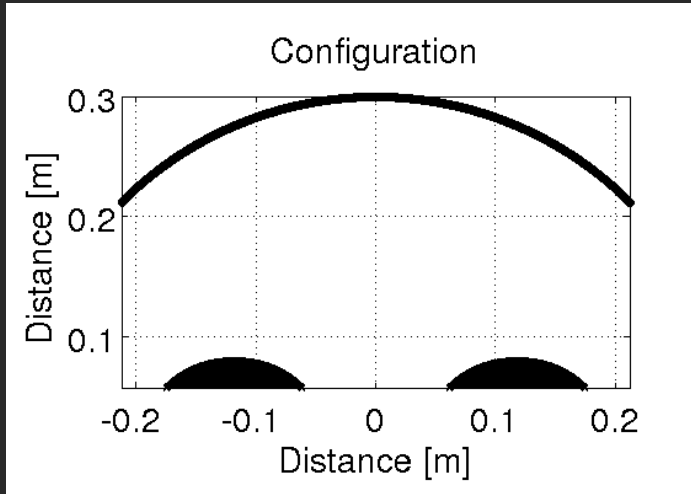


Computational Results: Performance

- RT execution time breakdown:
 - Program setup
 - OptiX validation
 - OptiX kernel
 - Ray aggregation
 - Saving fields

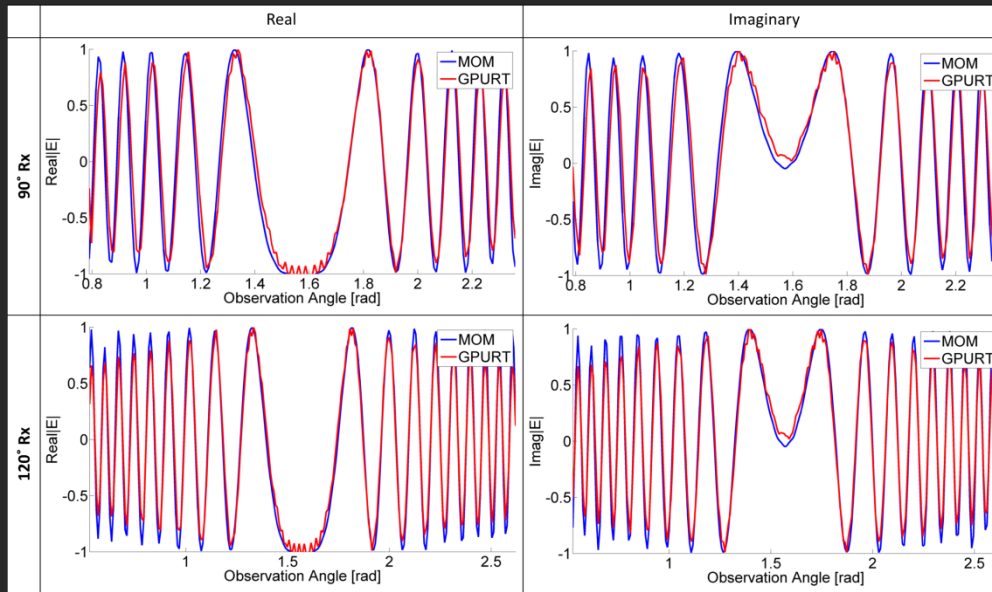


Computational Results: 2D Legs





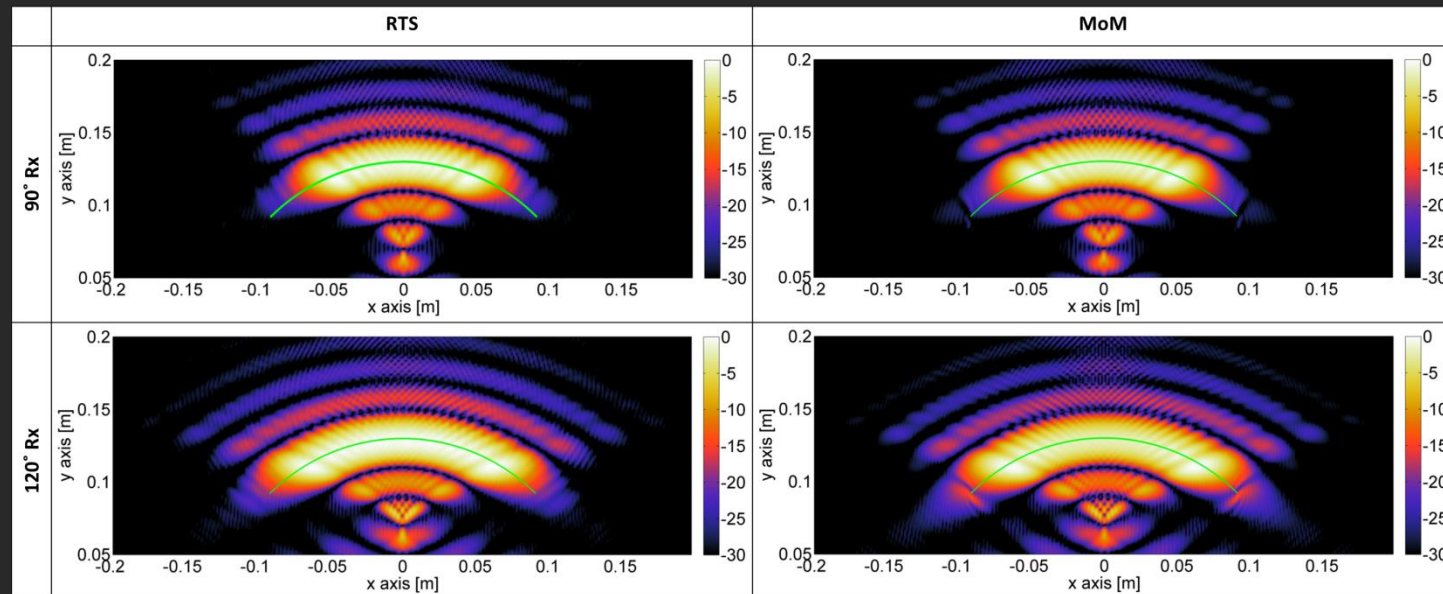
Computational Results



Facets: 80

Rays: 3072

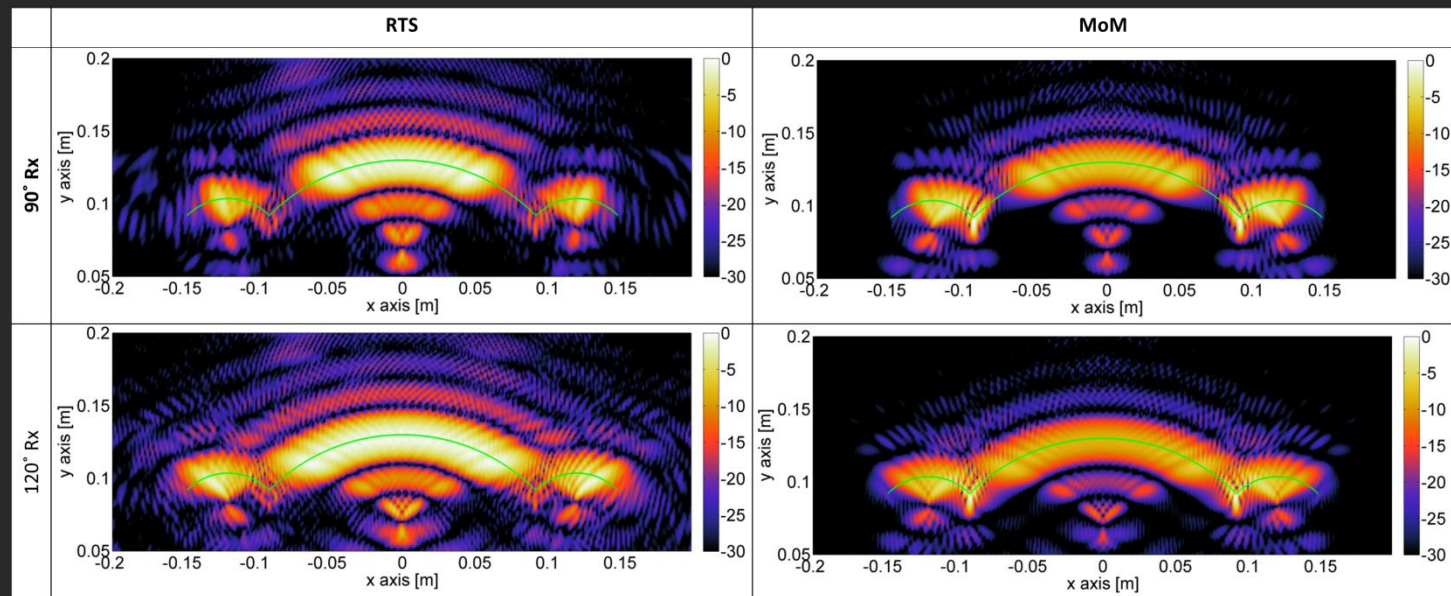
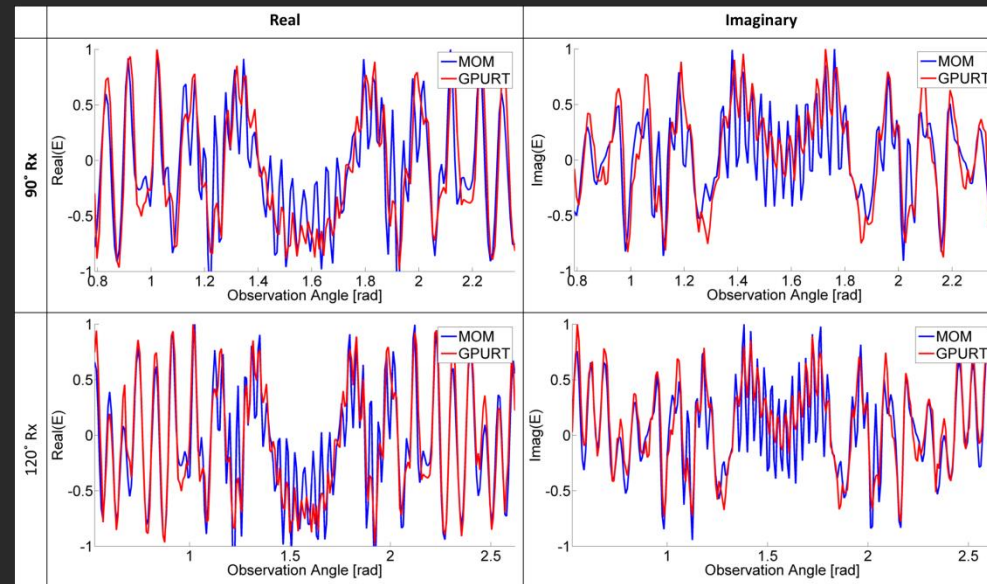
Receivers Bins: 199/266

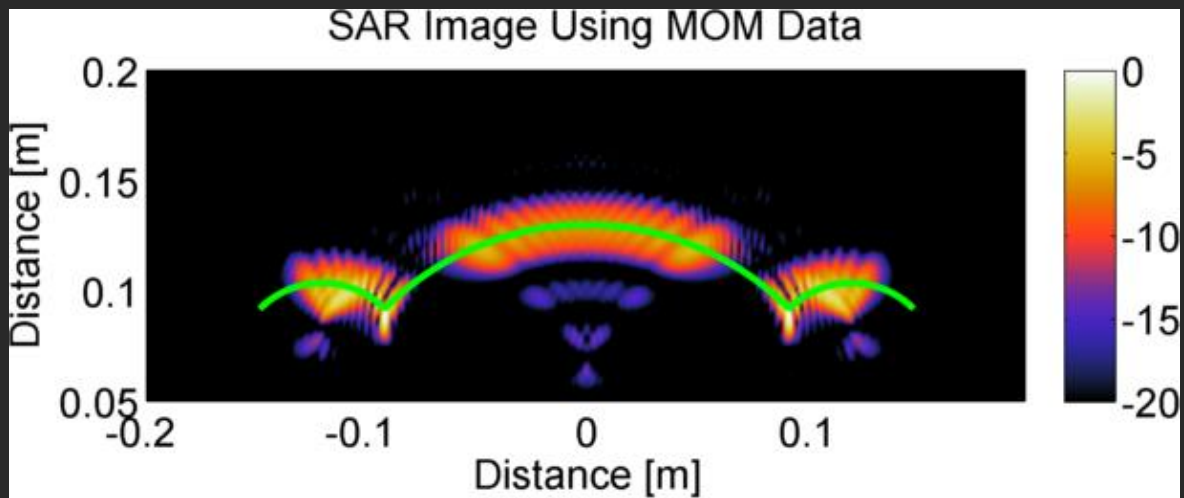
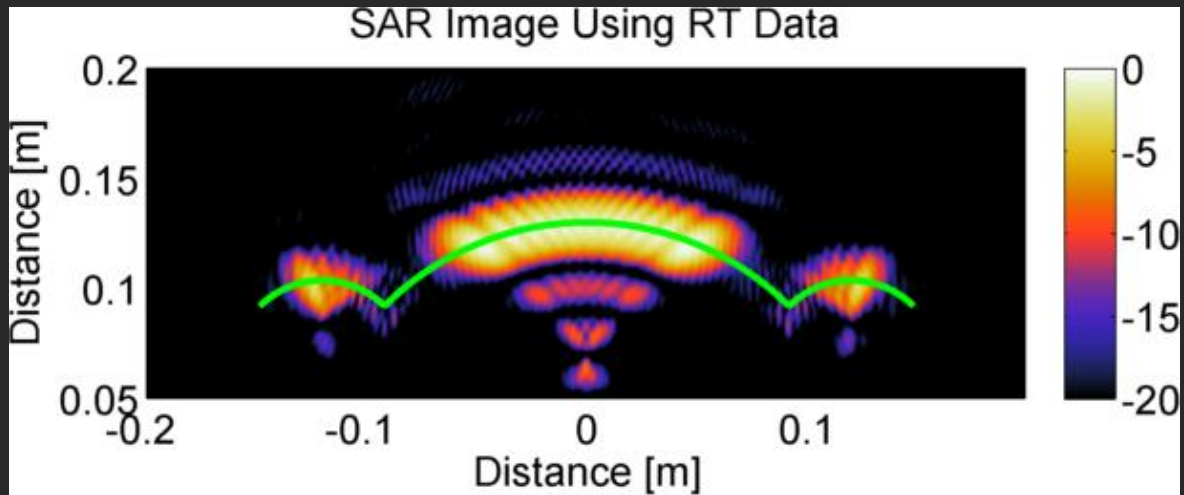




Computational Results

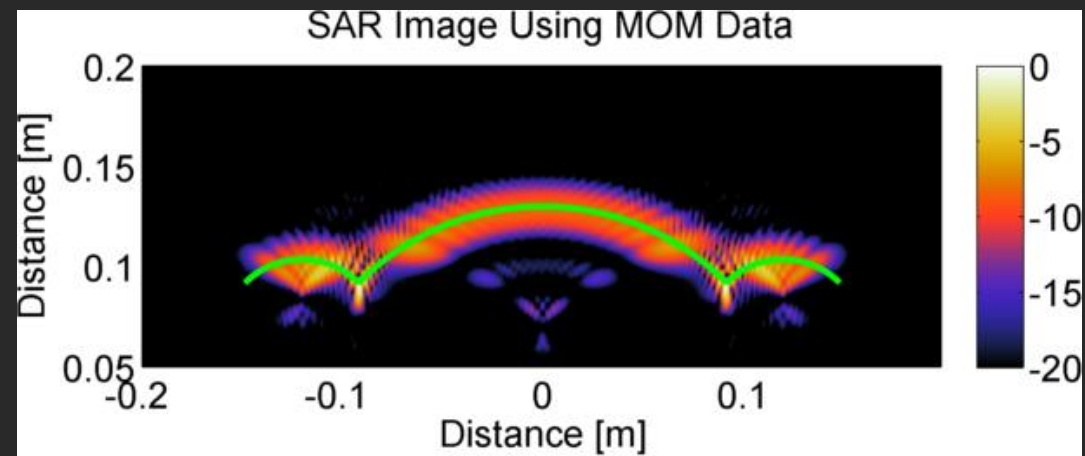
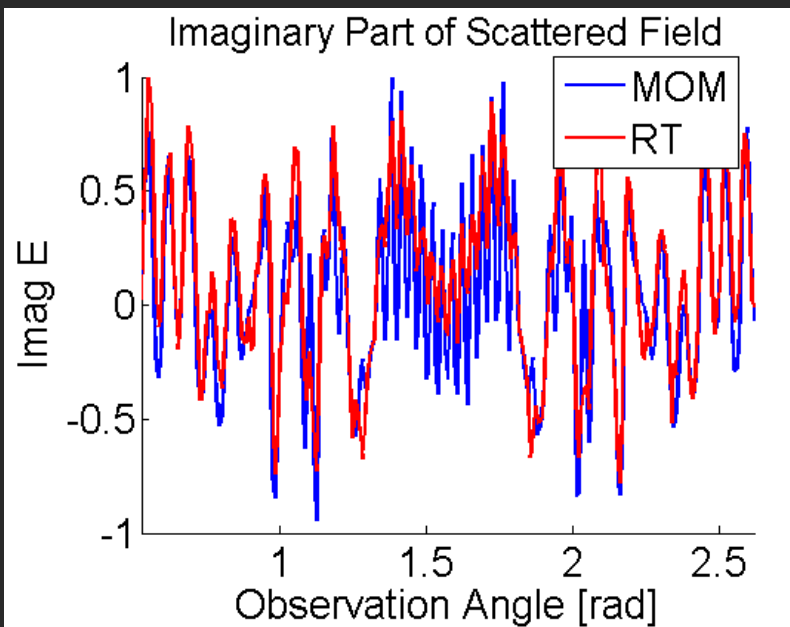
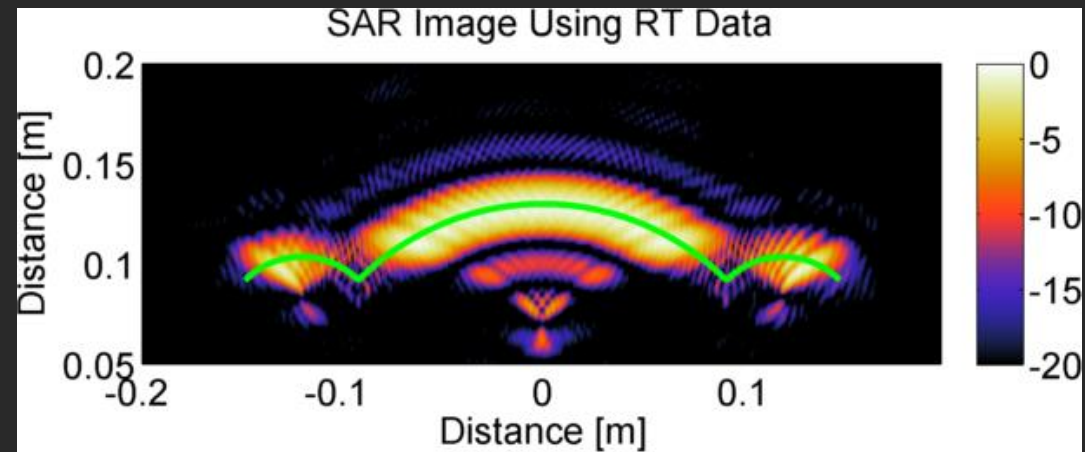
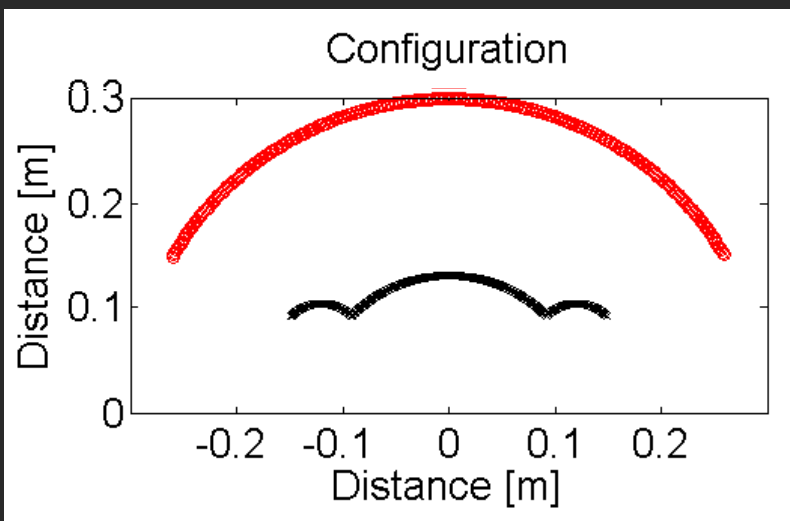
Facets: 134/134
Rays: 3072
Receivers Bins: 199/266







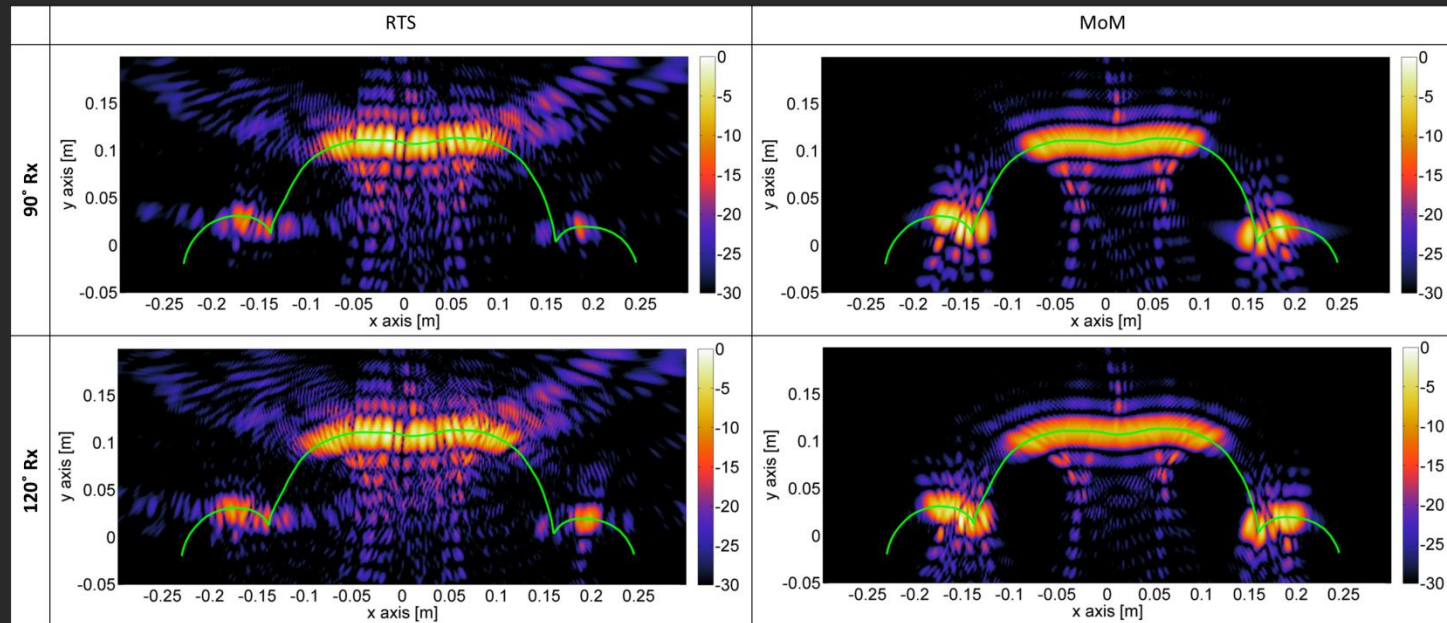
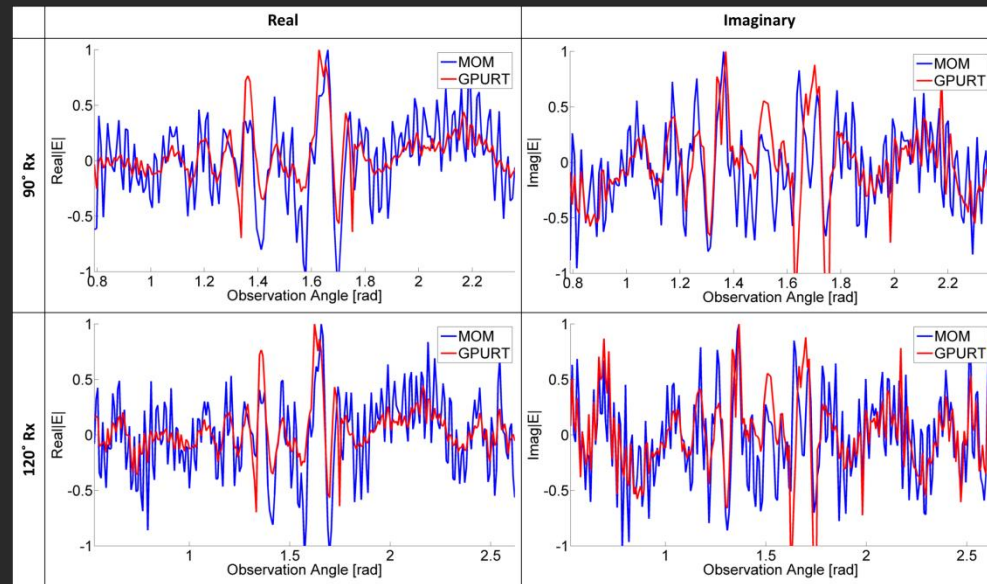
Computational Results





Computational Results

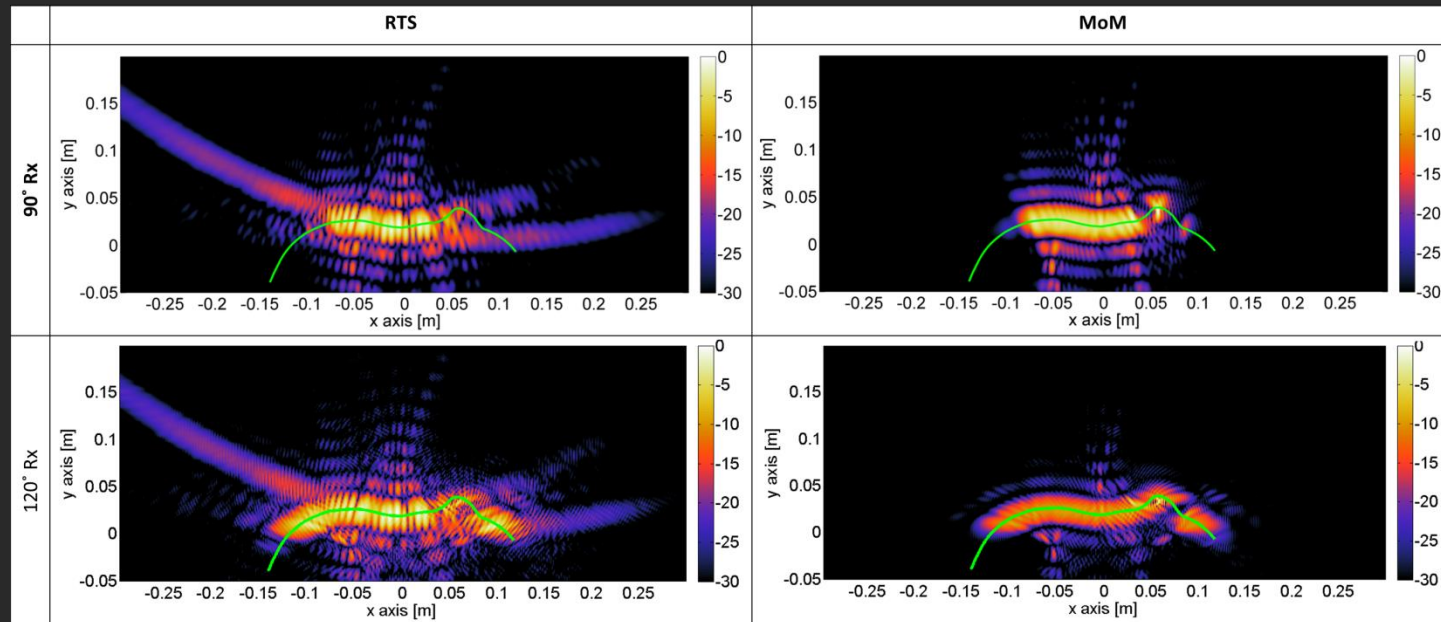
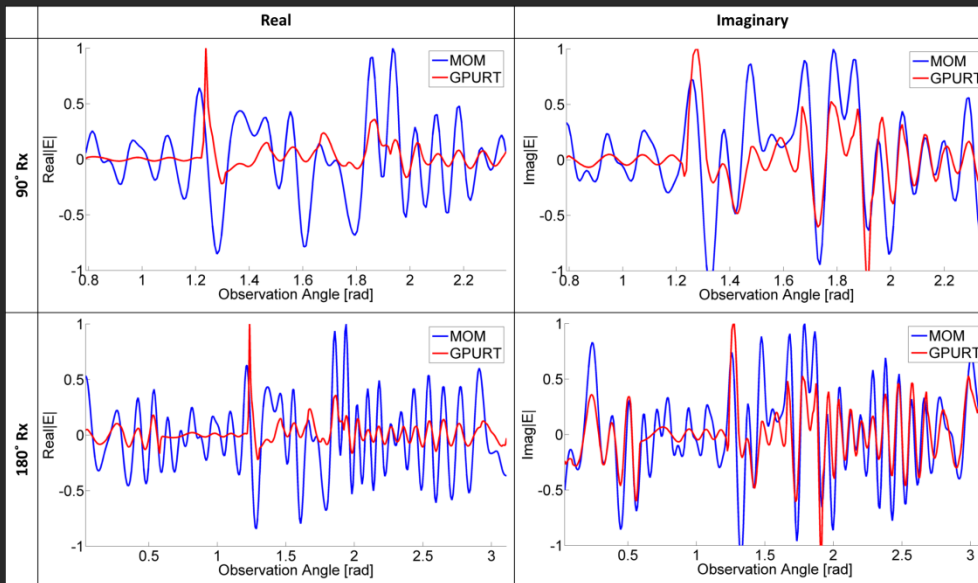
Facets: 282
Rays: 3072
Receivers Bins: 199/266





Computational Results

Facets: 126
Rays: 131,072
Receivers Bins: 199/389



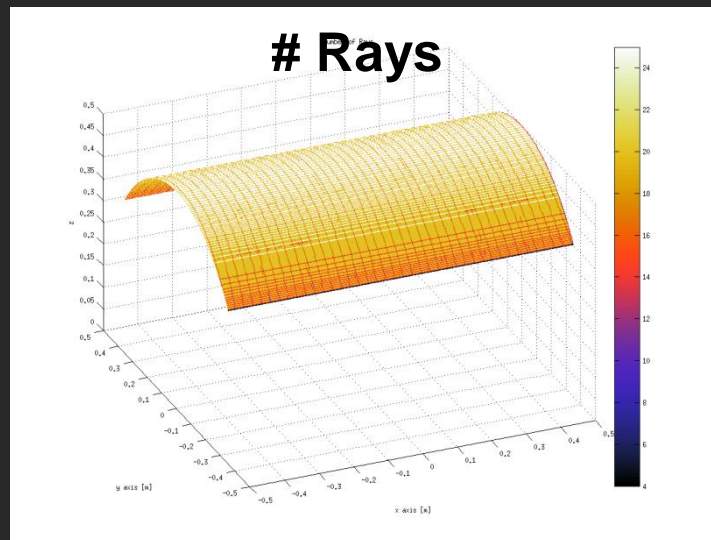
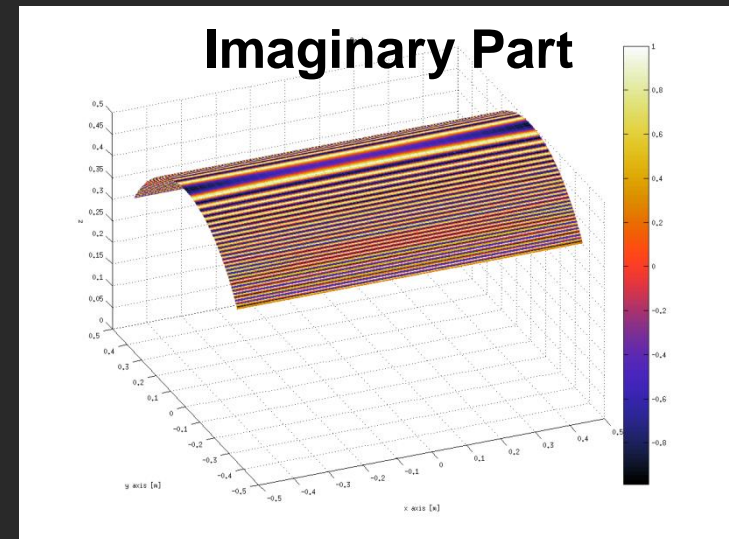
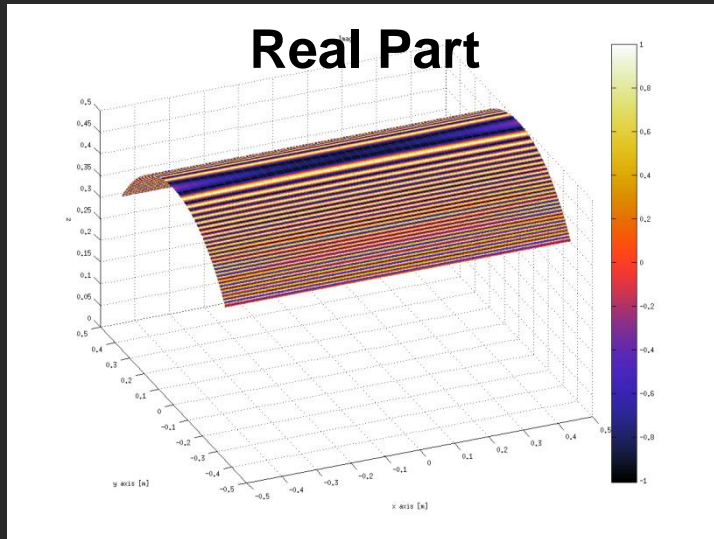


Computational Time

	Parameters			Time		
	# Freq	# Bins in Azimuth	# Bins in Height	RT Time (s)	MECA Time (s)	Factor Speedup (for these case only)
Case A	16	654	417	0.8843	5136	5808
Case B	32	654	417	0.9707	10272	10581
Case C	16	654	1	0.7970	13.68	17
Case D	32	654	1	0.8117	27.36	33



Visualization of Results: 1cm Plate



Facets: 80,000
Rays: 2048 x 2048
Receivers:

Computational Results: Template

