Solopulse

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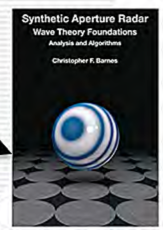
Georgia Institute of Technology

The Road to Solopulse:

Academic development from 2016 to 2022…

- 1986 - BS/MS in ECE from BYU
- 1989 - PhD in ECE from BYU (completed in 27 months) - Employed by GTRI
- 1993 - 1998 - THAAD Radar Research Signal & Data Processing SME
- 1998 - 2000 - **Cobra Judy Replacement Radar Research Signal & Data Processing SME**
- 2007 - 2011 - Air and Missile Defense Radar Research Software Architecture SME
- 2010 - Sea Based X-Band Radar Fault Evaluation Team
- 2013 - 2014 - FAA's MPAR/SENSR Radar Research Software Architecture SME
- 2016 - Army Sentinel Radar Research
- 2017 LTAMDS Radar Research

- 1993 – 2017 Taught SAR Short Courses
- 2002 - Tenure Track Position Georgia Tech Savannah Campus
- 2007 - Awarded Tenure
- 2007 – 2014 Research for SAR Book
- 2015 SAR Book (Self Published)



- 2013 - Transitioned back to Georgia Tech Atlanta Campus
- 2014 - 2015 - Program Developer Georgia Tech Professional Education
- "Full Time Commit" - to School of ECE 2015
- 2020 Quantum Field Theory & Quantum Electrodynamics

C. B. Barnes's work experience and academic background

Barnes – Subject Matter Expertise: Radar System Engineering, Radar Software Engineering, Computed Imaging, Synthetic Aperture Radar

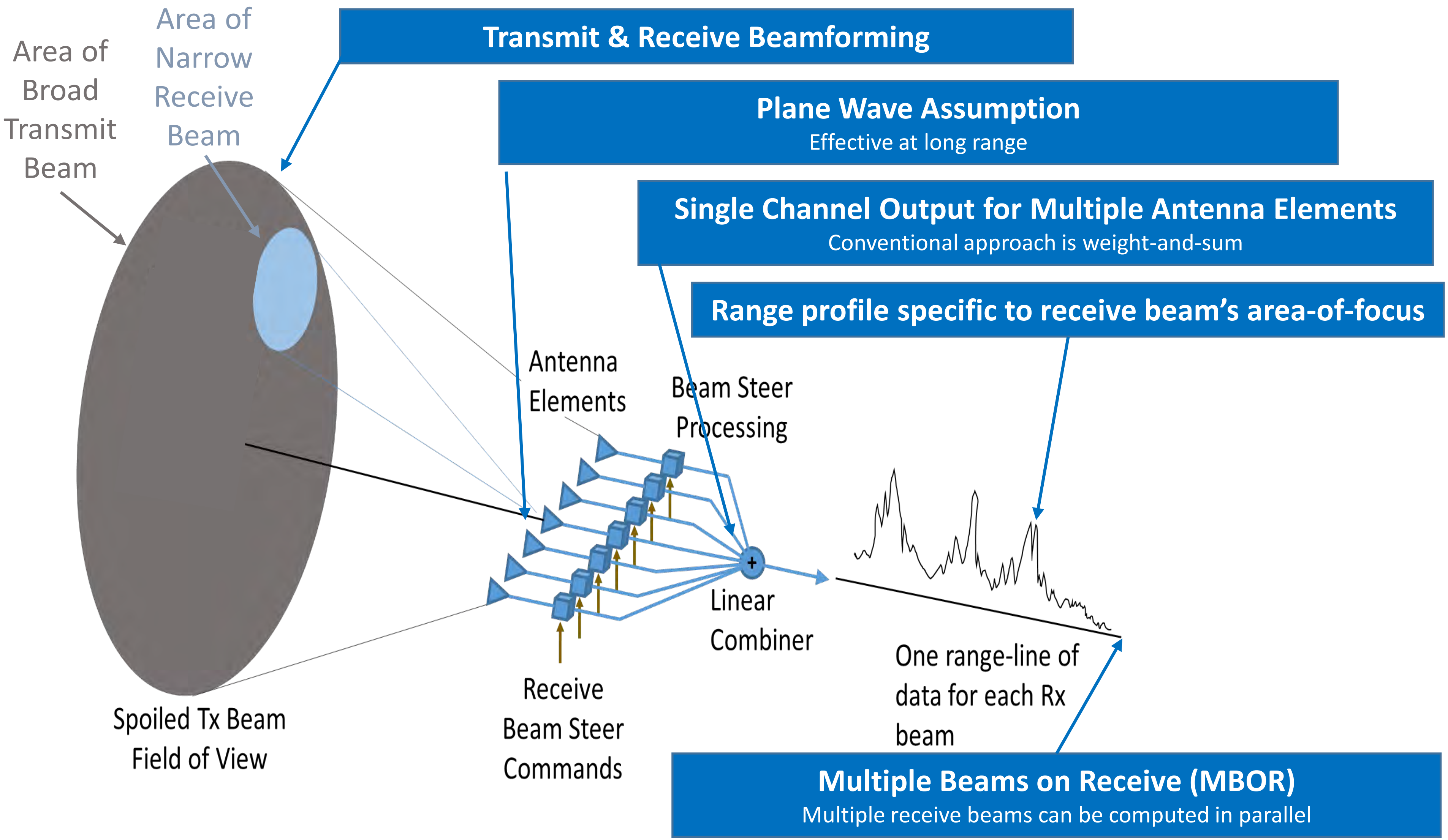
A Brief Solopulse Tutorial:

Solopulse has similarities with

Digital Beam Forming (DBF),
Synthetic Aperture Radar (SAR),
Colocated-MIMO on Digital Array Radars (DARs),
and etc…

Solopulse comparisons with DBF-on-receive and with SAR provide a tutorial framework for understanding methods and algorithms.

Digital Beamforming Overview

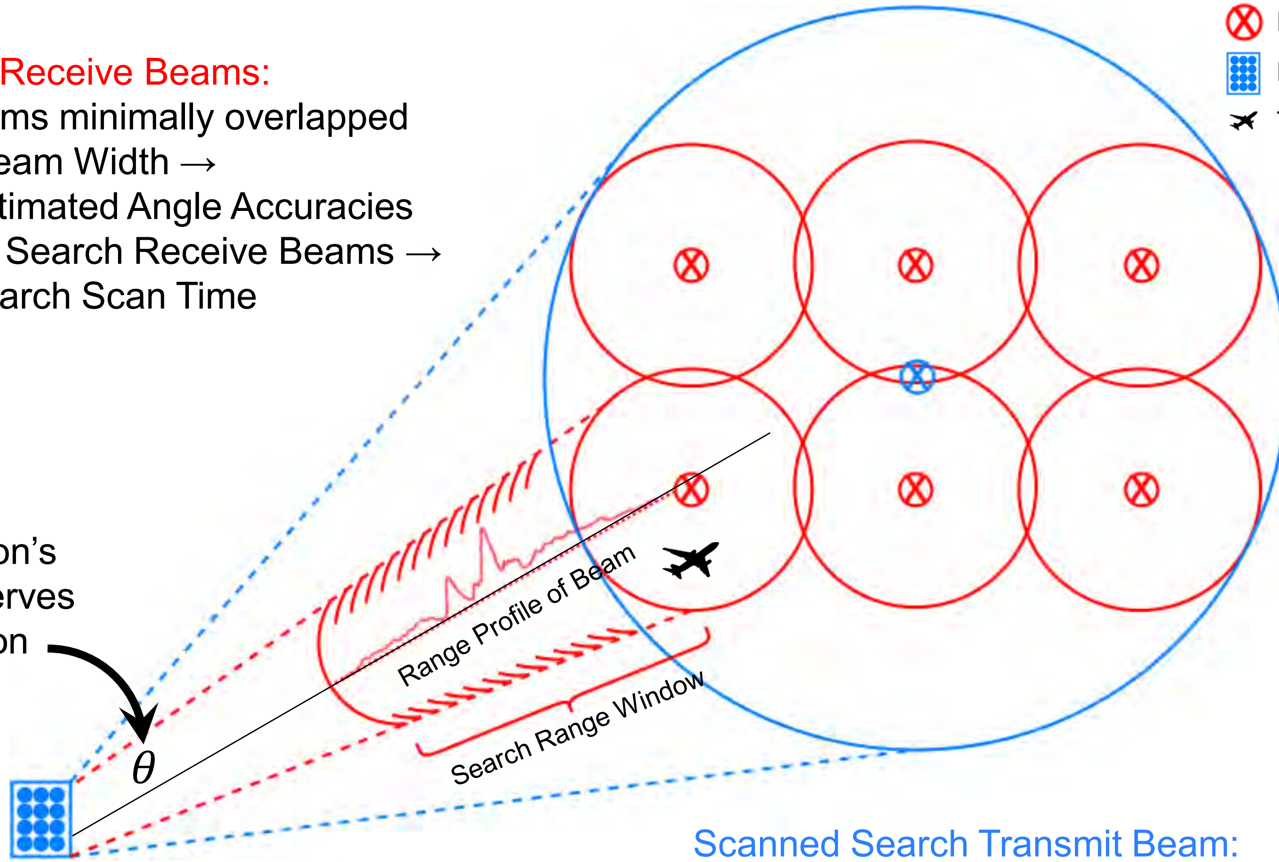


Multiple Beams on Receive (MBOR) for Search

- Transmit Beam
- Receive Beam
- Transmit Beam Aim Point
- Receive Beam Aim Point
- Digital Array Radar (DAR)
- Target

Multiple Search Receive Beams:

- Receive beams minimally overlapped
- ↓ Receive Beam Width → ↑ Estimated Angle Accuracies
- ↑ Number of Search Receive Beams → ↓ Search Scan Time



Transmit beam is scanned through search fence

Angle of detection's receive beam serves as initial detection angle

Scanned Search Transmit Beam:

- Expand to reduce search fence scan time
- ↑ Transmit Beam Width → ↓ Resolution
- ↑ Transmit Beam Width → ↓ Search Scan Time

* DAR: Digital Array Radar / FOV: Field of View

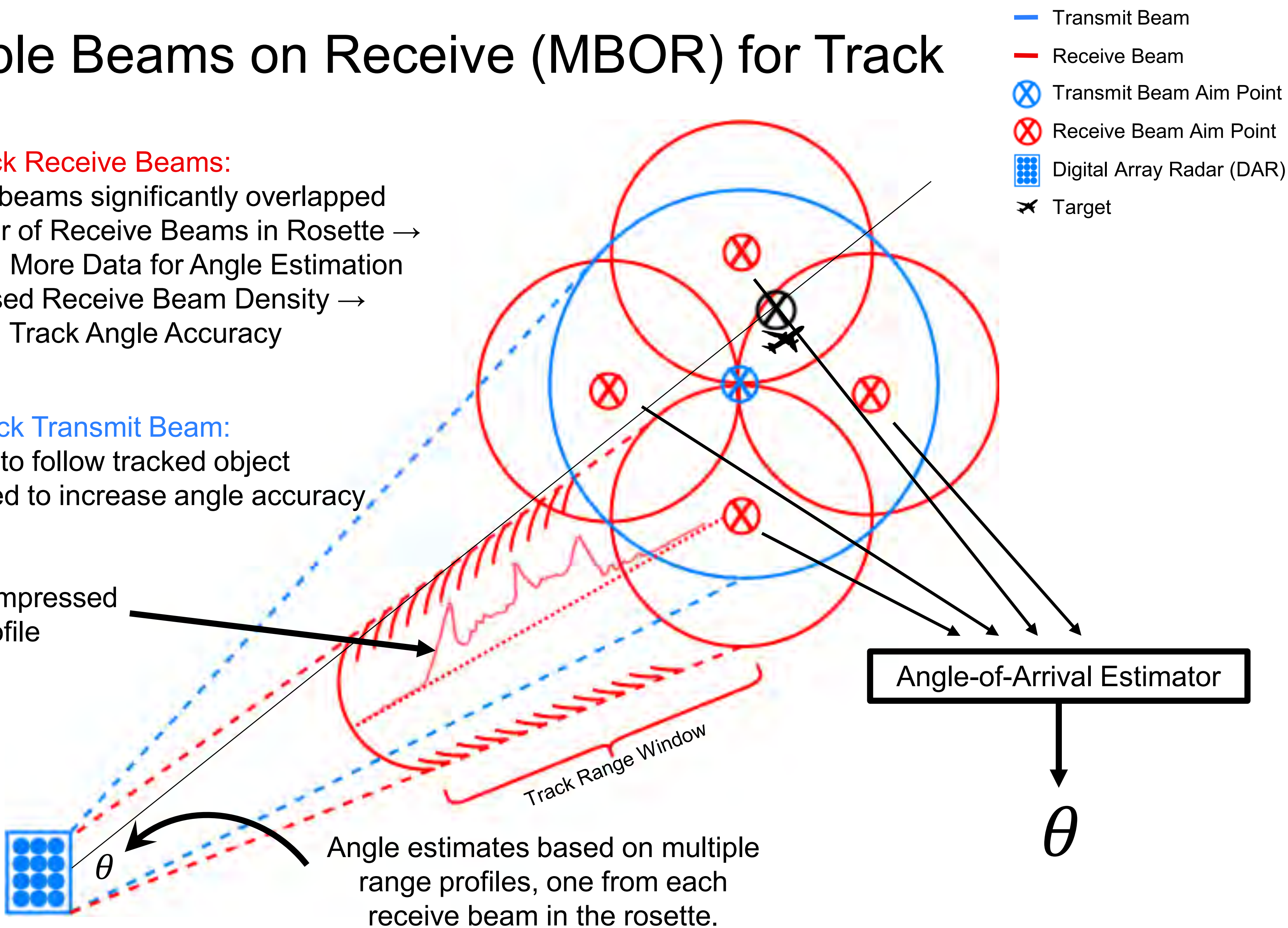
Multiple Beams on Receive (MBOR) for Track

Multiple Track Receive Beams:

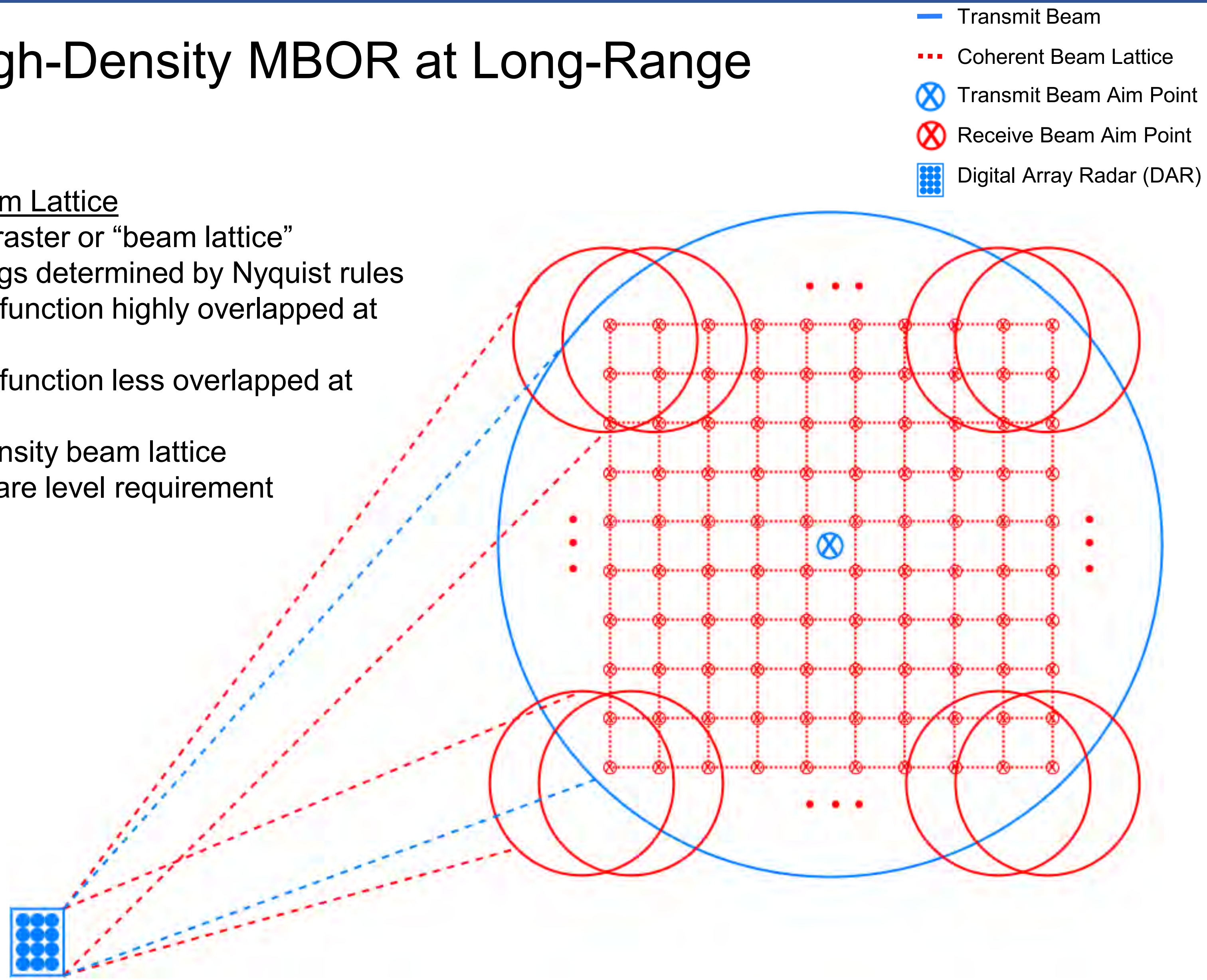
- Receive beams significantly overlapped
- ↑ Number of Receive Beams in Rosette → ↑ More Data for Angle Estimation
- ↑ Increased Receive Beam Density → ↑ Track Angle Accuracy

Steered Track Transmit Beam:

- Steered to follow tracked object
- Unspoiled to increase angle accuracy



Solopulse High-Density MBOR at Long-Range



<u>Solopulse Receive Beam Lattice</u>

- High-density beam raster or "beam lattice"
    - Lattice spacings determined by Nyquist rules
    - Beam spread function highly overlapped at long-range
    - Beam spread function less overlapped at short-range
- Solopulse's high-density beam lattice is a system & software level requirement

Quantum Formulations of Electromagnetic Propagation…

“When the revolutionary ideas of quantum physics where first coming out, people still tried to understand them in terms of old-fashioned ideas ***(such as, light goes in straight lines).”***

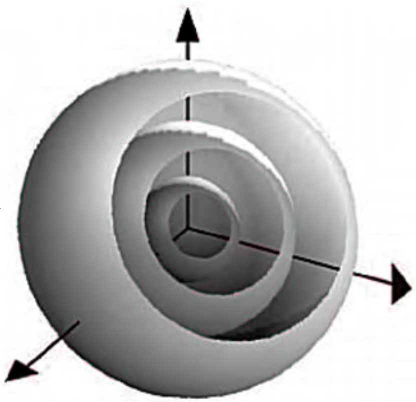
Richard P. Feynman
QED: The Strange Theory of Light and Matter, p56

Solopulse's Isotropic Wave Field Inversion

<u>Huygens Wavelet</u>
(Time-Space)
- Growing spherical singularity from point source

<u>Fresnel Wave Field</u>
(Frequency-Space)
- Static (time-independent)
- Passband represented by sets of Fresnel Fields of different frequencies

<u>Huygens-Fresnel Spectrum</u>
(Frequency-Wavenumber)
- Tonal phase data
- Ewald Sphere manifold

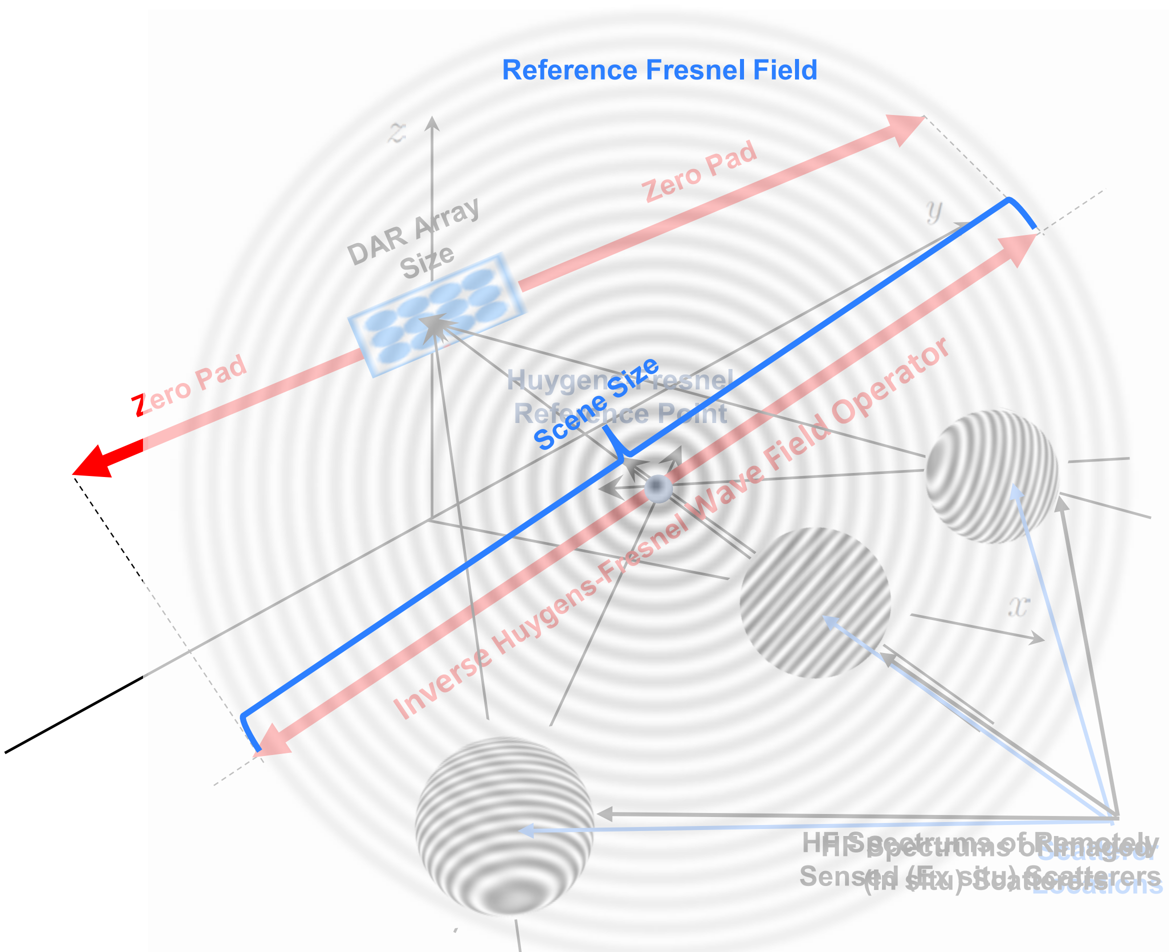


Time Fourier Transform

Spatial Fourier Transform

<u>Inverse Huygens-Fresnel Transfer Function</u>
- Identifies locations of scatterers
- Based on Huygens principles (not range-dependent matched filtering)

Solopulse's Huygens-Fresnel Transfer System



This illustration is a mix of frequency-space & frequency-wavenumber domains:

Reference Fresnel field
- Describes distance between sensor and center-of-scene.
- Spatial Fourier transform of this reference Fresnel field yields a "forward" Huygens-Fresnel transfer (HFT) function

Inverse HFT
- Conjugate produces "inverse" HFT
- Enables wave field inversion from sensor array back to scene

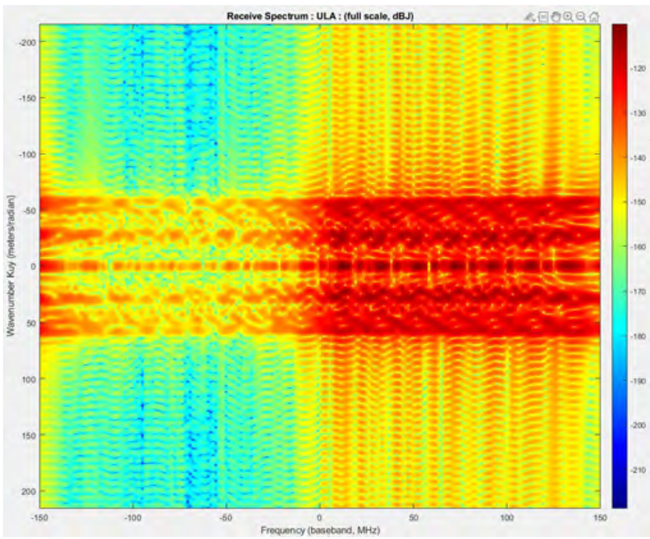
Expanded HFT
- Enables wave field inversion from small DAR sensor to a larger scene

Covariant* Change-of-Variables** Transforms Signal Spectrum to Scene Spectrum

Most Solopulse signal processing is performed in frequency-wavenumber domain.
Analysis of Huygens-Fresnel spectrum is challenging – key to solution is work of Dirac in QFT & QED.

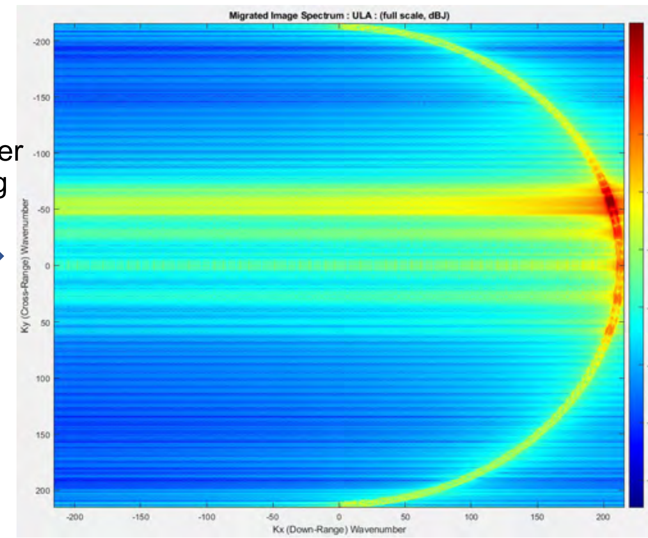
Digital Sensor Array

(2D) Array Time-Space 3-D FFT



Time-Space Signal Spectrum

Solopulse Wavenumber Processing



Huygens-Fresnel Spectrum (Ewald Sphere Manifold)

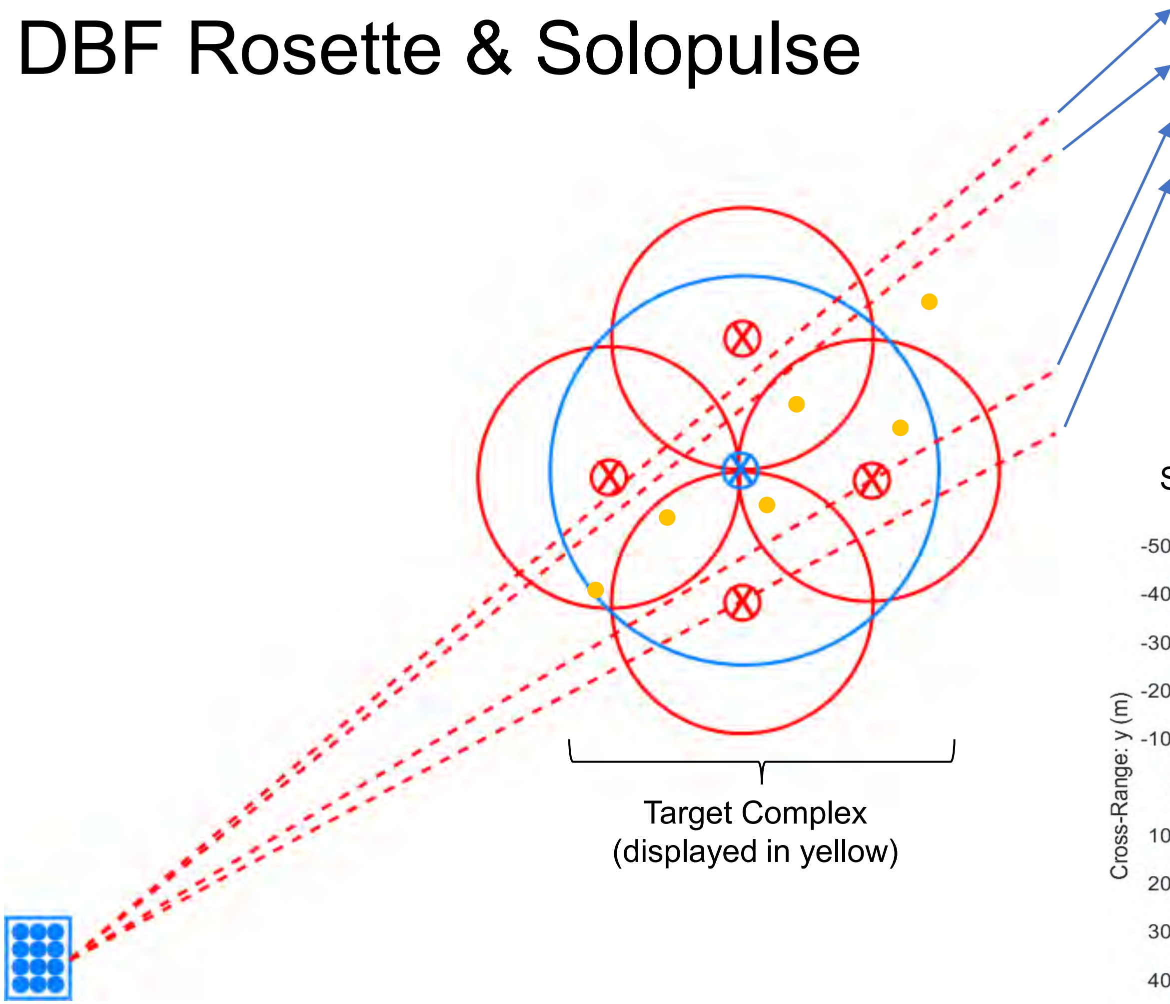
Image Spectrum 3-D Inverse FFT

3D Solopulse Image

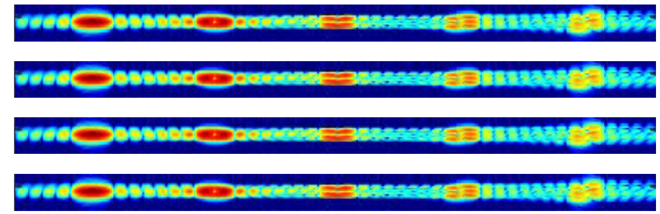
*Covariant in the sense of 4-vector potential field descriptions of Maxwell equations – Lorentz invariant.

**Related to a modified Stolt Transform (range migration) from SAR & seismic wavenumber migration.

Track Radar Example: DBF Rosette & Solopulse

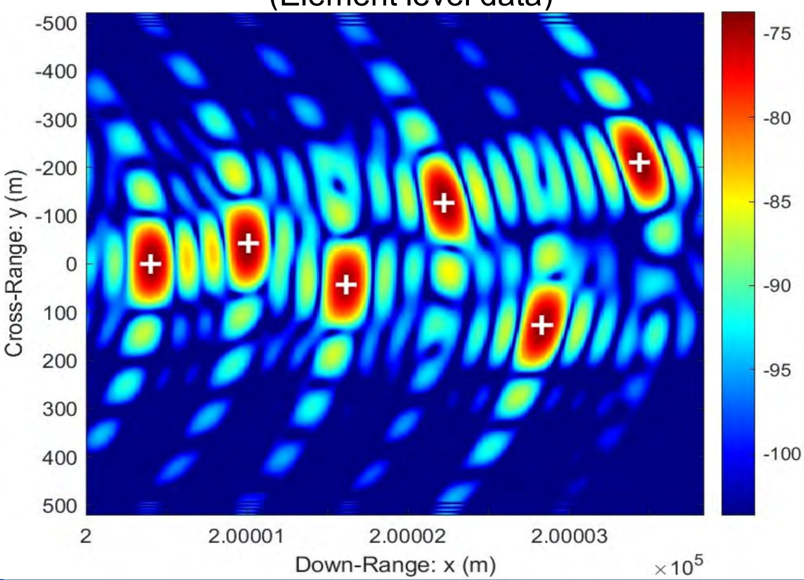


DBF Receive Beam Range Profiles
(Subarray level data)



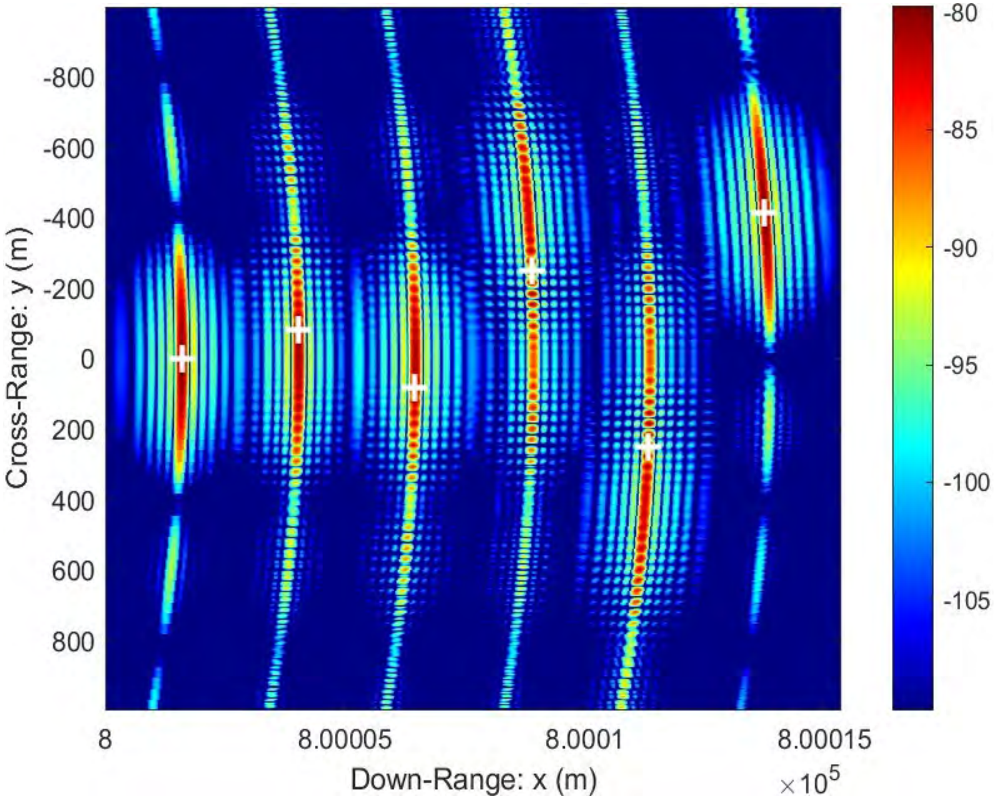
Angle-of-Arrival Estimator produces detections-with-features reports

Solopulse image produced from same radar return
(Element level data)



Solopulse Images for MFR & TWS Radars

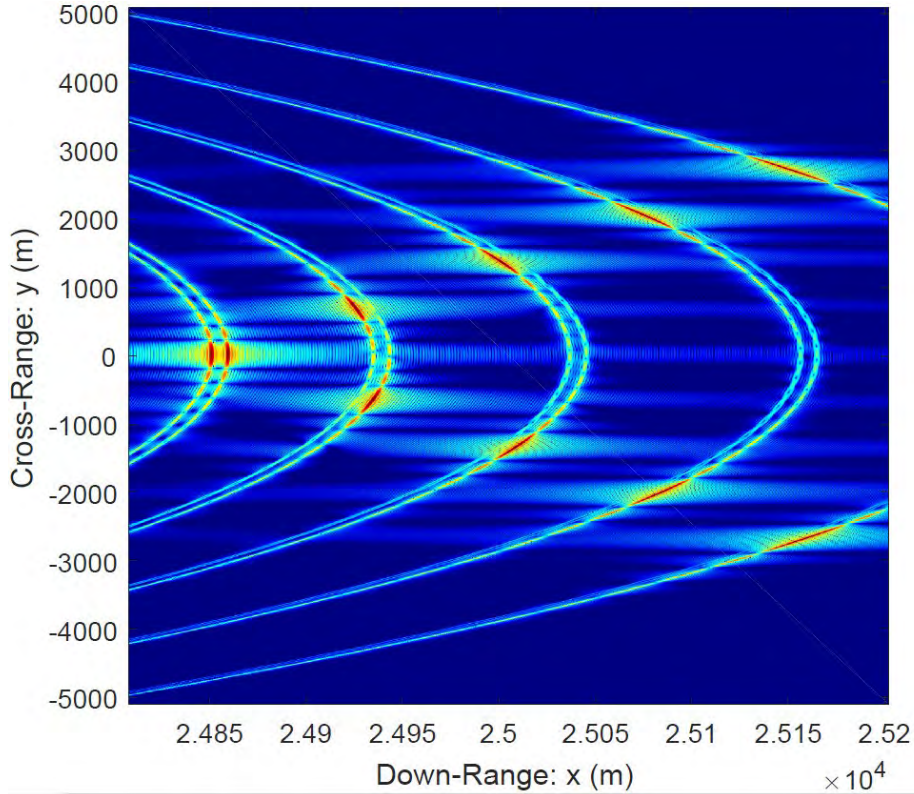
Multiple Function Radar (MFR) Track Radar



Simulation Parameters

- Range = 800 km
- X-Band = 9 GHz
- Bandwidth = 1 GHz
- Number of Array Elements = 2,048 (ULA - SIMO)
- Array Size = 30 m
- Angular Beamwidth = 0.062 degrees
- Spatial Beamwidth at Range = 800 m

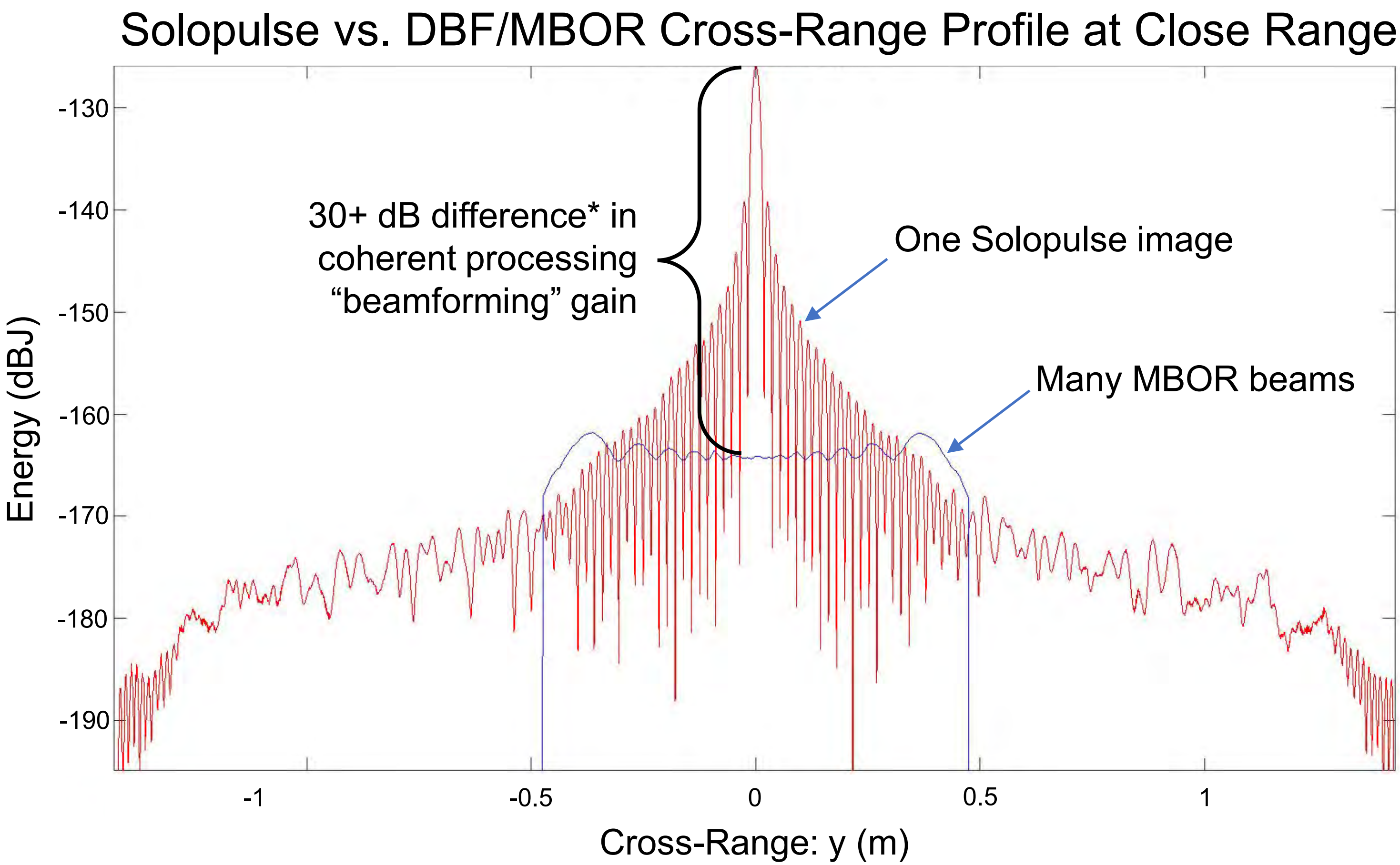
Track-While-Scan (TWS) Radar



Simulation Parameters (air route surveillance typical)

- Range = 25 km
- L-Band = 1.3 GHz, Bandwidth = 100 MHz
- Number of Elements = 256
- Array Size = 13 m
- Spatial Beamwidth at Range = 472 m
- Cross Field of View Width at Range = 10,175 m
- Angular field-of-view = 11 degrees

W-Band DBF/MBOR at Short Range with Large Array



Simulation Parameters
- W-Band = 77 GHz
- Bandwidth = 4 GHz
- Range = 8 m
- Number Elements = 1024
- Array Size = 0.95 m

*Software simulation tools not yet independently validated with measured data.

Solopulse Empowers Short-Range Imaging

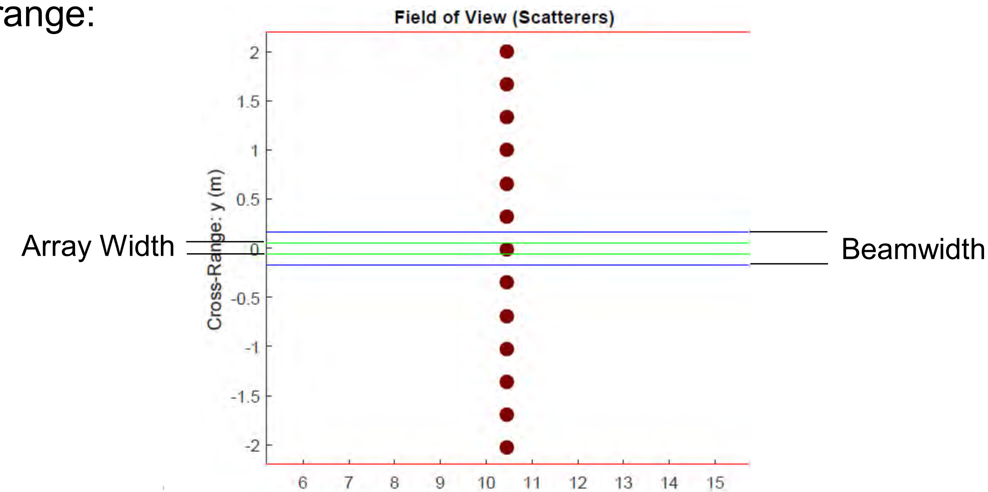
Simulation Parameters (autonomous vehicle)

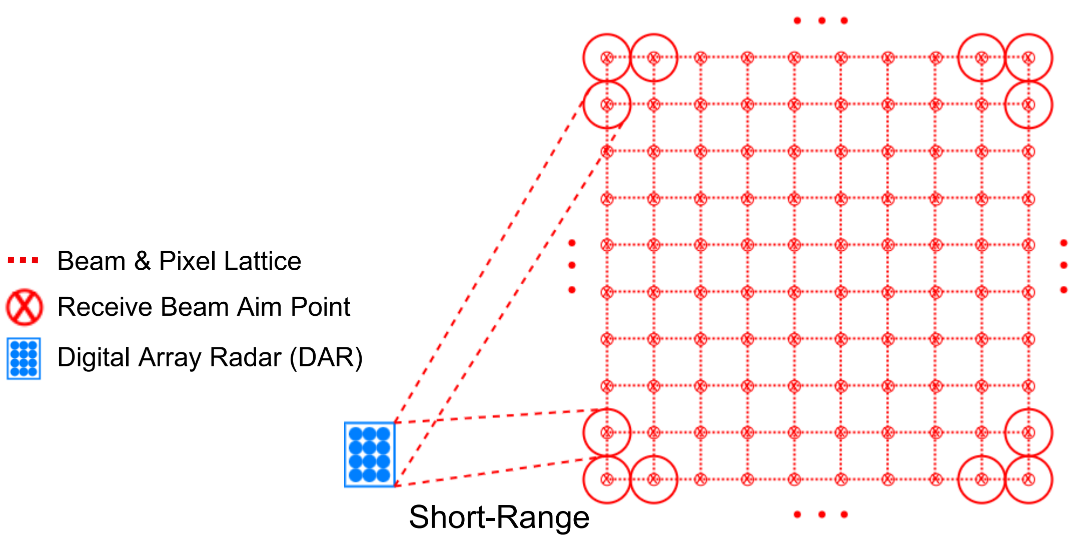
- W-Band = 79 GHz
- Bandwidth = 2 GHz
- Number of Elements = 128
- Array Size = 0.11 m

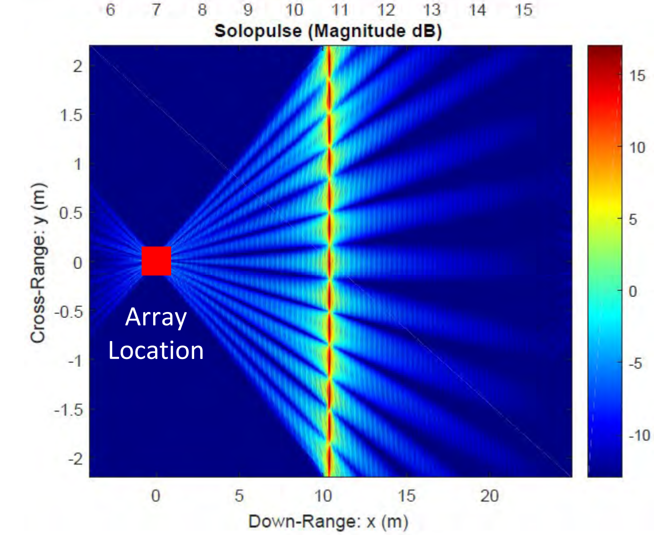
Solopulse's receive-beam overlap is reduced at short-range:

"Beam Spread Function" (BSF)
becomes
"Point Spread Function" (PSF)

"Beam Lattice" at long-range
becomes
"Pixel Lattice" at short-range.

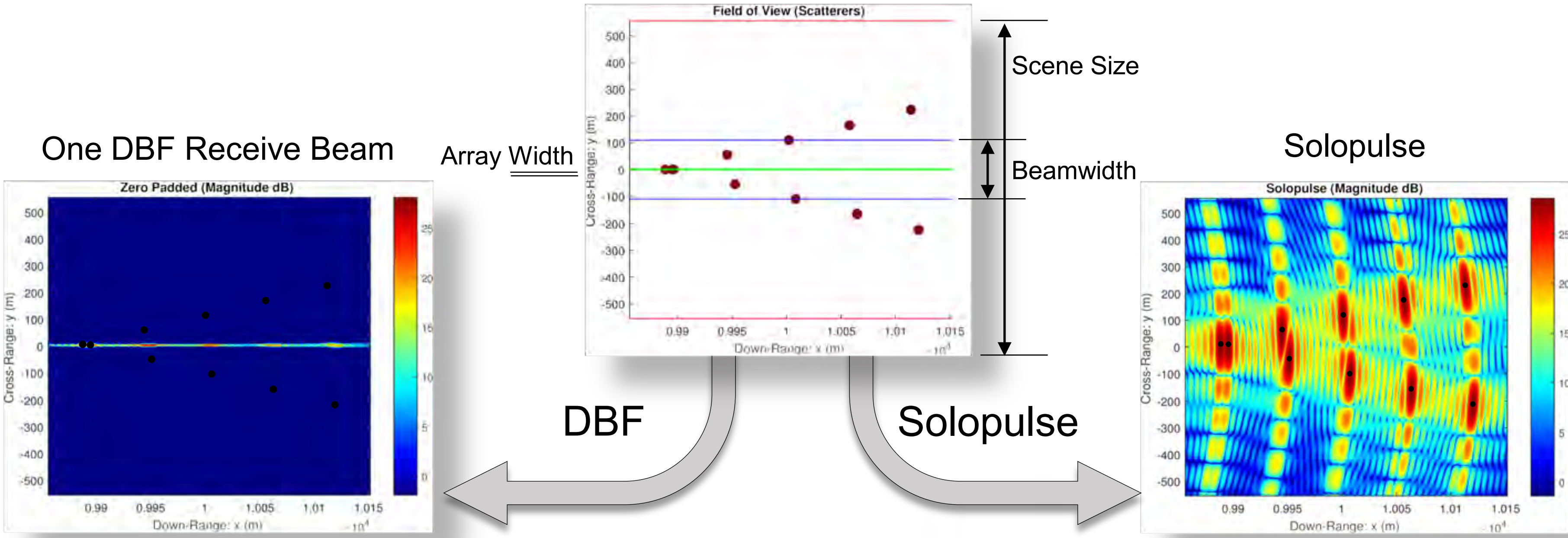






b. Solopulse

Solopulse & DBF Summary Comparison



Many steered DBF receive beams produces same image as Solopulse at long-range

Single-pulse beamwidth is the same as DBF's beamwidth

Computational cost comparison:

Total Op Count (Solopulse equivalent DBF image):
NumberBeams x NumTimeSmpls x NumAntElements

Total Op Count (Solopulse Signal Processing):
NumberBeams x NumRangePixels x NumTimeSmpls

This cost parameter can be reduced by algorithm modification.

In addition to being a new approach to DBF, Solopulse provides advanced, new capabilities; but first...

Solopulse’s similarities with

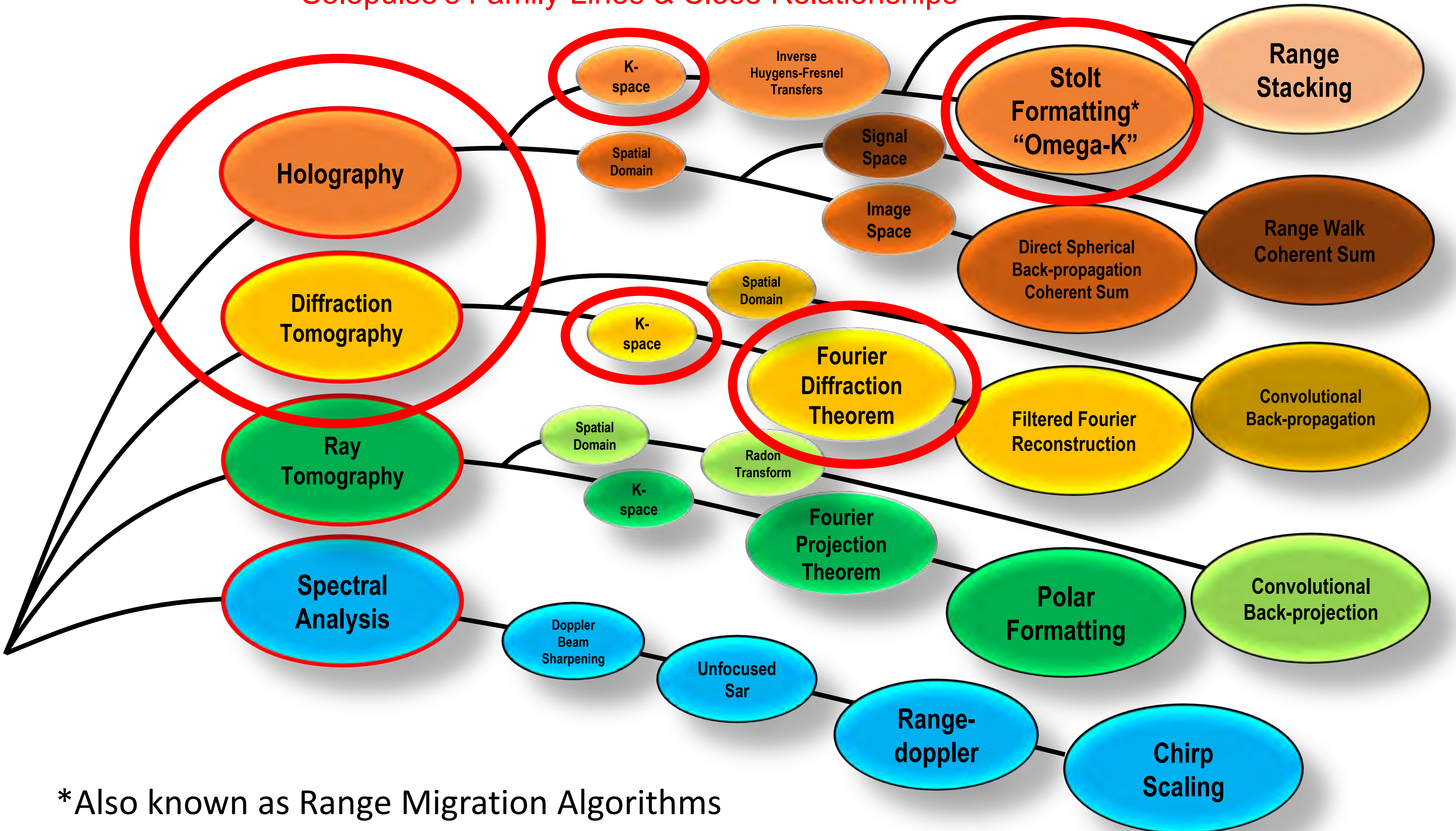
Synthetic Aperture Radar

SAR’s Holographic Foundations

- SAR’s core theoretical principles trace back to Gabor’s (1948) work in holography.
- SAR’s connection to holography recognized in 1960’s, but practical considerations forced radar community to take other approaches.
- Solopulse can be viewed as a return to holographic & diffraction-tomographic imaging techniques.
- Multiple-look versions of Solopulse merge the data capacities of DAR with the algorithm structures of SAR.

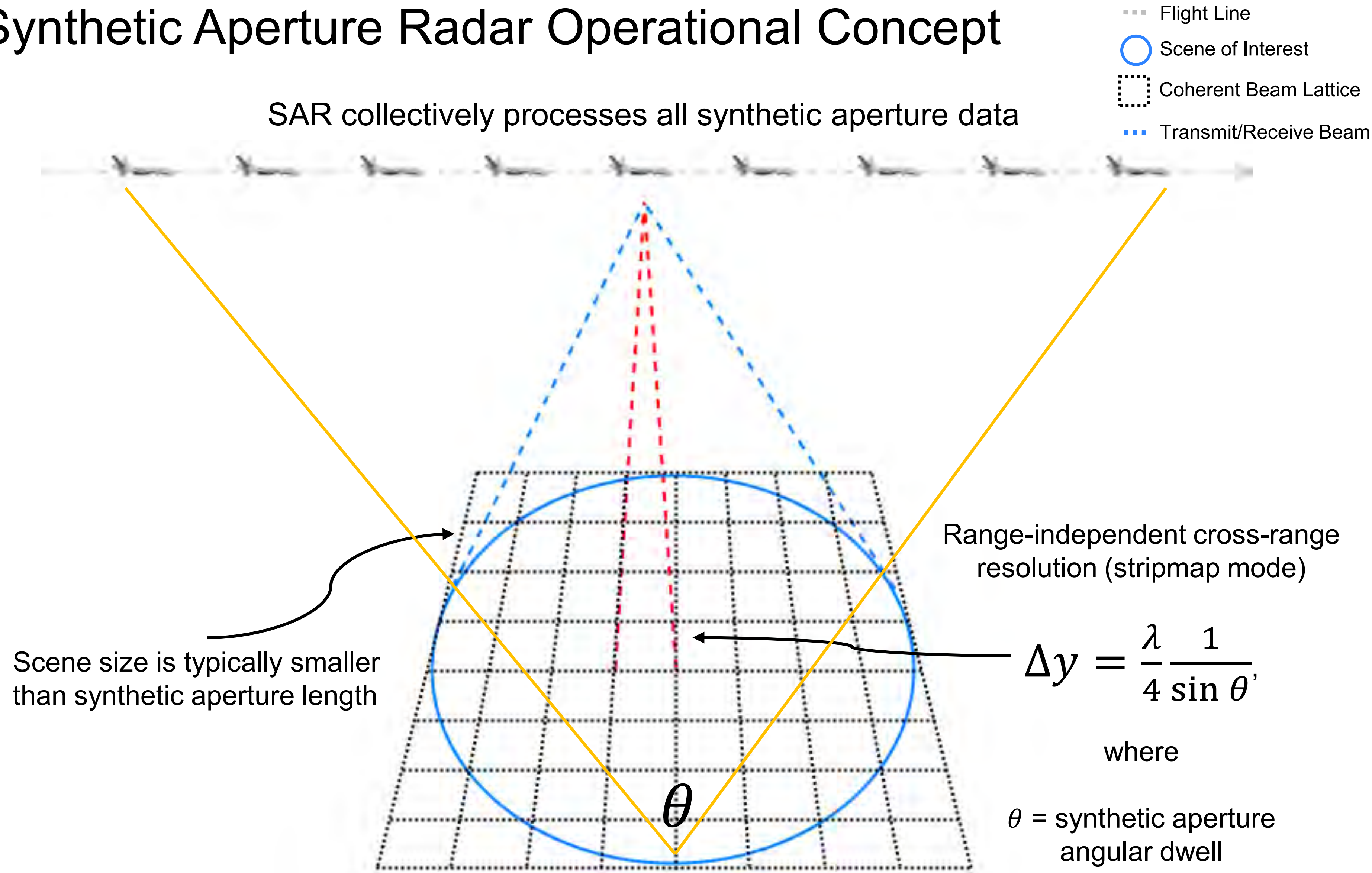
SAR Imaging Algorithm Family Tree

Solopulse's Family-Lines & Close Relationships



*Also known as Range Migration Algorithms

Synthetic Aperture Radar Operational Concept



$$\Delta y = \frac{\lambda}{4}\frac{1}{\sin\theta},$$

where

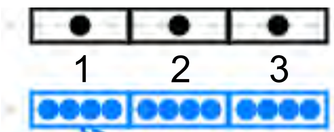
θ = synthetic aperture angular dwell

Towards “Solopulse’s SAR with DAR”

Flight Line
Scene of Interest
Coherent Pixel Lattice
Coherent Beam Lattice
Digital Array Radar (DAR)

Conventional SAR Flight Line

Synthetic Array Pulse Positions



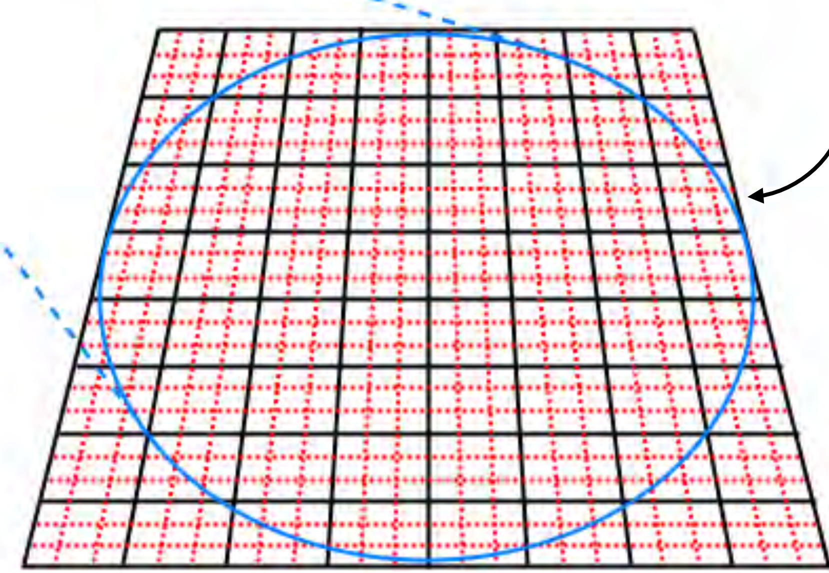
Digital Array Positions

Step 2: Reconstruct scene on a denser pixel lattice.

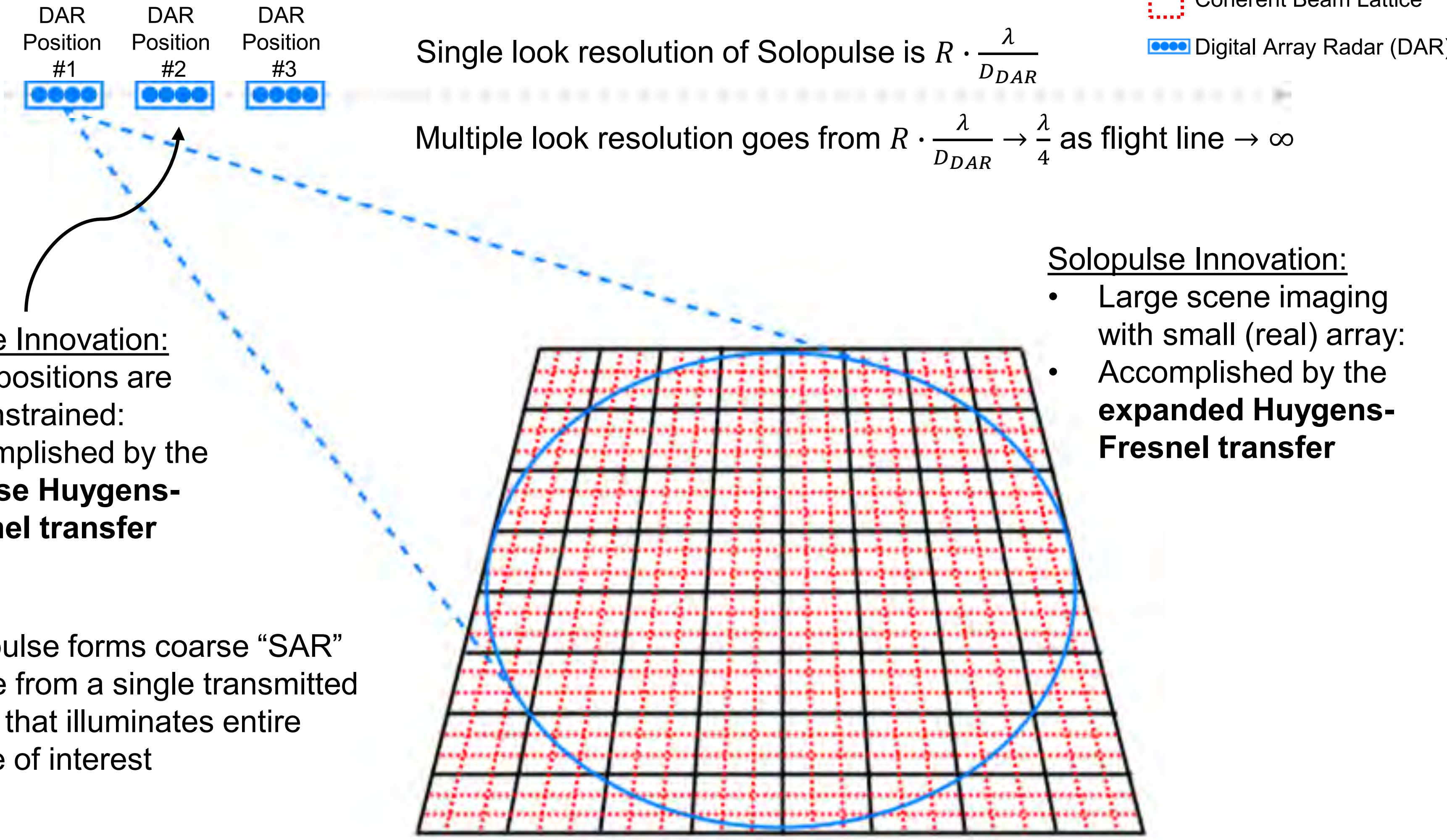
- Nyquist rules require pixel density to match antenna element spacings.

Step 1: Increase along-track sample density to match that of the DAR.

- Utilize element-level data
- Antenna element spacing sets the unambiguous angular field-of-view.
- Antenna element spacing sets spatial bandwidth of measured data



Solopulse's SAR with DAR



Single look resolution of Solopulse is $R \cdot \frac{\lambda}{D_{DAR}}$

Multiple look resolution goes from $R \cdot \frac{\lambda}{D_{DAR}} \rightarrow \frac{\lambda}{4}$ as flight line $\rightarrow \infty$

<u>Solopulse Innovation:</u>

- DAR positions are unconstrained:
- Accomplished by the **inverse Huygens-Fresnel transfer**

Solopulse forms coarse "SAR" image from a single transmitted pulse that illuminates entire scene of interest

<u>Solopulse Innovation:</u>

- Large scene imaging with small (real) array:
- Accomplished by the **expanded Huygens-Fresnel transfer**

Solopulse (DAR) data from pulse to pulse (SAR) can be coherently added → Progressive Super-Resolution.

Solopulse builds bridges from DAR-DBF to DAR-SAR:

Super*-Resolution** Solopulse

Multiple look resolution goes progressively from $R \cdot \frac{\lambda}{D} \to \frac{\lambda}{4}$

Moving-sensor(s) radar imaging & video

Multiple-sensors radar imaging

*Angle diversity from nonlinear flight profiles can be substituted for linear flight length – escapes $\frac{\lambda}{D_{DAR}}$.

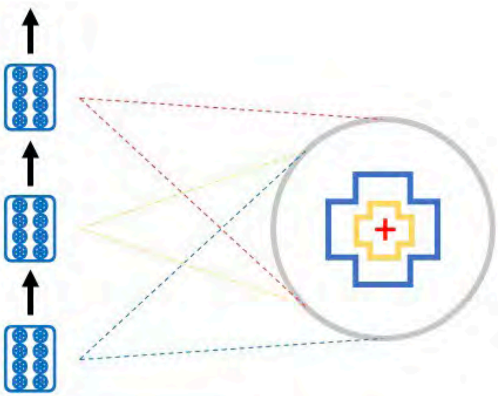
**Resolution limit is one-fourth wavelength for single-input/single-output modes, otherwise limit is one-half wavelength.

WARNING: Following PPT slides have embedded movies that illustrate progressive super-resolution with Solopulse. The initial frames are the most coarse, and subsequent movie frames illustrate progressive refinement. This feature is lost if this presentation is viewed as a PDF file (not a PPT file). PDF shows repeated pairs of images (beginning and end of movie sequence).

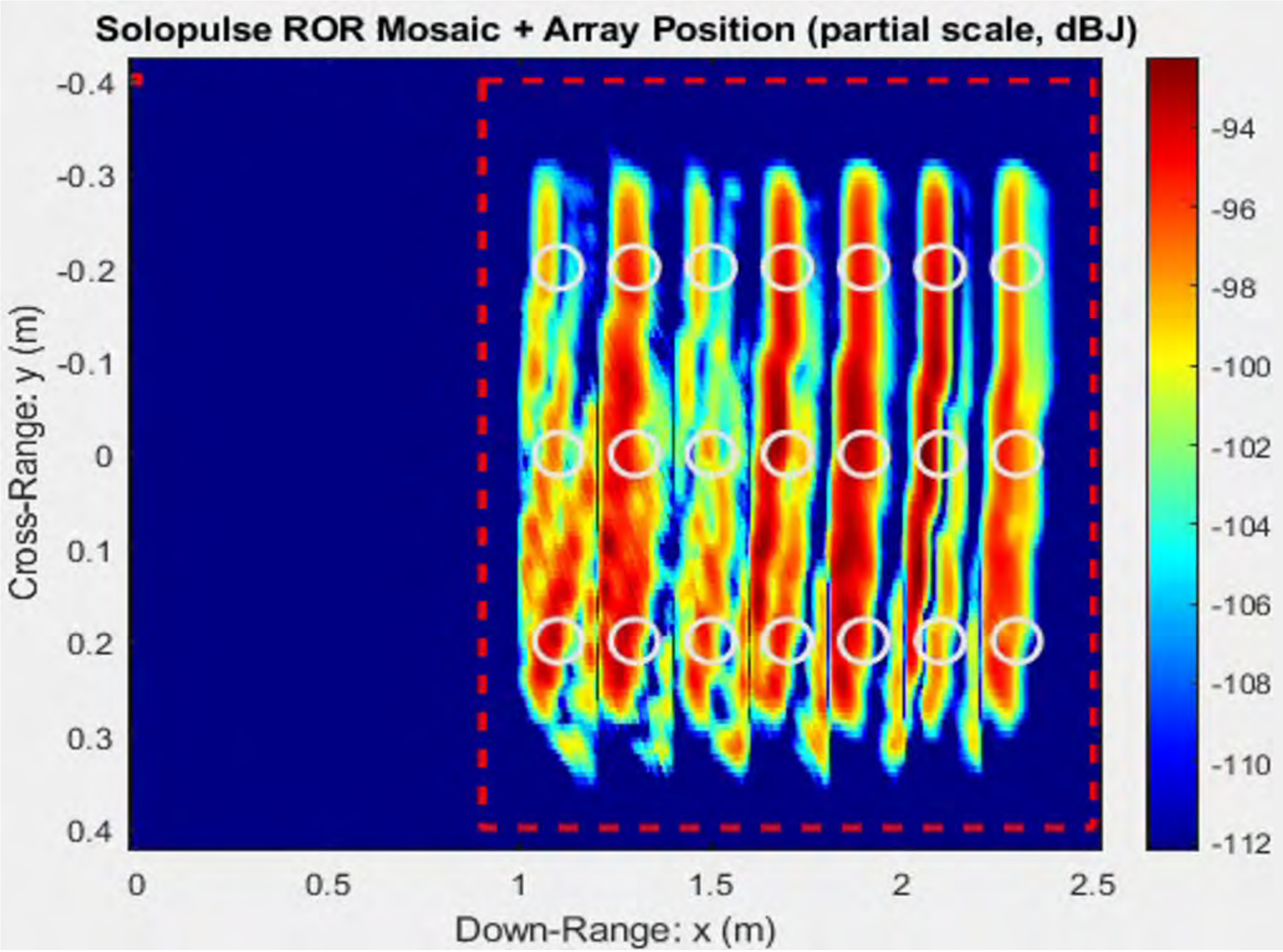
Super-Resolution Solopulse with Side-Stepping Sensor at 1m Range

Array Location
Illuminated Scene
Scatterer Ground Truth

Side-stepping sensor



1-look resolution
2-look resolution
3-look resolution

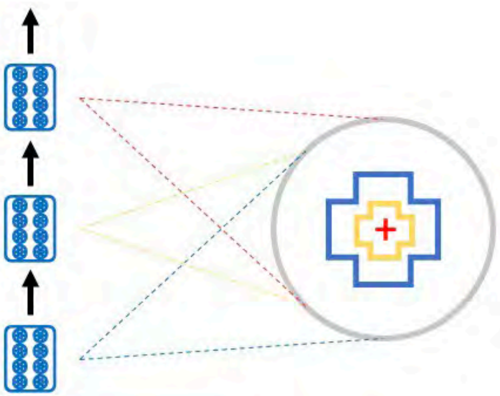


Simulation Parameters
- Antenna Elements = 4 (SIMO)
- Array Length = 0.05 m
- Step Size = 0.05 m
- Bandwidth = 3 GHz
- X-band = 9 GHz

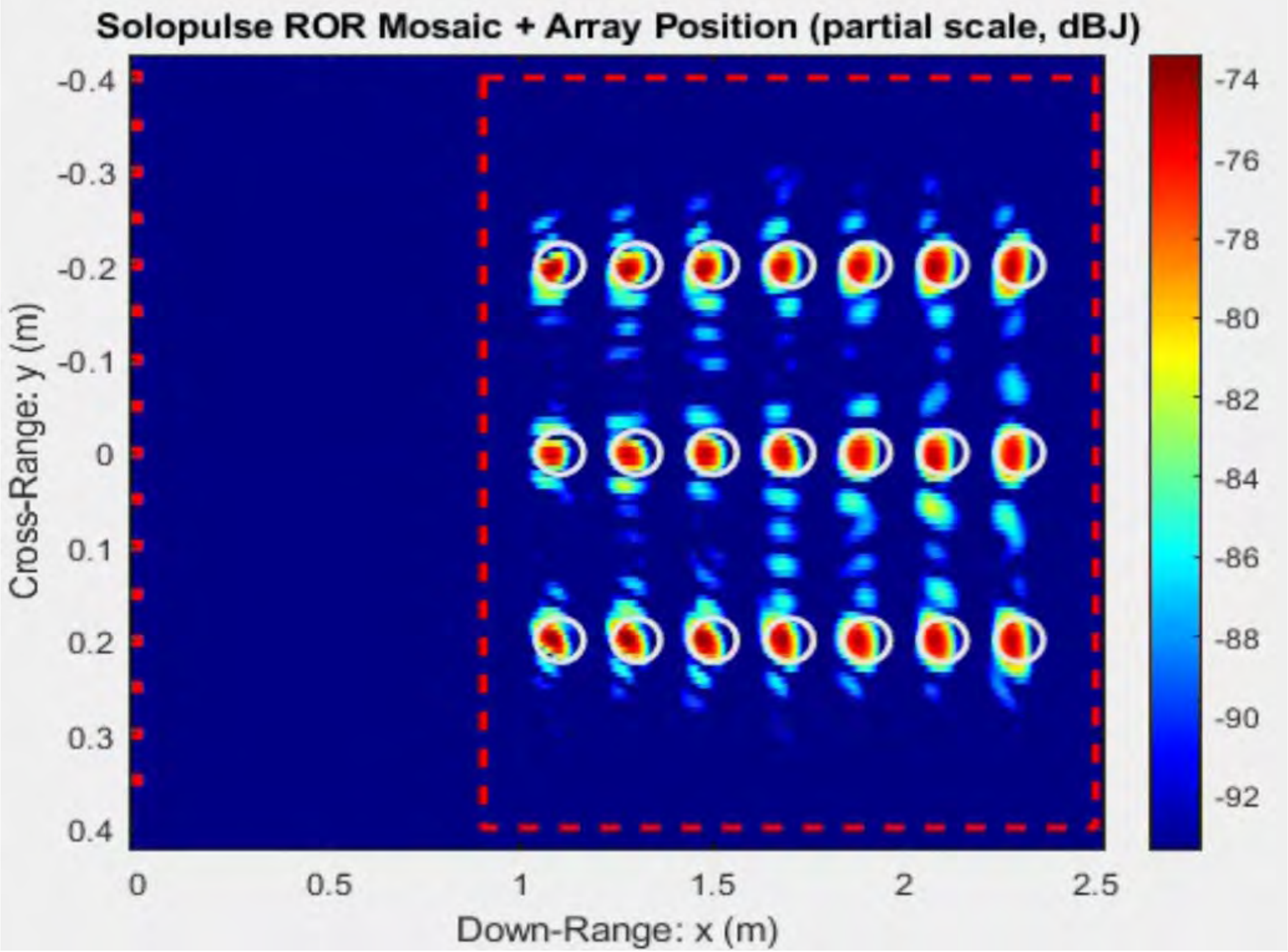
Super-Resolution Solopulse with Side-Stepping Sensor at 1m Range

Array Location
Illuminated Scene
Scatterer Ground Truth

Side-stepping sensor



1-look resolution
2-look resolution
3-look resolution

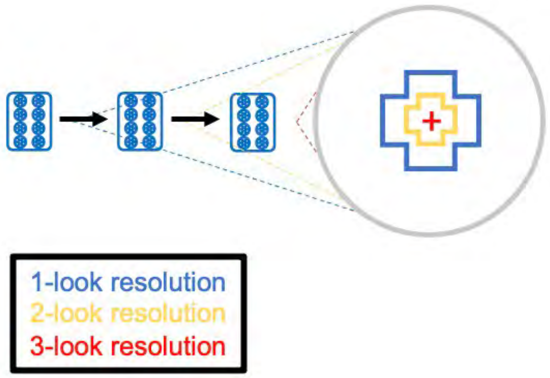


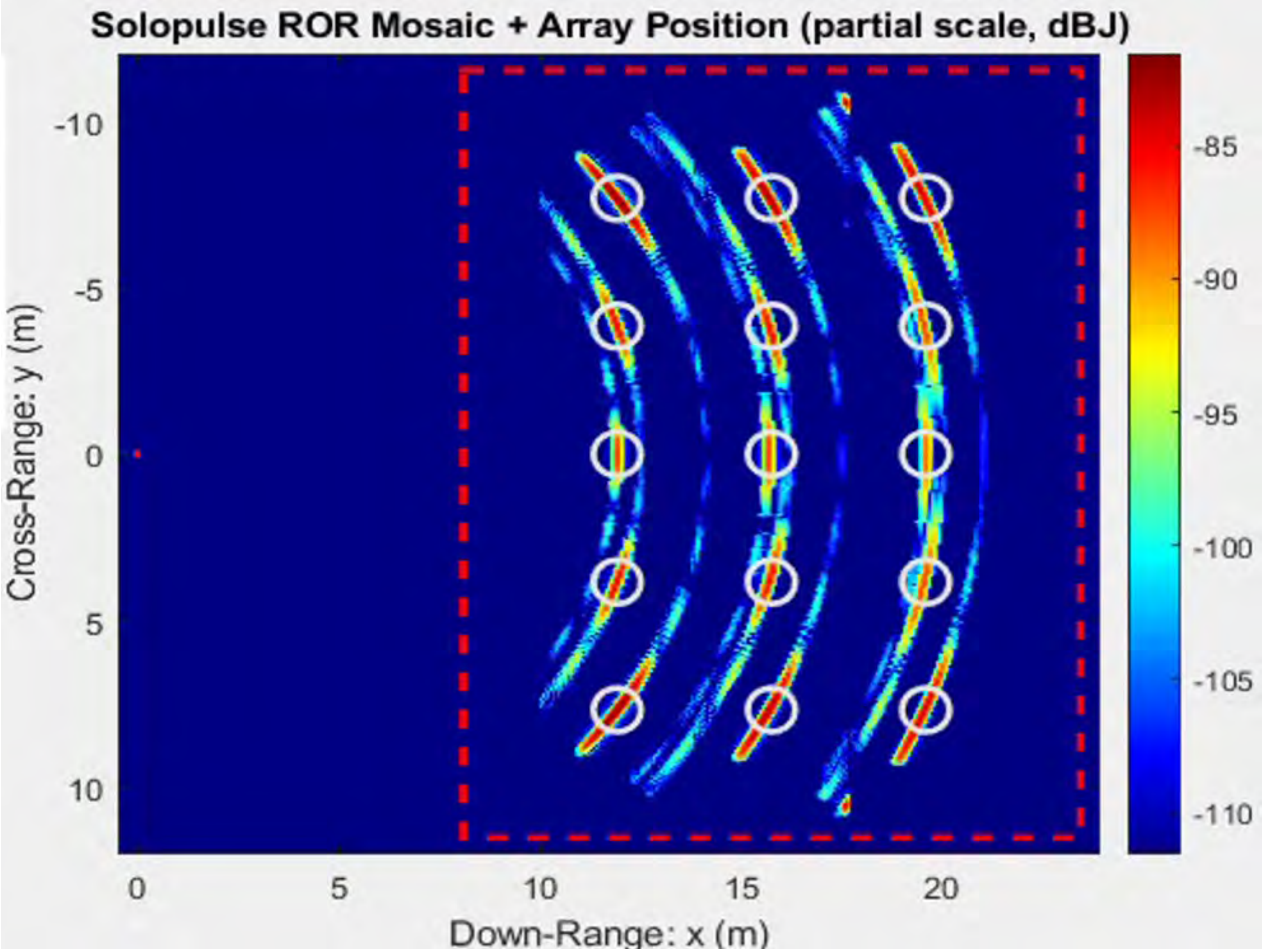
Simulation Parameters
- Antenna Elements = 4 (SIMO)
- Array Length = 0.05 m
- Step Size = 0.05 m
- Bandwidth = 3 GHz
- X-band = 9 GHz

Super-Resolution Solopulse with Forward-Stepping Sensor at 10m Range

Array Location
Illuminated Scene
Scatterer Ground Truth

Forward-stepping sensor

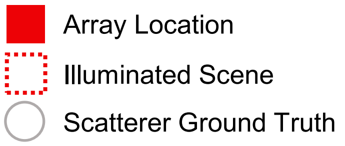




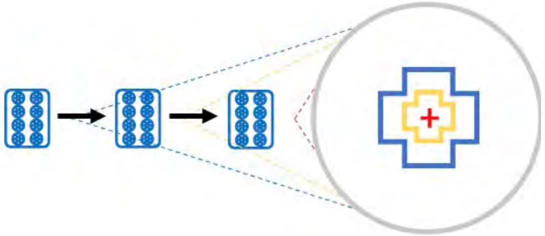
Simulation Parameters

- Antenna Elements = 8 (SIMO)
- Array Length = 0.12 m
- Step Size = 1.0 m
- Bandwidth = 1 GHz
- X-Band = 9 GHz

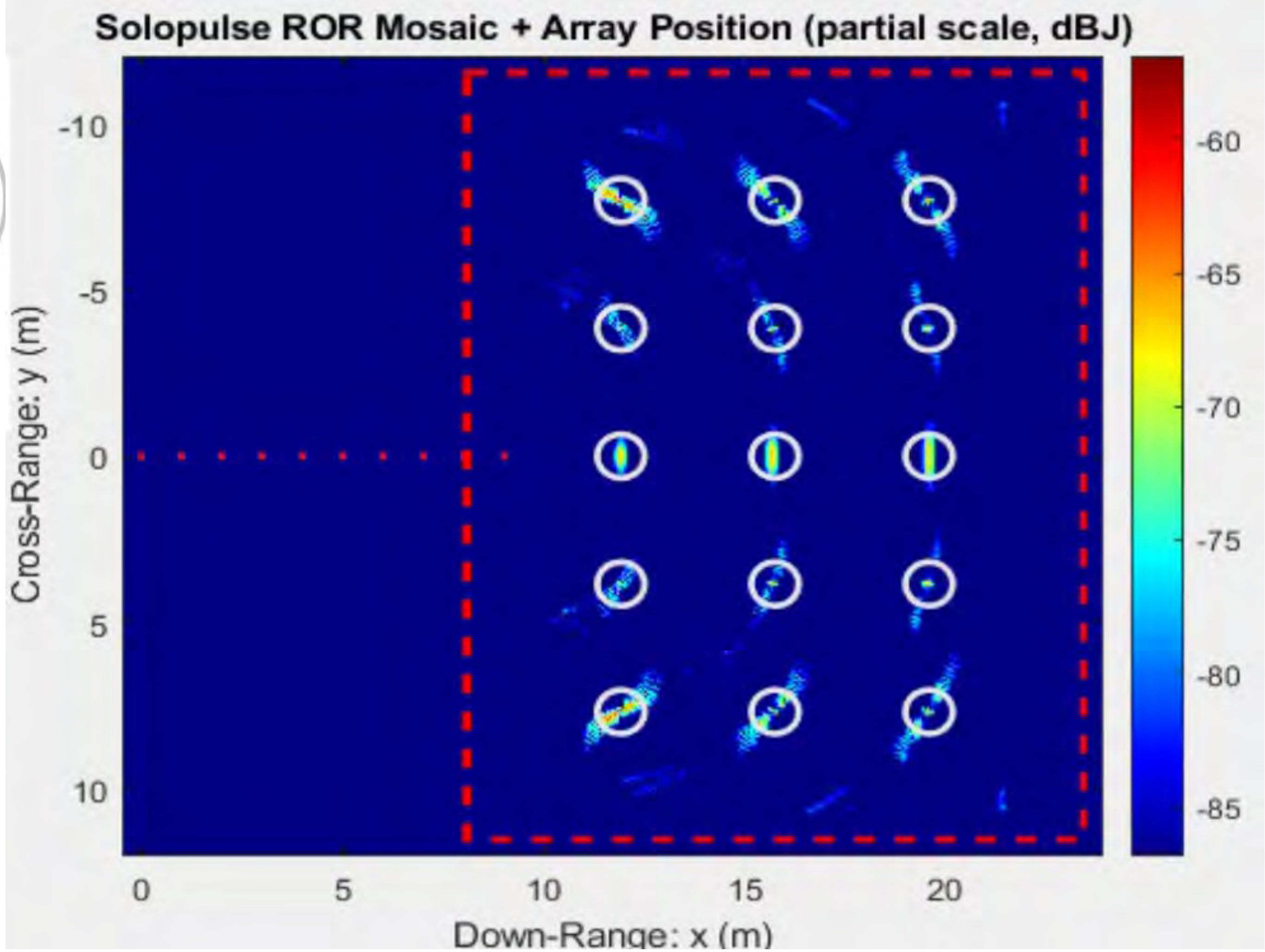
Super-Resolution Solopulse with Forward-Stepping Sensor at 10m Range



Forward-stepping sensor



1-look resolution
2-look resolution
3-look resolution



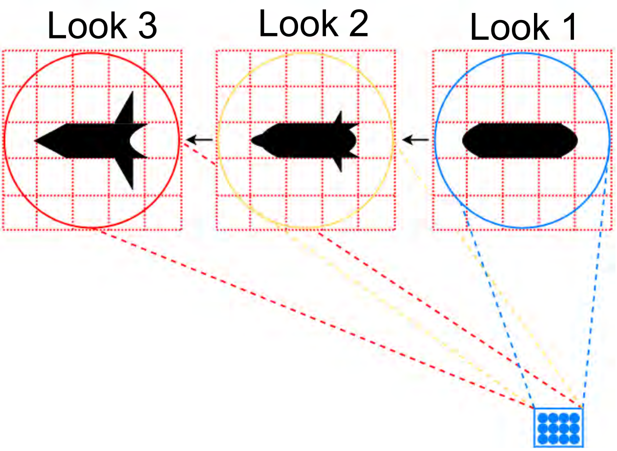
Simulation Parameters

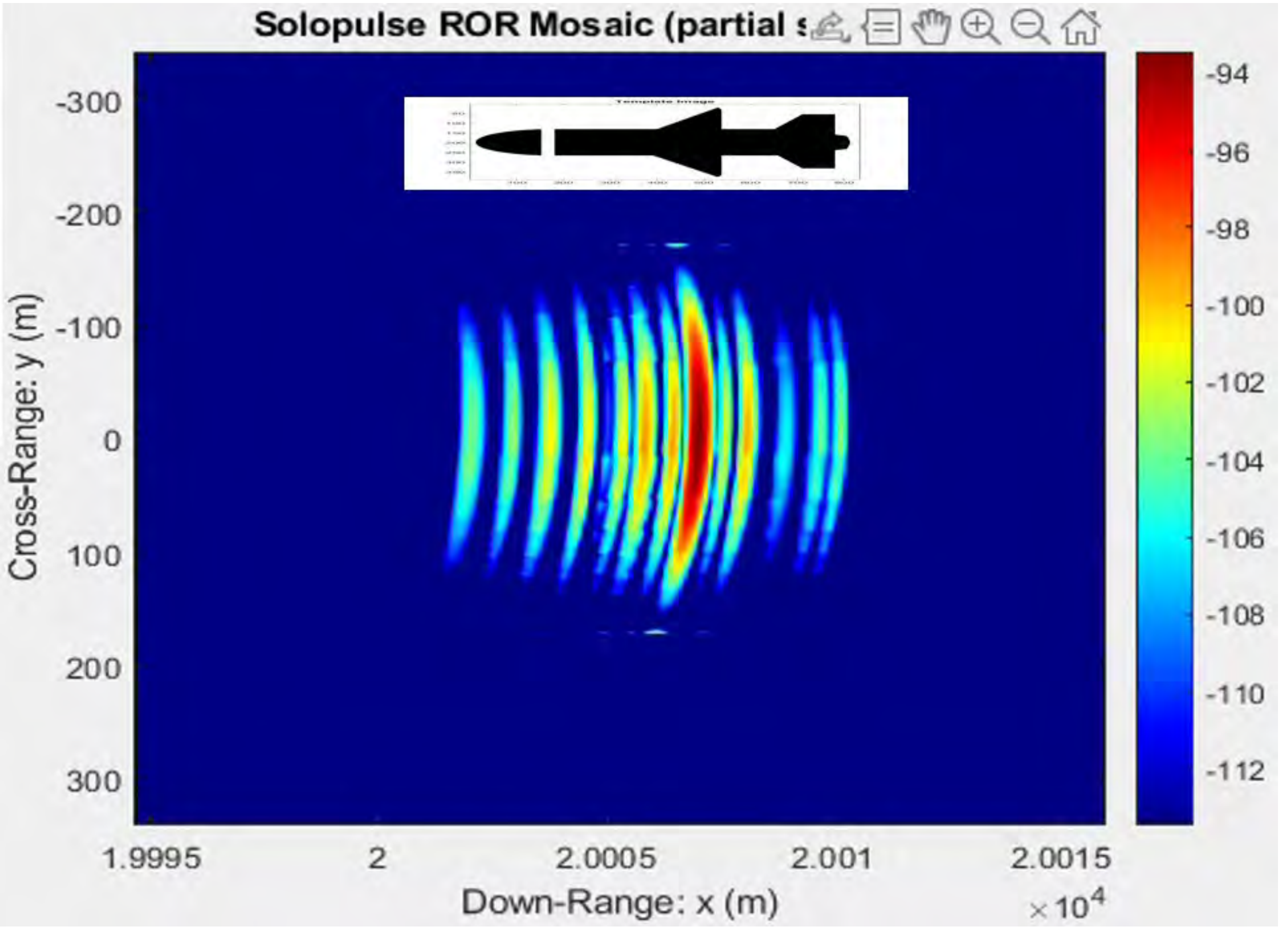
- Antenna Elements = 8 (SIMO)
- Array Length = 0.12 m
- Step Size = 1.0 m
- Bandwidth = 1 GHz
- X-Band = 9 GHz

Super-Resolution Solopulse with Stationary Sensor and Tracked Object at 20km Range

Conceptually similar to “Inverse-SAR” (ISAR)

Moving object & stationary sensor





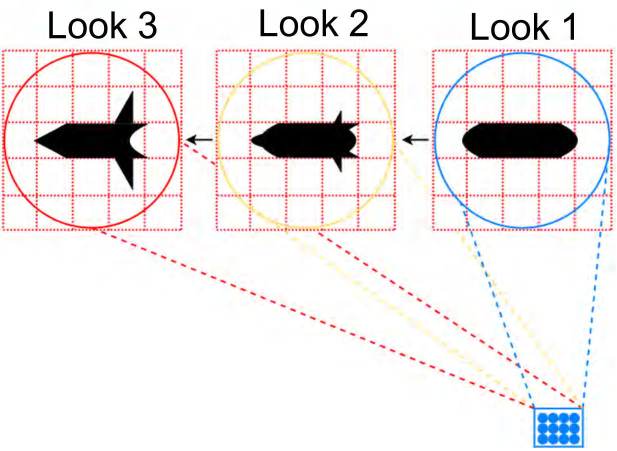
Simulation Parameters

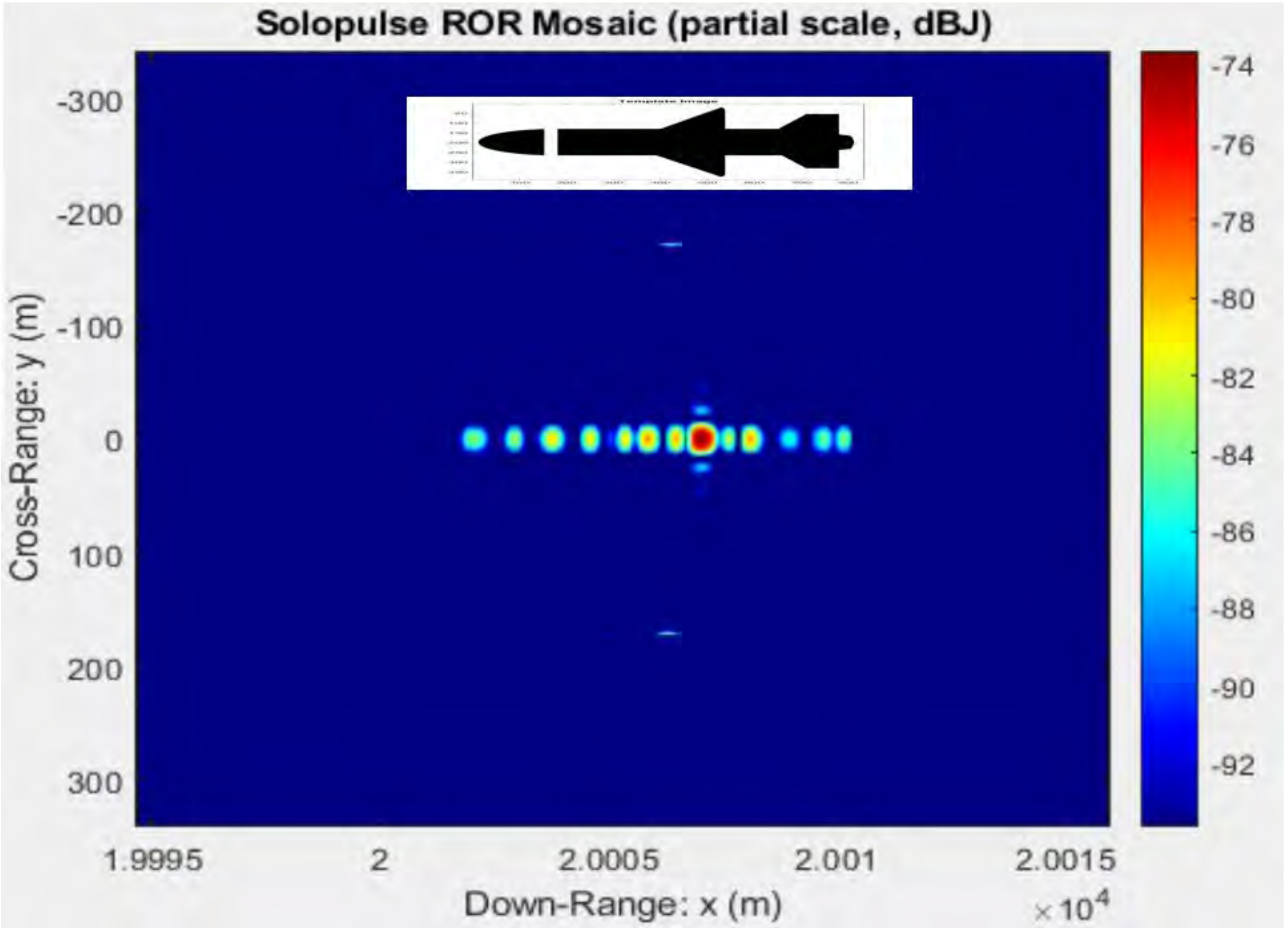
- Antenna Elements = 512 (SIMO)
- Array Length = 12.8 m
- Step Size = 15 m
    - Cross-range component of object movement
- Bandwidth = 1 GHz
- C-Band = 5 GHz

Super-Resolution Solopulse with Stationary Sensor and Tracked Object at 20km Range

Conceptually similar to “Inverse-SAR” (ISAR)

<u>Moving object & stationary sensor</u>



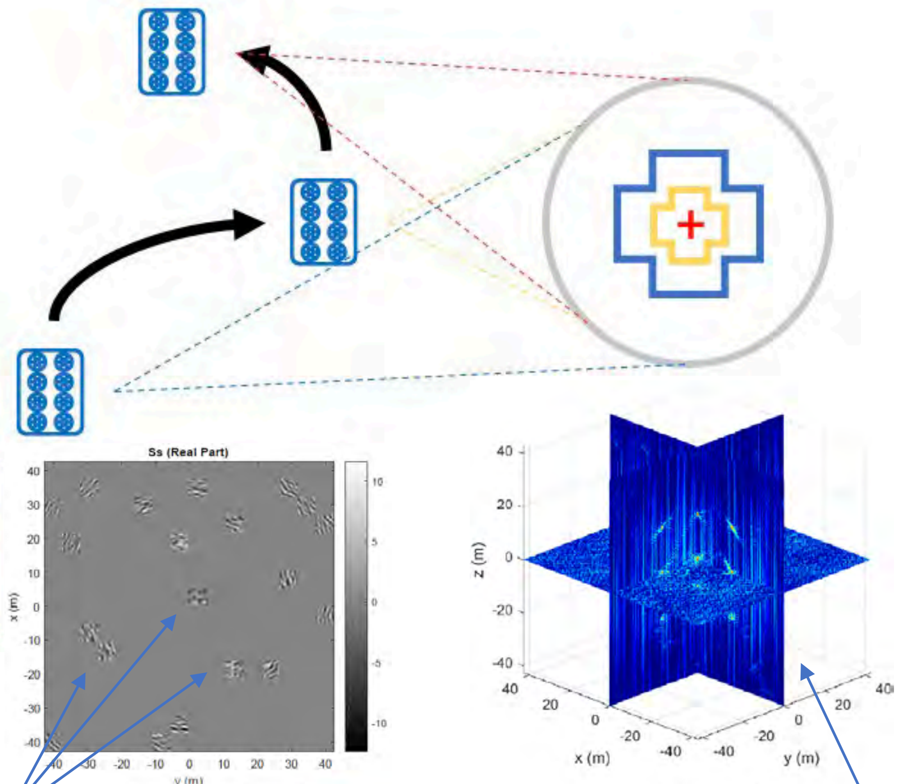


<u>Simulation Parameters</u>

- Antenna Elements = 512 (SIMO)
- Array Length = 12.8 m
- Step Size = 15 m
  - Cross-range component of object movement
- Bandwidth = 1 GHz
- C-Band = 5 GHz

Super-Resolution Solopulse with Randomly-Stepping Sensor or Swarms of Sensors

<u>Randomly-stepping sensor</u>



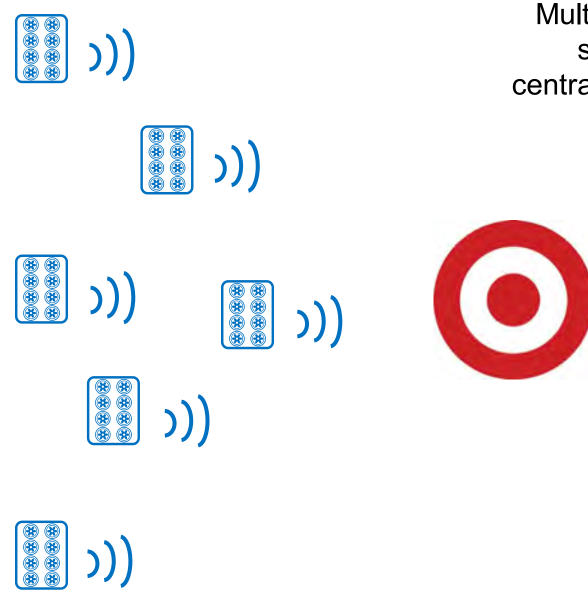
a. Sensor Swarm Phase History

b. Solopulse Hologram

Sensor positions & data measurements

<u>Coherent fusion of multiple sensors</u>

Multiple autonomous sensors with a centralized fusion center processor



Digital Array Radar (DAR)

Region of Interest (ROI)

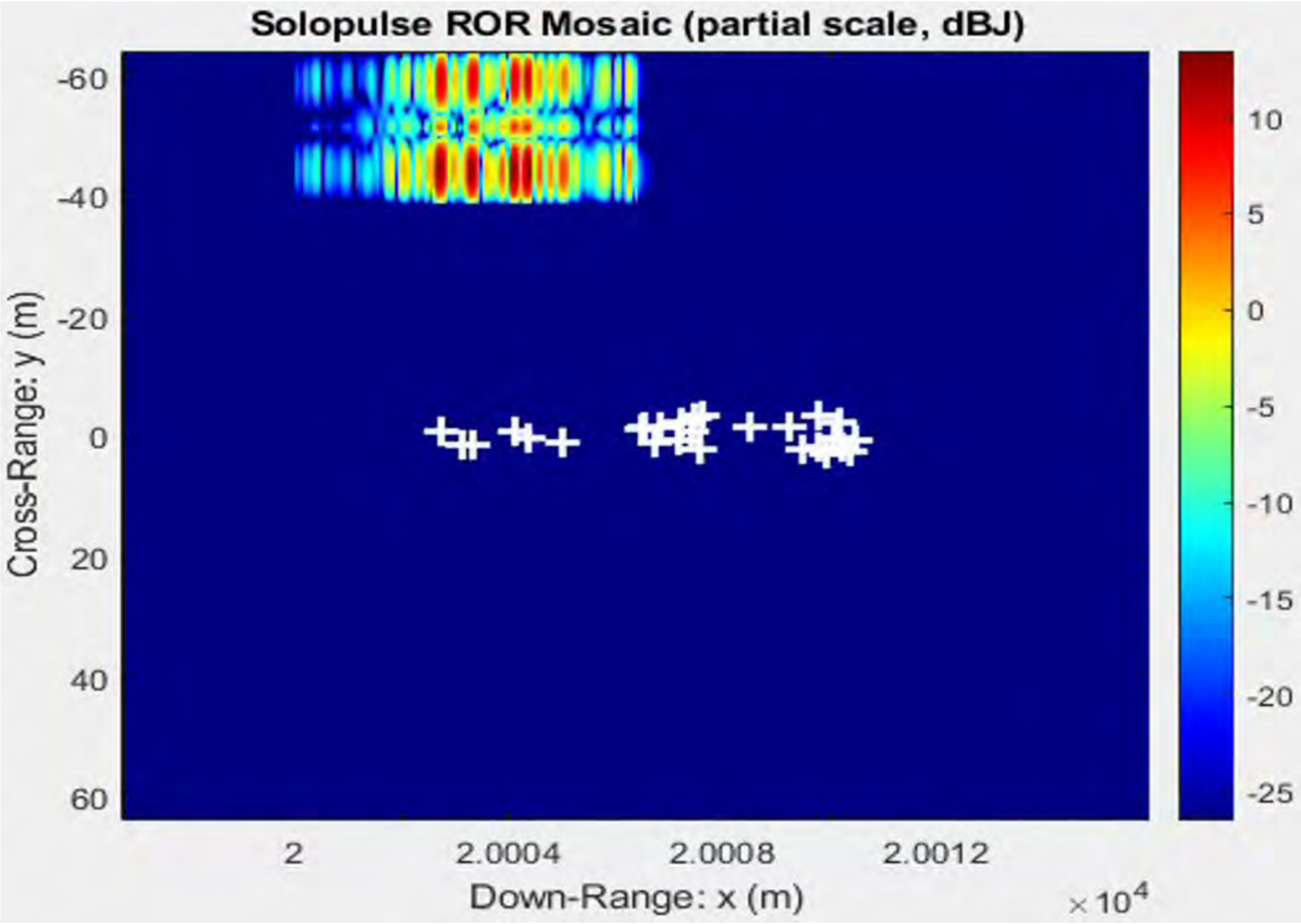
Multiple-frequency coherent fusion is also supported.

Volumetric Solopulse image (IEEE Barnes & Prasad 2018)

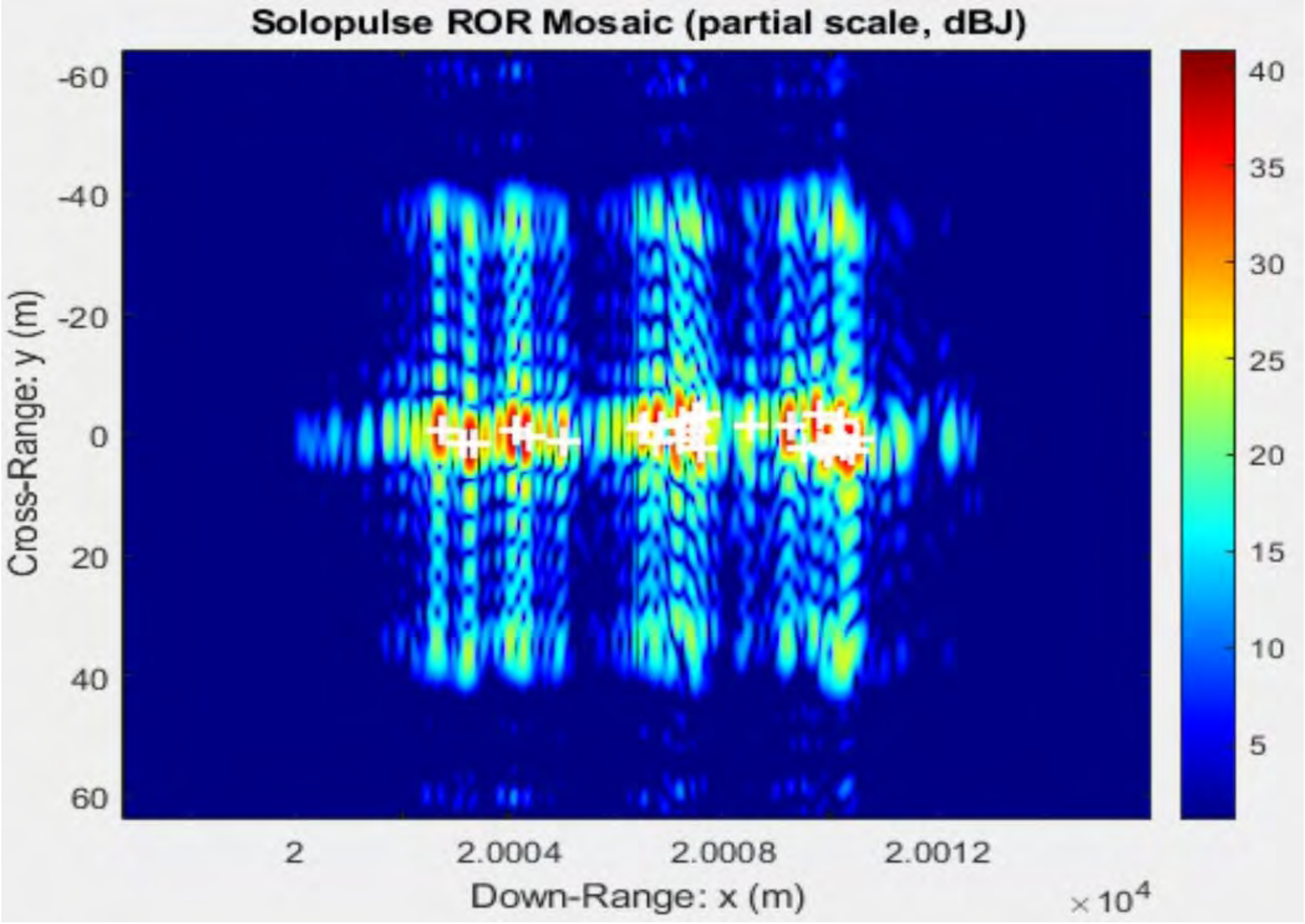
Solopulse's

Signal Processing
Functional Architecture
Architecture Scalability
Computational Costs

Multiple ROR Solopulse Signal Processing with Stationary Sensor and Tracked Object at 20km Range

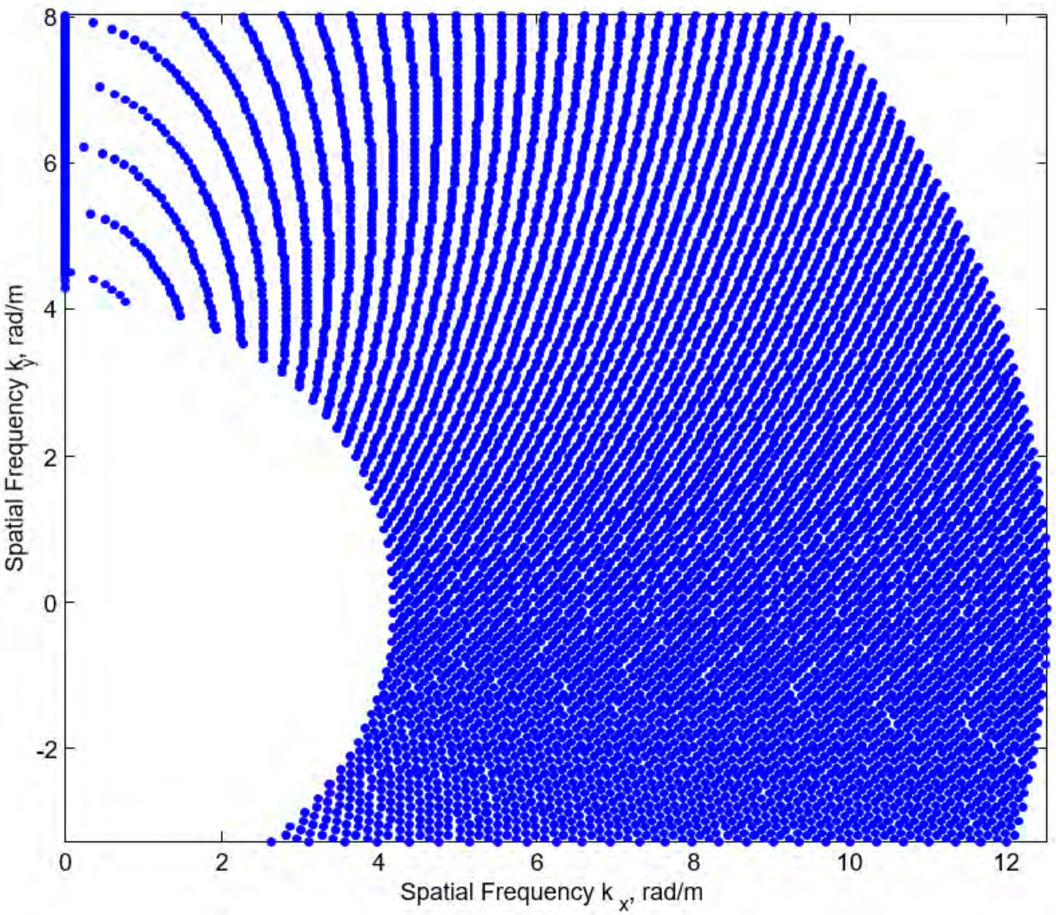


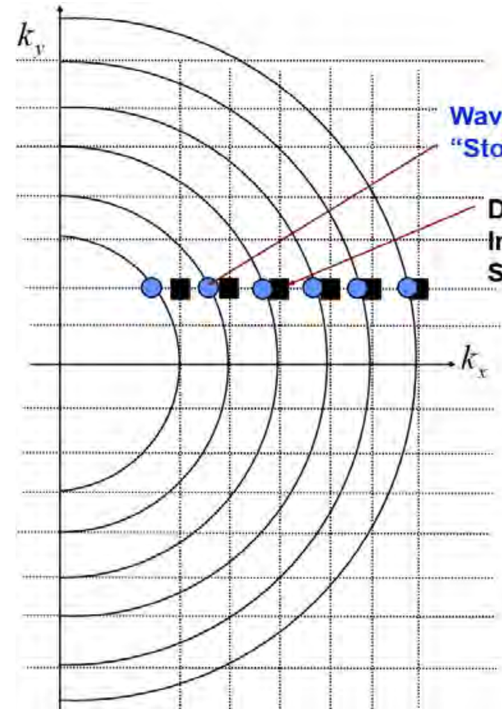
Multiple ROR Solopulse Signal Processing with Stationary Sensor and Tracked Object at 20km Range

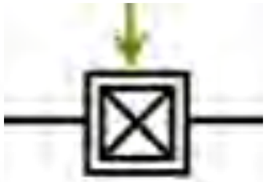


Stolt Change-of-Variables Transform

Covariant change-of-variables transform migrates signal spectrum data to nonuniform







Implemented by a matrix-vector product

Solopulse image spectrum obtained by a one-dimensional resampling task

Various approaches exist:

- Jacobian-weighted transform
- Least-squares solution
- etc

Summary - Solopulse Key Innovations:

1) Ability to image large scene with small digital array with single pulse:

Large Synthetic Array & Small Scene → SAR and Solopulse are duals ← Small Real Array & Large Scene

2) Ability to coherently integrate Solopulse images pulse-to-pulse:

Super-Resolution Radar Capabilities

3) Parallelized computational architecture based on RORs for large FOVs:

“Surround” Radar Imaging & Video Capabilities

Georgia Tech’s Solopulse Intellectual Property :

Sensor Array Imaging Device

- US Provisional Application 62/543,128; Aug. 9, 2017
- US Patent Application Publication 16/36,494, 7 August 2018
- World Intellectual Property Organization WO 2019/032594 A1, 14 February 2019
- US Patent Award 11,378,679, 5 July 2022

End of Solopulse Tutorial