Electromagnetic Simulation Software

Combining Physical Optics and Method of Equivalent Currents to Create Unique Near-Field Propagation and Scattering Technique for Automotive Radar Applications

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Introduction to Auto Radar Simulation

Significant innovation is taking place in automotive industry around capabilities for advanced driver assistance systems (ADAS)[1]-[2].

Radar sensors operating at millimeter wave bands are a key technology and require new modeling and simulation tools to predict their performance in driving environments.

Simulation of radar in realistic automotive scenarios poses several challenges:

- Near-field conditions that invalidate traditional RCS concepts
- Densely-faceted vehicle models too complex for traditional propagation ray-tracers
- Complex multipath from roadside structures (guard rails, signs, parked vehicles, etc.)
- Dynamic scenarios with multiple vehicles in motion

This presentation demonstrates a new modeling and simulation capability that addresses these challenges, combining ray-tracing and scattering simulations from Remcom's WaveFarer® with chirp Doppler analysis algorithms to assess radar performance for drive scenario simulations.

Key Elements of the Solution

Physical Optics (PO) [3] for backscatter

- Surface integration technique accurately predicts backscatter from highly-faceted vehicle models in full, 4-π steradians
- Does not make far-field assumptions, allowing for spherical wave incidence

Method of Equivalent Currents (MEC) [4] for edge effects

- Specially derived for Remcom's PO technique to find electric and magnetic line currents
- Included as line integrals to supplement PO surface integral

Geometric Optics and Uniform Theory of Diffraction (GO/UTD) [4]-[5]

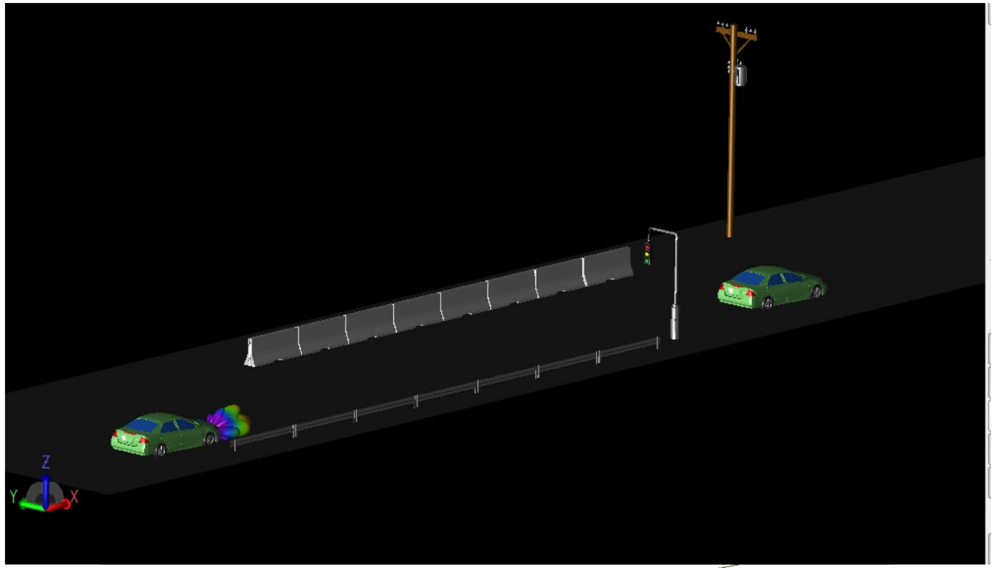
- Used to propagate to scattering surfaces to provide incident electric and magnetic fields for surface integration
- Used to propagate back to ensure reciprocity

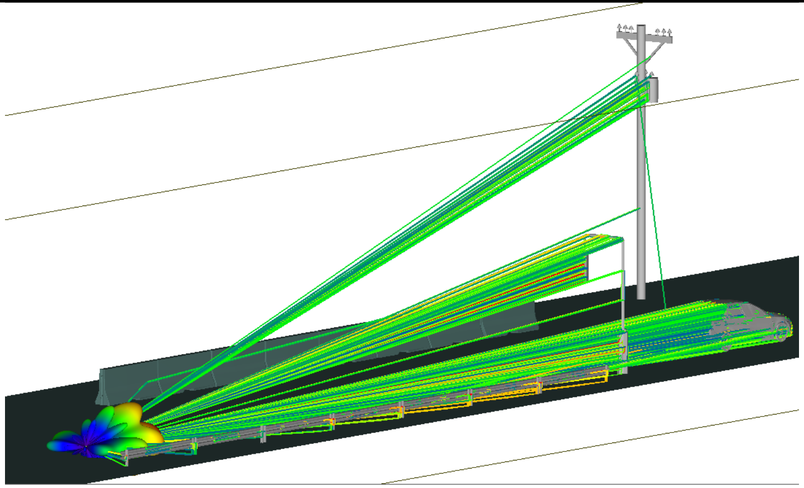
Ray-tracing Methods

Basic ray-tracing approach:

- Shooting and bouncing ray (SBR) method used to find propagation paths to scattering objects (vehicles & clutter)
- Augmented with algorithms to ensure that all paths illuminate every facet of scattering targets (critical enhancement)
- Paths corrected to precise geometric path to all integration points, maintaining mag, phase, polarization and time of arrival

Multipath is captured on the way to and from scattering objects.





Field Calculations

- GO/UTD: interactions with environment to compute incident fields and multipath to/from scattering integration surfaces
  - Includes multipath within scattering objects, such as corner reflectors
- PO/MEC used to compute backscatter from each surface integration point
  - At a high level, each facet and path to antenna has its own generalized Green's function:

$$G_{\text{facet,path}} = G(\vec{J}_{\text{Scat}}, \vec{M}_{\text{Scat}})\, e^{-j\vec{k}_{\text{Ant}}\cdot\vec{r}}$$

where J and M are scattered electric and magnetic current densities, and the exponential term gives phase variations on the facet surface

- Total returned power is computed through complex summation of all paths (reflected, diffracted, and scattered), including phase

$$P_{\text{Rx}} = \frac{\left|\Sigma V_{\text{facet,path}}\right|^2}{2 R_{\text{Ant}}}$$

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Applying to Auto-Radar

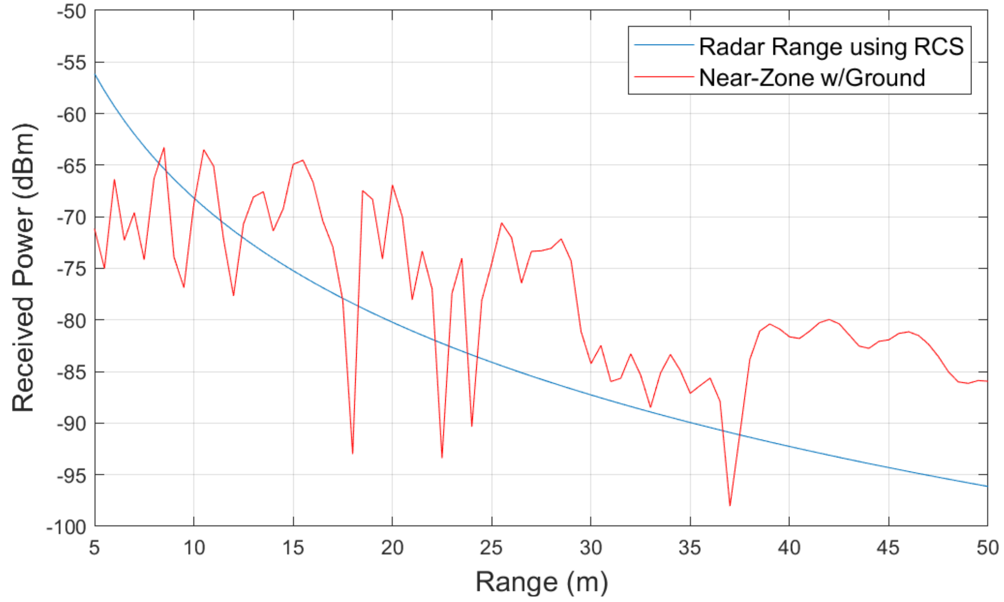
Key characteristics of radar

- Millimeter waves (e.g., 76-81 GHz)
- Antenna radiation patterns (far zone assumptions reasonable)
- Pulsed or chirped waveform

Interactions with car and environment

- Near-zone scattering (vehicle is large compared to wavelength and distance)
  - PO surface integration must include spherical and diffracted wave fronts
  - Also phase, polarization, range dependence
  - Offsets for antenna arrays also critical
- Multipath with ground and other structures both to and from targets

Ground Bounce Multipath Has Significant Effect on Received Power



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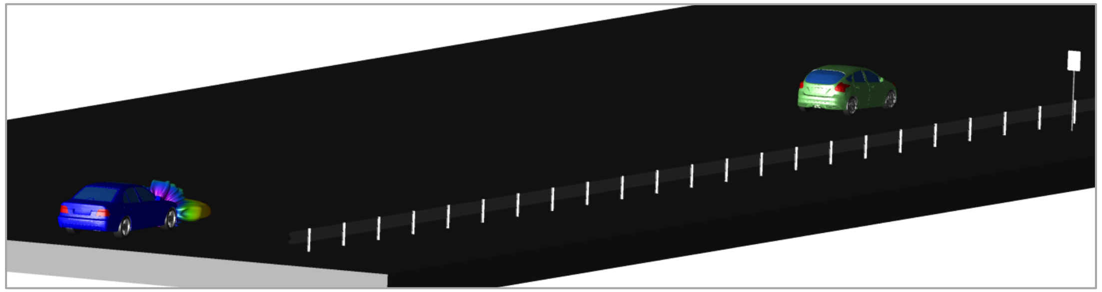
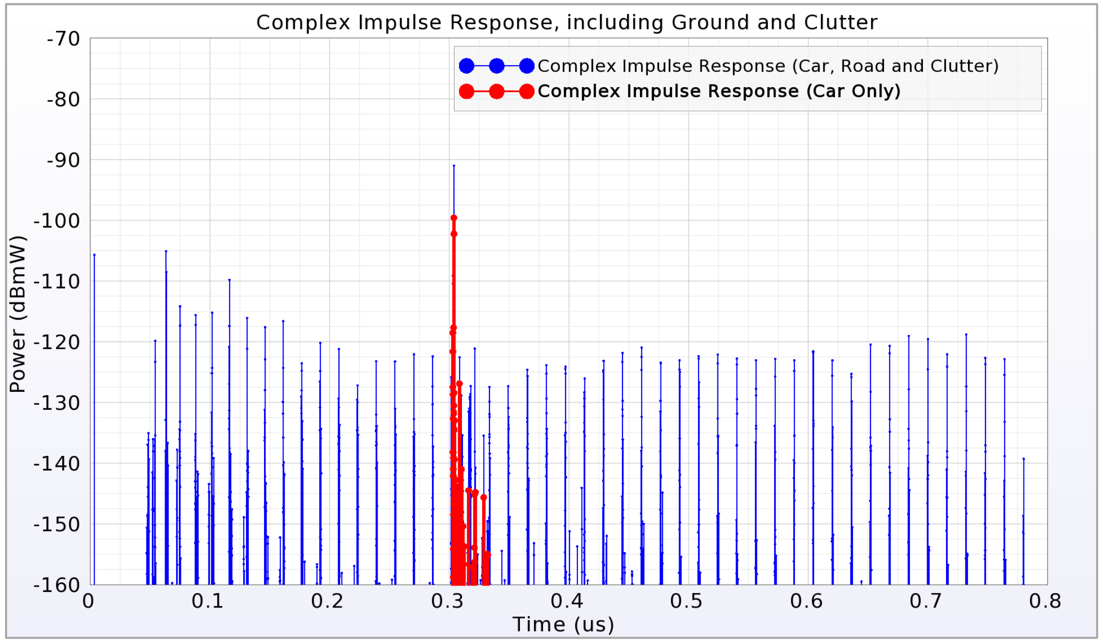
Drive Scenarios Modeling





Drive scenarios typically include roadside clutter, other structures

- Examples: guard rails, street sign
- Maybe buildings, walls, poles

Complex impulse response (CIR) shows mag and phase of returns vs. time of arrival

- Figure compares (a) Car alone vs. (b) car with ground & clutter
- Guard rail posts & sign add large number of secondary returns

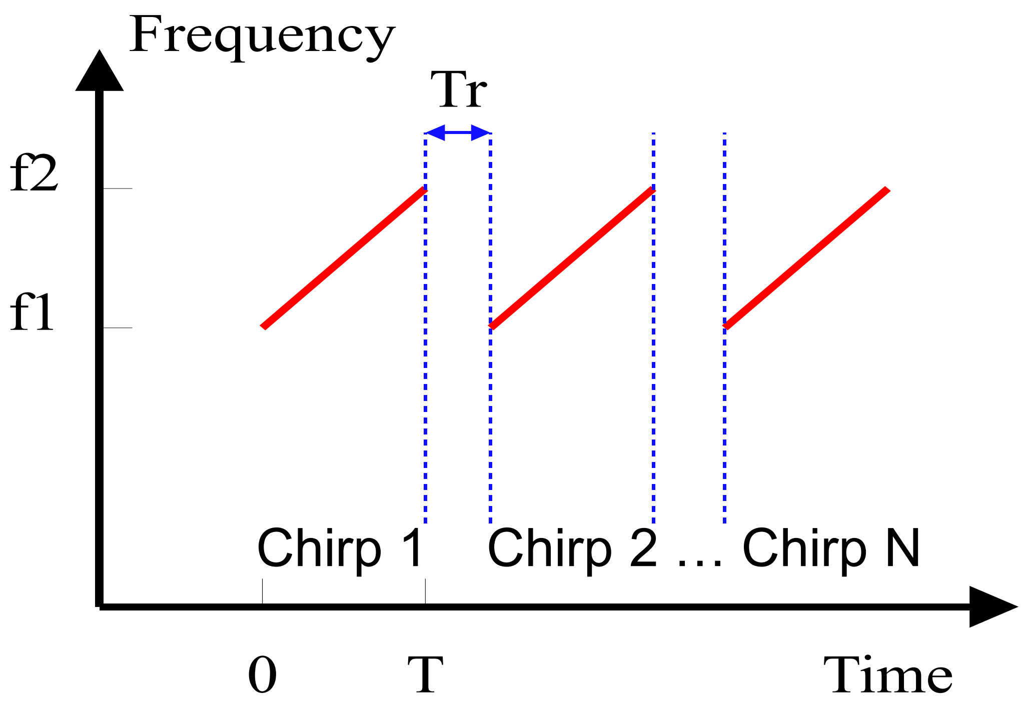
Analysis Using Chirped Waveforms

Developed scripts and post-processing in MATLAB® [9] for range & doppler analysis

Waveform: FMCW [8](chirped waveform), defined by:

- Lower & upper frequency (f1, f2)
- Chirp duration T
- Chirp rate k=(f2-f1) / T
- Optional reset time between chirps, Tr
- Number of chirps/frame, N

Simulated chirp frames at several time steps for two scenarios



Derive Broadband CIR

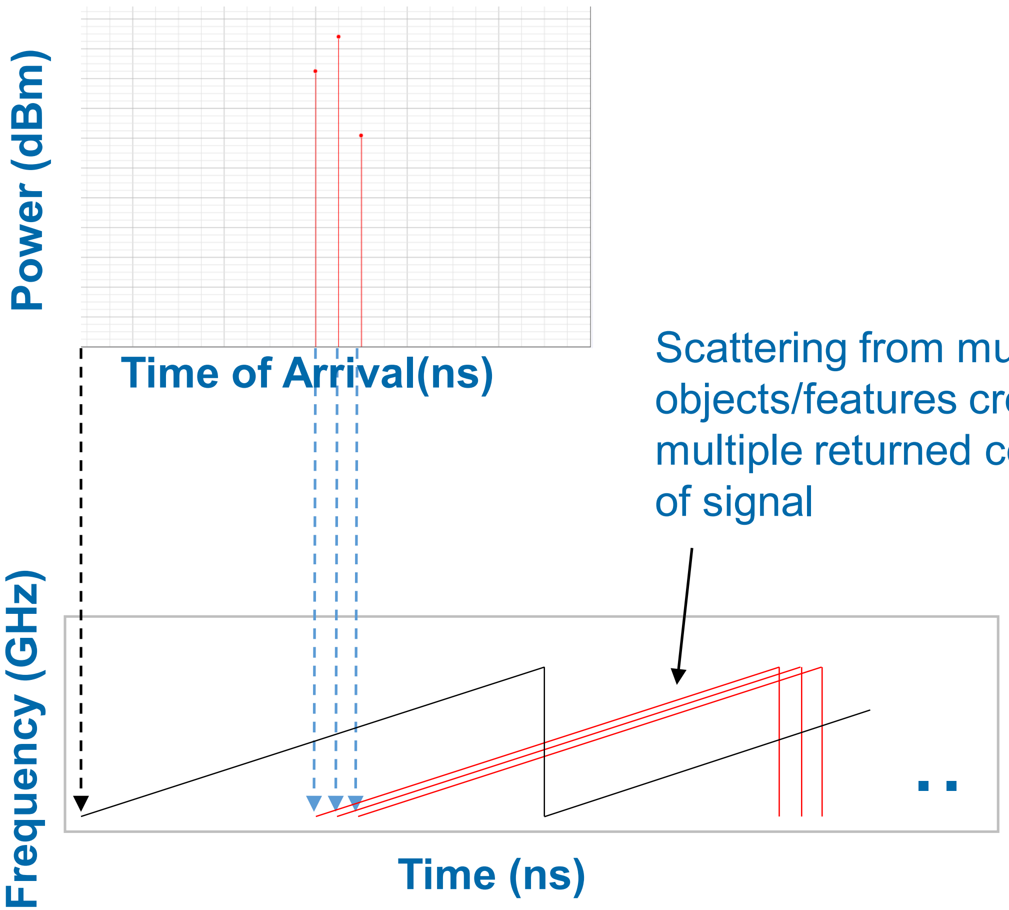
Derive broadband waveform by convolving CIRs with transmitted waveform

- Adjust phases to account for transmit frequency and time of arrival at time of transmission for each CIR return
- Generates time-sampled received voltage waveform

Assumptions

- *Non-dispersion:* in this study, waveform was assumed to not change shape due to interactions on way from Tx to Rx
- *Target object speeds:* objects are moving slow compared to light (each chirp sim is a static snapshot)

Complex Impulse Response



Scattering from multiple objects/features creates multiple returned copies of signal

Delays between transmitted & received copies of signal

Chirp Post-Processing

The critical simulation output is CIR (path mag & phase binned by time of arrival)

Scripts were developed in MATLAB to perform these signal processing steps using these outputs:

1. For each path bin, phase of received signal is determined from CIR and the transmitted chirp waveform

$$\beta(t) = \alpha_0 + \delta + 2\pi f_1 (t - t_d) + 2\pi \frac{k}{2} (t - t_d)^2$$

2. Received signal is mixed with transmitted signal [10]; phase difference is given by

$$\beta - \alpha = \delta - 2\pi f_1 t_d + 2\pi \frac{k}{2} t_d^2 - 2\pi (k t_d) t$$

3. Time-dependent term results in beat frequency related to range of interaction

$$f_{beat} = k t_d = k d / s = 2 k r / s$$

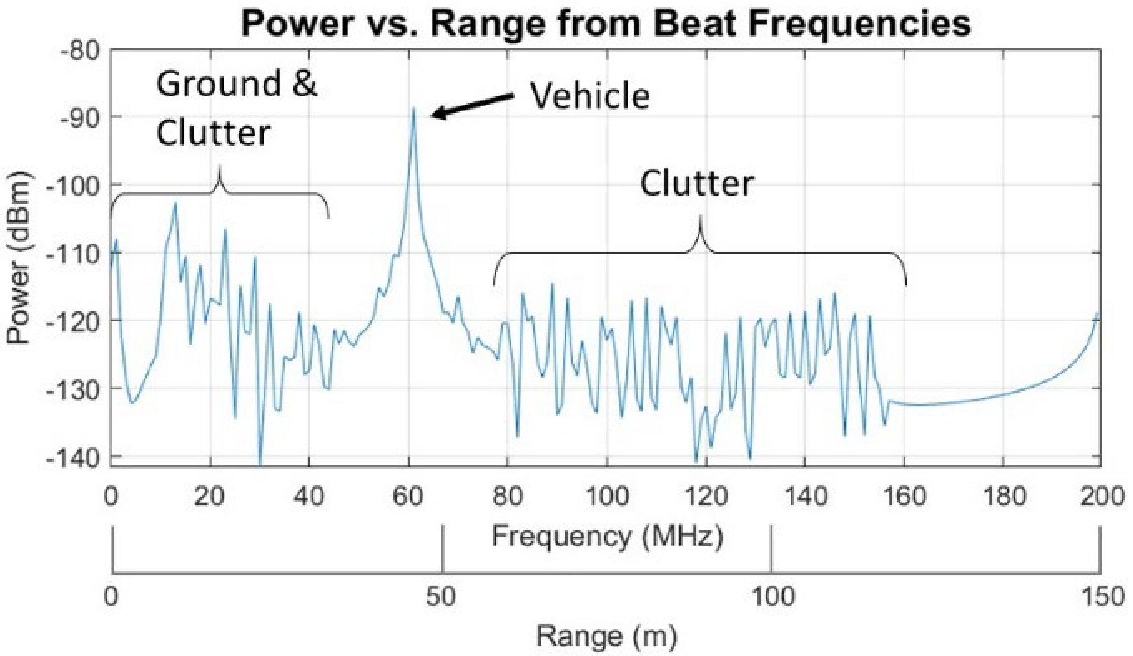
4. This is performed for each path, and results are combined in manner equivalent to a time-domain convolution of waveform and CIRs

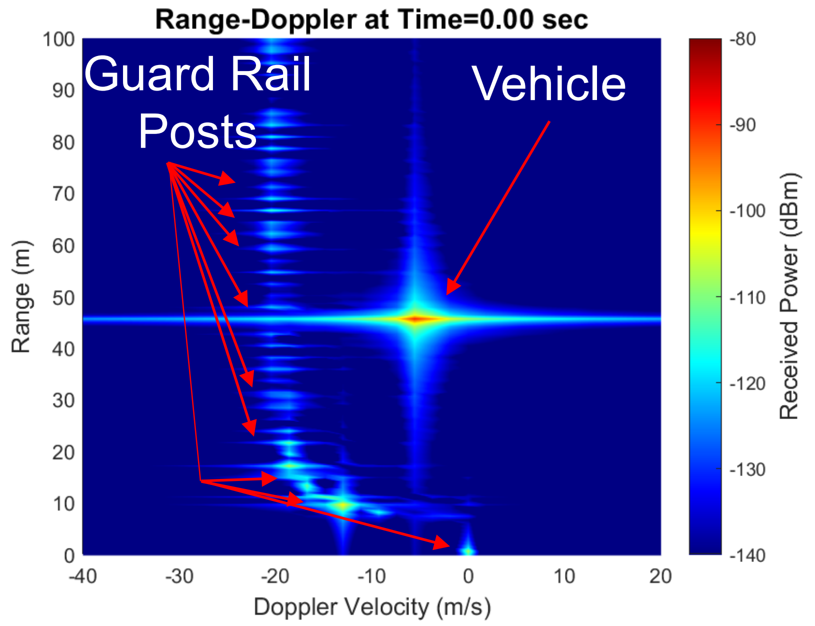
DFTs are then used to determine range and Doppler (next slide)

Chirp Post-Processing (continued)

DFT of combined mixed-down signal from all paths (I&Q) provides power vs. frequency, which can be converted to power vs. range.

DFT across chirps in a frame then determines the Doppler from path phase shifts between chirps as the vehicles move through the scene.





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Scenario 1: Vehicle Braking

First scenario involved radar host closing on a braking vehicle

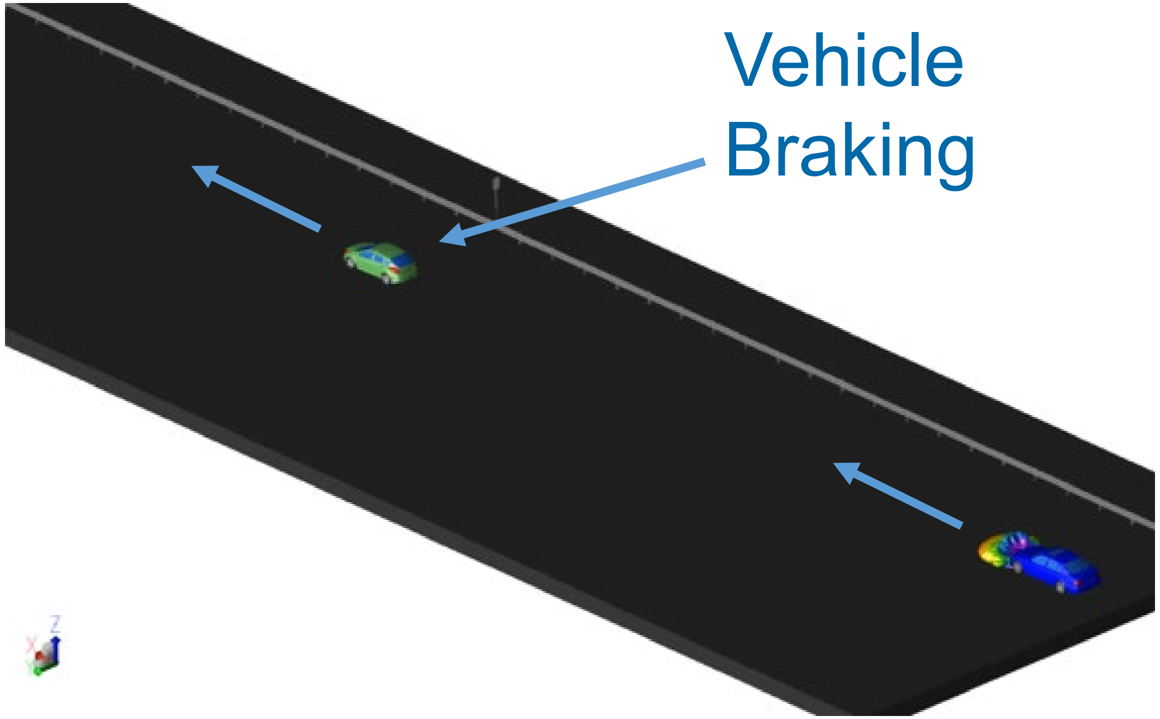
- Used chirp waveform, 51 chirps / frame

Range-doppler calculated for 6 points in time over 2.5 second duration

- For each, simulated returns for 51 chirps (a single frame)

TABLE I. PARAMETERS OF BRAKING SCENARIO

Category	Parameter	Value
Chirp Waveform	Frequency	77 – 81 GHz
	Modulation	Sawtooth
	Chirp Duration	20 us
	Chirps / Frame	51
Motion: Host	Velocity	20 m/s
Braking Vehicle	Initial Velocity	15 m/s
	Deceleration	4 m/s^2



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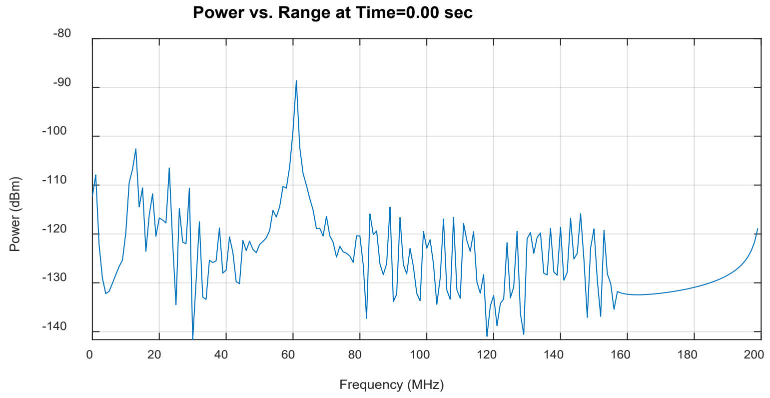
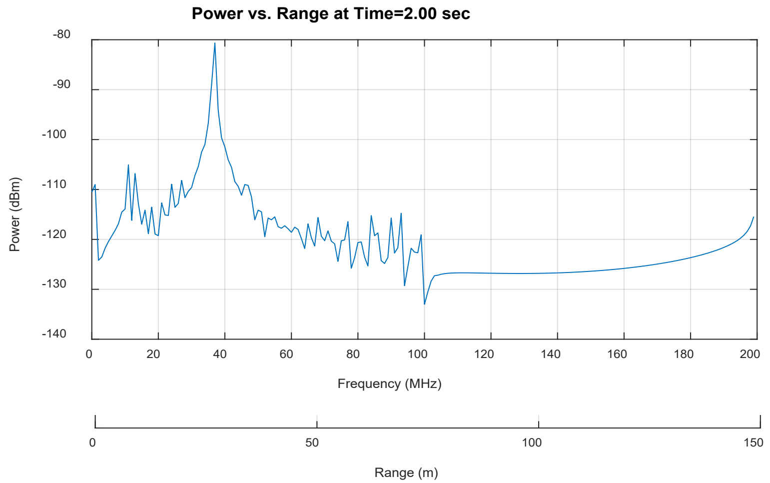
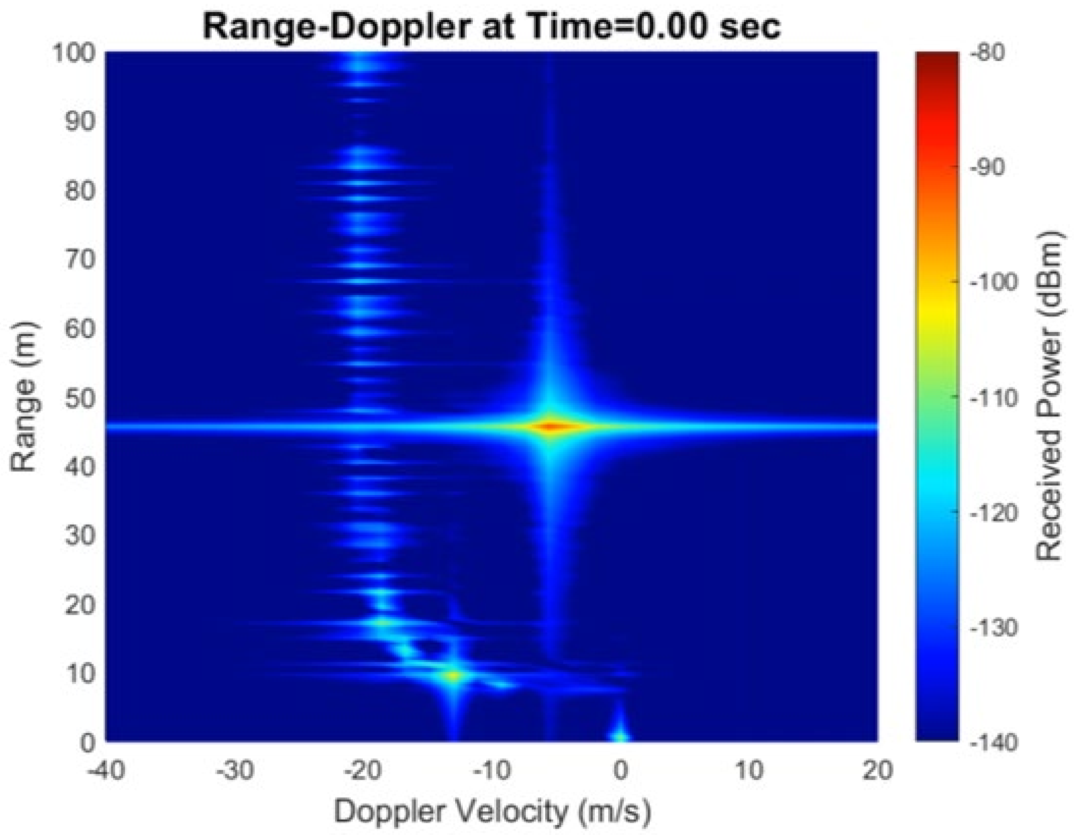
DFTs of I&Q Determine Range-Doppler

DFT of Beat Frequencies Determines Return vs. Range





DFT across Chirps in Frame Determines Range-Doppler



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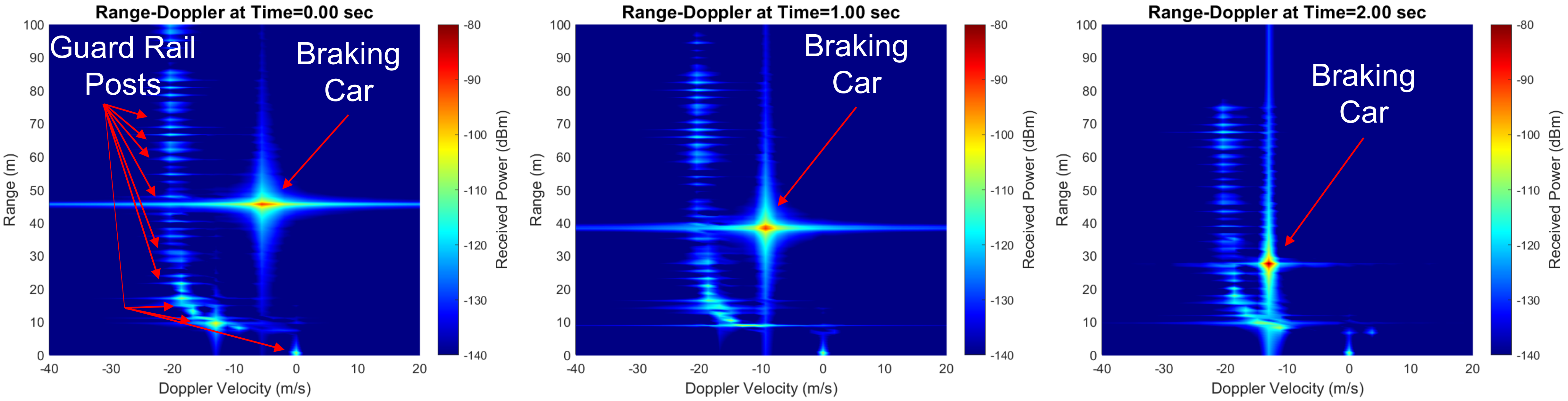
Scenario 1 (Braking): Range Doppler

Results show returns from guard rail posts and vehicle at 1-second intervals

- Vehicle appears at expected ranges
- Relative velocity starts 5 m/s slower; decelerates to 9 m/s and 13 m/s slower as expected
- Guard rails close at full velocity, but slide toward 0 and then negative as car passes them



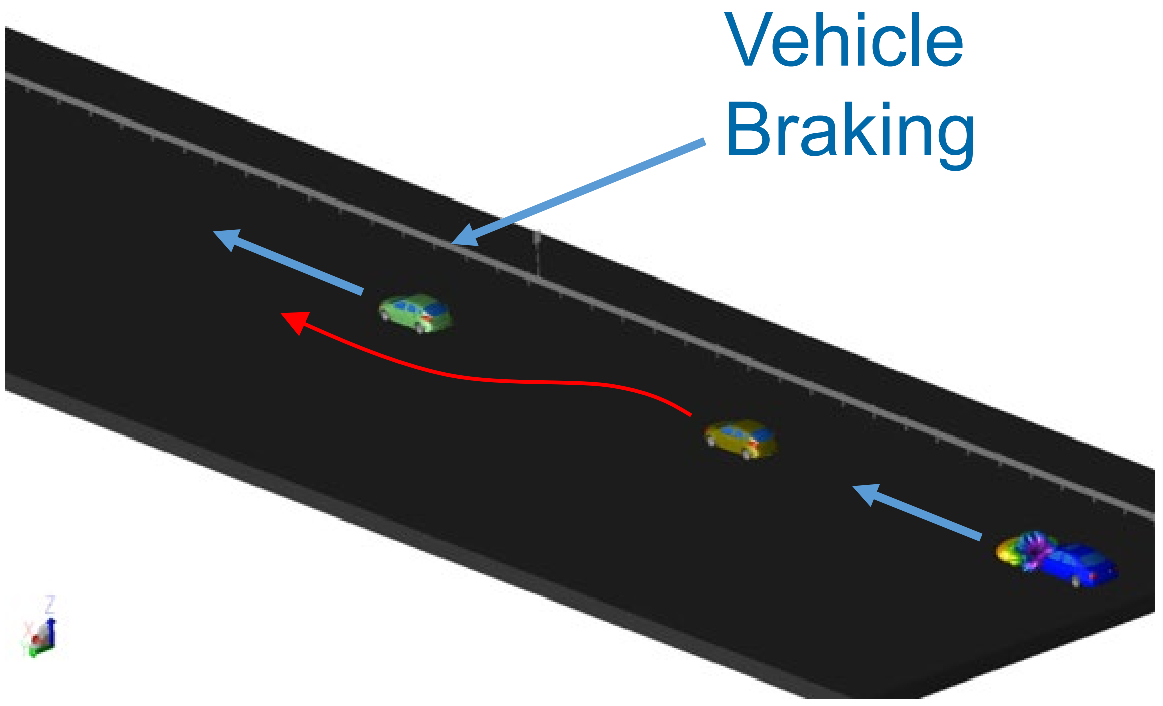
Scenario 2: Lane Change Reveals Braking Vehicle

In 2nd scenario, braking vehicle is obstructed at first

Then blocking vehicle changes lanes, revealing braking car to radar

Scenario parameters:

- Obstructing vehicle matches radar host forward velocity of 20 m/s
- Changes lane along curved path to left
- All other parameters are the same as first scenario



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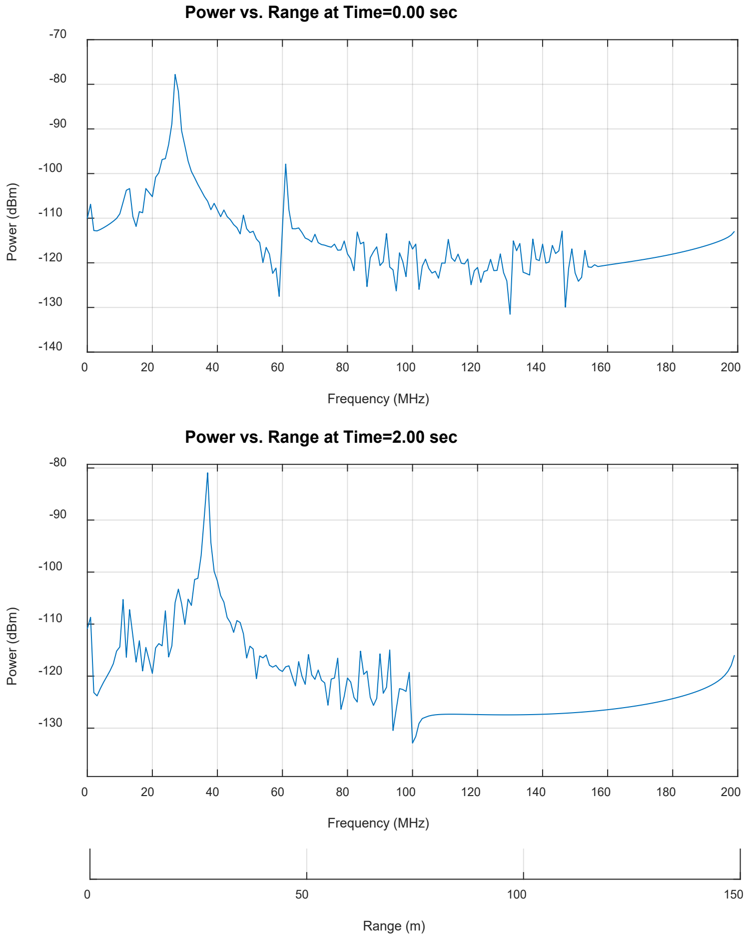
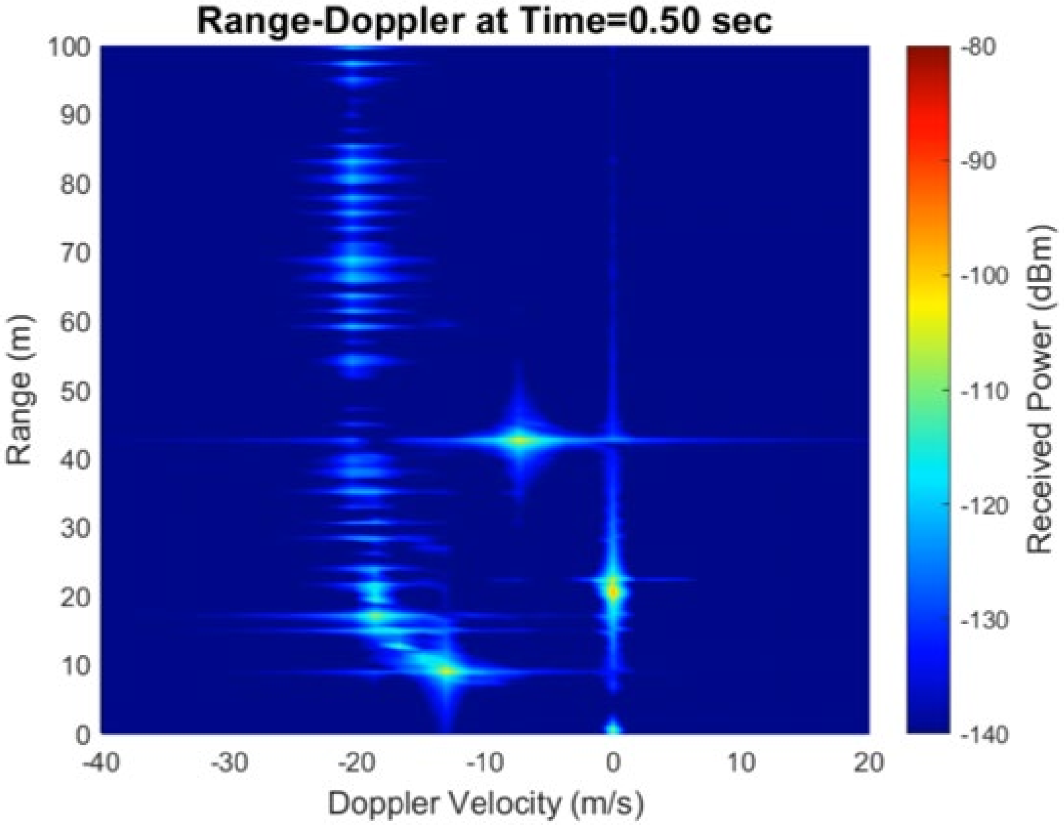
Scenario 2 Returns vs. Range & Range-Doppler

DFT of Beat Frequencies Determines Return vs. Range



DFT across Chirps in Frame Determines Range-Doppler



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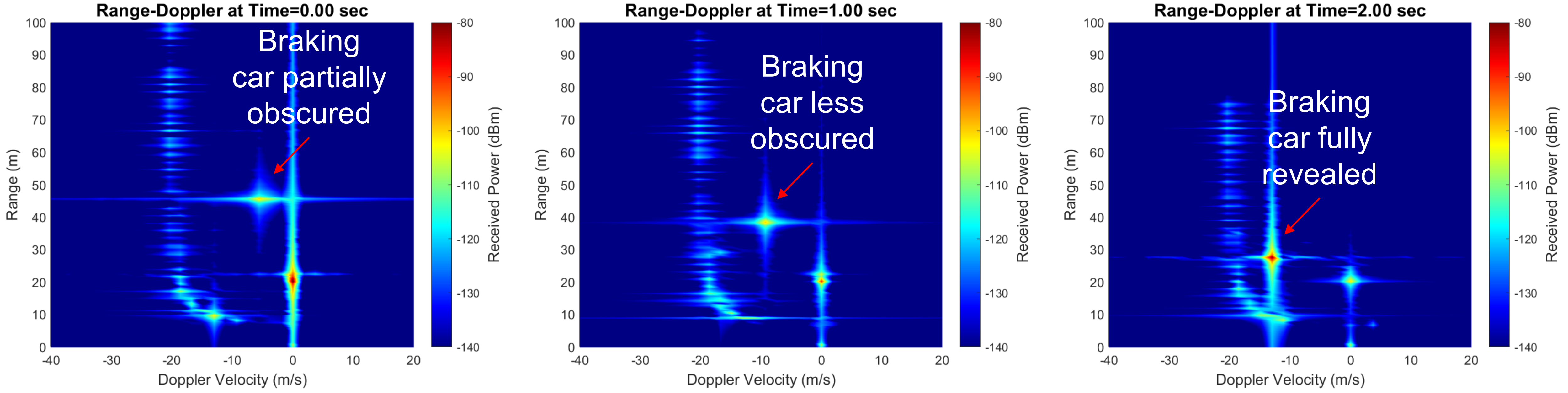
Scenario 2 (Reveal): Range Doppler

Results show returns from vehicles and clutter at 1-second intervals

- Braking vehicle is obscured at start (approx. 20 dB below blocking vehicle)
- Begins to emerge at 1-second point (approx. 8.5 dB down), and fully emerges by end
- Relative positions, velocities, and deceleration for vehicles match expected values



Summary

We have presented a unique solution for predicting radar returns for automotive radar drive scenario simulations.

- Based on Remcom's WaveFarer®, combines ray-tracing and radar scattering methods with techniques specifically designed to handle near-zone conditions, dense multipath, and scattering environments found in typical drive scenarios
- Augmented with post-processing analysis scripts developed in MATLAB to perform range-Doppler analysis for chirp waveforms

The methods were applied to simulate two drive scenarios for comparison.

- In both, the predicted range-Doppler results consistently match the simulated positions and velocities of vehicles and roadside clutter.
- The second scenario demonstrated how an obstructing vehicle might reduce the ability of a radar to observe a braking car in the front.

Successful results verify ability to simulate chirp Doppler for cases relevant to automotive radar, demonstrating a predictive simulation capability that can be used to assess concepts and alternatives during the radar design process.

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