Tracking of Moving Targets with MIMO Radar

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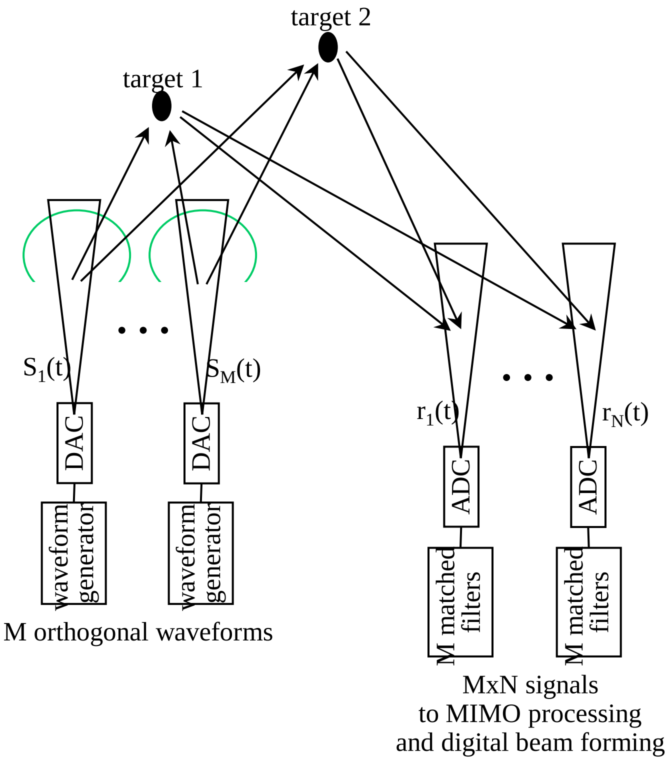
MIMO Radar



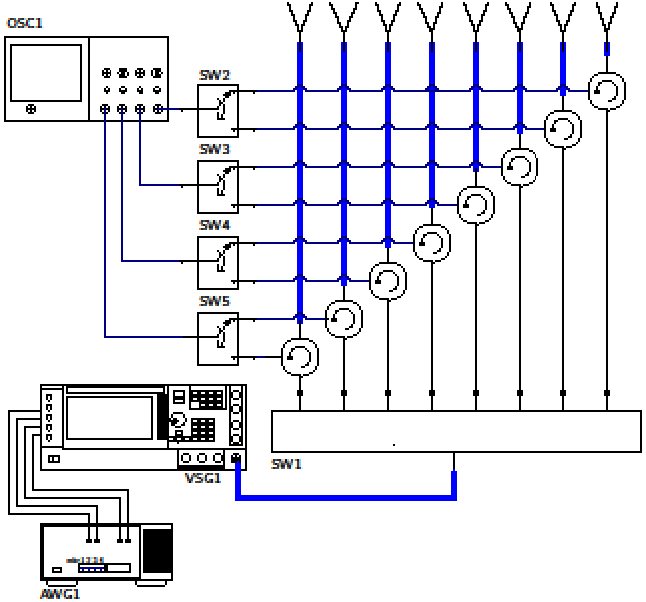
- Potential benefits of MIMO architecture:
  - improved detection and localization
  - new search strategies: “ubiquitous mode”
  - transmit steering on receive
  - sparse arrays
- Challenges:
  - orthogonal waveform design
  - increased computational complexity
  - longer integration times to compensate for reduced transmitter gain
- **How does the tracking performance of MIMO Radar compare with that of traditional phased array radar?**
- Coherent MIMO: transmitters, receivers are co-located.

Problem Description

- Radar has linear array with M elements
    - Directed Beam mode: elements transmit the same waveform with a phase shift to steer the beam (traditional phased array)
    - MIMO mode: elements transmit distinct orthogonal waveforms.
        - Ideal orthogonality and matched filtering is assumed.
- Goal: Compare tracking performance of Directed Beam mode and MIMO mode.
    - Metrics: track completeness, track accuracy (position RMSE)
- Beamwidth Θ is related by $\Theta_{MIMO} = \Theta_{dir}$.
- Doppler bin width Ω is related by $\Omega_{MIMO} = \Omega_{dir}/M$, due to the longer integration time of MIMO mode.
- Probability of detection due to range-Doppler migration needs to be quantified.

Antenna Patterns for Direct Beam and MIMO

- Goal: derive the two-way antenna beam pattern of Directed Beam mode and MIMO mode
  - Theory shows that beam patterns are identical
  - Conduct experiments to verify theory



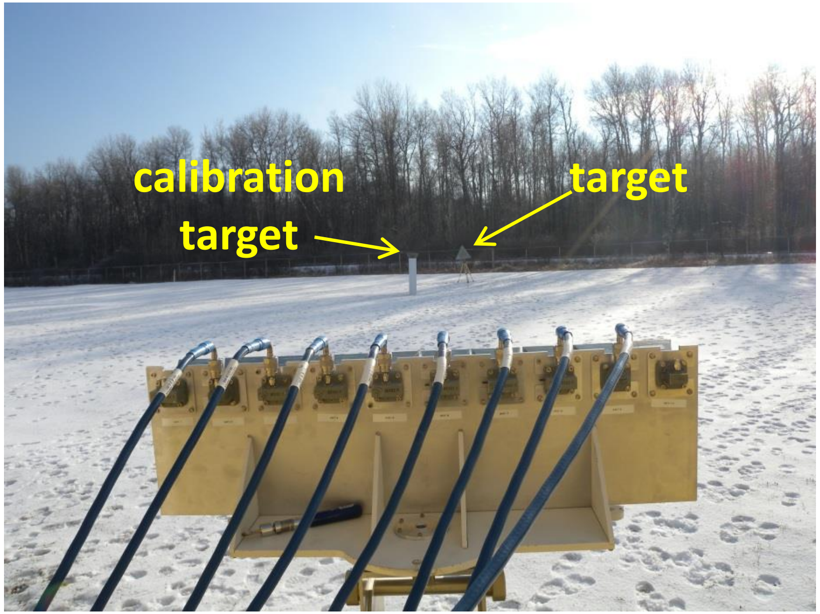
Antenna Array

Narda 640 Antenna

- Frequency: 8.2-12.4 GHz
- Dimensions: 6.0 cm (E-field) x 7.9 cm (H-field)
- 3-dB beamwidth: 28 deg (E-plane), 26 deg (H-plane)
- Antenna Gain: 16.2 dB at 10 GHz

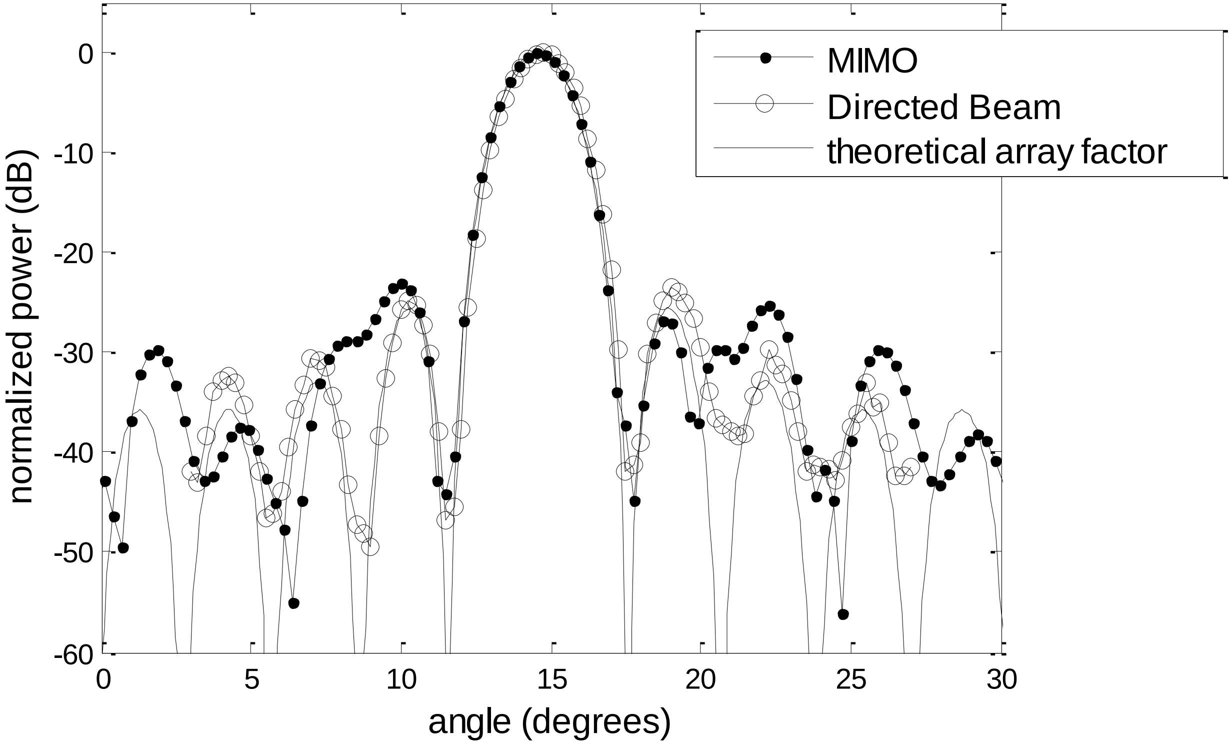
- 8 active elements, with terminated element at each end
- 8 cm spacing between elements
- Can be configured for H and V pol

Experimental Setup



- Target: corner reflector
    - 75 cm side trihedral
    - RCS 32 dBsm
    - Range = 45 m
- Calibration target: corner reflector
    - 45 cm side trihedral
    - Range = 35 m
- Far field > 20 m
- Linear FM signal, centered at 9 GHz.
- Bandwidth 150 MHz, pulse width 100 µs

Antenna Beam Pattern Results



- Experimental results verify that Directed Beam and MIMO have identical two-way antenna beam patterns.

Probability of Detection

- Need to develop an expression for probability of detection that explicitly accounts for range-Doppler migration.
- Receive signal is subject to range sampling and Doppler processing.
- Envelope detection in each range-Doppler bin.
- Returns from high velocity or acceleration targets may be spread over multiple range-Doppler bins
    - This effect is more pronounced for longer integration times.

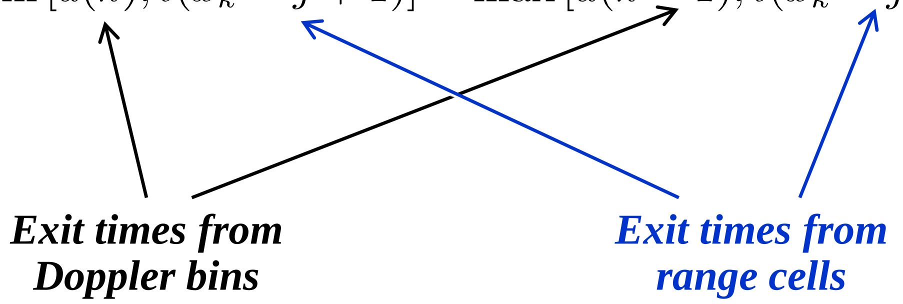
Probability of Detection

Final expression:

$$P_d = 1 - \prod_{k=1}^{D} \prod_{n=1}^{i_k} \int_0^H \frac{2x}{\sigma^2} \exp\left(-\frac{x^2 + c(k,n)^2 y^2}{\sigma^2}\right) I_0\left(c(k,n)\,\frac{2xy}{\sigma^2}\right) dx$$

For $j=0,\ldots,i_k-1$,

$$c(k, i_k - j) = \frac{1}{T}\left(\min\left[d(k), t(x_k - j + 1)\right] - \max\left[d(k-1), t(x_k - j)\right]\right)$$



Exit times from Doppler bins

Exit times from range cells

- A closed-form expression for *c(k,n)* has been derived but is not included here.
- The integral can be evaluated numerically.

Tracking Comparison

- Compare tracking performance of MIMO and Directed Beam modes.
  - MIMO has enhanced range rate estimation accuracy, due to smaller Doppler bin width
  - MIMO may have degraded probability of detection, due to range-Doppler migration.
- X-band tracking scenario considers four cases:
  1. Directed Beam mode
  2. MIMO mode with full velocity or acceleration compensation
  3. MIMO mode with partial velocity or acceleration compensation
  4. MIMO mode without compensation

Scenario Details

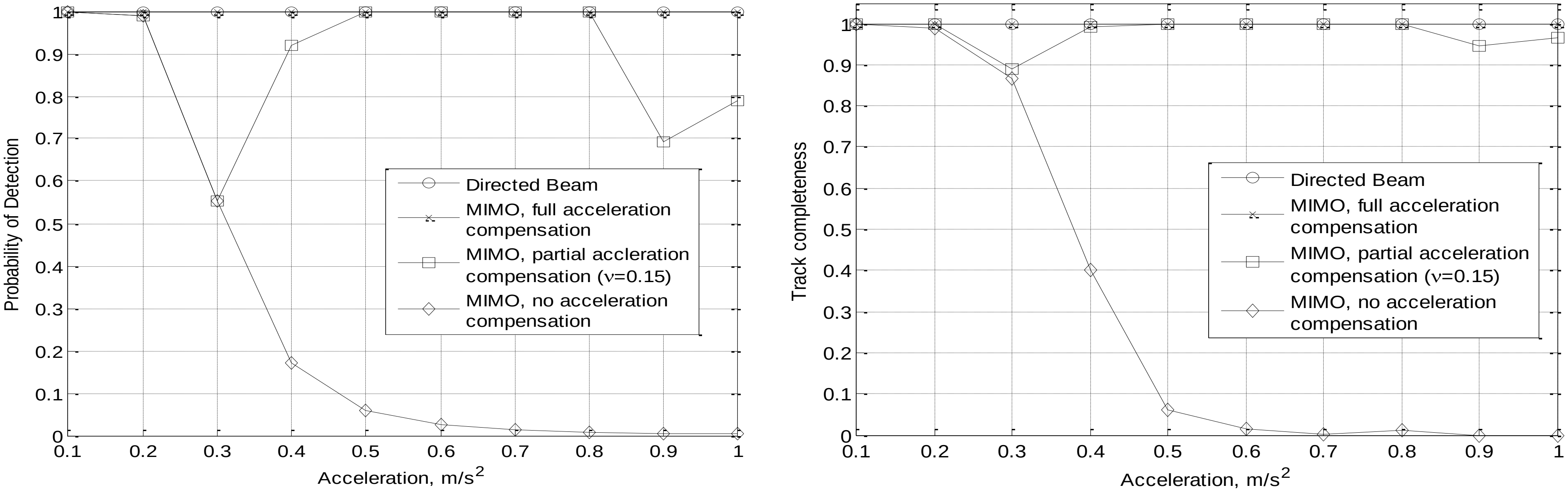
- X-band radar
    - 8-element linear array, physical aperture 2 m, range cell 10 m
    - Beamwidth: 0.76 degrees (both modes)
    - Doppler bin width: 20 Hz (Directed Beam), 2.5 Hz (MIMO)
- Single constant RCS target
    - 100 km initial range, zero degree azimuth, SNR is 19 dB
    - Target travels towards the radar for 90 seconds, velocity *v*, acceleration *a*
- IMM Tracker
    - Update interval of 2 sec, $P_{fa}=10^{-5}$, probability of detection P_d
    - 500 Monte Carlo runs for each value of *v*, *a*. Metrics are averaged over all runs.

Scenario B Description

- Velocity *v* = 75 m/s
- Acceleration *a* varies from 0.1 m/s^2 to 1.0 m/s^2
- Full velocity compensation
- Step sizes for full and partial acceleration compensation:

$$\begin{aligned} \tilde{a}_{opt} &= 0.094 \\ \tilde{a}_{0.15} &= 0.625 \end{aligned}$$

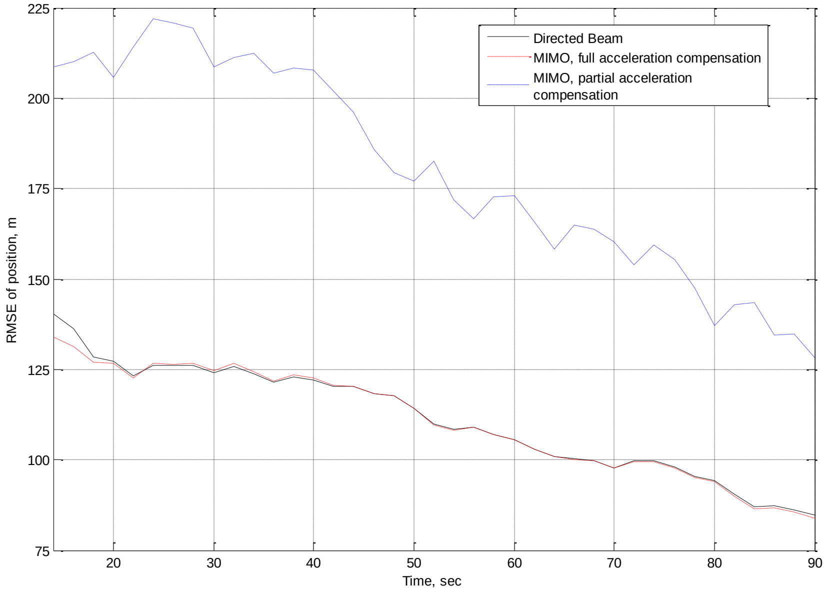
Scenario B: P_d and Track Completeness



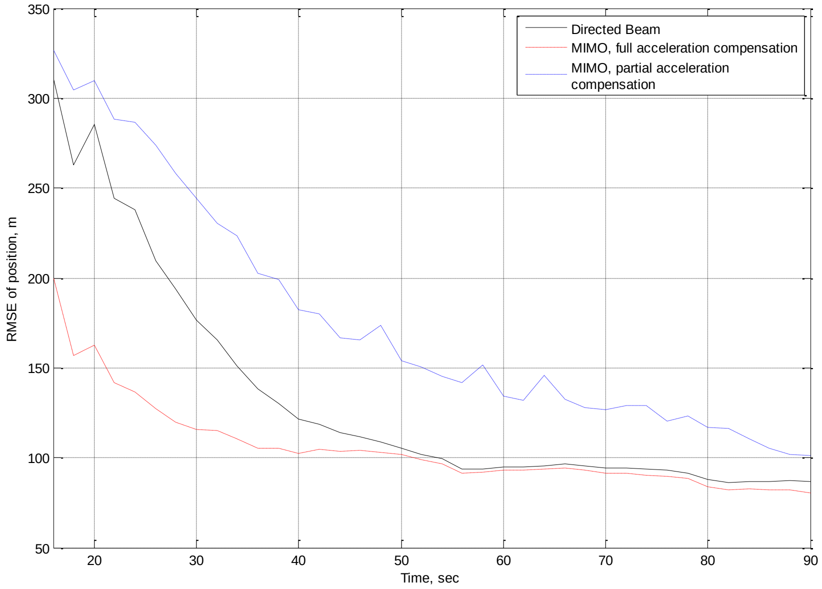
- Acceleration compensation is required for *a* > 0.3 m/s^2.
- MIMO with full acceleration compensation achieves the same Pd and track completeness as Directed Beam.
- MIMO with partial acceleration compensation is subject to coasting over missed measurements.

Scenario B: Track Accuracy

v= 75 m/s, a = 0.3 m/s^2



v= 75 m/s, a = 0.9 m/s^2



- MIMO with partial acceleration compensation takes longer to converge to steady state, due to coasting over missed measurements.
- For larger values of target acceleration, MIMO with full compensation converges to steady state faster than Directed Beam, due to enhanced target Doppler accuracy.

Conclusions

- Due to longer integration times, MIMO radar has increased target Doppler accuracy, as well as degraded probability of detection as a result of range-Doppler migration.
- Through experiments, Directed Beam and MIMO were shown to have identical two-way antenna patterns
- An analytical formula for probability of detection was formulated, with range-Doppler migration explicitly accounted for.
- Velocity and acceleration compensation can ameliorate the effects of range-Doppler migration, at a cost of increased computational complexity.
- For larger values of velocity or acceleration, full compensation is required for MIMO mode to achieve the same detection and track completeness performance as that of Directed Beam mode.
- MIMO with partial compensation suffers from degraded tracking performance due to missed detections which force the tracker to coast.

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