Challenges in Advanced Moving-Target Processing in Wide-Band Radar

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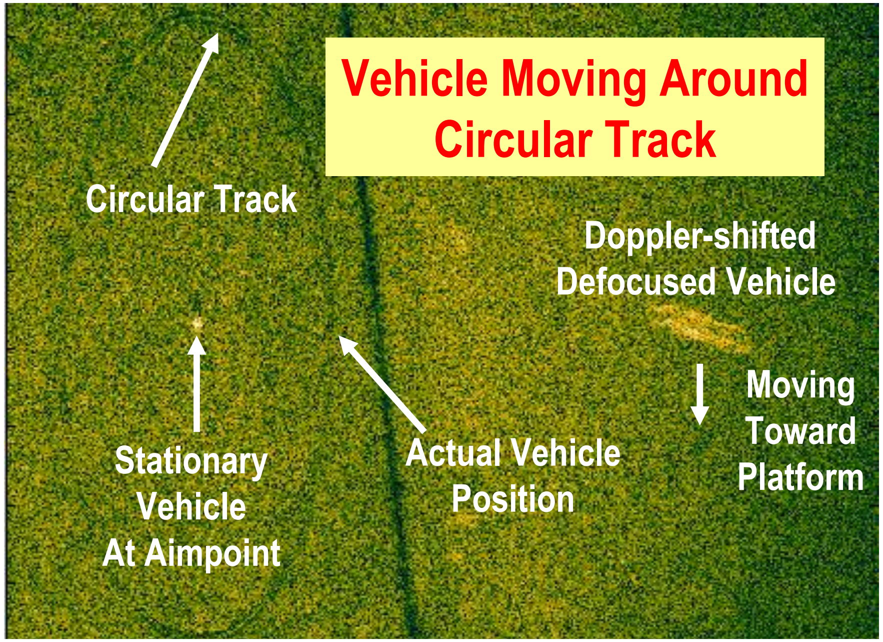
Doppler shift and defocus of moving targets in SAR imagery

- SAR imaging filter is designed to image stationary targets
  - Compensates for Doppler shift produced by platform motion
- As illustrated, moving targets will be displaced in a SAR image due to the Doppler shift produced by target motion
- Additionally, moving target responses will be defocused in a SAR image, especially if accelerating
  - Target Doppler shift varies over radar collection time or coherent processing interval (CPI), thus producing defocus



Challenges for processing moving targets in SAR imagery

- Moving targets may often be Doppler shifted near bright “clutter” returns from stationary objects (such as buildings)
  - Amplitude of target responses may be well below amplitude of competing clutter returns
- SAR defocus also reduces amplitude of target responses, making detection even more difficult
- For effective tracking, accurate estimation of target location and velocity estimates is needed
  - Location estimation typically performed using angle of arrival (AOA) estimates
  - Velocity estimation performed using estimation of target Doppler shift
  - Presence of competing clutter will reduce accuracy of geolocation estimates through reduction of the signal to interference plus noise ratio (SINR)
  - Defocus will further reduce accuracy of both location and velocity estimates
- Multiple movers in field of view can produce additional tracker confusion
- Techniques to mitigate the effects of clutter and defocus and allow accurate target location and velocity estimates are desired

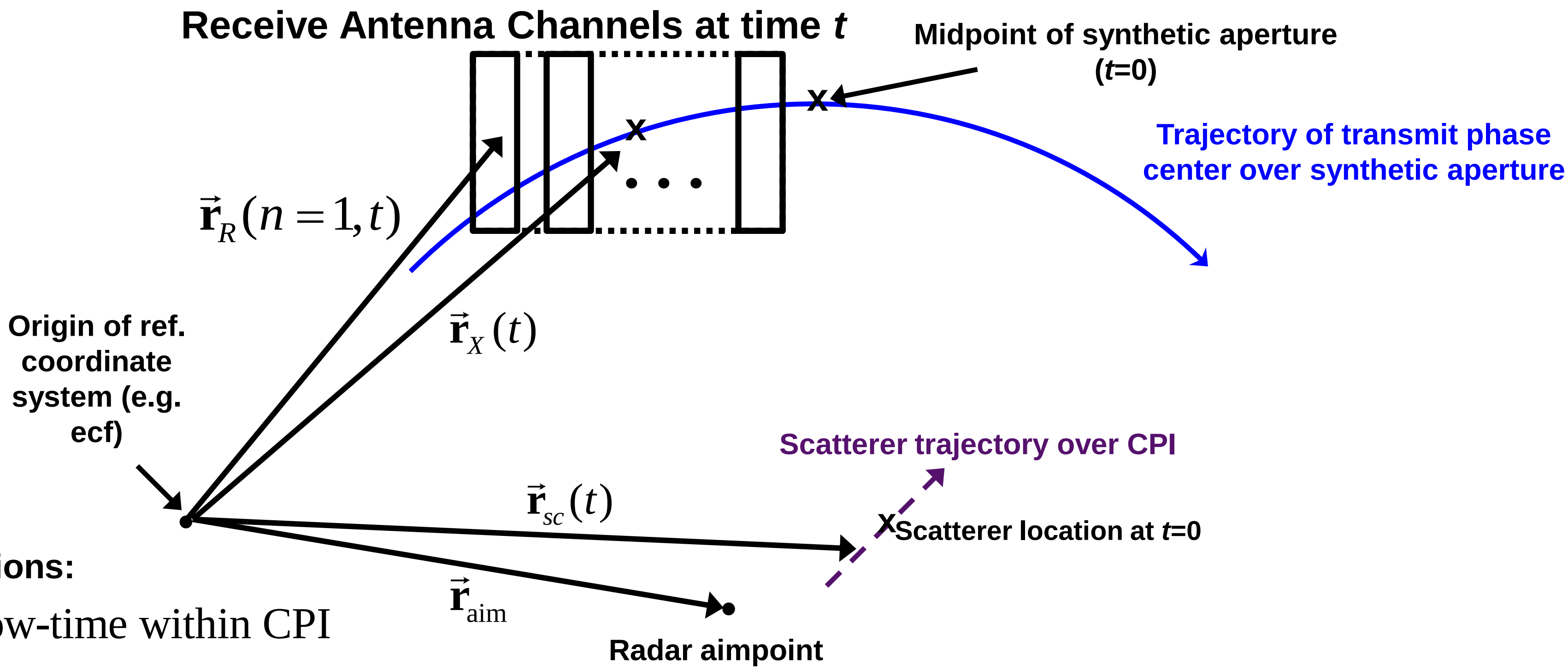
Techniques for improving processing of movers in SAR imagery

- Use of tracker feedback
  - Allows smaller image sizes and reduced detection thresholds by focusing attention on targets of interest
- Moving Reference Processing (MRP)
  - Reprocesses the SAR data to focus up moving target responses [1]
- Space-time adaptive processing (STAP)
  - Improves ratio of amplitude of moving targets to stationary clutter using multiple antenna channels, adaptive estimation of clutter statistics, and adaptive filtering [2]
  - Can combine estimates of clutter statistics with maximum likelihood estimation to provide location and velocity estimates for tracking
- Change Detection
  - Uses multiple orbits of radar platform around scene of interest
  - Coherent or noncoherent combination of returns from multiple orbits improve ability to distinguish between moving targets and stationary objects
- A framework for studying these techniques will be presented, along with examples illustrating their use

[1] S. Scarborough, C. Lemanski, H. Nichols, G. Owirka, M. Minardi, T. Hale, "SAR Change Detection MTI," Algorithms for Synthetic Aperture Radar Imagery XIII, Edmund G. Zelnio, editor, Proceedings of SPIE, 2006.

[2] I. S. Reed, J. D. Mallett, and L. E. Brennan, "Rapid convergence rate in adaptive arrays," IEEE Trans. Aerospace Elec. Sys., Vol. 10 No. 6, pp. 853-863 (Nov. 1974).

Definitions of quantities appearing in multi-channel SAR MRP scatterer model



Definitions:

$t \equiv$ slow-time within CPI

$n \equiv$ receive antenna channel index

$\vec{\mathbf{r}}_X(t) \equiv$ location of transmit phase center at time t

$\vec{\mathbf{r}}_R(n,t) \equiv$ location of receive channel n phase center at time t

$\vec{\mathbf{r}}_{sc}(t) \equiv$ location of moving point scatterer at time t

$\vec{\mathbf{r}}_{\text{aim}} \equiv$ location of radar aimpoint

Scatterer phase history model and polar format definitions

- The motion-compensated phase history of a moving point scatterer is assumed to be given by :

$$P_{sc}(n,\lambda,t) = A_{sc} \cdot \exp[-j \cdot \frac{2\pi}{\lambda} \cdot \{|\vec{\mathbf{r}}_X(t) - \vec{\mathbf{r}}_{sc}(t)| + |\vec{\mathbf{r}}_R(n,t) - \vec{\mathbf{r}}_{sc}(t)| - 2|\vec{\mathbf{r}}_{MC}(n,t) - \vec{\mathbf{r}}_{aim}|\}]$$

where

$\lambda \equiv$ radar wavelength sample (varies across radar bandwidth)

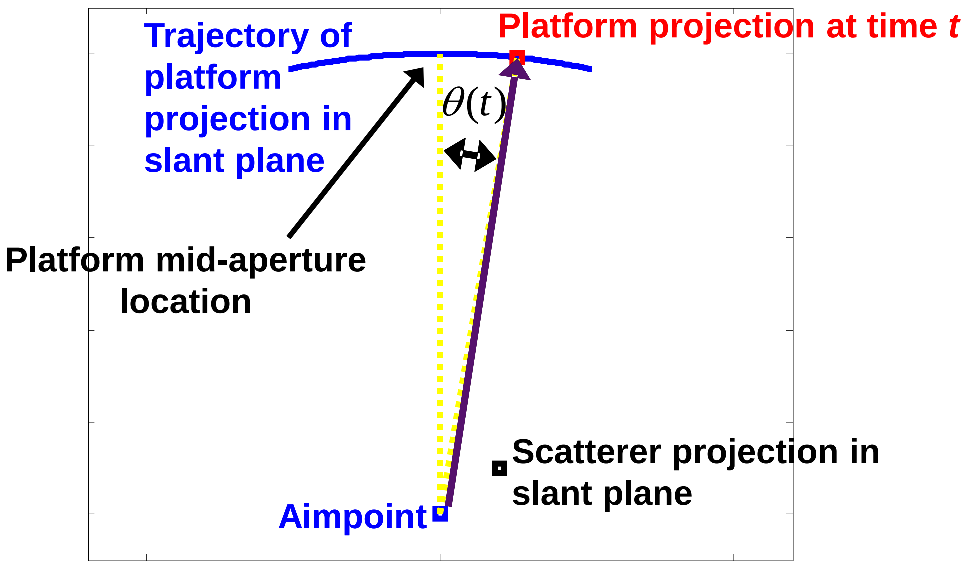
$\vec{\mathbf{r}}_{MC}(n,t) \equiv$ motion compensation reference point for channel n (assumed = $\vec{\mathbf{r}}_X$ (t) in following)

- Polar format SAR defines:

$$\mathbf{k}_y(\lambda,t) = \frac{1}{s(t)} \cdot \frac{4\pi}{\lambda} \cos\theta(t)$$

$$\mathbf{k}_x(\lambda,t) = \frac{1}{s(t)} \cdot \frac{4\pi}{\lambda} \sin\theta(t)$$

$$k(\lambda) \equiv \sqrt{\mathbf{k}_x(\lambda,t)^2 + \mathbf{k}_y(\lambda,t)^2}$$



Polar format SAR Image formation

- Typically a rectangular k-space grid is formed, and output (complex) image amplitudes are given by

$$Q(n, x_{im}, y_{im}) = \sum_{\mathbf{k}_x} \sum_{\mathbf{k}_y} \exp(-j \cdot [\mathbf{k}_x \cdot x_{im} + \mathbf{k}_y \cdot y_{im}]) \cdot \tilde{P}(n, \mathbf{k}_x, \mathbf{k}_y)$$

where interpolation is used to produce:

$$\tilde{P}(n, \mathbf{k}_x, \mathbf{k}_y) \equiv P(n, \lambda(\mathbf{k}_x, \mathbf{k}_y), t(\mathbf{k}_x, \mathbf{k}_y))$$

and

$$x_{im} \equiv \text{x coordinate in image}$$

$$y_{im} \equiv y \text{ coordinate in image}$$

- For stationary scatterers close to the radar aimpoint, we have the following approximation:

$$\tilde{P}_{sc}(n, \mathbf{k}_x, \mathbf{k}_y) \approx A_{sc} \cdot \exp(j \cdot [\mathbf{k}_x \cdot x_{sc} + \mathbf{k}_y \cdot y_{sc}]) \cdot \exp(j \cdot \phi_n)$$

  - The corresponding SAR image response will be focused and located at x_{sc},y_{sc}, due to the linear dependence of the phase on $\mathbf{k}_x$ *and* $\mathbf{k}_y$

Application of MRP to focus moving target responses

- General target motions will lead to a phase that is not linear in k-space
  - Leads to significant defocus in SAR image, even for scatterers close to the aimpoint
- Instead of reprocessing the entire phase history, one can perform MRP after polar formatting and compensate for a nonlinear k-dependent phase using:

$$Q(n, F, x_{im}, y_{im}) = \sum_{\mathbf{k}_x} \sum_{\mathbf{k}_y} \exp(-j \cdot [\mathbf{k}_x \cdot x_{im} + \mathbf{k}_y \cdot y_{im}]) \cdot M(F, \mathbf{k}_x, \mathbf{k}_y) \cdot \tilde{P}(n, \mathbf{k}_x, \mathbf{k}_y)$$

where

$M(F, \mathbf{k}_x, \mathbf{k}_y) \equiv$ MRP focus function in k-space

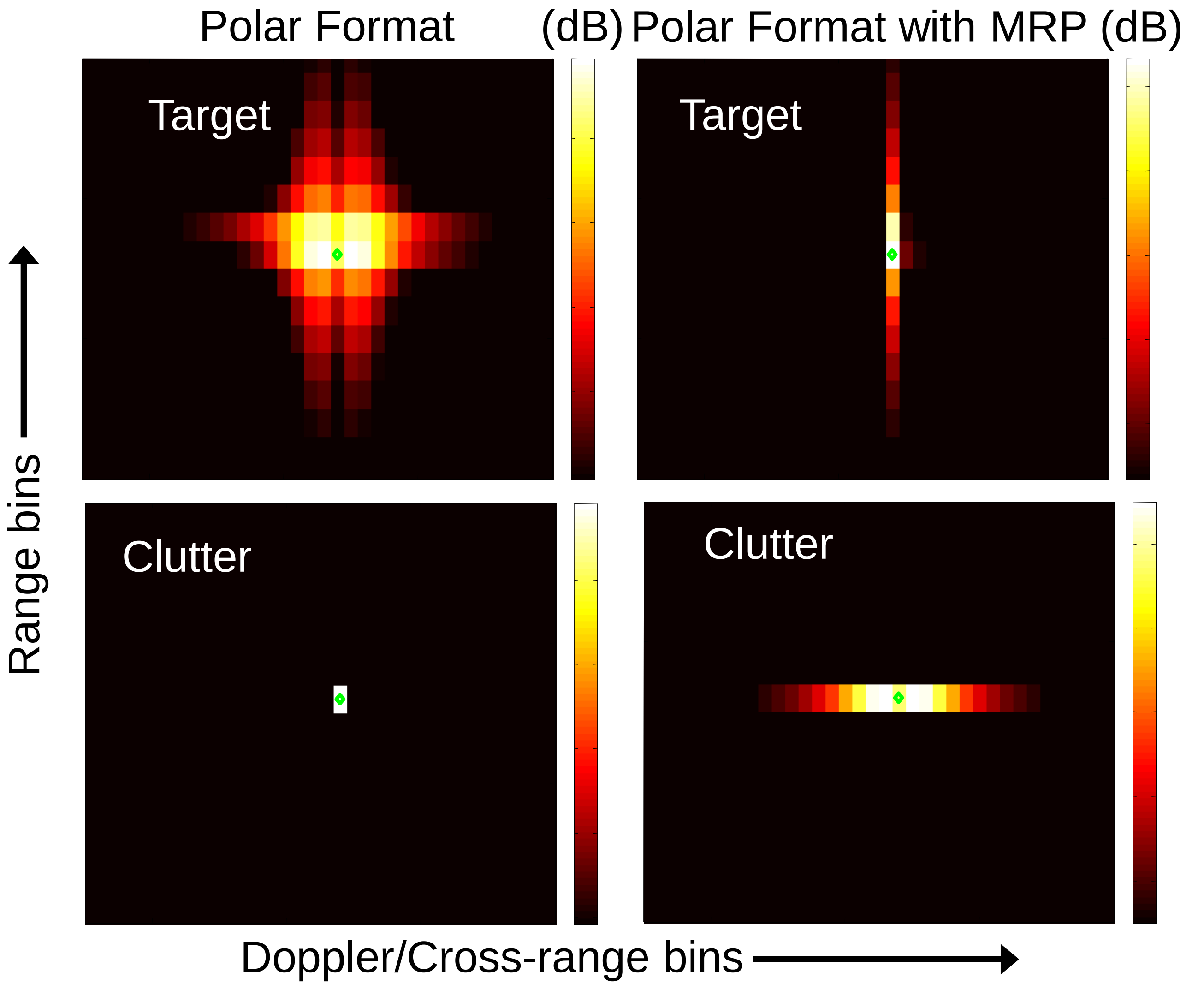
$F \equiv$ MRP focus parameter or set of parameters

- The form of the MRP k-space focus function depends on the target motion assumed
  - The next slide shows an example for a constant acceleration target with the following motion over the CPI:

$$\vec{\mathbf{r}}_{sc}(t) = \vec{\mathbf{r}}_{sc}(0) + \vec{\mathbf{v}}_{sc}(0) \cdot t + \frac{1}{2} \vec{\mathbf{a}}_{sc}(0) \cdot t^2$$

Simulated MRP example of a constant acceleration target and stationary clutter scatterer

- SAR image responses shown for an accelerating point scatterer (target, top plots) and a stationary point scatterer (clutter, bottom plots)
- Responses shown before (left) and after (right) MRP based on the known target motion
- An MRP filter designed to focus the target will in general defocus clutter



Application of STAP to MRP-processed SAR data

- In post-Doppler STAP, covariance estimation is performed using:

$$\mathbf{R}(x,y) = \frac{1}{N_{y'}} \sum_{y' \neq y} \vec{\mathbf{d}}(x,y')\vec{\mathbf{d}}(x,y')^H$$

where

$$\vec{\mathbf{d}}(x,y') \equiv \text{vector of adaptive degrees of freedom (DOFs) in pixel } x, y'$$

- An adaptive weight vector maximizing the SINR is then calculated using

$$\vec{\mathbf{w}}(\beta,x,y) = \mathbf{R}(x,y)^{-1}\vec{\mathbf{s}}(\beta),$$

$$\vec{\mathbf{s}}(\beta) \equiv \text{model target response "steering" vector across DOFs for target parameters } \beta$$

- Detection and parameter estimation can then be performing using the adaptive matched filter (AMF) metric [3]:

$$AMF(\beta,x,y) = \frac{|\vec{\mathbf{w}}(\beta)^H \vec{\mathbf{d}}(x,y)|^2}{\vec{\mathbf{w}}(\beta)^H \mathbf{R}(x,y)\vec{\mathbf{w}}(\beta)},$$

[3] Frank C. Robey, Daniel R. Fuhrmann, Edward J. Kelly, Ramon Nitzberg, “A CFAR Adaptive Matched Filter Detector,” IEEE Transactions on Aerospace and Electronic Systems, Vol. 28, pp. 208-216, (1992)

Simulated SINR Loss in constant acceleration example

- Clutter to noise ratio (CNR) of clutter scatterer is varied and output SINR determined for different algorithms:

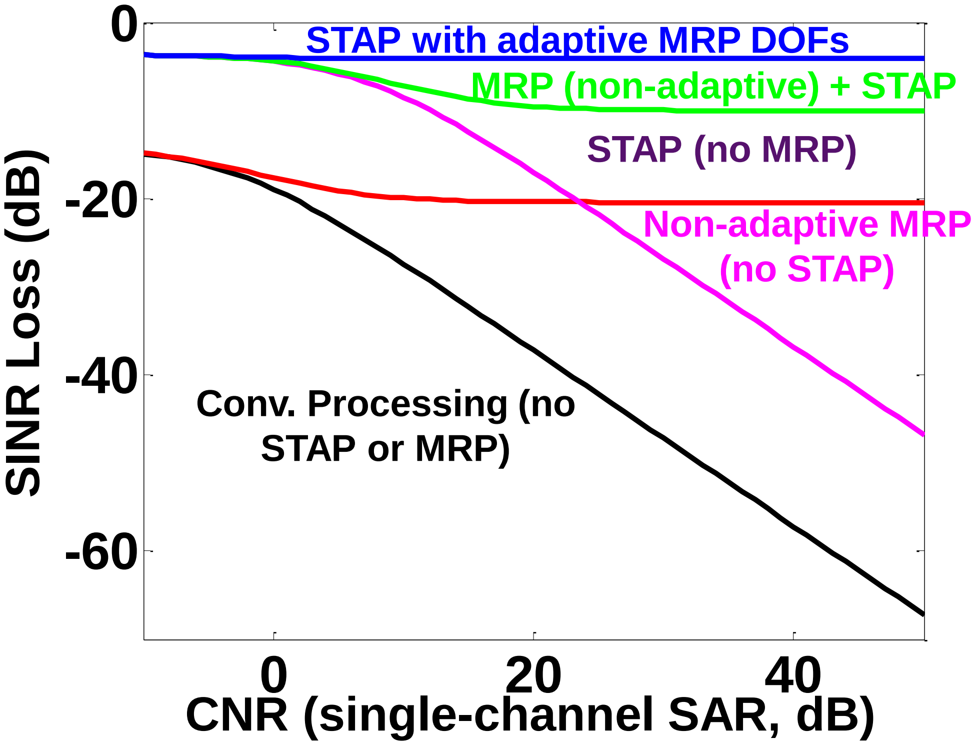
Conventional processing : apply conventional beamforming across antenna channels, no MRP

Non-adaptive MRP : apply MRP using known target parameters, then apply conventional beamforming across antenna channels

STAP (no MRP): apply adaptive filtering across antenna channels

MRP (non-adaptive): apply MRP using known target parameters, then apply adaptive filtering across antenna channels

STAP with adaptive MRP DOFs: apply MRP using different parameter sets *F*, apply adaptive filtering across channels and MRP parameter sets

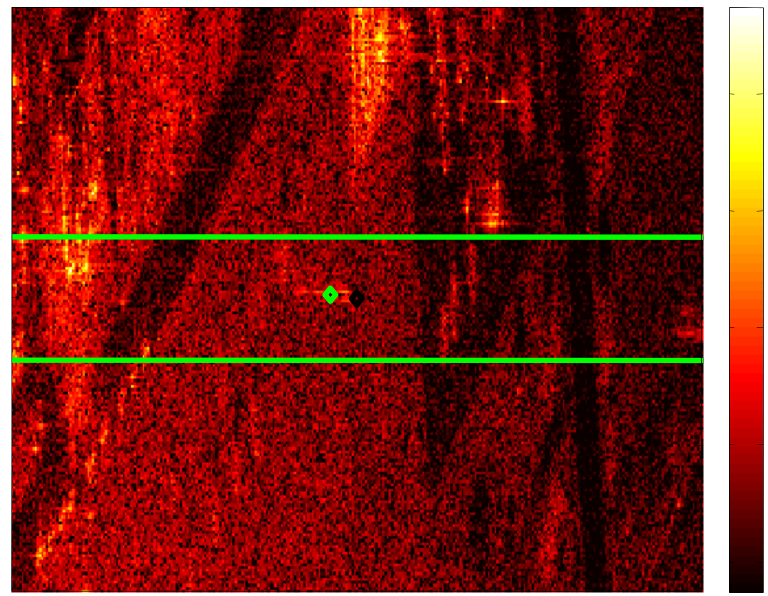


- Using STAP with adaptive MRP DOFs clearly provides the best SINR in this simulated example

Extracted SAR chip and imaging geometry – "easy" example

Collection geometry

Extracted target chip



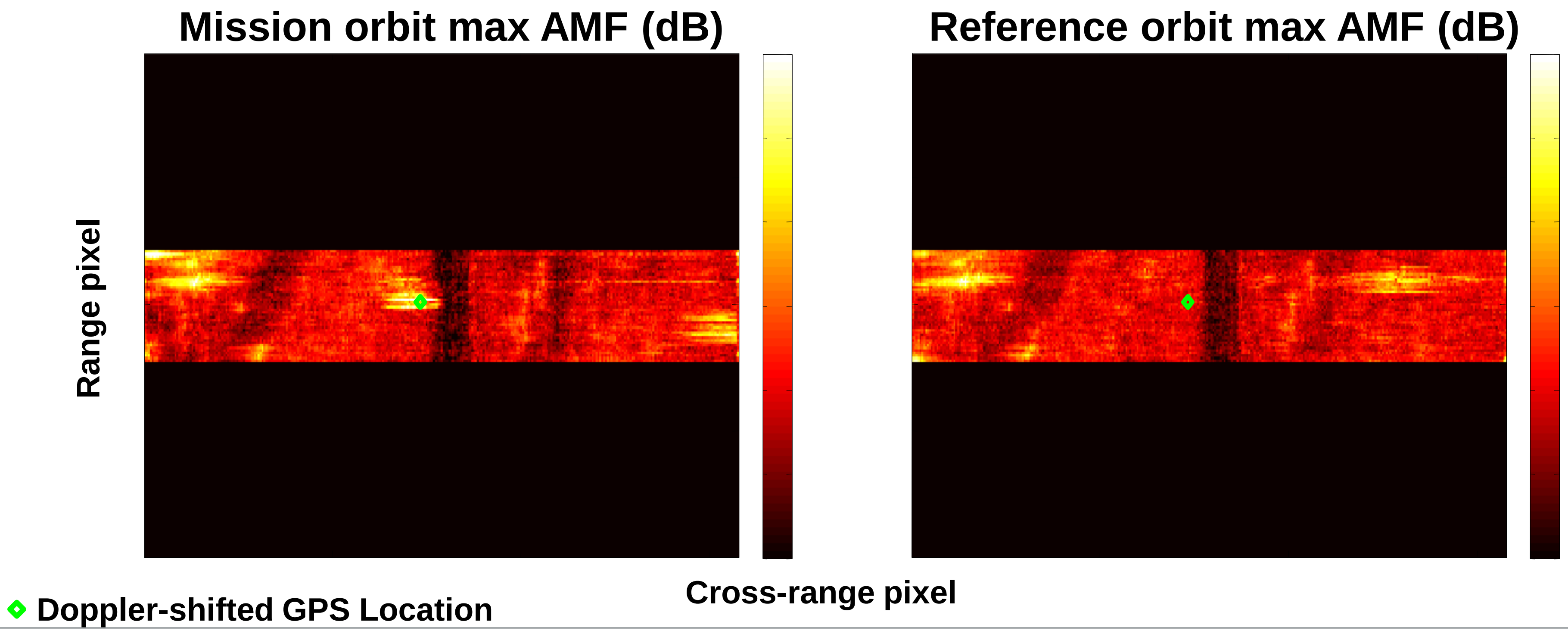
◆ Doppler-shifted GPS Location

Note, Doppler-shifted track prediction is the chip center

- Target response in SAR image visible close to Doppler-shifted GPS truth location in this example

STAP AMF images for two passes of radar platform

- Change detection employs two passes of radar platform about scene
  - Mission pass in which target assumed to be present
  - Reference pass in which target is assumed to be absent
  - AMF images shown for each pass are maximized over target parameters



Detection, false alarm mitigation, and parameter estimation techniques

- Threshold detection using AMF:

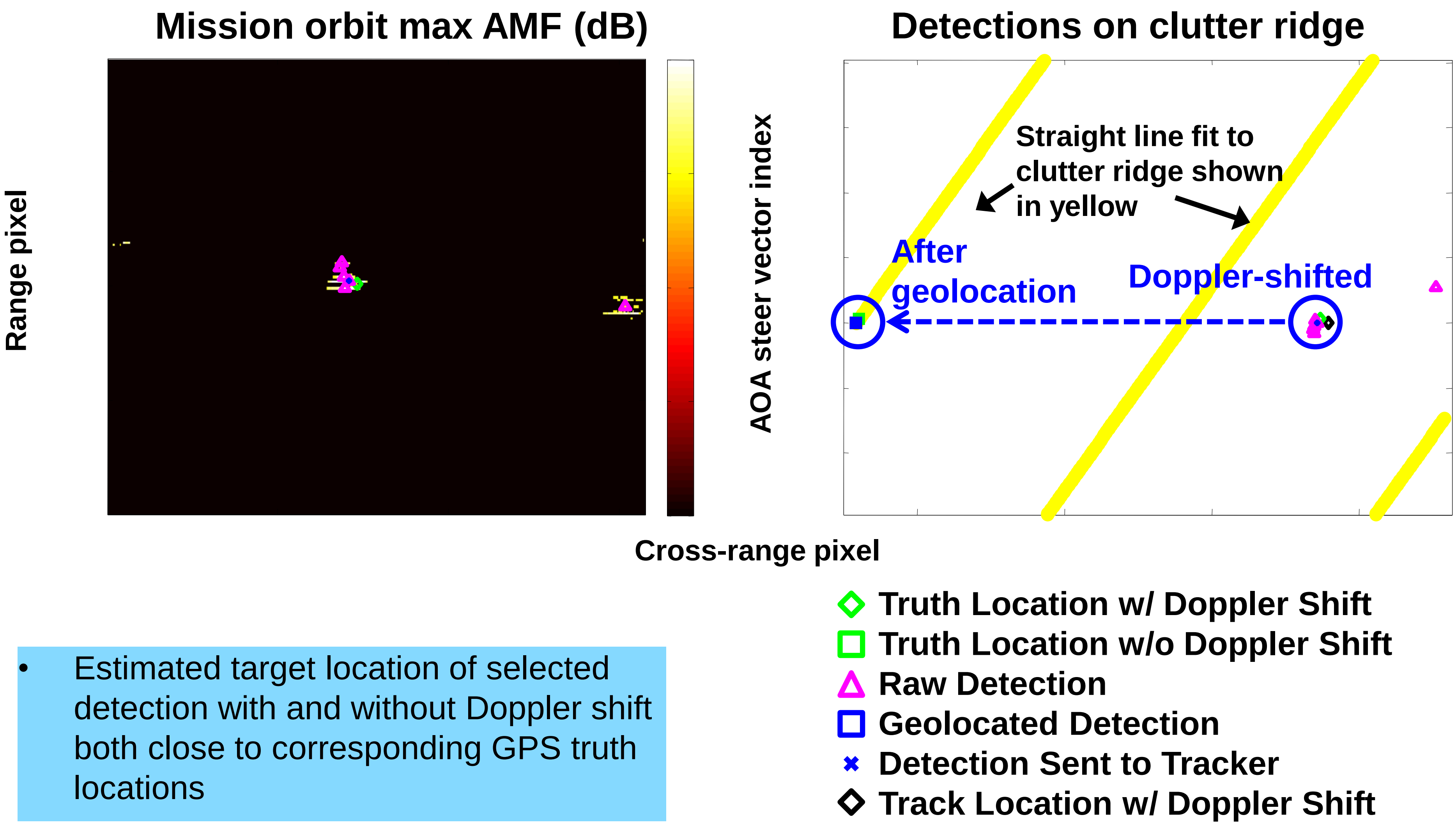
$$\max_{\beta} AMF(\beta, x, y) >= T$$

- Change detection (CD) to reduce false alarms
  - Use mission and reference pass AMF images to reject threshold crossings appearing on both passes
- Parameter estimation (target AOA and MRP motion state)

$$\hat{\beta}(x, y) = \arg\max_{\beta} AMF(\beta, x, y)$$

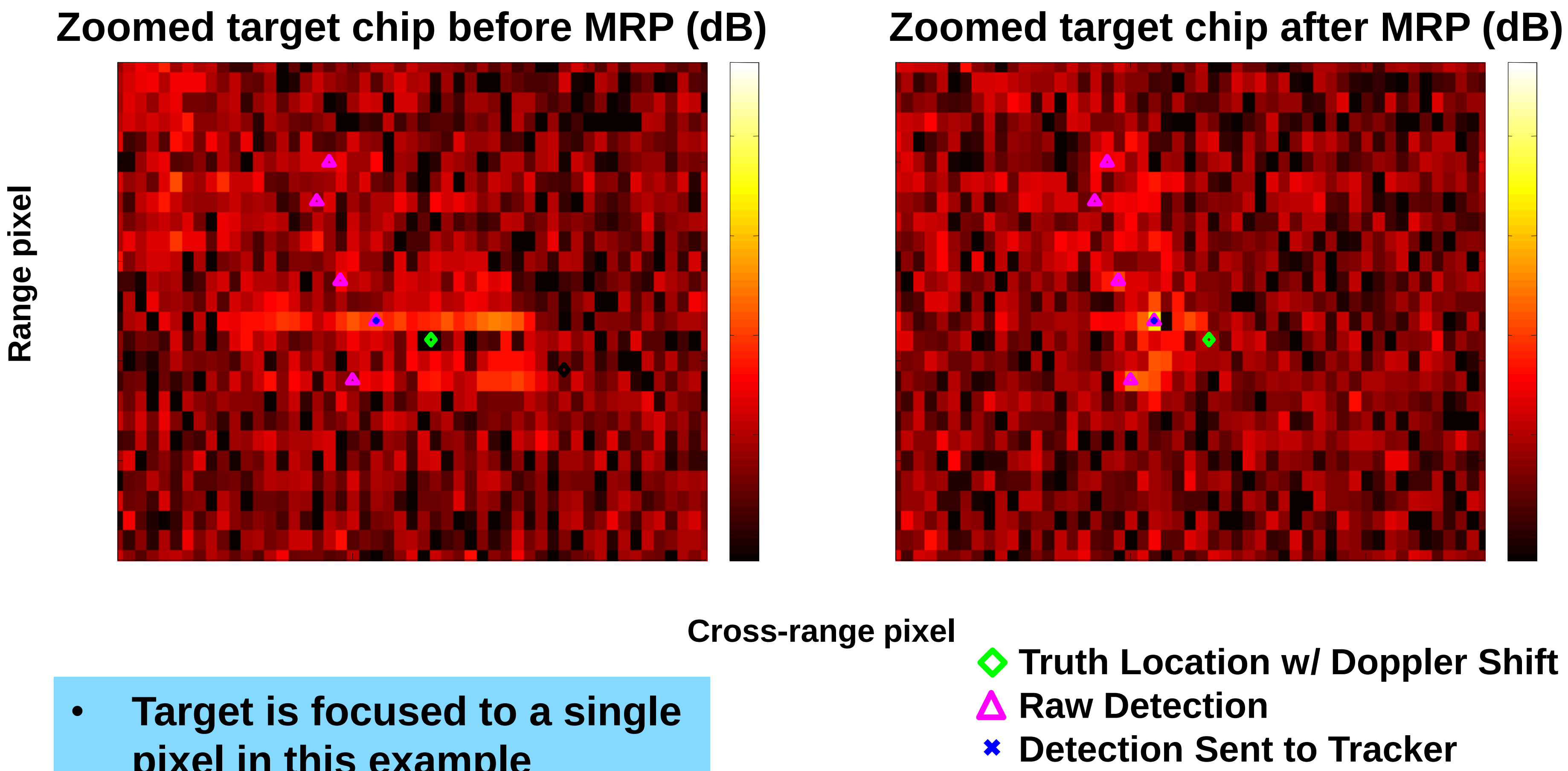
- Measurement of clutter ridge
  - Specifies angle of arrival (AOA) of clutter versus cross-range
  - Allows determination of true target location (i.e. without Doppler shift)
- Selection of detection correlating best with target under track
  - Use a likelihood score to select a single detection to update track
  - Reduces false alarms and tracker confusion when only a single target is of interest

Detections after false alarm mitigation for "easy" example



- Estimated target location of selected detection with and without Doppler shift both close to corresponding GPS truth locations

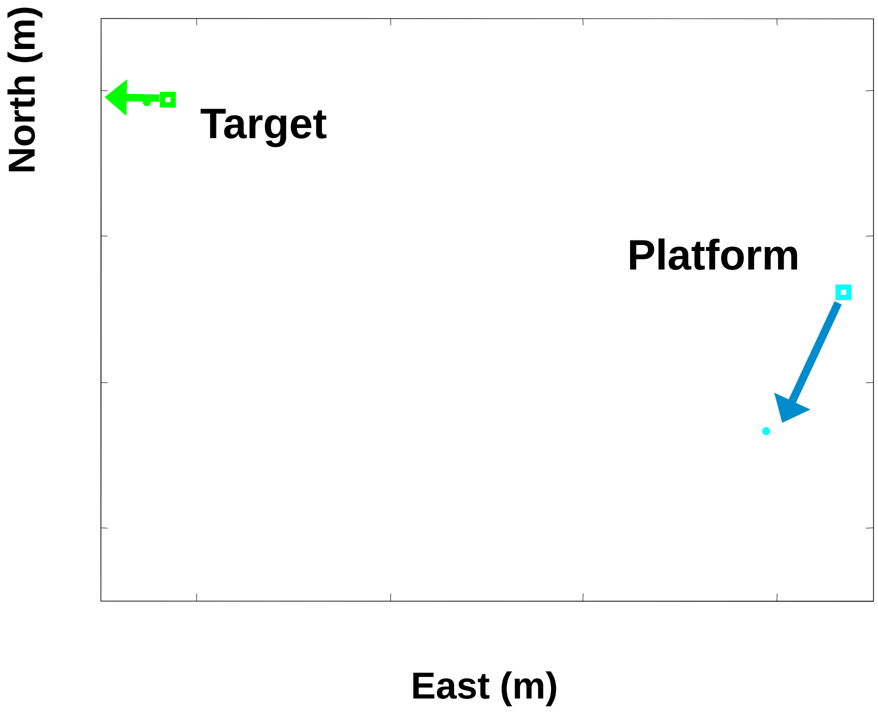
Zoomed portion of SAR chip containing target before and after MRP



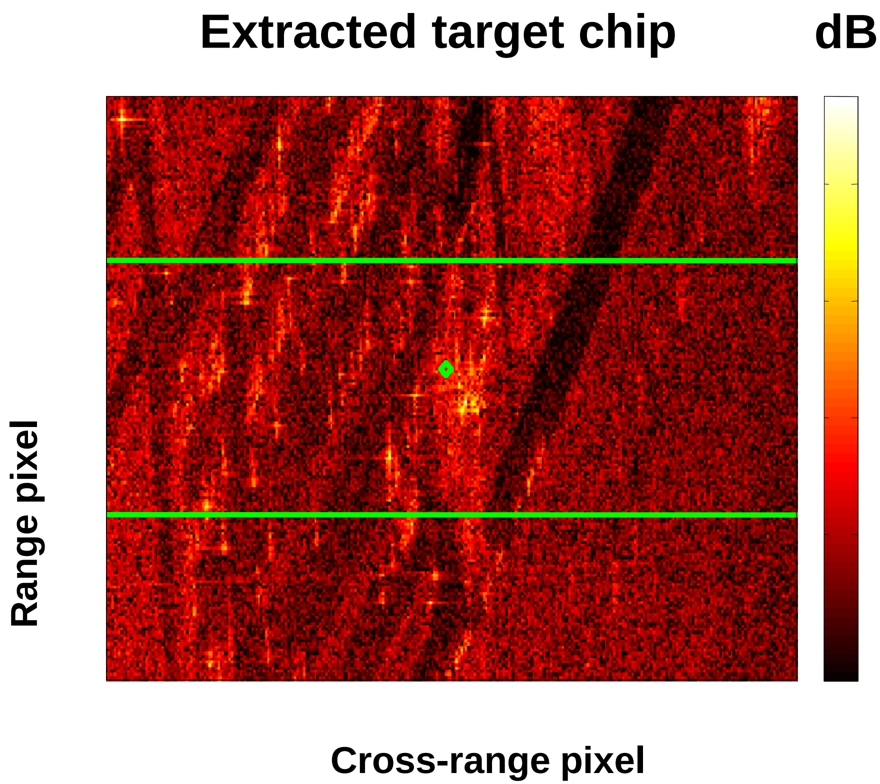
- Target is focused to a single pixel in this example

Extracted SAR chip and imaging geometry – 2nd example

Collection geometry



Extracted target chip



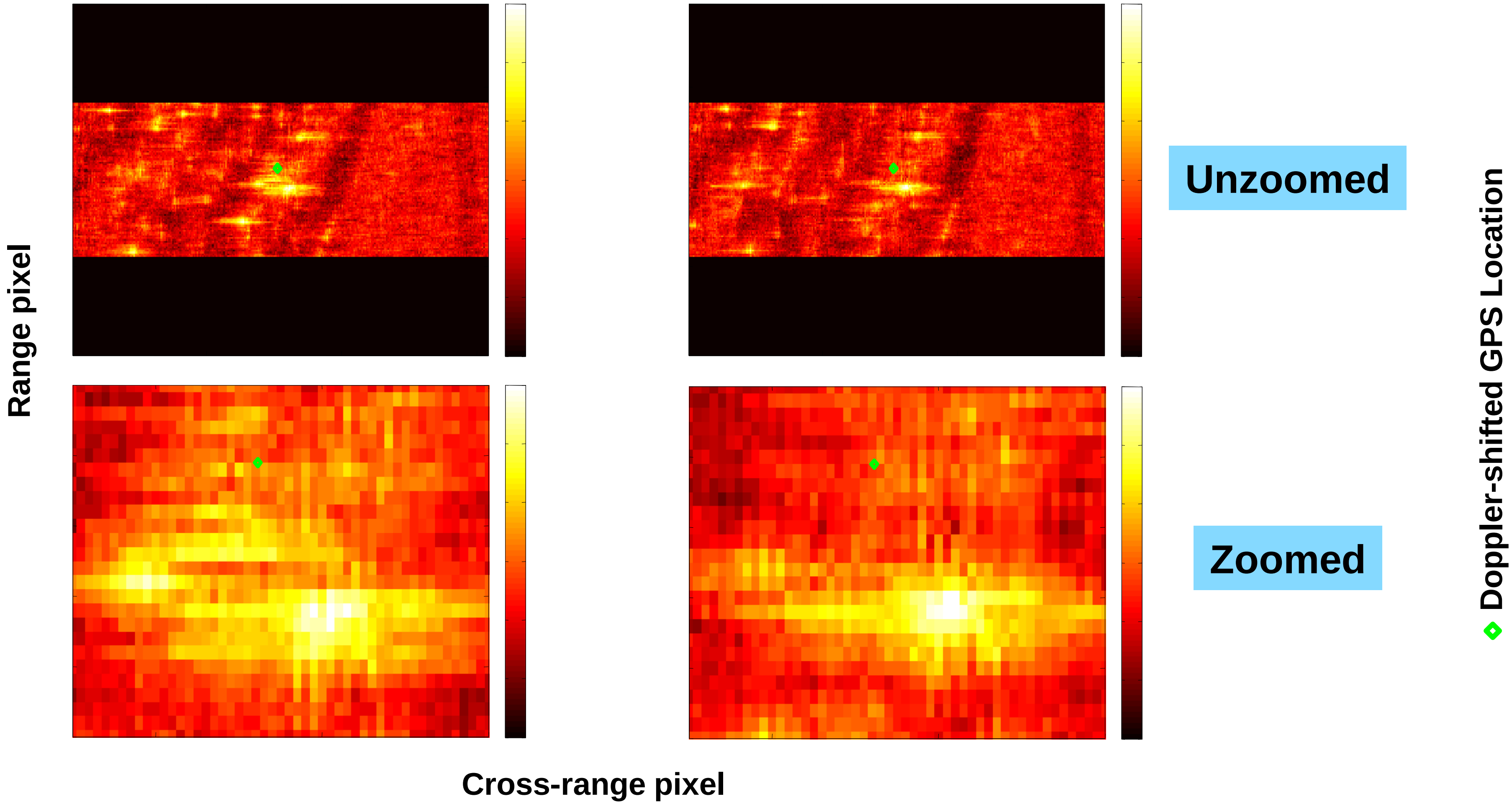
- Target SAR response not clearly visible above clutter in this example

◆ Doppler-shifted GPS Location

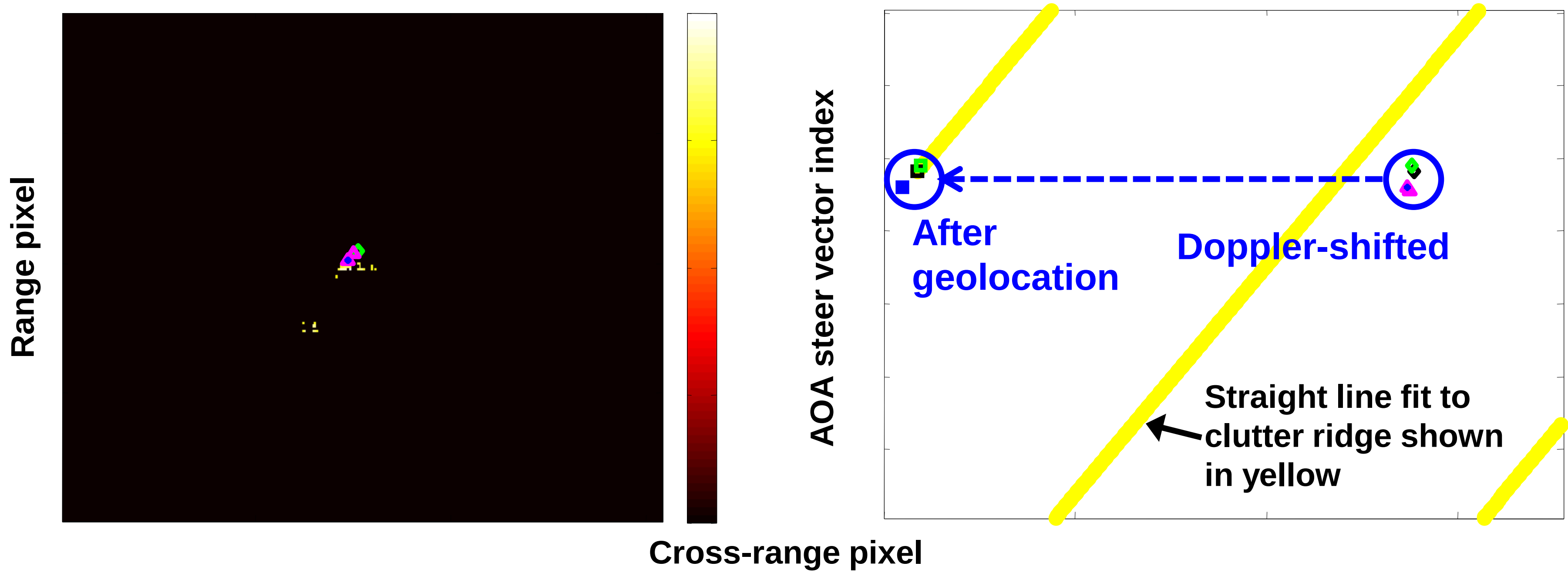
Note, Doppler-shifted track prediction is the chip center

STAP AMF images for mission and reference passes (2^{nd} example)

Mission orbit max AMF (dB) **Reference orbit max AMF (dB)**



Detections after false alarm mitigation for 2nd example



- False alarm mitigation has removed clutter discretes
- Estimated target location of selected detection with and without Doppler shift both close to corresponding GPS truth locations

◇ Truth Location w/ Doppler Shift
□ Truth Location w/o Doppler Shift
△ Raw Detection
□ Geolocated Detection
× Detection Sent to Tracker
◇ Track Location w/ Doppler Shift

Summary

- Discussed challenges for processing moving targets in SAR imagery
- Presented a framework for studying different techniques for improving detection and tracking of moving targets in SAR imagery
  - MRP to compensate for moving target defocus
  - STAP to separate targets from clutter interference
  - Change detection to reduce false alarms
  - Tracker feedback to reduce false alarms and tracker confusion
- Presented examples from simulated and measured data
  - SINR loss for different algorithm configurations
  - SAR imaging geometries and extracted target chips
  - STAP AMF images for mission and reference passes
  - Comparison of detections with truth after applying techniques listed above