NAVAL
POSTGRADUATE
SCHOOL

Image Quality SAR Refocus of Moving Targets undergoing Complicated Rolling Maneuvers

Prof. David A. Garren, Ph.D.

Department of Electrical and Computer Engineering

Presented at: 2022 Sensor and Signal Processing for Defence (SSPD) in London, United Kingdom

DoD Distribution Statement A: Unlimited Distribution

Recent Work

- SAR radar signal processing is matched to the stationary reflectors in the scene but is mismatched with targets that are moving during the synthetic aperture collection interval
  - Thus, moving targets are often smeared in the radar cross-range direction to an extent that they can no longer be recognized
- Recent analysis has yielded an ability to perform Arbitrary Rigid Object Motion Autofocus (AROMA) in order to perform automatic refocus of targets which exhibit arbitrary temporal profiles of target translation and rotation during the SAR collection interval
- AROMA is basically a three-dimensional (3-D) extension of the one-dimensional (1-D) Phase Gradient Autofocus (PGA) technique that is often used to refocus stationary scenes

Current Work

- This investigation examines the potential of using the AROMA autofocus methodology to perform automatic refocus of moving targets which are characterized by complicated rolling maneuvers
- Specifically, this analysis examines the efficacy of AROMA for targets with complex heading profiles amidst a background of measured Ku-band SAR imagery
- It is found that AROMA can ingest the input smeared imagery of these targets with complicated rolling maneuvers and then generate well focused imagery which corresponds with the true structure of the target scattering shapes
- Therefore, AROMA performance is validated for this class of target motion

AROMA Assumptions

- AROMA models a moving target as a rigid body in which the target rotation and translation can be arbitrarily non-uniform in time t

- As such, it is convenient to delineate a coordinate system that locked onto the target as it rotates and translates within the scene

- Thus, one can define a radius $r(t)$ temporal function of time, and corresponding elevation and azimuthal angles, as given by $\theta(t)$ and $\phi(t)$, respectively, of the radar position relative to the spherical target-centered coordinate system

NAVAL POSTGRADUATE SCHOOL

AROMA Error Function Estimation

- The estimation of the error functions required to refocus the target are based upon the application of the strongest scattering center on each range line of the input defocused target image
  - This strategy is similar to PGA for autofocus of SAR imagery

- Define the coordinate x_k, with the integer index k, to be radar down-range position of a dominant target scattering center

- Also, use the function notation $\tilde{y}(x_k)$ to denote the corresponding radar cross-range value

AROMA Phase Change

- Phase change of the radar return from a given radar waveform 1 to the next 2 due to this dominant scattering center is:

$$\Delta\omega_k(t) \equiv 2\pi\rho_c\{\Delta\zeta(t) + x_k\Delta\mu(t) + \tilde{y}(x_k)\Delta\nu(t)\}$$

- Center spatial frequency $\rho_c = 2f_c/c$, with center frequency f_c
- Difference functions are defined via:

$$\Delta\zeta(t) = r_2(t) - r_1(t)$$

$$\Delta\mu(t) = \cos\big(\theta_2(t)\big)\cos\big(\phi_2(t)\big) - \cos\big(\theta_1(t)\big)\cos\big(\phi_1(t)\big)$$

$$\Delta\nu(t) = \cos\big(\theta_2(t)\big)\sin\big(\phi_2(t)\big) - \cos\big(\theta_1(t)\big)\sin\big(\phi_1(t)\big)$$

AROMA Process Diagram

Input SAR Image

↓

Data Preprocessing
- Select Smear Region

↓

Defocused Target Image Chip → Error Function Estimation

Error Function Estimation
- Fourier Transform: $g(x_k, y_\ell) \rightarrow G(x_k, \eta_n)$
- Compute Moments: $\{x_k\}^p \{y_k\}^q G^*_{k,n} H_{k,n}$
- Sum over Range Bins: $\Psi_{p,q,n} = \sum_k \{\cdots\}$
- Estimate Differences: $\{\widehat{\Delta\zeta_n}, \widehat{\Delta\mu_n}, \widehat{\Delta\nu_n}\}$
- Integrate Along Aperture: $\{\hat{\zeta}_n, \hat{\mu}_n, \hat{\nu}_n\}$

↓

Refocus using Error Estimates
- Phase Factor: $\exp\left(-j2\pi\rho_c\left\{\hat{\zeta}_n + x_k\hat{\mu}_n\right\}\right)$
- Phase Shift: $G(x_k, \eta_n - \rho_c\hat{\nu}_n) \rightarrow W(x_k, \eta_n)$
- Fourier Transform: $W(x_k, \eta_n) \rightarrow w(x_k, y_\ell)$

↓

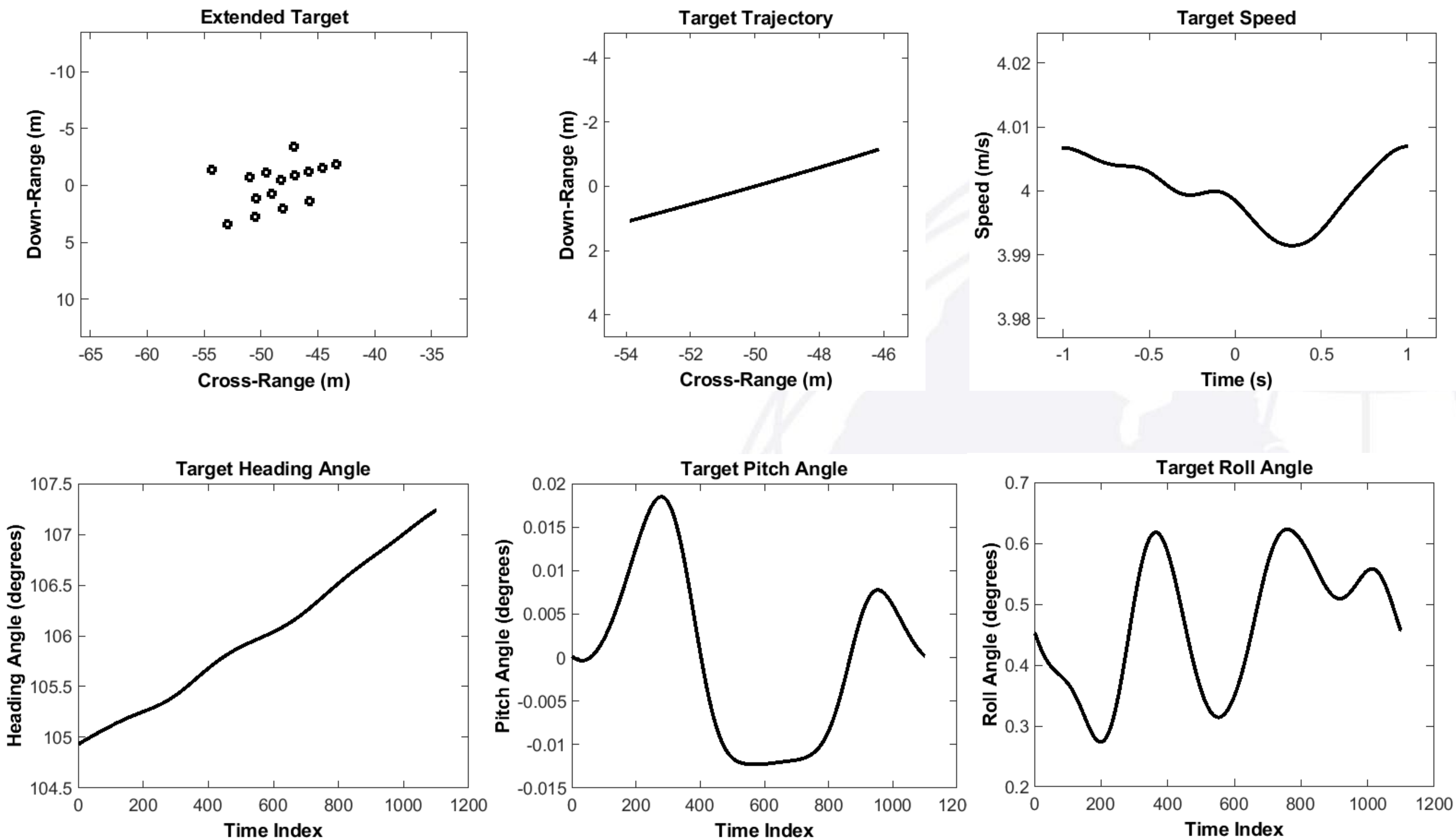
Refocused Target Image → Error Function Estimation

Multiple iterations are performed until suitable target refocus is obtained, either via a fixed number of iterations or some optimization function such as image sharpness

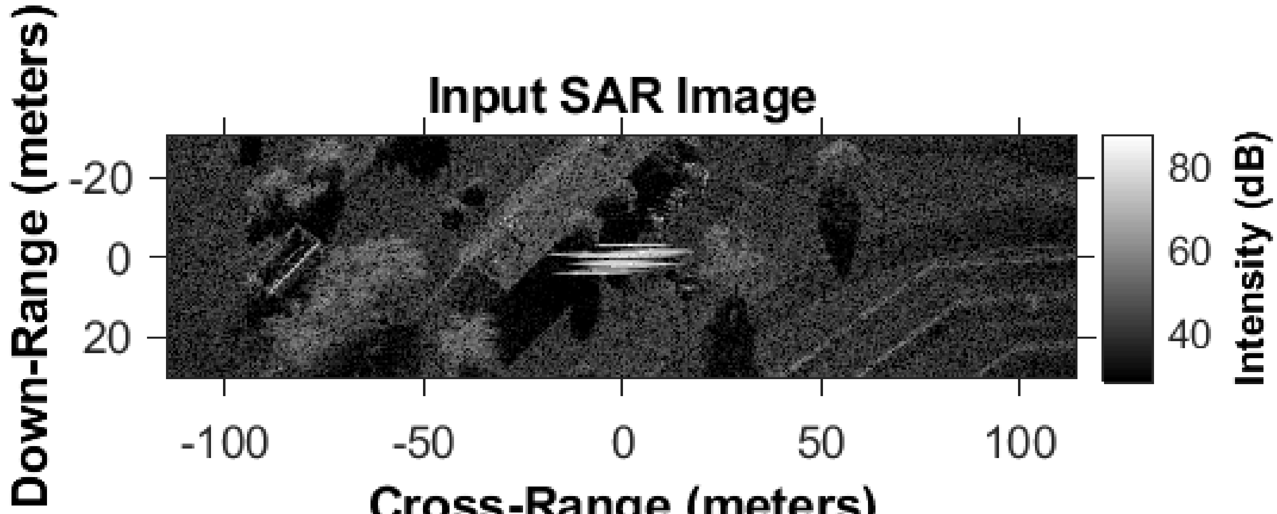
Background of Measured SAR Data

- AROMA refocus performance with regards to target pitching motions is examined by injecting a simulated target into a background of measured SAR data collected at Ku-band
  - Provided courtesy of Sandia National Laboratories, Airborne ISR
- These SAR data are measured using a broadside image geometry from an airborne radar platform that is moving along a straight flight path with at constant altitude $Z_0 = 1.496\ \text{km}$, a constant speed $V_0 = 71.3763\ \text{m/s}$, and a total coherent collection time of $T_0 = 2.017\ \text{sec}$
- The mean stand-off distance of the radar relative to scene center is $X_0 = 2.914\ \text{km}$
- The bandwidth of the radar pulses is 829.6 MHz, and the center frequency of the radar is $f_c = 16.8\ \text{GHz}$

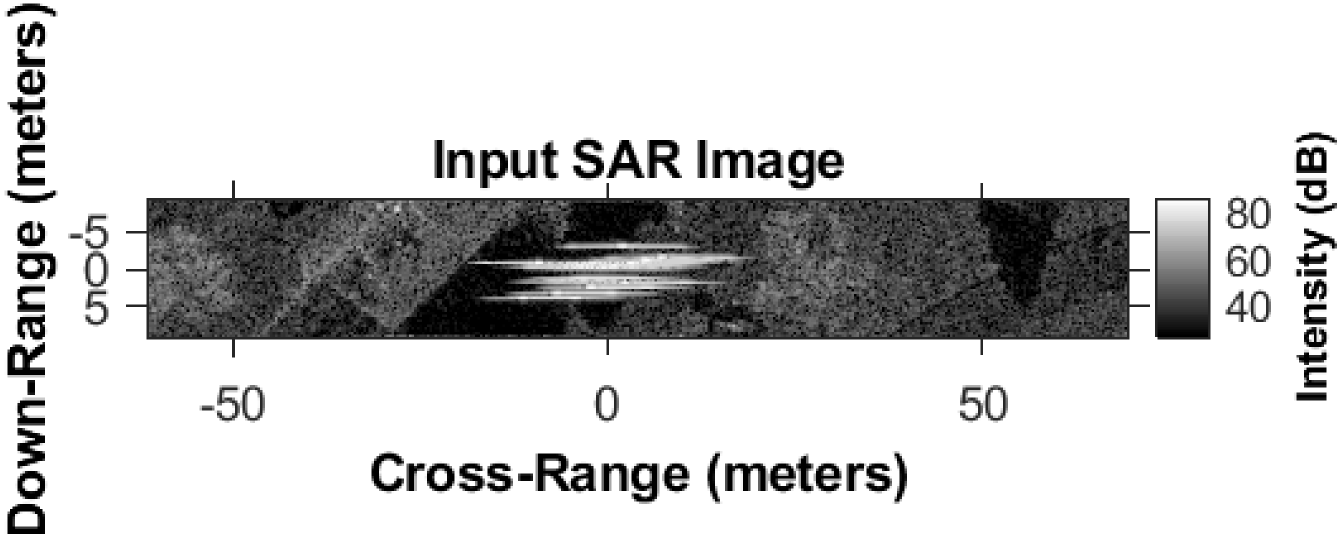
AROMA Example: Truth



AROMA Example: Input

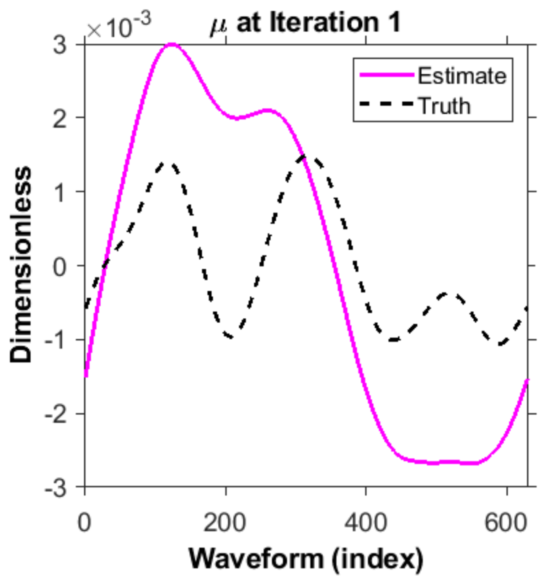


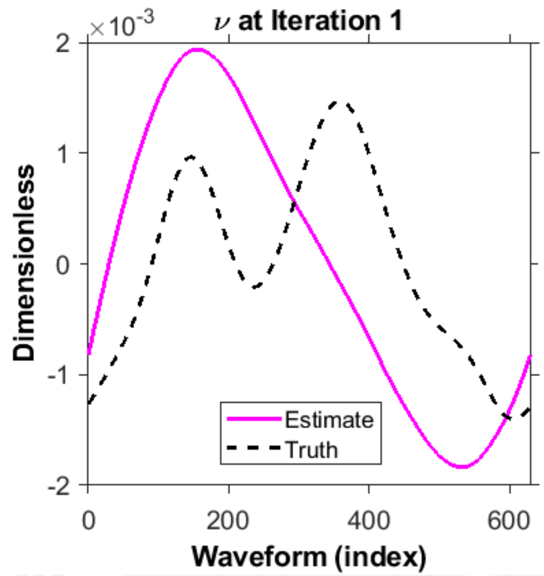
Initial Imagery

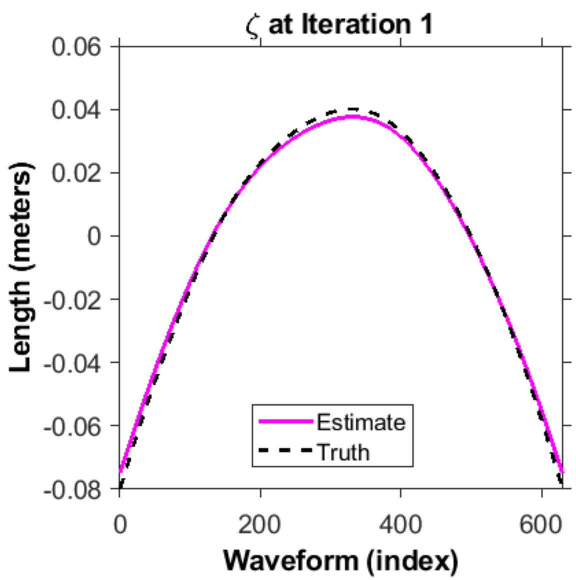


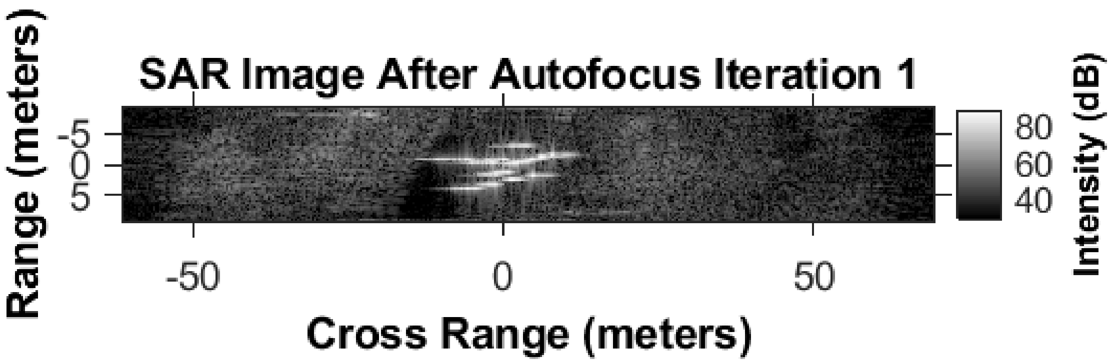
Selected Image Chip

AROMA Example: Iteration 1

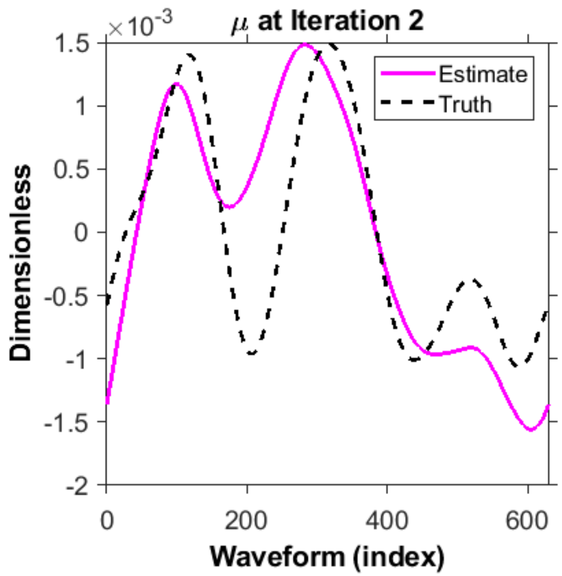


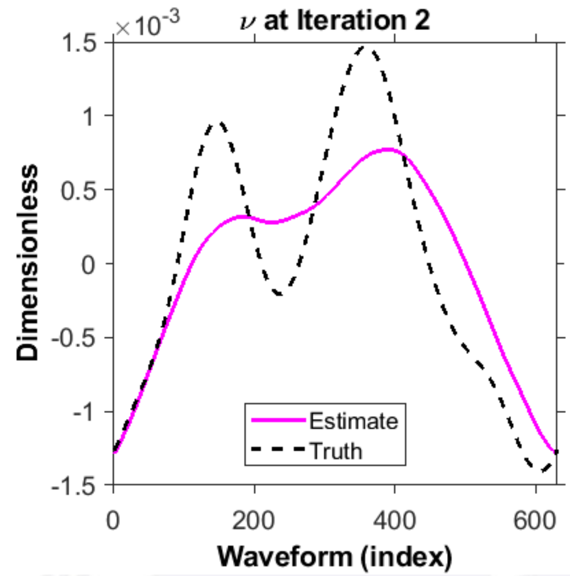


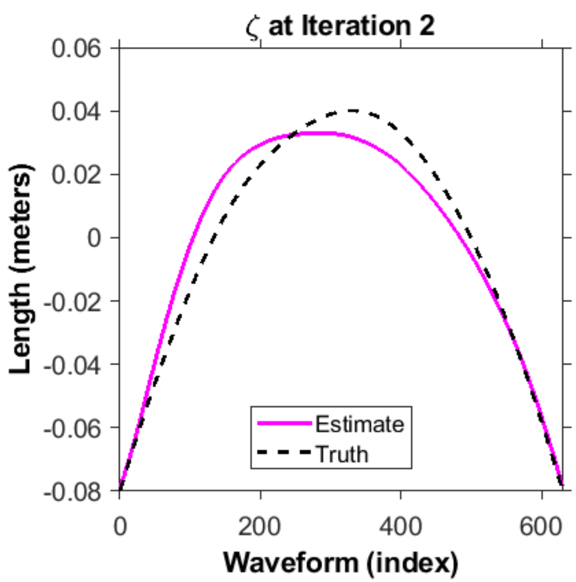


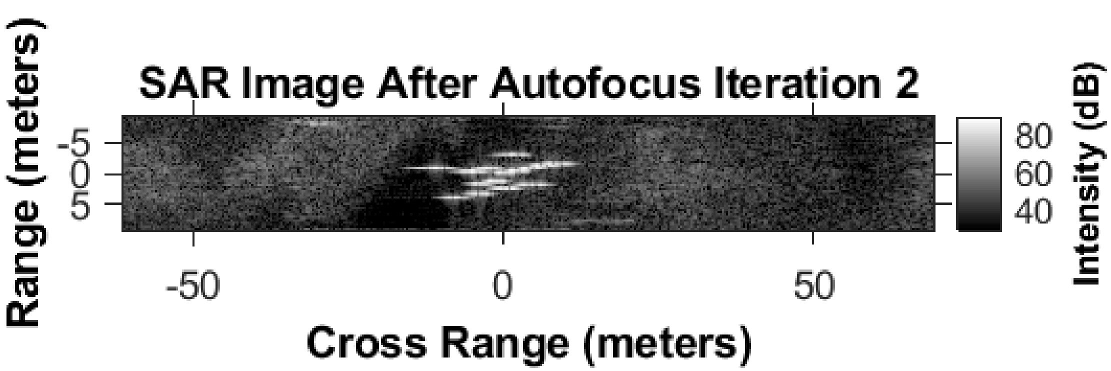


AROMA Example: Iteration 2

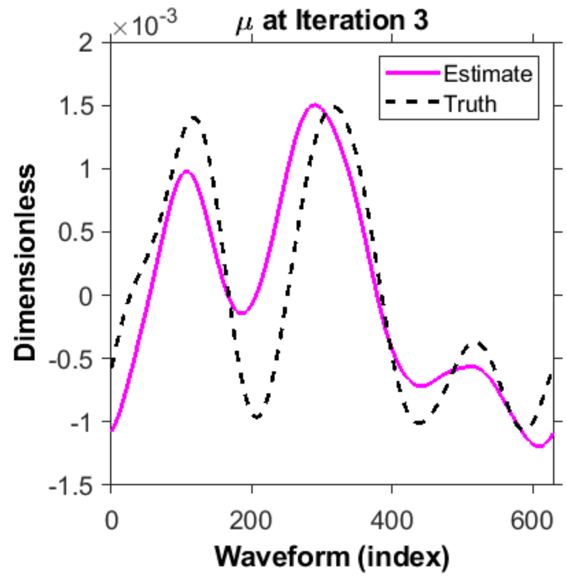


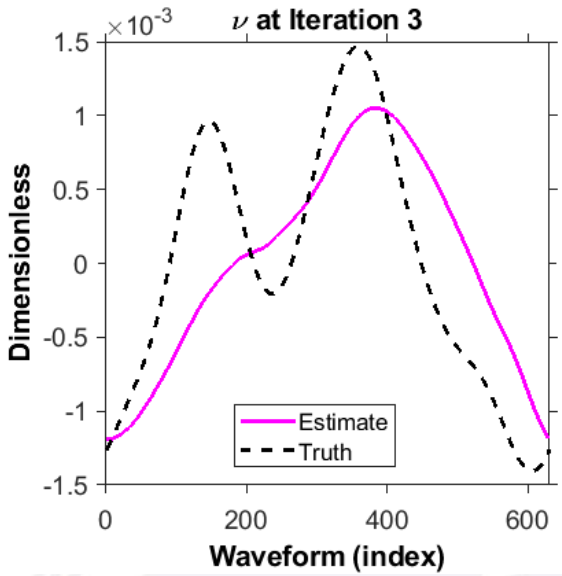


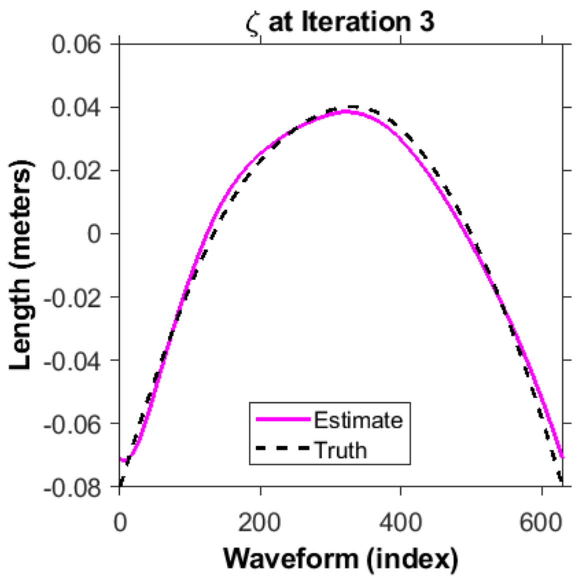


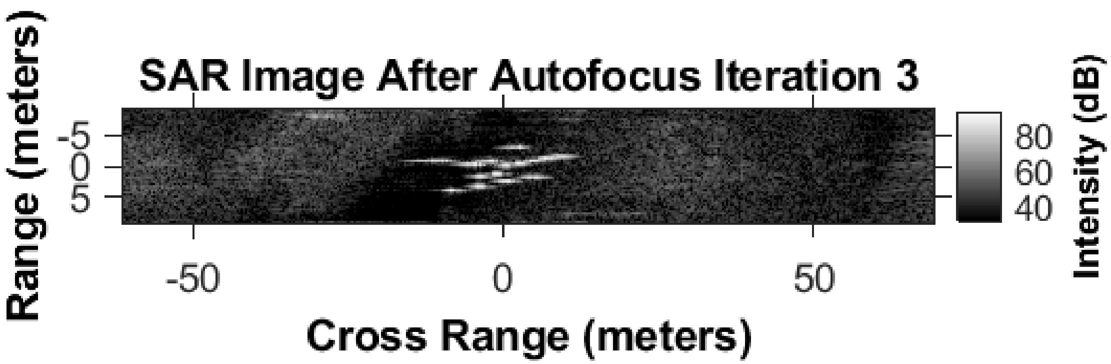


AROMA Example: Iteration 3

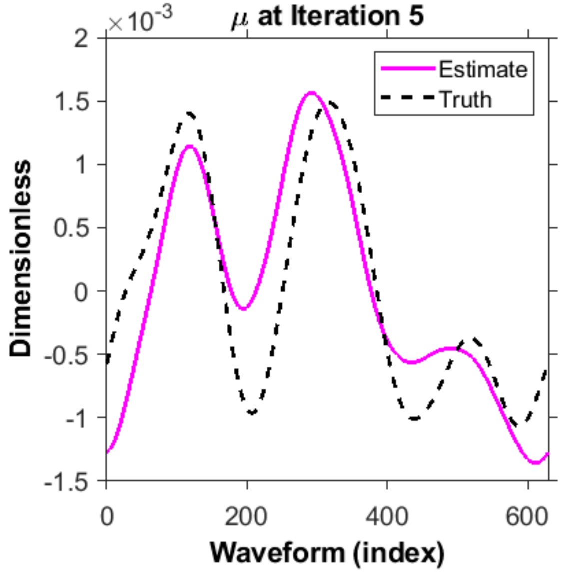


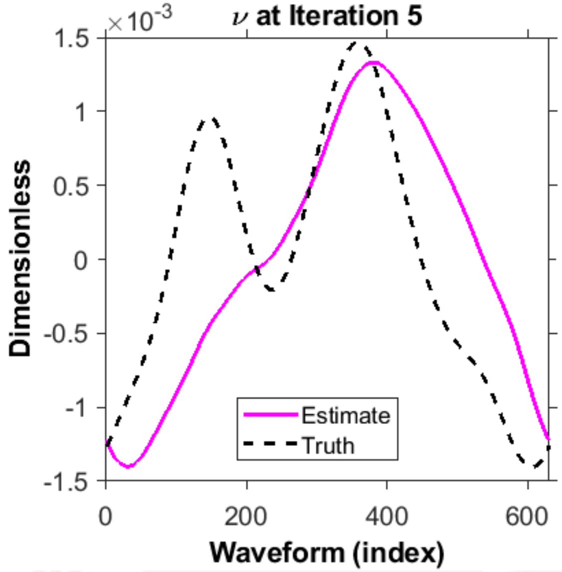


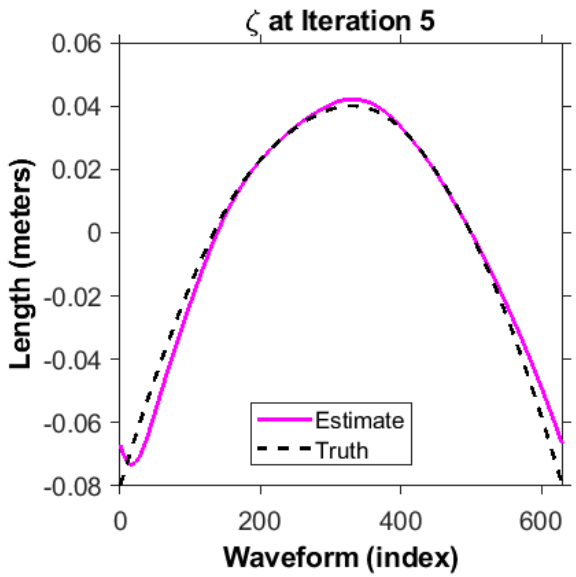


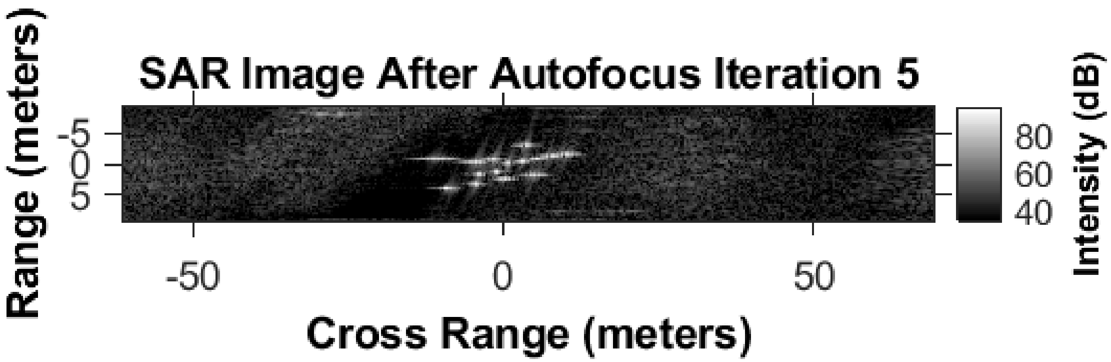


AROMA Example: Iteration 5

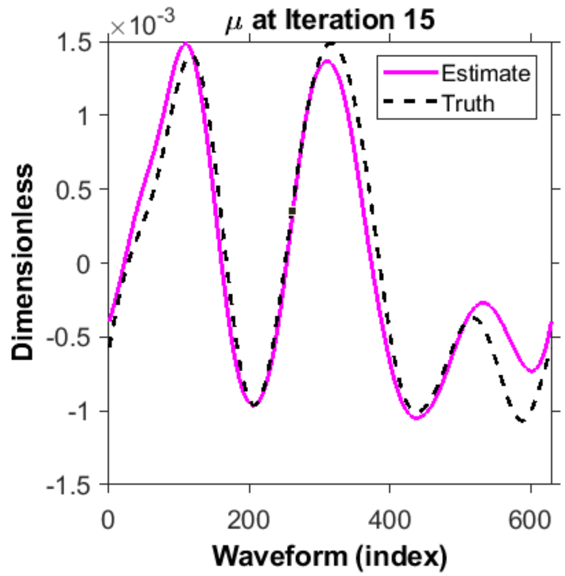


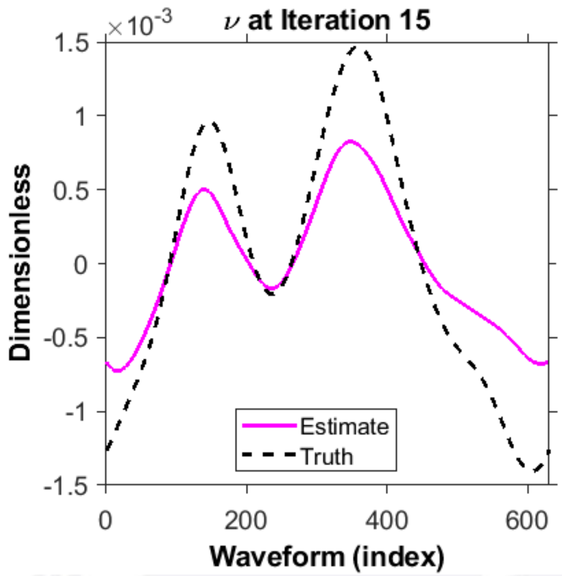


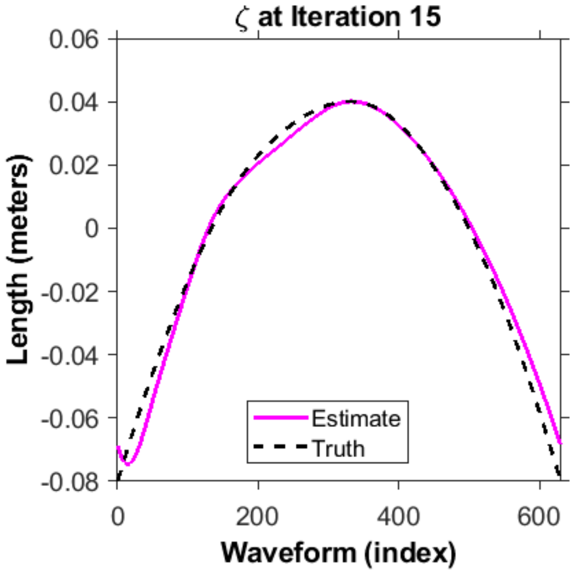


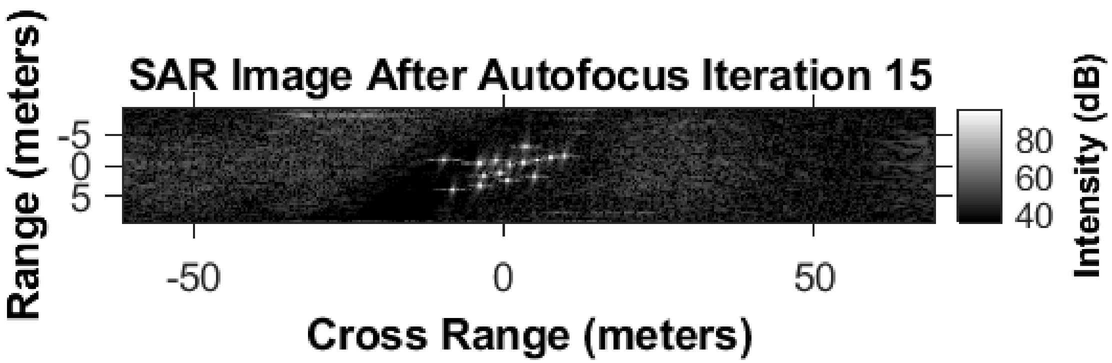


AROMA Example: Iteration 15

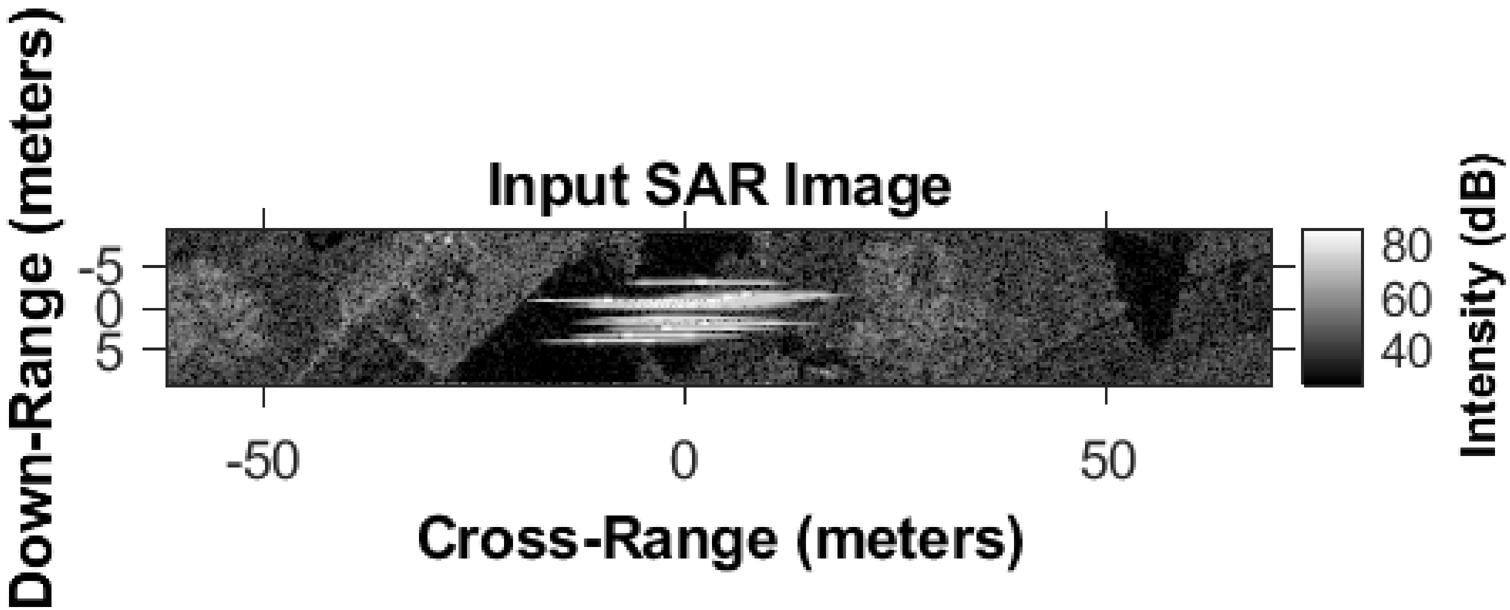


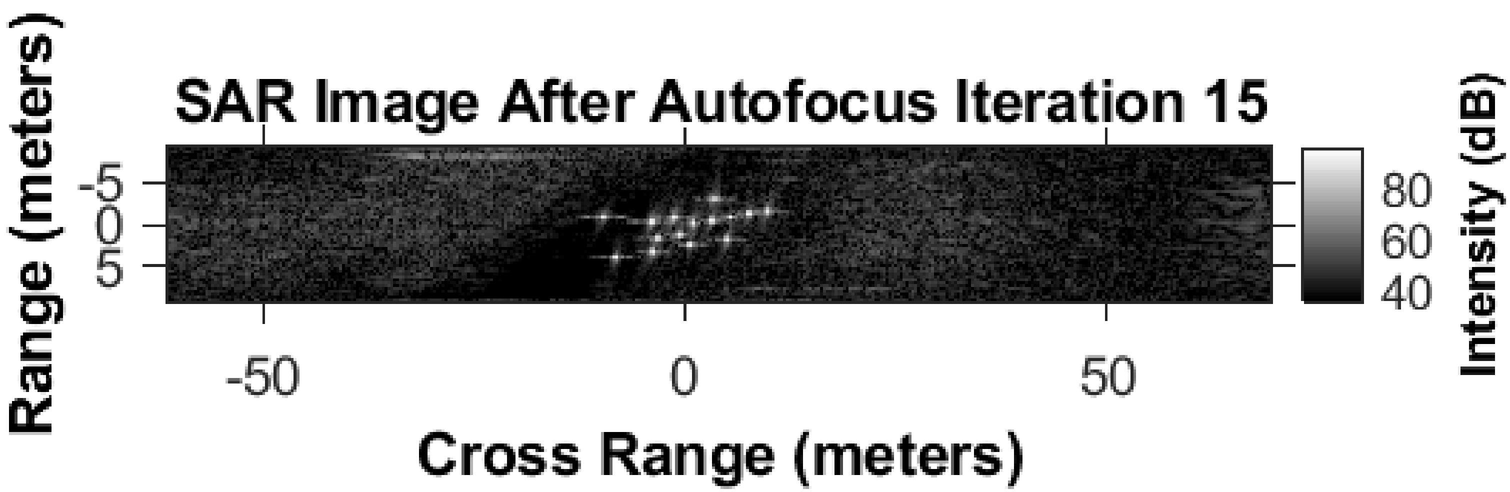




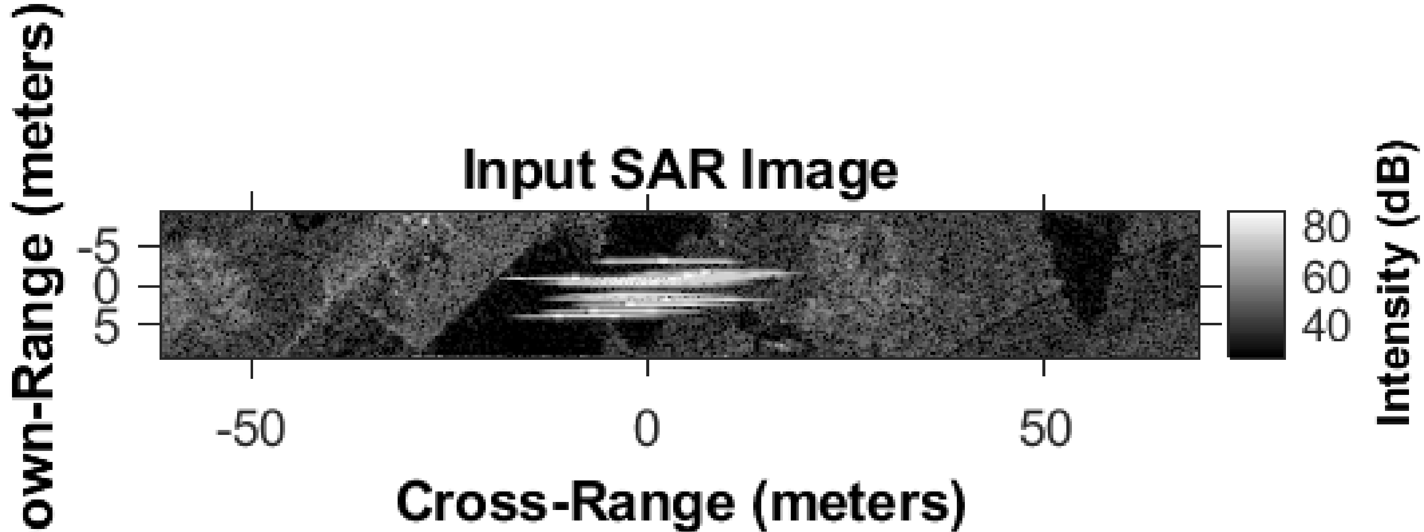


AROMA Example: Input vs. Output

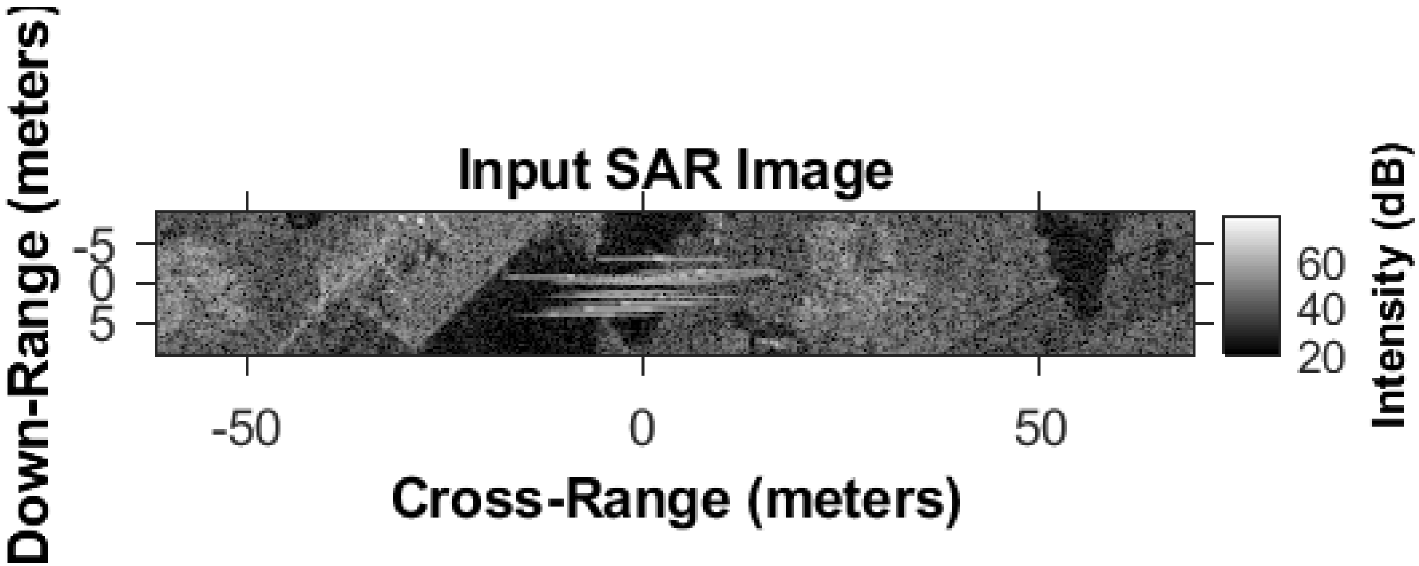




AROMA Stronger Clutter: Input

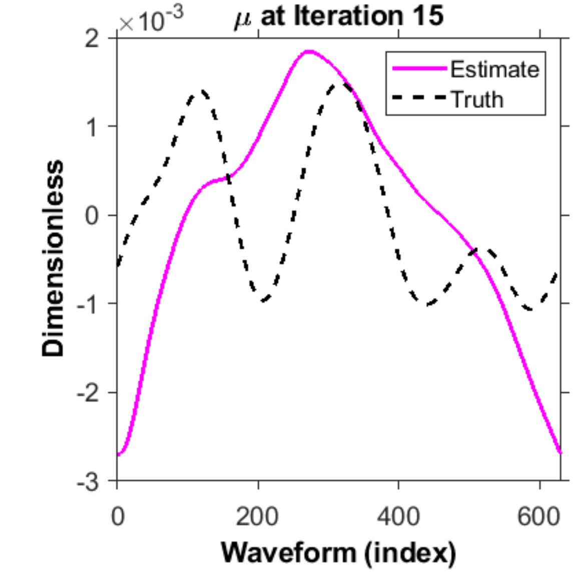


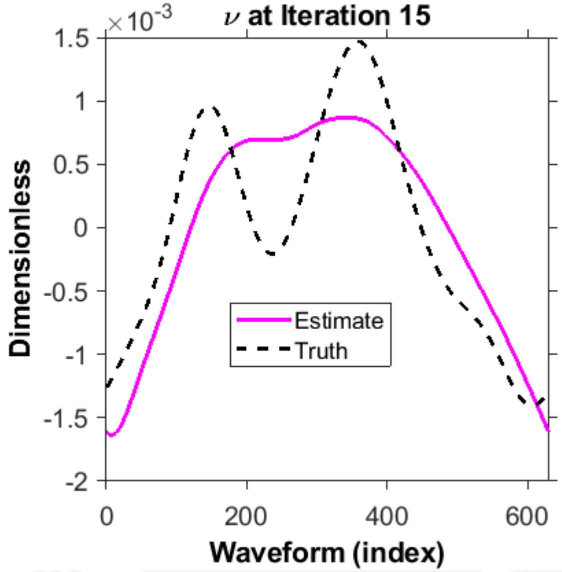
Previous Example

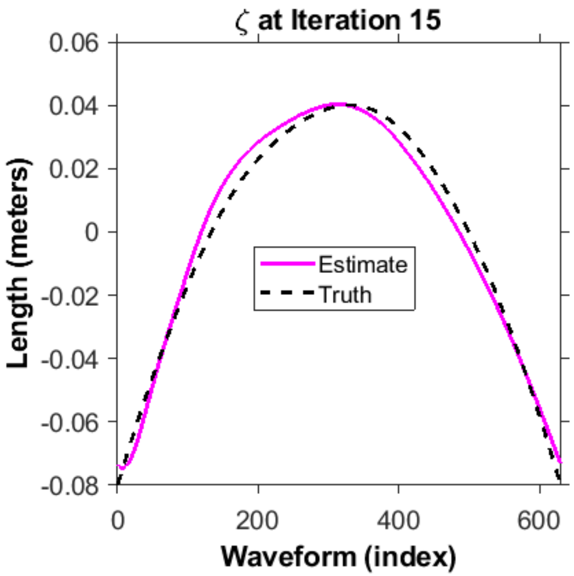


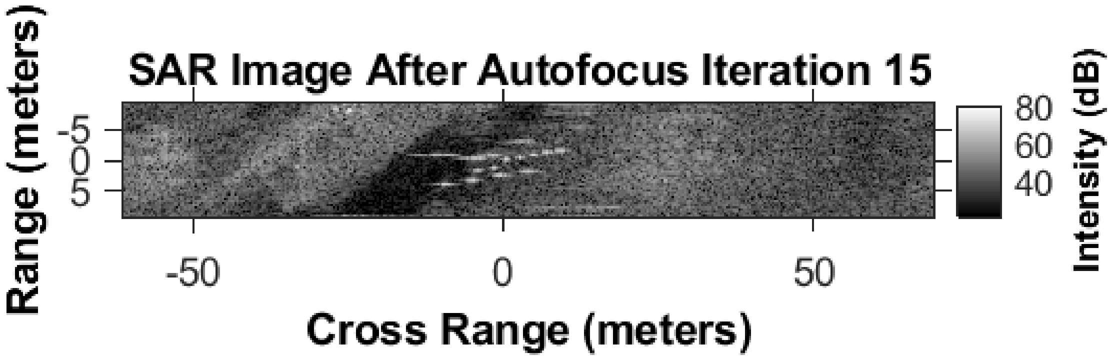
Strong Clutter Example

AROMA Stronger Clutter Example

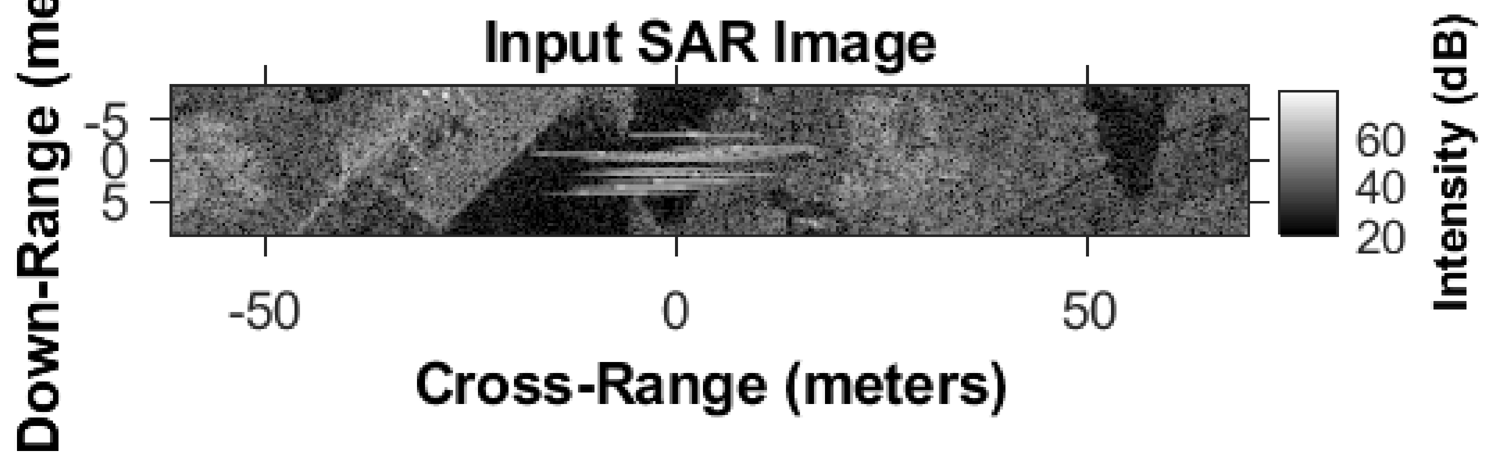


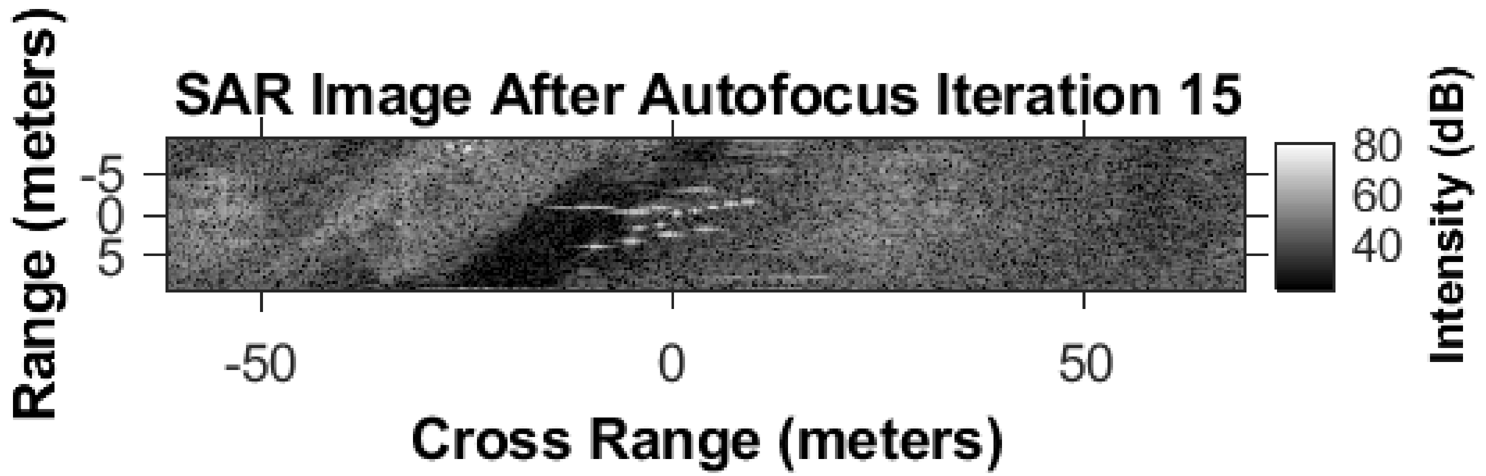




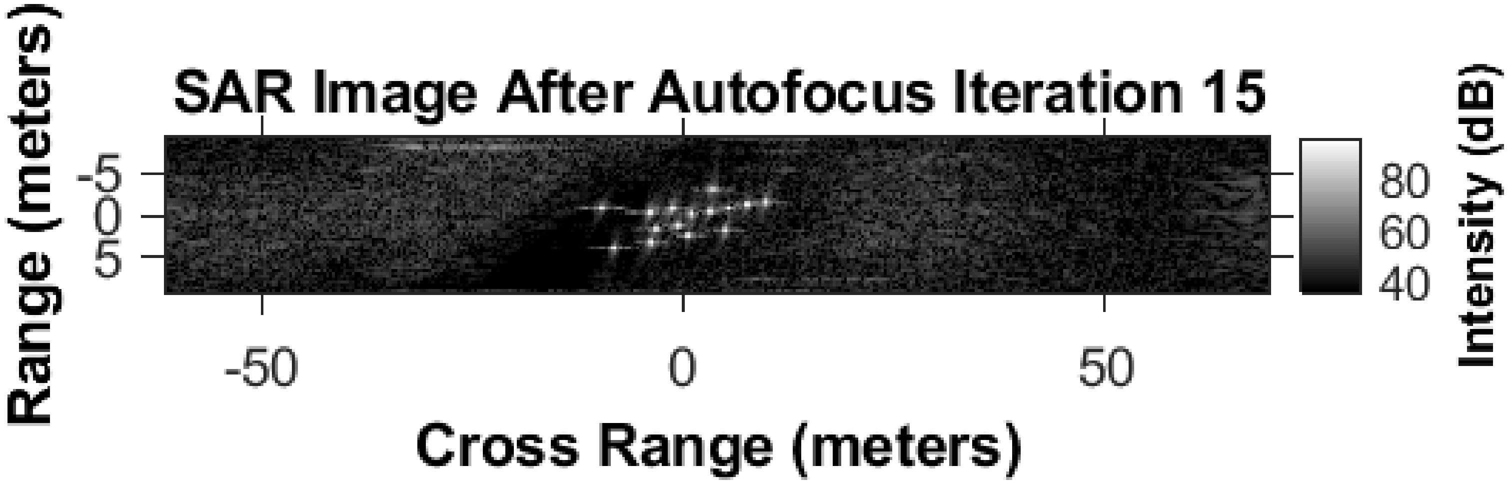


AROMA Stronger Clutter: Input vs. Output

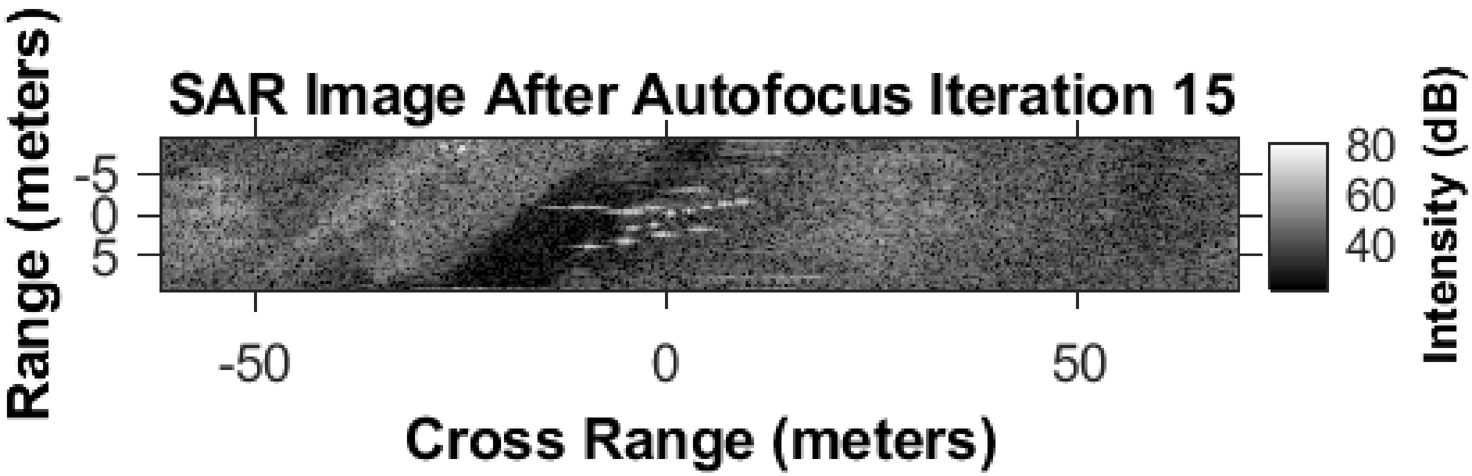




AROMA Stronger Clutter: Output

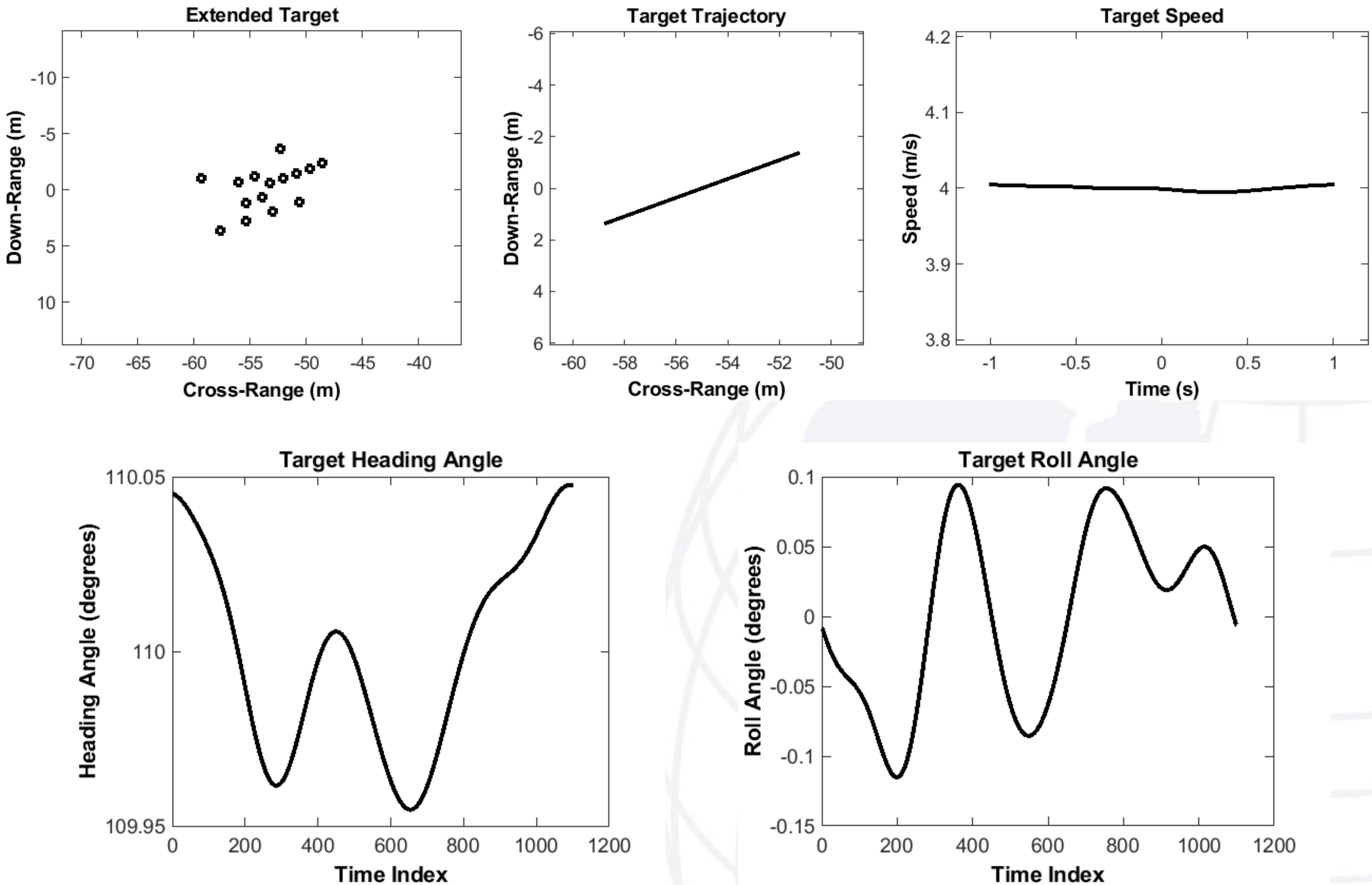


Previous Example

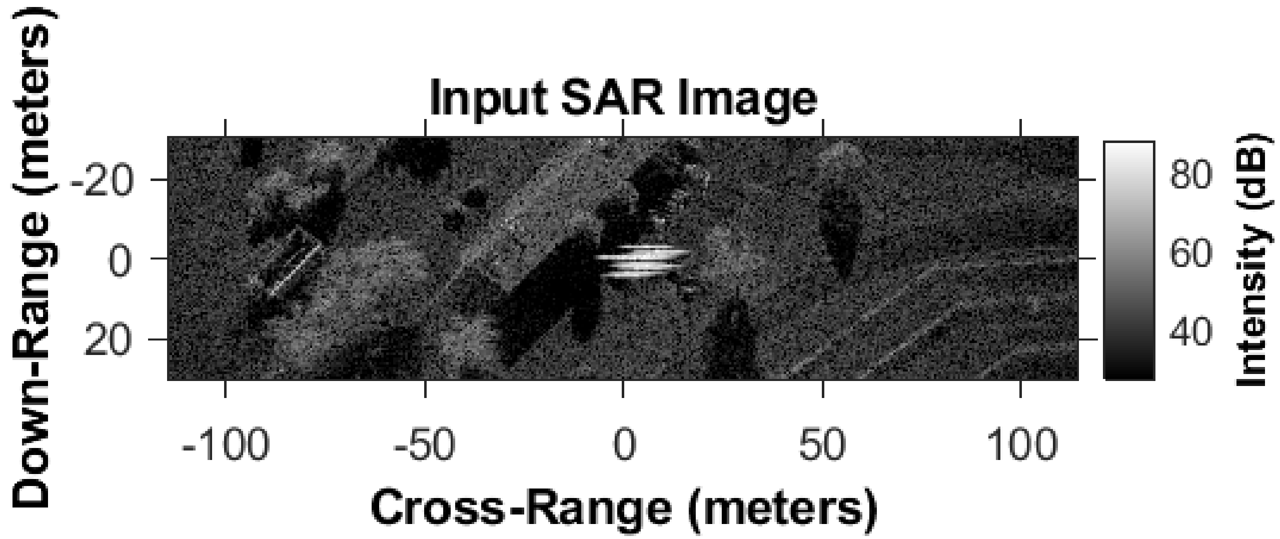


Strong Clutter Example

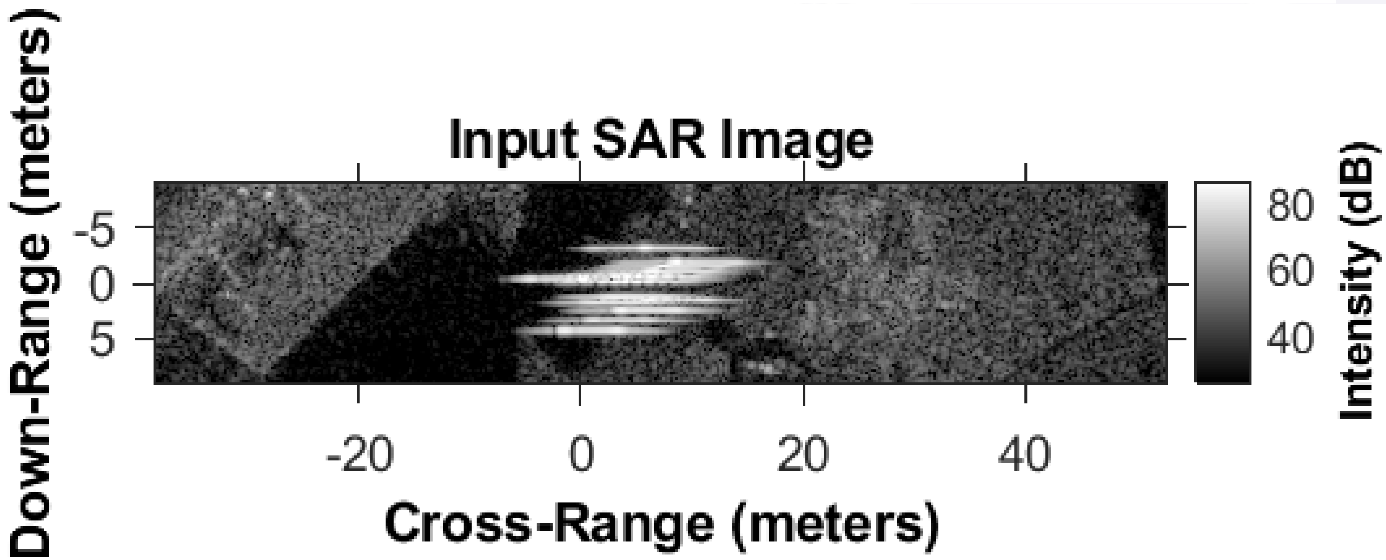
Light Target Maneuver: Truth



Light Target Maneuver: Input

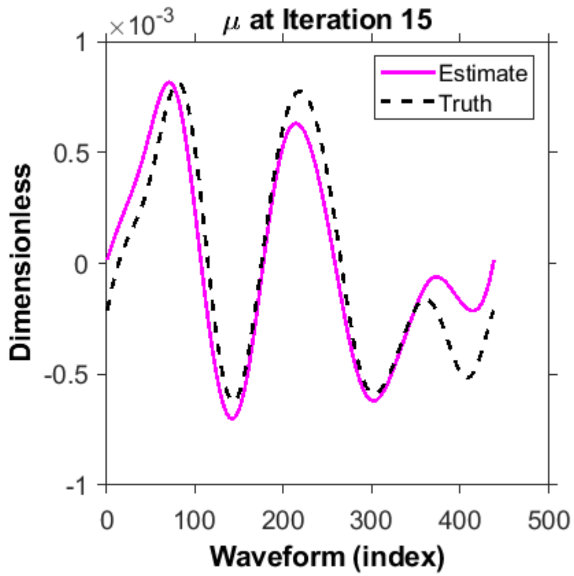


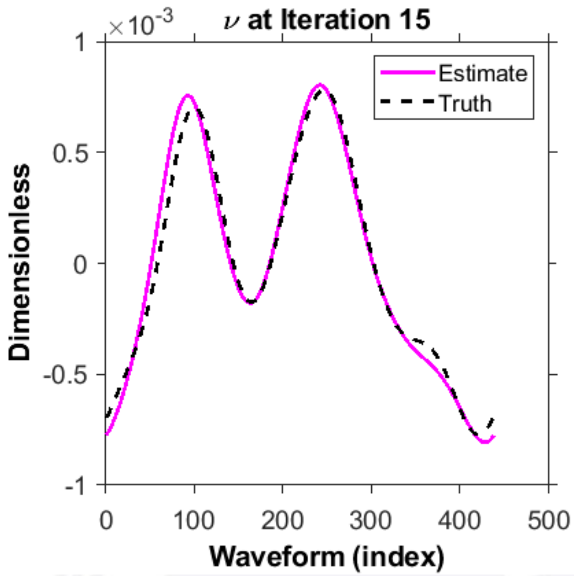
Initial Imagery

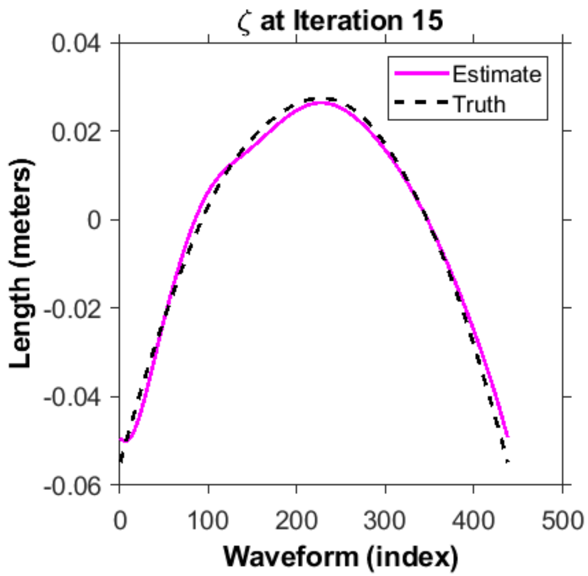


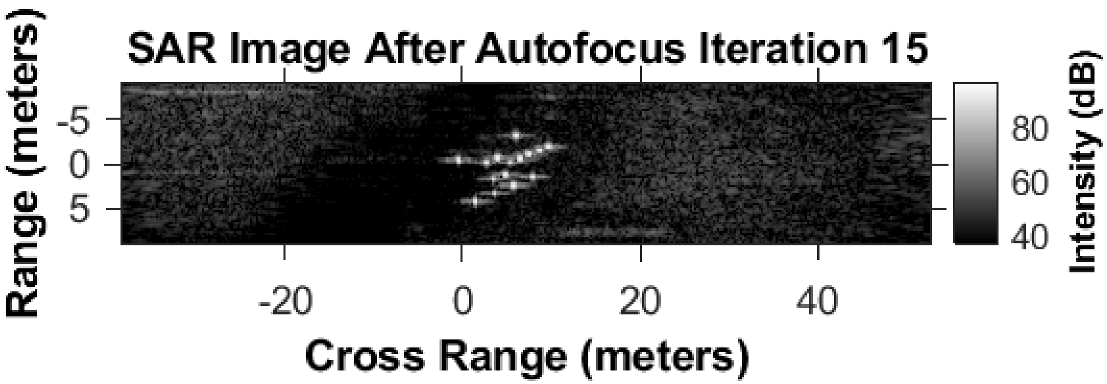
Selected Image Chip

Light Target Maneuver: AROMA

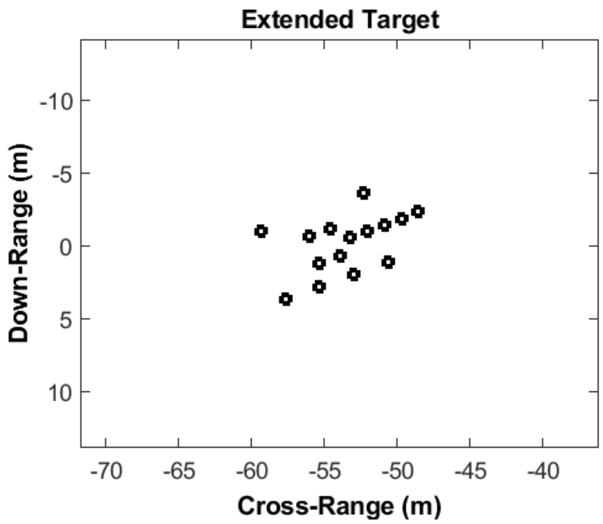


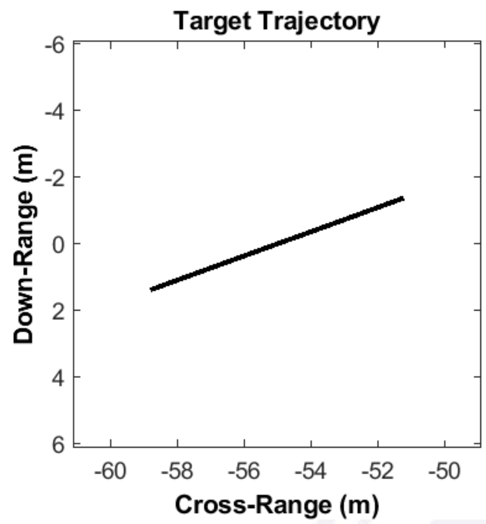


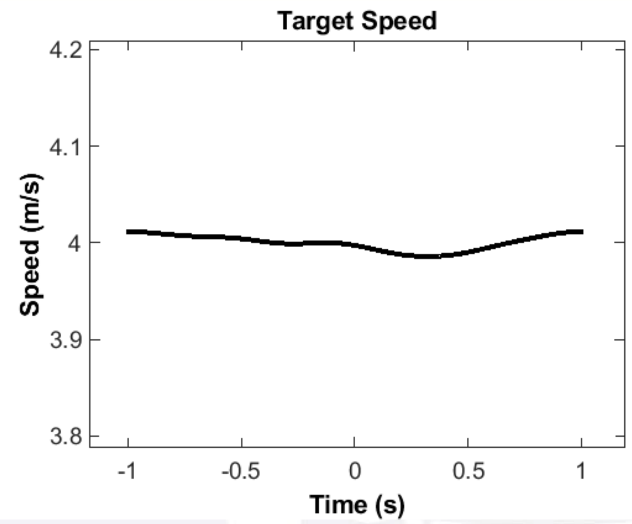


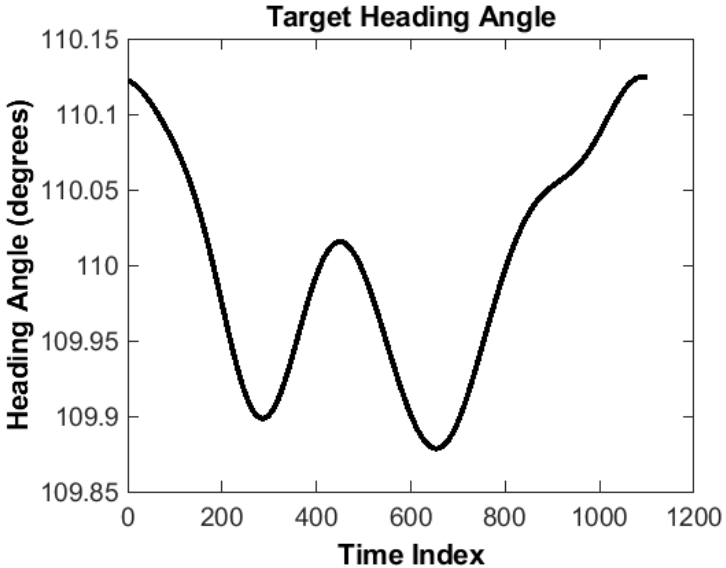


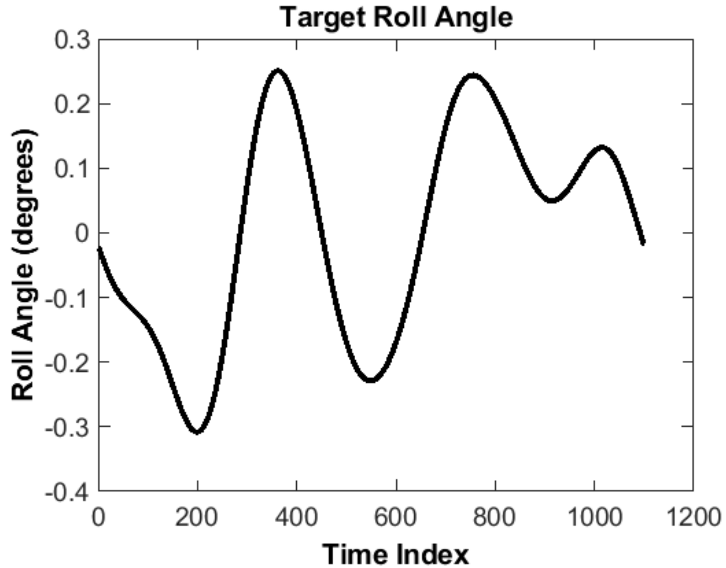
Moderate Target Maneuver: Truth



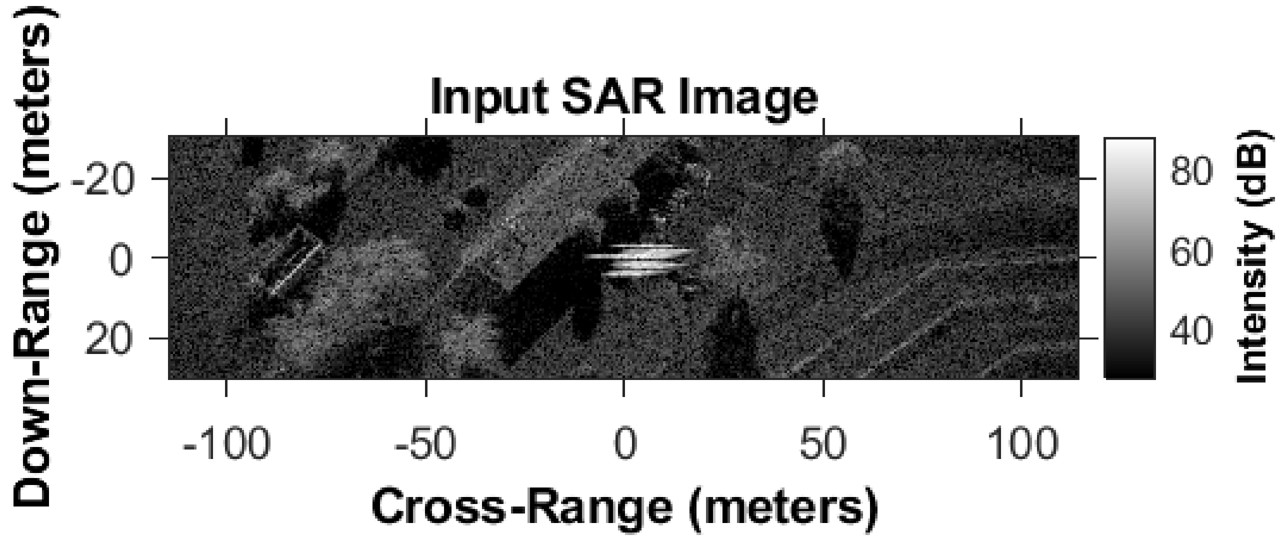




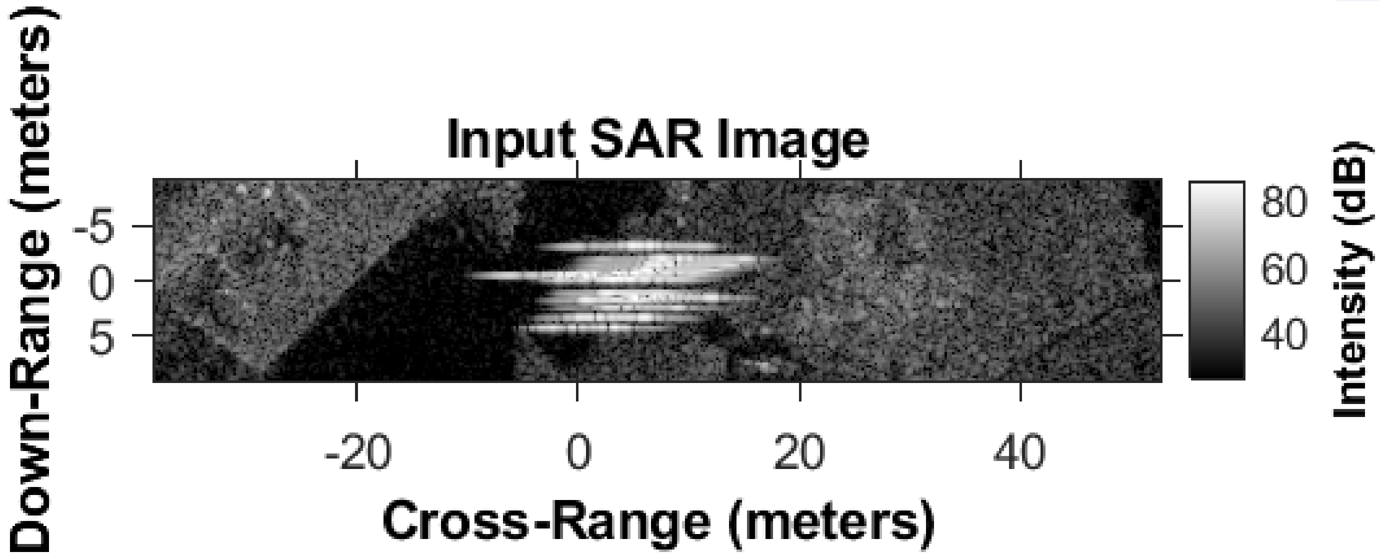




Moderate Target Maneuver: Input

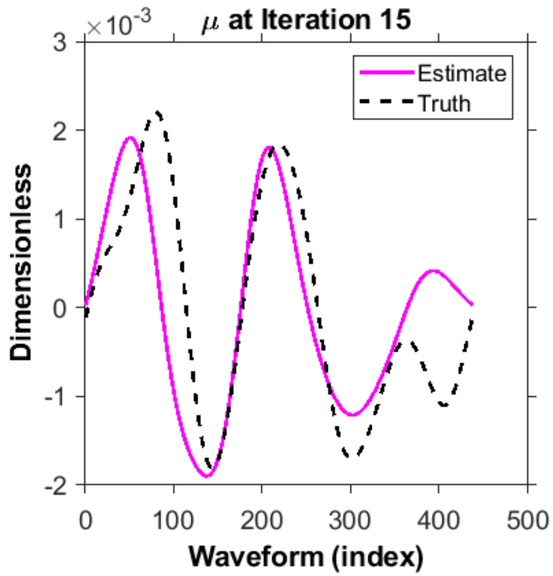


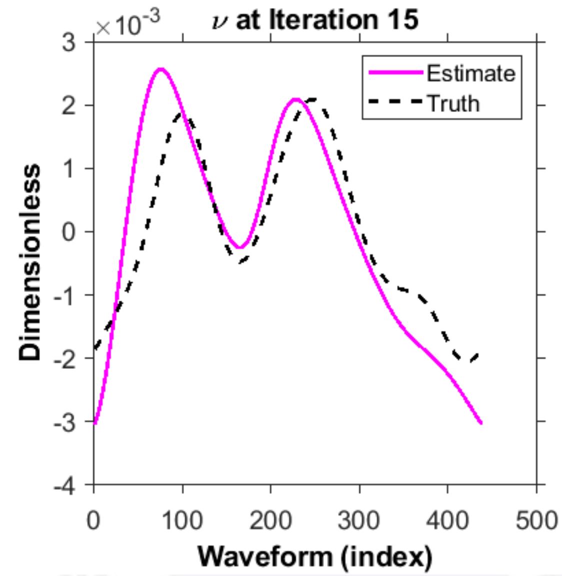
Initial Imagery

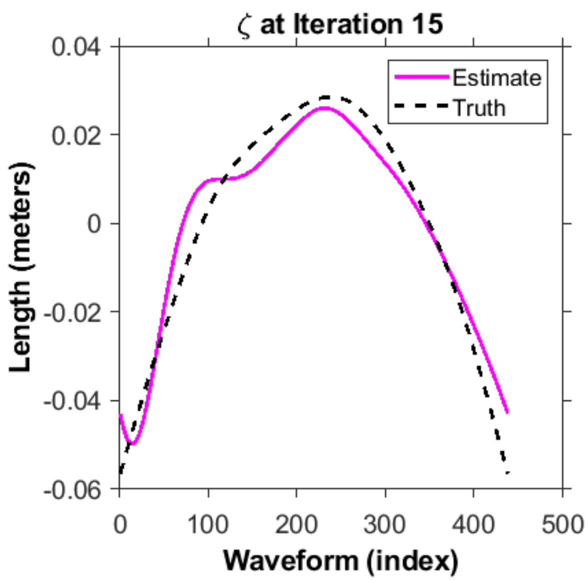


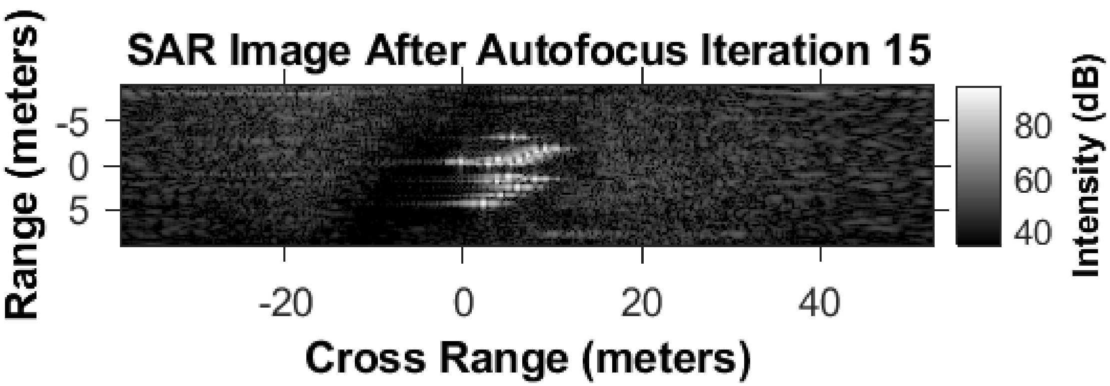
Selected Image Chip

Moderate Target Maneuver: AROMA

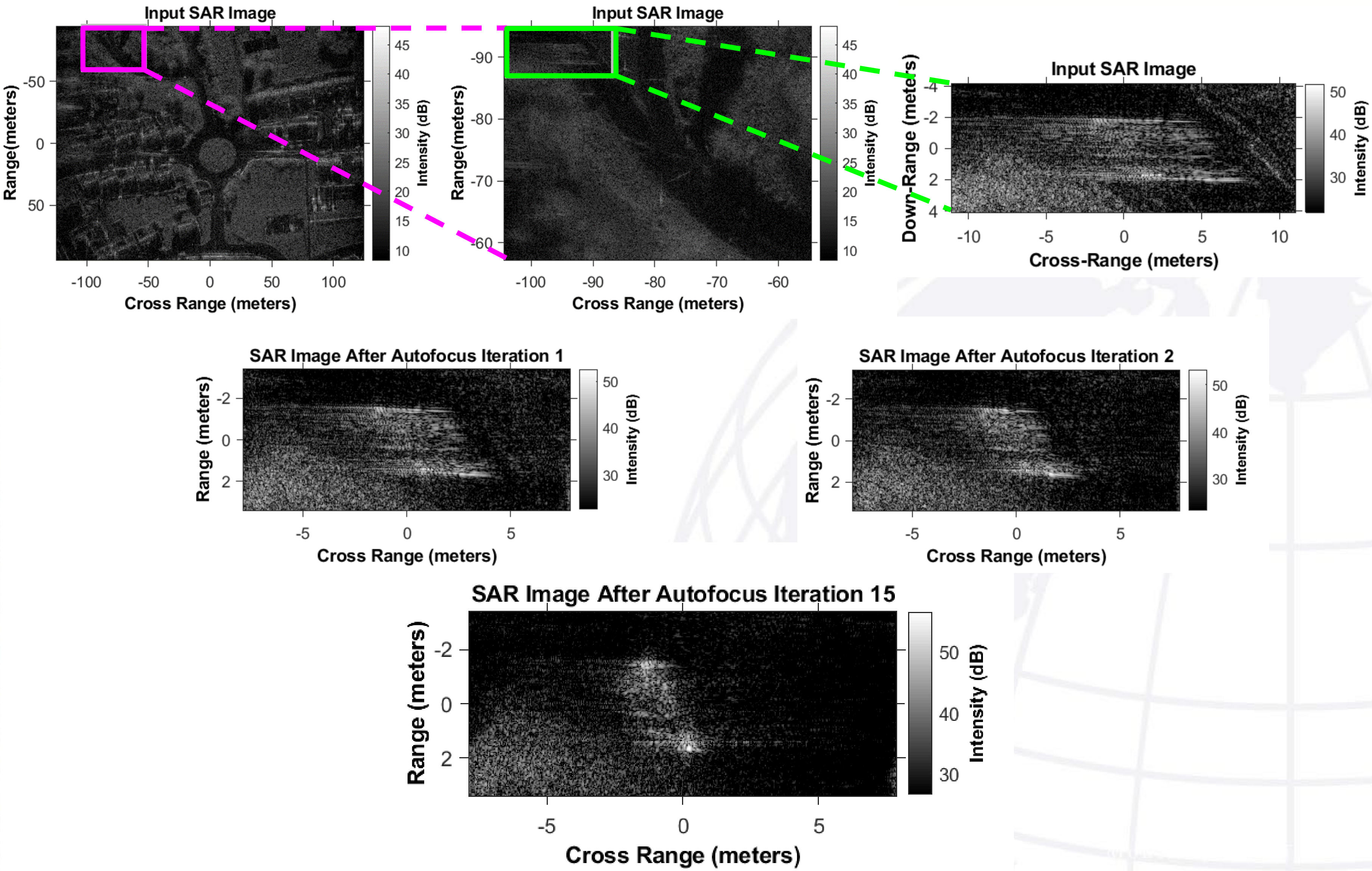








AROMA on Bright Spark Data



Conclusions

- The current investigation has examined AROMA performance in refocusing moving targets which exhibit complicated maneuvers during the SAR collection
- Cases are examined in which a moving target of discrete point scattering centers is injected into a background of measured complex-valued Ku-band SAR imagery
- Case of relatively small amount of variation in the maneuver yields a high-quality refocused image which had a high level of correlation with the true target configuration
- Case of a larger amount of maneuver variation revealed a significant amount of residual defocused, although the overall target shape and configuration of the discrete scattering centers are visible within the refocused imagery

References

- Jakowatz, C. V., Jr., Wahl, D. E., Eichel, P. H., Ghiglia, D. C., Thompson, P. A., *Spotlight-Mode Synthetic Aperture Radar: A Signal Processing Approach*, Kluwer, Boston, 1996

- Garren, D. A., "Theory of arbitrary rigid object motion autofocus for non-uniform target rotation and translation," IET Radar, Sonar & Navigation; Vol. 14, Issue: 11, November 2020, pp. 1803-1814; Print ISSN 1751-8784, Online ISSN 1751-8792; Available online as an IET E-First article: 18 September 2020; DOI: 10.1049/iet-rsn.2020.0201

- Garren, D. A., "Theory of Data-Driven SAR Autofocus to Compensate for Refraction Effects," IET Radar, Sonar & Navigation; Vol. 13, Issue: 2, February 2019, pp. 254-262; Print ISSN 1751-8784, Online ISSN 1751-8792; Available online as an IET E-First article: 17 September 2018; DOI: 10.1049/iet-rsn.2018.5143