SAND2015-2541C

Leveraging the Information in the Shadows of Synthetic Aperture Radar

Dagstuhl Seminar 15192

The Message in the Shadows: Noise or Knowledge?

Leibniz Center for Computer Science, Germany

May 3-8, 2015

Ann Marie Raynal

Sandia National Laboratories, United States of America

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

National Nuclear Security Administration

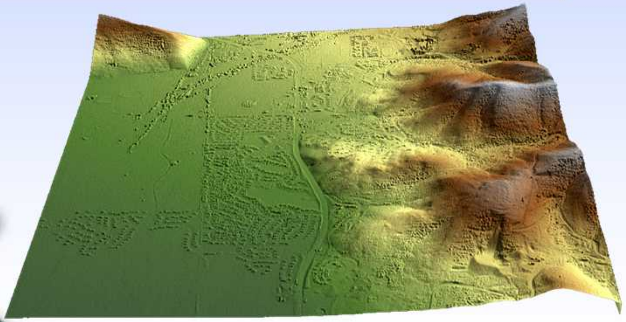
Sandia National Laboratories

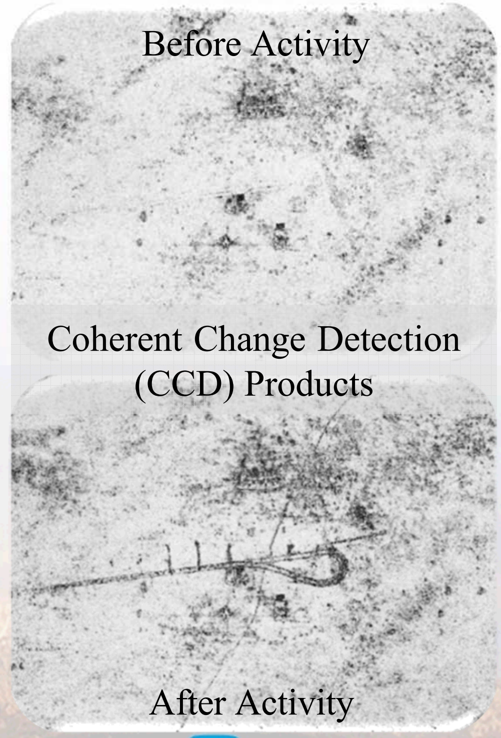
Outline

- Brief Synthetic Aperture Radar Definition
- Challenge of Radar Image Interpretation
- Utility of Shadows for Radar
- Shadow Detection Challenges, Assessment Needs, and Enhancement Possibilities
- Multiple Shadow Advances and Future Possibilities
- Conclusions

What is Synthetic Aperture Radar (SAR)?

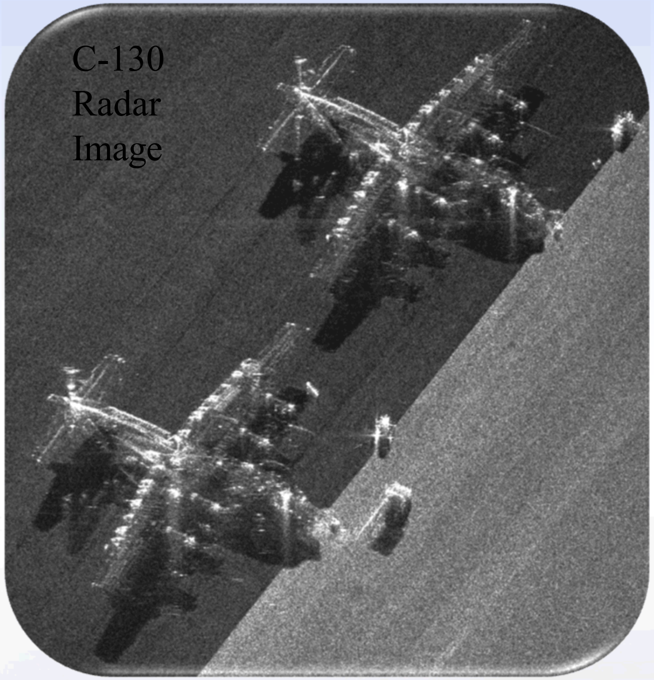
- Air- or space-borne radar for:
  - Ground imaging of small or large areas
  - Terrain mapping & characterization
  - Change detection
  - Target detection, location, tracking, and recognition
  - Video surveillance
- “Synthesizes” imagery from a large antenna (i.e. finer resolution) by aggregating signals of a scene sent from a small antenna over a time period during flight
- Assumes scene is stationary during imaging
- All weather, day or night sensor
- Many applications from environmental monitoring to search and rescue



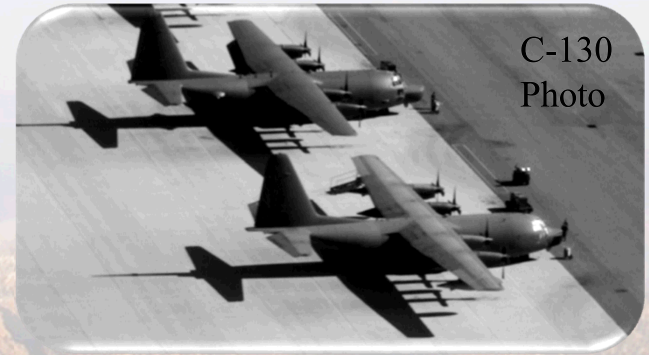


Challenges in Radar Image Interpretation

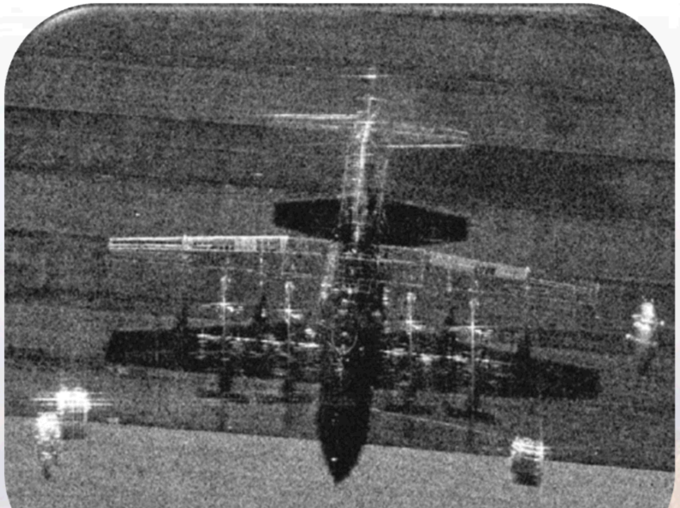
- **Image phenomenology does not look optical**
- **Extensive training of radar operators and image analysts required**
- **Significant algorithm and post-processing needed to exploit key information**
- **Delay from data to decisions**
- **Shadows can bridge unfamiliar radar scattering to known optical objects**



C-130 Radar Image



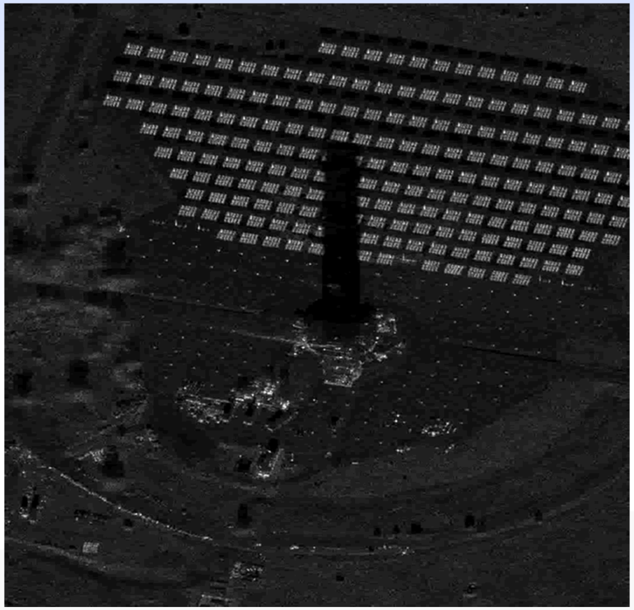
C-130 Photo

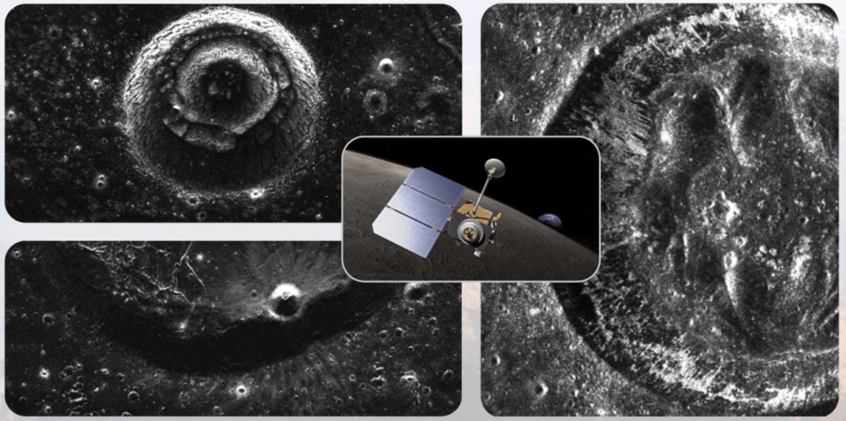


C-130 Radar Shadow Detail

Human Shadow Perception for SAR Utility

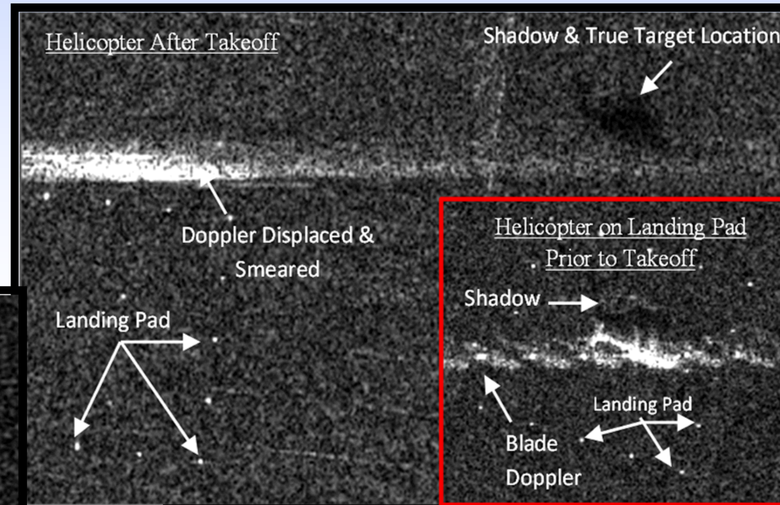
- Occurs subconsciously and early in visual process to detect depth & 3D location
- Triggers innate recognition/reconstruction of 3D objects (to a fault)
- Is the preferred means of inferring object motion due to sensitivity to luminance, edge, and spatial coherence changes
- Leverages luminance and spatial coherence sensitivity via shadow signal-to-noise ratio, change detection, or video redundancy
- Unfortunately causes overestimation of target motion when tracked target disappears

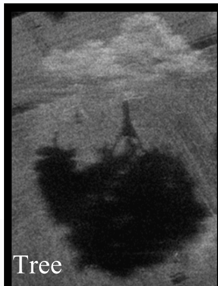


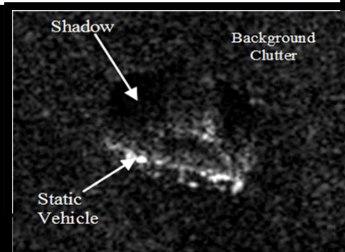


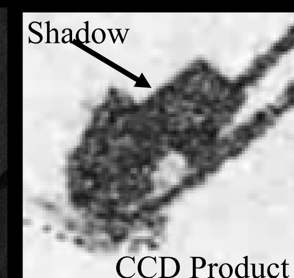
Shadow Advantages versus Traditional Radar Observables

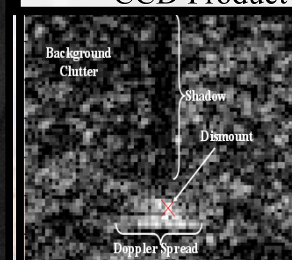
- Intuitive and "optical-like" for human training
- Show true location of moving target whereas radar target scattering may suffer smearing and displacement, possibly even outside the scene
- Delineate shape and physical dimensions for identification
- Applicable to images, video, and exploitation products



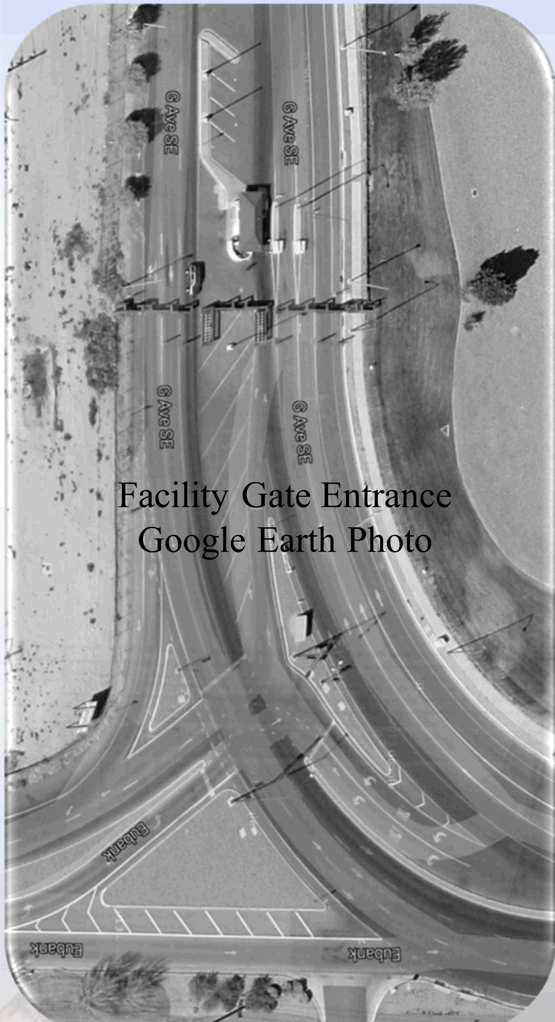








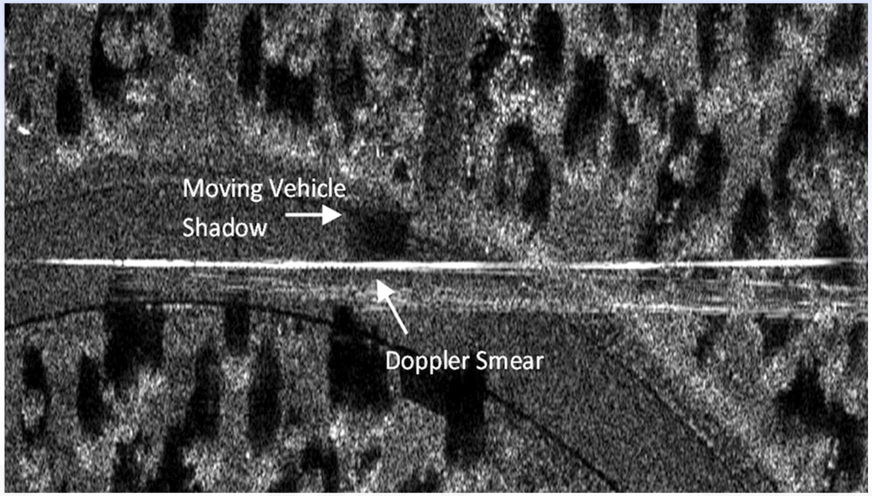
Shadow Advantages versus Traditional Radar Observables (cont'd)

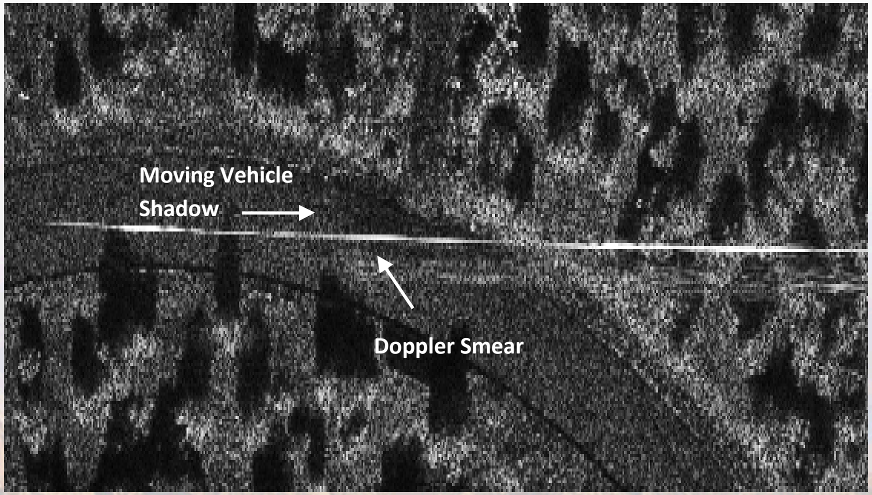


Facility Gate Entrance
Google Earth Photo

SAR Product Shadow Detection Challenges

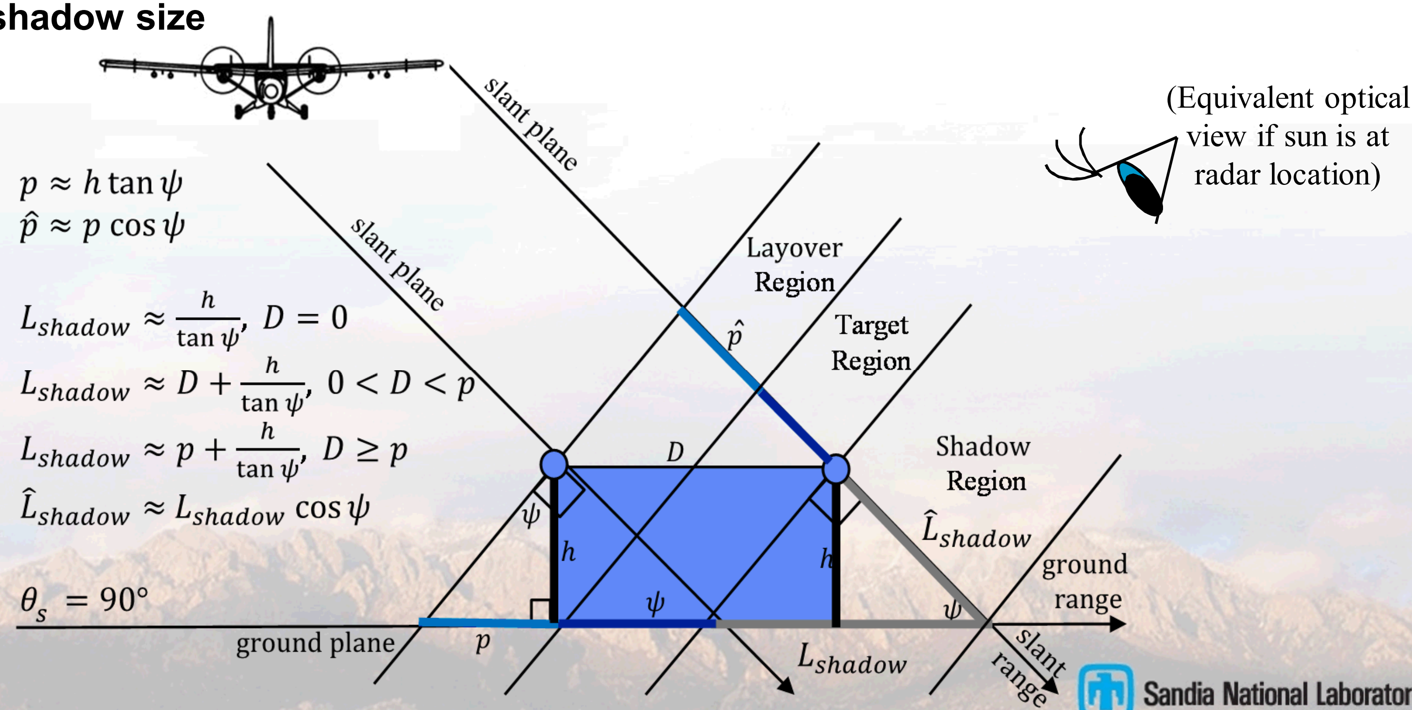
- Quality and observation depend on scene clutter contrast, target size and motion, and platform and radar imaging parameters
- Moving target shadows can quickly be washed-out/degraded across clutter cells
- Shape and interior degraded by diffraction, noise, and other scattering physics or radar processing (e.g. multipath, averaging from the synthetic aperture, bleeding of nearby targets/clutter, or windowing)
- May be many shadows in a scene, areas of no return perceived as "shadows", or artifacts that are not of interest (e.g. water, multiple tree shadows, decorrelation in CCD)
- **Static and moving target shadow dimensions, intensity degradation, platform and radar imaging parameter, and post-processing assessments needed to develop algorithms that aid and automate human analysis**





Ideal Static Target Shadow Dimensions for Radar

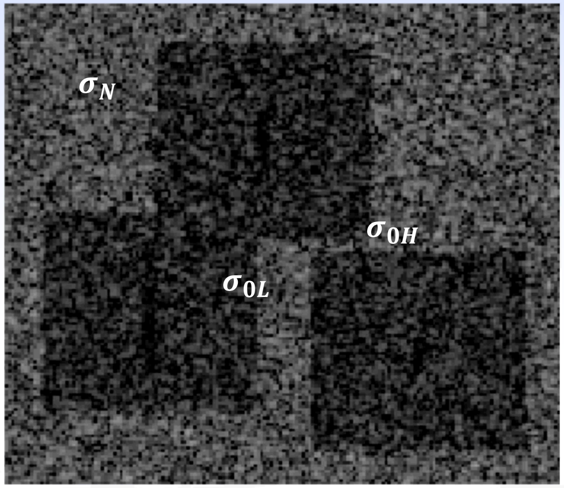
- **Shadow is the obscuration of radar energy by a target from illuminating resolution cells behind it**
- **Shadow Length**
  - **Increases with height and downrange depth**
  - **Decreases with grazing angle**
- **Shadow width determined by physical target cross-range width for an arbitrary pose**
- **Note: No-return areas due to Doppler-shifted moving target energy can increase apparent shadow size**



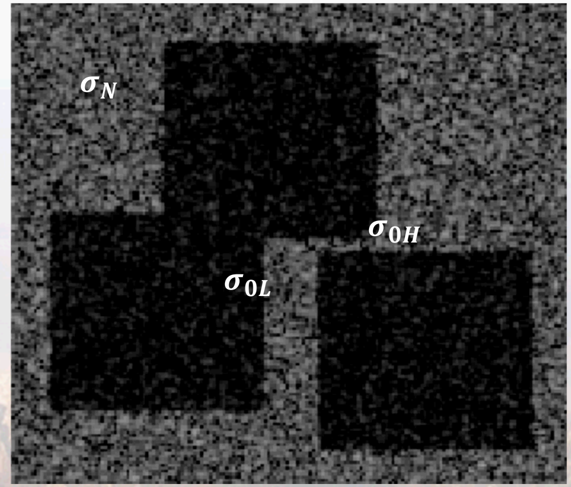
Static Shadow Quality

- Shadow quality is determined by:
  - Differentiation of shadow from clutter (contrast ratio)
  - Crisp shadow edges
  - Resolution
- Distributed Target Contrast Ratio:
  - $\mathrm{DTCR} = \frac{\sigma_{0H}+\sigma_N}{\sigma_{0L}+\sigma_N} > 1.5\ \mathrm{dB}$, where $\sigma_N = \sigma_n + \mathrm{MNR}\,\overline{\sigma_0}$ (additive/thermal and multiplicative/speckle noise)
  - Depends on relative separation in intensity between shadow and clutter
- Resolution must not exceed target width, since clutter will be introduced to the shadow resolution cell
- Crisp shadow edges are determined by:
  - Shadow motion during synthetic aperture
  - Diffraction effects of target scattering (minimal)
  - Relative motion perturbations between target and platform

DTCR = 7 dB

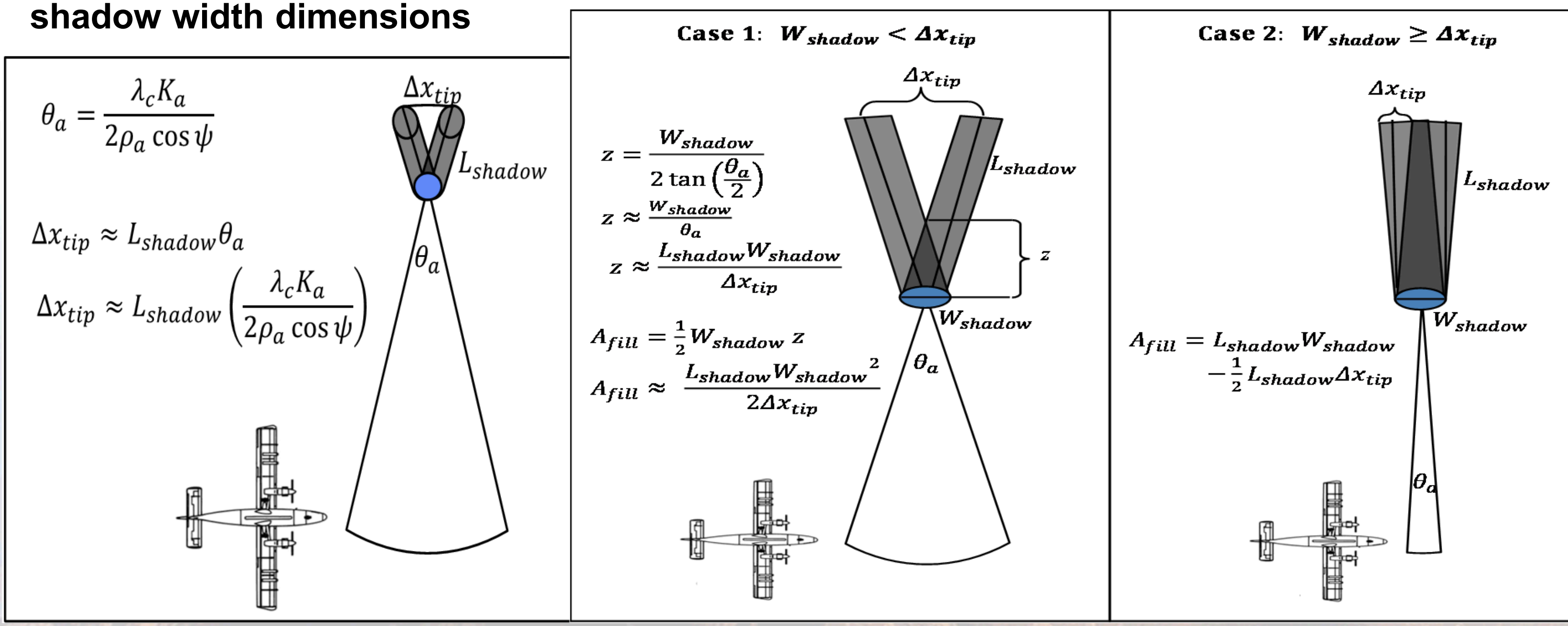


DTCR = 1.5 dB



Static Target Shadow Motion

- Synthetic aperture formation causes direction changes in the obscuration of energy with azimuth angle which decreases with increasing frequency, grazing angle, and coarse resolution
- Shadow's lack of signal is combined complexly with brighter surrounding clutter returns over a circular sector as it moves
- Shadow fill-in (or reinforcement of the lack of signal) over aperture depends on target width
- How much shadow motion and fill-in occurs impacts edge and interior quality and expected shadow width dimensions



Static Target Shadow Motion (cont'd)

- Intensity degradation vs. shadow length gradual from shadow base to tip
- Degradation can be approximated by discretizing the ideal shadow length by the range resolution
- Severe measurement errors in estimation of shadow length due to degradation between shadow and clutter not expected (even at tip)
- Lower grazing angles better for shadow length observation as higher angles prove to minimally degrade shadow quality
- Coarser resolutions out-perform finer resolutions in distinguishing shadow from clutter
- Cumulative average of shadow area segment intensities across length should approach total shadow area intensity of the distributed target
- Detection algorithms should search over a trapezoidal area with height equal to the shadow length and bases equal to the ideal target shadow width and tip aperture motion width, finding overall average shadow-to-clutter shown

$$\Delta x_n = n\rho_r\theta_a,$$

for $n = 0,1,2,\dots,N = \left\lfloor \frac{L_{shadow}}{\rho_r} \right\rfloor$

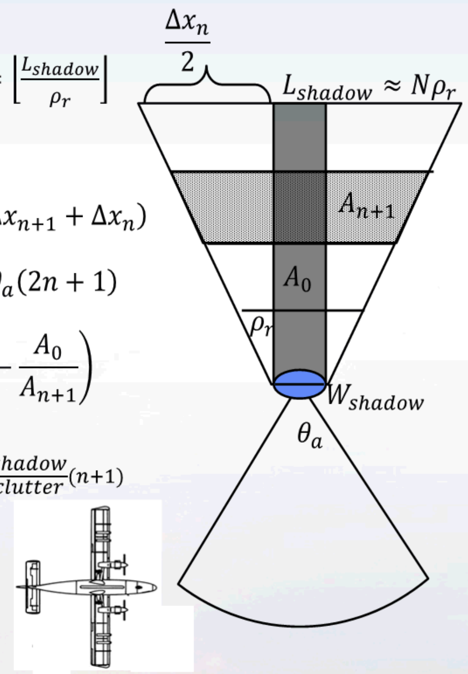
$$A_0 = \rho_r W_{shadow}$$

$$A_{n+1} = A_0 + \frac{1}{2}\rho_r(\Delta x_{n+1} + \Delta x_n)$$

$$A_{n+1} = A_0 + \frac{1}{2}{\rho_r}^2\theta_a(2n+1)$$

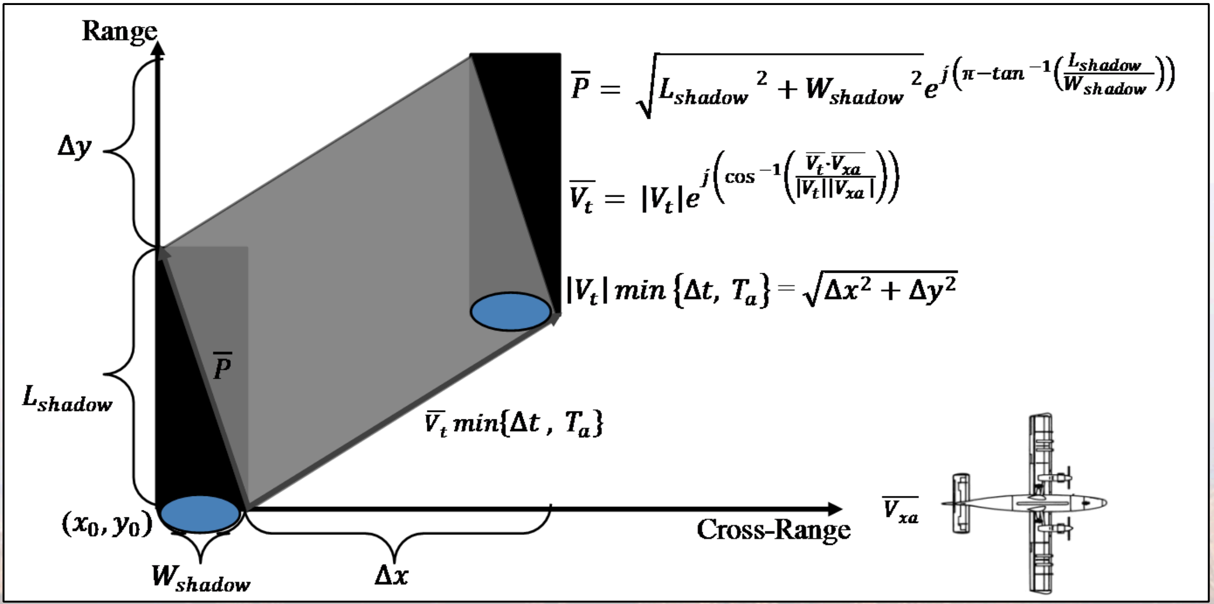
$$\sigma_{\frac{shadow}{clutter}(n+1)} = \left(1 - \frac{A_0}{A_{n+1}}\right)$$

$$\sigma_{\frac{shadow}{clutter}} \approx \frac{1}{N}\sum_{n=0}^{N} \sigma_{\frac{shadow}{clutter}(n+1)}$$



Moving Target Shadow Dimensions

- Shadow Area Span:
  - Roughly a parallelogram for target motion plus ideal static shadow size
  - Decreases with coarser resolution and platform velocity due to shorter aperture times
  - Increases with increasing range due to longer aperture times
  - Decreases with increasing grazing angle and decreasing target velocity and physical size
  - Varies with travel direction relative to platform; decreases maximally (reinforced) in range
- Assumptions:
  - Target rarely starts, stops, or changes trajectory in aperture
  - Synthetic aperture motion of shadow negligible for moving target



Sandia National Laboratories

Moving Target Shadow Intensity

- Shadow intensity is an average over the fraction of the time there is no return versus clutter return in a resolution cell during the synthetic aperture
- An approximation is to assume a moving target shadow intensity will be proportional to the clutter blockage (i.e. shadow area span) afforded by the target while in motion during the aperture versus the ideal static target physical shadow area:

$$\sigma_{Shadow} \approx \sigma_N + \sigma_{0H}\left(1 - \frac{A_{stationary\_shadow}}{A_{moving\_shadow}}\right)$$

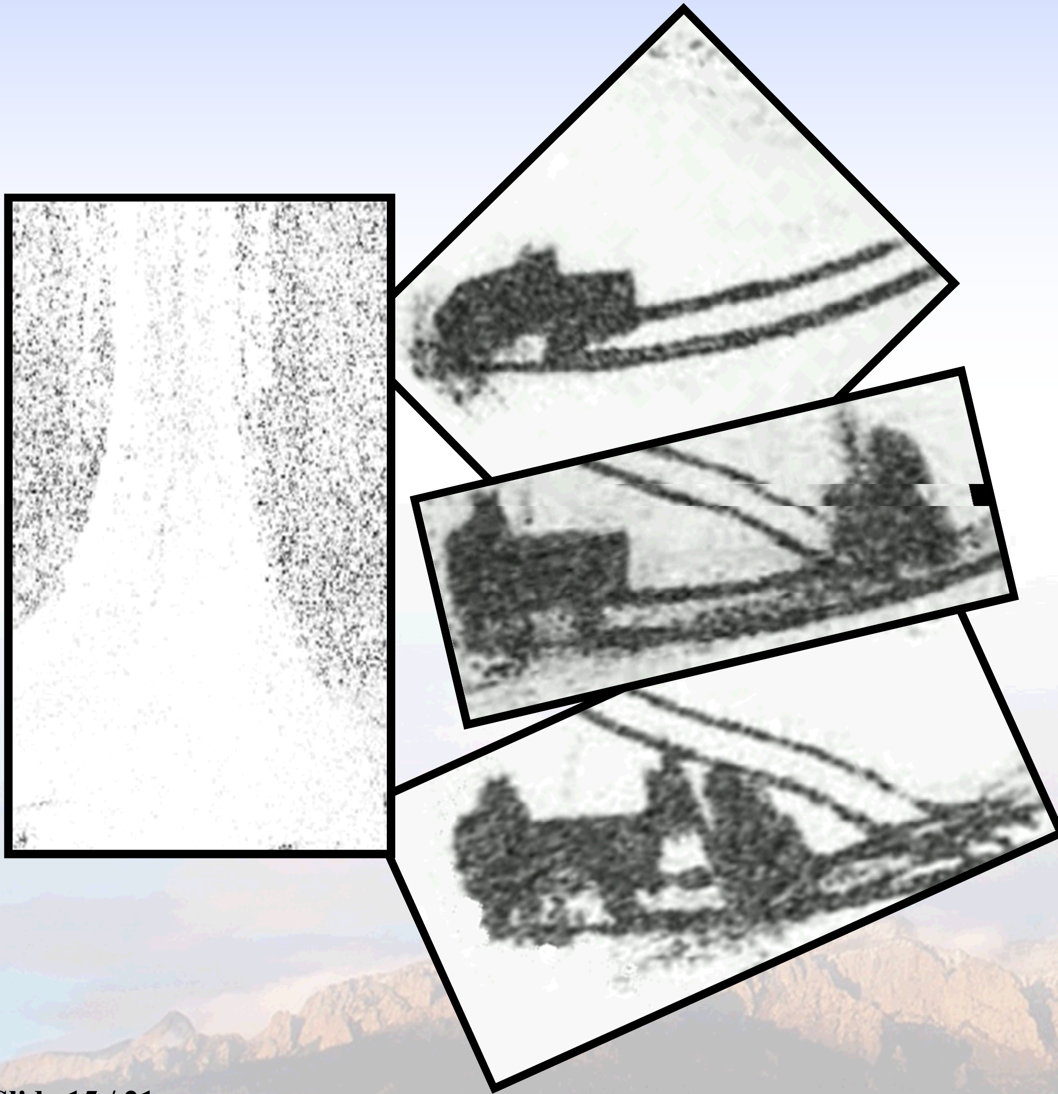
$$\sigma_{Shadow} \approx \sigma_N + \sigma_{0H}\left(1 - \frac{L_{shadow}W_{shadow}}{L_{shadow}W_{shadow} + \left|\overline{V_t}\, min\{\Delta t\,, T_a\} \times \overline{P}\right|}\right)$$

- The target shadow-to-clutter ratio is thus:

$$\frac{\sigma_{shadow}}{\sigma_{clutter}} = \left(1 - \frac{A_{stationary\_shadow}}{A_{moving\_shadow}}\right)$$

- Moving shadows hard to detect in SAR: short ranges, fast platform, high frequencies, and quasi-static targets or targets traveling in range most favorable

Shadows in Change Detection Products



- As with SAR, difficult to detect small shadows in CCD with shadow SNR and coherence given by:

$$\frac{\sigma_{shadow}}{\sigma_N} \approx \frac{\sigma_{0H}}{\sigma_N}\left(1 - \frac{A_{stationary\_shadow}}{A_{moving\_shadow}}\right)$$

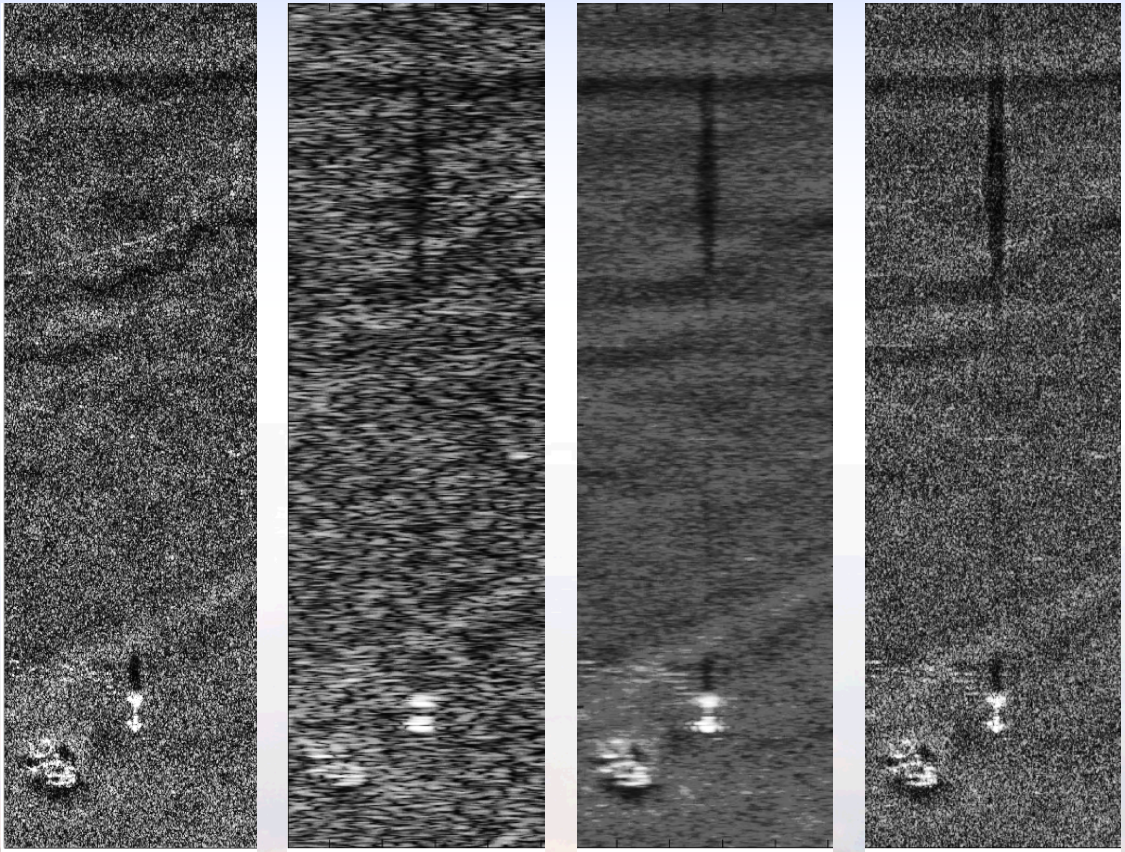
$$\gamma_{shadow} = \frac{1}{1 + (\sigma_{shadow}/\sigma_N)^{-1}}$$

- Video products such as VideoSAR and VideoCCD afford a redundant depiction of sequential target shadow behavior changes
- Spatial and temporal coherence key to enhancing the detection and discernment of mobile target behavior over still-frame imagery
- Track history preservation and progression can aid in motion observations for VideoCCD

Shadow Enhancement Possibilities

- **Optimal Resolution**
  - $W_{shadow,P(5\%)} \geq \rho_a \geq \Delta x_{tip}, \forall \psi$
  - **Noise variance high**
  - **Target features not distinct**
  - **Shadow only visible near tip**
- **Multi-look**
  - **Can be akin to mean filtering for speckle reduction**
  - **Shadow visible throughout**
  - **Target features averaged**
  - **Coarsened resolution**
- **Range-of-Focus**
  - **Best overall quality shadow**
  - **Degraded focus of targets at other ranges (unless shadow blended into original image)**
  - **Assumes stationary targets**
- **What about other image processing techniques for shadow detection?**

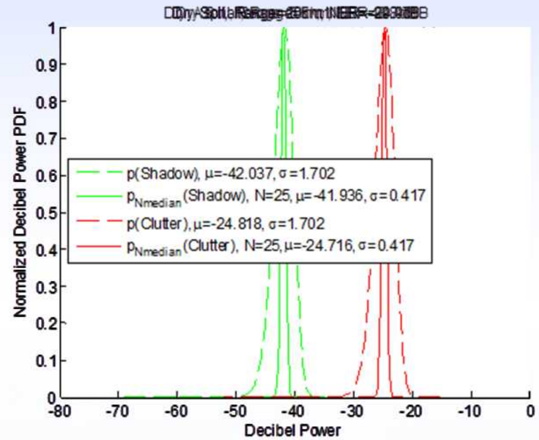
J. Groen, et al., *IEEE Journal of Oceanic Engineering*, 34(3), 2009

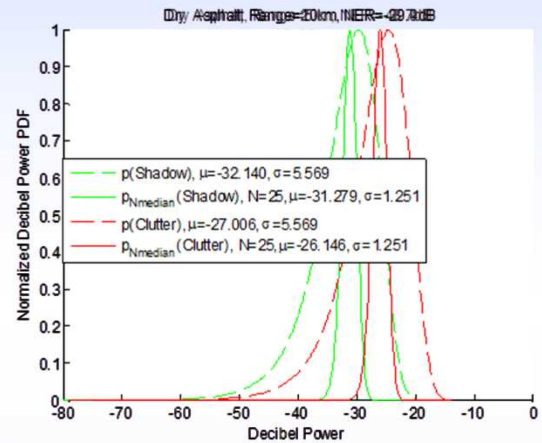


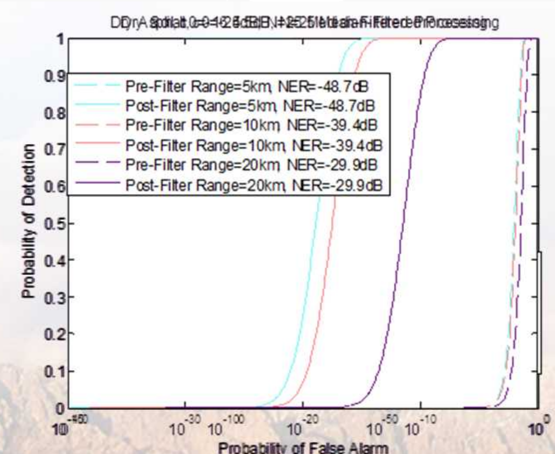
Original | Optimal Resolution | Multi-look | Range-of-Focus

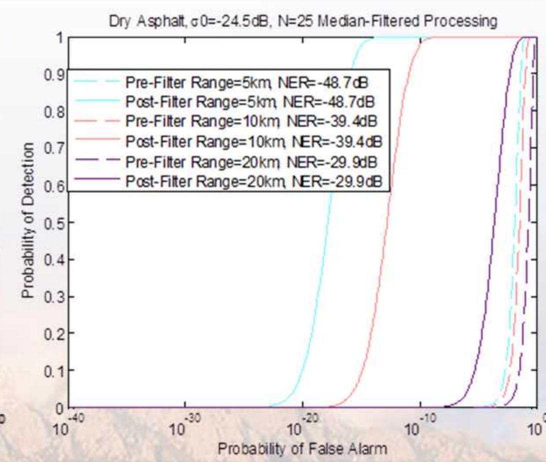
Median & Multi-Look Filtering for Detection

- **Probability of detection (PD) and probability of false alarm (PFA) quantifies distinction between signal (i.e. shadow) and interference (i.e. clutter) probability distributions**
- **PD & PFA affected by statistical changes in the distribution of image pixels due to post-processing**
- **Median filtering**
  - **Nonlinear speckle reduction and edge preservation with coarsened resolution**
  - **Increases shadow-to-clutter ratio for increased PD & decreased PFA**
  - **Makes probability distributions more Gaussian-like with increasing window size**
- **Multi-look enhances PD & PFA less**
- **Multi-look with median filtering better PD & PFA shadow approach**







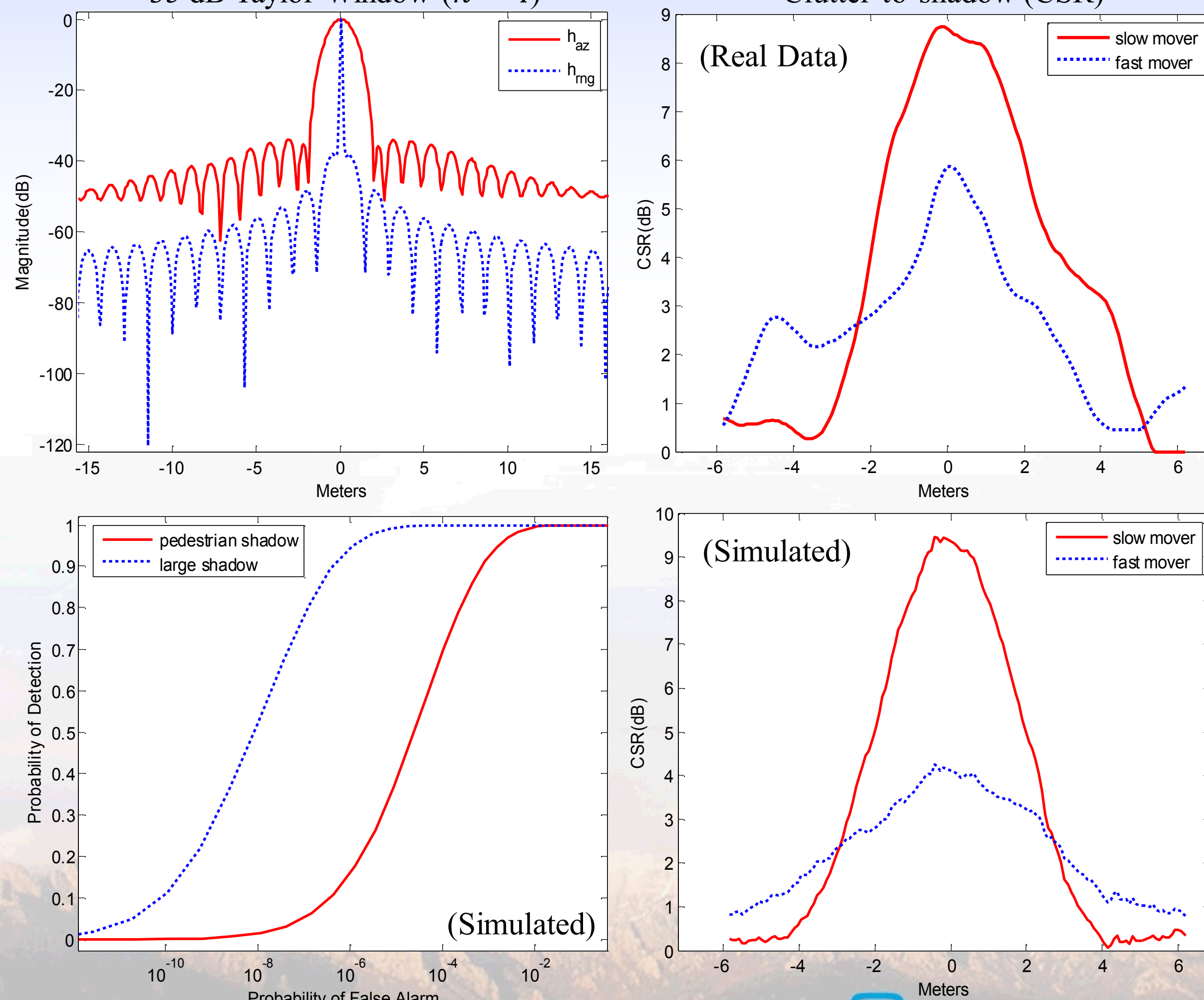


Window Processing & Moving Target Shadow Intensity for Detection

- **Windows processing:**
  - **Used to enhance target peak signal versus sidelobe dynamic range**
  - **Weights image pixels differently**
  - **Causes shadow-to-clutter ratio to vary with moving target location in scene**
- **Accounting for windowing in simulation matches real data of moving target shadow-to-clutter measurements**
- **Simulations show:**
  - **Small moving target shadows cause decreased PD and increased PFA**
  - **Increased target speeds, and bleeding of mixed clutter or targets near shadow, worsen shadow-to-clutter distinction**

J. Miller, et al., *Proc. of SPIE*, April 2015

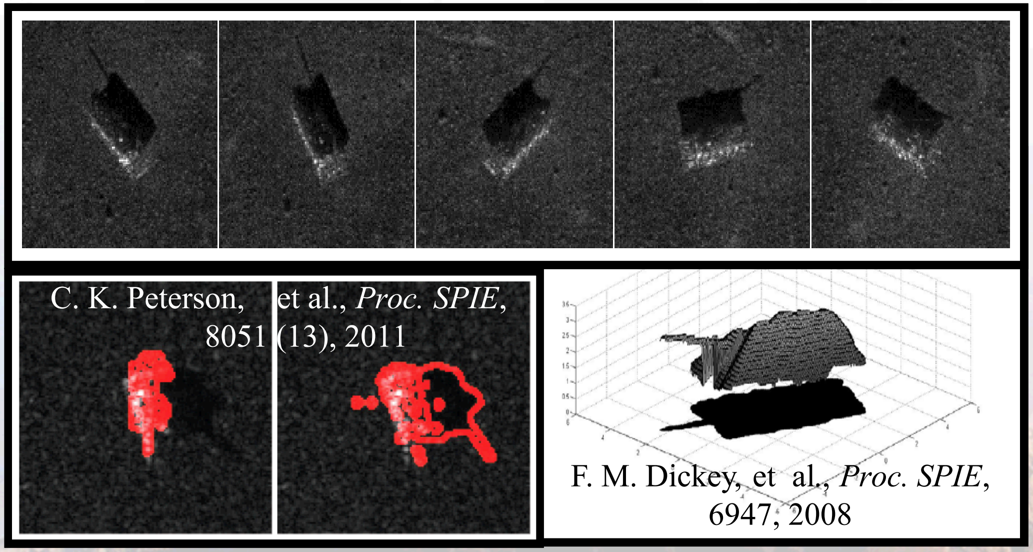
-35 dB Taylor Window ($\bar{n} = 4$) Clutter-to-shadow (CSR)



Sandia National Laboratories

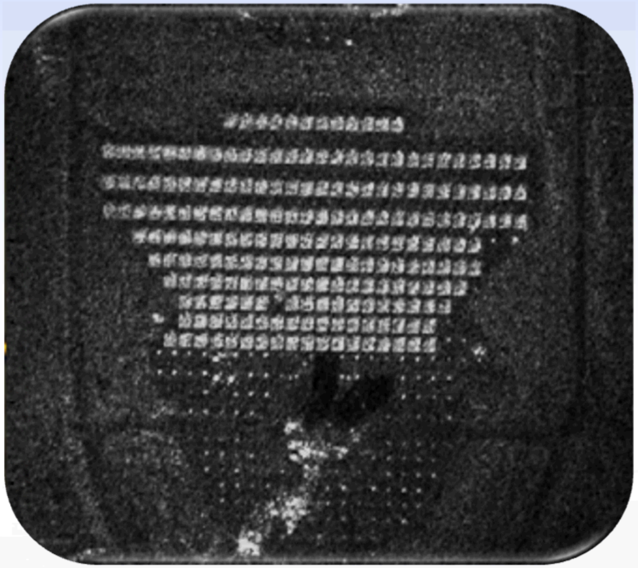
Target Multiple Shadow Advances and Future Possibilities

- **Monostatic (i.e. co-located transmitter and receiver) shadow tomography and orientation determination of static targets demonstrated**
- **Bistatic (i.e. different transmitter/receiver location) imagery contains 2 shadows in 1 image**
- **Can bistatic shadows help create faster or less ambiguous tomographic reconstruction?**
- **As with monostatic, can bistatic shadows pinpoint stationary and moving target location and orientation but more accurately, quickly, and with less data?**



C. K. Peterson, et al., *Proc. SPIE*, 8051 (13), 2011

F. M. Dickey, et al., *Proc. SPIE*, 6947, 2008



- **Can shadow holographic or tomographic and orientation recognition approaches be applied to coherent change detection products?**
- **What are the limitations to such techniques for these modes and multi-static/MIMO expansion?**

Sandia National Laboratories

Conclusions

- Radar shadows can be more intuitive for target detection, location, tracking, and shape observation than other target traits due to human visual perception preferences but characteristics depend on many factors
- Shadow algorithm development and requirements are necessary to overcome flaws in visual perception; shadow intensity degradation with scene clutter, target motion and size, platform motion, and radar imaging parameters; and drive image analysis automation
- The following optimize shadow observability:
  - High frequencies
  - Low grazing angles
  - Short aperture times with short ranges and fast platform velocities
  - Arbitrary flight paths to keep target travel direction solely in range
  - Multi-look with median filtering and window processing considerations
  - Image or temporal shadow redundancy (e.g. video and bistatics)
- Some requirements non-negotiable for a mission (including the target size and behavior)
- Consideration of best imaging techniques, desired operations, shadow enhancement and exploitation methods require careful examination

References

- B. T. Backus and I. Oruç, "Illusory motion from change over time in the response to contrast and luminance," *Journal of Vision*, vol. 5, no. 11, December 30, 2005.
- G. Mather, "Luminance change generates apparent movement: implications for models of directional specificity in the human visual system," *Vision Res.*, vol. 24, no. 10, pp. 1399-1405, 1984.
- H. M. Dee and P. E. Santos, "The perception and content of cast shadows: an interdisciplinary review," *Spatial Cognition & Computation: An Interdisciplinary Journal*, vol. 11, no. 3, pp. 226-253, 2011.
- S. Taya and K. Miura, "Cast shadow can modulate the judged final position of a moving target," *The Physiognomic Society, Attention, Perception, & Psychophysics*, vol. 72, no. 7, pp. 1930-1937, 2010.
- W. G. Carrara, R. S. Goodman, and R. M. Majewski, *Spotlight Synthetic Aperture Radar: Signal Processing*
- F. M. Dickey and A. W. Doerry, "Recovering shape from shadows in synthetic aperture radar imagery", *Proc. SPIE*, vol. 6947, no. 694707, 2008.
- J. Groen, R. E. Hansen, H. J. Callow, J. C. Sabel, and T. O. Sabo, "Shadow enhancement in synthetic aperture sonar using fixed focusing," *IEEE Journal of Oceanic Engineering*, vol.34, no.3, pp.269-284, July 2009.
- H. J. Callow, J. Groen, R. E. Hansen, and T. Sparr, "Shadow enhancement in SAR imagery," *2007 IET International Conference on Radar Systems*, pp.1-5, Oct. 15-18, 2007.
- M. Jahangir, "Moving target detection for synthetic aperture radar via shadow detection," *2007 IET International Conference on Radar Systems*, pp.1-5, 15-18 Oct. 2007.
- L.M. Novak, "Optimal target designation techniques," *IEEE Transactions on Aerospace and Electronic Systems*, vol. AES-17, no.5, pp.676-684, Sept. 1981.
- F. T. Ulaby and M. C. Dobson, *Radar Scattering Statistics for Terrain*, Artech House, Inc., Norwood, MA, 1989.
- H.A. Zebker and J. Villasenor, "Decorrelation in interferometric radar echoes," *IEEE Transactions on Geoscience and Remote Sensing*, vol.30, no.5, pp.950-959, Sep 1992.
- D. L. Bickel, “SAR Image Effects on Coherence and Coherence Estimation,” *Sandia National Laboratories Report*, Albuquerque, NM, SAND2014-0369, January 2014.
- A. M. Raynal, D. L. Bickel, and A. W. Doerry, “Stationary and Moving Target Shadow Characteristics in Synthetic Aperture Radar,” *Proc. SPIE*, vol. 9077, no. 90771B-1, 2014.
- A. M. Raynal, J. Miller, E. Bishop, V. Horndt, and A. W. Doerry, “Shadow Probability of Detection and False Alarm for Median-Filtered SAR Imagery,” *Sandia National Laboratories Report*, Albuquerque, NM, SAND2014-4877, June 2014.
- J. Miller, E. Bishop, V. Horndt, A. W. Doerry, and A. M. Raynal “Impact of Ground Mover Motion and Windowing on Stationary and Moving Shadows in Synthetic Aperture Radar Imagery,” *Proc. SPIE*, April 2015.
- C. K. Peterson, P. Murphy, and P. Rodriguez, “Target Classification in Synthetic Aperture Radar Using Map-Seeking Circuit Technology,” *Proc. SPIE*, vol. 8051, no. 13, 2011.