Simulation and Analysis of Adaptive Interference Suppression for Bistatic Surveillance Radars*

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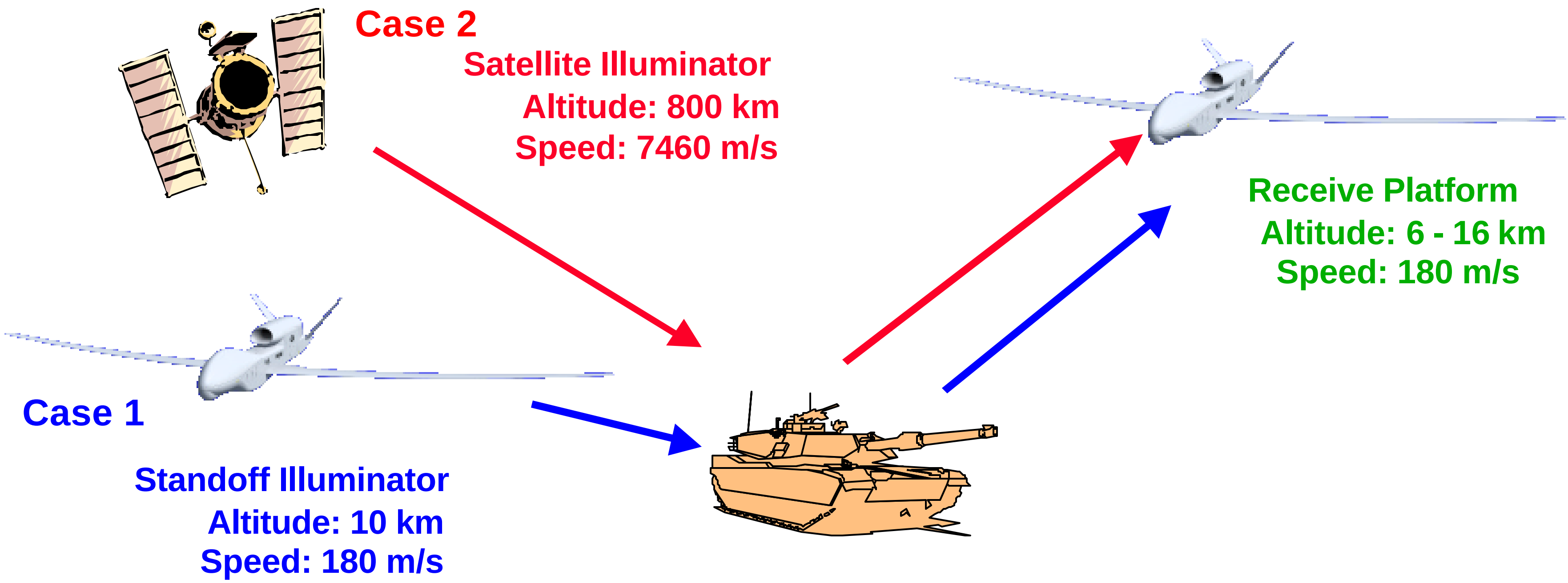
Outline

- ➨ **Problem Overview**
- **Bistatic Algorithms - Description and Analysis**
- **Summary and Future Work**

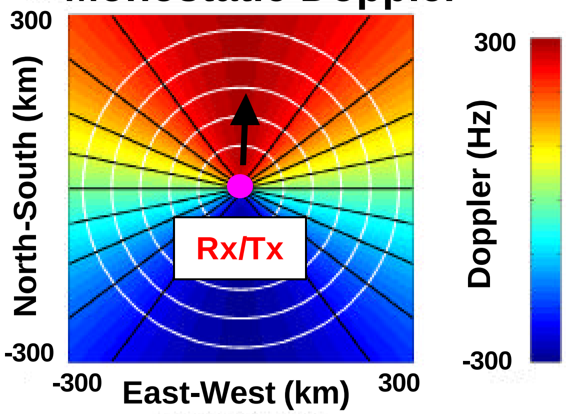
Problem Overview

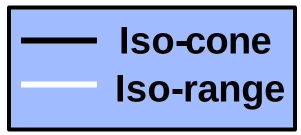


- **Bistatic geometry involves separate transmit and receive platforms**
  - **Platforms are moving independently**
- **Receive only platform for surveillance or strike**
  - **Extend coverage area**
  - **Improve target localization**
  - **No transmitter on receive platform**
    - **Reduce size, weight, power**
    - **Improve stealthiness**

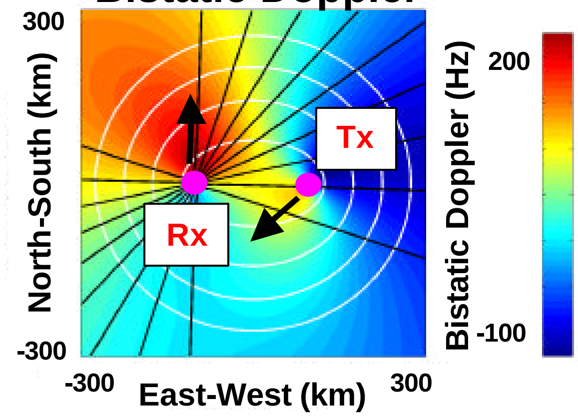
Challenges for Bistatic Operation

Monostatic Doppler

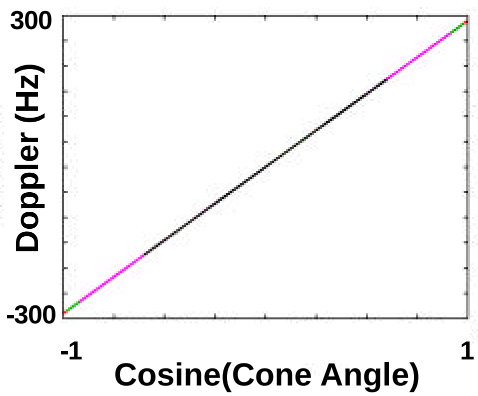




Bistatic Doppler

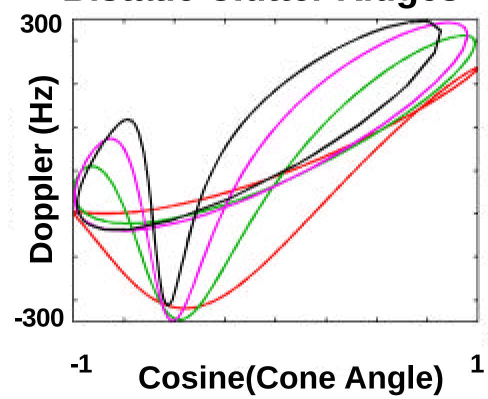


Monostatic Clutter Ridges



Two-way range
25 km
50 km
100 km
300 km

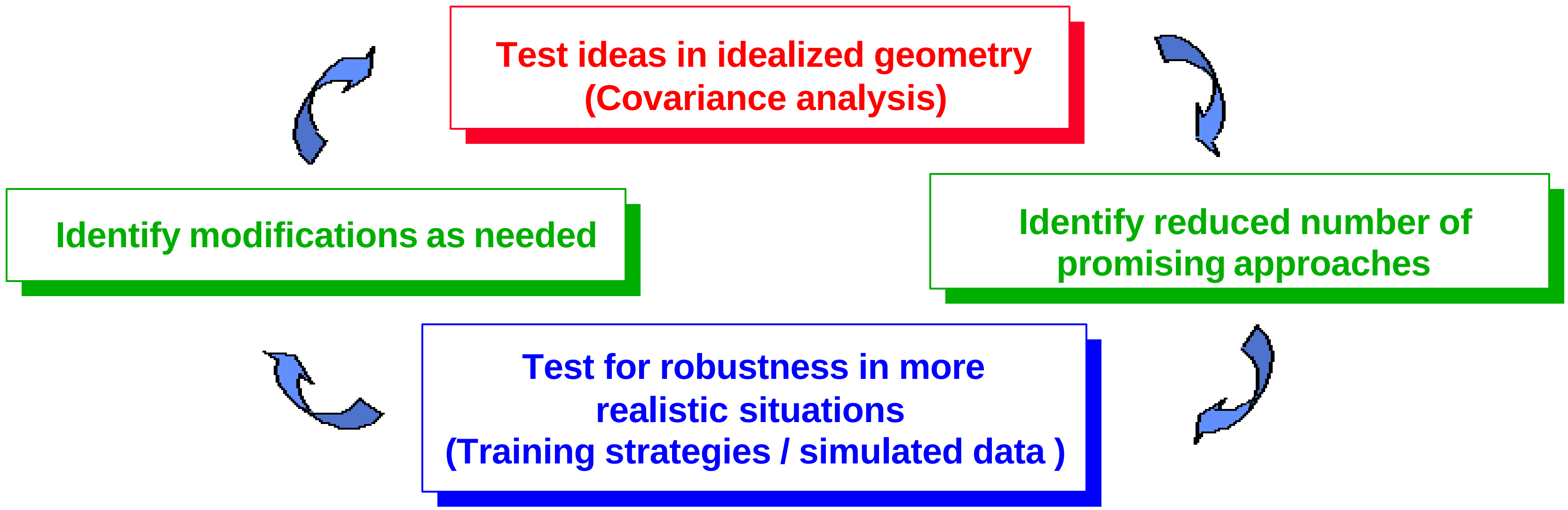
Bistatic Clutter Ridges



Bistatic
Range
225 km
250 km
300 km
500 km

- **Benefits of bistatic operation come at a price**
  - **Azimuth / Doppler structure of clutter interference varies with range**
- **Challenge is to find training strategies to estimate covariance *R***

Algorithm Development Approach

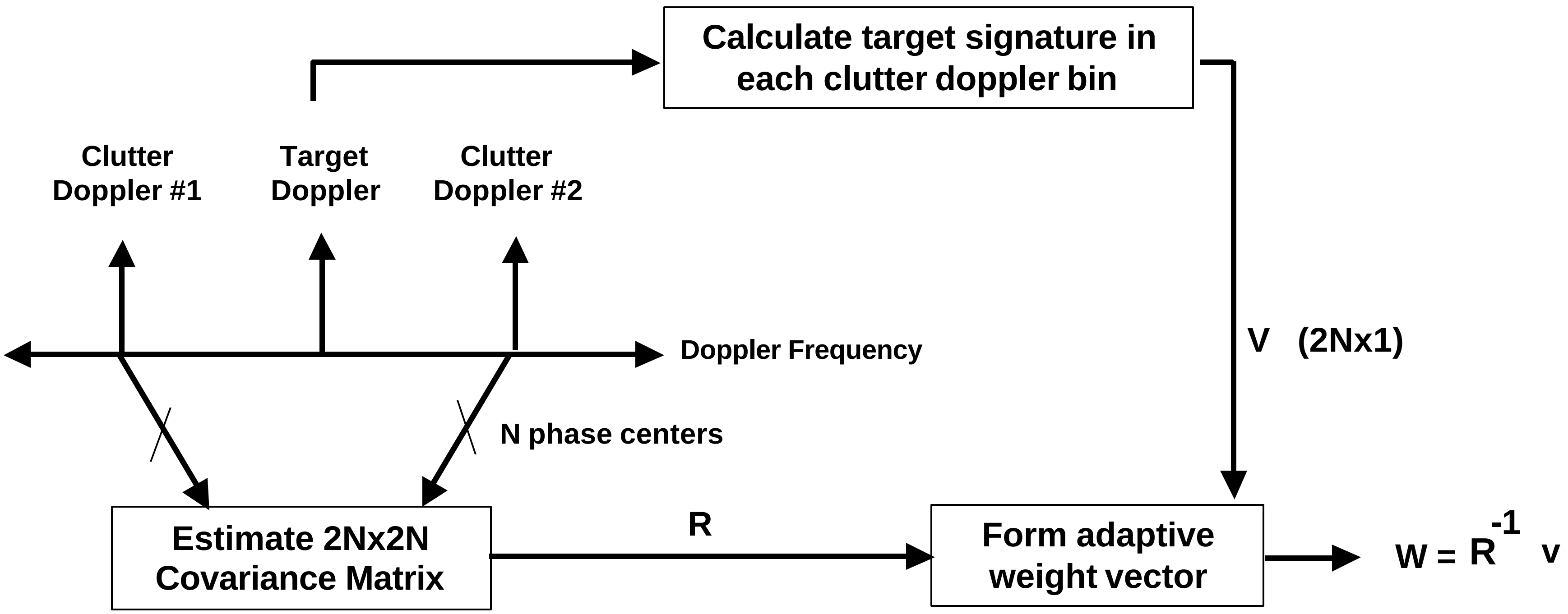


- **Covariance model is used to compare algorithms with**
  - **large number of geometries**
  - **coarse range sampling**
- **Modeling goal is to quickly survey algorithm performance**
  - **simplified scattering model**
- **Time series model is used to compare algorithms with**
  - **small number of geometries**
  - **fine scale range sampling**
- **Designed to examine “real world” effects on algorithm performance**

Outline

- **Problem Overview**
- **Bistatic Algorithms - Description and Analysis**
  - ➔ **Algorithm description**
    - – **"Standard" 2 - bin Post - Doppler**
    - – **2 - bin Post - Doppler with Derivative Based Updating (DBU)**
      - – ***Uses only radar data but doubles the degrees of freedom (DOF's)***
        - – **Requires increased sample support**
    - – **2 - bin Post - Doppler with High Order Doppler Warping (HODW)**
      - – ***Uses knowledge of bistatic clutter ridge***
        - – **Receiver must know position and velocity of transmitter**
  - – **Algorithm performance**
- **Summary and Future Work**

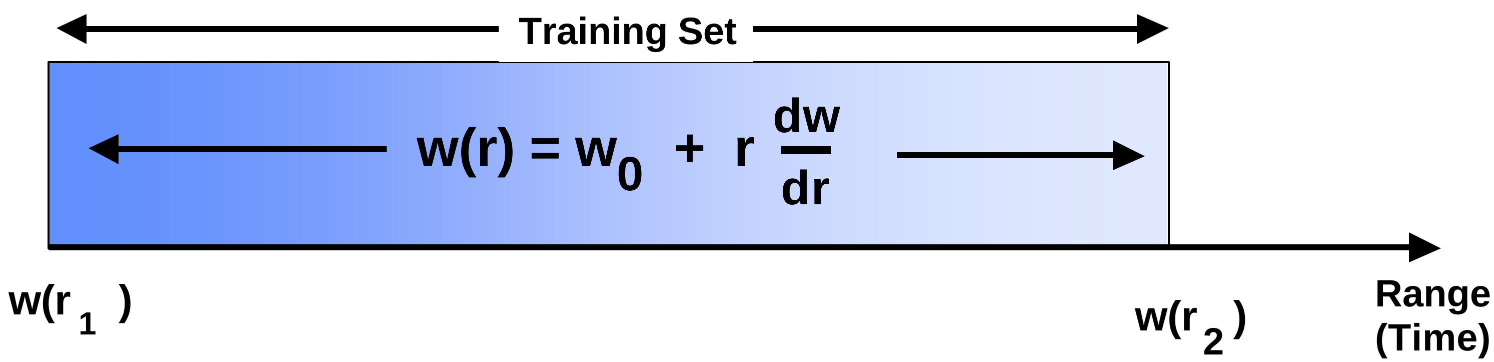
2 - Bin Post - Doppler Algorithm



- **Two-Bin nulling algorithm:**
  - **Train on clutter in Doppler bin #'s 1 and 2 to null clutter at the target Doppler frequency**
- **Well established approach for monostatic STAP applications**
  - **Typically assume *range invariance* and estimate covariance with *range average***

Derivative-Based Updating Algorithm

- **Derivative-Base Updating Algorithm (DBU):**
  - Hayward (1996), Zatman & Kogon (2000 ASAP), Zatman (2001 ASAP)



- **Assumes weight vector varies linearly with range**
  - Effectiveness depends on accuracy of weight vector model
- **Doubles the number of degrees of freedom (DOF) in the STAP problem**
  - Covariance matrix size is doubled
  - Number of training samples required to estimate covariance is doubled

Derivative Based Updating - Interpretation

- Assume optimal filter $w_k = w_0 + k\,w'$ (at k^{th} relative range gate)
- $w_k^H x_k = w_0^H x_k + k\,w'^H x_k = [\,w_0^H \;\; w'^H\,]\,[\,x_k\,;\,k\,x_k\,]$
- Form sample set based on extended vector $[\,x_k\,;\,k\,x_k\,]$ to obtain *extended covariance*

$$R_{est} = (1/N)\begin{bmatrix} \sum_k x_k x_k^H & \sum_k k\,x_k x_k^H \\ \sum_k k\,x_k x_k^H & \sum_k k^2 x_k x_k^H \end{bmatrix} \rightarrow \begin{bmatrix} R_0 & a\,R' \\ a\,R' & a\,R_0 \end{bmatrix} \quad \left(a = \sum_k k^2\right)$$

$$[\,w_0^H \;\; w'^H\,]\,[\,x_k\,;\,k\,x_k\,] = [\,v^H \;\; 0\,]\,(R_{est})^{-1}[\,x_k\,;\,k\,x_k\,] = v^H D_k^{-1} x_k$$

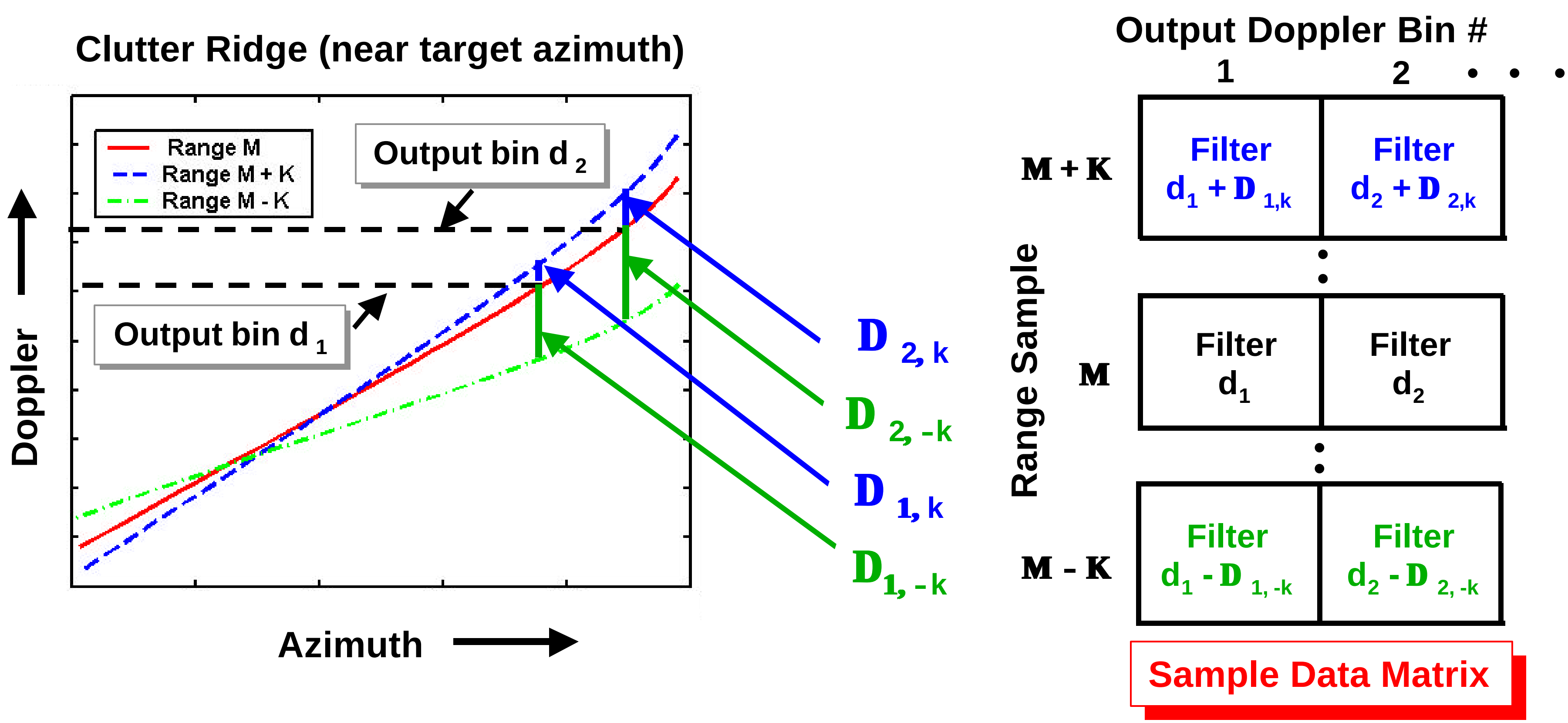
(have used sample set symmetry ($\sum_k k = 0$) and $R_k = \langle x_k\, x_k^H \rangle = R_0 + k\,R'$)

DBU equivalent to applying filter $w_k = D_k^{-1}\, v$

with $D_k^{-1} = (I - k\,R_0^{-1} R')\,(R_0 - a\,R'\,R_0^{-1} R')^{-1}$

- First order perturbation: $R_k^{-1} = (R_0 + k\,R')^{-1} \approx (I - k\,R_0^{-1} R')\,R_0^{-1}$
  - DBU matches perturbation up to terms quadratic in *R'*
  - the a term grows quadratically with the size of training set

High Order Doppler Warping (HODW)



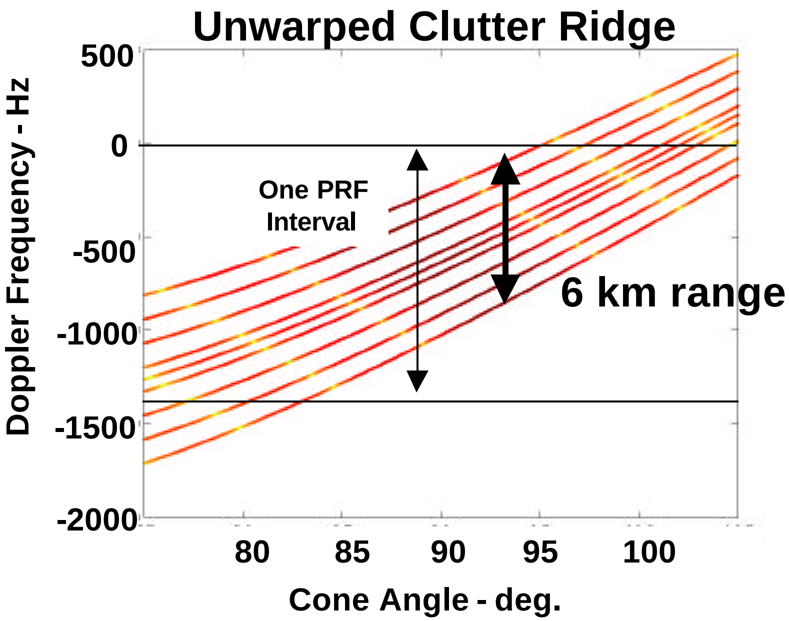
- In each Doppler filter apply a range-dependent Doppler frequency shift
  - Shift is different in each Doppler filter, at each range
    - Original warping algorithm used same shift in each Doppler filter
  - *Interference structure nearly homogeneous in range for each output Doppler bin*

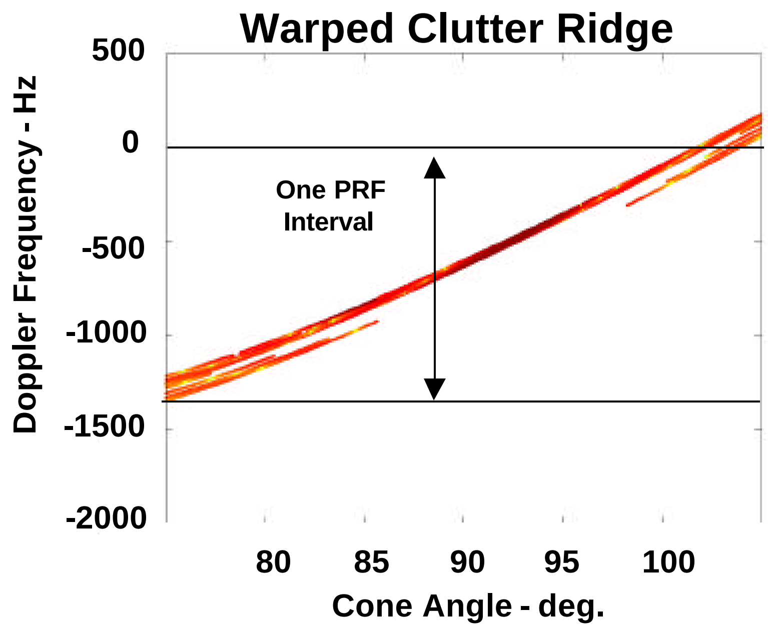
Clutter ridge calculation requires knowledge of transmitter position and velocity

High-Order Doppler Warping

Bistatic Space to Air Example

Clutter Ridges Over 6 km at Target Range





- **Frequency shift is derived from the clutter ridge geometry**
  - **Clutter ridge multiplicity (front lobe / back lobe, aliasing) resolved by choosing highest transmit power branch**
- **"High Order" Warping has made the clutter interference *range invariant"* on a *bin by bin* basis**

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  - Algorithm description
    - "Standard" 2-bin Post - Doppler
    - Derivative Based Updating
    - High Order Doppler Warping
  - ➔ Algorithm performance
- Summary and Future Work

Measuring Performance

- Standard measure of performance is ***SINR Loss***
- For signal element response vector v ($|v|^2 = 1$) and filter w :

  - $SINR = |s|^2 \, | w^H v |^2 / (w^H R w)$

    where R is the true "interference + noise" covariance matrix $< x x^H >$ and s is the signal amplitude

- For uncorrelated noise (unit power) $< n n^H > = I$ and with $w = v$
  - $SNR = |s|^2 \, | v^H v |^2 / (v^H v) = | s |^2$
- For correlated noise $< n n^H > = N$ and with $w = N^{-1} v$
  - $SNR = |s|^2 \, | v^H N^{-1} v |^2 / (v^H N^{-1} v) = | s |^2 \; v^H N^{-1} v$

- Ratio is $SINR\ Loss = | w^H v |^2 / ((w^H R w) (v^H N^{-1} v))$ £ 1
  - Optimal $w = R^{-1} v$ and $max(SINR\ Loss) = v^H R^{-1} v / (v^H N^{-1} v)$
  - In practice use estimated R_{est} and $w = R_{est}^{-1} v$

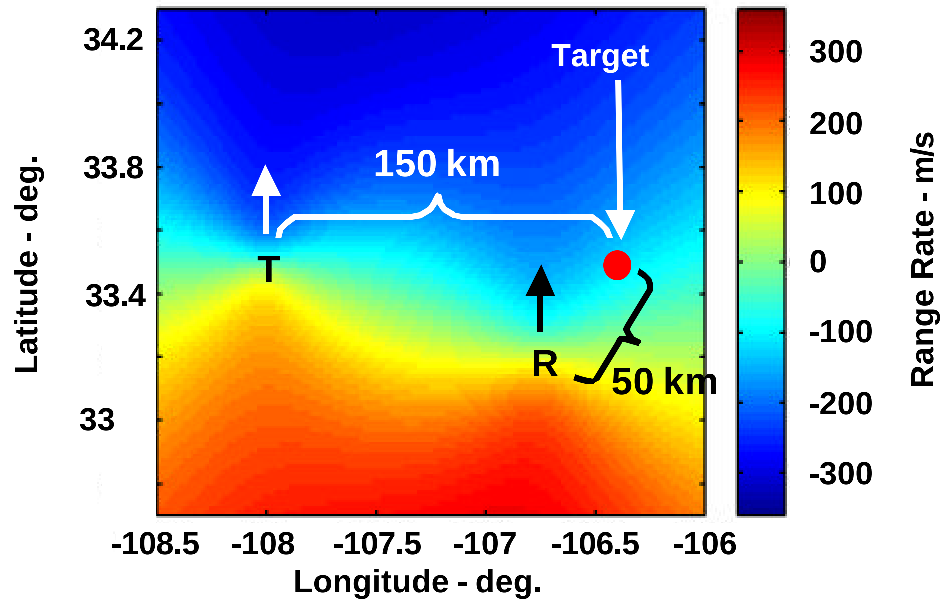
Case 1: Air to Air Geometry

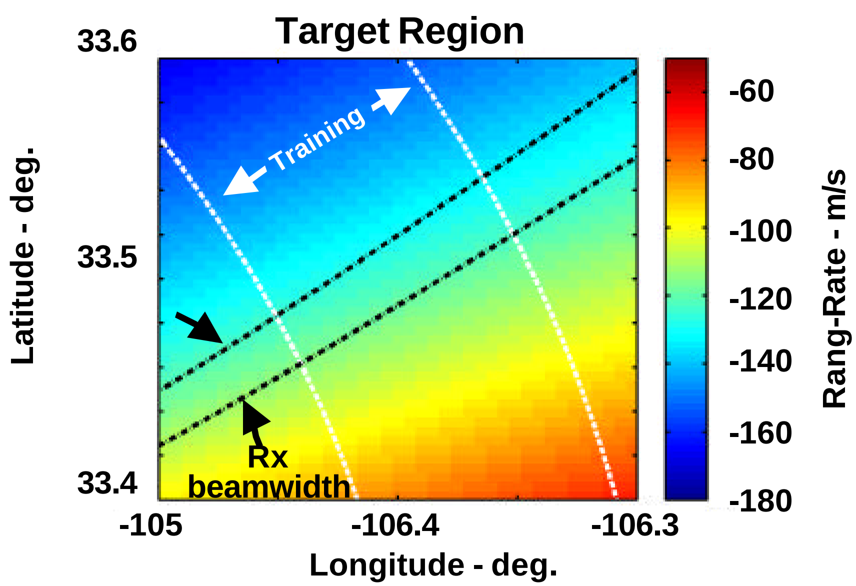
Transmitter

Altitude	10 km
Speed	180 m/s
Heading	North
Freq.	5.2 GHz
Bandwidth	5 MHz
Array Elements	8 Hor. X 24 Ver.

Receiver

Altitude	16 km
Speed	180 m/s
Heading	North
Array Elements	32 Hor. X 1 Ver.
# DOFs	32



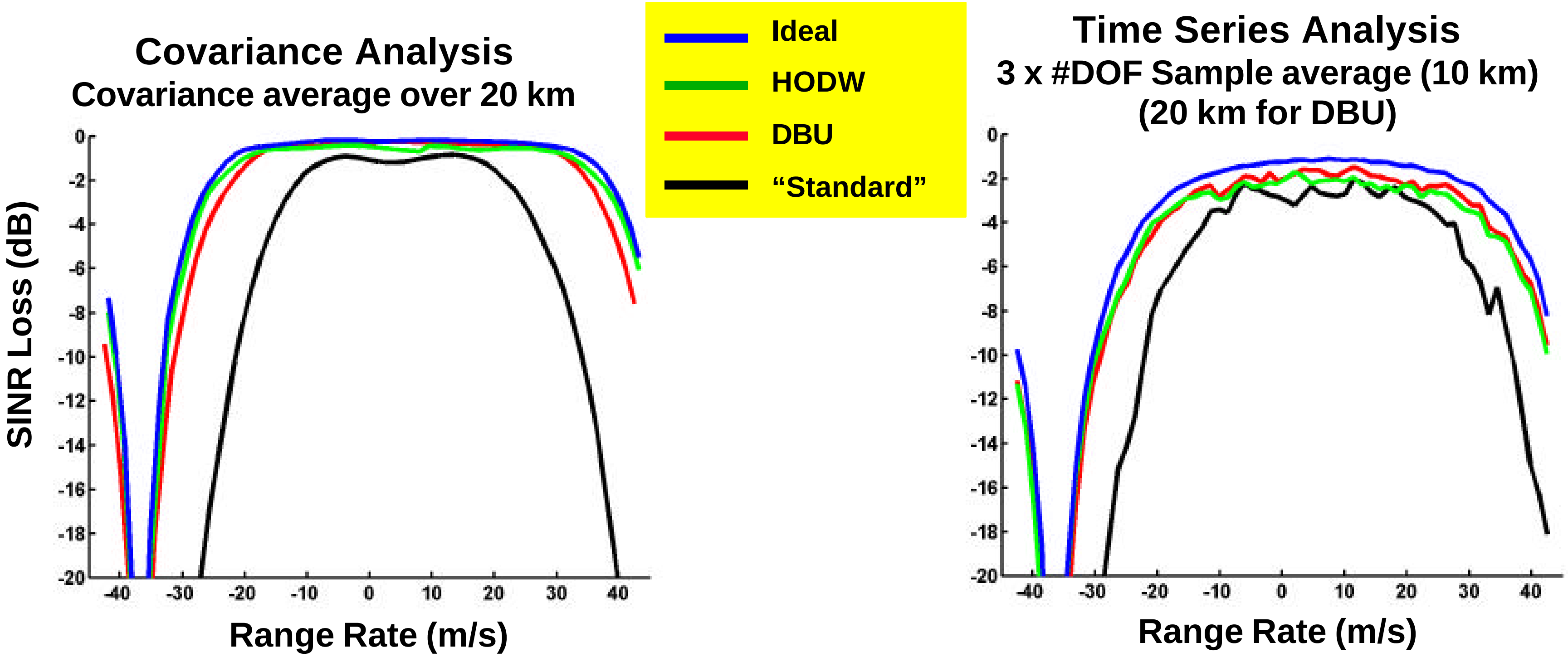


Training Region - 20 km

Receiver Beamwidth - 4.6 deg.

- **Moderate variation of clutter ridge with range**

Algorithm Performance - Bistatic Air to Air (Case 1)



- **Standard Sample Covariance Matrix approach significantly degraded**
  - Only moderate variation of clutter interference structure across training region
  - Standard approach preserves 60% of useable Doppler space (UDSF)
- **Both DBU and HODW methods yield near - ideal performance**
  - DBU preserves 80% UDSF, HODW 85%, Ideal 85%

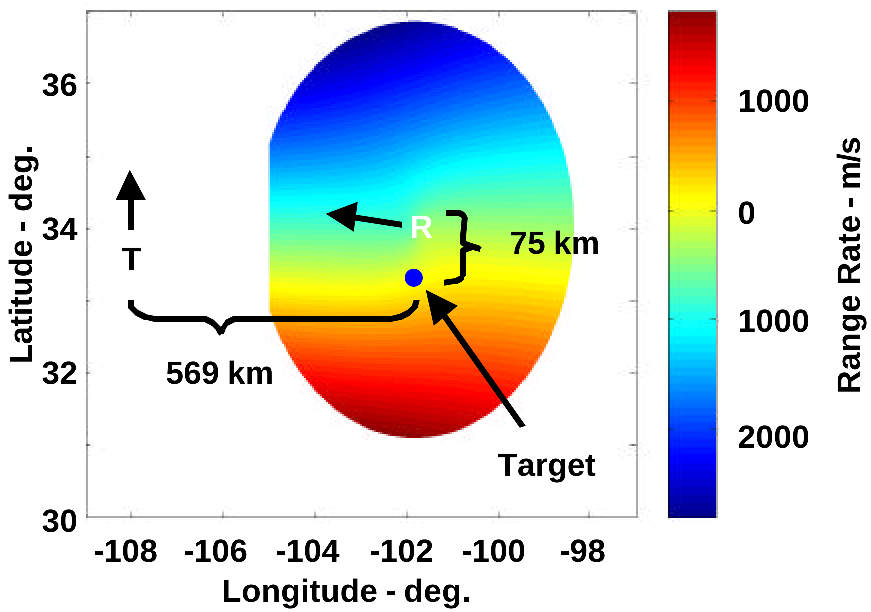
Case 2: Space to Air Geometry

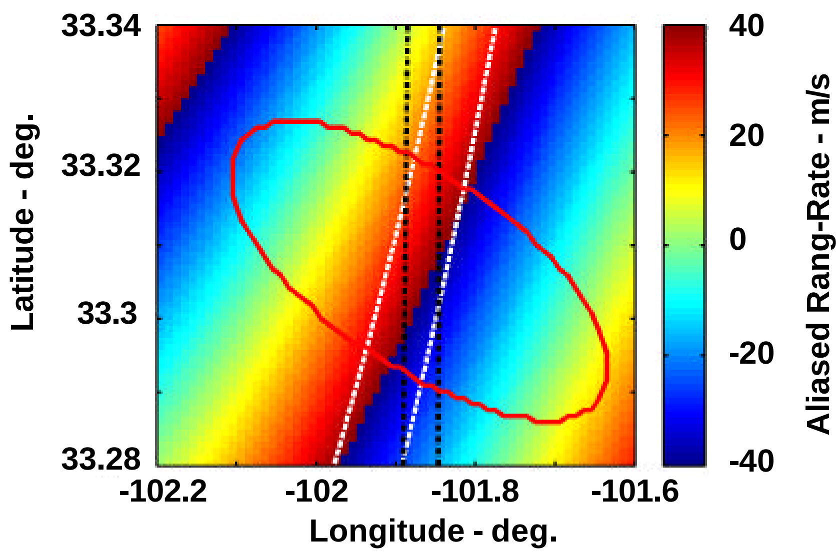
Transmitter

Altitude	800 km
Speed	7540 m/s
Heading	North
Freq.	5.2 GHz
Bandwidth	12 MHz
Array Elements	501 Hor. X 51 Ver.

Receiver

Altitude	6 km
Speed	200 m/s
Heading	-86^{o} wrt North
Array Elements	36 Hor. X 24 Ver.
# DOFs	36
CNR	40 dB

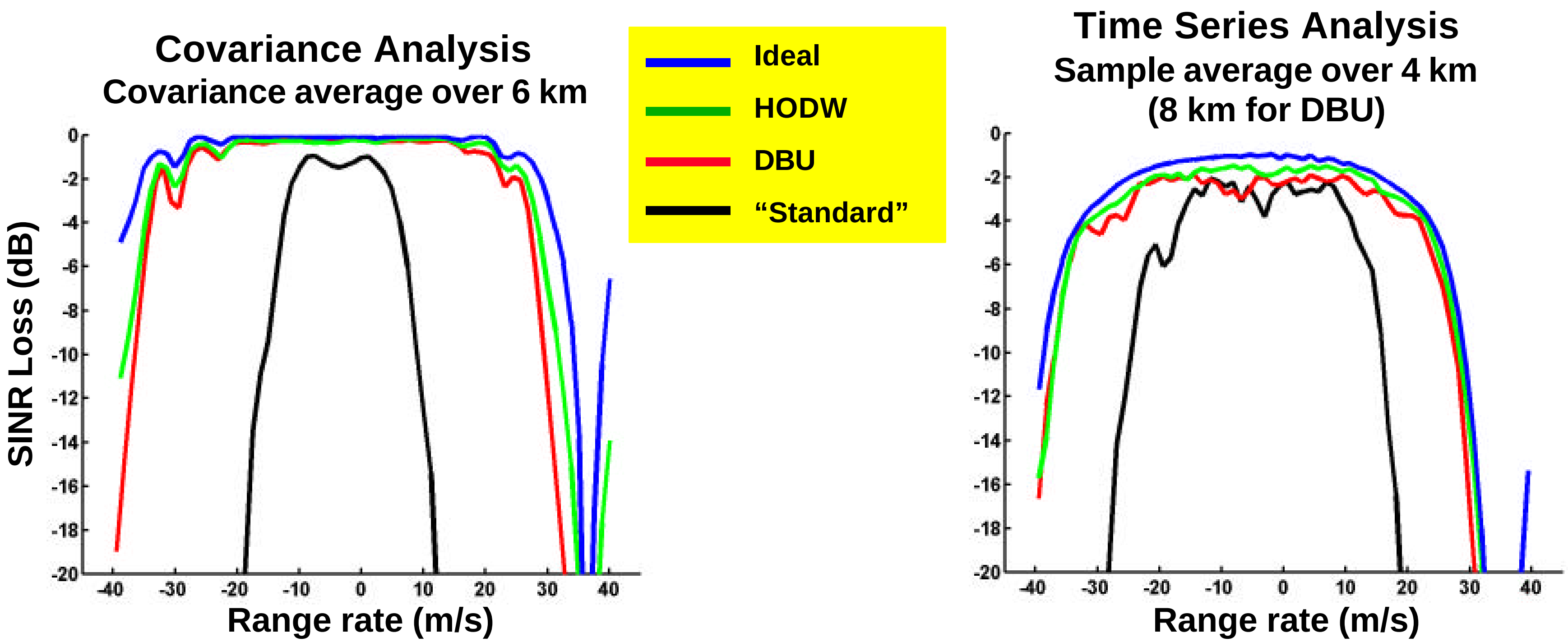




- Training Region - 4 km
- Receiver Beamwidth - 2.8 deg.
- 3 dB Transmitter Beamwidth

- **Clutter ridge varies rapidly with range**

Algorithm Performance - Bistatic Space to Air
Case 2



- **Standard Sample Covariance Matrix approach performs poorly**
  - Very rapid variation of clutter interference structure across training region
  - Much worse performance than in air to air case
  - UDSF degrades from 45% with 4 km training to 25% with 6km training
- **Both DBU and HODW methods again yield near - ideal performance**
  - UDSF is 80% for both DBU and HODW, UDSF for ideal is 90%

Bistatic STAP Algorithms - Recap

- Standard training approach for STAP works poorly
  - Poor choice for non - stationary interference
- DBU approach
  - Advantages
    - No knowledge of transmitter position and velocity required
  - Disadvantages
    - Doubles the STAP degrees of freedom
      - Doubles the number of training samples required
      - Increases cost of weight computation by factor of 8
        - No significant impact on weight application computation
- HODW Approach
  - Advantages
    - No increase in degrees of freedom required
    - Fully adaptive in spatial dimension
  - Disadvantages
    - Requires knowledge of transmitter position and velocity
    - Increased complexity of Doppler filtering
      - FFT techniques may not be possible

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Summary

- **Bistatic clutter interference suppression poses new challenges**
  - **Clutter interference exhibits strongly range dependent structure**
- **Doppler warping technique generalized**
  - **"High Order Doppler Warping" algorithm**
- **2-bin Post- Doppler Algorithms examined both with covariance analysis and more realistic direct time series analysis**
- **Preliminary assessments of selected algorithms in Air - to - Air and Space - to - Air bistatic scenarios presented**

  All algorithms rely on sample average over range to estimate clutter interference covariance

  - **Standard training - POOR**

    (no attempt to address range variation)
  - **Derivative Based Updating (DBU) - GOOD**

    Requires doubling problem dimensionality
  - **High Order Doppler Warping (HODW) - GOOD**

    Requires knowledge of transmitter position and velocity

    Doppler filter implementation more complex

Future Directions

- Extend analyses to other engagement geometries
- Assess impact of imperfections
  - Array element calibration uncertainties
    - Both DBU and HODW are fully data adaptive in the spatial dimension
      - No deterministic spatial transformations
      - Anticipate impact similar to that on monostatic STAP
  - Engagement geometry uncertainties
    - HODW requires *a priori* knowledge of transmitter position and velocity
- Develop computational complexity estimates for HODW
  - Determine optimal implementation strategy