Spatial and Temporal Processing for a Compact Landmine Detection Radar

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Outline

- Introduction & Motivation
- Our Approach
- A Compact Landmine Detector
- Experiments and Results
- Optimum Signal Processing Algorithms
- Conclusions & Future Work

Landmine Detection – The Challenge

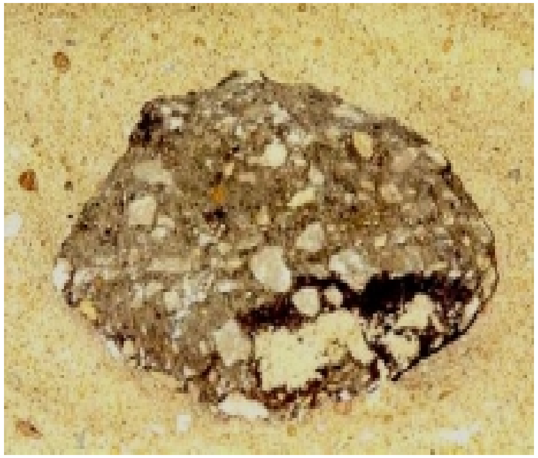
- UN estimates 70 million mines buried all over the world.

- Challenges in Landmine Detection
  - Clearance Rate
  - Probability of False alarm(P_{FA}) and Missed detection (P_M).

- Landmine Detection Schemes use
  - Metal Detectors.
  - Infra Red Sensors.
  - Chemical Sensors.

- Efficient Landmine Detection Scheme: High P_D and also a low P_{FA}.

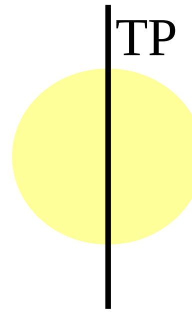
Our Approach

- Is there a property in landmines which is absent in clutter?
- Mines are symmetric and clutter is asymmetric.
- Landmines exhibit reflection symmetry.
- Reflection Symmetry?

Symmetry in Landmines

- Top View of a landmine



- TP is Target Reflection Symmetric Plane.
- How can we detect Symmetry in Landmines?
- **Our Approach** : Use Ground Penetrating Radar (GPR).
- GPR can be used for detecting subsurface target, but….
- How can symmetry be established with GPR?

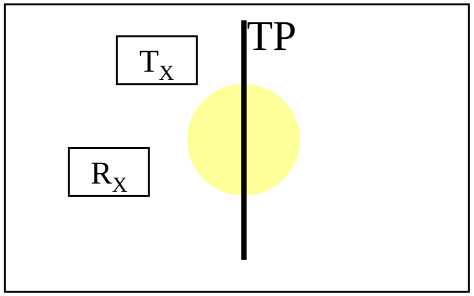
Bistatic Measurements

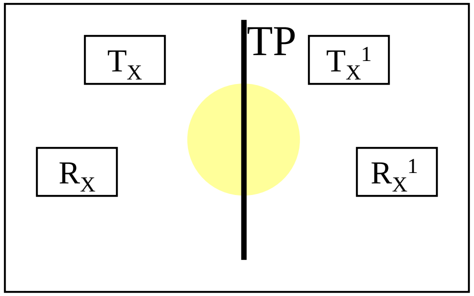
- Bistatic Measurement T_X-R_X.
- Target has reflection Symmetry:

  Record measurement T_X-R_X.
  Reflect the target about TP.
  Record measurement T_X- R_X again.

- Reflect the bistatic measurement T_X-R_X.
  - TP is also Measurement Reflection Symmetric Plane.
- Identical Bistatic measurements $y_1(t)$ and $y_2(t)$.

$$x_1(t) = w(t)y_1(t)$$
$$x_2(t) = w(t)y_2(t)$$





Mirrored Bistatic Observation Pair

Target Detection and Classification

- Is a subsurface target present?

$$\text{sum}\,(\Sigma) = \int \left| x_1(t) + x_2(t) \right|^2 dt$$

- Is the subsurface target symmetric?

$$m = \frac{\int \left| x_1(t) - x_2(t) \right|^2 dt}{\int \left| x_1(t) + x_2(t) \right|^2 dt} = \frac{\int \left| x_1(t) - x_2(t) \right|^2 dt}{\text{sum}(\Sigma)}$$

- Typical values for *m* coefficient
  - Low *m* values for symmetric targets.
  - For asymmetric targets:ranges from low to high values.

- Is one *m* value sufficient for Target classification?

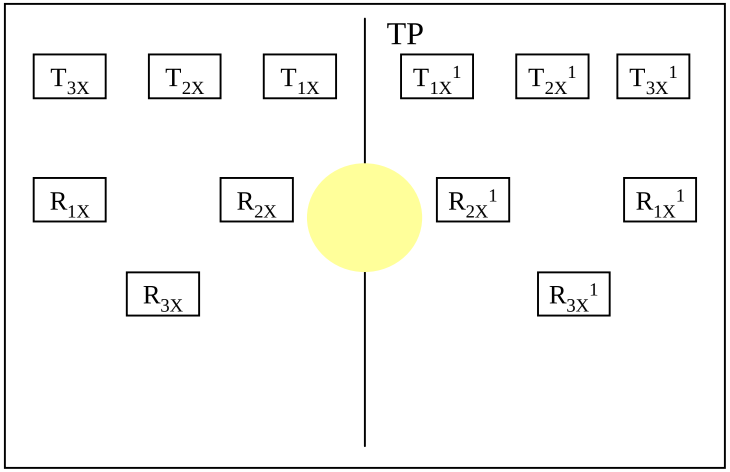
Target Detection and Classification

- Single *m* coefficient $\Rightarrow$ High P_{FA}.

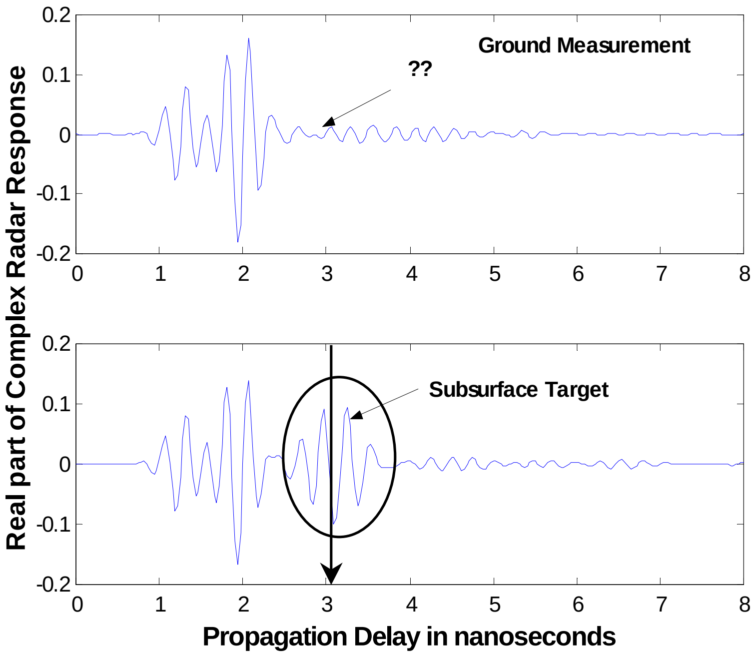
- How many *m* coefficients are needed?

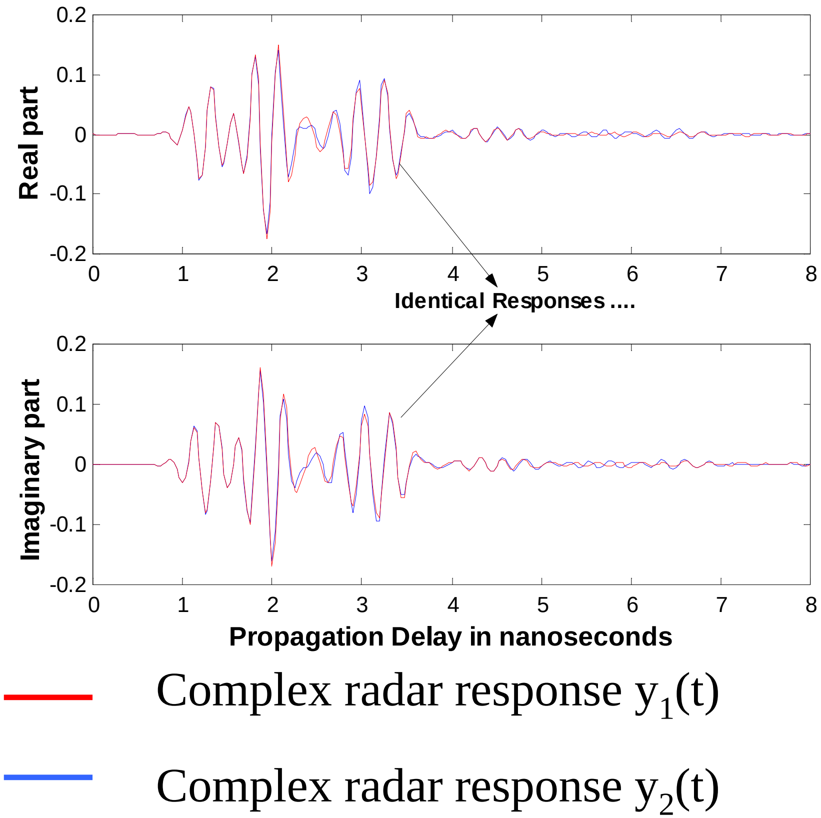
  - Higher the number *m* values, higher is the confidence level in target classification.

- Solution: Collect many mirrored observation pairs.



Initial Results





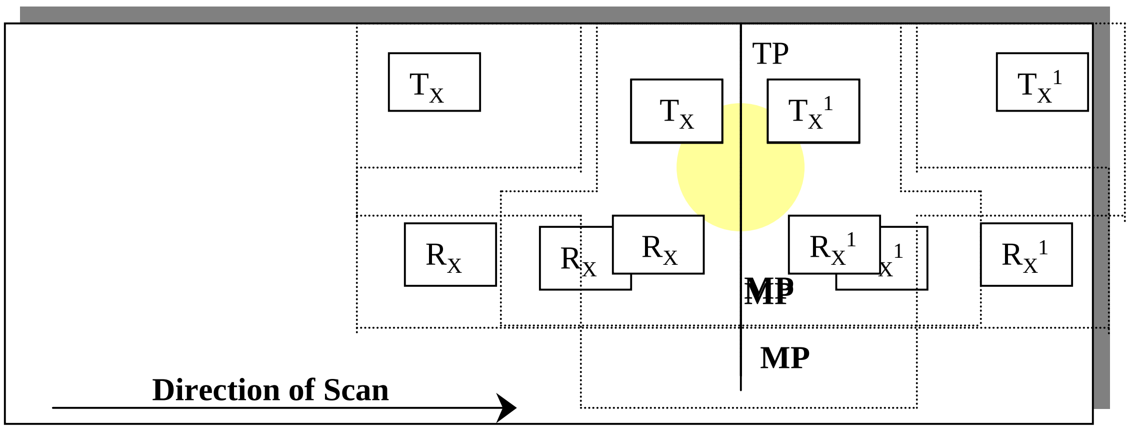
Subsurface target detected based on electromagnetic scattering.

Symmetry in subsurface targets manifests itself as identical scattering.

A Compact Landmine Detector

Handheld Model

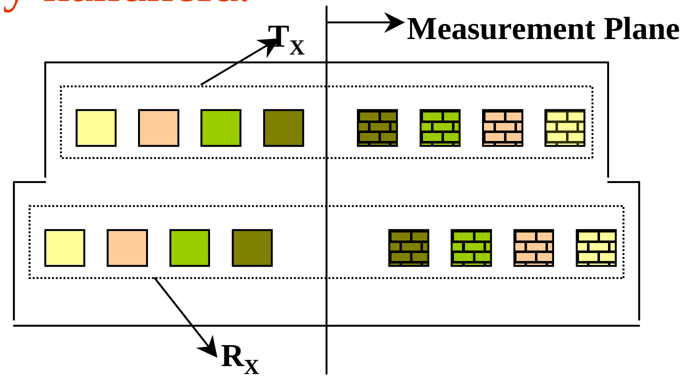
- Possible Handheld model (Top View)



- TP is the target reflection symmetric plane.
- MP is the measurement reflection symmetric plane.
- The combination T_X-R_X T_X^1-R_X^1 is called a *Sensor Geometry*.
- MP for every point in the scan: *Measurement Plane*

Multiple Sensor Geometry Handheld

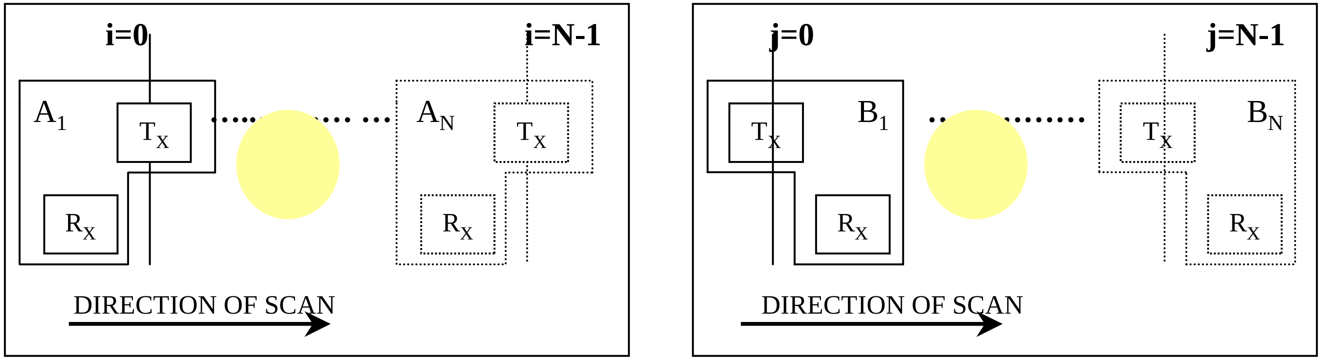
- Scan with a single Sensor geometry
  - Target classification based on one *m* value.
  - P_{FA} can be high.
- Solution
  - Repeat scans with different sensor geometries.
  - Develop a Multiple Sensor Geometry handheld.
- N sensor geometries ⇒N *m* values for classifying the target.



- Higher N lesser the P_{FA} …but greater the complexity.

Data Collection Scheme

- The data collection scheme should
  - reduce the complexity greatly.
  - synthesize Multiple Sensor Geometry Handheld.
- The data collection scheme consists of two scans.



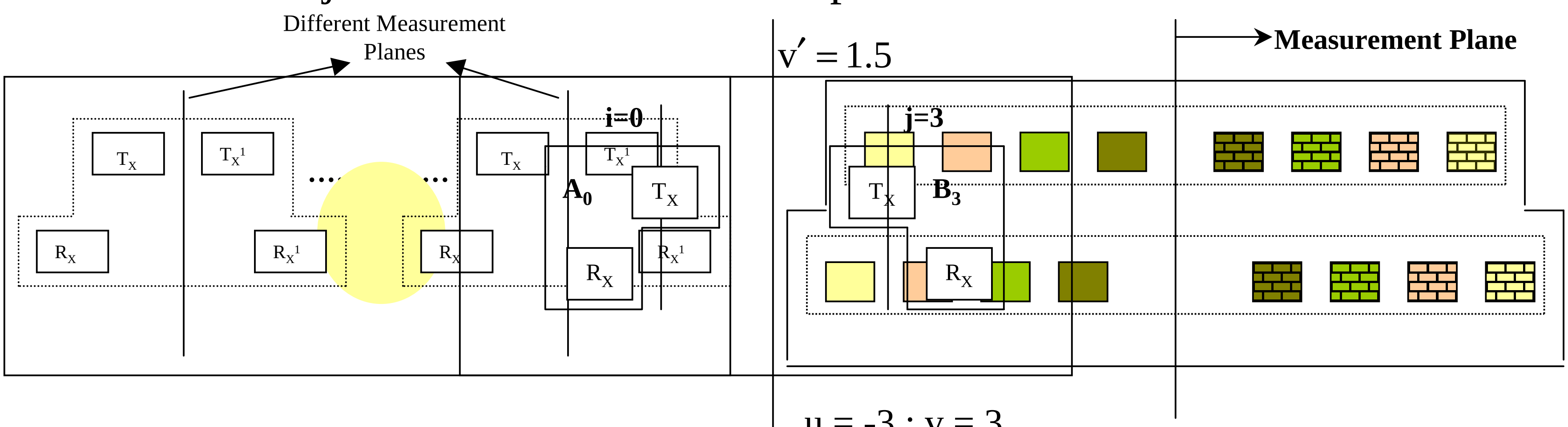
A_i : bistatic measurement at location i

B_j : bistatic measurement at location j

- Synthesize Multiple sensor geometry handheld!! How?

Synthesizing Multiple Sensor Geometry Handheld

- Reconstruct Multiple sensor geometry handheld
  - Combine A_i and B_j to form mirrored bistatic observation pairs.
  - $u = i - j$ defines the sensor geometry.
  - $v = i + j$ defines the measurement plane.

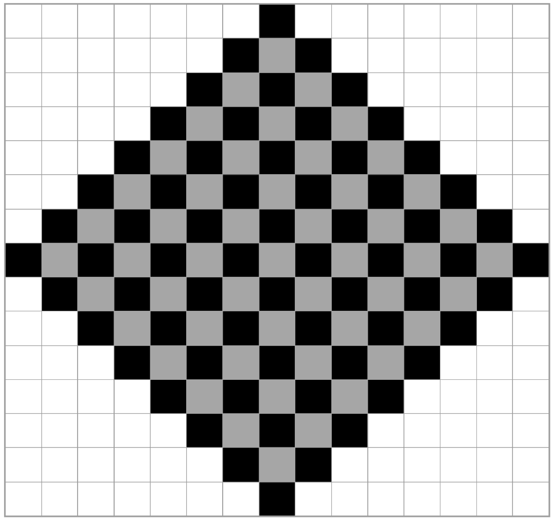


Multiple measurement planes for a single sensor geometry (u is constant).

Multiple sensor geometries for a single measurement plane (v is constant)

Expected Results

- For each sensor geometry-measurement plane combination
  - sum $\Sigma(u,v) = \int \left| x_{A_i}(t) + x_{B_j}(t) \right|^2 dt$
  - $m(u,v) = \dfrac{\int \left| x_{A_i}(t) - x_{B_j}(t) \right|^2 dt}{\int \left| x_{A_i}(t) + x_{B_j}(t) \right|^2 dt}$



Is a subsurface target present?

Inspect the **sum** value matrix. The presence of the subsurface target is reflected as high sum values for some measurement planes.

Is the subsurface target symmetric?

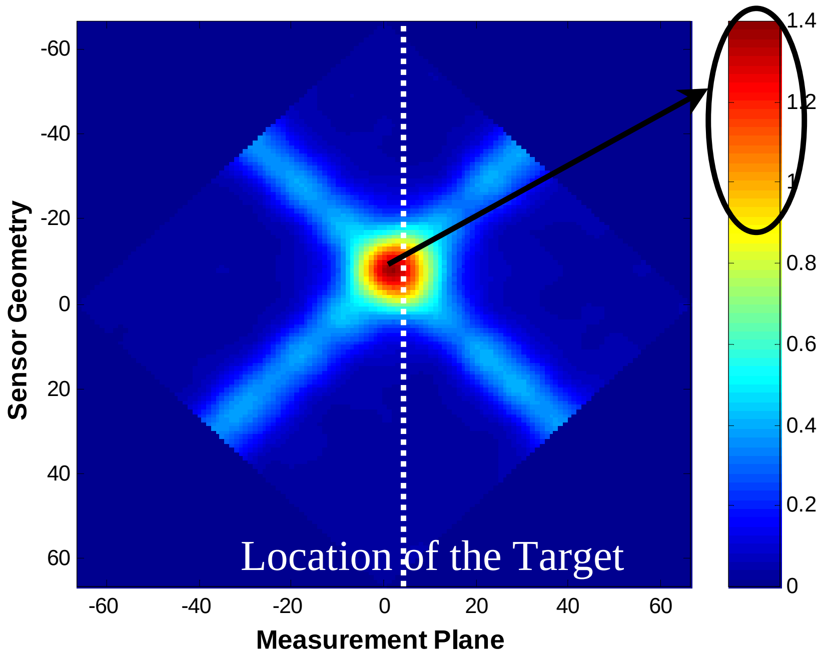
Inspect the ***m*** value matrix. Low *m* values for all sensor geometries when measurement plane aligns with plane of target symmetry.

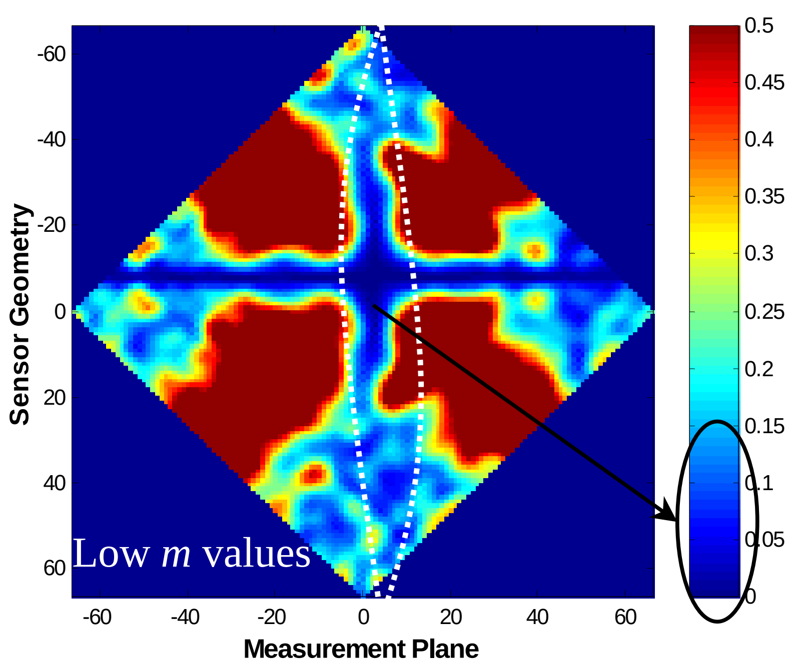
Experiments in Sandbox

- Targets used in sandbox experiments
  - Styrofoam Disc.
  - Rock.
  - Crushed Milk Jug.

- Data Processing
  - Matched Filter – radar response as function of time
  - Form *m* values and sum values matrices
  - Generate color-coded plots.

Styrofoam Disc

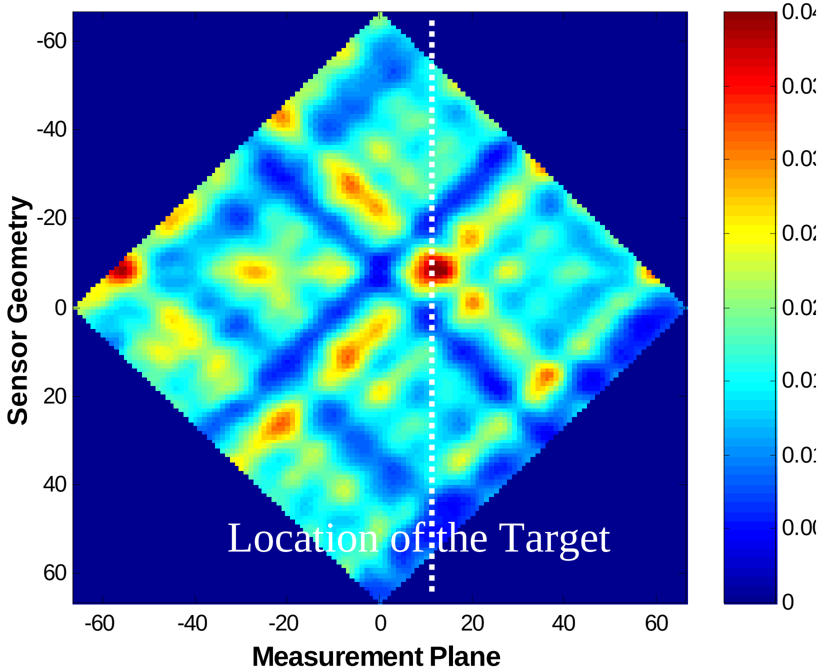


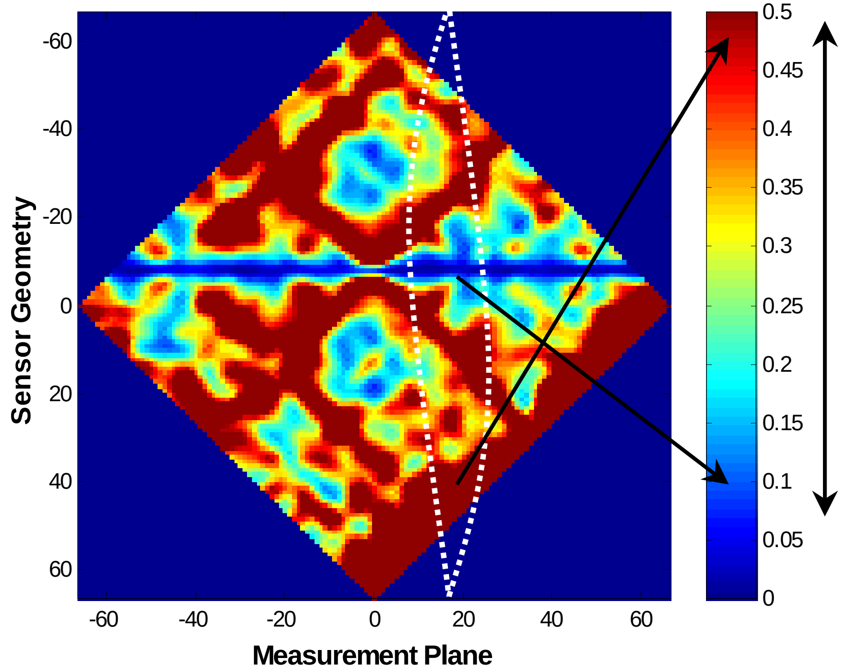


Sum plot indicates presence of the subsurface target!

m plot indicates the subsurface target is symmetric.

Crushed Milk Jug



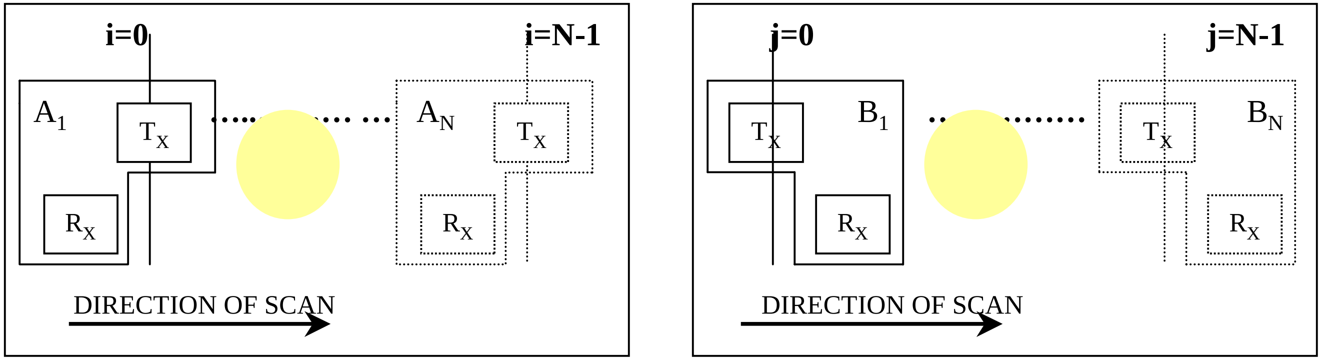


Sum plot indicates presence of the subsurface target!

m plot indicates the subsurface target is clutter.

Sensor Array

- A sensor array can be synthesized using the data collected

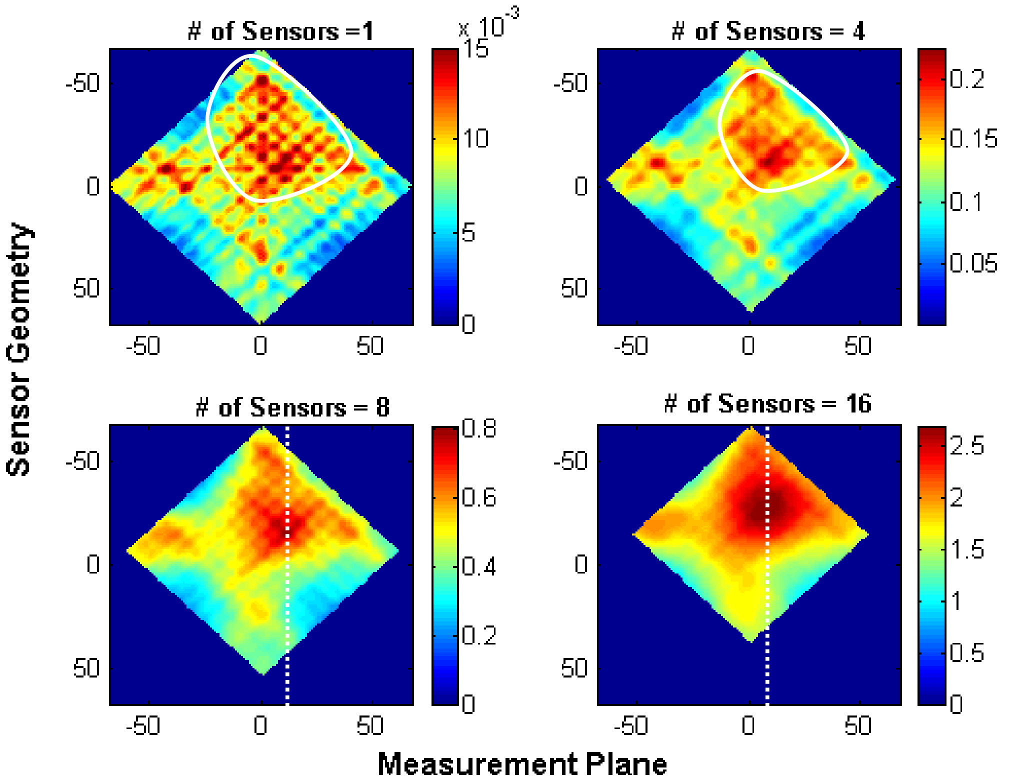


$$x^{c}_{A_i} = \sum_{k=i}^{i+K-1} x_{A_k}$$

$$x^{c}_{B_j} = \sum_{k=j}^{j+K-1} x_{B_k}$$

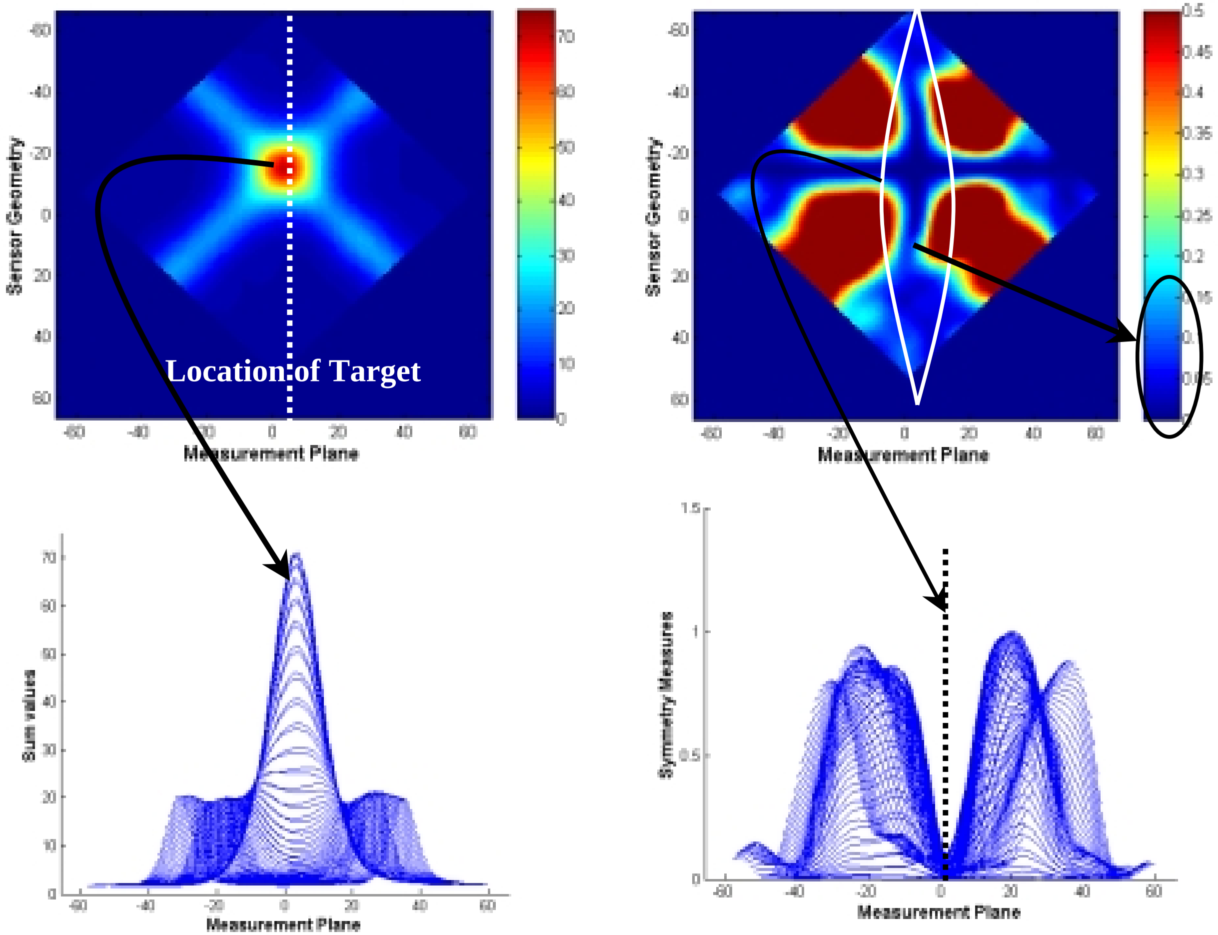
Sensor Array Processing

VAL-69   Antipersonnel Mine



Sensor array with 8 or 16 sensors solves the uncertainty in target detection.

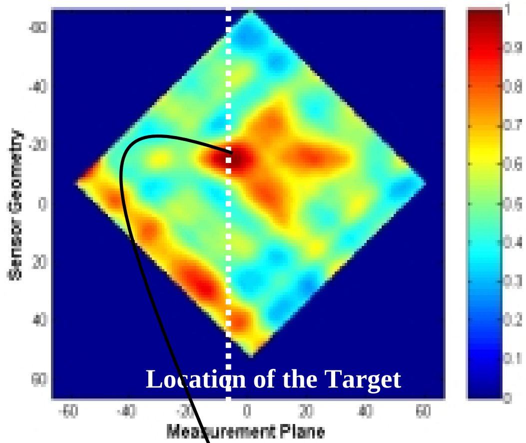
Sandbox Experiment
Styrofoam Disc

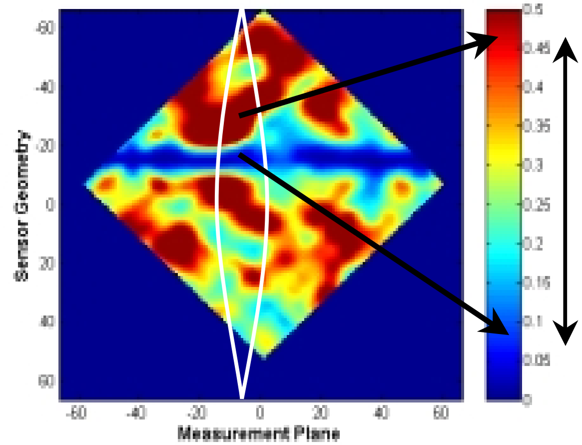


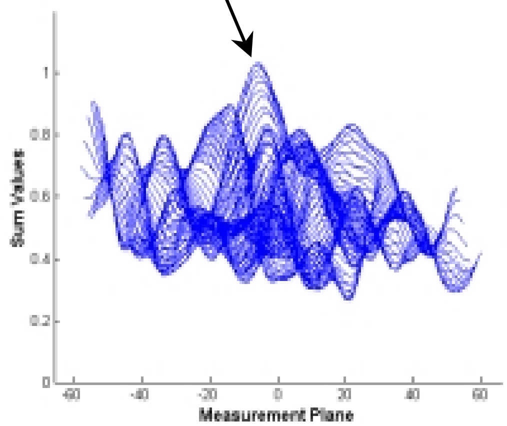
Sum plot indicates presence of target

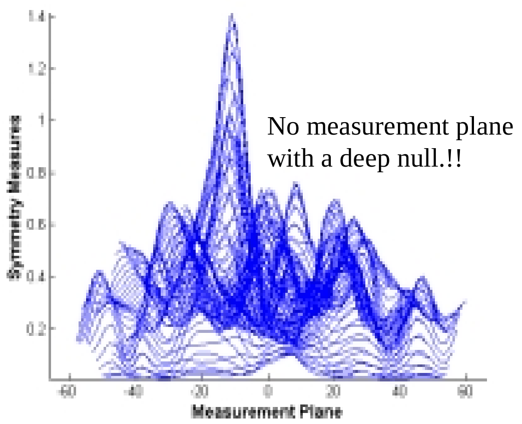
m plot indicates that target is a symmetric

Sandbox Experiment-Rock





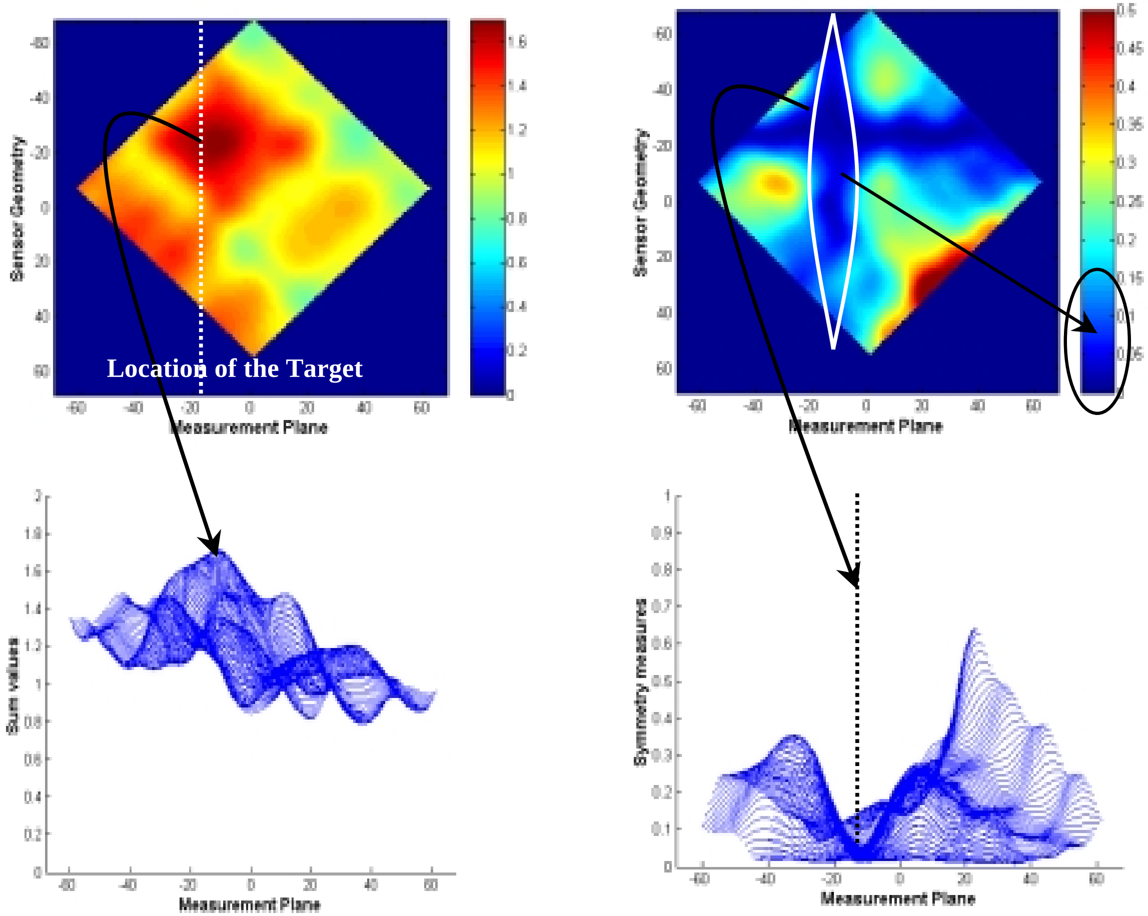




Sum plot indicates presence of target

m plot indicates that target is a clutter

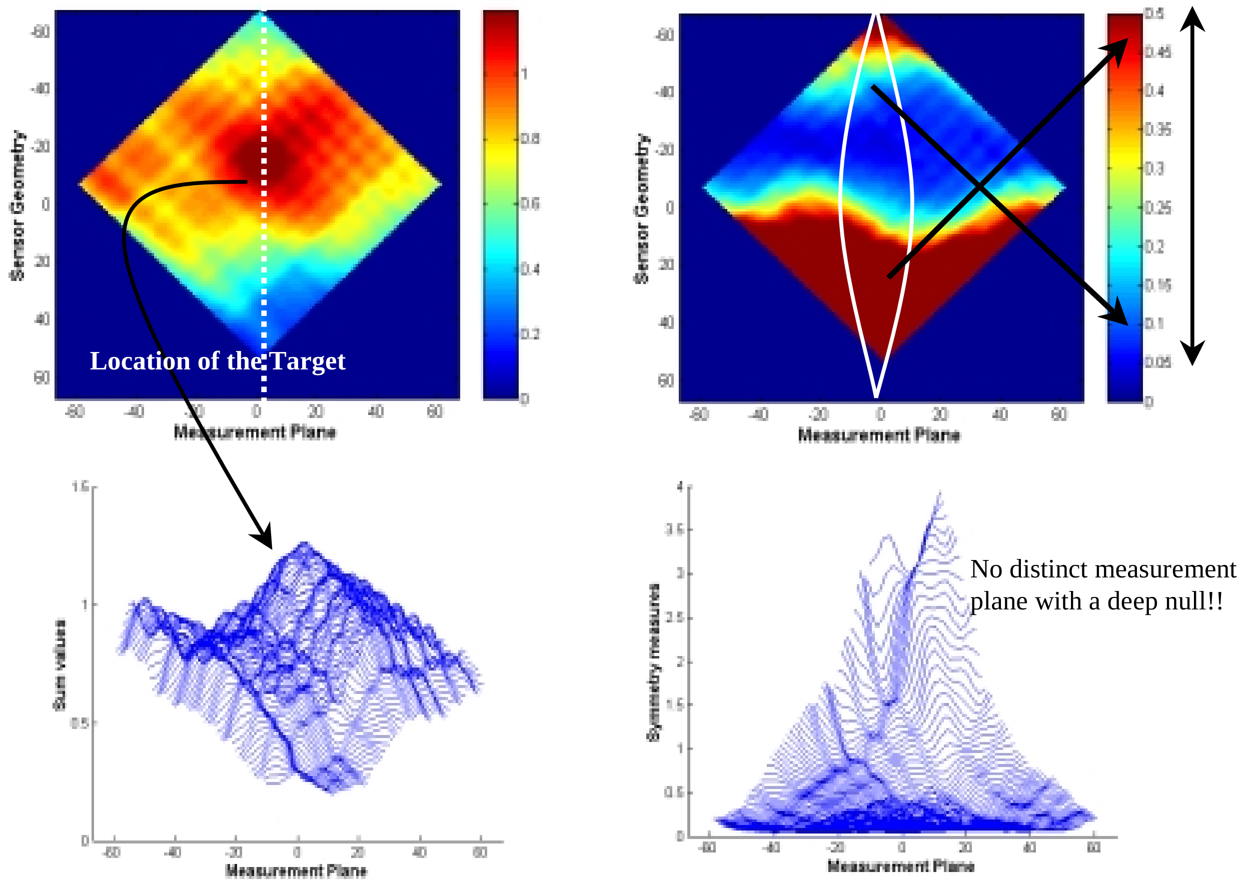
Field Experiment PMA-3



Sum plot indicates presence of target

m plot indicates that target is a mine

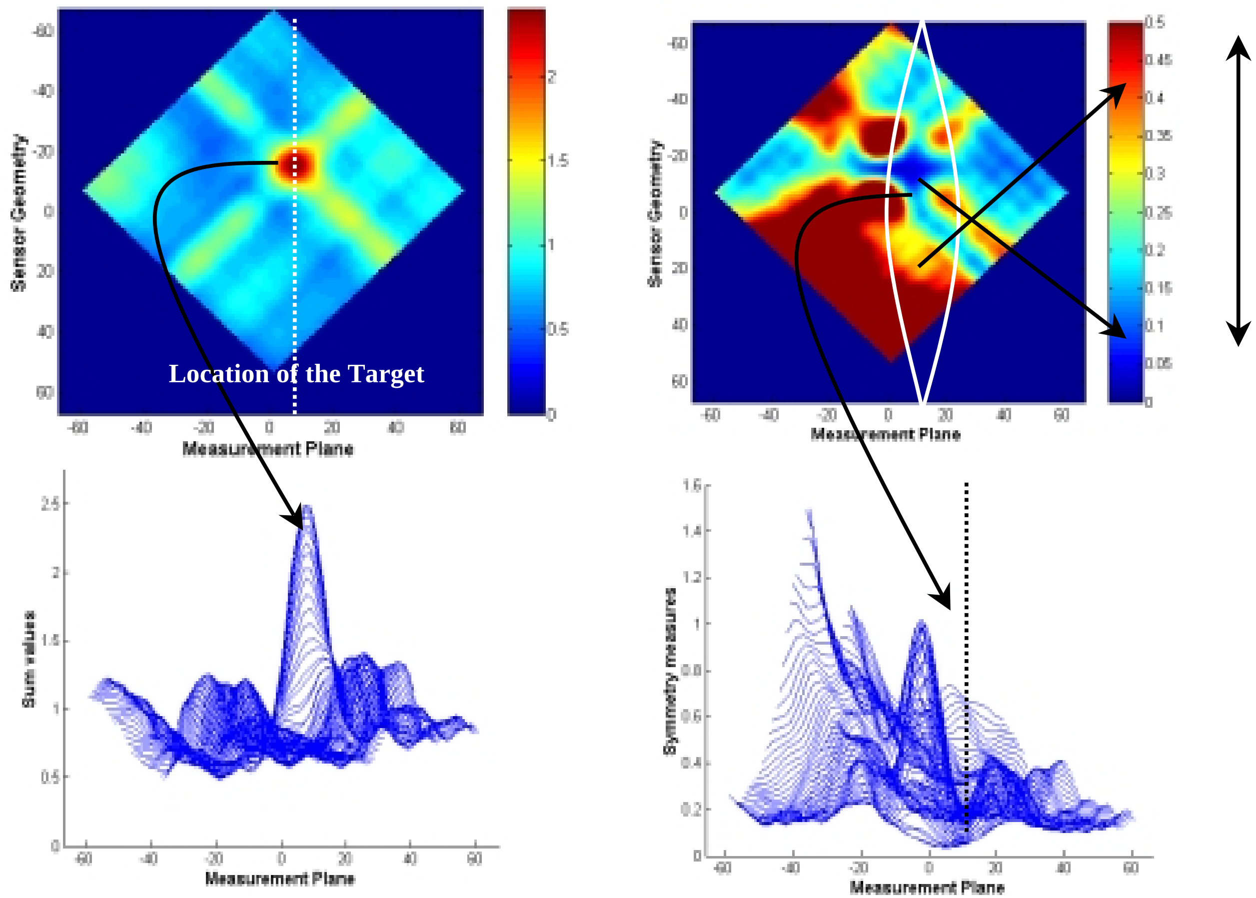
Field Experiment
Irregular Wood



Sum plot indicates presence of target

m plot indicates that target is clutter

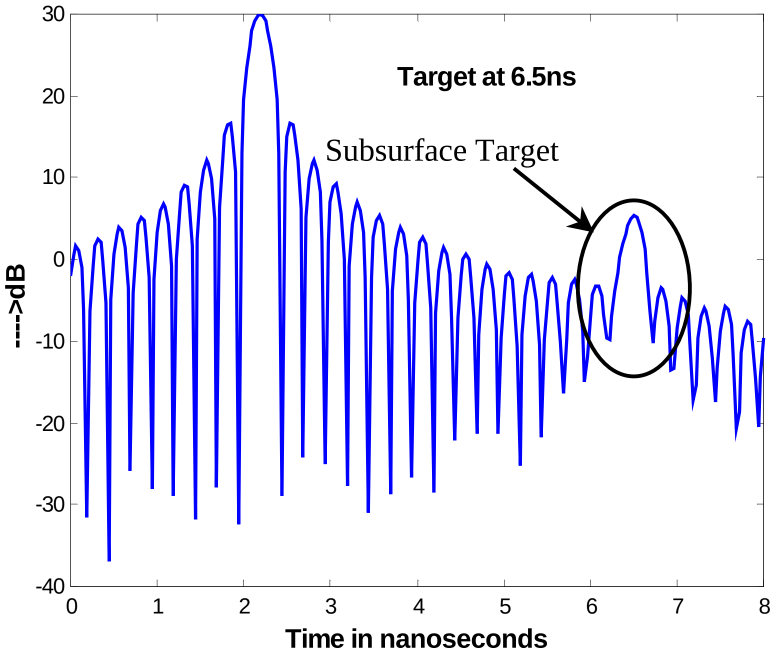
Field Experiment
TM-46

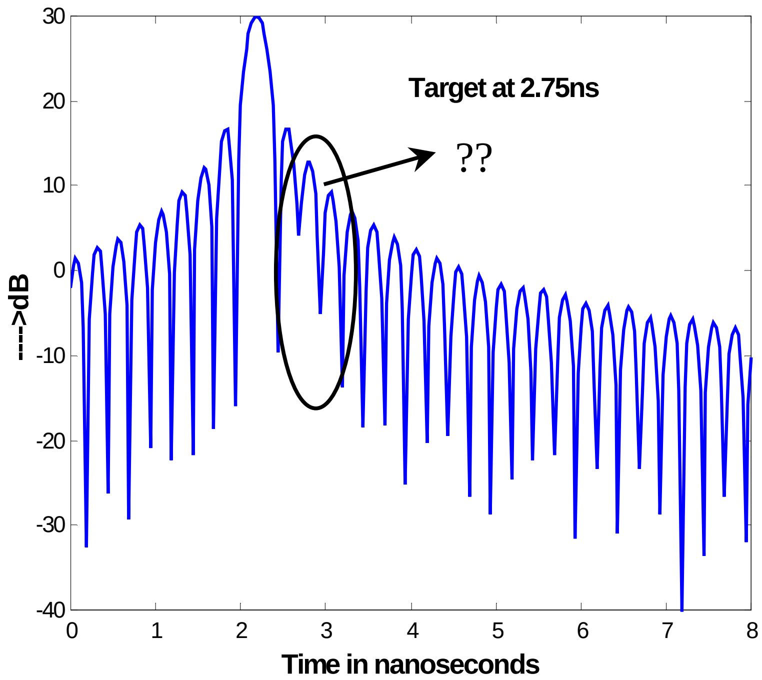


Sum plot indicates presence of target

Is the subsurface target a mine or clutter?

Matched Filter



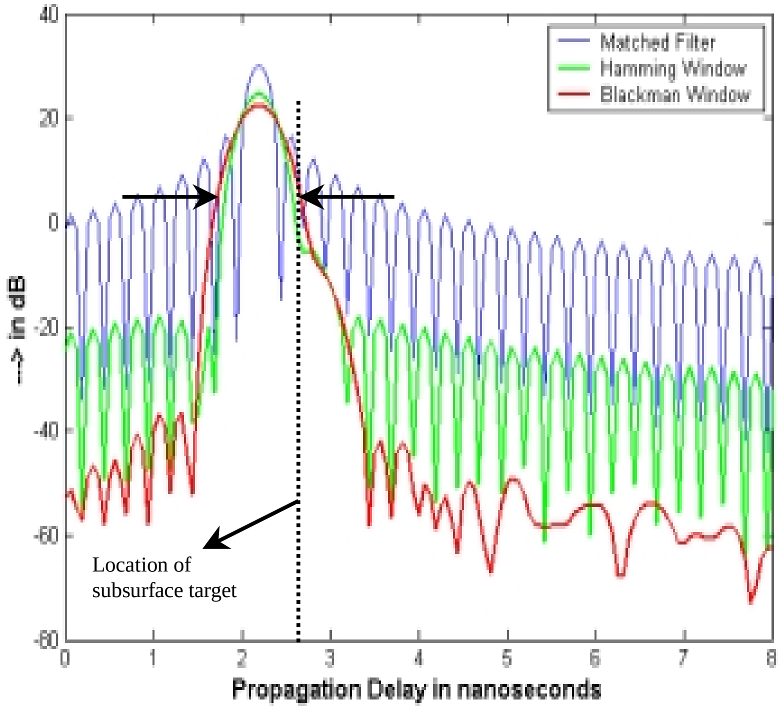


- Time domain side lobes mask subsurface target.
- Can a better signal processing algorithm be developed?

Optimum Signal Processing Algorithms

- Conventional solution
  - Use Windowing Functions.
  - Is it an efficient solution?

- Motivation
  - Interference dominated by clutter….not by noise.
  - Matched Filter maximizes SNR.
  - Criterion: Maximize SIR

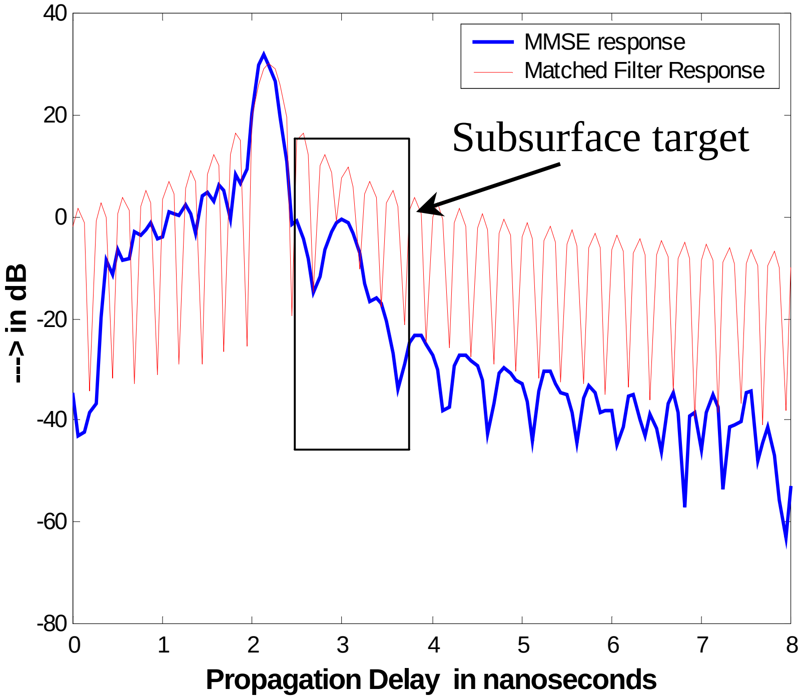


Basis for developing a robust signal processor:
a priori information about the scattering scenario.

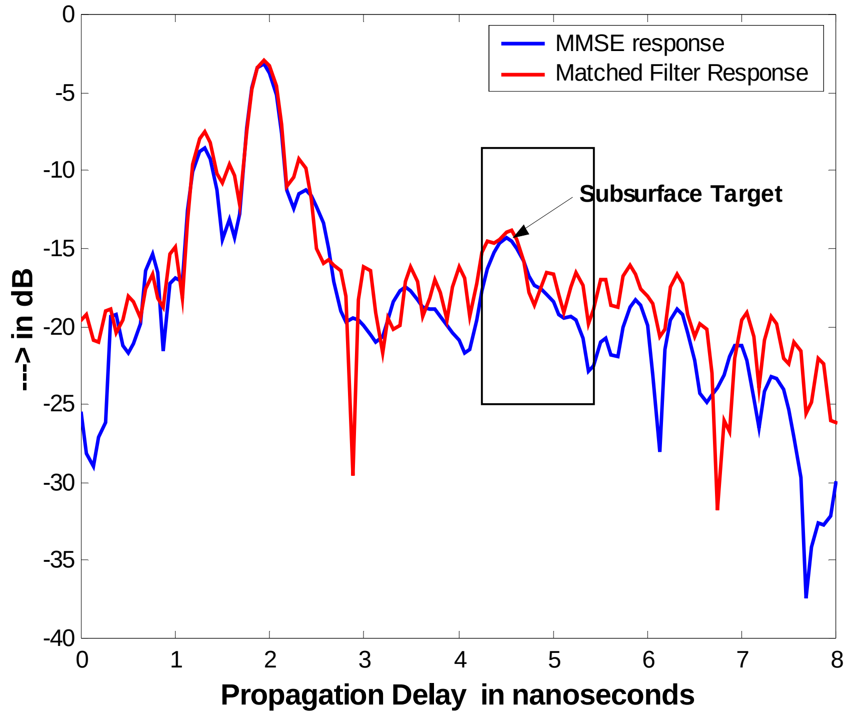
MMSE GPR Processor

- Radar Response Model: $r = \sum_{j} \gamma_j \rho_j + n$
    - Using Linear Algebra $r = P\gamma + n$ where P is the expected response matrix.
- The estimate of scattering $\hat{\gamma} = W_{EST} r$
- The criterion to be minimized $\varepsilon = \hat{\gamma} - \gamma$
- The MMSE Estimator $W_{EST} = K_{\gamma} P' \left[P K_{\gamma} P' + K_n \right]^{-1}$
    - W_{EST} is the MMSE Estimator.
    - $K_{\gamma} = E\{\gamma\gamma'\}$ is the target correlation matrix.
    - K_n is the noise covariance matrix.

Results



Simulation Results



TM-46 Antitank mine

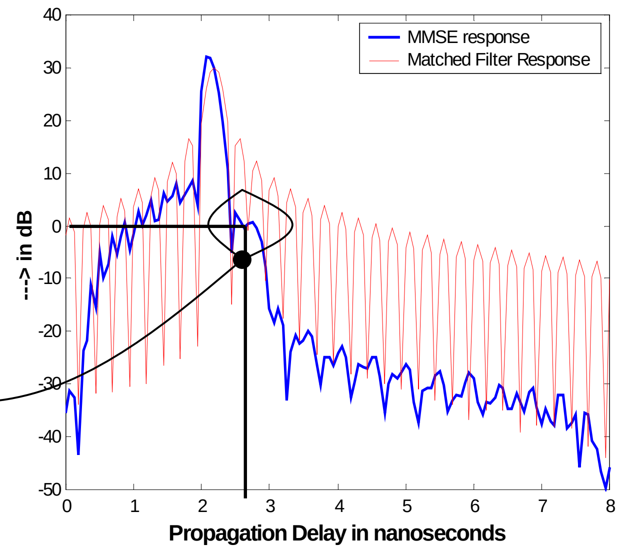
MMSE GPR processor performs better than Matched Filter.

MMSE GPR Processor-Summary

- MMSE GPR Processor
  - Reduces the effects of surface clutter on subsurface scattering.
  - Maximizes SIR, performs better than Matched Filter.
  - Gives accurate estimates of scattering.

- Problems with the MMSE GPR Processor
  - Time consuming algorithm.
  - If target buried at very shallow depths.

Subsurface Target ??



Kalman Filter Implementation

- Motivation
  - Reduce processing time.
  - Performance improvement.
- Kalman Filter based on two fundamental equations
  - State Equation : $x(m+1) = A(m)x(m) + u(m)$
  - Observation Equation: $y(m) = C(m)x(m) + n_1(m)$
- Develop a Kalman filter for our application.

Kalman Filter Algorithm

$$K_\gamma(m \mid m-1) = K_\gamma(m-1 \mid m-1) + K_u(m)$$

$$K_\gamma(m) = E\{\gamma(m)\gamma'(m)\} \quad K_u(m) = E\{u(m)u'(m)\}$$

Error Covariance Matrix

The Kalman Gain

$$G(m) = K_\gamma(m)P'(m)\left[P(m)K_\gamma(m \mid m-1)P'(m) + K_n(m)\right]^{-1}$$

The innovation Process

$$\upsilon(m) = r(m) - P(m)\hat{\gamma}(m-1 \mid m-1)$$

The Estimate of Scattering

$$\hat{\gamma}(m \mid m) = \hat{\gamma}(m-1 \mid m-1) + G(m)\upsilon(m)$$

$$K_\gamma(m \mid m) = \left[I - G(m)P(m)\right]K_\gamma(m \mid m-1)$$

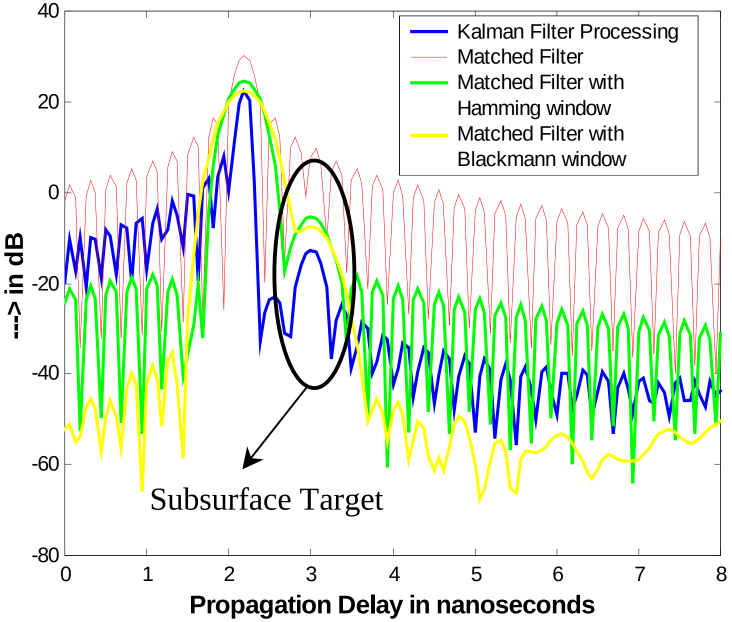
Initial Condition have to be set to initiate the Kalman Filter

Simulations

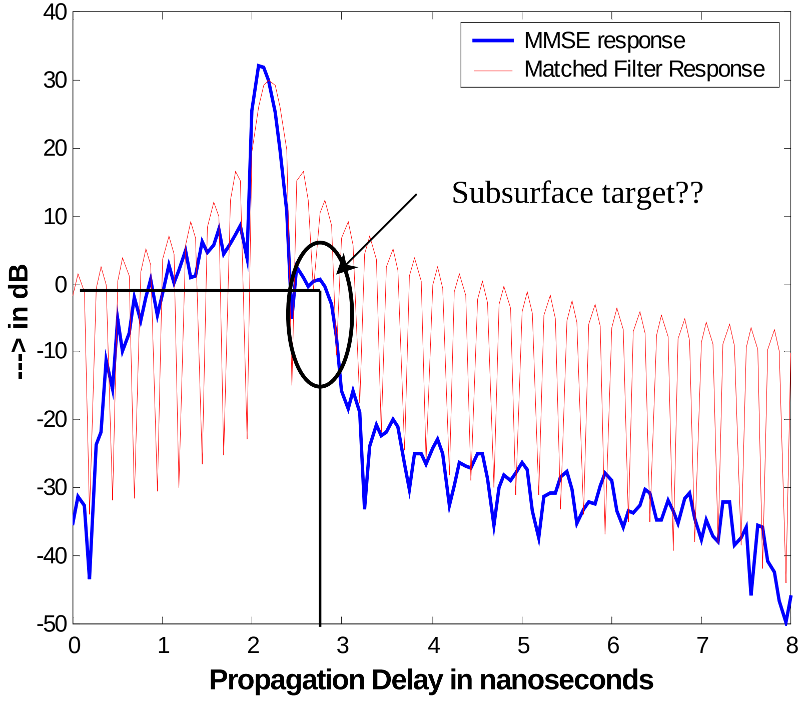
- Initial Conditions set for
  - Error Covariance Matrix
  - Target Correlation matrix
  - Initial Scattering
- Optimum length of radar data segment: One

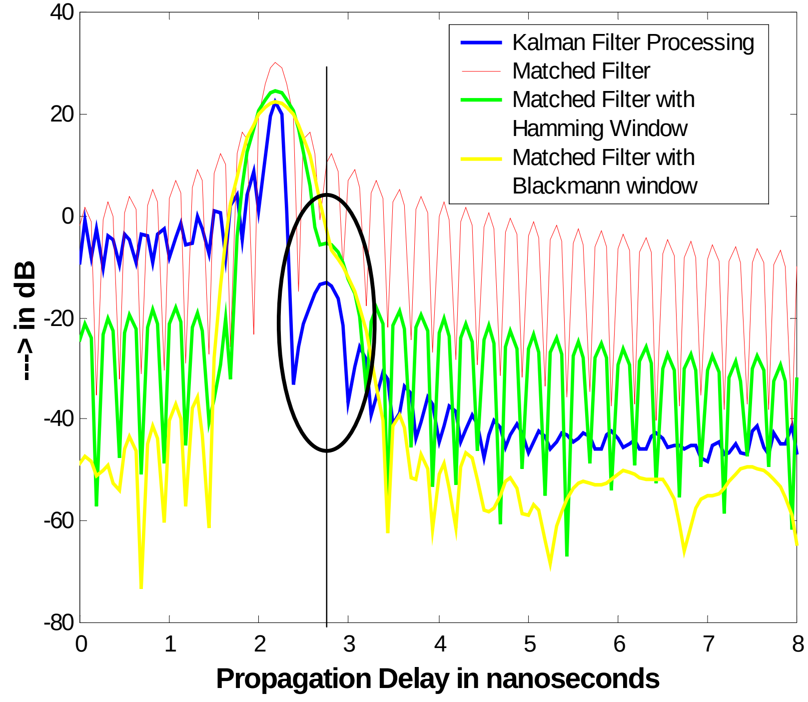
Kalman Filter performs better than Matched Filter.

How is this a performance improvement over MMSE GPR Processor?



Simulation Results

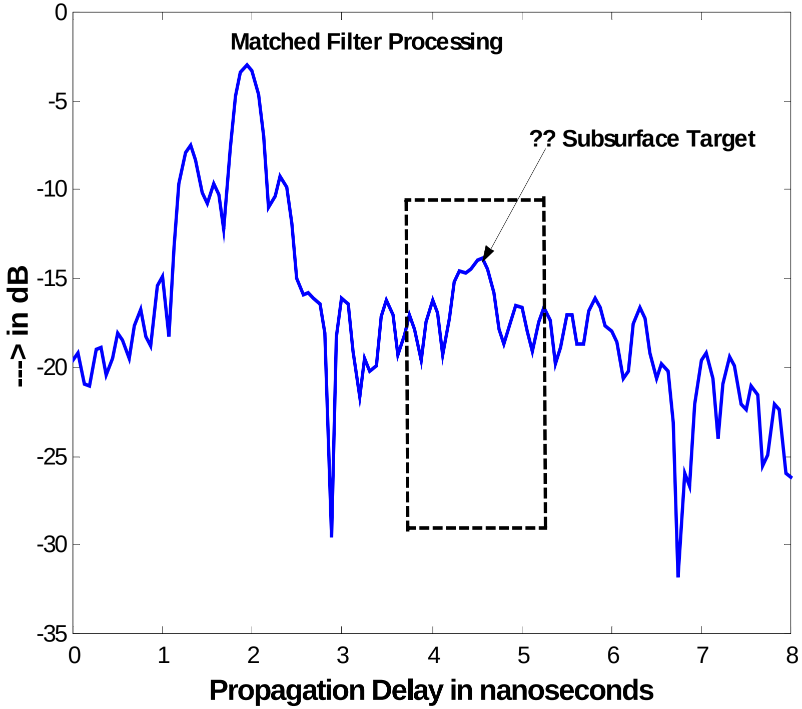


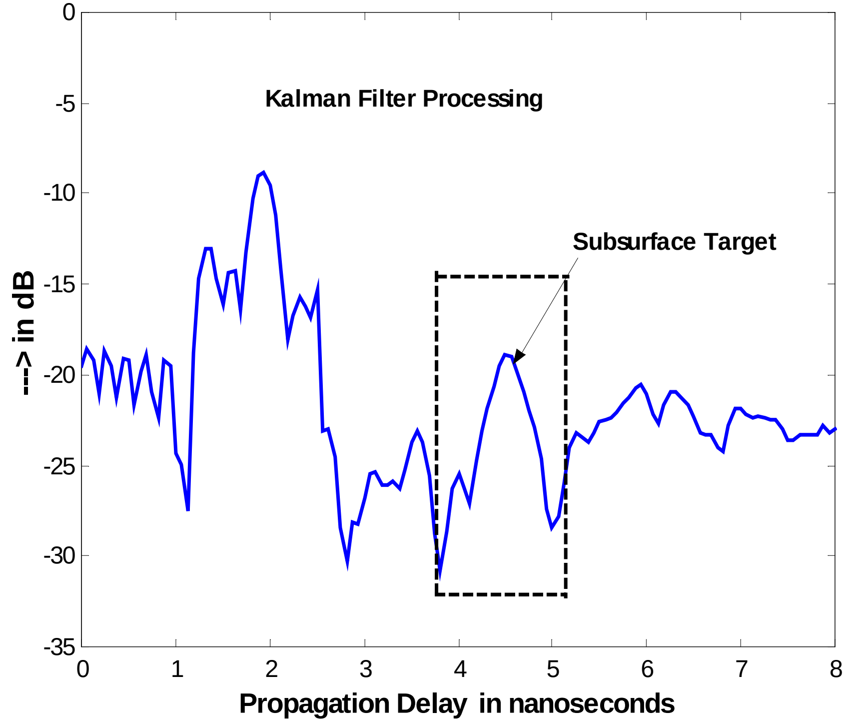


MMSE Filter: Subsurface target at 2.75ns??

Kalman Filter: Robust for target detection.

TM-46

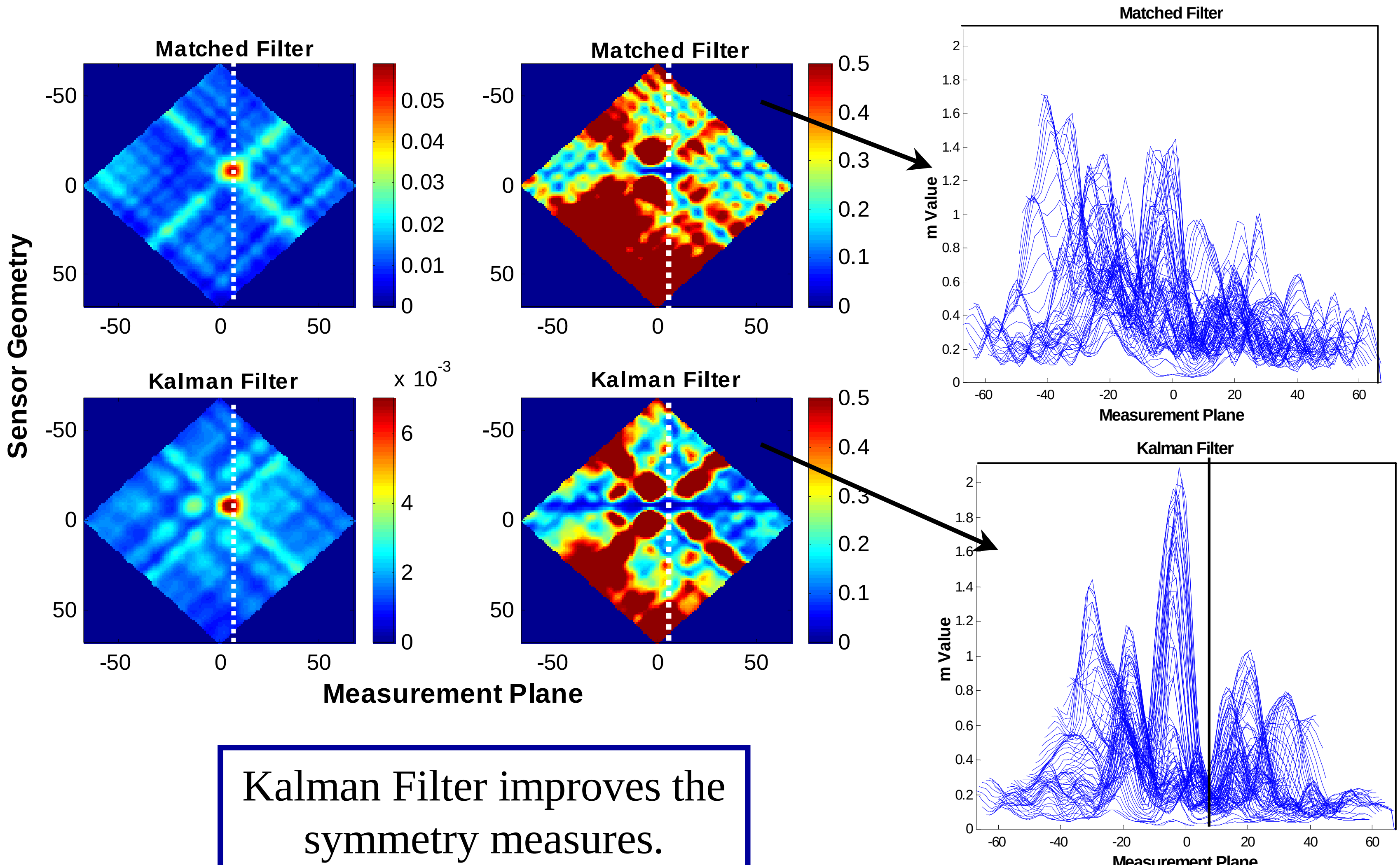




Matched Filter: Uncertainty in Target detection

Target can be easily detected at a delay≈4.5ns

TM-46



Kalman Filter improves the symmetry measures.

Conclusions and Future Work

- Detection Scheme with a potential of a low P_{FA}.
- Proposed a working model for a handheld detector.
- On the signal processing front
  - Developed a robust signal processor for subsurface target detection.
  - Validated and tested the algorithms.

- As future work
  - Combination of MMSE GPR Processor and Kalman Filter.
  - Develop a Robotic arm for data collection!

Questions?