Thesis review

High performance satellite AIS and Radar data fusion for maritime surveillance

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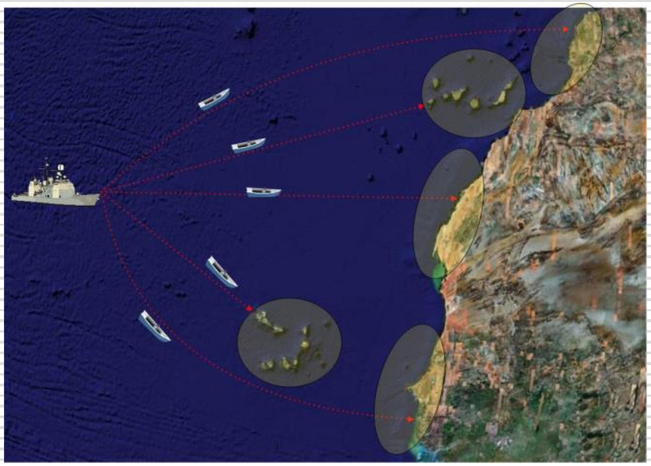
Agenda

- Introduction
  - Overview
  - Generalities AIS
  - Generalities BFR radar
  - Motivation
  - Thesis subject
- The four research topics
  - Simulator description
  - Description of 1st research topic
  - Description of 2nd research topic
- Conclusions
- Next steps

Introduction

- Why maritime surveillance?
  - Safety and security of navigation in general
  - Application of regulation to protect the marine environment
  - Fishery control
  - Fight against trafficking and illegal immigration

Illicite traffic



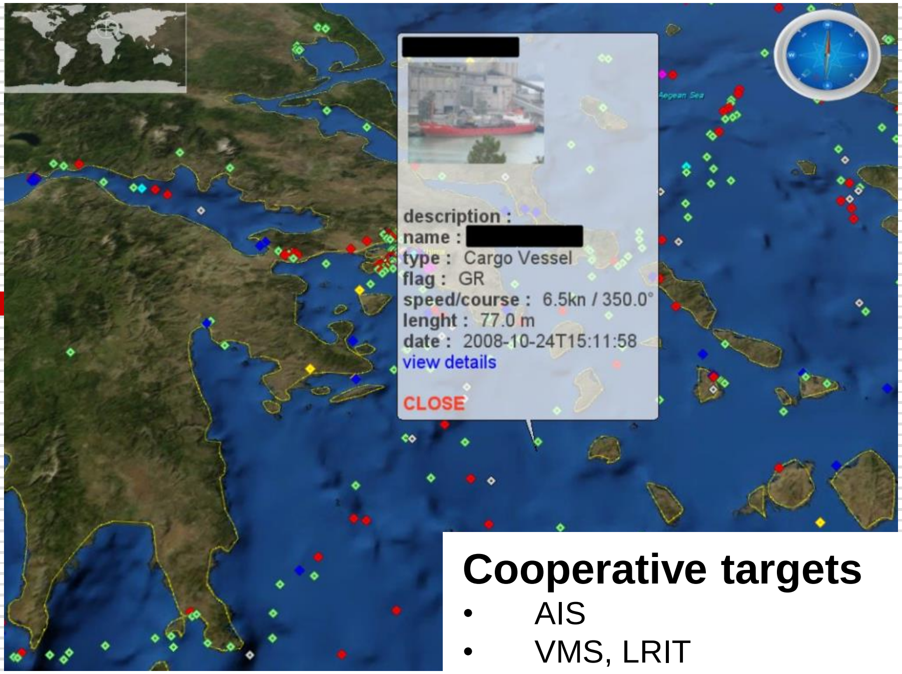
Sea safety

Pollution

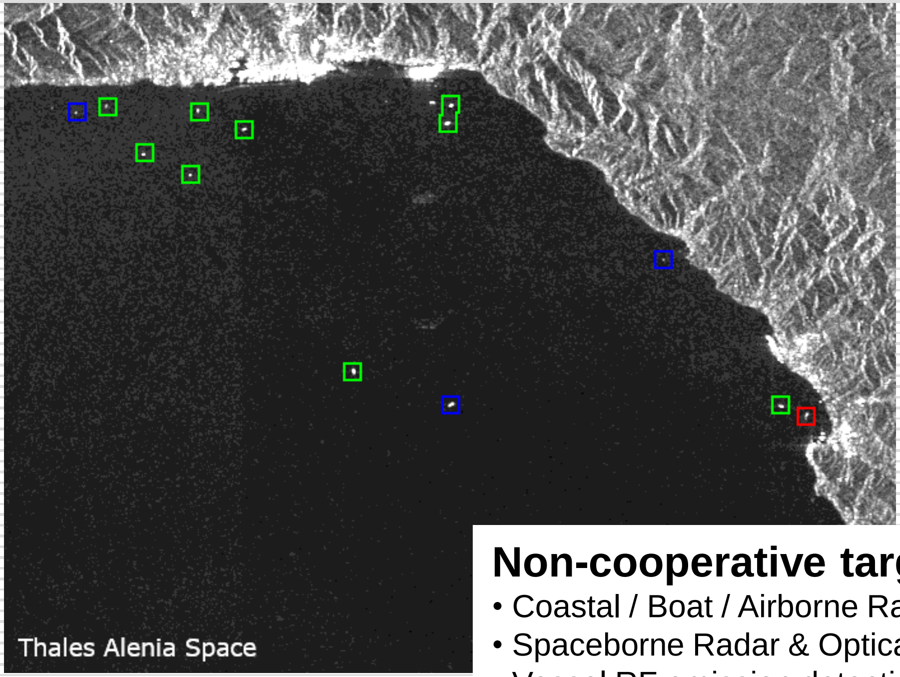
Illegal Fishing

Introduction

- Desirable characteristics
  - It must deal with the surveillance scenario diversity



Cooperative targets
- AIS
- VMS, LRIT
- ARGOS



Non-cooperative targets
- Coastal / Boat / Airborne Radar
- Spaceborne Radar & Optical
- Vessel RF emission detection

- Cover both cooperative and non-cooperative targets
- High availability
- Global coverage

Overview

- A constellation of satellites with embedded vessel detection sensors was proposed to monitor ship activity on sea
- Two sensors
  - AIS – Automatic Identification System
  - SAR - Synthetic Aperture Radar

AIS receiver

- Decodes AIS transmissions containing ID, position, heading, size, speed, etc.
- Vessels cooperatively broadcast AIS messages at regular times following the AIS protocol specification
- Covers large areas
- Susceptible to message errors and intentional deception

SAR sensors

- Characteristics of Synthetic Aperture Radar (SAR) sensors
  - Operational duty cycle limited to 10/20%
  - Limited swath and accessibility
  - Not dedicated to perform ship detection mission in maritime surveillance
- Poor operational availability and limited area coverage regarding maritime surveillance needs

BFR radar

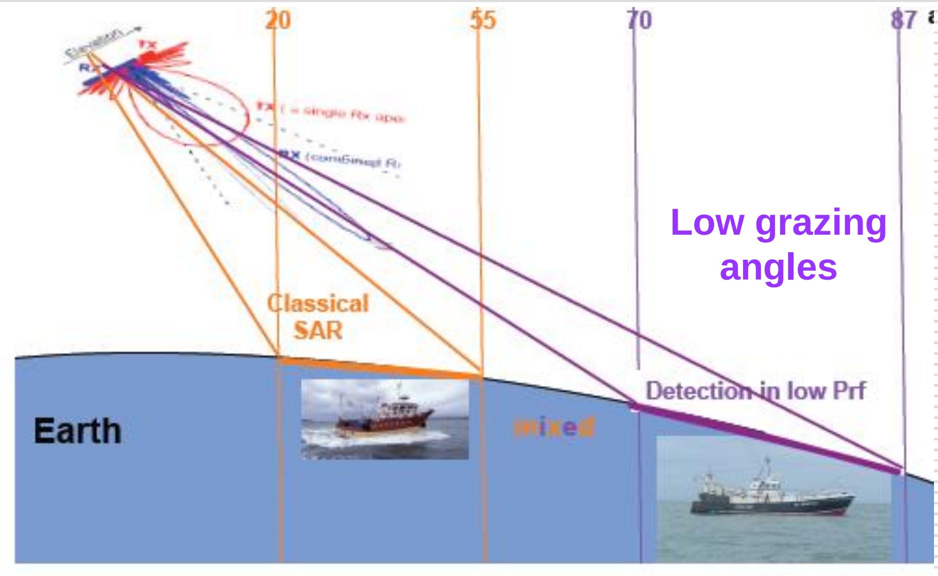
- The BFR radar is a SAR at a high incidence angle and a low PRF - pulse repetition frequency
- Broads the radar coverage at the expense of adding ambiguities

Ambiguities

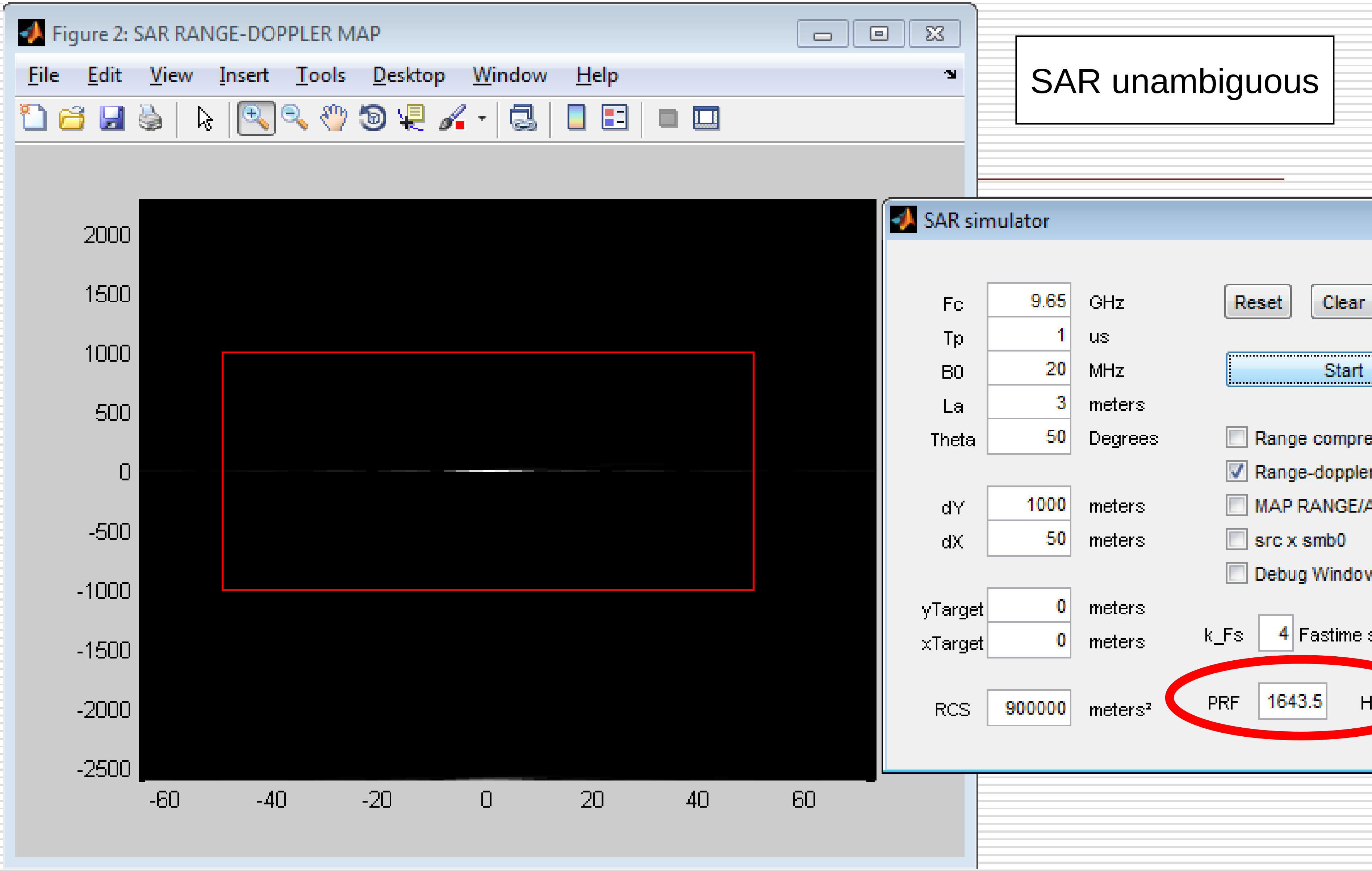
- Problematic for radar imaging
- Can be managed when image quality is not a constraint (detection)

Low grazing angle

- Less radar clutter from sea
- Better ship cross section (RCS) due to the low grazing angle



SAR unambiguous



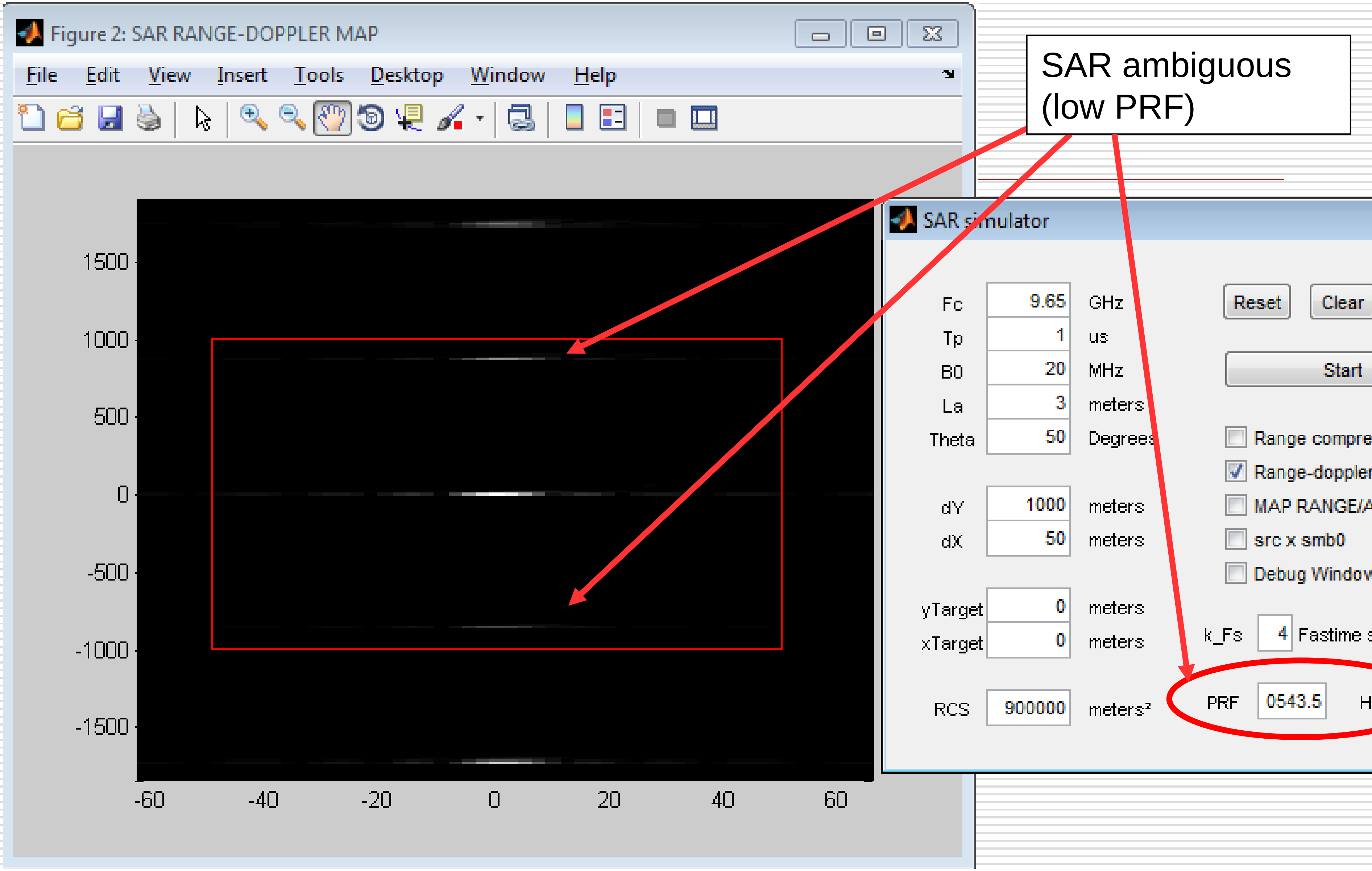
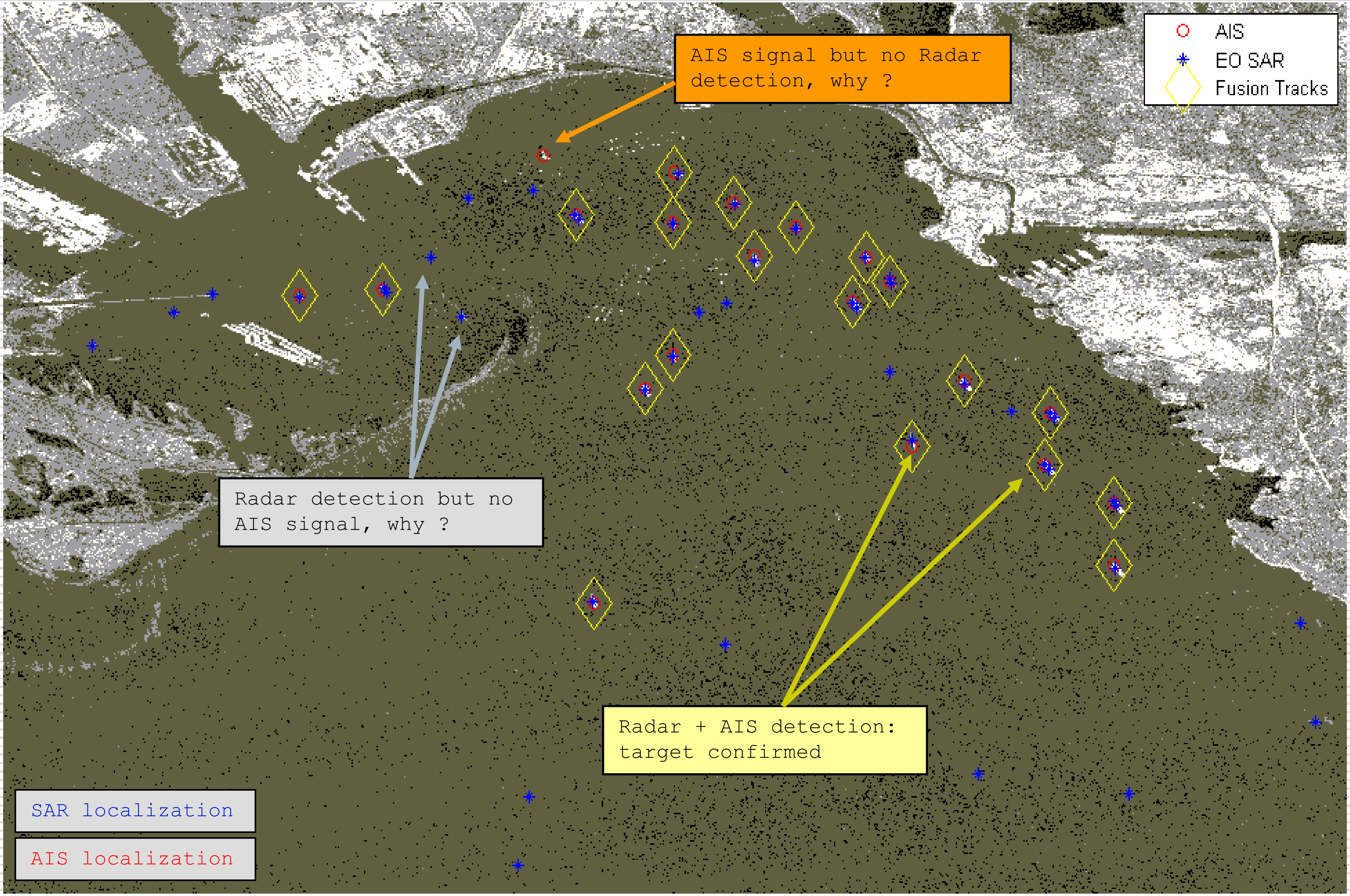


Figure 2: SAR RANGE-DOPPLER MAP
File Edit View Insert Tools Desktop Window Help
1500
1000
500
0
-500
-1000
-1500
-60 -40 -20 0 20 40 60
SAR ambiguous
(low PRF)
SAR simulator
Fc 9.65 GHz
Tp 1 us
B0 20 MHz
La 3 meters
Theta 50 Degrees
dY 1000 meters
dX 50 meters
yTarget 0 meters
xTarget 0 meters
RCS 900000 meters²
Reset
Clear
Start
Range compre
Range-doppler
MAP RANGE/A
src x smb0
Debug Window
k_Fs 4 Fastime s
PRF 0543.5 H


AIS signal but no Radar detection, why ?
AIS
EO SAR
Fusion Tracks
Radar detection but no AIS signal, why ?
Radar + AIS detection: target confirmed
SAR localization
AIS localization

Motivation

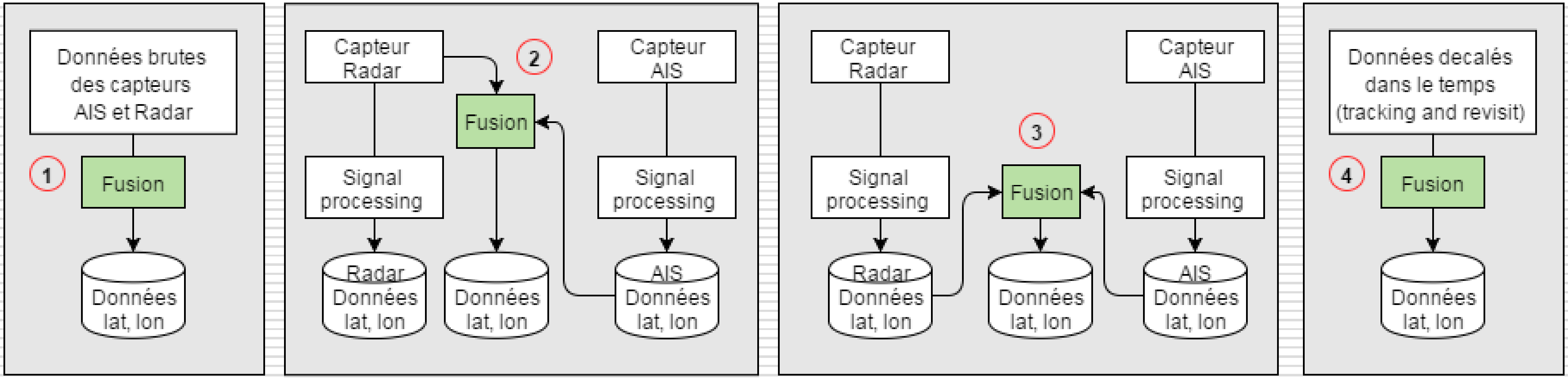
- Deal with the diversity of maritime surveillance scenarios including cooperative and non-cooperative ships
- A natural solution is to integrate different sources of information
- Today’s methods are based on merging sensor post-processed data
- The main objective is to search for improved sensor data fusion techniques to obtain high performance maritime surveillance

Thesis subject

- Fusion of satellite AIS and low PRF radar data for high performance maritime surveillance
- Explore the diversity of both low PRF radar and AIS sensors to
  - Improve small vessel detection
  - Identify ships
  - Track non-uncooperative ships

The four research topics

- We proposed some research topics to improve target detection using sensor data fusion
- Four levels of sensor data fusion were identified



The four research topics

1. **Explore the diversity of raw sensor signals**
   - Considers data before any signal processing
2. **Explore AIS processed data to improve radar detection**
   - Use extra information from AIS message (e.g., speed, position, time) to improve the radar detection
3. **Explore AIS and radar processed data to improve detection**
   - In this case, both AIS and radar processed data provide separate lists of detections that need to be merged
4. **Slow time integration**
   - Integrate slow time data from satellite scene revisit for tracking

Fundamentals

- Satellite orbit simulator
  - Auxiliary to the study
    - Simulate satellite parameters (speed / Doppler, altitude, look angle, elevation, heading, position, etc.)
    - Transformation of coordinates
- Low PRF SAR model
  - Generate raw signatures targets
    - At specific configuration of radar, ship and satellite (altitude, power, speed, view angle, frequency, resolution, etc.)
    - Radar equation (model the target RCS (radar cross section) and SNR)
- Low PRF SAR imaging simulator
  - Generates a radar image of punctual targets
    - Range-Doppler algorithm
- AIS signal simulator
  - Generates raw AIS signatures
    - Referenced on satellite and ship dinamics

Fundamentals

- Maximum likelihood estimation (MLE)
  - MLE algorithm to estimate unknown parameters of the AIS signal model
  - Estimate ship coordinates (Lat/Lon) from AIS and radar raw signatures
- Detection using the generalized likelihood ratio test (GLRT)
  - Simpler model with added constraints
- Performance evaluation
  - Statistical model and Receiver Operational Characteristics (ROC) curves.

The four research topics

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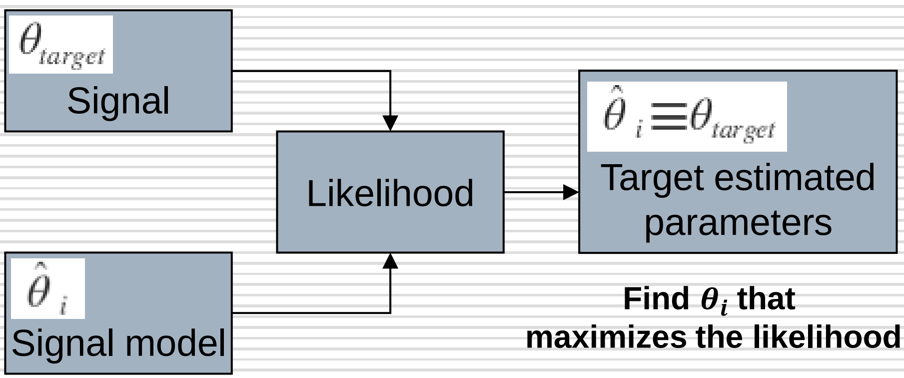
1st topic : Explore the diversity of raw sensor signals

MLE - Maximum likelihood estimator

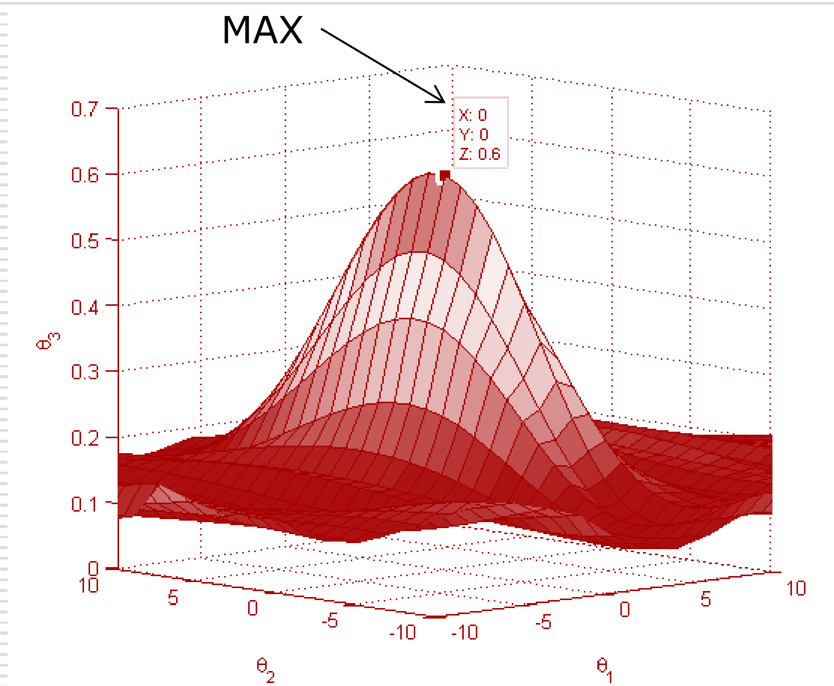
- The idea is to estimate some information from target signatures associated with AIS and radar sensors
- The target signatures are for the raw sensor data after complex quadrature demodulation
- The information is contained into the unknown parameters of the signal model that we need to estimate (e.g., lat/lon);
- The MLE determines the parameters that maximize the likelihood function

1st topic : Explore the diversity of raw sensor signals

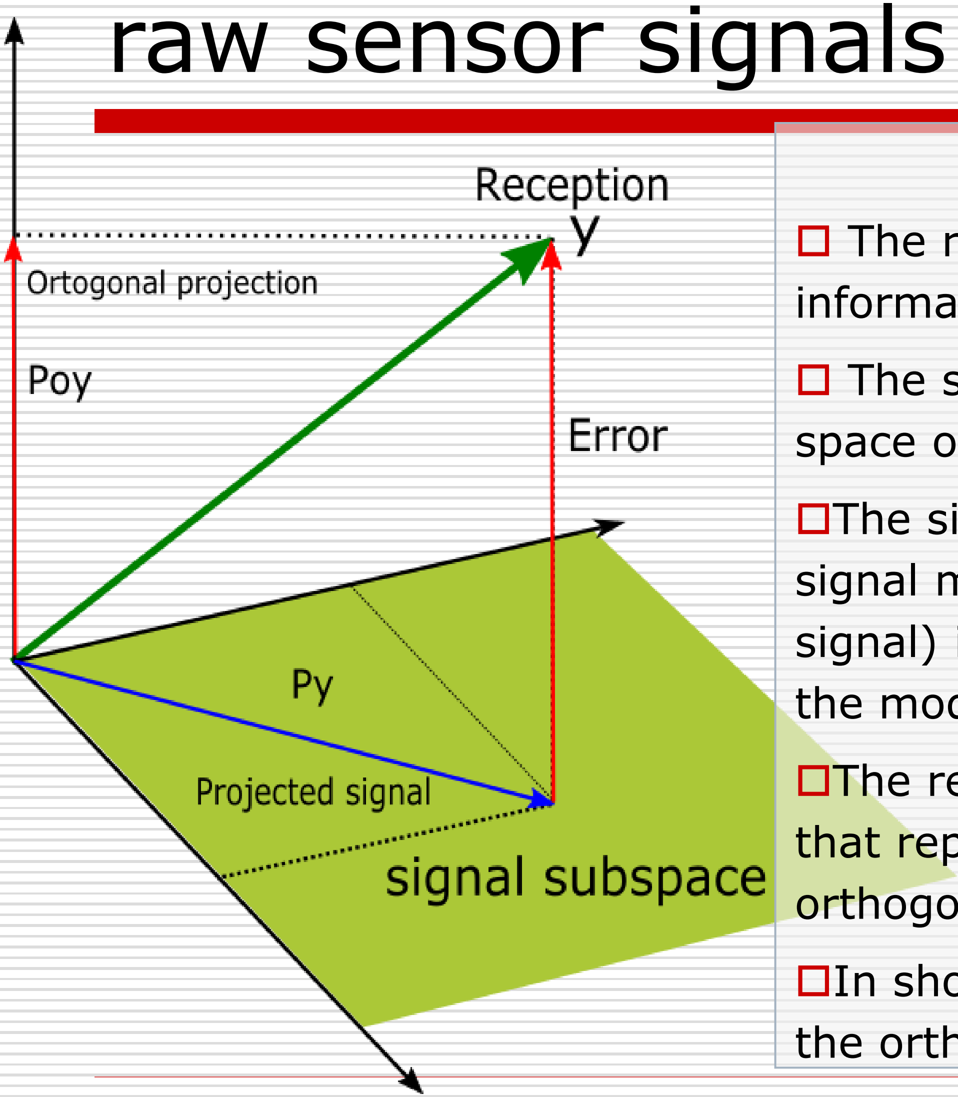
- Maximizing the likelihood corresponds to finding the vector of parameters θ_i that is the most likely with respect to the measurements y



Find θ_i that maximizes the likelihood



1st topic : Explore the diversity of raw sensor signals



Geometric representation

- The received message is a composition of information (signal) and some error (noise)
- The signal subspace is a subset of the total space of all possible signals in C^N
- The signal subspace is characterized by the signal model (where the reception (target signal) is a linear span of a set of vectors from the model)
- The reception can be split into components that represent the signal subspace and the orthogonal subspace (error)
- In short, we separate signal from error with the orthogonal projection operation

1st topic : Explore the diversity of raw sensor signals

- Equations

Signal representation
$$\begin{cases} y_{radar} = A(\theta)\alpha + n_{radar} \\ y_{ais} = B(\theta)\beta + n_{ais} \end{cases}$$

Signature = y
Models = A;B
Parameter vector = θ
Noise = n

Note:
θ = Lat/Lon for AIS
θ = X,Y Coords in radar

MLE - Maximum likelihood estimator

Case 1:
known noise power
$$\theta = ArgMax\left[\frac{{y_{radar}}^H P_A(\theta) y_{radar}}{{\sigma_{radar}}^2} + \frac{{y_{ais}}^H P_B(\theta) y_{ais}}{{\sigma_{ais}}^2}\right]$$

Case 2:
unknown noise power
$$\theta = ArgMin\left(\left[{y_{radar}}^H \left(I - P_A(\theta)\right) y_{radar}\right]^{N_{radar}} \left[{y_{ais}}^H \left(I - P_B(\theta)\right) y_{ais}\right]^{N_{ais}}\right)$$

where
$$P_A(\theta) = A[A^H A]^{-1} A^H$$
$$P_B(\theta) = B[B^H B]^{-1} B^H$$

1st topic : Explore the diversity of raw sensor signals

- The MLE provide the optimal solution (no information is discarded)
- The research of the maximum is conducted into a $(2+K)M$ dimensional space
  - M is the number of ships in the scene (and need to be estimated)
  - K is the number of unknown parameters to estimate for each ship (identification, speed, frequency, delay, among others)
- This solution is not implementable unless for a very small area with few ships
- An alternative is to exchange the estimation approach into a detection problem

1st topic : Explore the diversity of raw sensor signals

Detection using the GLRT - Generalized Likelihood Ratio Test

- The problem is now to test a single position for the two classical hypotheses in detection
  - H0 : There is a ship **AND** AIS detection $(\alpha = \beta = 0)$
  - H1 : There is **no** ship **AND no** AIS detection $(\alpha \neq 0, \beta \neq 0)$

Signal model

$$\begin{cases} y_{radar} = A(\theta)\alpha + n_{radar} \\ y_{ais} = B(\theta)\beta + n_{ais} \end{cases}$$

Likelihood ratio

$$\frac{p\left(y_{radar}, y_{ais}/H_1, \widehat{\theta_1}\right)}{p\left(y_{radar}, y_{ais}/H_1, \widehat{\theta_1}\right)} > T$$

H0

$$\begin{cases} y_{radar} = n_{radar} \\ y_{ais} = n_{ais} \end{cases}$$

H1

$$\begin{cases} y_{radar} = a(\theta)\alpha + n_{radar} \\ y_{ais} = b(\theta)\beta + n_{ais} \end{cases}$$

Case 1: known noise power

$$\left(\frac{{y_{radar}}^H P_a(\theta) y_{radar}}{{\sigma_{radar}}^2} + \frac{{y_{ais}}^H P_b(\theta) y_{ais}}{{\sigma_{ais}}^2}\right) > T$$

Case 2: unknown noise power

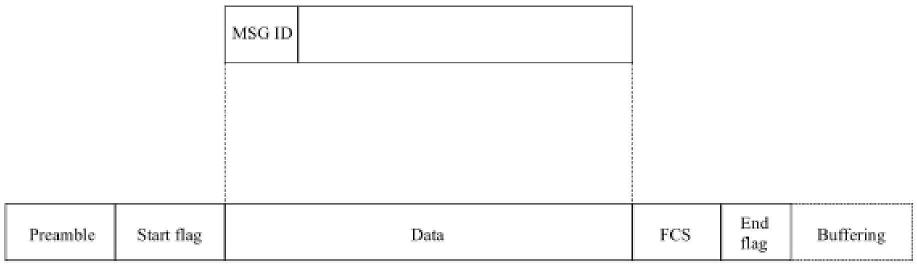
$$\left(\left[1 + \frac{{y_{radar}}^H P_a(\theta) y_{radar}}{{y_{radar}}^H \left(I - P_a(\theta)\right) y_{radar}}\right]^{N_{radar}} \left[1 + \frac{{y_{ais}}^H P_b(\theta) y_{ais}}{{y_{ais}}^H \left(I - P_b(\theta)\right) y_{ais}}\right]^{N_{ais}}\right) > T$$

Results

- Using AIS, radar and to AIS and radar
- Comparison of the MLE algorithm with SAR range-Doppler image processing
- Constraints are used to ease the signal modelling (no collision in AIS messages, bit stuffing disabled, no false AIS, maximum of one ship at a single position, etc.)

Note: The measurements are simulated signals with additive white Gaussian noise

AIS signal

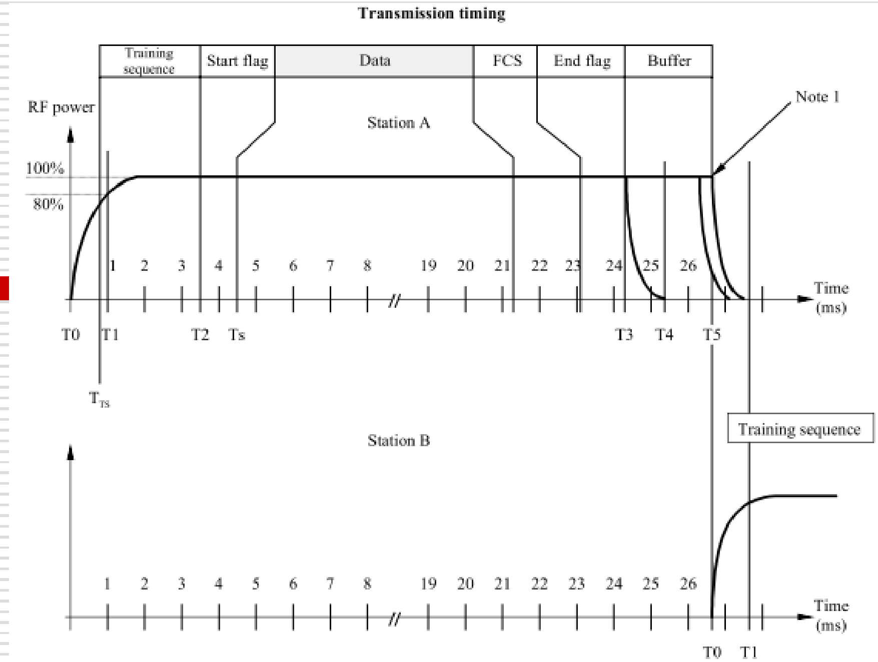


Bit Order	M----L--	M-------	--------	--------	--LML000
Symbol	TTTTTTDI	MMMMMMMM	MMMMMMMM	MMMMMMMM	MMMNN000
Byte Order	1	2	3	4	5

Output order to VHF data link (bit-stuffing is disregarded in the example):

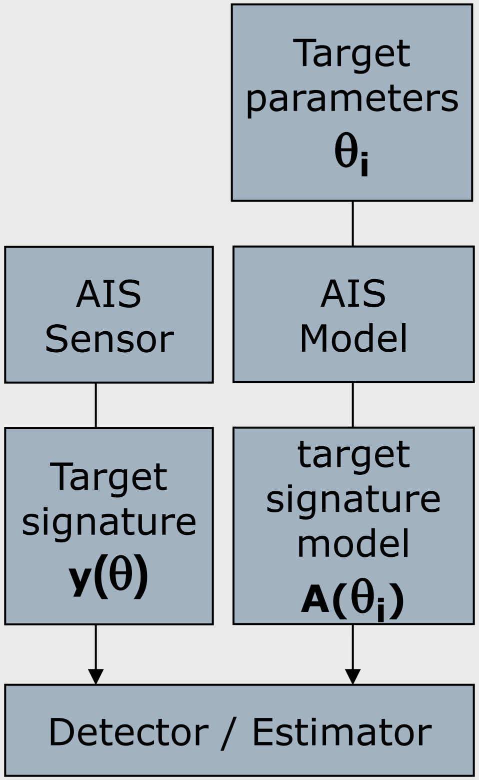
Bit Order	--L----M	-------M	--------	--------	000LML--
Symbol	IDTTTTTT	MMMMMMMM	MMMMMMMM	MMMMMMMM	000NNMMM
Byte Order	1	2	3	4	5

Ramp up	8 bits	T0 to T1 in Figure 6
Training sequence	24 bits	Necessary for synchronization
Start flag	8 bits	In accordance with HDLC ($7E_h$)
Data	168 bits	Default
CRC	16 bits	In accordance with HDLC
End flag	8 bits	In accordance with HDLC ($7E_h$)
Buffering	24 bits	Bit stuffing distance delays, repeater delay and jitter
Total	256 bits	



- **Bit-stuffing**
- **Flip-bits**
- **Delta between ship and satellite frequencies**
- **Time offset of the signal in the reception window**
- **Initial phase of the signal**

MLE AIS

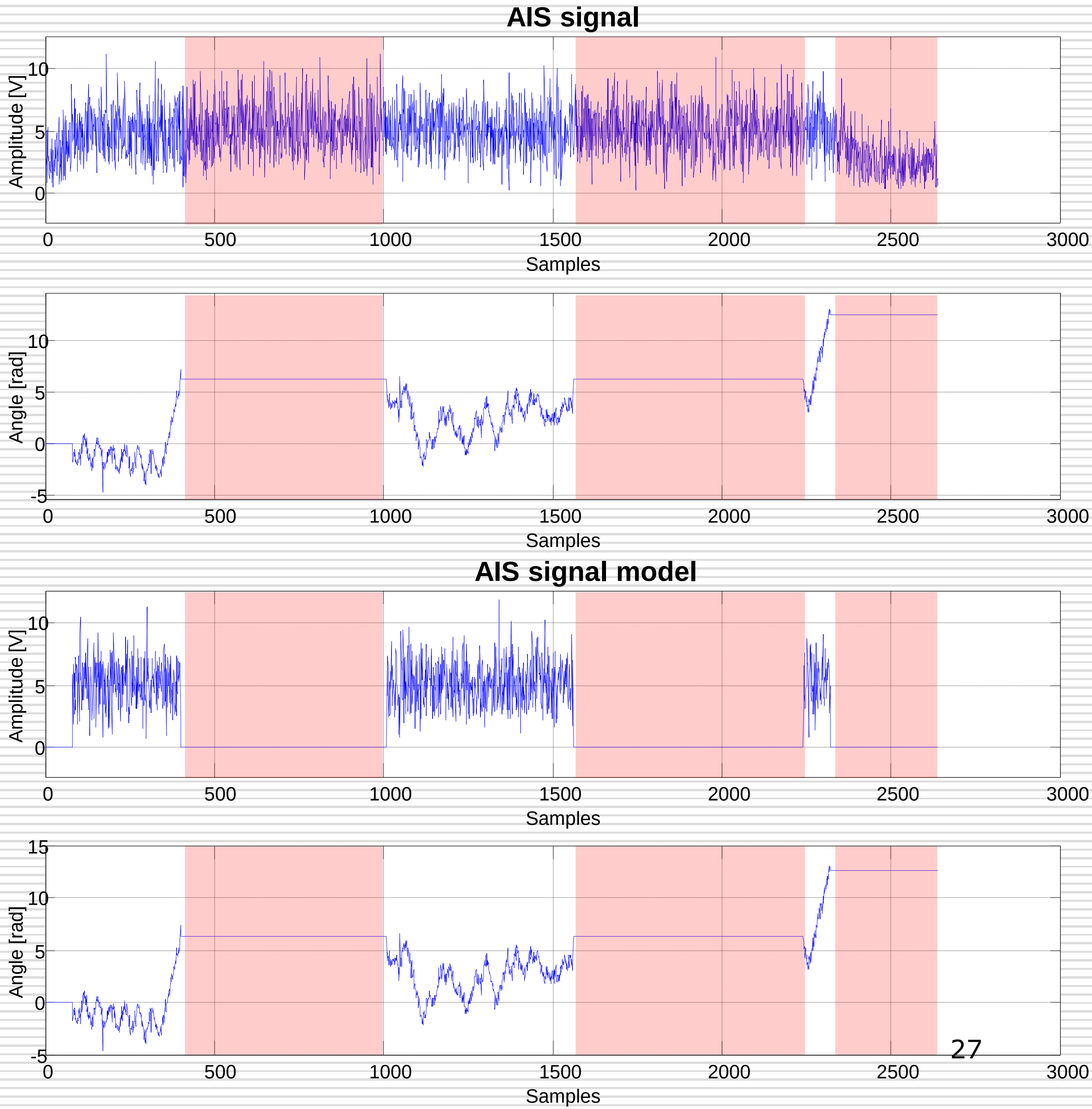


$$\hat{\theta} = ArgMin\left(\frac{y_{AIS}^{H} P_A(\theta_i) y_{AIS}}{\sigma_{AIS}^2}\right)$$

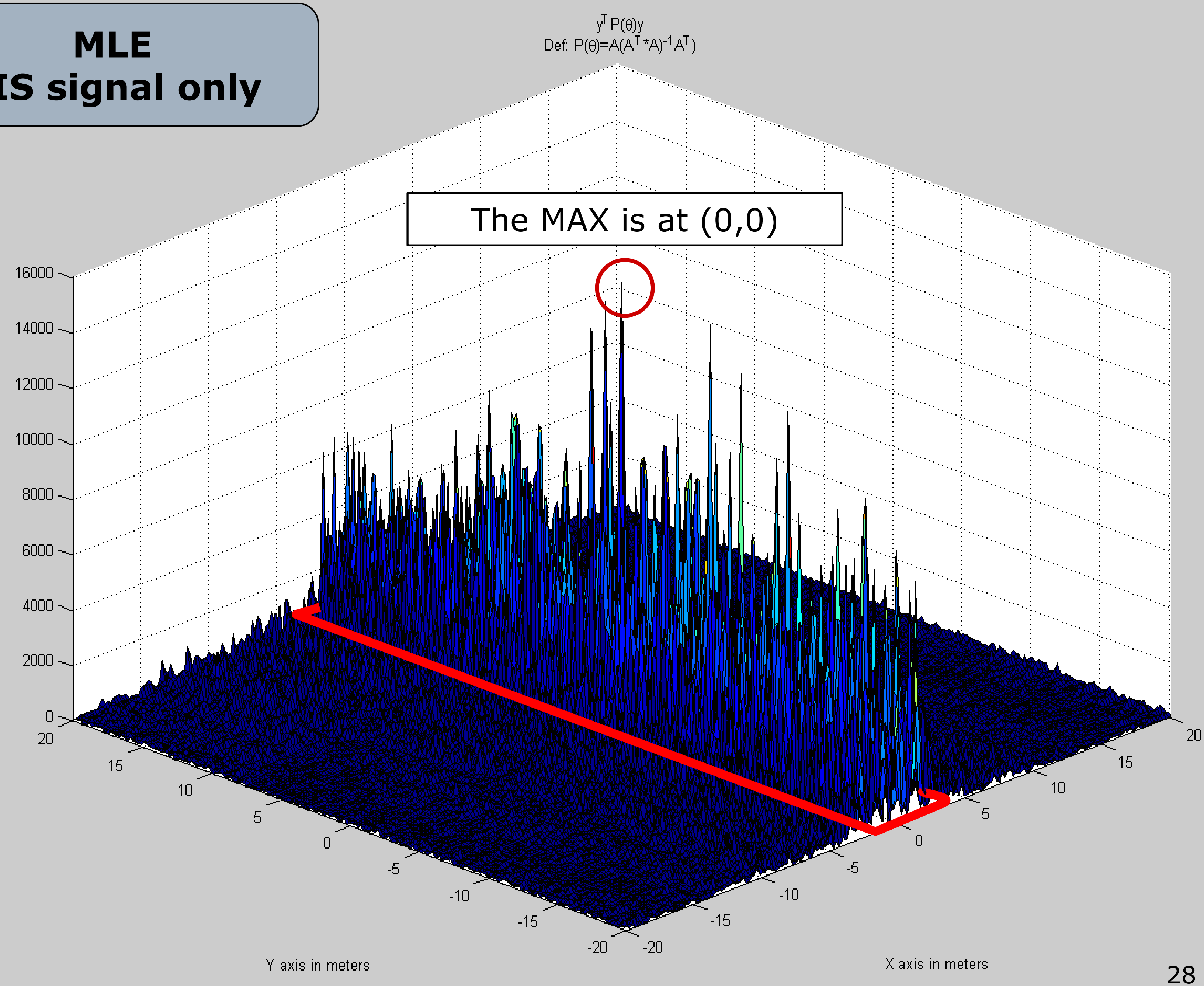
$$T_{AIS} = \frac{y_{AIS}^{H} P_A(\theta_i) y_{AIS}}{\sigma_{AIS}^2}$$

NOTES:

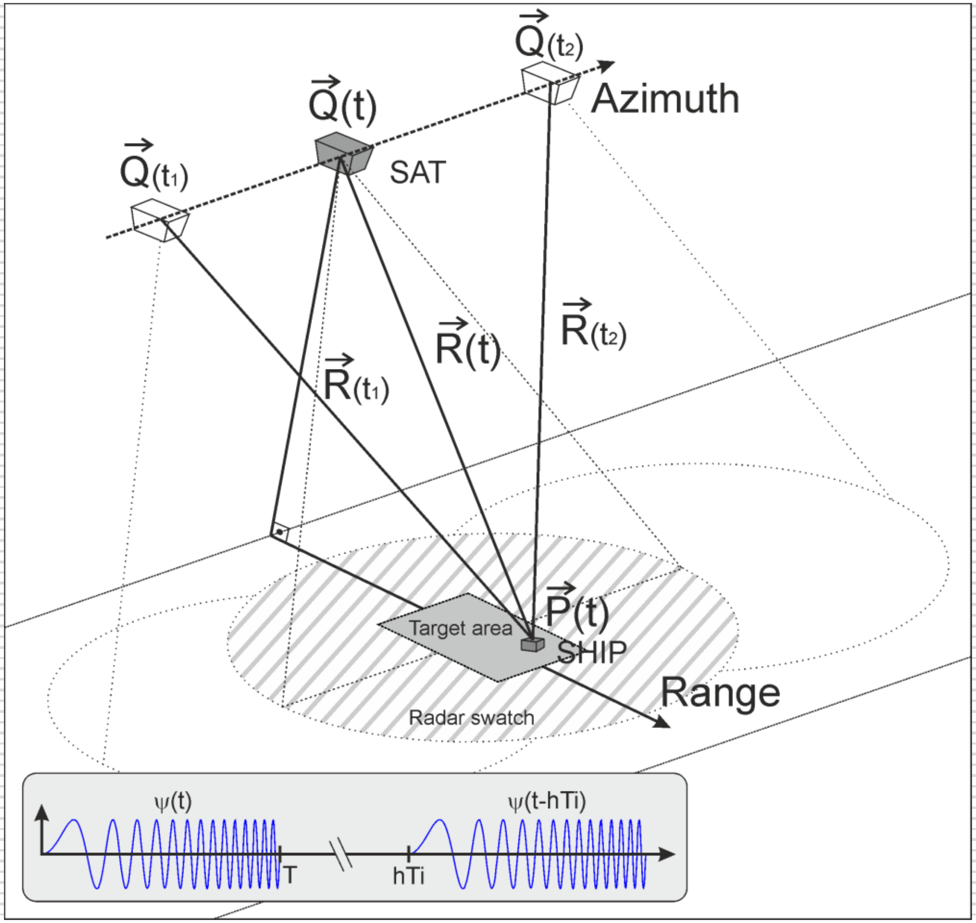
- In red the data that are unknown (replaced by zeros);
- θ_i = sample theta;
- θ = real theta(to be found);



MLE
AIS signal only



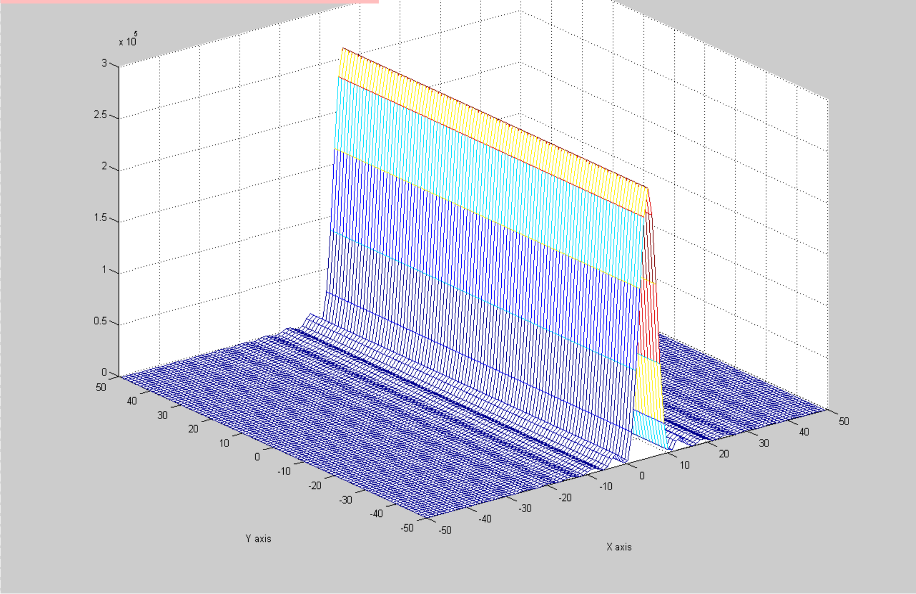
Radar signal



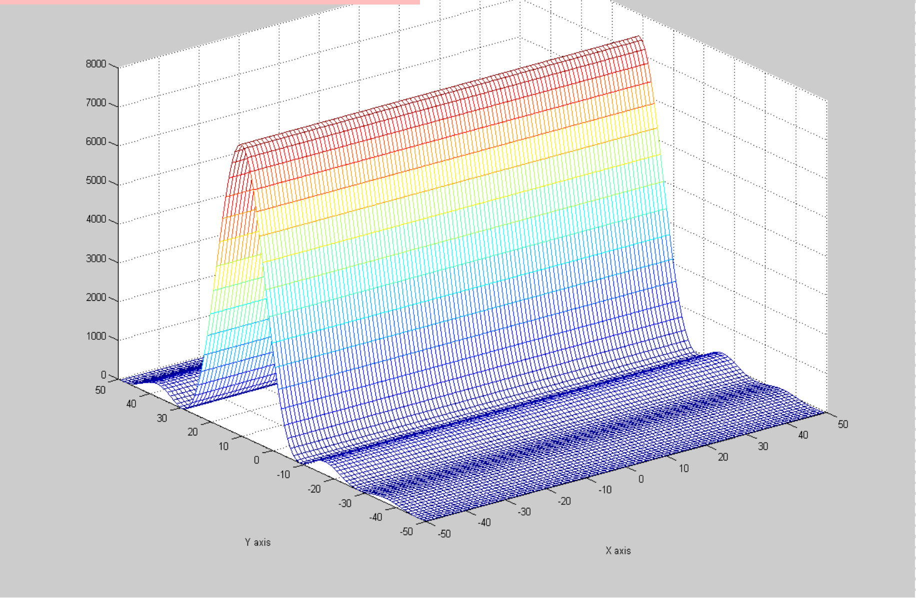
$$\psi(t) = 1_T(t)e^{j\gamma t^2}$$
$$s(t) = \sum_{h=1}^{N_P} \psi(t - hT_i)e^{j2\pi f_0 t}$$
$$Ar(t) = As(t - \tau_\theta(t))$$
$$\tau_\theta(t) = 2R_\theta(t)/c$$
$$R_\theta(t) = \left\| \vec{P}(t) - \vec{Q}(t) \right\|$$

- Range-Doppler process uses matched filter for imaging
- MLE correlation outputs an image

Radar only results:
Stage 1 : X axis (range)



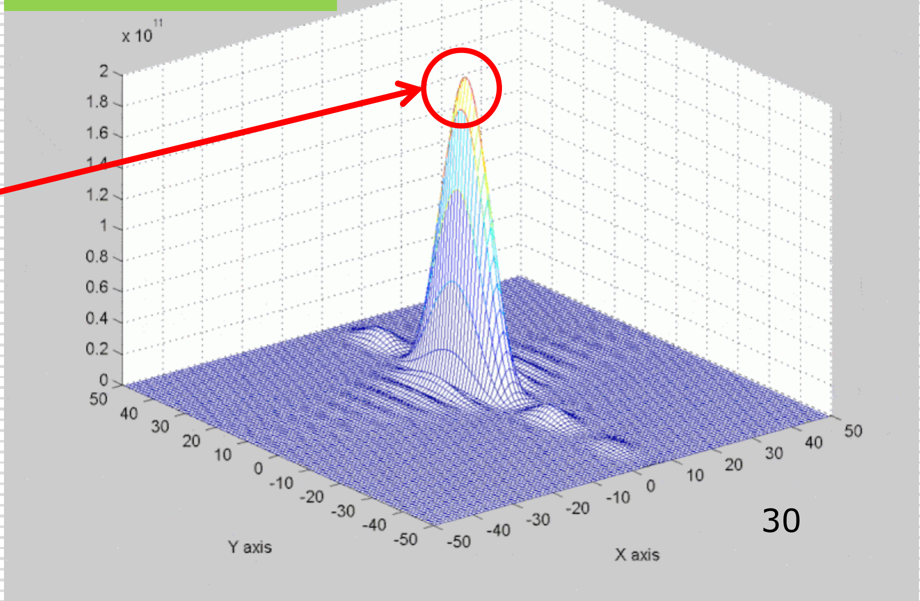
Radar only results:
Stage 2 : Y axis (Doppler)



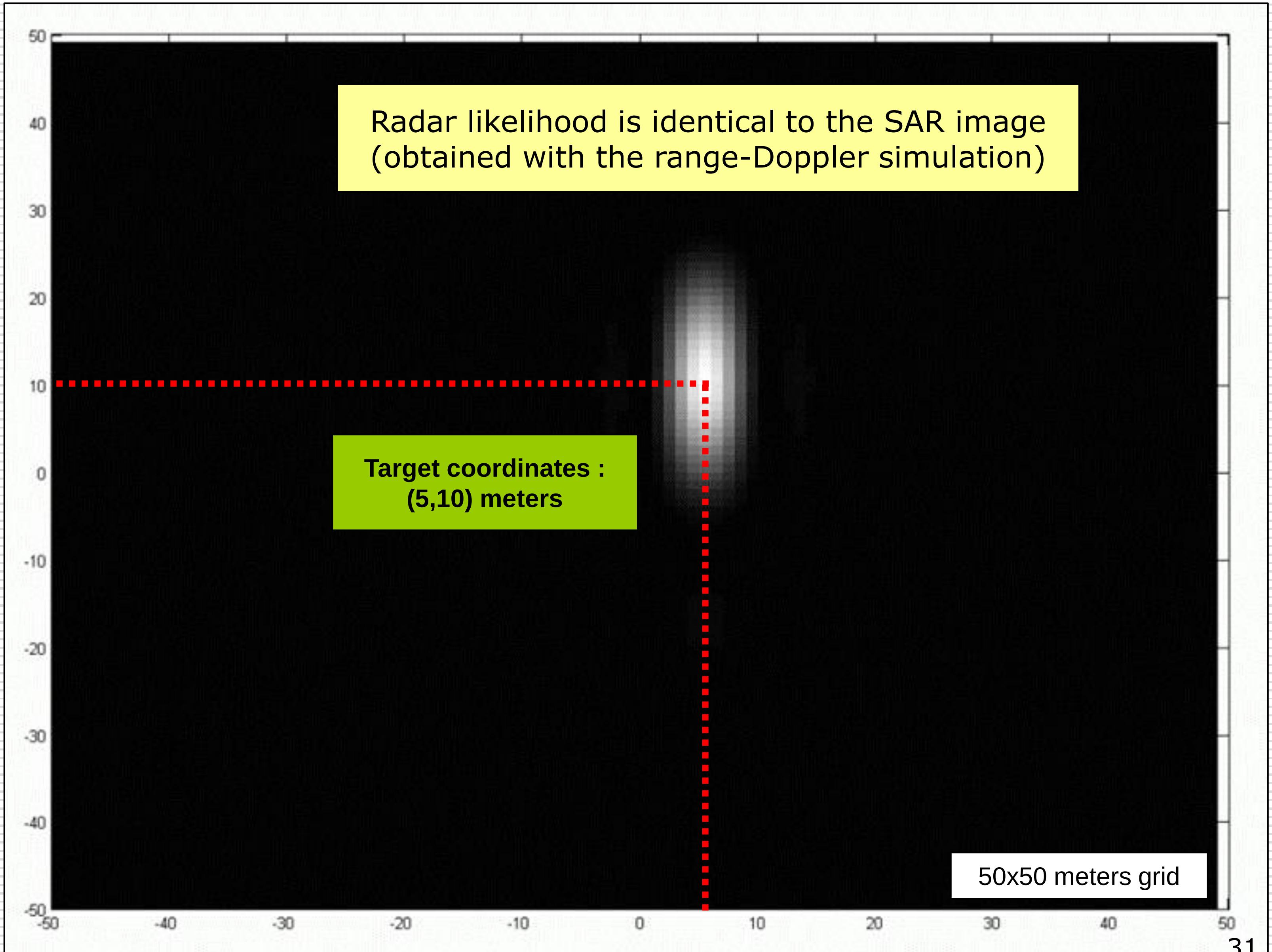
MLE
Radar signal only

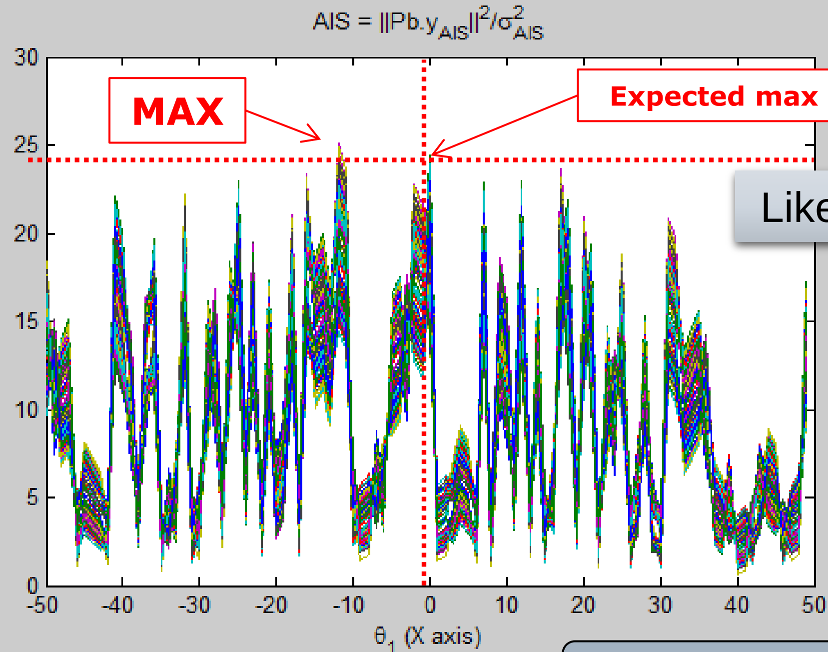
Target coordinates:
(5,10) meters

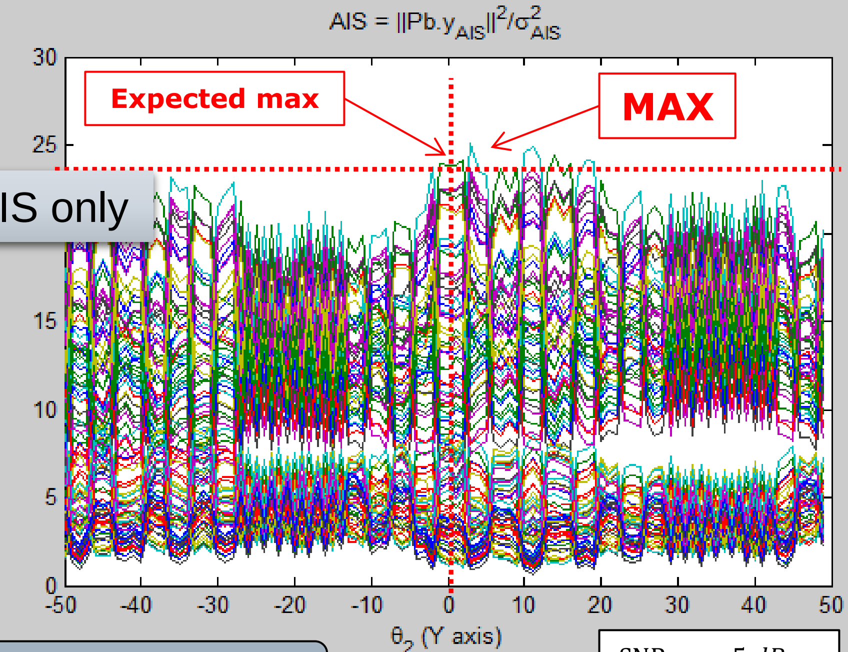
Radar only results:
Range-Doppler



SAR range-Doppler image



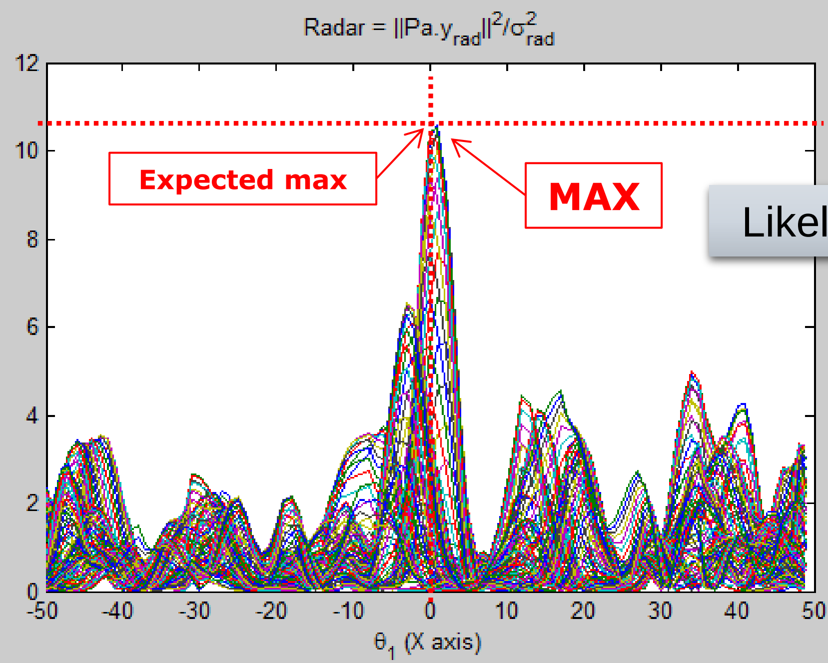


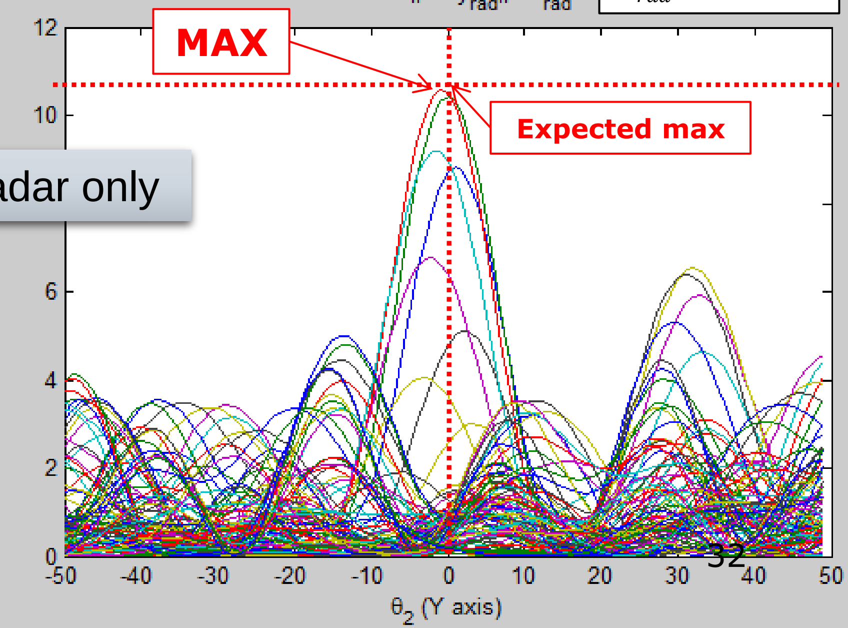


Likelihood AIS only

Radar and AIS likelihoods

$\mathrm{SNR}_{\mathrm{AIS}}: -5\ dB$
$\mathrm{SNR}_{\mathrm{rad}}: -30\ dB$
$N_{AIS}: 95$
$N_{rad}: 17487$

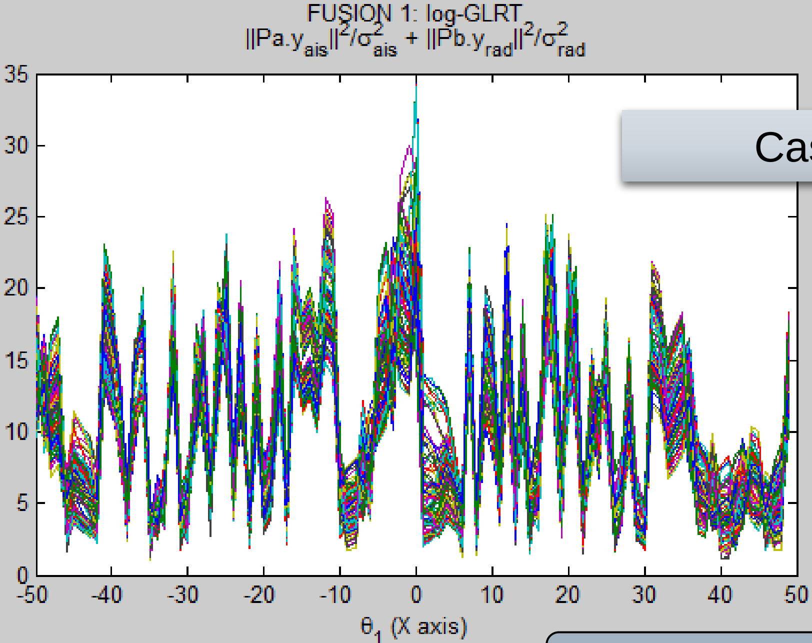


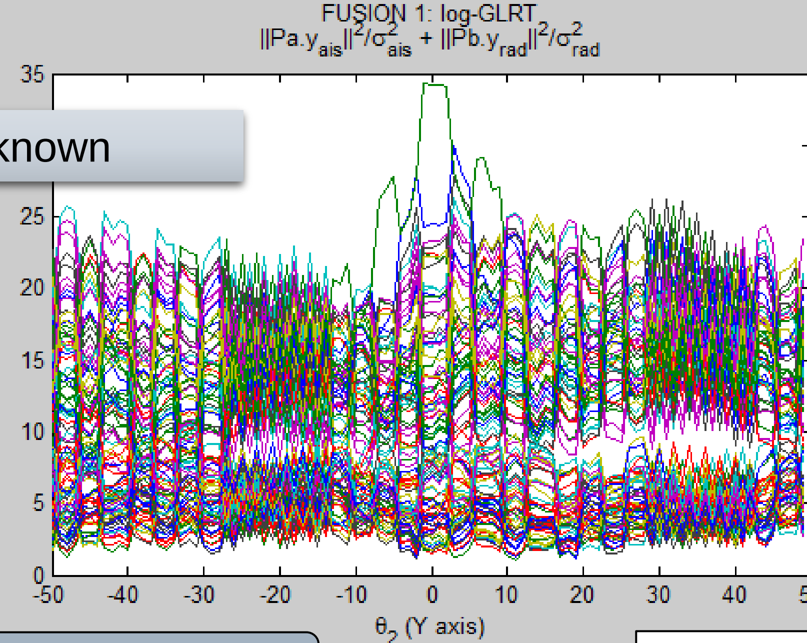


Likelihood Radar only

Fusion of Radar and AIS

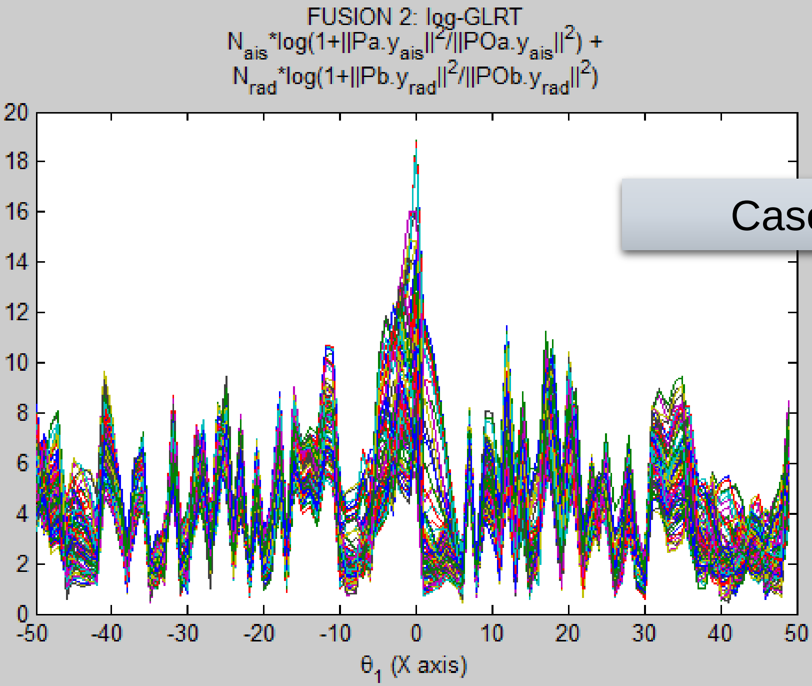
Case 1: σ^2 known

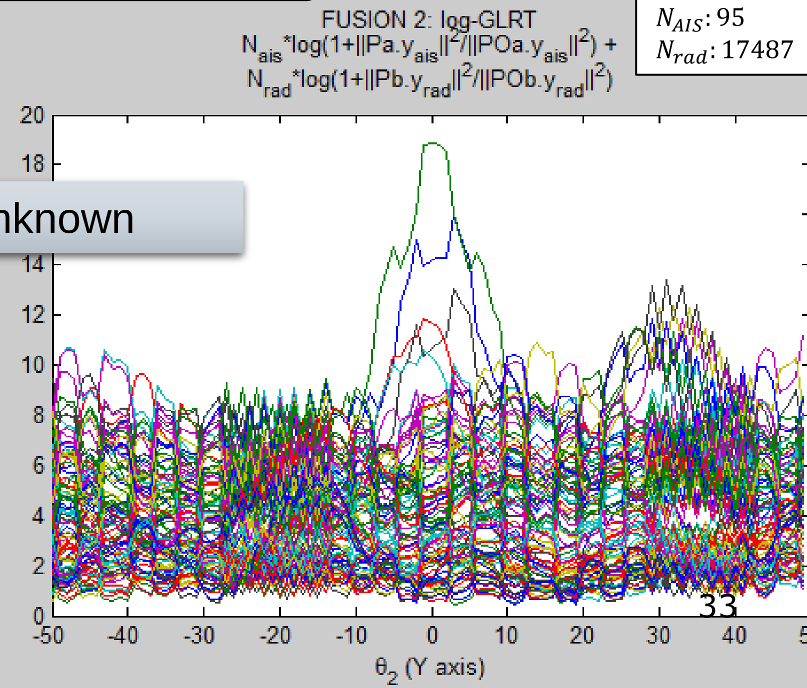


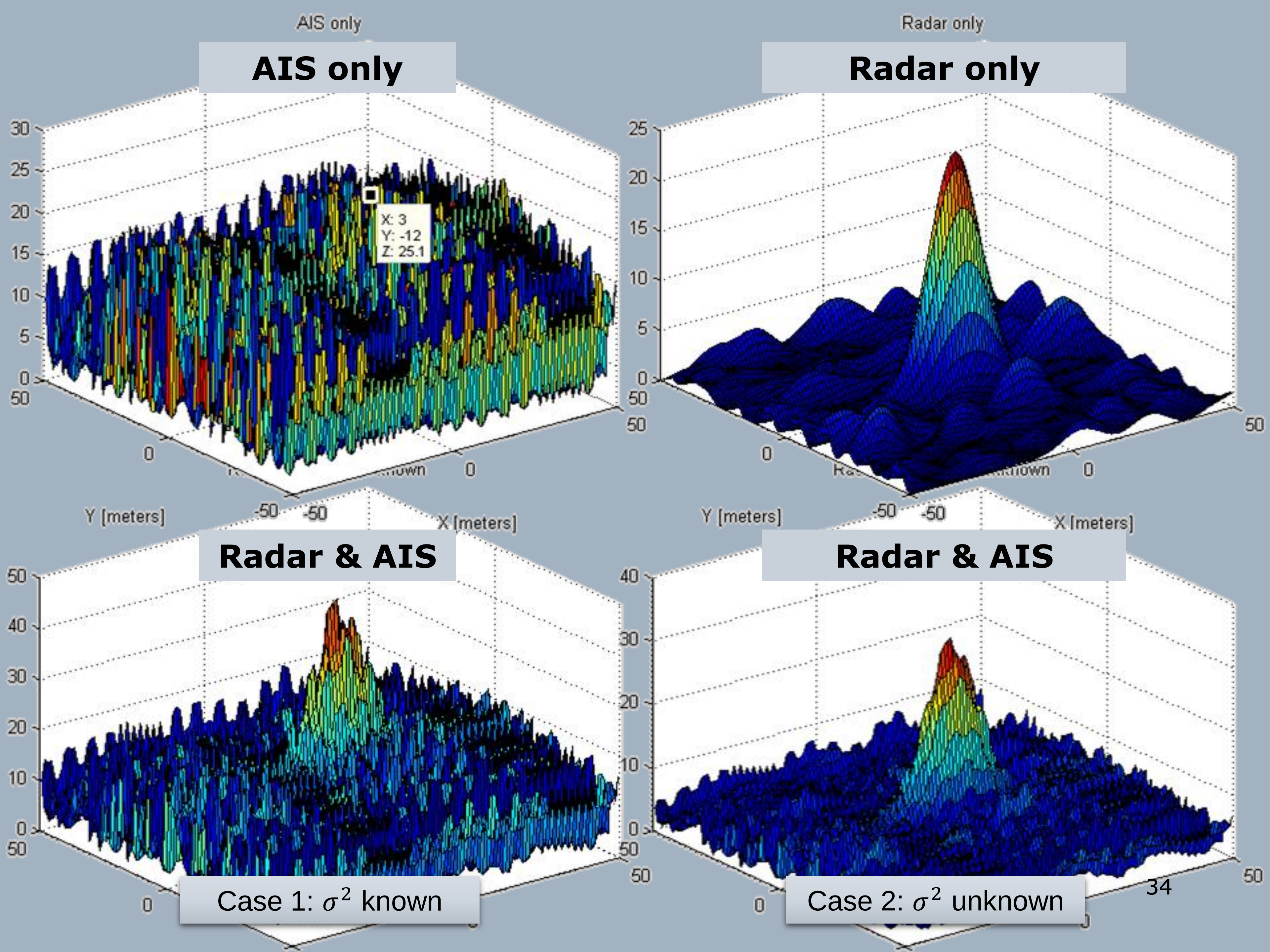


$\mathrm{SNR}_{\mathrm{AIS}}: -5\ dB$
$\mathrm{SNR}_{\mathrm{rad}}: -30\ dB$
$N_{AIS}: 95$
$N_{rad}: 17487$

Case 2: σ^2 unknown







AIS only

Radar only

Radar & AIS

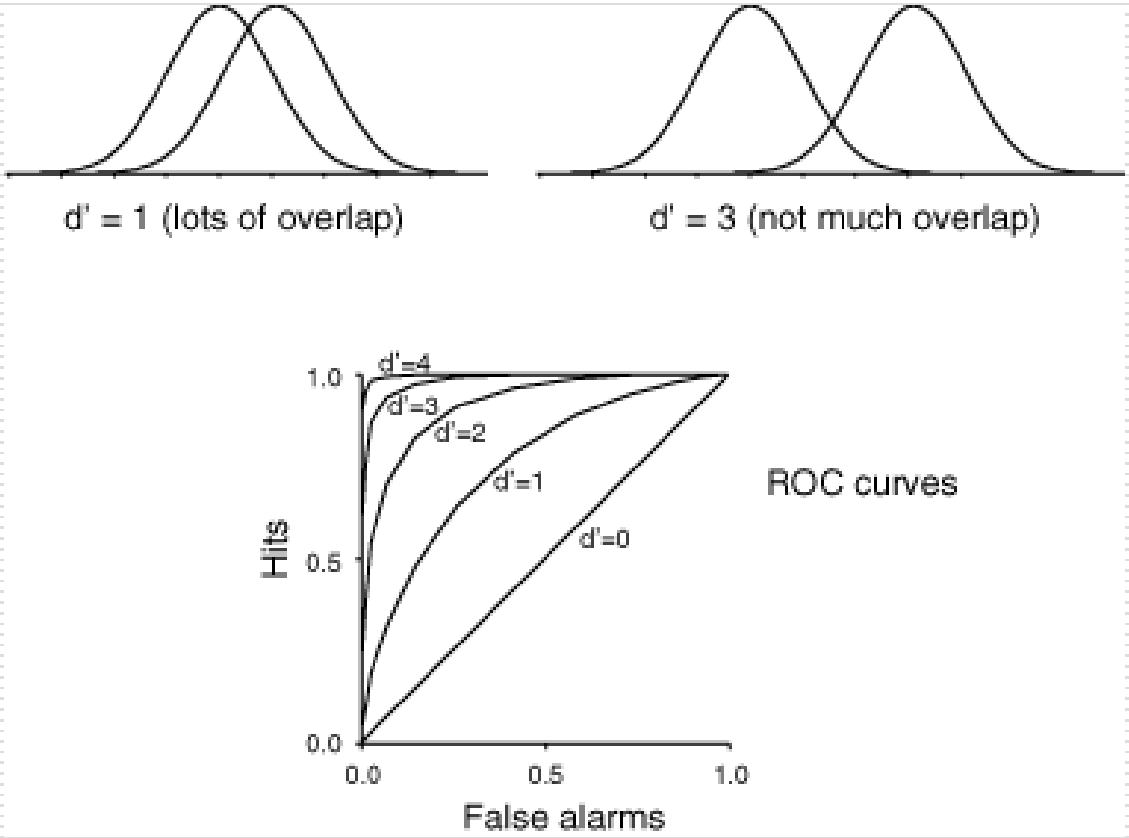
Radar & AIS

Case 1: σ^2 known

Case 2: σ^2 unknown

1st topic : Performance analysis

- We can trace the PFA versus the detection probability to compare the different detectors with the receiver operating characteristics (ROC curves)



1st topic : Performance analysis

- Determine the distribution of the test statistics under both hypotheses for all detectors
- The statistics of the detectors are

$$T_{\mathrm{f}} \sim \begin{cases} \frac{1}{2}\chi_4^2(0) & \text{under } H_0 \\ \frac{1}{2}\chi_4^2(\lambda_{\mathrm{AIS}} + \lambda_{\mathrm{rad}}) & \text{under } H_1 \end{cases}$$

$$T_{\mathrm{rad}} \sim \begin{cases} \frac{1}{2}\chi_2^2(0) & \text{under } H_0 \\ \frac{1}{2}\chi_2^2(\lambda_{\mathrm{rad}}) & \text{under } H_1 \end{cases}$$

$$\lambda_{\mathrm{rad}} = 2N_{\mathrm{rad}}\,\mathrm{SNR}_{\mathrm{rad}} = 2\,\mathrm{SNRo}_{\mathrm{rad}}$$

$$\lambda_{\mathrm{AIS}} = 2N_{\mathrm{AIS}}\,\mathrm{SNR}_{\mathrm{AIS}} = 2\,\mathrm{SNRo}_{\mathrm{AIS}}$$

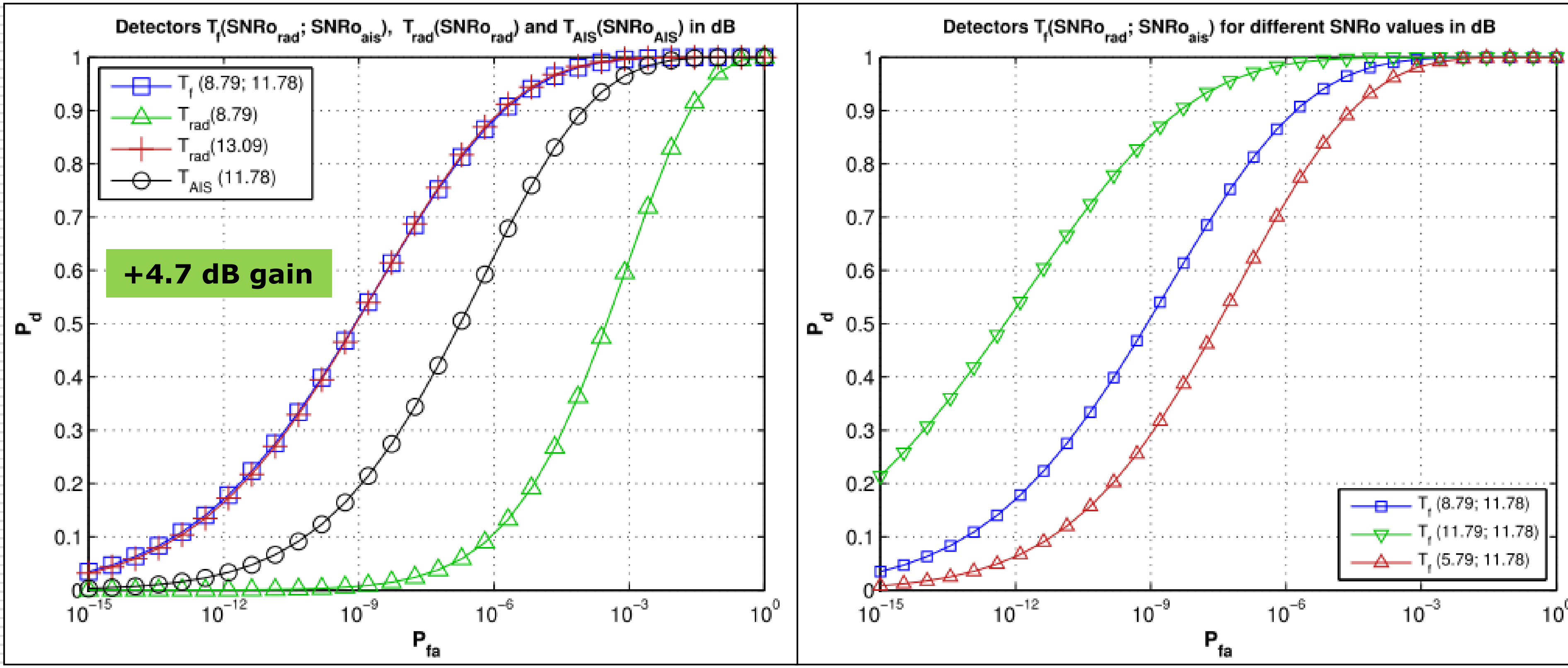
Signal representation:

$$\mathbf{y}_{\mathrm{rad}} = \alpha\mathbf{a}(\theta) + \mathbf{n}_{\mathrm{rad}}$$
$$\mathbf{y}_{\mathrm{AIS}} = \beta\mathbf{b}(\theta) + \mathbf{n}_{\mathrm{AIS}}$$

Modeling assumptions

- Both radar and AIS signals are synchronous with respect to the ship position
- There is a maximum of one single ship per test position
- Bit stuffing is disabled
- The signal model only depends on the position θ (the other parameters are known)

1st topic : Performance analysis



Parameters:
SNR input : $\mathrm{SNR}_{rad} = -33\mathrm{dB}$, $\mathrm{SNR}_{AIS} = -8\mathrm{dB}$
For correct AIS demodulation $\mathrm{SNR}_{AIS} > +10\mathrm{dB}$ **is needed**

1st topic : Results

- We cannot infer about detection performance of the detector only by looking at the likelihoods
- The ROC curves show a considerable gain by integrating both sources of data
- Model constraints are very restrictive
- Estimation of AIS parameters is time-consuming
  - Significant computational power is necessary to allow the practical implementation of the method
- **We decided to advance to the second method which could provide interesting results with reduced computational complexity**

The four research topics

1. **Explore the diversity of raw sensor signals**
   - Considers data before any signal processing
2. **Explore AIS processed data to improve radar detection**
   - Use extra information from AIS message (e.g., speed, position, time) to improve the radar detection
3. **Explore AIS and radar processed data to improve detection**
   - In this case, both AIS and radar processed data provide separate lists of detections that need to be merged
4. **Slow time integration**
   - Integrate slow time data from satellite scene revisit for tracking

2nd topic : Explore AIS processed data to improve radar detection

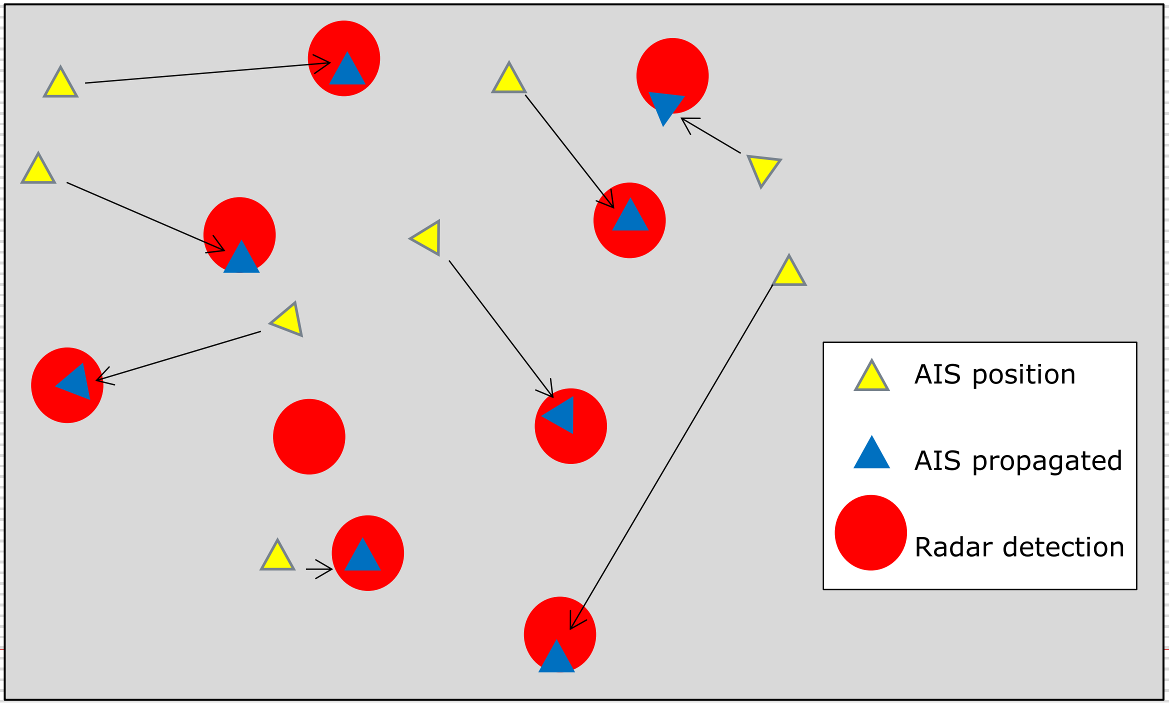
- ***Main idea***
  The knowledge of the existence of a ship at some position due to AIS information can be consolidated by radar data to improve detection

- Target signatures are now only the radar raw signals

- The AIS is a list of target positions with timestamps

2nd topic : Explore AIS processed data to improve radar detection

- The AIS list is propagated to their expected positions at the instant of the radar measurement



2nd topic : Explore AIS processed data to improve radar detection

- Formulation

Signal representation :

$$y_{radar} = A\left(\theta_{ais\_pro}\right)\alpha + a(\theta_i)\beta + n_{radar}$$

Signal = y
Radar signature = A,a
Parameter vector = θ
Noise = n

Note:
θ = X,Y coords in radar

Where:

θ_i is the parameter vector of the test case i

$a(\theta_i)$ is the radar signature for θ_i

θ_{ais_pro} is the parameter vector of AIS targets propagated into the radar scene

$A\left(\theta_{ais\_pro}\right)$ is the radar signature for θ_{ais_pro}

Formulation on a two hypotheses test

$H_0\!:\{y = A\left(\theta_{ais\_pro}\right)\alpha + n\,;\beta = 0$ (no radar echoes, only noise)

$H_1\!:\{y = A\left(\theta_{ais\_pro}\right)\alpha + a(\theta_i)\beta + n\,;\beta \neq 0$ (signal and noise)

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Signal model

Model for unknown signal amplitude and noise power

Hypothesis H0 : $y = A(\theta_{ais\_pro})\alpha + n,\ \beta = 0$

Estimator for the signal amplitude : $\widehat{\alpha}_0 = (A^H A)^{-1} A^H y$

Estimator for noise power : $\hat{\sigma}_0^2 = (y - A\alpha)^H (y - A\alpha)/N$

Likelihood : $L_0 = K_0 (y^H P_A^{\perp} y)^{-N} = K_0 \left\| P_A^{\perp} y \right\|^{-N}$

$$K_0 = \left(\frac{\pi}{N} e\right)^{-N}$$

2nd topic : Explore AIS processed data to improve radar detection

Hypothesis H1 : $y = A(\theta_{ais\_pro})\alpha + a(\theta_i)\beta + n,\ \beta \neq 0$

Model for unknown signal amplitude and noise power

Estimator for noise power: $\hat{\sigma}_1^2 = (y - A\alpha - a\beta)^H (y - A\alpha - a\beta)/N$

Estimator for signal amplitudes : $\hat{\alpha}_1 = (A^H A)^{-1} A^H (y - a\beta)$
$\hat{\beta}_1 = (a^H P_A^{\perp} a)^{-1} P_A^{\perp} a^H y$

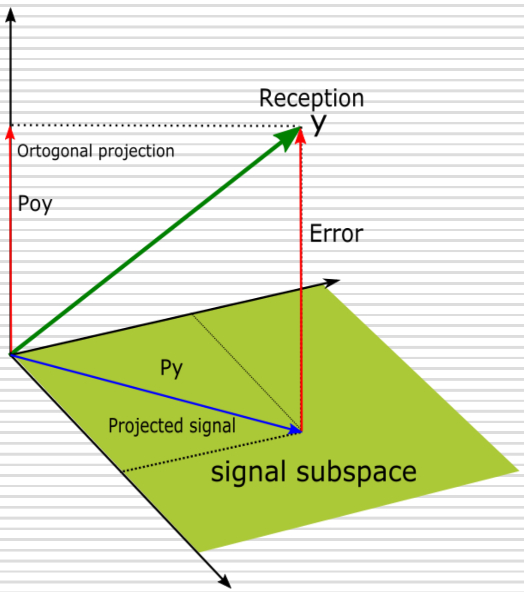
Likelihood : $L_1 = K_0 \left(y^H P_A^{\perp} y - \frac{y^H P_A^{\perp} a a^H P_A^{\perp} y}{a^H P_A^{\perp} a} \right)^{-N}$ $K_0 = \left(\frac{\pi}{N} e \right)^{-N}$

GLRT – Generalized Likelihood ratio test

$\mathrm{T} = \frac{H_1}{H_0};\ \grave{T} = \frac{\|a'^H y'\|^2}{\|a'\|^2 \|y'\|^2} = \cos^2\theta$ θ is the angle between a' and y'

2nd topic : Explore AIS processed data to improve radar detection

The proposed detector explores the knowledge about the (possible) existence of a target at θ and detects the signal amplitude that is outside the subspace $\langle A \rangle$ (the AIS list)

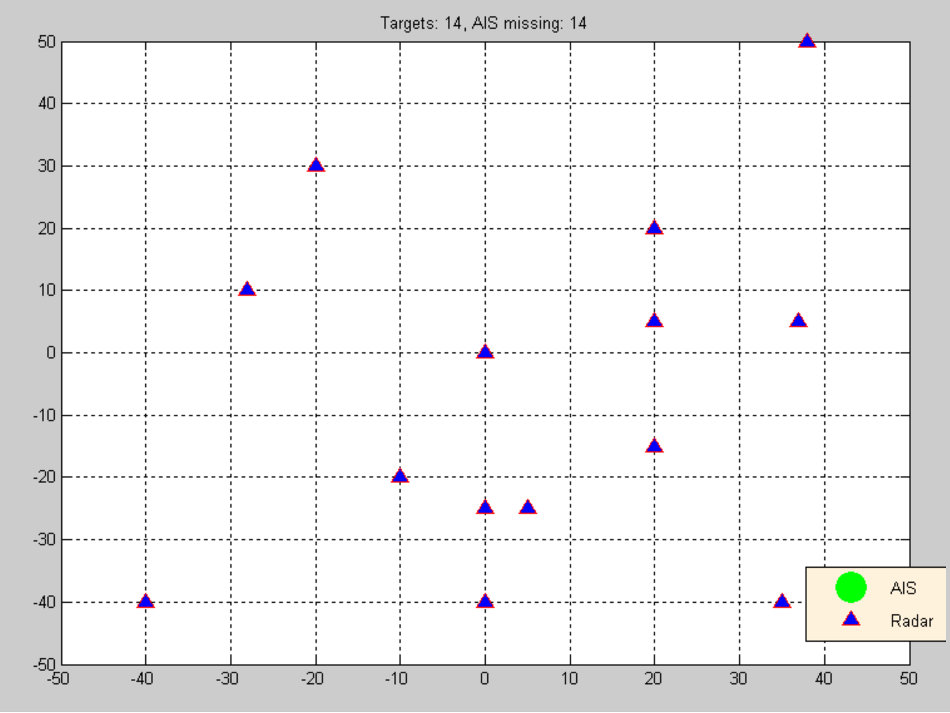


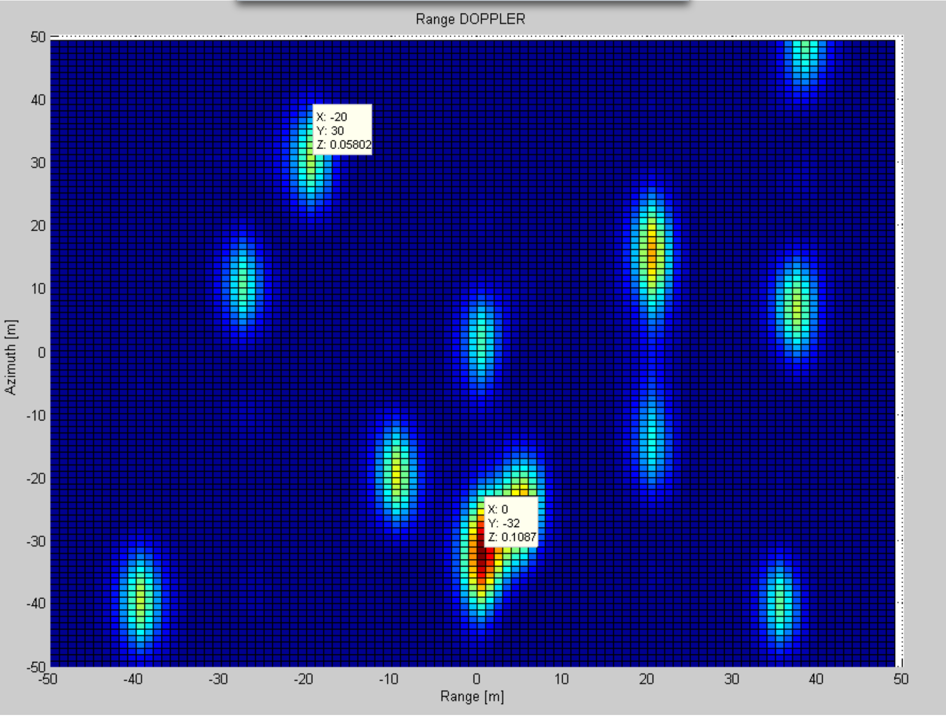
- $A(\theta)\alpha$ is the amplitude of a signal at θ
- $a(\theta)\beta$ is the amplitude measured at θ that is not present inside $\langle A \rangle$ subspace
- n is the measurement noise
- In H0, there is no radar signal (measurement is outside $\langle a \rangle$ and $\langle a \rangle \subset \langle A_\perp \rangle$)
- In H1, the measurement at θ can be partially inside $\langle A \rangle$ and inside $\langle a \rangle \subset \langle A_\perp \rangle$

2nd topic :Study case

- Consider a scenario with 14 identical ships at a scene
- Some are not separable with the radar detector

Radar detector





2nd topic :Study case

- Considering the AIS information of targets propagated to the current radar scene

AIS and radar targets

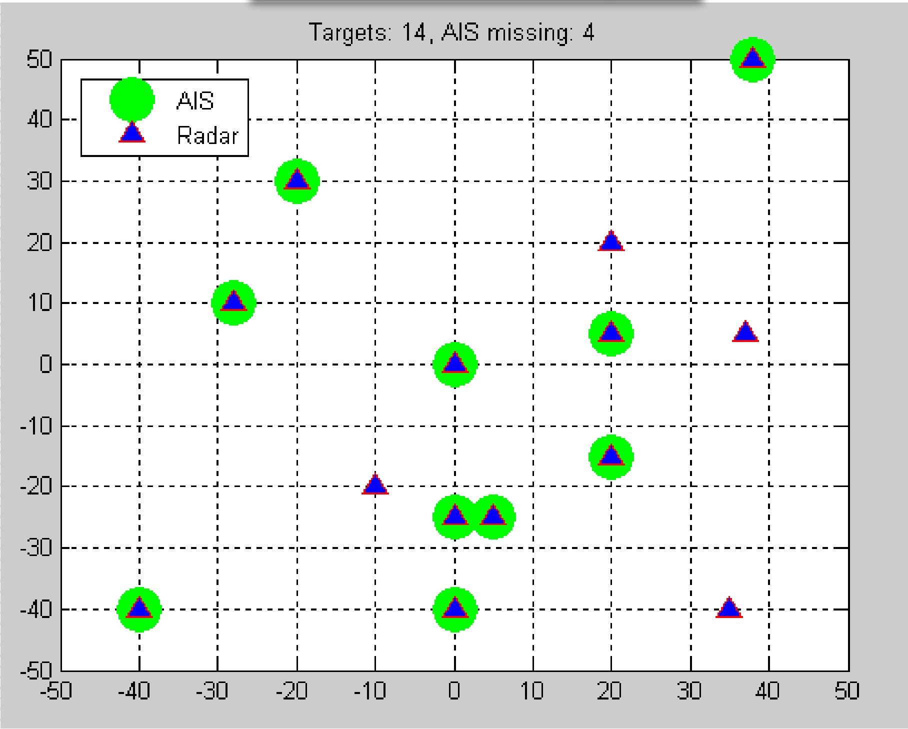
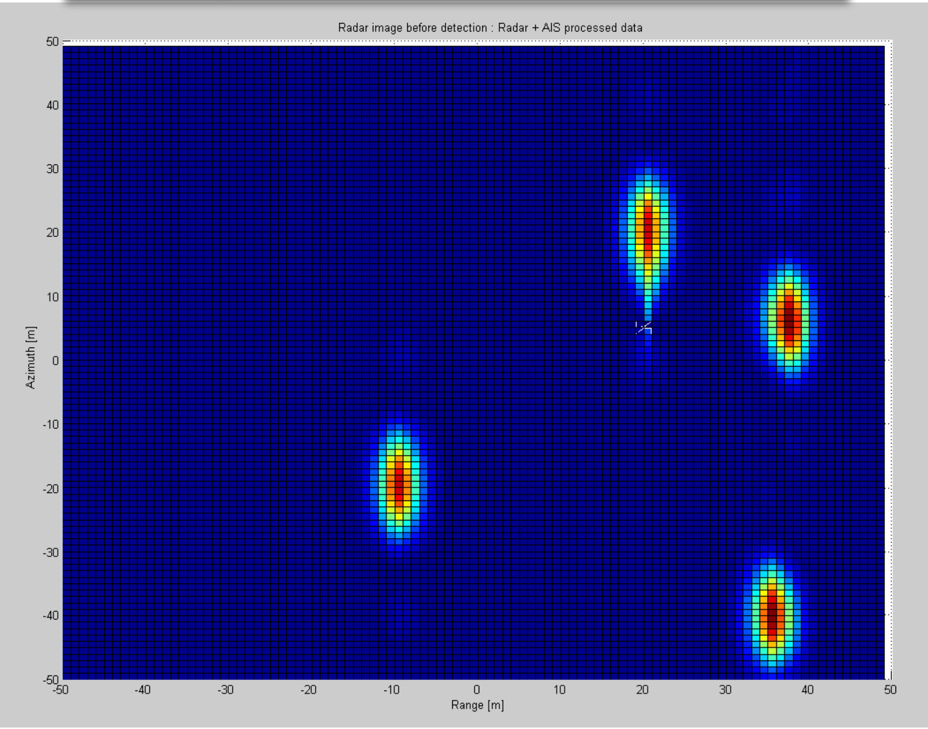
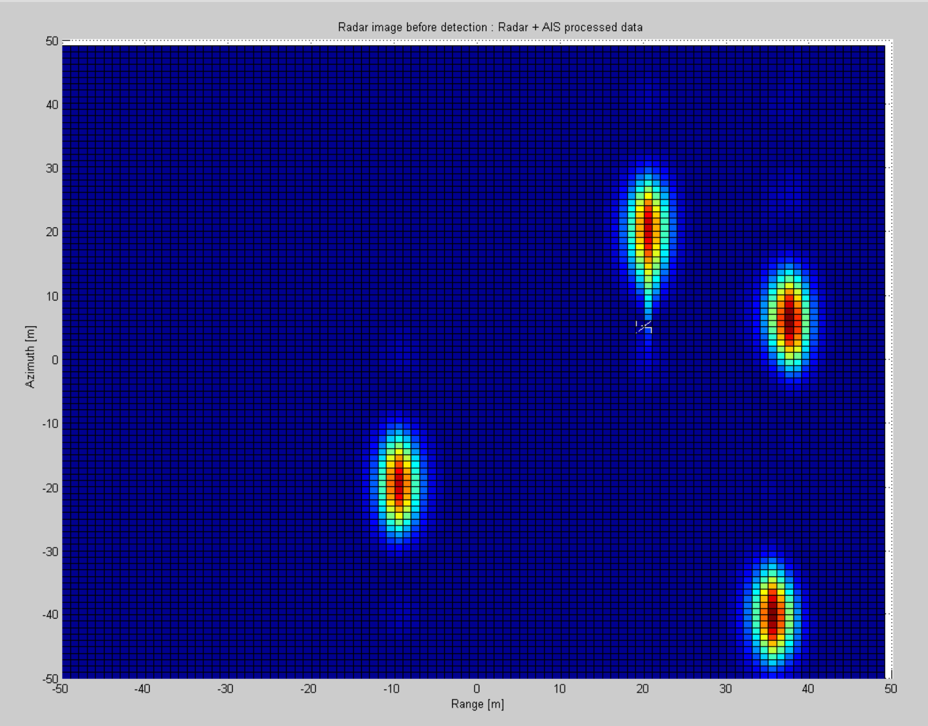


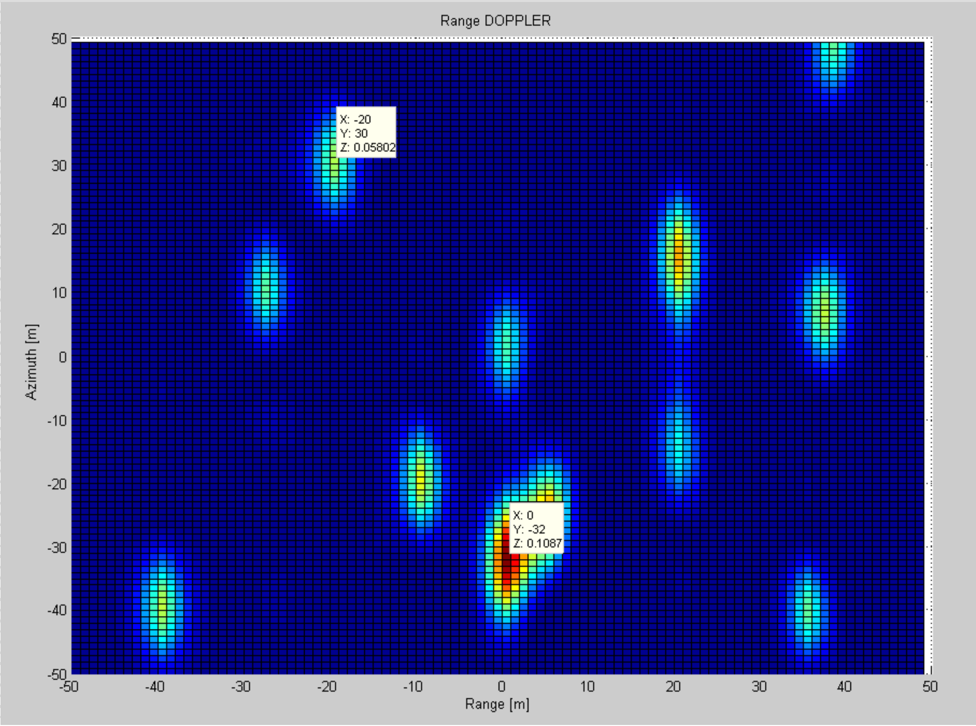
Image with the proposed detector



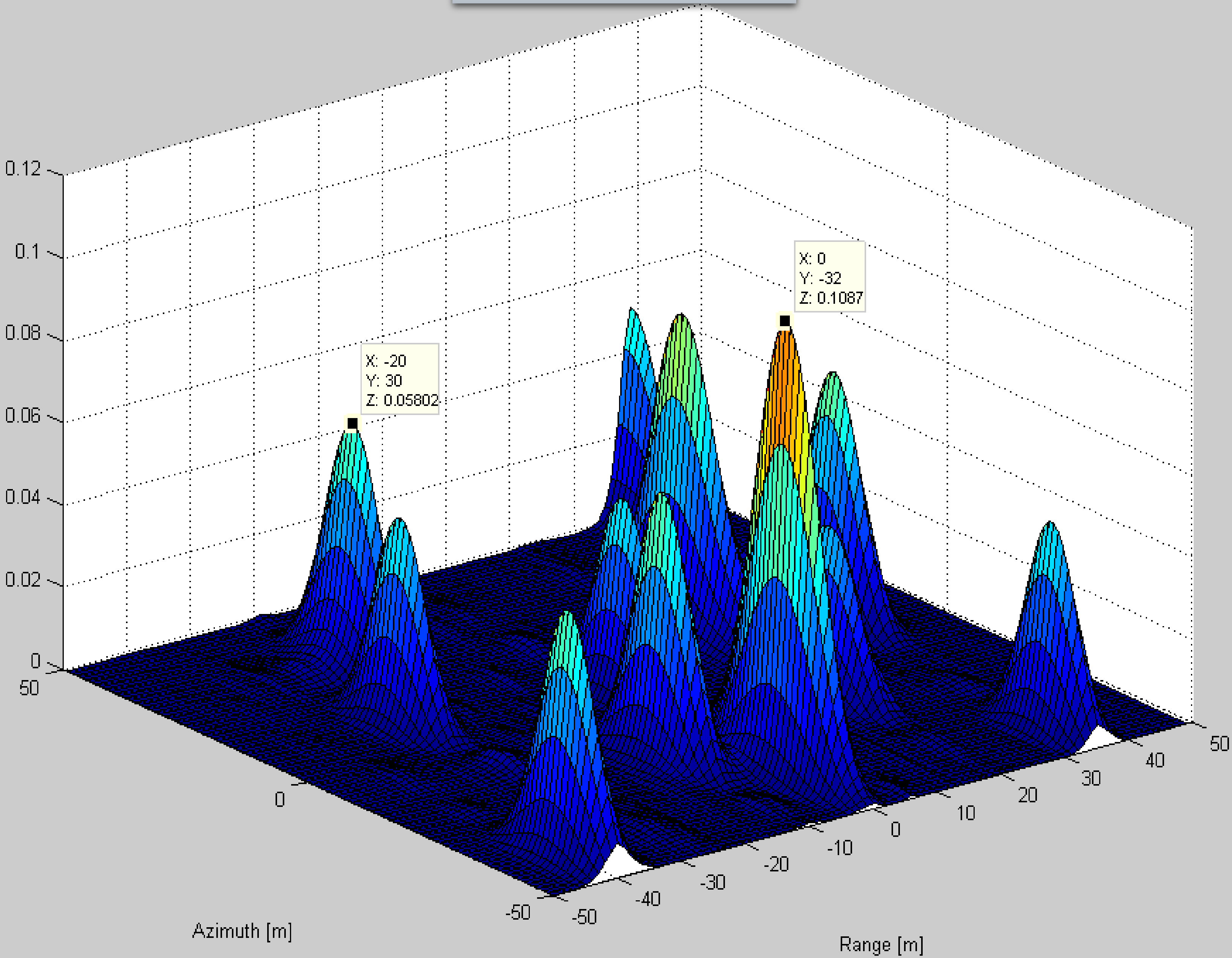
2nd topic :Study case

- Comparing both detectors
- Targets are now separable if AIS information is present

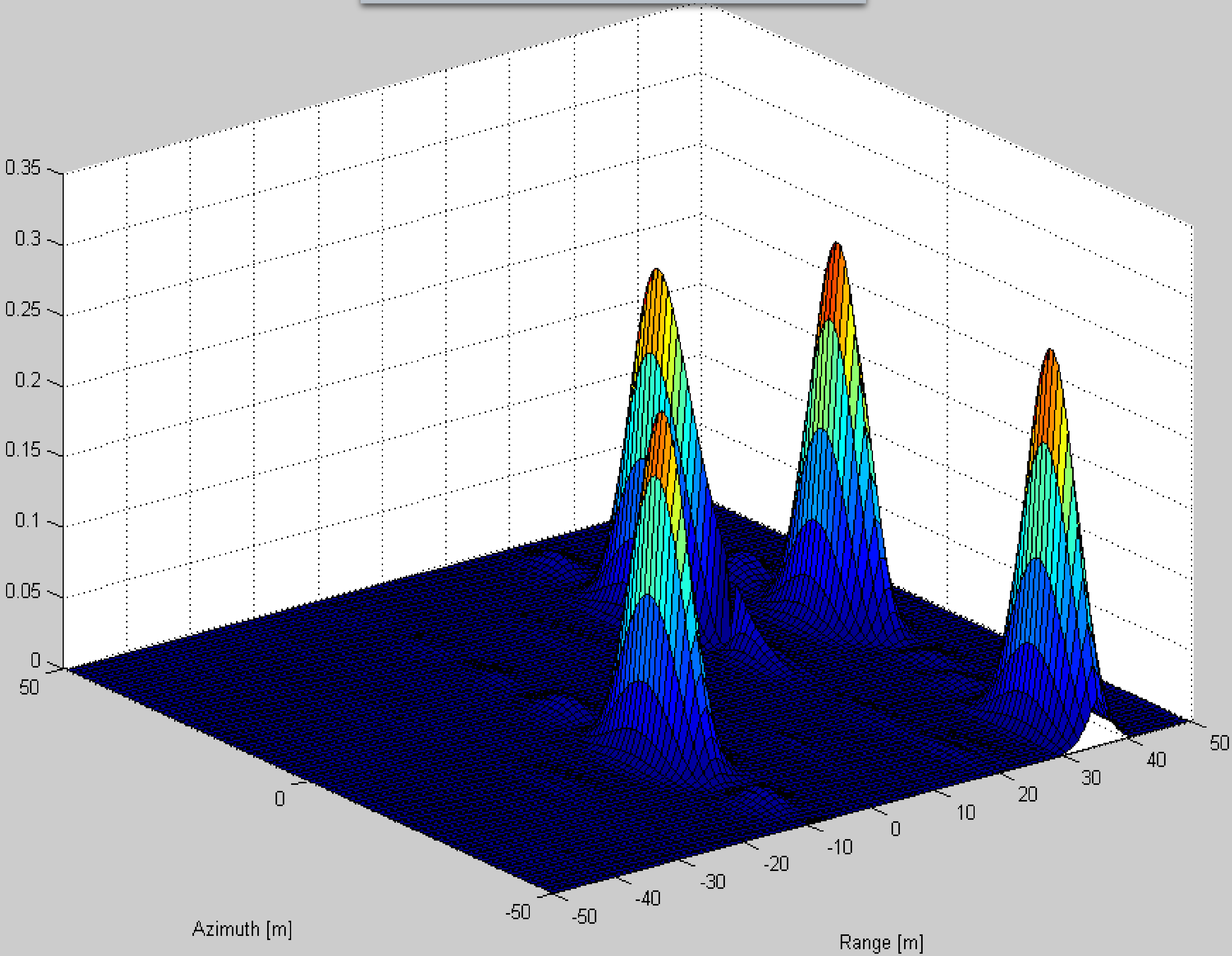




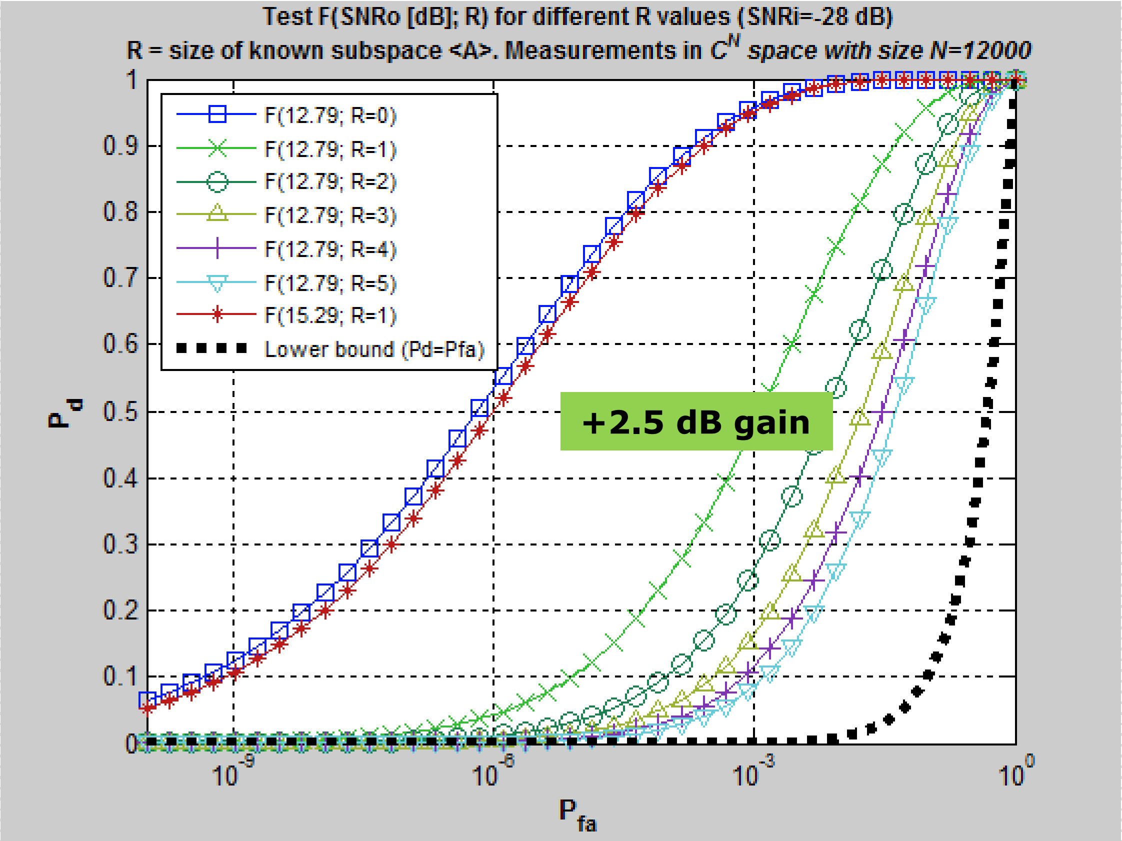
Radar detector



Detection using the AIS list



2nd topic : Performance analysis



Parameters:
SNR input : $\mathrm{SNR}_{rad} = -33\mathrm{dB}$, $\mathrm{SNR}_{AIS} = -8\mathrm{dB}$
For correct AIS demodulation $\mathrm{SNR}_{AIS} > +10\mathrm{dB}$ **is needed**

2nd topic : Explore AIS processed data to improve radar detection

- AIS positions may have errors
  - GPS error, propagation error, false data

Scenarios:

1. **Small errors in AIS position (error <rad. resolution)**
   - Errors are acceptable, but AIS positions may be false
   - A solution is to test the AIS list to remove the wrong data vectors
2. **Important errors in AIS position (error>rad. resolution)**
   - The detector needs to consider positioning errors
   - Approaches
     A. Errors are obtained by secondary data
     B. Errors are formalized by Bayesian approach

2nd topic : Explore AIS processed data to improve radar detection

2. **Important errors in AIS position (error>rad. resolution)**
   A. Use of secondary data
      - We include the uncertainty of the ship position in the detector model

$$\begin{cases} y_{radar} = A(\theta_r)\alpha + a(\theta_a)\beta + n_r \\ \theta_a = \theta_r + n_a \end{cases}$$

      - Sources of information to deal with position noise power
        - GPS precision data
        - Ship history data about heading and speed
        - Those can lead to a good estimation of σ_a^2

Conclusions

- In the first method AIS raw signals improved radar detection performance in a conditioned scenario
  - Without decoding the AIS message
  - Even when the AIS signal-to-noise ratio (SNR) is not sufficient to decode the AIS message
  - The gain with the first method is the theoretical limit (optimal detector)
    - Reference for other detectors based on processed data
- In the second method, the AIS decoded message provided information for a detector that uses radar raw data to improve ship detection
  - It separates the signals that are related to the AIS positions from new detections
- Second method is less computer intensive than first method
  - It does not need to model the AIS signal
  - It is more prone to be implemented in practice

Next steps

- Continue the performance evaluation of the second method
- Compare performance of different methods
- Evaluate special scenarios and practical problems
  - Multiples hypotheses in both first and second methods
  - AIS deception and message collisions
  - Low PRF SAR ambiguities
- Implement the model with positioning errors
- Use the Bayes approach to deal with positioning errors
- Advance to evaluate the third and forth fusion methods
  - Data association using processed data from sensors
  - Tracking and long term integration
- Explore other AIS information (e.g. identification, ship size)
  - Ship discrimination, estimation of other parameters and errors