Data Association in Multistatic Passive Radar Systems

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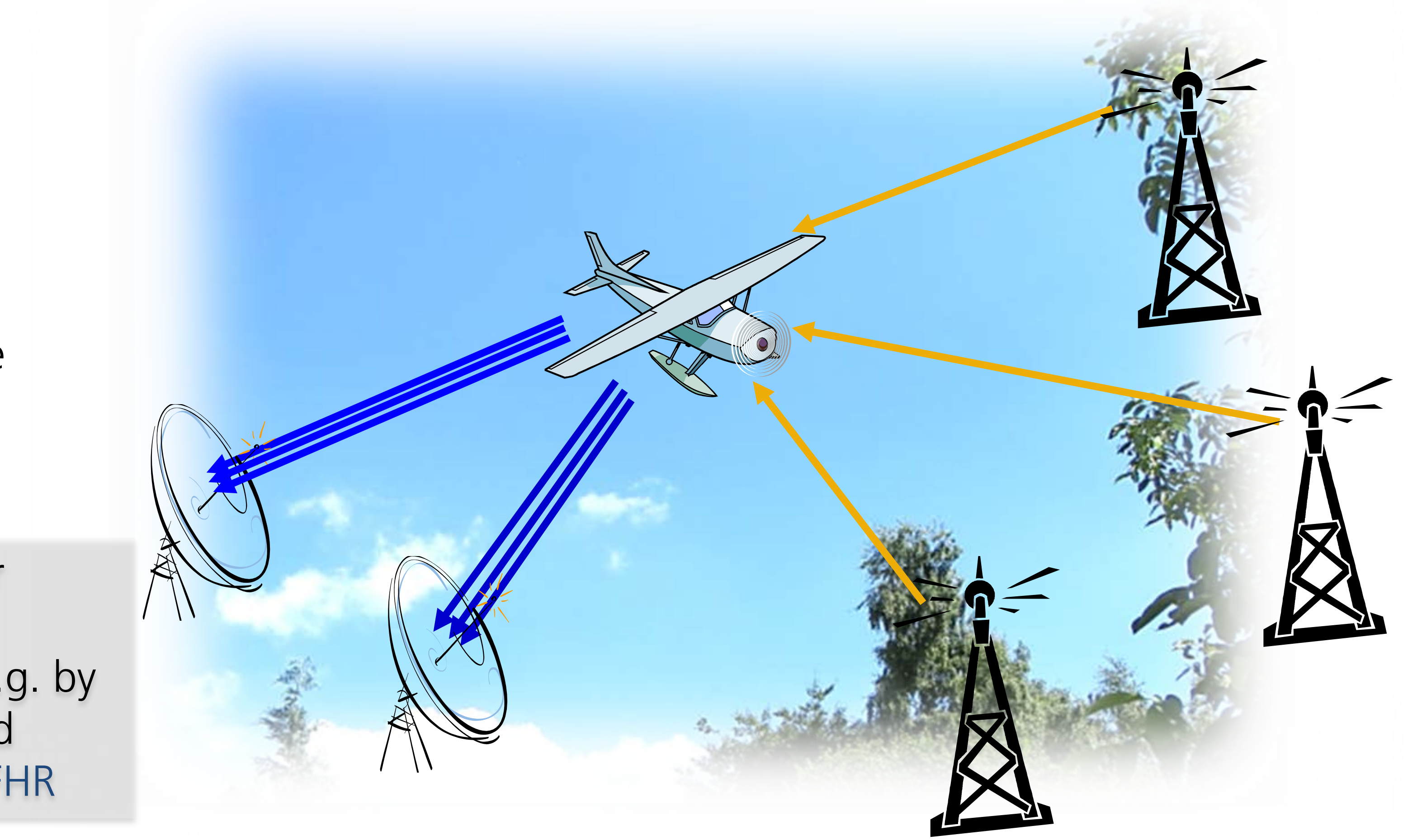
Fraunhofer
FKIE

Passive Radar Application: Air Surveillance

using transmitter of opportunity, e.g. tv, radio, mobile phone stations

Possibly
long range
and
high altitude



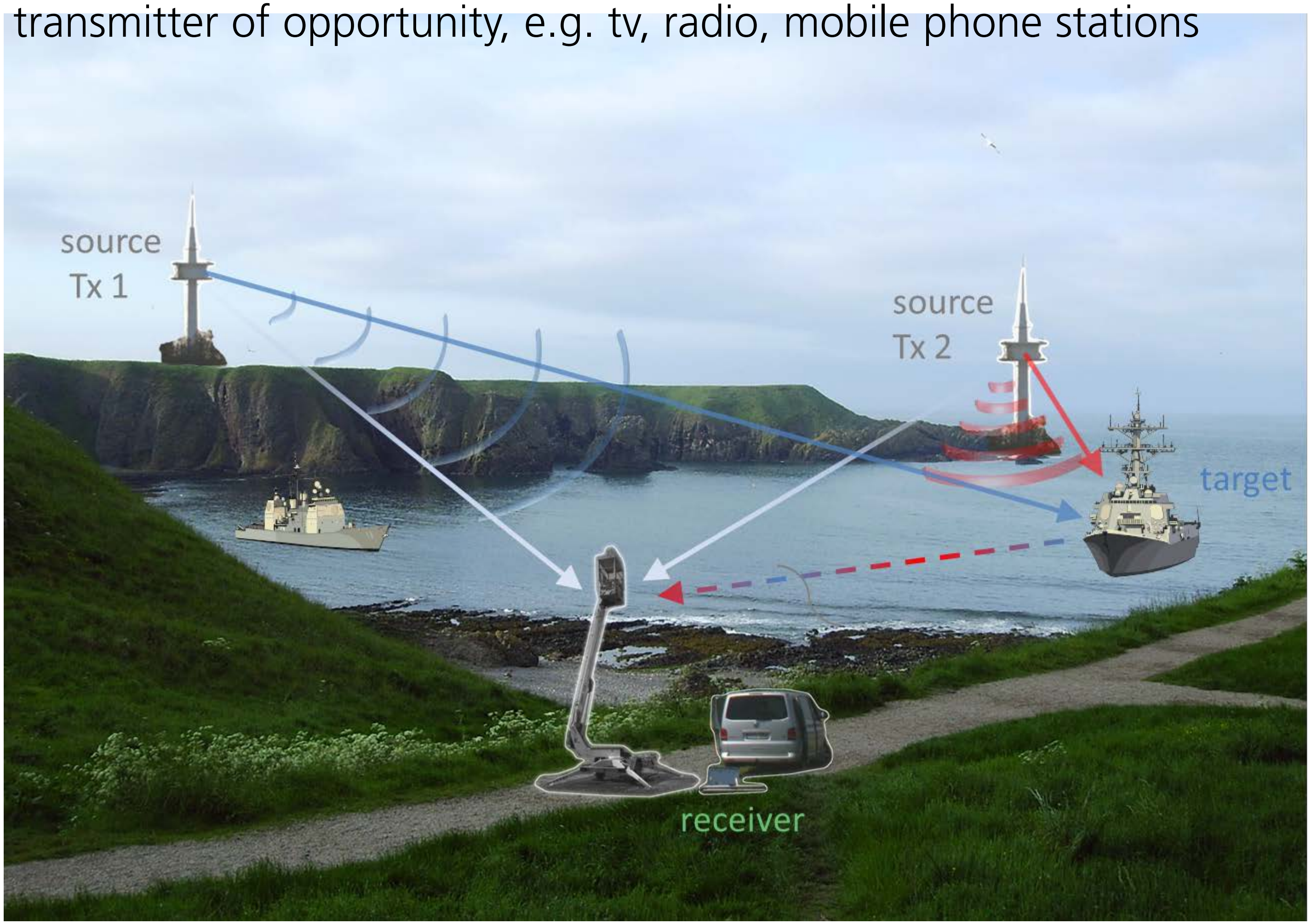
Passive radar
systems are
developed e.g. by
Hensoldt and
Fraunhofer FHR

Passive Radar Application: Maritime Surveillance

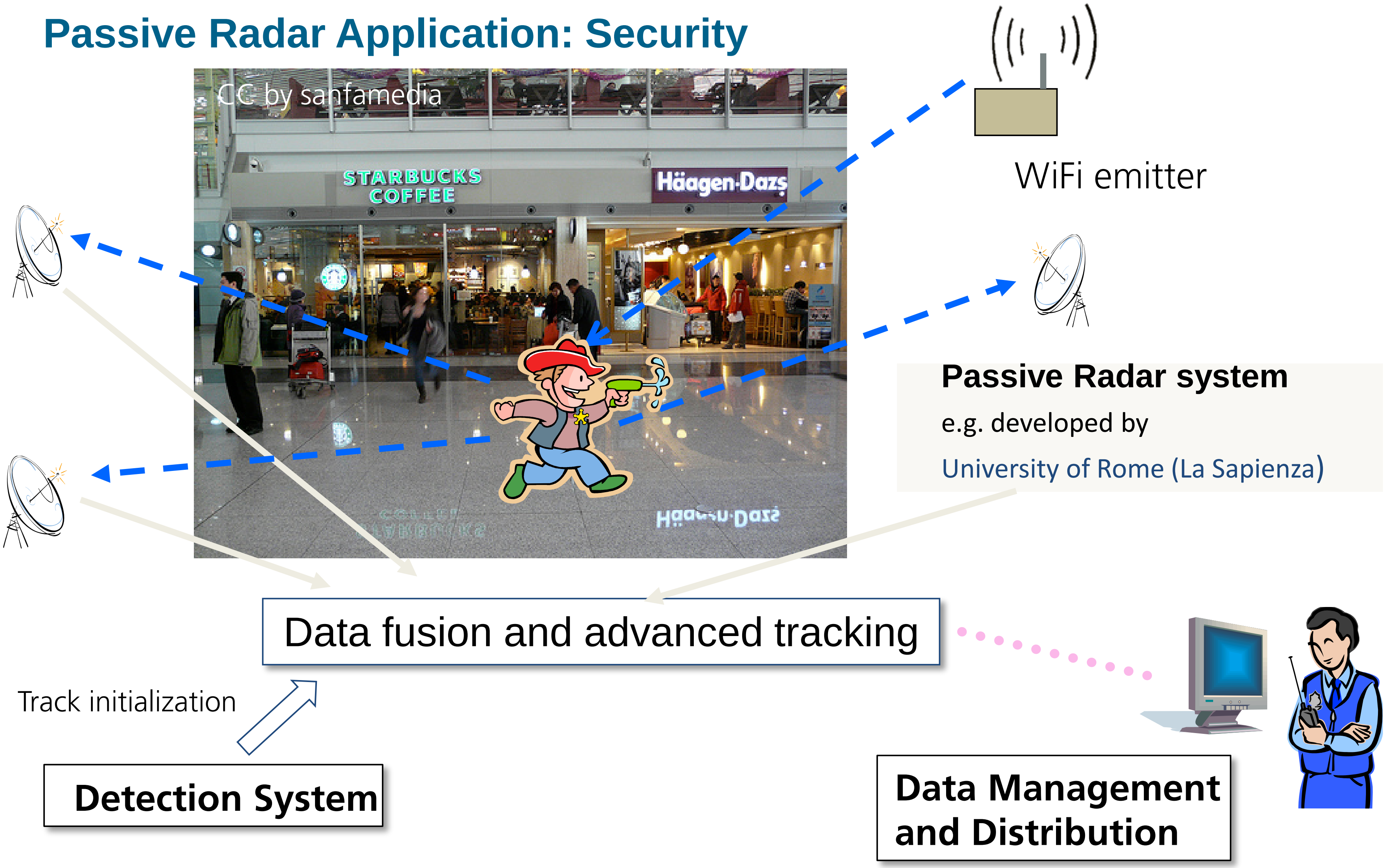
using transmitter of opportunity, e.g. tv, radio, mobile phone stations

Range is limited by the radar horizon

Fraunhofer FKIE develops a demonstrator for GSM passive radar



Passive Radar Application: Security



WiFi emitter

Passive Radar system

e.g. developed by

University of Rome (La Sapienza)

Data fusion and advanced tracking

Track initialization

Detection System

Data Management and Distribution

Motivation

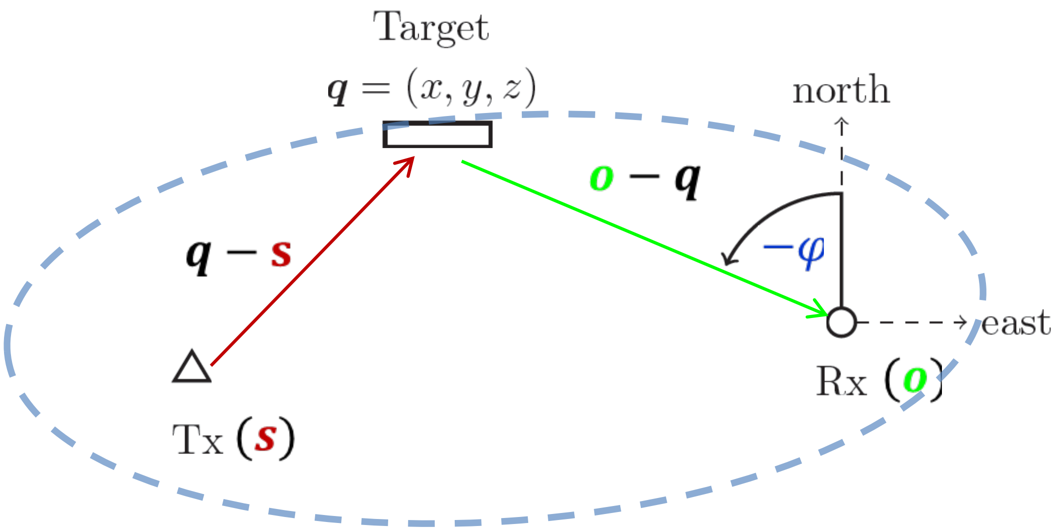
- **Advantages of multistatic systems**
  - *Improved detection* (different bistatic angles, redundancy)
  - *Improved target localisation*
  - *Passive systems*: no need for own transmitters (no frequency permission, low power consumption, covert operation)

- **Target tracking in multistatic systems**
  - Target localization in Cartesian coordinates
  - Important for sensors of low accuracy

- **Particular challenges:**
  - Robust target tracking algorithms for large numbers of false alarms
  - Target tracking algorithms for passive radar using digital broadcasting signals

The bistatic measurement

Target state: $\boldsymbol{x} = (\underset{\underset{\text{position}}{\nearrow}}{\boldsymbol{q}}, \underset{\underset{\text{velocity}}{\uparrow}}{\boldsymbol{v}})$

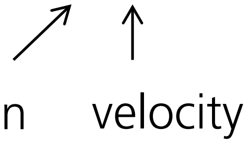


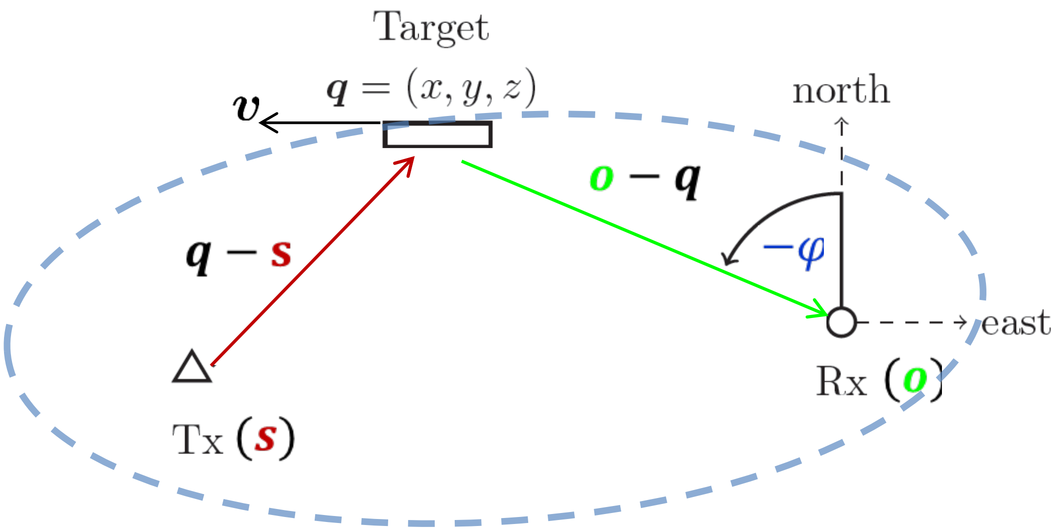
Bistatic range:

- TDoA τ between direct signal and echo signal
- Bistatic Range: $r = \tau \cdot c + \|s - o\|$ or
  $$r = \|q - o\| + \|q - s\|$$
- describes ellipse in 2D and ellipsoid in 3D
- accuracy depends on the band width of the signal

The bistatic measurement

Target state: $\boldsymbol{x} = (\boldsymbol{q}, \boldsymbol{v})$





Bistatic range-rate:

- measured Doppler shift in Hz f_d
- velocity component of bistatic range

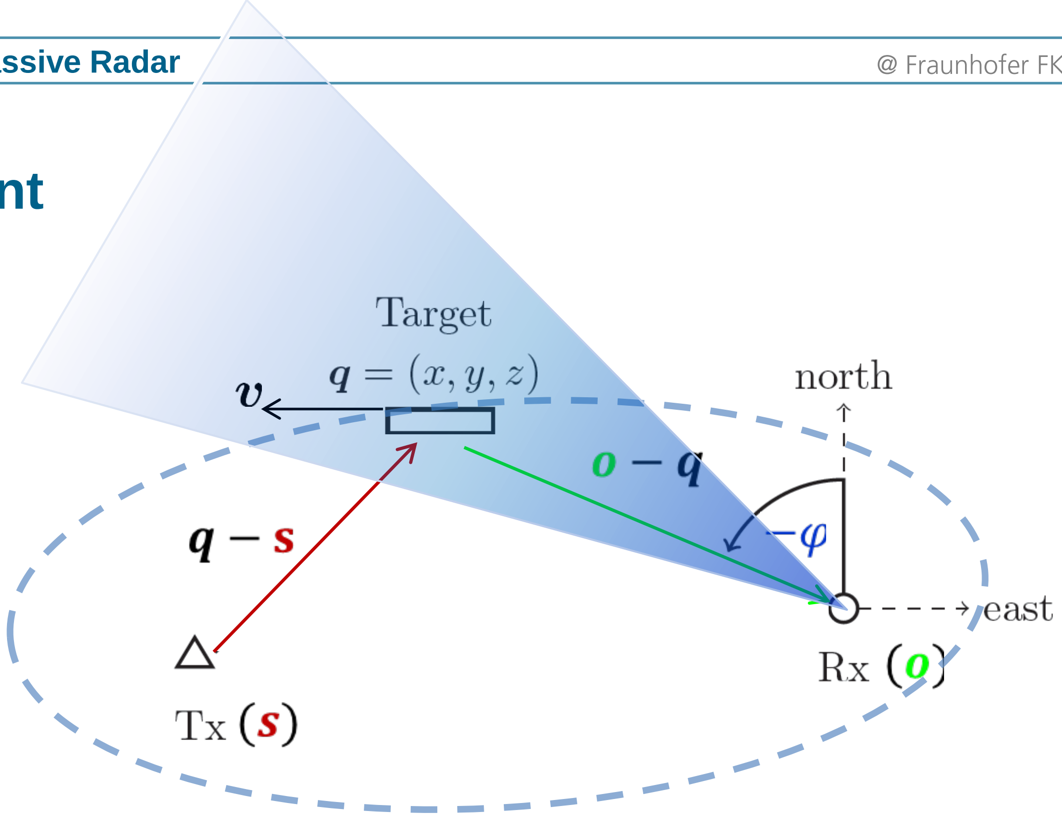
$$\dot{r} = -f_d\lambda = \left(\frac{\boldsymbol{q}-\boldsymbol{s}}{\|\boldsymbol{q}-\boldsymbol{s}\|} + \frac{\boldsymbol{q}-\boldsymbol{o}}{\|\boldsymbol{q}-\boldsymbol{o}\|}\right)^T \cdot \boldsymbol{v}$$

- accuracy depends on the wave length of the signal and the integration time

The bistatic measurement

Target state: $\boldsymbol{x} = (\boldsymbol{q}, \boldsymbol{v})$

$\nearrow$ position $\uparrow$ velocity



Azimut Winkel:

- $\varphi = \operatorname{atan2}(x - o_x, y - o_y) \in (-\pi, \pi]$
- accuracy depends on the apperture size and the wavelength of the signal

Characteristics of different passive radar broadcasters

- FM (analogue radio):
  - high power
  - Low bandwidth → poor range resolution
- DAB / DVB-T (digital radio and television):
  - High bandwidth → good range resolution
  - Single frequency characteristics
- GSM (mobile phone):
  - Many base stations available
  - Low power
  - Low bandwidth → poor range resolution
- WIFI (WLAN):
  - Very high bandwidth → very good range resolution
  - Very low power → only for near field operation

Principle of target tracking

Propagation of *posterior pdf* according to Bayes formalism

$\{\underline{\mathbf{X}}_k\}$: target state process (r.v.)

$\{\underline{\boldsymbol{\Upsilon}}_k\}$: measurements process (r.v)

$\mathcal{Z}_{1:k}$: collection of measurements from time t_1 up to time t_k (realisations)

- Initialisation: $p_{\underline{\mathbf{X}}_1|\underline{\boldsymbol{\Upsilon}}_1}(\boldsymbol{x}|\mathcal{Z}_{1:1})$
- Prediction:

motion model

$$p_{\underline{\mathbf{X}}_k|\underline{\boldsymbol{\Upsilon}}_{1:k-1}}(\boldsymbol{x}|\mathcal{Z}_{1:k-1}) = \int p_{\underline{\mathbf{X}}_k|\underline{\mathbf{X}}_{k-1}}(\boldsymbol{x}|\boldsymbol{y})\; p_{\underline{\mathbf{X}}_{k-1}|\underline{\boldsymbol{\Upsilon}}_{1:k-1}}(\boldsymbol{y}|\mathcal{Z}_{1:k-1})d\boldsymbol{y}$$

- Filtering:

Likelihood function (sensor model)

$$p_{\underline{\mathbf{X}}_k|\underline{\boldsymbol{\Upsilon}}_{1:k}}(\boldsymbol{x}|\mathcal{Z}_{1:k}) \propto p_{\underline{\boldsymbol{\Upsilon}}_k|\underline{\mathbf{X}}_k}(\mathcal{Z}_k|\boldsymbol{x})\; p_{\underline{\mathbf{X}}_k|\underline{\boldsymbol{\Upsilon}}_{1:k-1}}(\boldsymbol{x}|\mathcal{Z}_{1:k-1})$$

The Multisensor Likelihood Function

n_t: number of transmitters n_t

$$p(Z_k|x_k) = \prod_{i=1}^{n_t} p(Z_k^i|x_k)$$

not valid for SVN !

assuming perfect association:

$$p(Z_k|x_k) = \prod_{i=1}^{n_t} p(z_k^i|x_k)$$

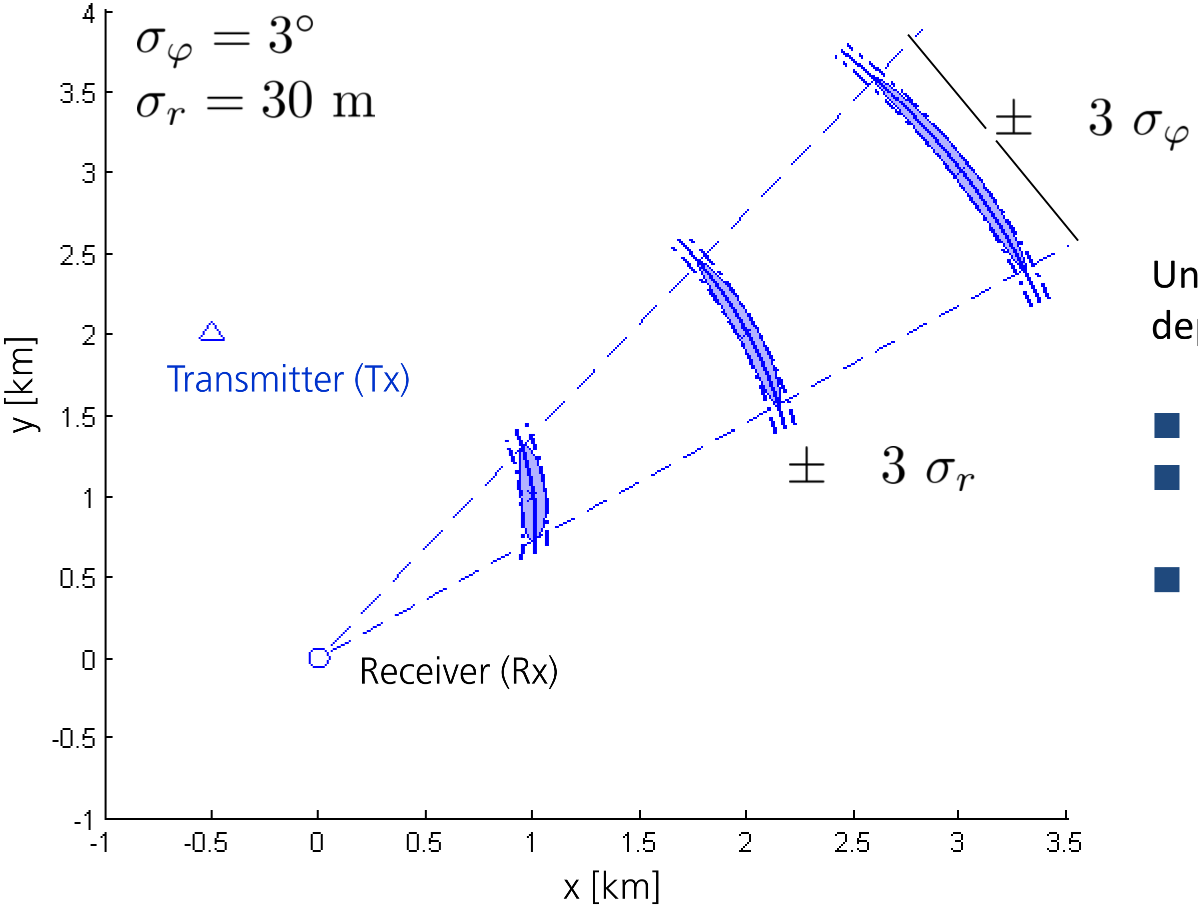
$$\approx \prod_{i=1}^{n_t} N(z_k^i; h(x_k), R)$$

assuming Gaussian Measurement Model

A linear propagation- and measurement model leads to the well known Kalman Filter propagation formula

Measurement uncertainty in Cartesian coordinates

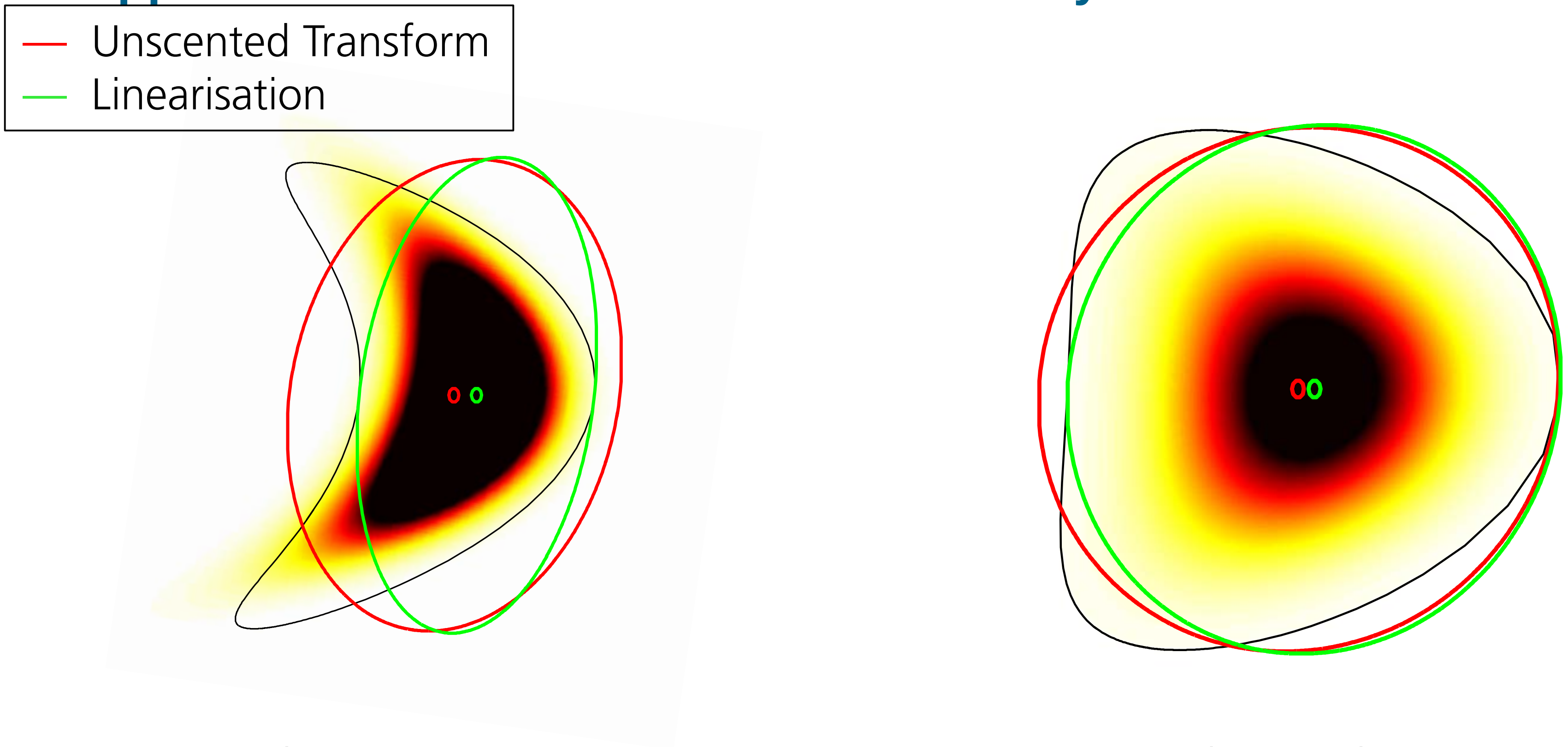
Single transmitter, one instant of time



Uncertainty in Cartesian depends on:

- Bistatic geometry
- Range and angle accuracy (here Gaussian)
- non-Gaussian shape due to non-linearity of measurement equation

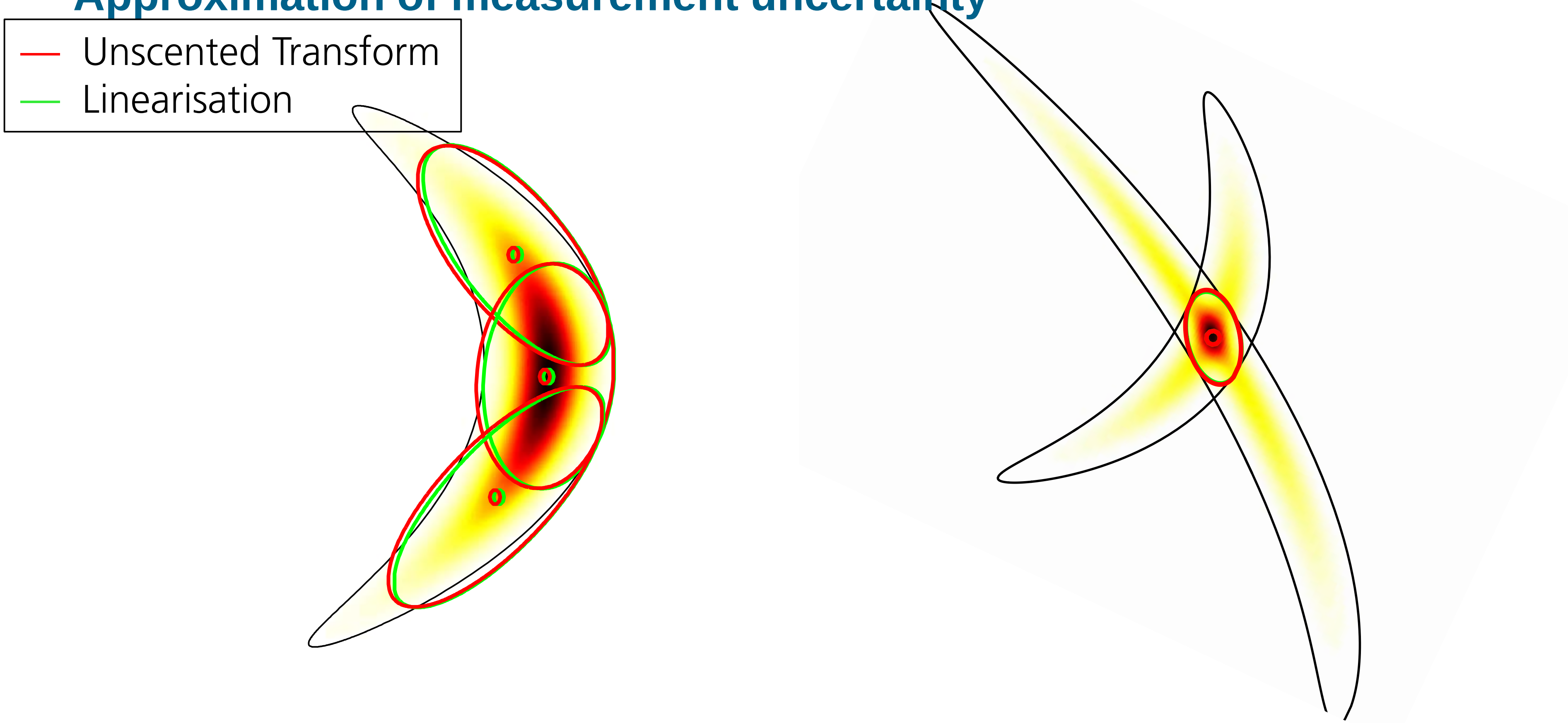
Approximation of measurement uncertainty



Good range, poor azimuth

Poor range and azimuth

Approximation of measurement uncertainty



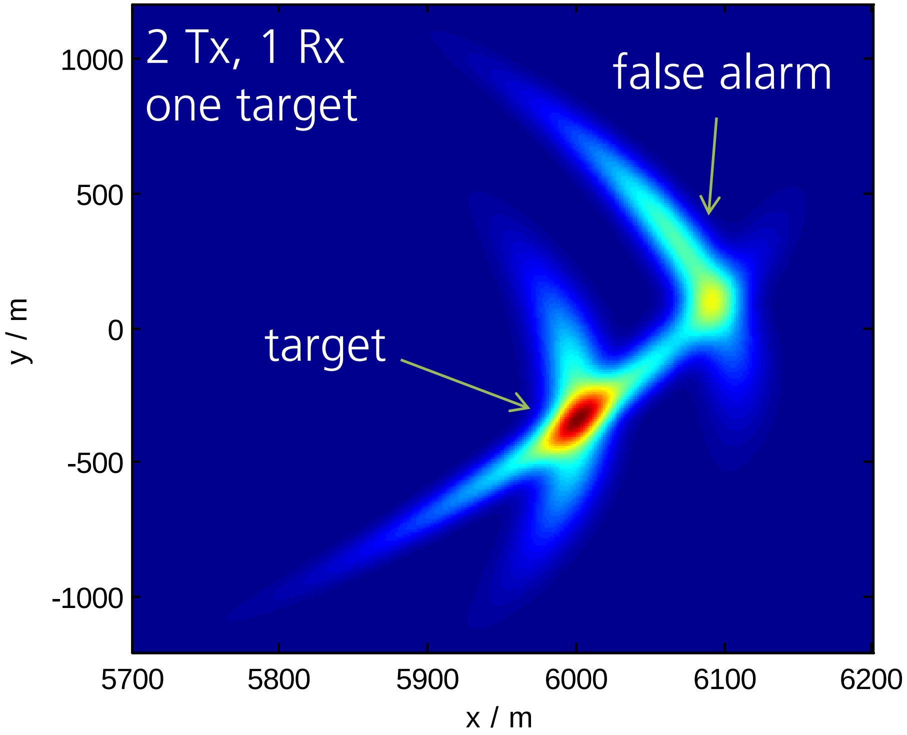
Gaussian mixture approximation

Approximation by ellipse intersection

⇨ Approximation by Gaussian or Gaussian sum is typically adequate to handle the non-linearity in passive radar tracking

The Multi-Sensor Likelihood function

- Describes also data ambiguity



Association between measurements and target is *ambiguous*:

- false alarms
- missed detections (dependent on PD)

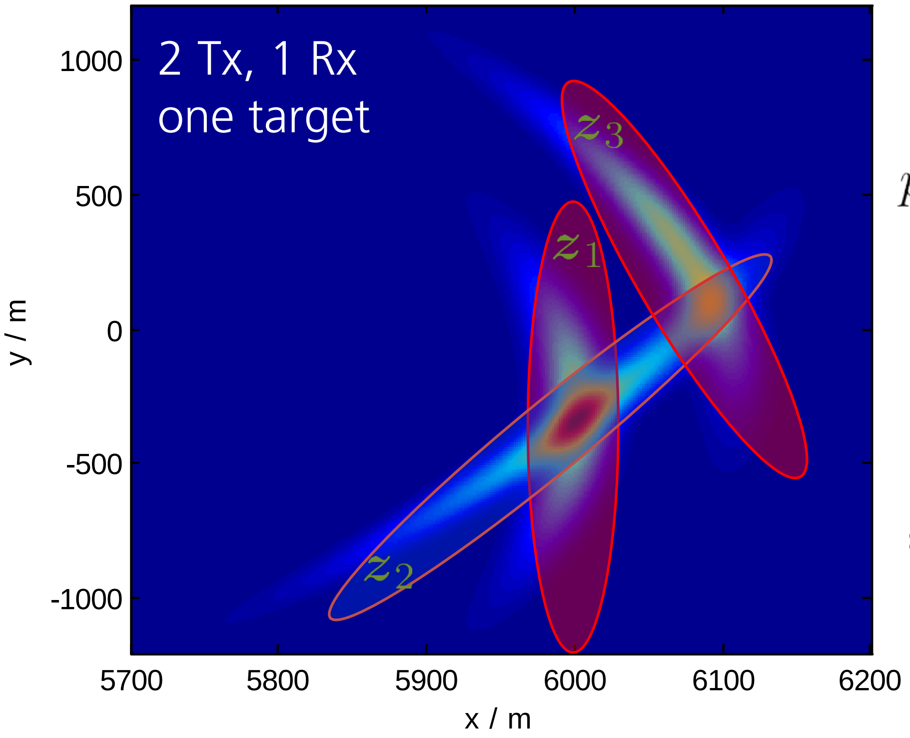
Likelihood function of 2 Tx/Rx pairs:

$$p_{\underline{\Upsilon}_k|\underline{\mathbf{X}}_k}(\mathcal{Z}_k|\boldsymbol{x})$$
$$= p_{\underline{\Upsilon}_k|\underline{\mathbf{X}}_k}(\mathcal{Z}_k^1|\boldsymbol{x})\; p_{\underline{\Upsilon}_k|\underline{\mathbf{X}}_k}(\mathcal{Z}_k^2|\boldsymbol{x})$$

$\mathcal{Z}_k = \{\mathcal{Z}_k^1, \mathcal{Z}_k^2\}$

measurements of different Tx/Rx pairs are independent

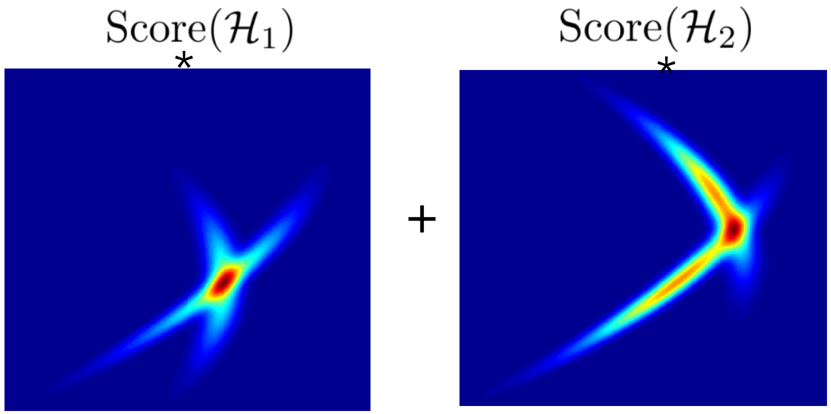
Multi Hypothesis Tracking: Principles



Single-target hypotheses:

$$\mathcal{H}_1 : z_1 \& z_2$$
$$\mathcal{H}_2 : z_3 \& z_2$$
$$\Downarrow$$

$$p_{\underline{\Upsilon}_k|\underline{\mathbf{X}}_k}(\mathcal{Z}_k|x) = \text{Score}(\mathcal{H}_1) + \text{Score}(\mathcal{H}_2)$$



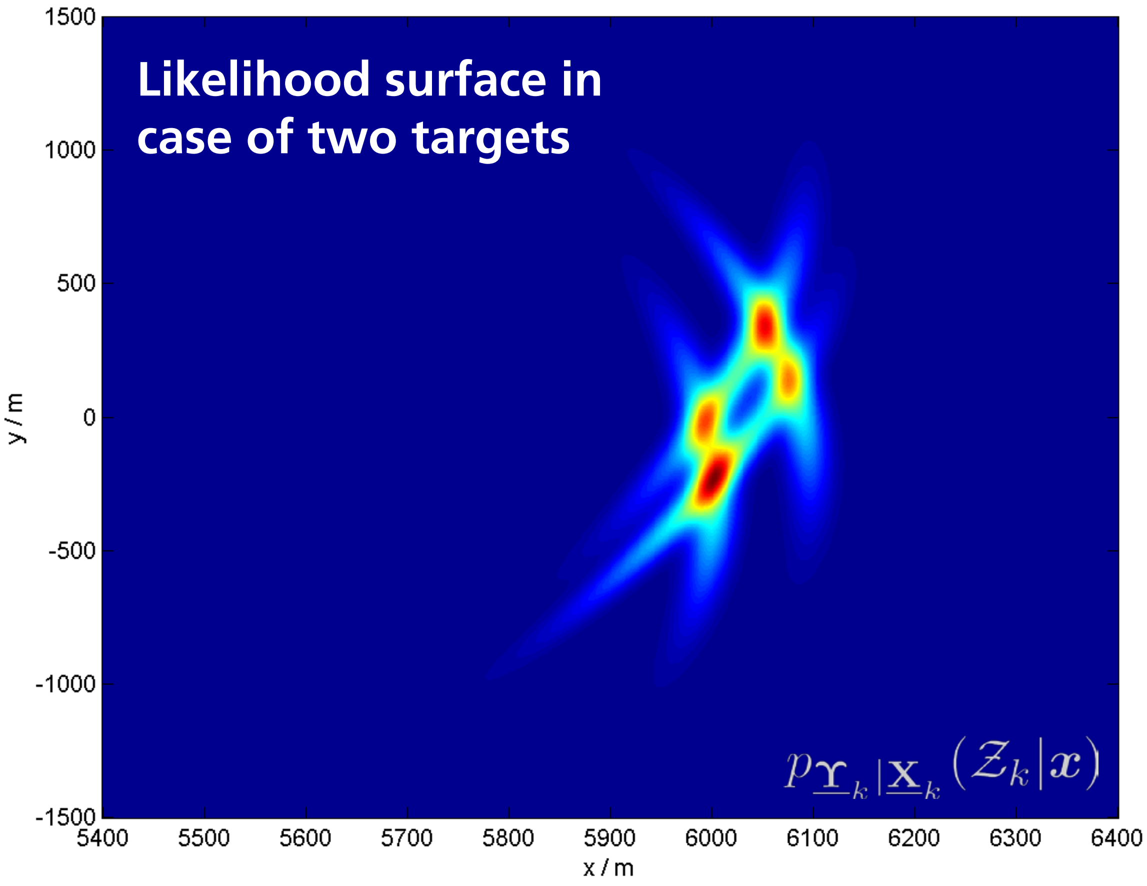
Discretisation of the event space (2 tasks):

- Data association
- Target state estimation

In reality:

- Increasing number of hypotheses
- Approximation techniques required

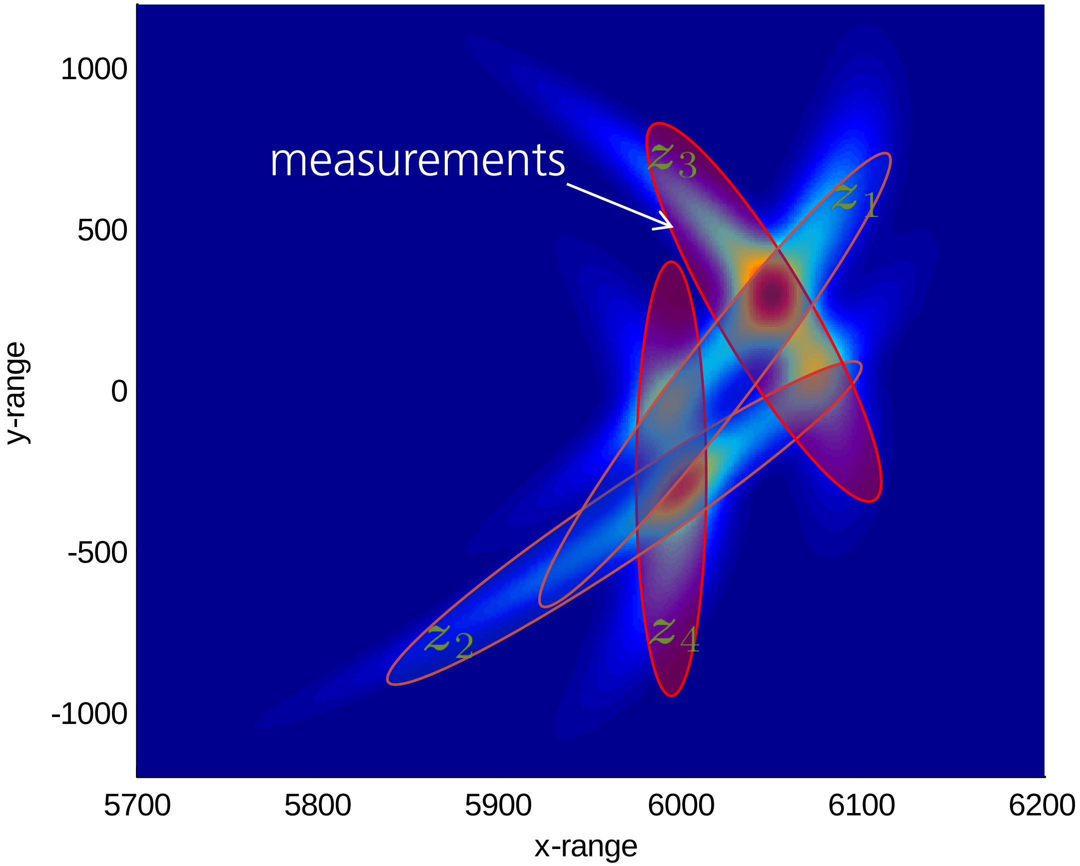
Multi Hypothesis Tracking: Multiple targets



- Single-target assumption fails in case of closely spaced targets

⇨ Multi-target likelihood: calculation by multi-target hypotheses

Multi-target hypotheses



single-target hypotheses:

$\mathcal{H}_1 : \boldsymbol{z}_3 \& \boldsymbol{z}_1$

$\mathcal{H}_2 : \boldsymbol{z}_4 \& \boldsymbol{z}_1$

$\mathcal{H}_3 : \boldsymbol{z}_3 \& \boldsymbol{z}_2$

$\mathcal{H}_4 : \boldsymbol{z}_4 \& \boldsymbol{z}_2$

⇩

multi-target hypotheses:

$\mathcal{H}_1 \& \mathcal{H}_4$

$\mathcal{H}_2 \& \mathcal{H}_3$

Multi-target Likelihood:

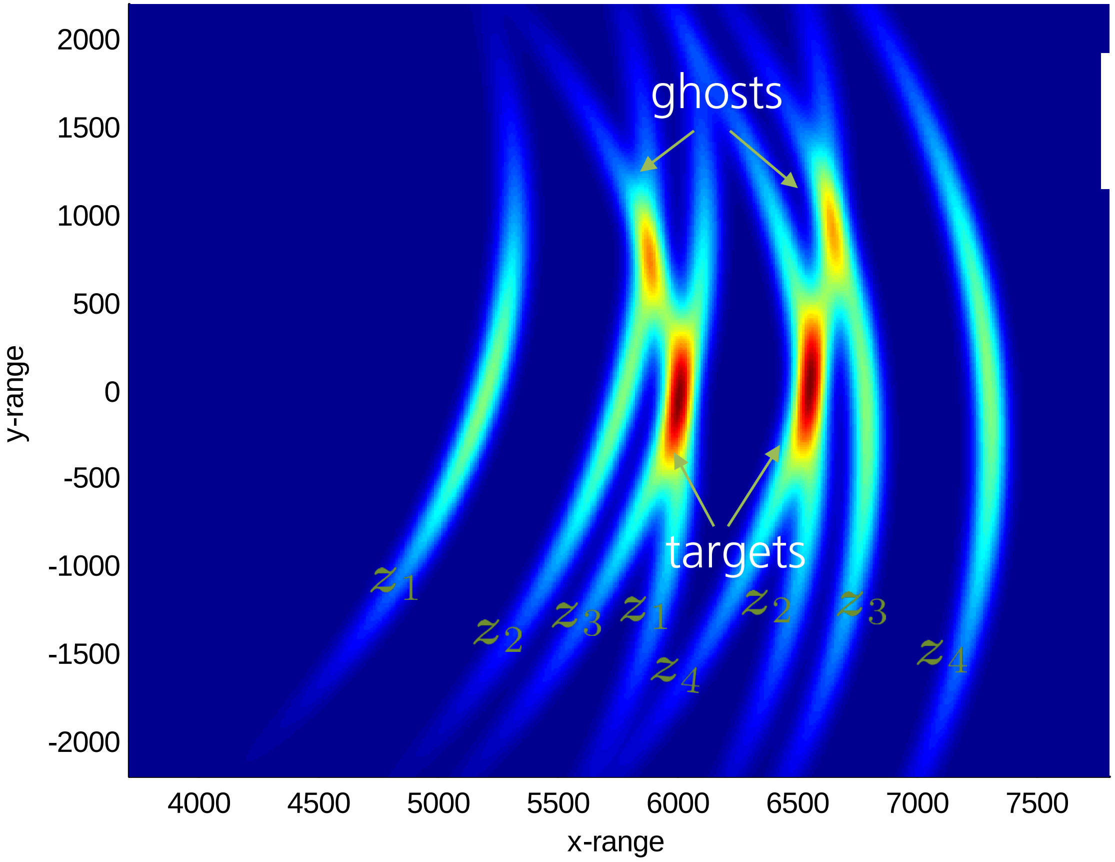
$$p_{\underline{\boldsymbol{\Upsilon}}_k|\underline{\boldsymbol{\Xi}}_k}(\mathcal{Z}_k|\xi) = p_{\underline{\boldsymbol{\Upsilon}}_k|\underline{\mathbf{X}}_k}(\boldsymbol{z}_1, \boldsymbol{z}_3, \mathcal{H}_1|\boldsymbol{x}_1)\; p_{\underline{\boldsymbol{\Upsilon}}_k|\underline{\mathbf{X}}_k}(\boldsymbol{z}_2, \boldsymbol{z}_4, \mathcal{H}_4|\boldsymbol{x}_2)$$

$$+\, p_{\underline{\boldsymbol{\Upsilon}}_k|\underline{\mathbf{X}}_k}(\boldsymbol{z}_1, \boldsymbol{z}_4, \mathcal{H}_2|\boldsymbol{x}_1)\; p_{\underline{\boldsymbol{\Upsilon}}_k|\underline{\mathbf{X}}_k}(\boldsymbol{z}_2, \boldsymbol{z}_3, \mathcal{H}_3|\boldsymbol{x}_2)$$

Association problem for single frequency networks (DAB/ DVB-T)

Unknown association between measurements and illuminators

Example: 2 targets, 2 Tx, 1 Rx $p_{\underline{\Upsilon}_k|\underline{\mathbf{X}}_k}(\mathcal{Z}_k|\boldsymbol{x}) \neq p_{\underline{\Upsilon}_k|\underline{\mathbf{X}}_k}(\mathcal{Z}_k^1|\boldsymbol{x})\; p_{\underline{\Upsilon}_k|\underline{\mathbf{X}}_k}(\mathcal{Z}_k^2|\boldsymbol{x})$



single-target hypotheses:

$\mathcal{H}_1 : \boldsymbol{z}_1 \& \boldsymbol{z}_3$

$\mathcal{H}_2 : \boldsymbol{z}_1 \& \boldsymbol{z}_2$

$\mathcal{H}_3 : \boldsymbol{z}_3 \& \boldsymbol{z}_4$

$\mathcal{H}_4 : \boldsymbol{z}_2 \& \boldsymbol{z}_4$

multi-target hypotheses:

$\mathcal{H}_1 \& \mathcal{H}_4$

$\mathcal{H}_2 \& \mathcal{H}_3$

multi-target conflicts:
not only for close targets

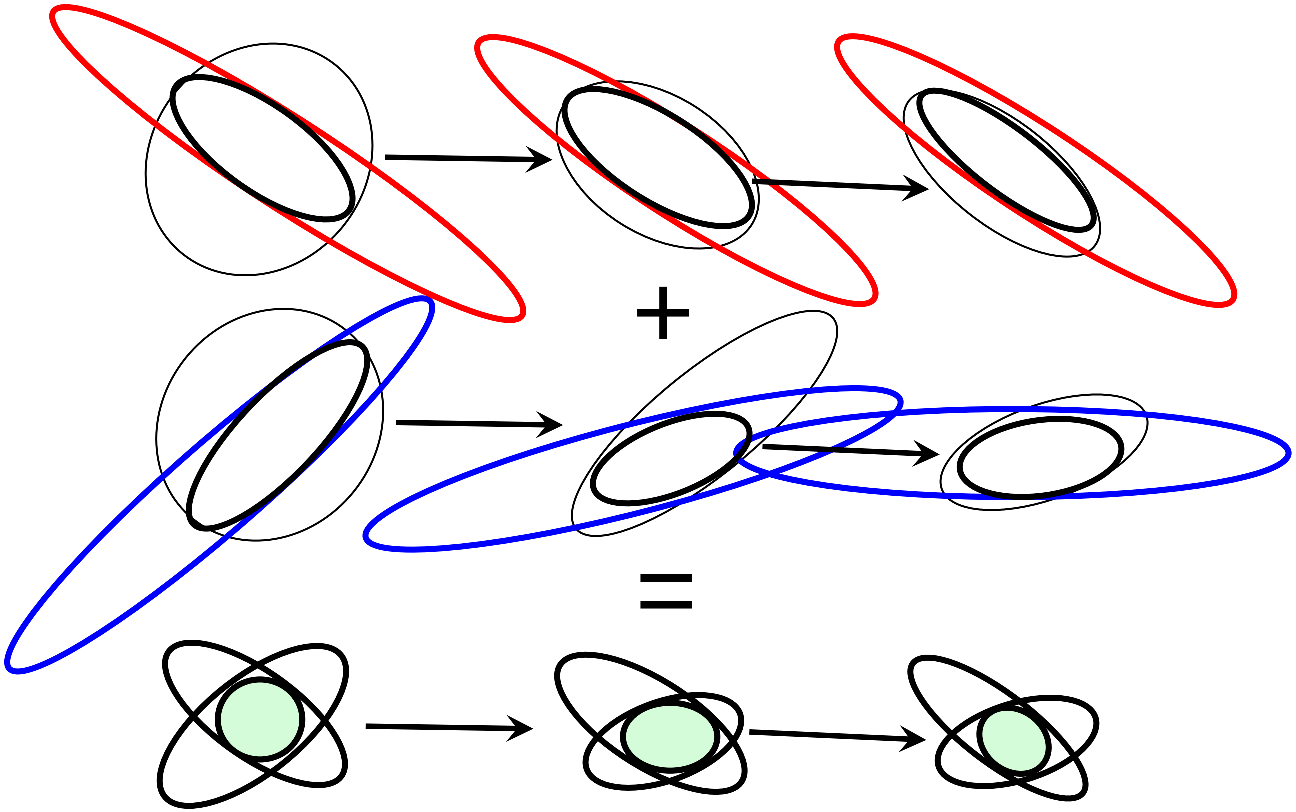
Task of Target Tracking

- For known association the multi-sensor likelihood function describes the sensor specific estimation task
- The second task of target tracking is to solve the data ambiguity by associating measurements with targets (association task)
  - for SFN additionally associating measurements with transmitters

- The degree of difficulty in target tracking is dependent on:
  - the measurement error and the Cartesian shape of the bistatic measurement
  - the number of false alarms
  - the number of targets (and the closeness of targets in measurement coordinates)

⇨ Choice of appropriate fusion architecture for different passive radar systems

Multi-sensor fusion techniques: Distributed tracking



Processing measurements of sensor 1

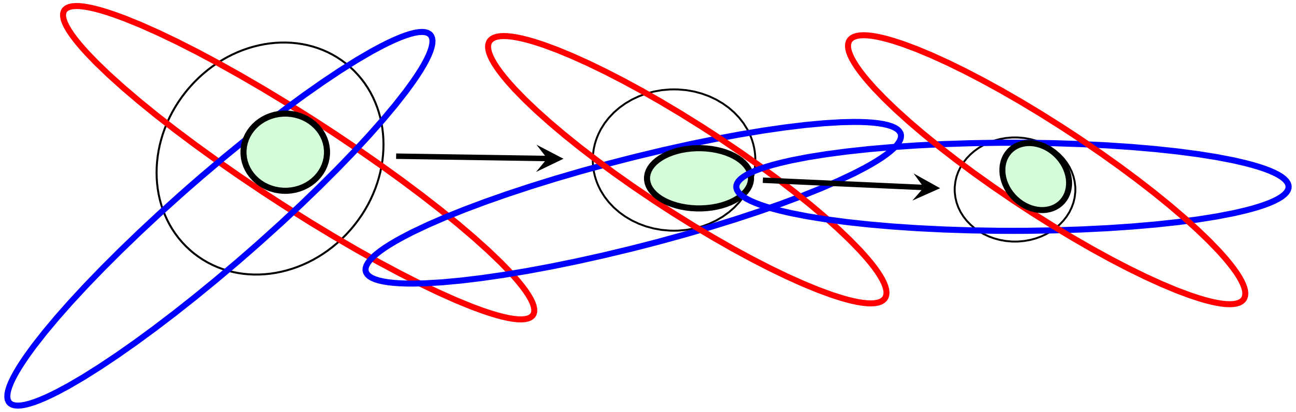
Processing measurements of sensor 2

Fused results

Multi-sensor fusion techniques: Centralised tracking

Processing measurements of sensor 1 and 2

and fused results



Advantages:

- Good association due to localisation gain (small prediction covariance)
- Robust in case of large number of false alarms

Disadvantages:

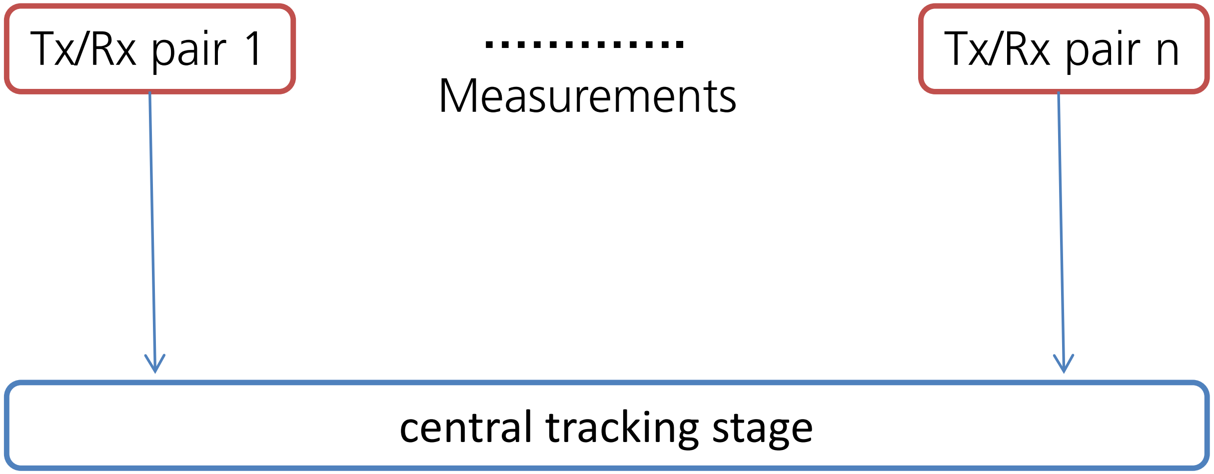
- Higher complexity
- Sensitive against mismatch between data and model

Distributed Tracking in Passive Radar

- Separate tracking for each Tx/Rx pair in measurement coordinates
  - ⇨ R/D Tracking
  - avoid loose due to approximation in Cartesian coordinates
  - identify Tx/Rx combinations which contribute to target detection

- Cartesian localisation by correlation of R/D tracks from different Tx/Rx pairs

Centralized Tracking in Passive Radar (1-Stage MHT)



Tx/Rx pair 1

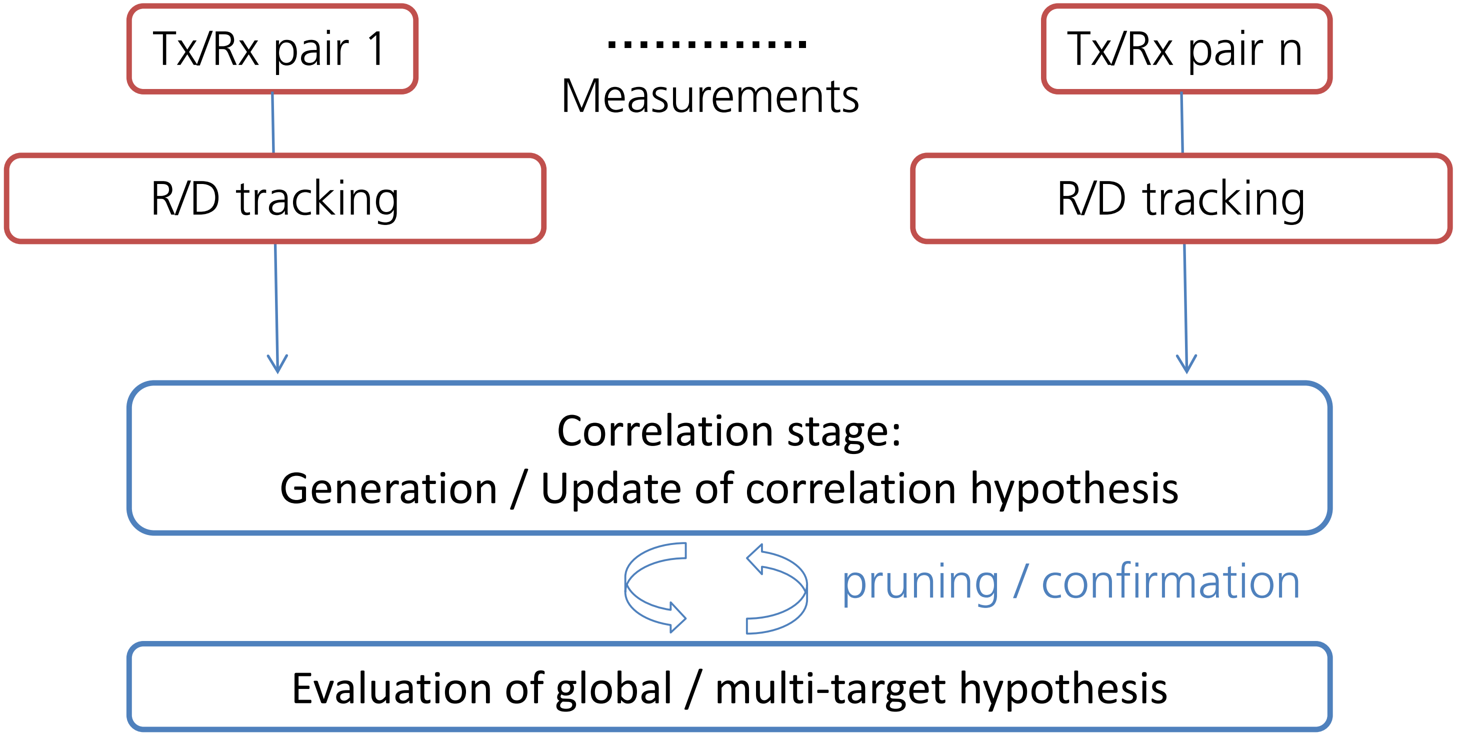
……………

Measurements

Tx/Rx pair n

central tracking stage

Distributed Tracking in Passive Radar (2-Stage MHT)



Tx/Rx pair 1

……………

Measurements

Tx/Rx pair n

R/D tracking

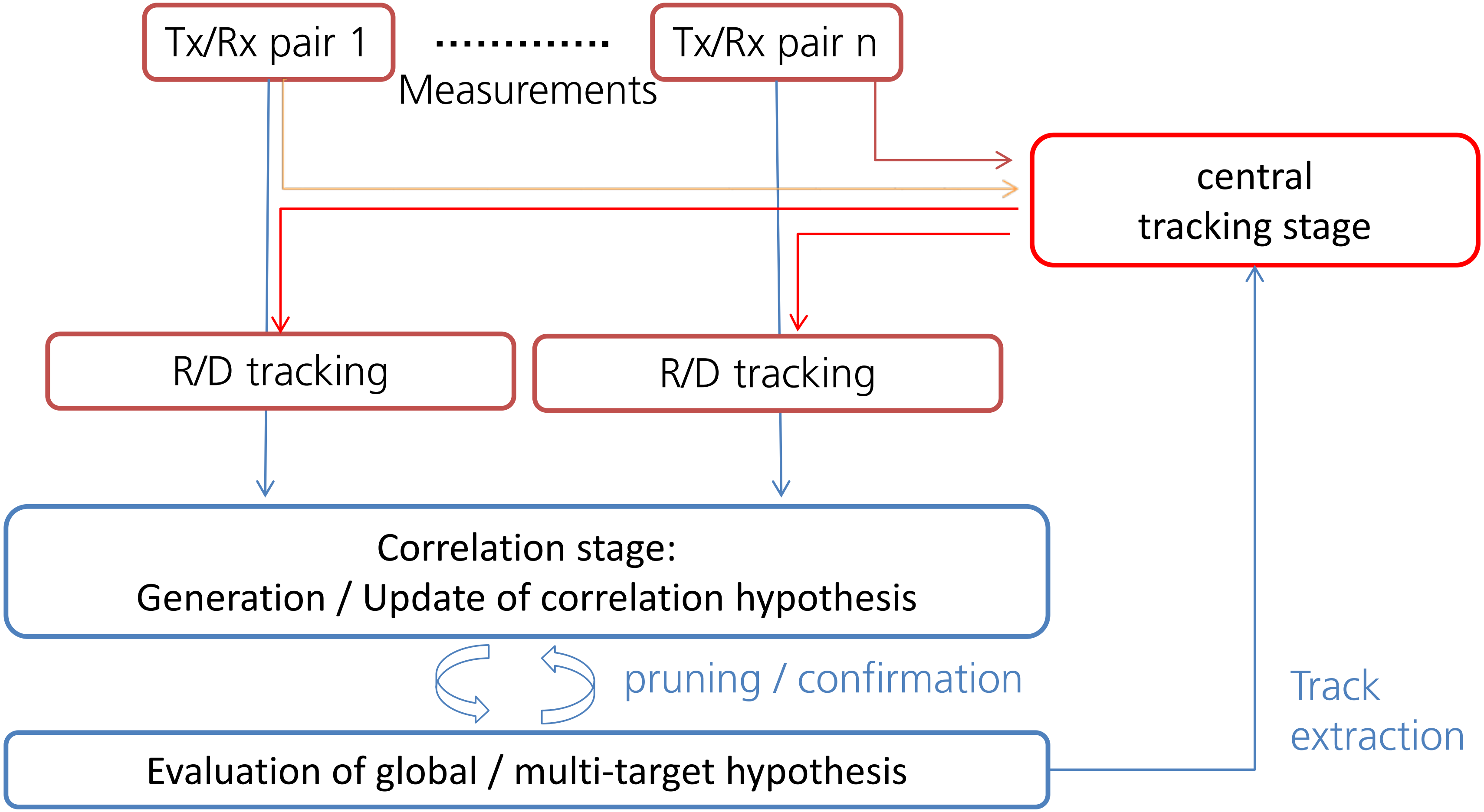
R/D tracking

Correlation stage:
Generation / Update of correlation hypothesis

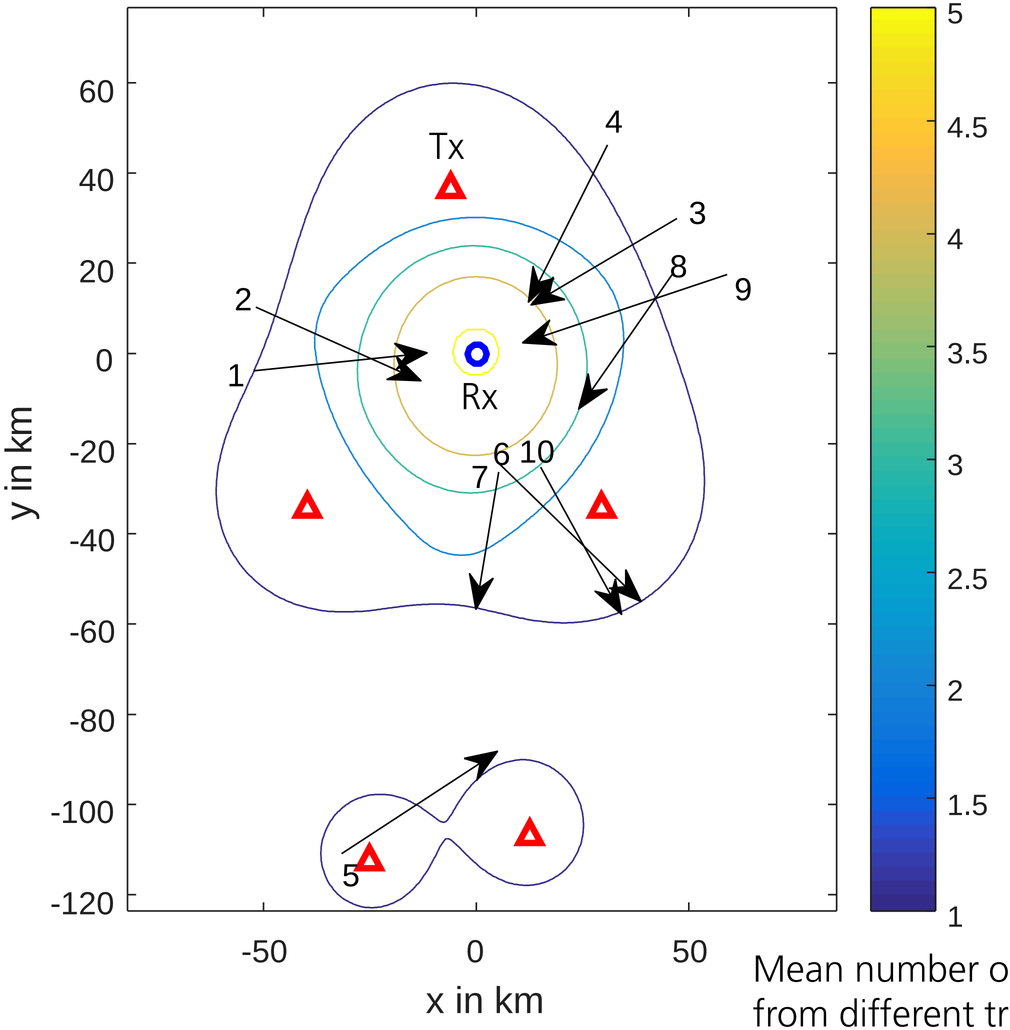
pruning / confirmation

Evaluation of global / multi-target hypothesis

Combinded Distributed and Centralized Tracking (3-Stage MHT)



Simulation Scenario



Mean number of detections from different transmitters

- 10 targets in different geometries ←
- 1 receiver ○
- 5 transmitters △

accuracy	Scenario A	Scenario B
bist. range [m]	500	30
Azimuth [°]	3	3
range-rate [m/s]	0.6	0.6

Simulation Scenario

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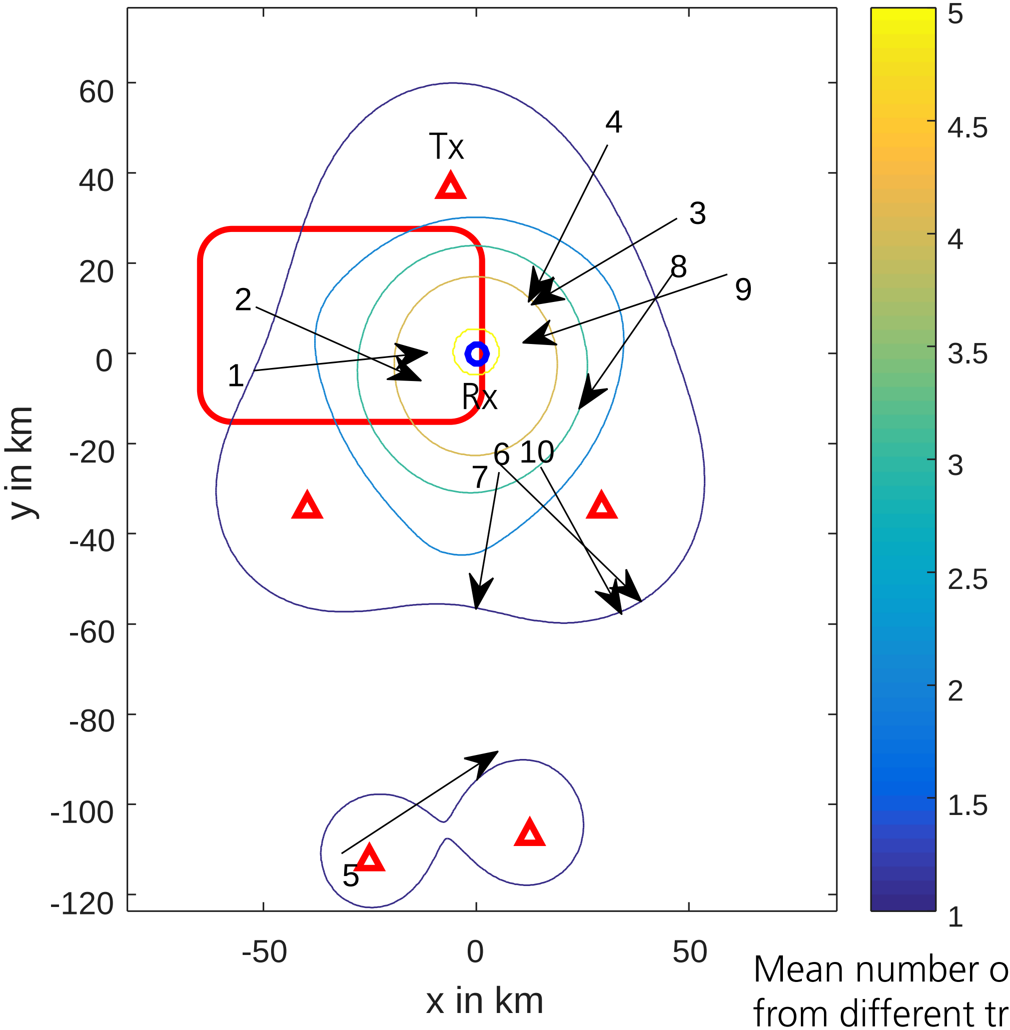

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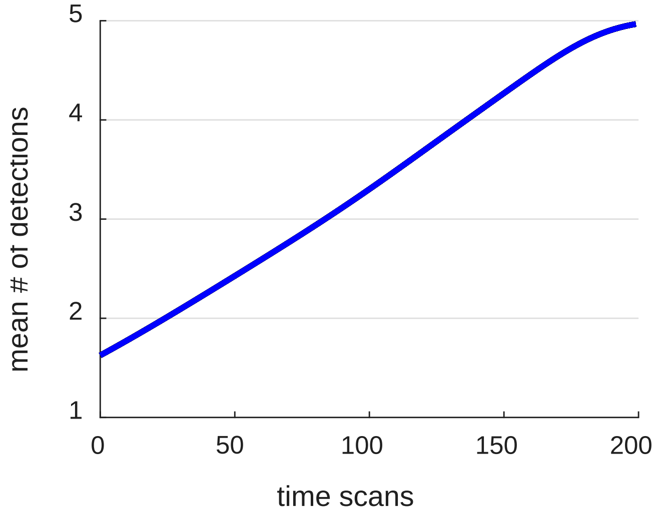
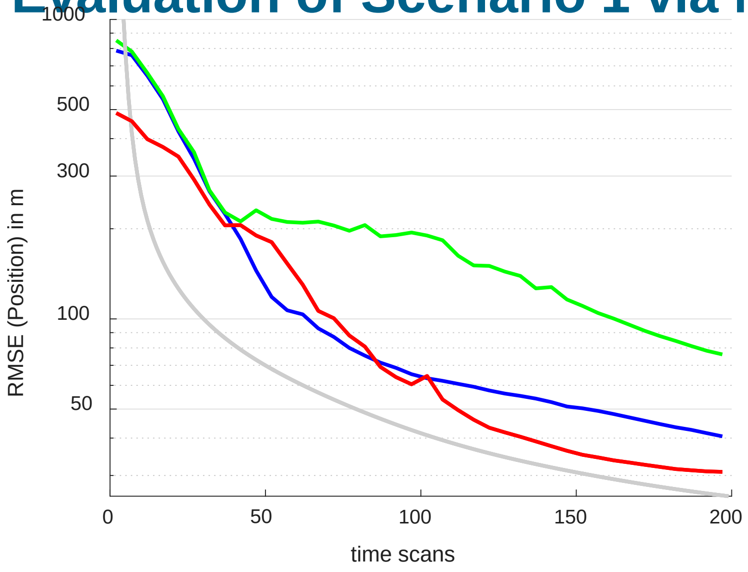
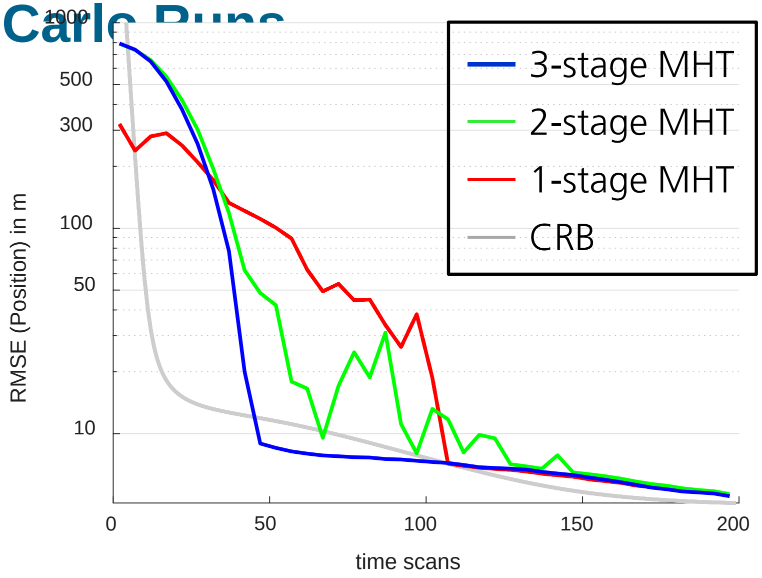
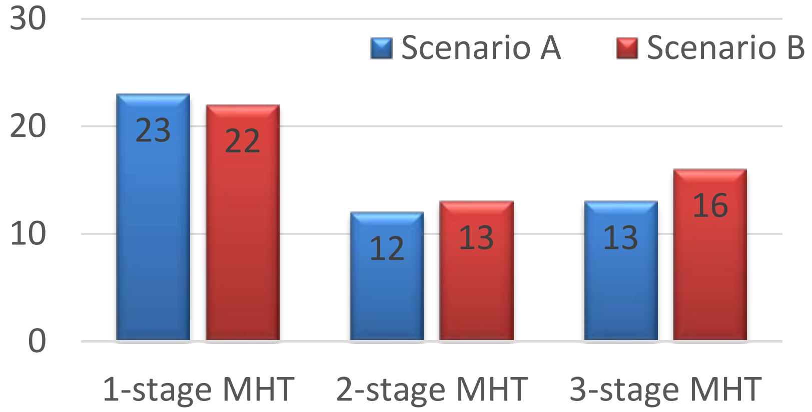


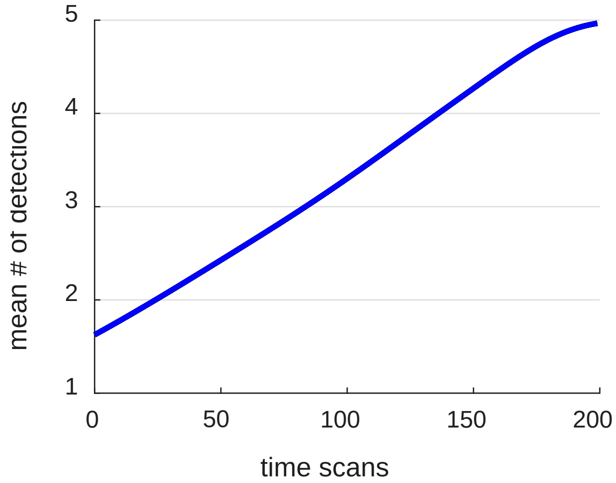
Evaluation of Scenario 1 via Monte Carlo Runs





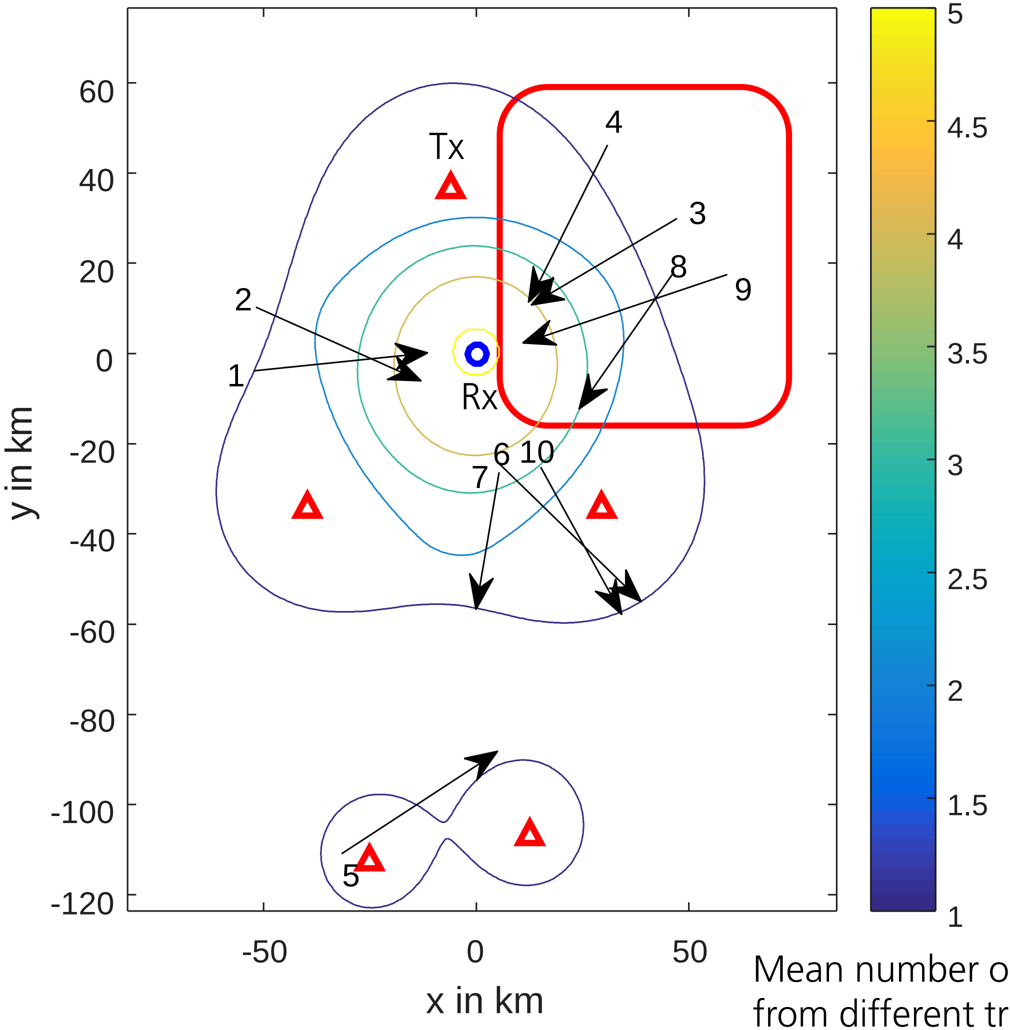
Time needed to extract 90% of the targets





1-stage MHT: - good estimation performance in scenario A
- long track extraction time

Simulation Scenario



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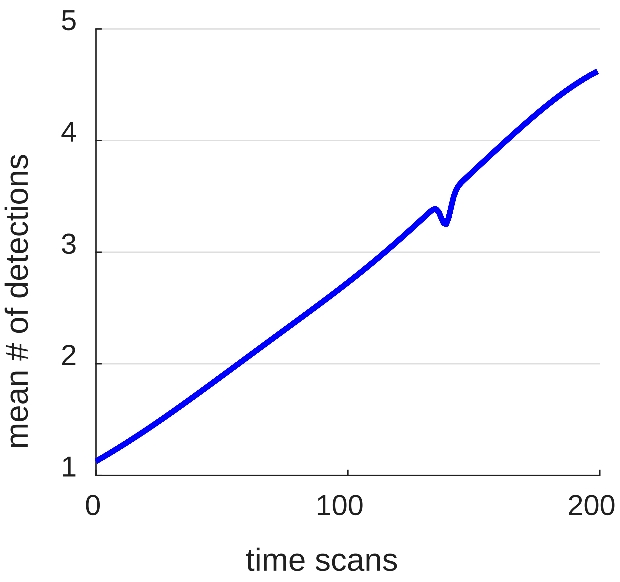

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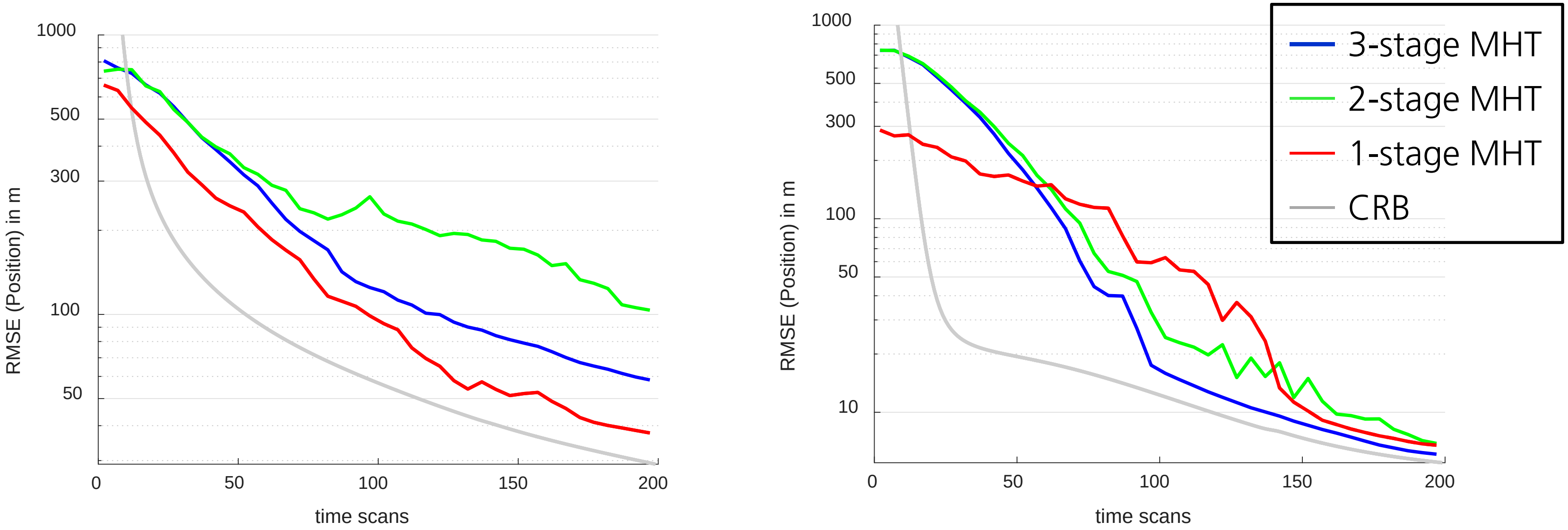

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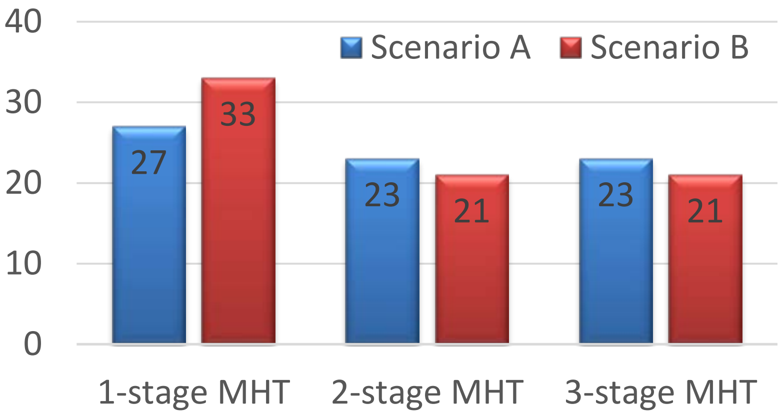

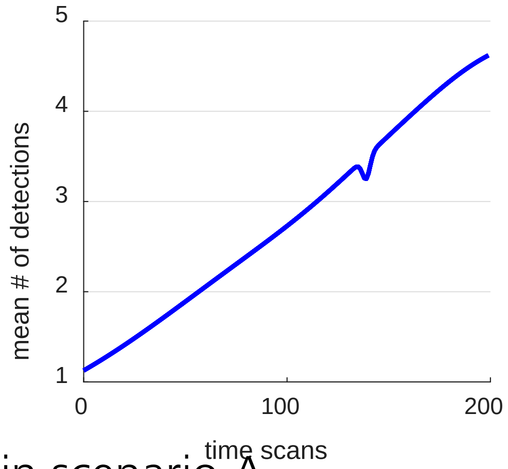

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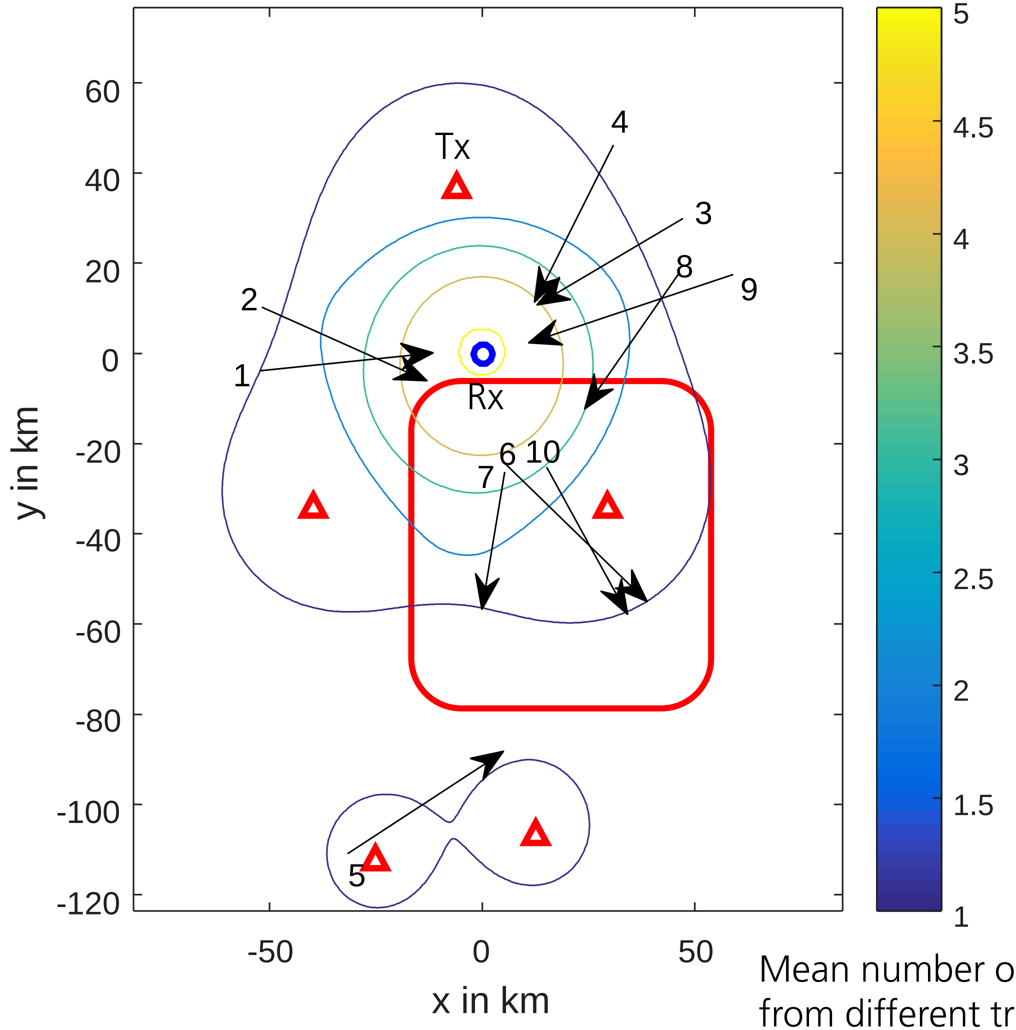

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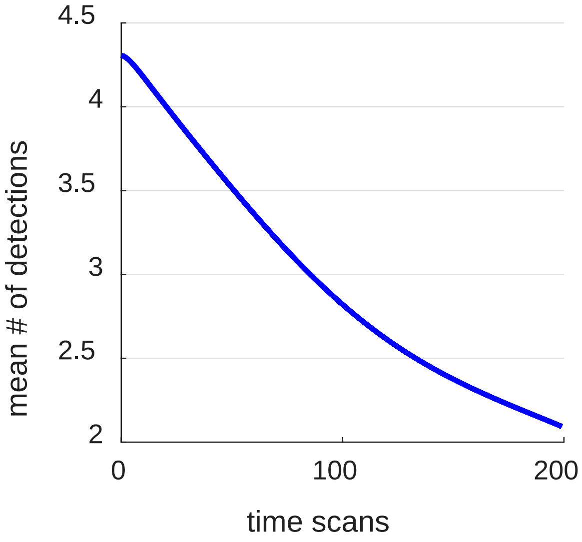
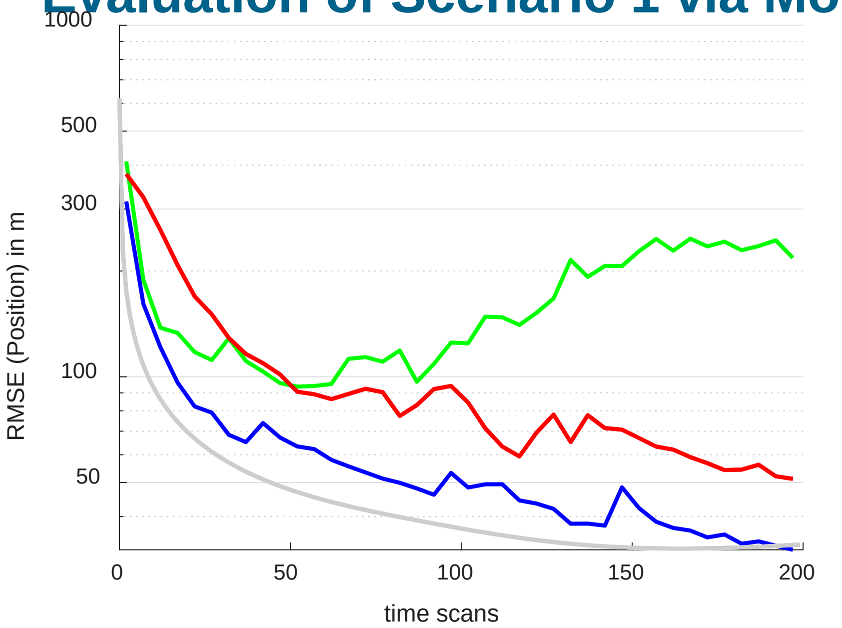
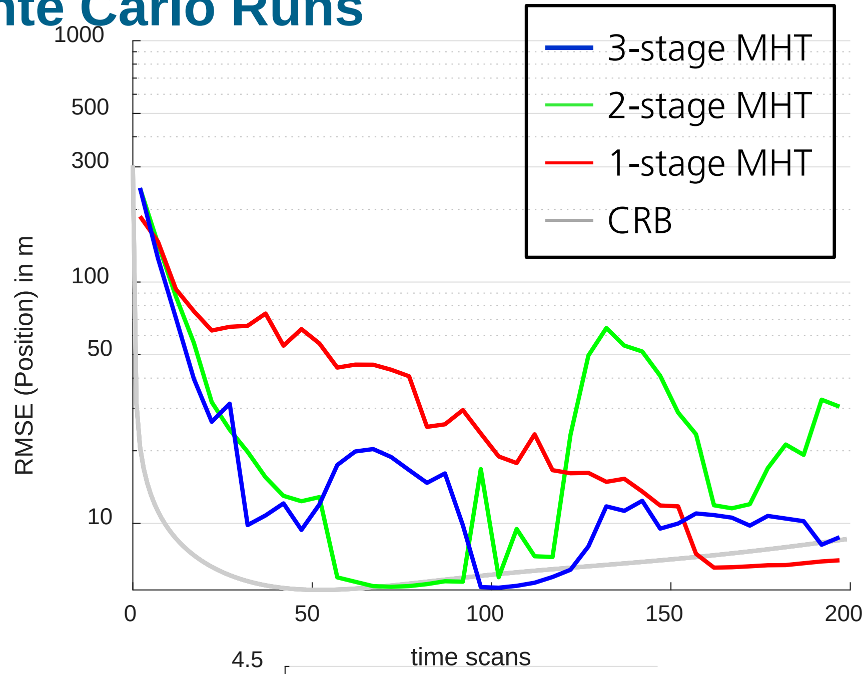
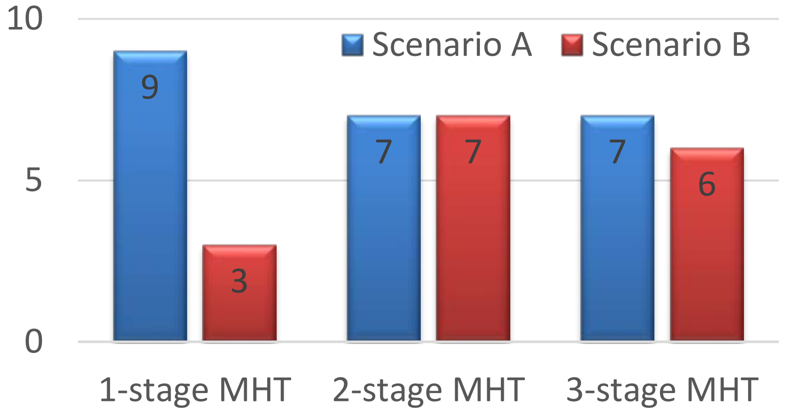
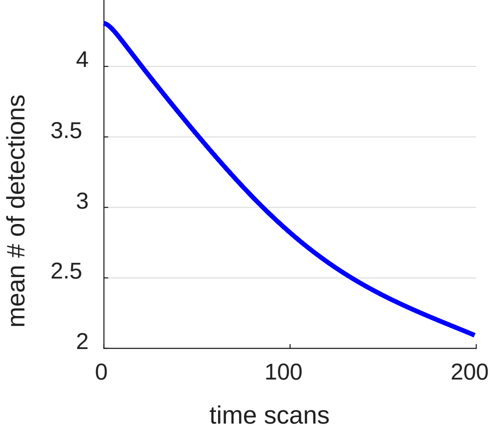


Evaluation of Scenario 1 via Monte Carlo Runs



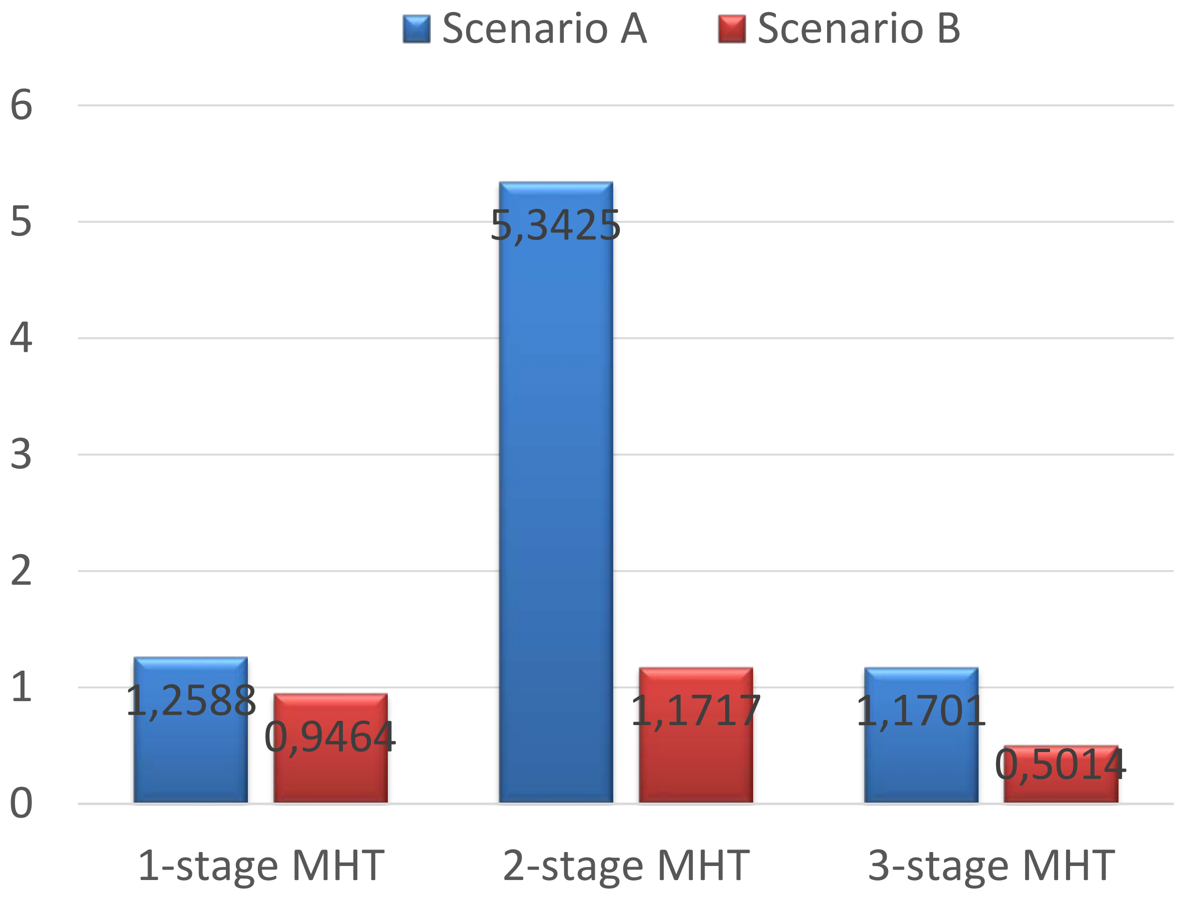






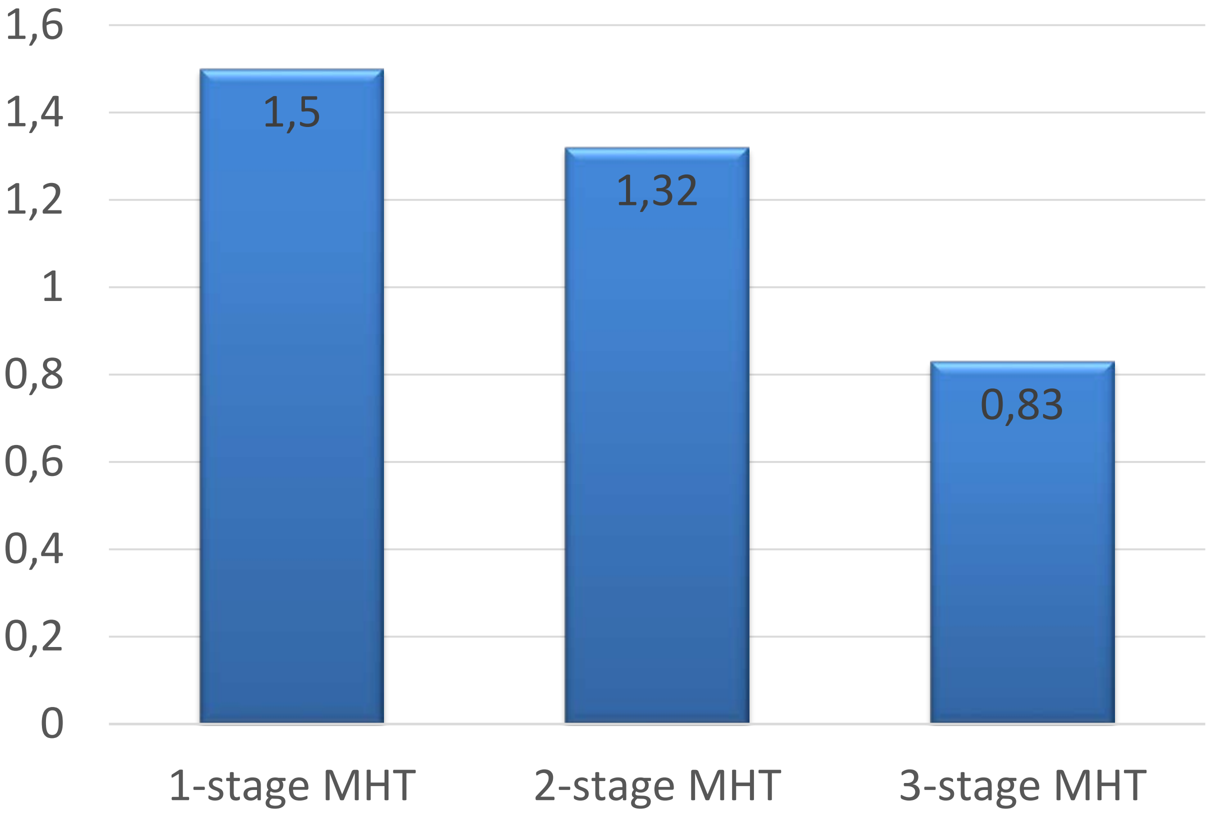
3-stage MHT is a compromise of centralized and distributed tracking

Number of false tracks per second



Poor performance of 2-stage MHT in scenario with low range accuracy

Runtime Comparison (Runtime per Second)



Conclusions

- The fusion of measurements from multiple bistatic sensor pairs is a key feature of passive radar (increased coverage, improved estimation accuracy)
- Task: realize this fusion gain by correctly associating measurements of the different bistatic sensor pairs and by appropriate estimation techniques.
- The dimension of the association problem in passive radar applications depends strongly on the precision of the bistatic measurements. Multi-target conflicts can arise, even if the targets are geographically well-separated. The association problem further increases when transmitters are arranged in single-frequency networks.
- The design of the tracking algorithms needs to be adapted to the specific characteristics of the passive radar system and the application scenario.