On PNT Integrity in Snapshot and Recursive Positioning Algorithms for Maritime Applications

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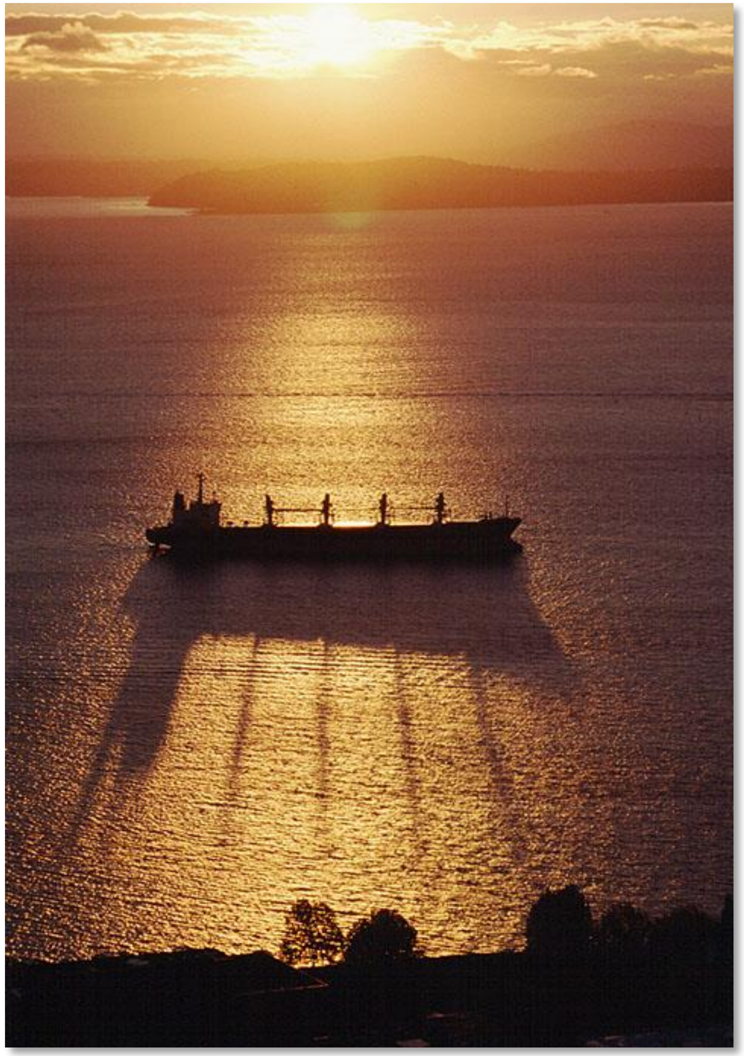
Agenda

- Motivation
  - PNT Unit
- Scope
- Experimental Setup
- Methods
- Results
- Summary and Outlook



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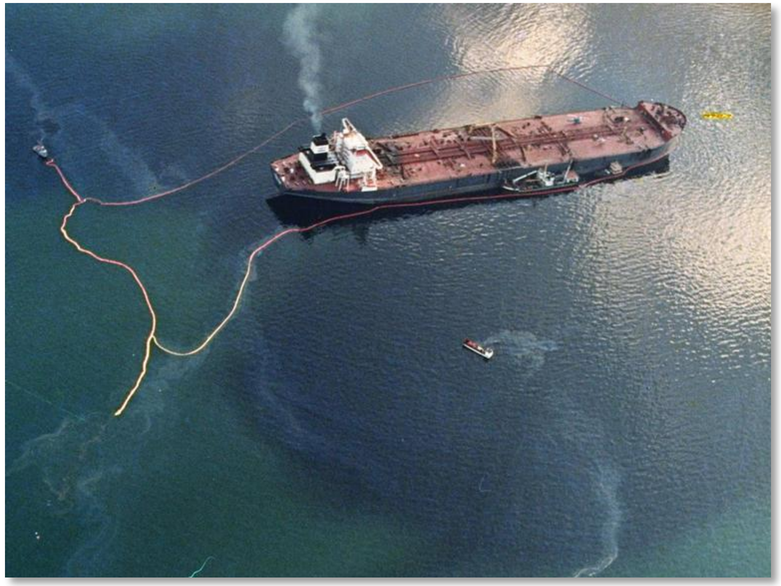
Motivation



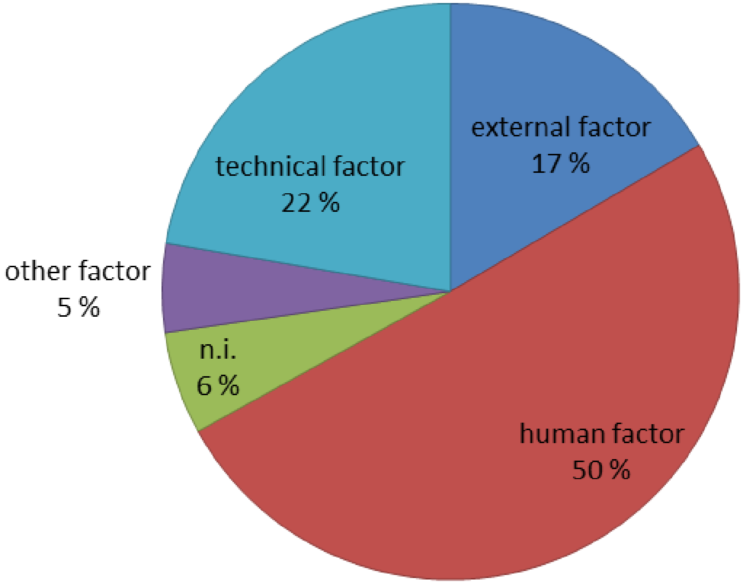
Motivation: Safety in Maritime Navigation

- IMO **e-navigation strategy: Electronically enhancement** of maritime navigation in order to **minimize the risk** of occurrence of situations that **could compromise the safety of the crew, vessel and marine environment**

- **I**ntegrated **N**avigation **S**ystem (INS) has to "ensure the **accurate and reliable** ship's PNT data **and** assigned **integrity data** during all phases of navigation"

- **Onboard** and **ashore** components

- **PNT Data** encompasses**:**
  - **Position, velocity and Time (PVT)**
  - **Navigation data describing the vessel's current movement** (attitude, rate of turn)



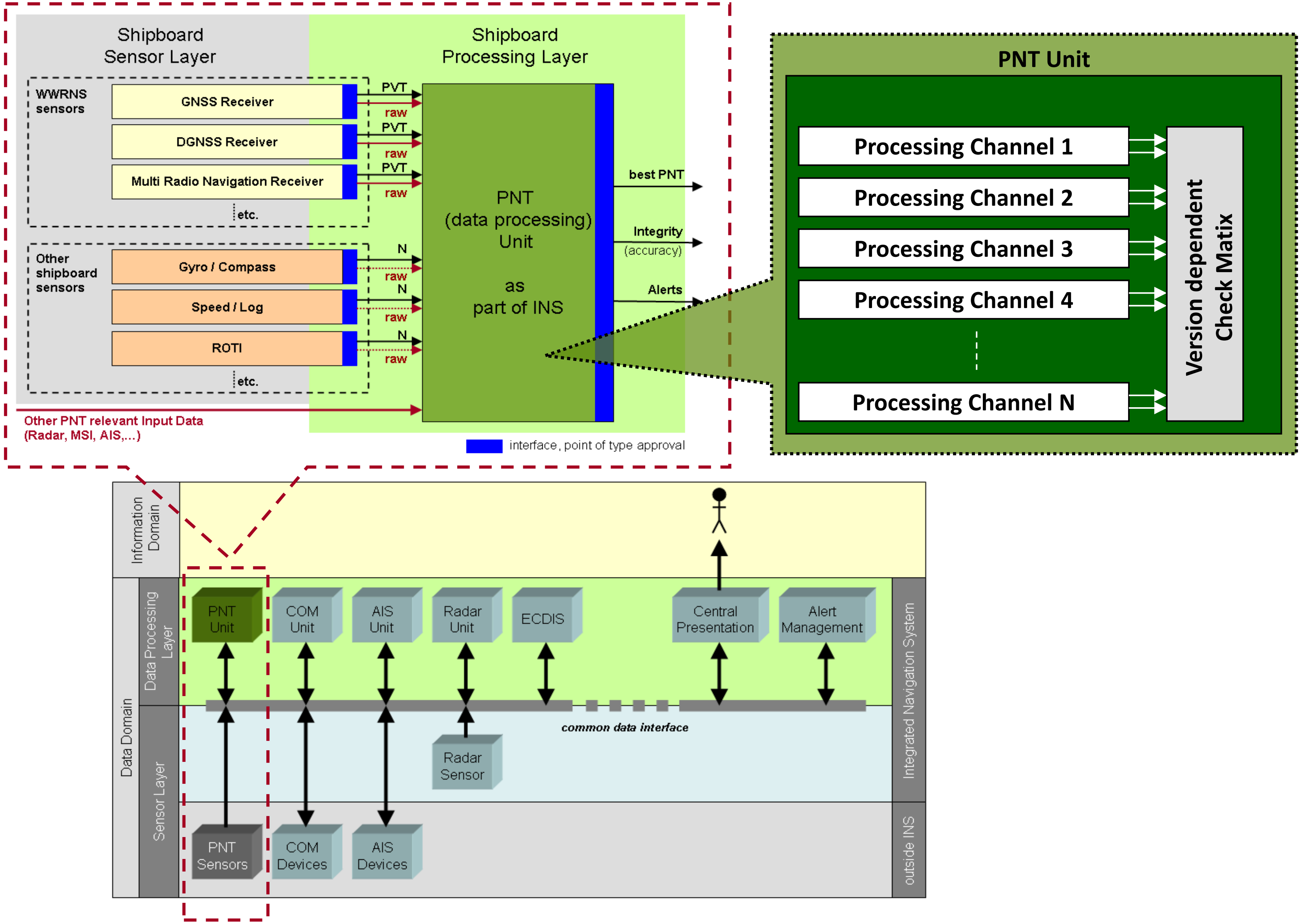
Causes of accidents in the Baltic Sea during 2011

50% of all accidents in 2011 were caused by human factors

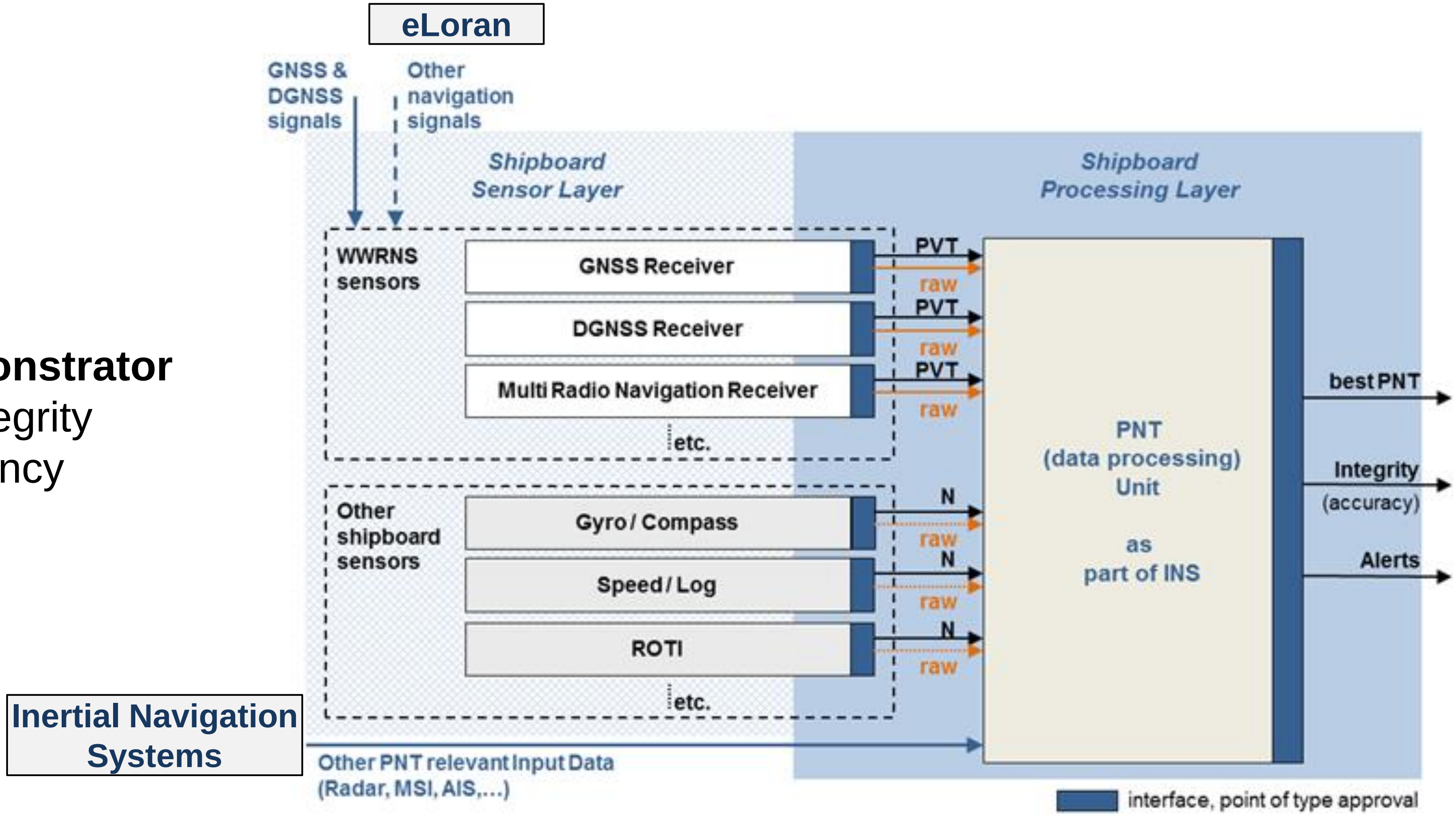
source: HELCOM SAFE NAV 3/2013

PNT Unit Approach

- **Resilience:** multi-sensor based redundancy is exploited to detect sensor failures and malfunctions.
- **High Integrity:** PNT system integrity monitoring capability (improve trustiness)



PNT Unit Approach



- Development of the **PNT unit demonstrator** realizing real-time accuracy and integrity assessment and providing contingency functionality

Scope

- Perform **analysis of Fault, Detection and Exclusion (FDE) schemes performance** for non-augmented GPS code-based and inertial augmented GNSS position estimation techniques in a typical maritime port operation scenario
  - **Snapshot approach**: Least Squares Residuals (LSR)
  - **GNSS recursive approach**: Kalman filter innovations (KFI)
  - **IMU/GNSS recursive approach**: Kalman filter innovations (Inertial KFI)

- Generation of data using a **simulator based on Monte-Carlo techniques,** where **true measurements** are **contaminated with artificially induced GNSS faults**

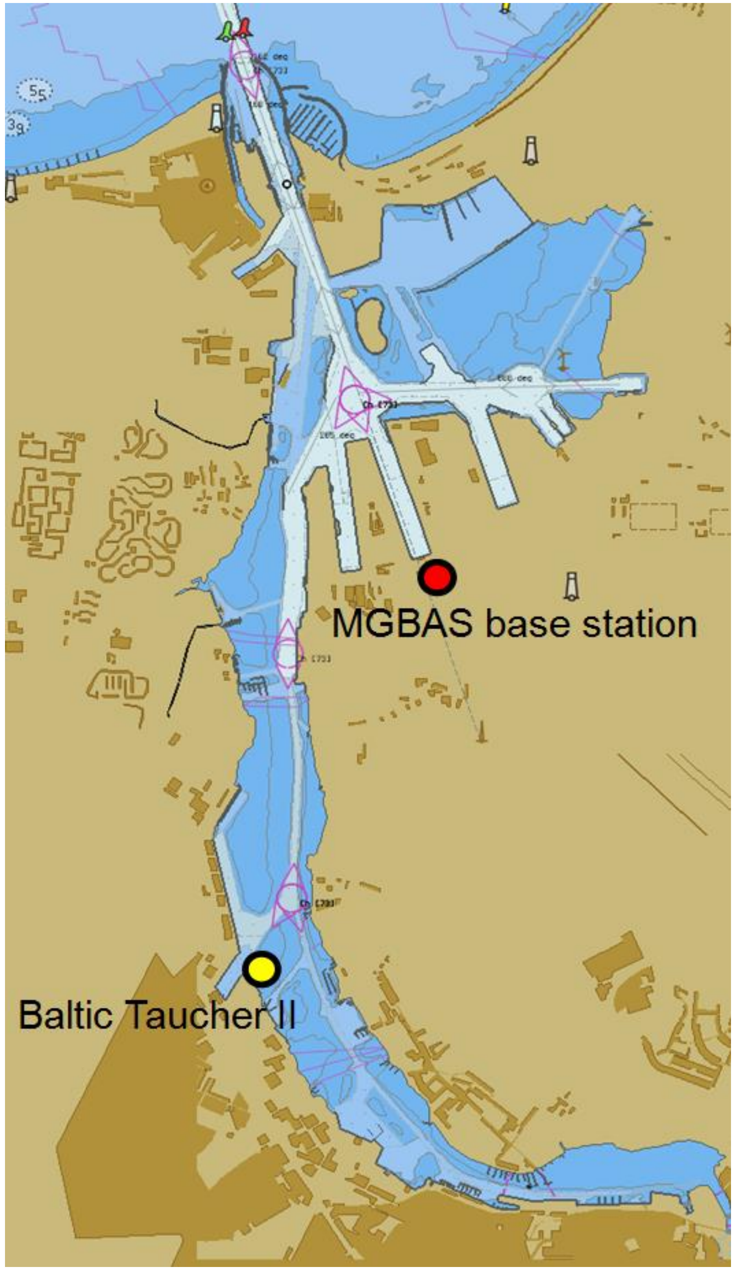
- Evaluate a **constant GNSS measurement weighting** approach **and Carrier-to-Noise density ration** (CNo)**-based weihgting approach**

- Evaluate the performance of GNSS fault detection methods in **tightly-coupled IMU/GNSS systems**

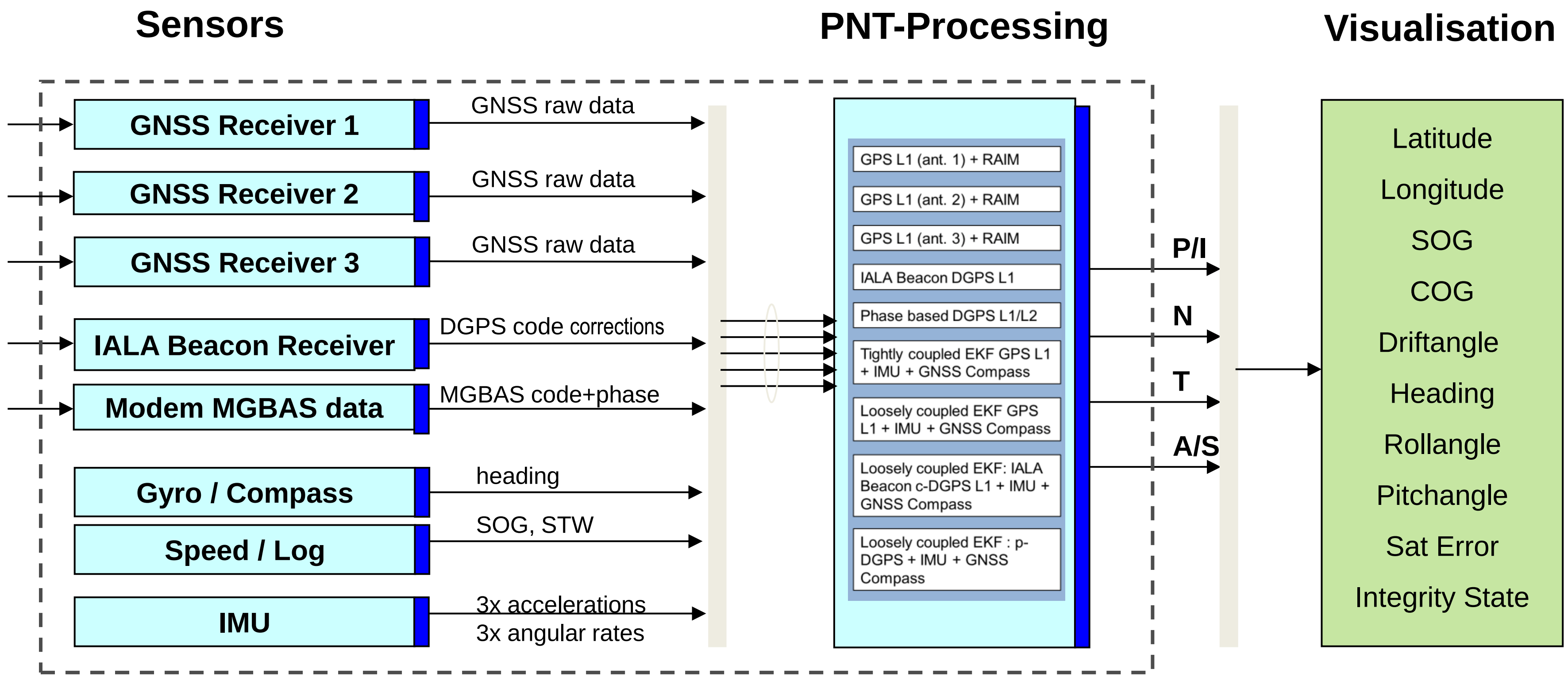
- Perform **measurement domain** and **position domain** analysis

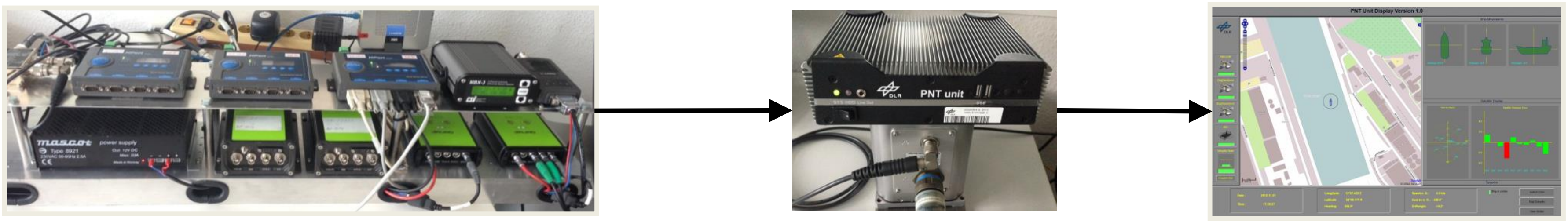
Experimental Setup: Scenario

- Quasi-static scenario: Baltic Taucher II was moored
    - Weak wind and little waves
- Observed weak interference (multipath) caused most likely by the surrounding ship superstructure and water reflections



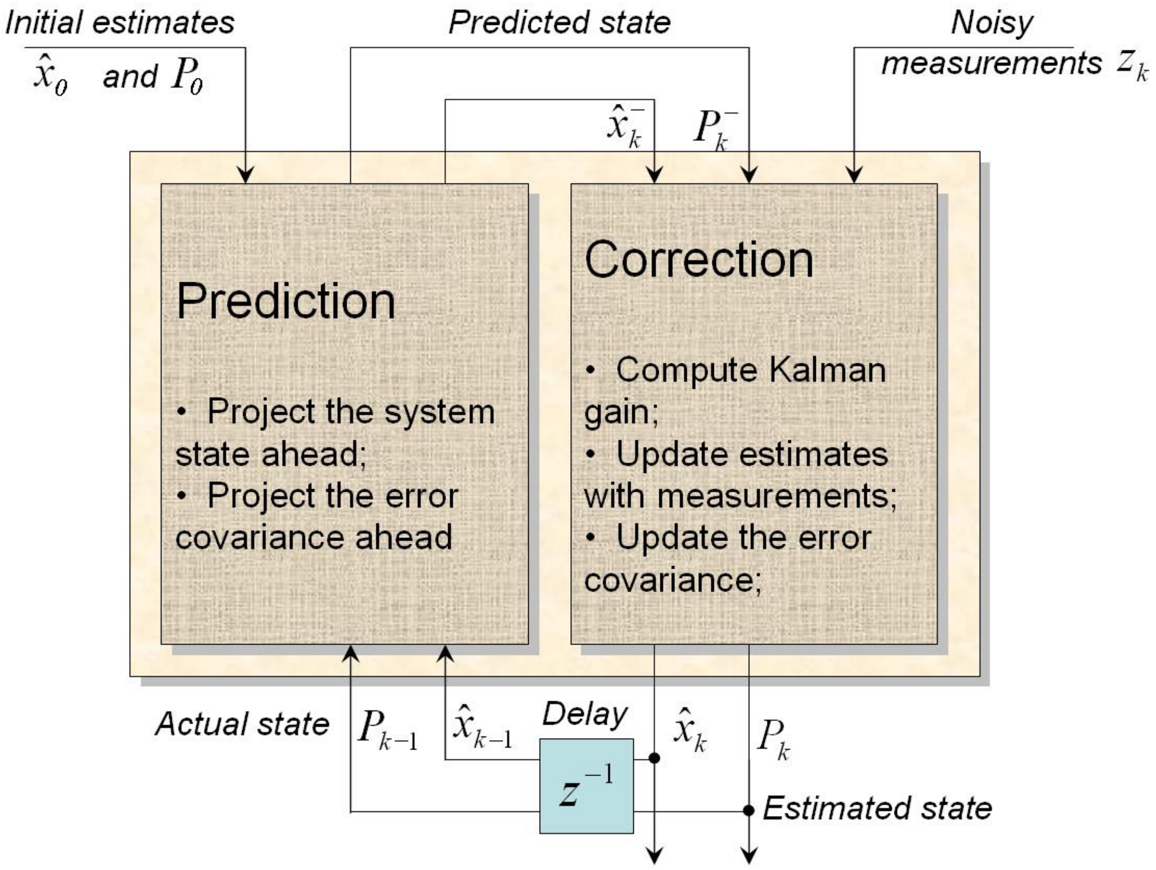
Experimental Setup: Onboard PNT Unit





Methods: Recursive Bayesian Estimation Framework

- Standard approach for multi-sensor fusion, navigation algorithms and motion parameter estimation under dynamics and measurement uncertainties/noises.
- Allows incorporation of all the available information (noise statistics, dynamical models, kinematic constraints) in a **statistically consistent way**
- Different implementations available
  - Kalman filtering (linear, **extended**, unscented, …)
  - Particle filtering
  - …
- **Models**



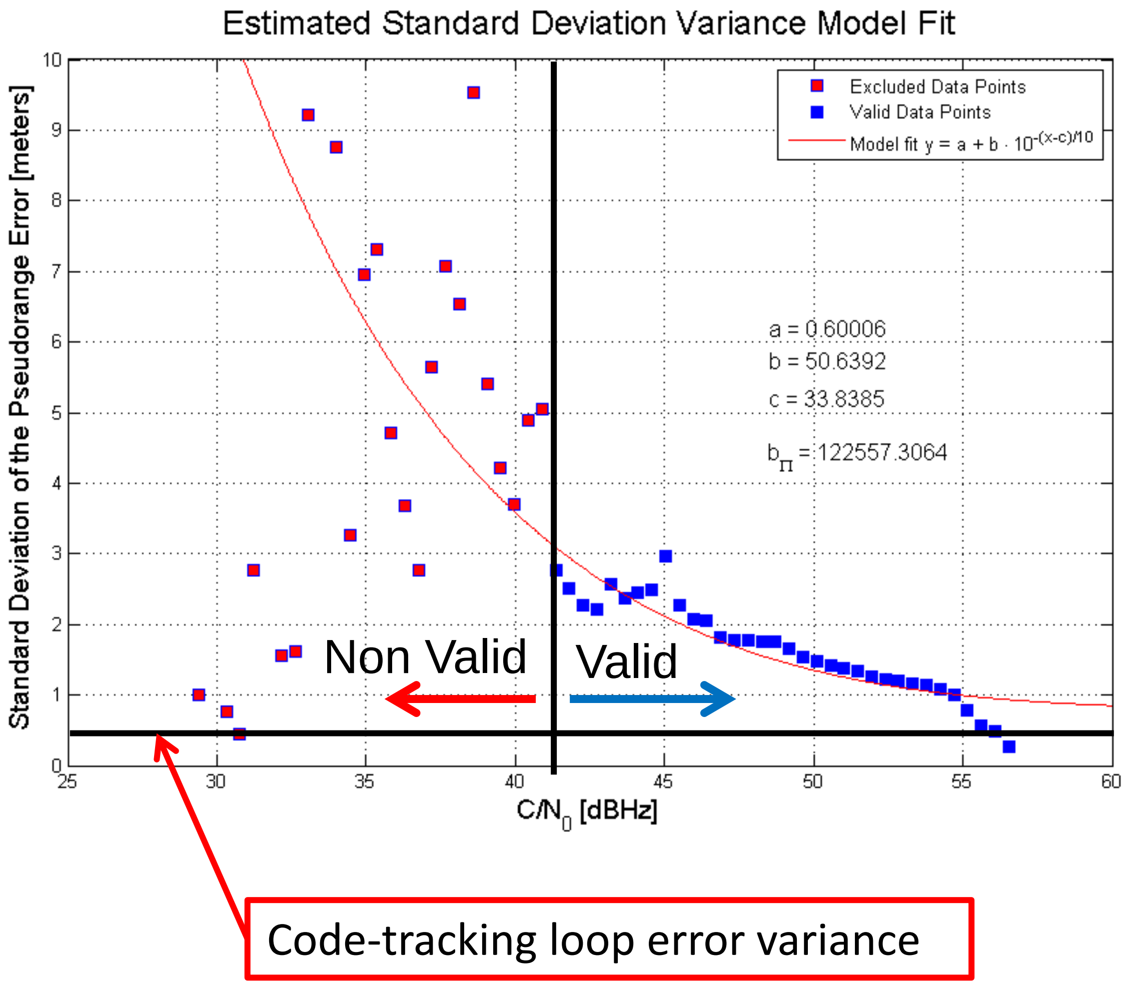
Methods: Adaptive GNSS Pseudorange Error Variance Model

CNo is a measurable value of the signal quality present at the output of a GNSS receiver

- Three parameter fitting model:

$$\sigma^2 = a + b \cdot 10^{-\frac{CNo-c}{10}}$$

- Obtained from experimental data with fixed receiver with known position.



Methods: Least Squares Residuals (LSR) FDE

- **Estimated residuals**

$$\hat{e} = z - h(\hat{x}_o)$$

$$\|\hat{e}\|^2 \sim \chi^2_{dof} \qquad dof = m - n$$

- **Hypothesis Test**

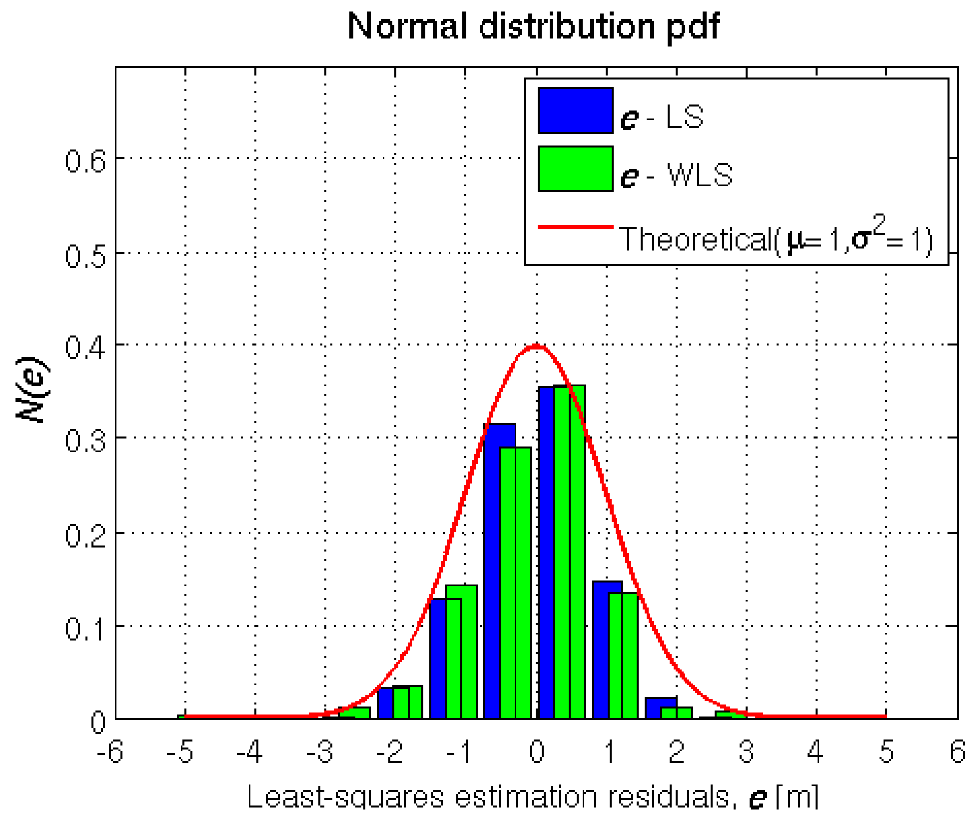
$$Global - Test = \begin{cases} H_o \; if \;\; t_s \leq Th \\ H_1 \; if \;\; t_s > Th \end{cases}$$

- **Test statistics**

$$ts = \sqrt{\|\hat{e}\|^2} \qquad \|\hat{e}\|^2 = \hat{e}^T R^{-1} \hat{e}^T$$

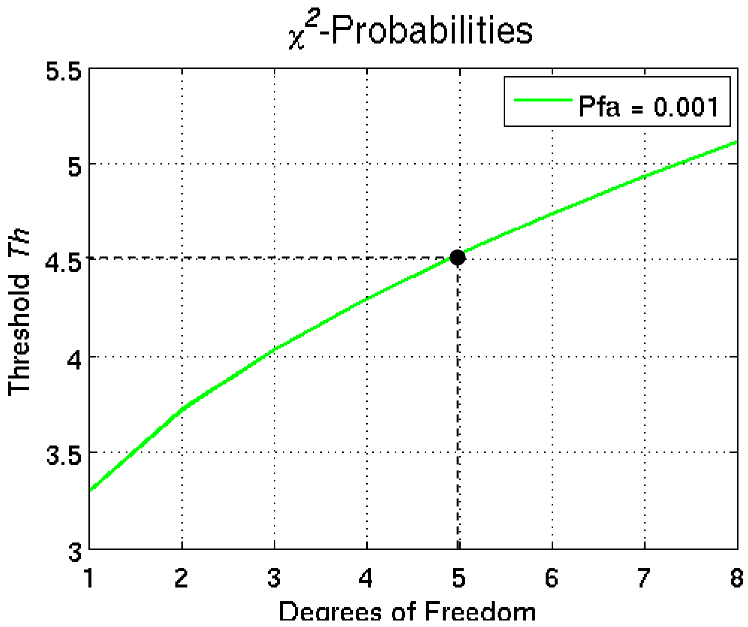
- **Test threshold**

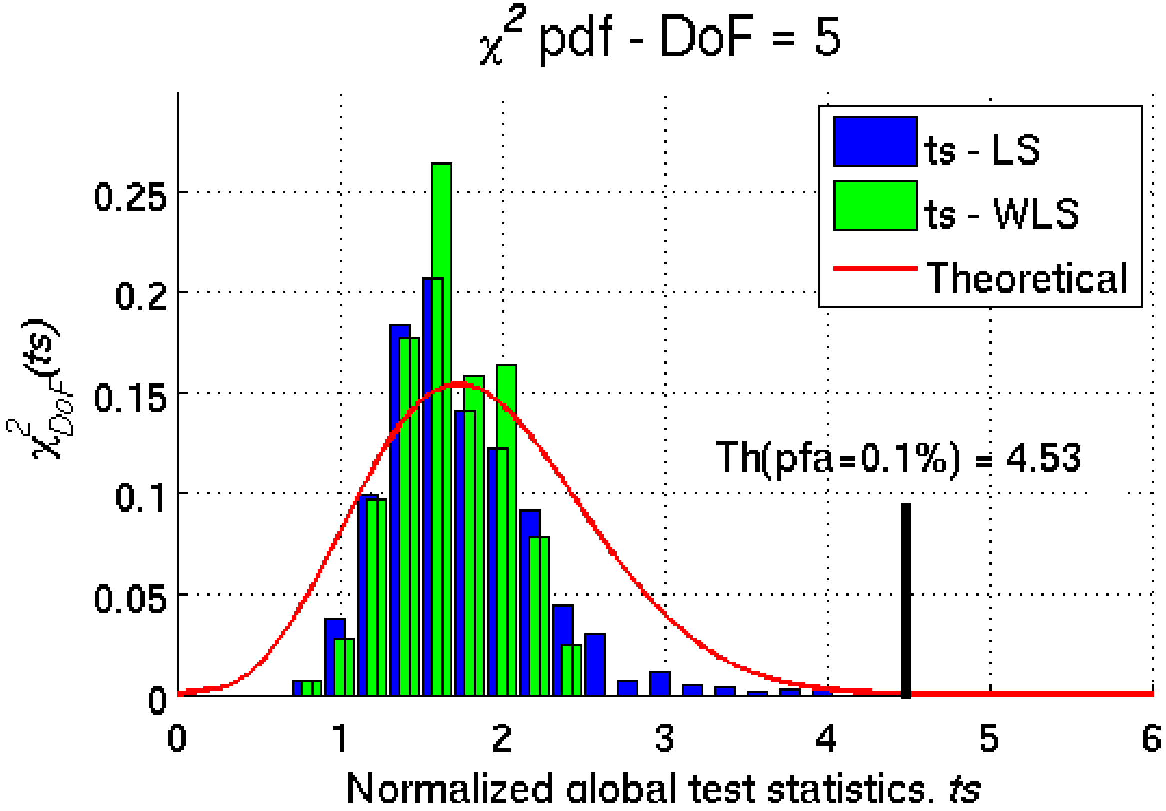
$$1 - Pfa = \frac{1}{2^{\left(\frac{dof}{2}\right)}\Gamma\left(\frac{dof}{2}\right)} \int_{Th^2}^{\infty} e^{-\frac{x}{2}} x^{\frac{dof}{2}-1} dx$$



Methods: Hypothesis Testing

- Theoretical model is conservative compared to the test statistics calculated from measured data in the weighted measurement approach





- Non-weighted approach distribution shows long tail effect close to the threshold and this could trigger false alarm

Methods: Kalman Filter Innovations FDE

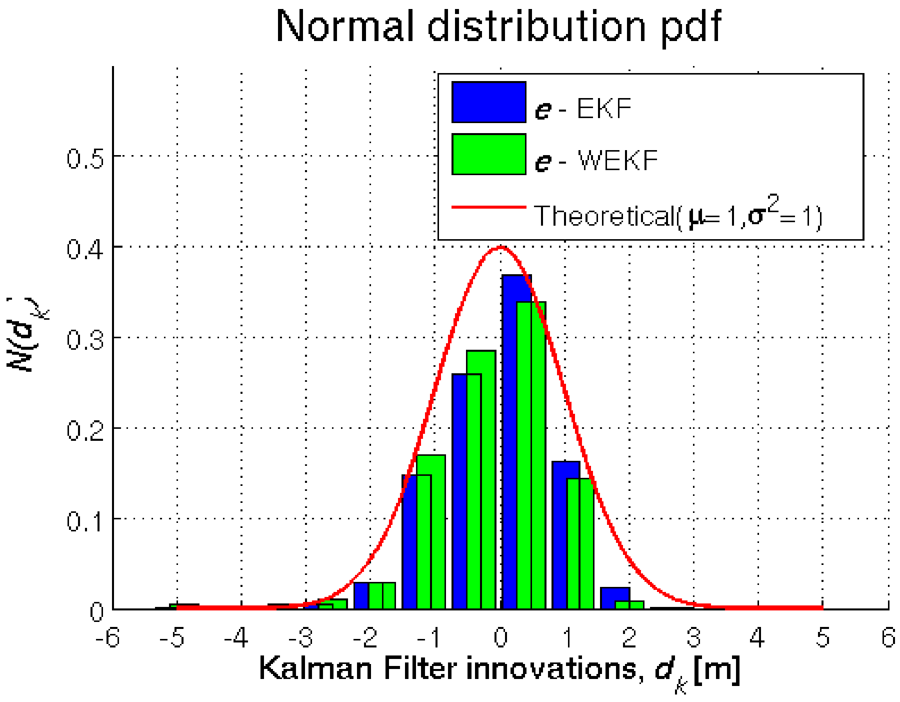
- Innovations (nonlinear measurement model EKF)

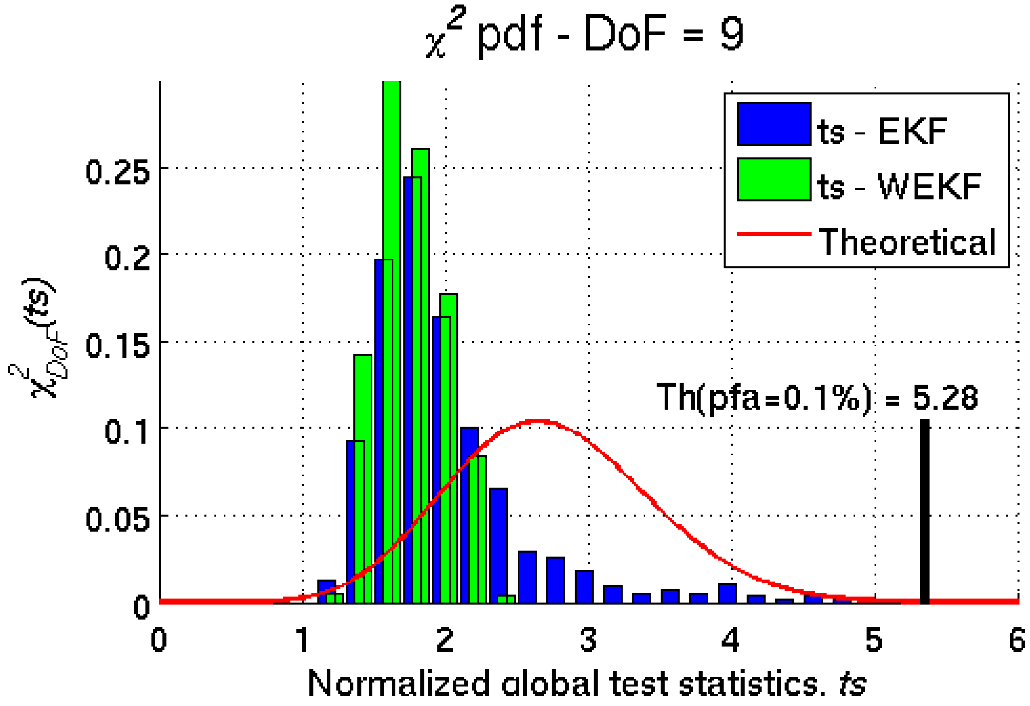
$$d_k = z_k - h(x_k)$$

- Test Statistics

$$ts_{KF} = \sqrt{\hat{d}^T S^{-1} \hat{d}}$$

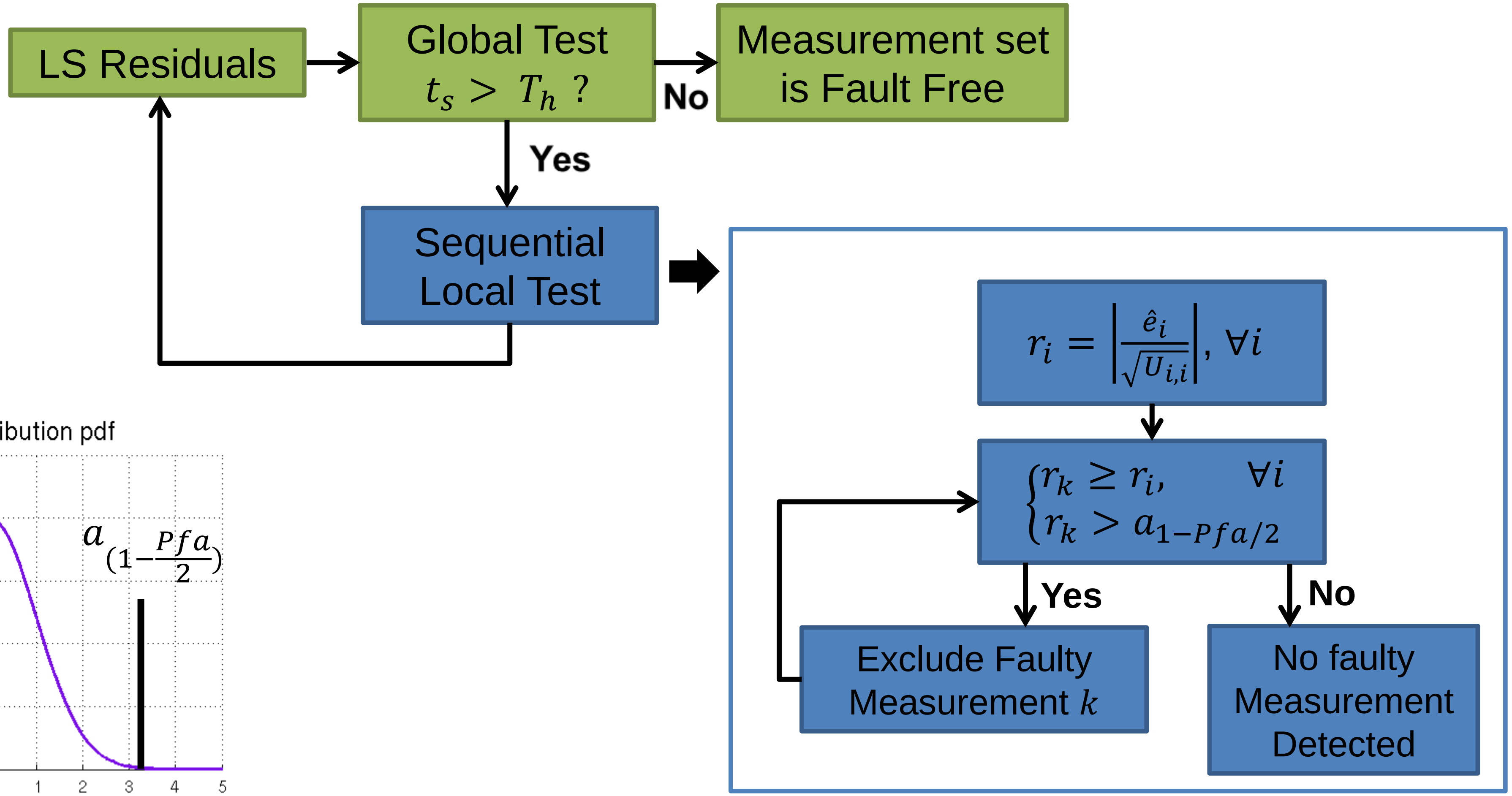
$$dof = m$$

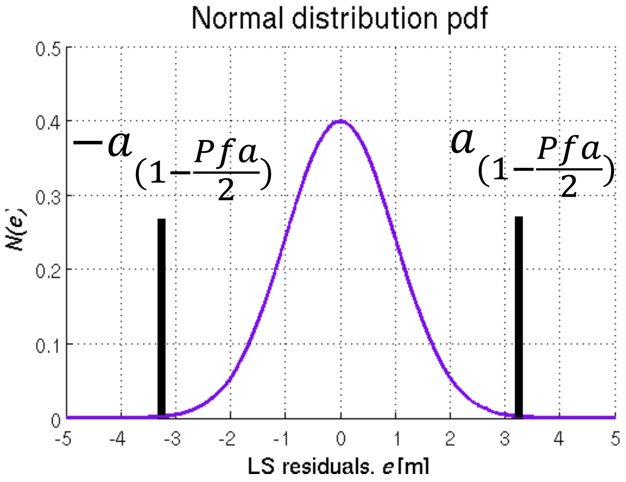




- Process noise assumption has a strong impact on ts distribution.
- Increasing the process noise pushes the distribution into the theoretical distribution (to the right).

Methods: Global Test and Sequential Local Tests
LSR FDE Scheme





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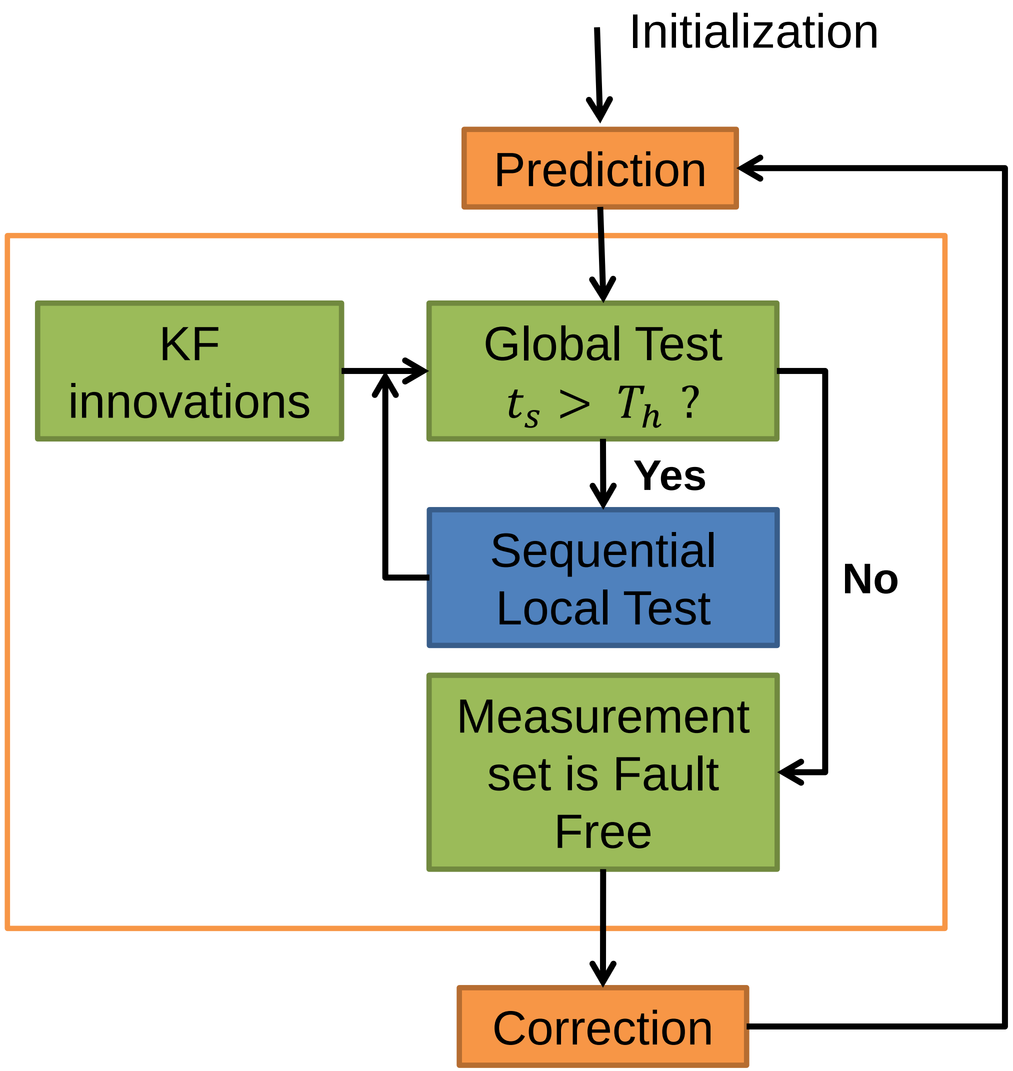
Methods: Global Test and Sequential Local Tests
KFI FDE Scheme



GNSS Outlier Simulation

- Monte-Carlo technique where **real measurements** are **contaminated** with artificial GNSS faults
  - Strategy preserves true measurement noise statistics and realistic Cno values

- Raw **measurements are mostly error-free** to avoid overlap of the inherent and the artificially introduced outliers

- Constant **single amplitude step outliers**
  - Representative of outlier effect in PR caused by environment multipath

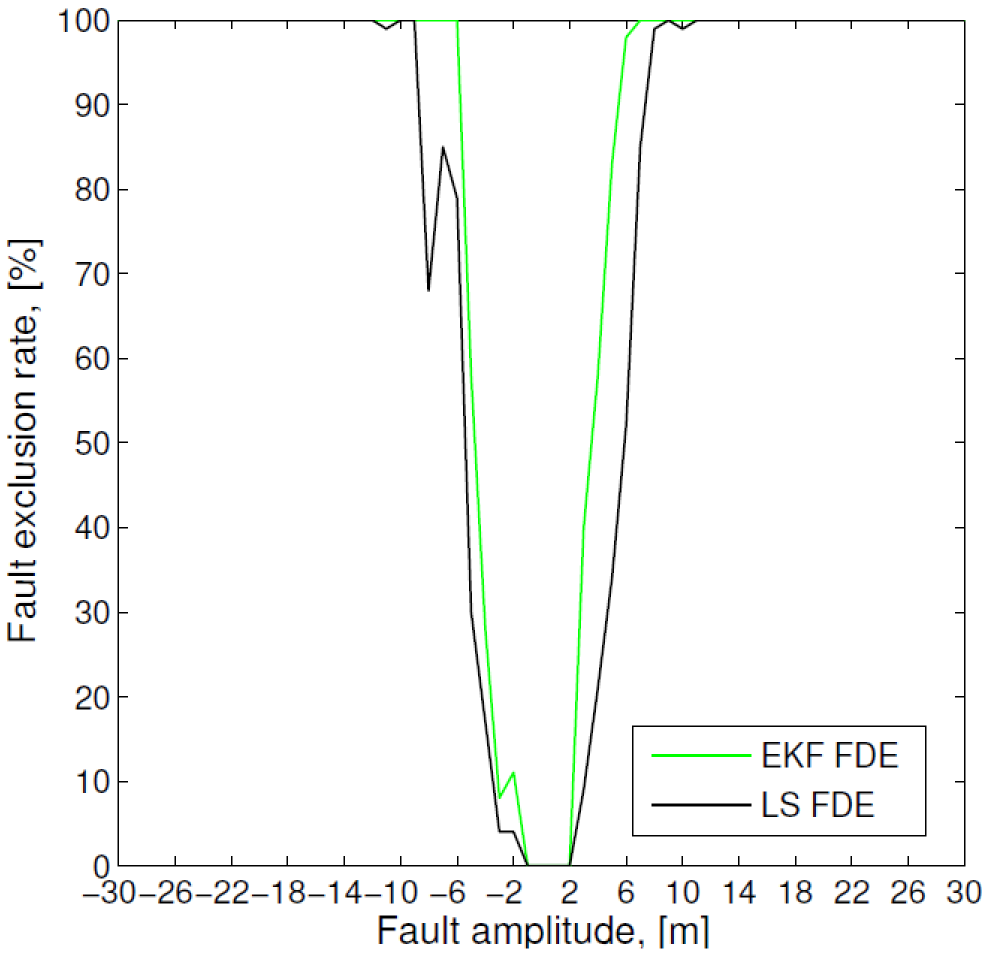
- For each amplitude value a random visible satellite was chosen and random (valid) start time within the data time span was selected for the outlier injection
  - **Convergence time has been taken into account for KF**

- Simulation parameters:
  - GNSS outlier range: [-15…15] meters: typical range for narrow correlator multipath envelope
  - Outlier duration: 30 samples (15 sec. @ 2 Hz output rate)
  - 20 outlier injections for each amplitude

Results: Measurement Domain Analysis (1/2)
Outlier Amplitude vs. Exclusion Rate

Non-Weighted approach:

- Outlier amplitude detection sensitivity of around 2 meters
  - Similar performance for both LSI and KFI
- Asymptotically similar performance for negative and positive values
- EKFI reaches ~100% exclusions with outliers amplitude ~ 6 meter
  - ~ 2 meters more sensitive than LSR
- EKFI FDE performance is systematically better than LSR for all outlier amplitudes
  - Some variations can be explained by statistical nature of MC simulation

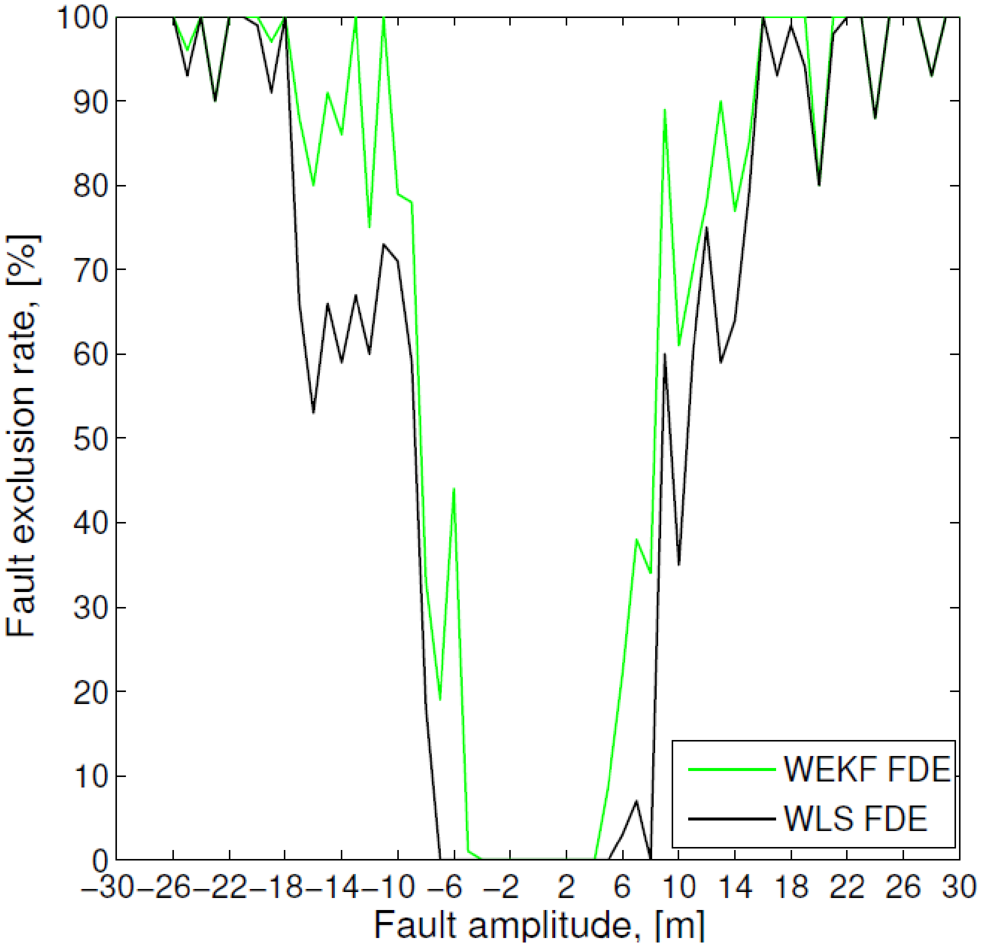


Results: Measurement Domain Analysis (2/2) Outlier Amplitude vs. Exclusion Rate

Weighted approach

Scenario 1
- Scaled Cno raw data value with respect to outlier amplitude injected using extracted noise model
- **Weighting scheme shows 0% exclusion rate for both LSR and EKFI**
- Reweighting based on Cno acts as an **equivalent** FDE scheme

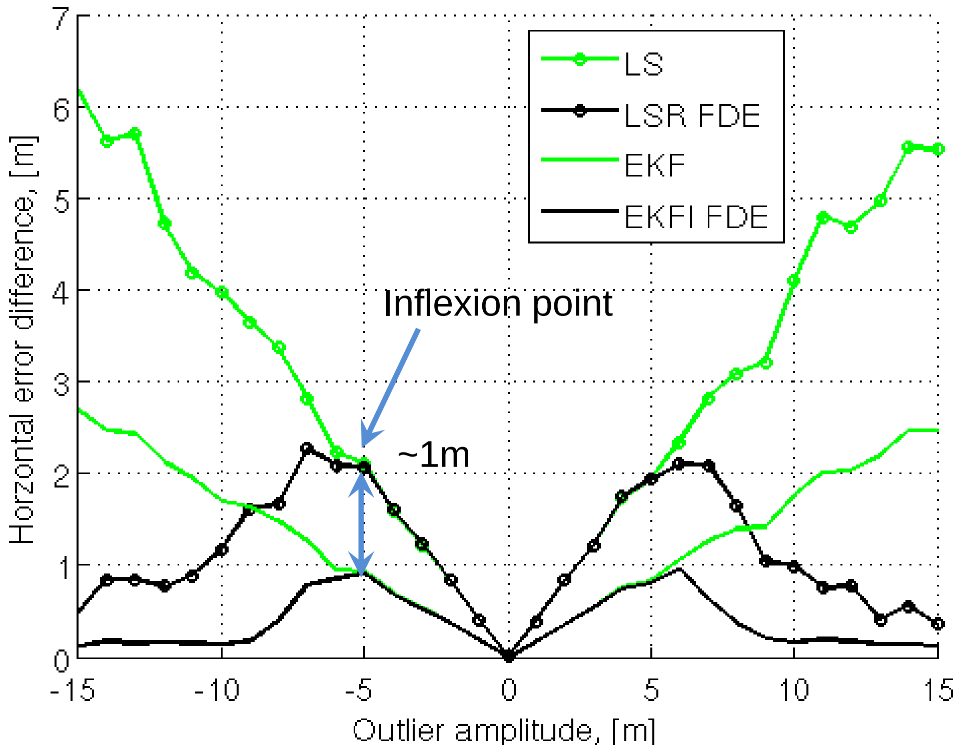
Scenario 2
- Non-scaled Cno (e.g. satellite clock drift)
- EKFI FDE performance is systematically better than LSR for all outlier amplitudes



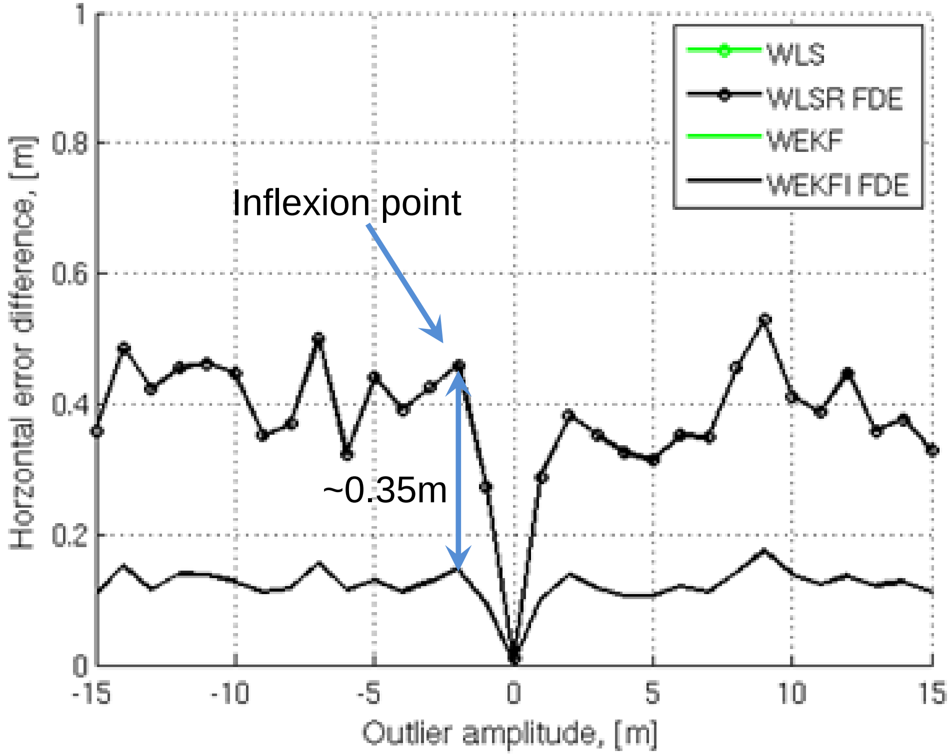
Results: Position Domain Analysis

- Position Difference Between Outlier Free and Contaminated Solution

Non-weighted approach

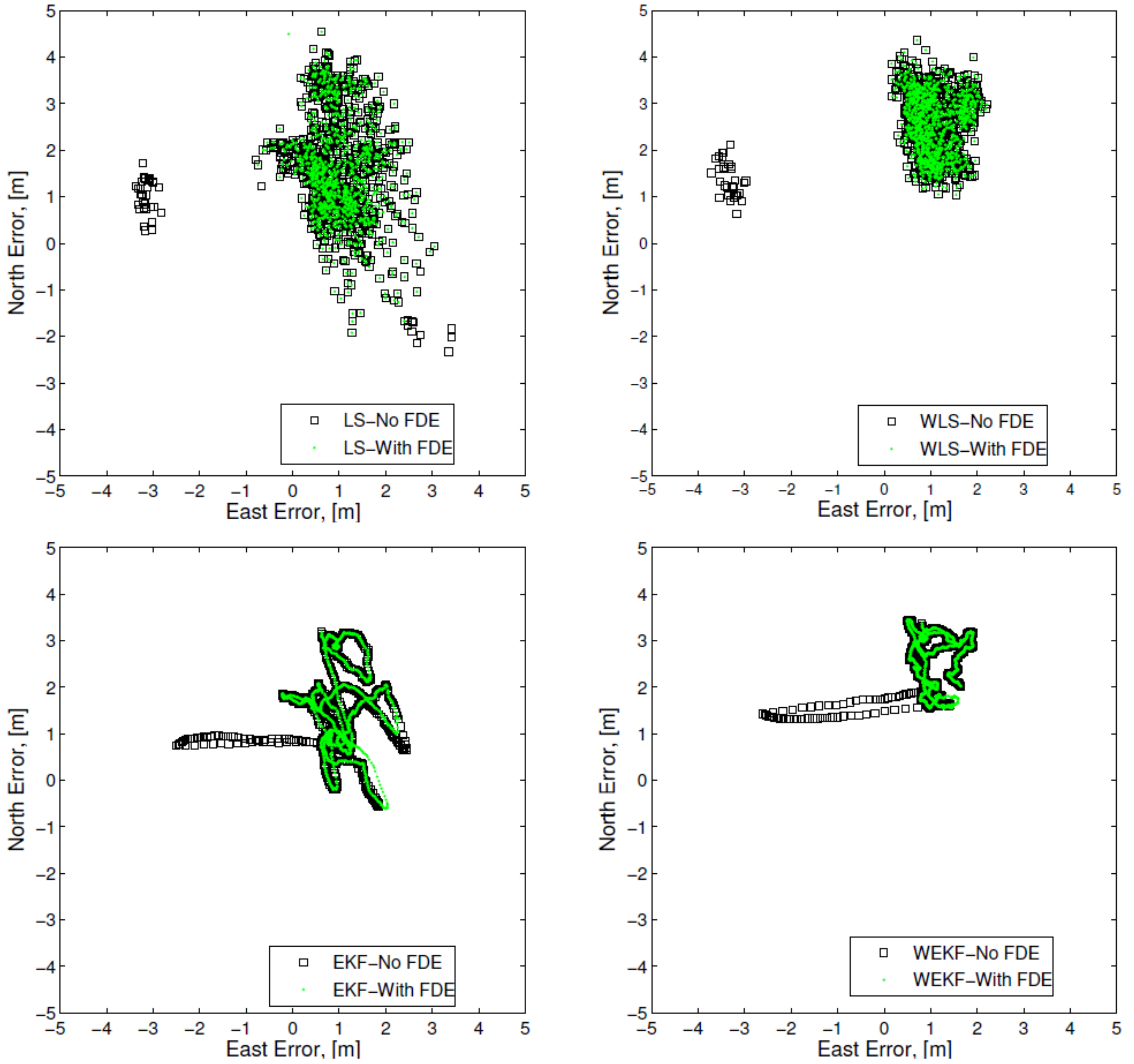


Weighted approach using rescaled CN0 measurements



Results: Position Domain Analysis

- Step outlier: 15 meters
- Precision of the approaches with and w/o FDE schemes (East vs. North position error):
    - LS with constant noise level (top left)
    - LS with weighted noise model (top right)
    - EKF with constant noise model (bottom left)
    - EKF with weighted noise model (bottom right)

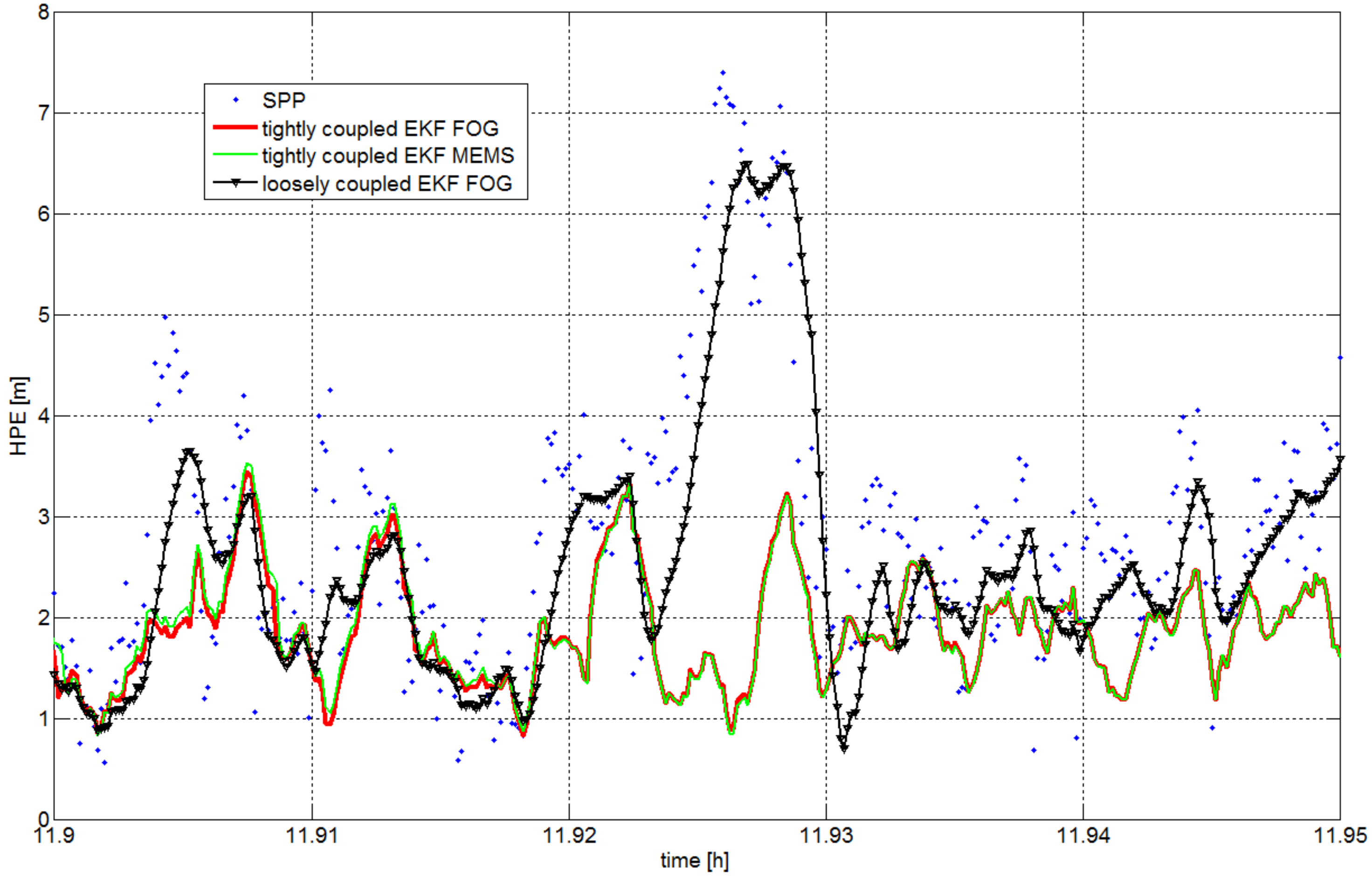


Outlier Detection in Integrated IMU/GNSS Solution

- FDE mechanism implementation in Extended KF for tightly-coupled IMU/GNSS navigation system

- Performance is independent on the quality of the inertial sensor (lower quality MEMS vs. higher quality FOG IMU)

- Loosely-coupled (non-FDE) integration scheme essentially provides only smoothed version of the memoryless LS (SPP) solution



Summary and Outlook

- Systematic analysis of different strategies (memoryless LS vs. recursive KF) for GNSS outlier detection and exclusion in positioning applications
- Successful implementation of a controlled environment simulator for systematic analysis of GNSS outliers
- Superiority of FDE schemes performance based on KF against LS estimation due to dynamic modelling (process model)
- Successful application of the strategy in multi-sensor integrated navigation system (tightly-coupled IMU/GNSS)
- KFI is a strong candidate for multisensory data fusion approach based on RBE framework
- The developed weighting model based on CNo can be used as an **equivalent to FDE scheme**

Outlook

- Extension of the presented methodology to velocity (GNSS Doppler) measurements

- Application of framework to other failure modes
    - E.g. failure of inertial sensors, Doppler Velocity Log (DVL) etc.

- Integrity monitoring algorithms for slowly varying errors
    - Ramp errors in GNSS signals

- Extension of the integrity methods and requirements to **Velocity** and **Attitude** information

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