Robust Position and Velocity Estimation Methods in Integrated Navigation Systems for Inland Water Applications

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Integrated Inertial Navigation

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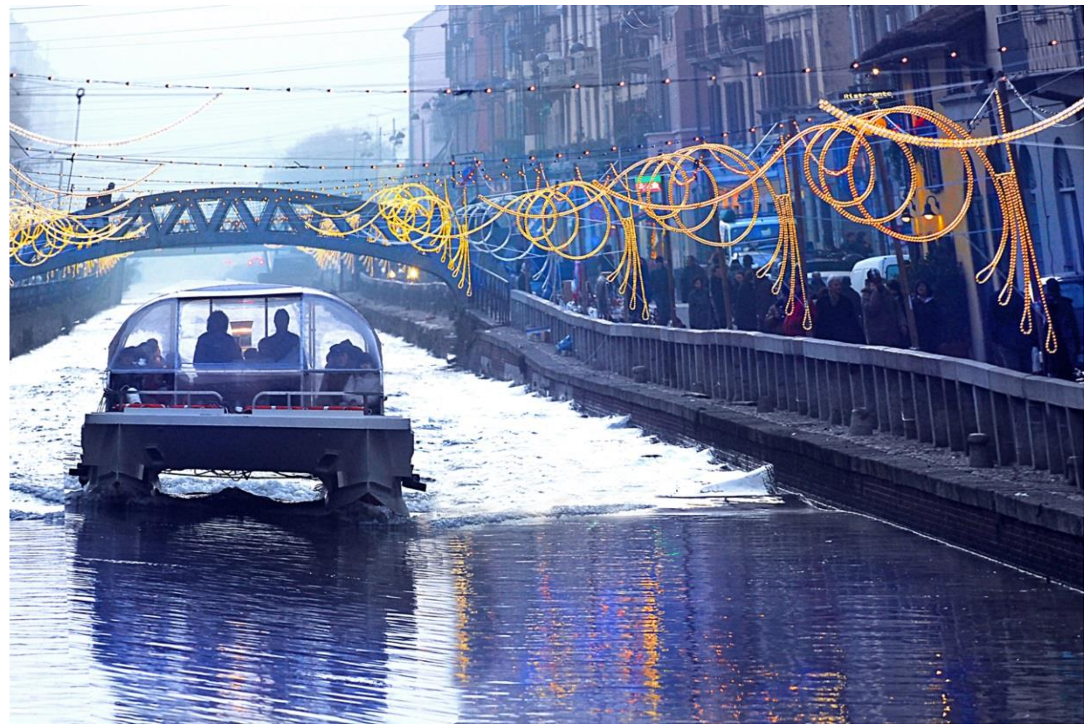
Agenda

◊ Introduction
- Motivation
- Objectives

◊ Methods
- Robust Estimation
- Sensor Fusion

◊ Tests and Results

◊ Summary and Outlook



source: www.waterways-forward.eu

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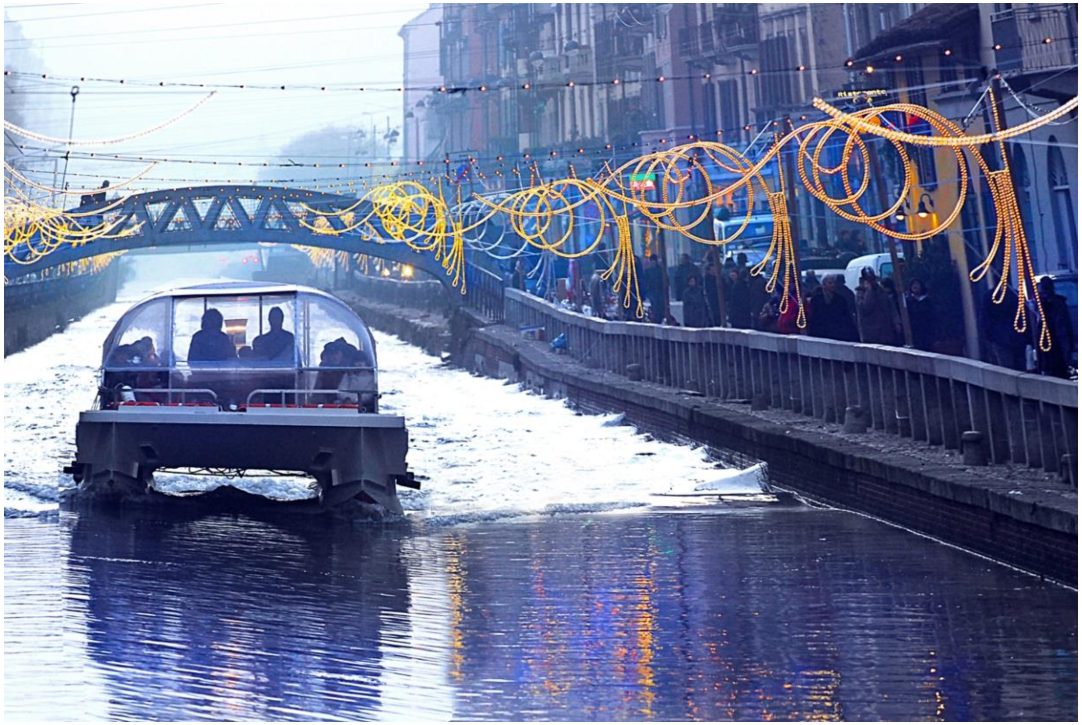

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Motivation

- Maritime transport is the backbone of international trade and the global economy:
  - ~80% global trade by volume is made by sea
  - Around 400 Mio. passengers move through European ports each year

Nautical Transport Systems are essential for the global economic development, competitiveness and prosperity

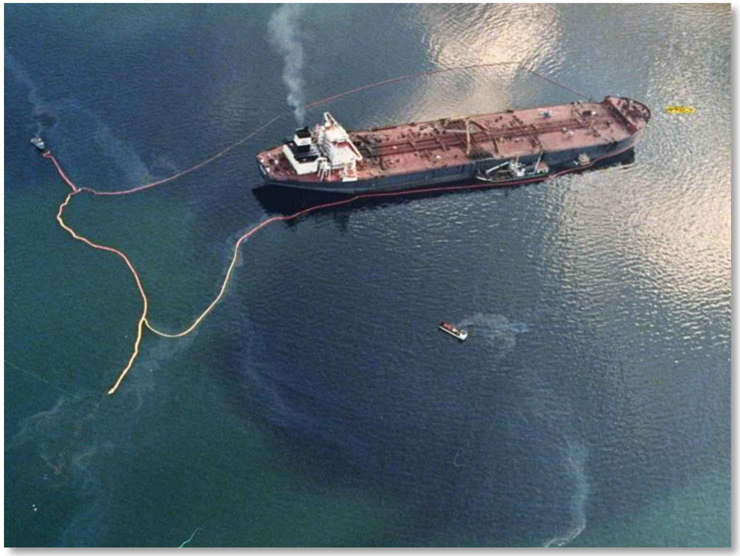
Unfortunately…

- The number of shipping accidents is not decaying over the years

Motivation

source: www.maritimearticsegurity.ca


source: www.fyens.dk


source: www.abc.es

source: www.marinetraffic.com

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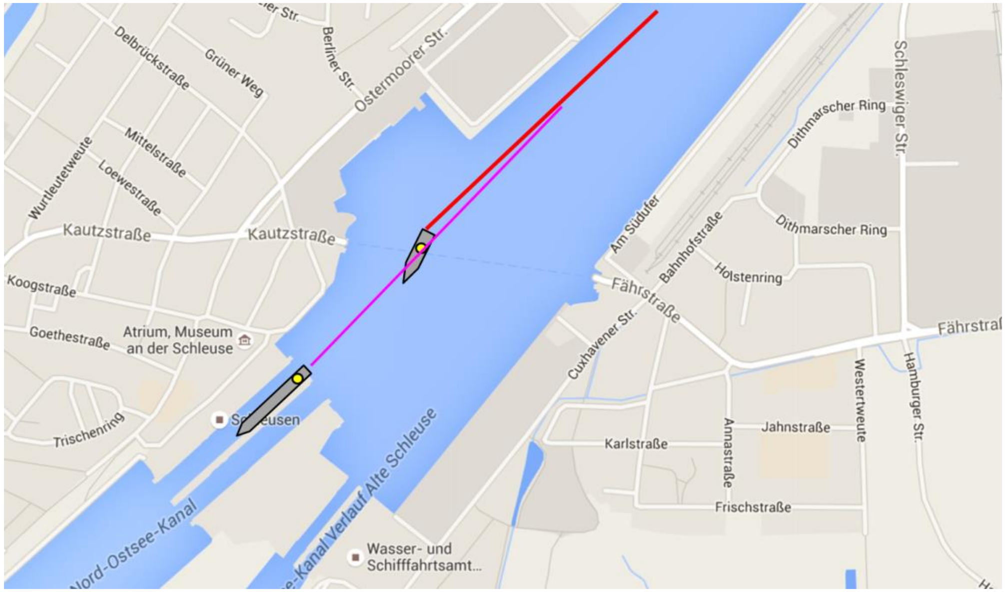
Motivation

- Kiel Canal: world busiest artificial waterway
- Collision of two medium-sized vessels at night
- Positioning systems on both vessels **showed a safe passing-distance**
- RADAR **was not** used



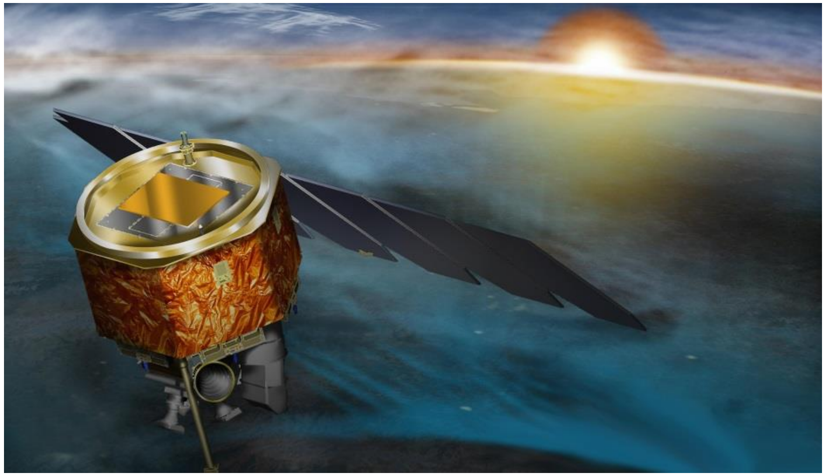
Global **N**avigation **S**atellite **S**ystems (**GNSS**) are the cornerstone and main information supplier for **P**ositioning, **N**avigation and **T**iming (**PNT**) in maritime systems.

Motivation

- The performance of satellite – based navigation can be easily disturbed due to space weather events, jamming, reflection of the signals, …

- Classical positioning is solved applying a **L**east **S**quares (**LS**) method →
  <u>single contaminated signal induce large errors in the position</u>

- **R**eceiver **A**utonomous **I**ntegrity **M**onitoring (**RAIM**) is the standard for GNSS fault detection **but…** it cannot handle multiple simultaneous faults!



source: www.nasa.gov

- Satellite – based navigation lacks ***robustness***:
  capability of a system to continue operating despite abnormalities

Objectives

- **What do we want?**

Provide a reliable navigation solution mitigating GNSS faulty signals

- **What is the problem?**
  - ✘ Multiple simultaneous faulty signals, specially in urban canyons or waterways
  - ✘ Standard RAIM is not sufficient

- **What is our solution?**
  - Implementation of robust estimators for the positioning problem
  - Integration of these algorithms within an inertial + satellite based navigation

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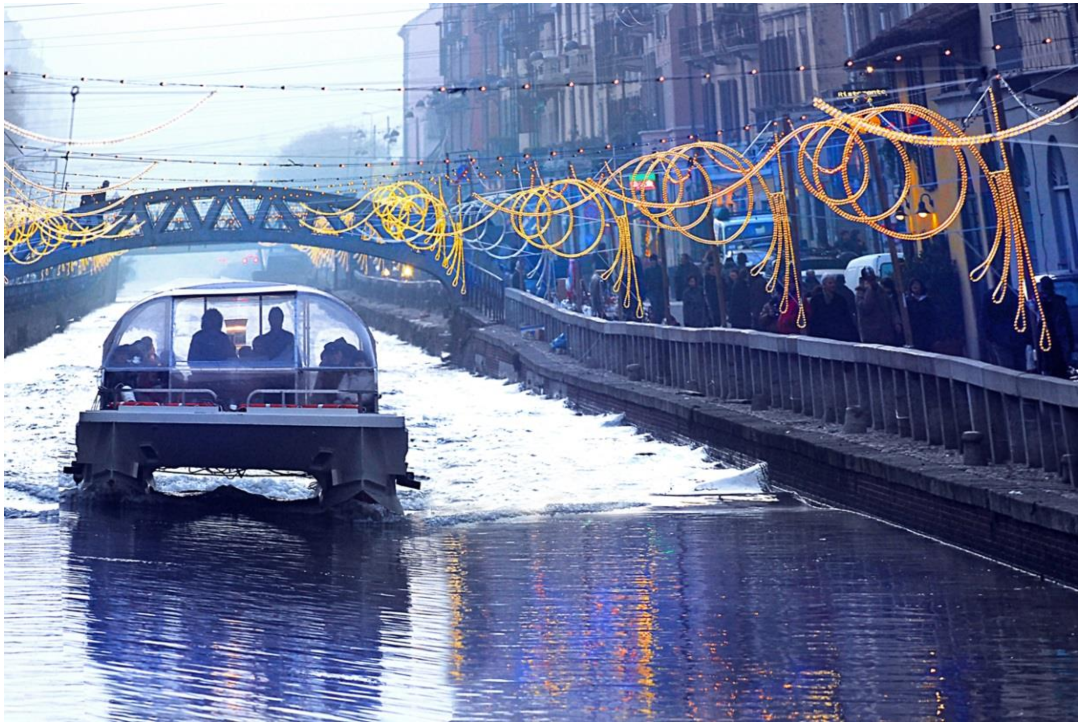

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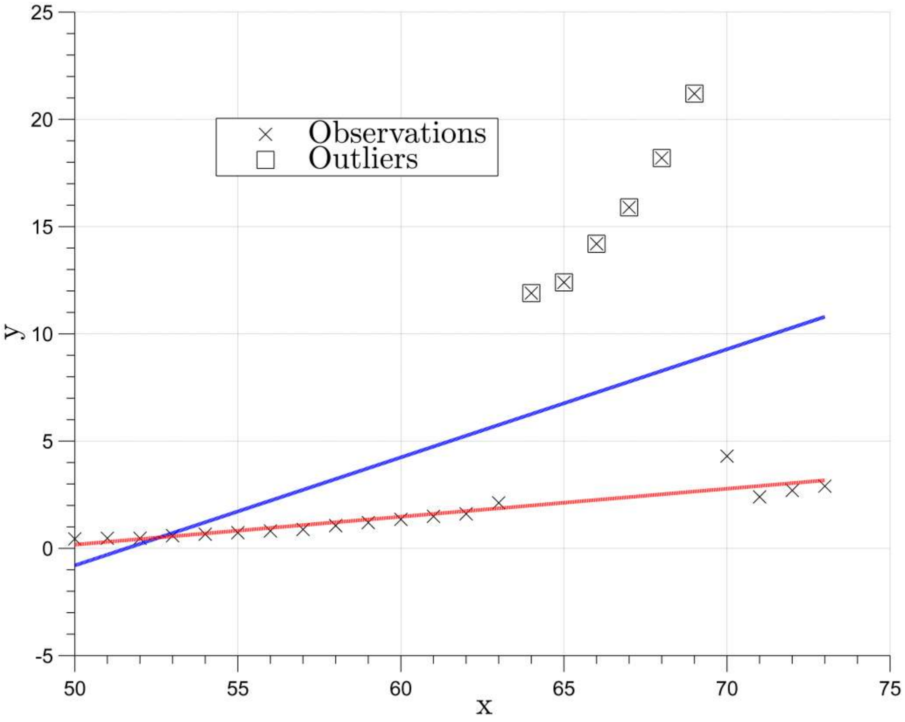
Robust Estimation

- GNSS positioning problems are generally solved → LS estimator
- In a LS, it is assumed that the noises are Gaussian…

But this is often not the case!

Clue definitions

- *Outliers* – observations that appear unusually large or small and "out of place"
- *Breakdown Point* ϵ^* – smallest percentage of contaminated data that can cause the estimator to take arbitrarily large values
- *Gaussian Efficiency* – similarity of a method to classical LS under Gaussian conditions



Robust Estimation

- Overpassing the limitations of LS for regression has concerned mathematicians and engineers for years…

Iteratively Reweighted Least Squares (IRLS)

- Full set approach → all observations are used to compute a solution, observations with large residuals are downweighted
- Appealing implementation for its similarity to regular LS
- Gaussian efficient
- Breakdown point ϵ^* not very high

➢ M – estimator

$$\min \sum_{i=1}^{n} \rho\left(\frac{r_i}{\hat{\sigma}}\right), \qquad \epsilon^* = 0$$

➢ GM – estimator

$$\min \sum_{i=1}^{n} w(x_i)\rho\left(\frac{r_i}{w(x_i)\hat{\sigma}}\right), \qquad \epsilon^* = \frac{1}{n+1}$$

➢ S – estimator

$$\min \mathrm{s}(r_1, \dots, r_n), \qquad \epsilon^* = \left(\frac{n}{2} - p + 2\right)/n$$

Best Subset Selection

- Bottom – up approach → from n observations, $\binom{n}{p}$ subsets are made
- The solution is checked using the observations not taking part in the solution
- The best subset is the one to minimize/maximize the cost function
- Breakdown point ϵ^* up to 50%
- Low Gaussian efficiency

➢ **L**east **M**edian of **S**quares (**LMS**)

$$\min \operatorname{med} r_i, \qquad \epsilon^* = 0.5$$

➢ **L**east **T**rimmed of **S**quares (**LTS**)

$$\min \sum_{i=1}^{h} (r)^2_{i:n}, \qquad \epsilon^* = 0.5$$

There are also other approaches…

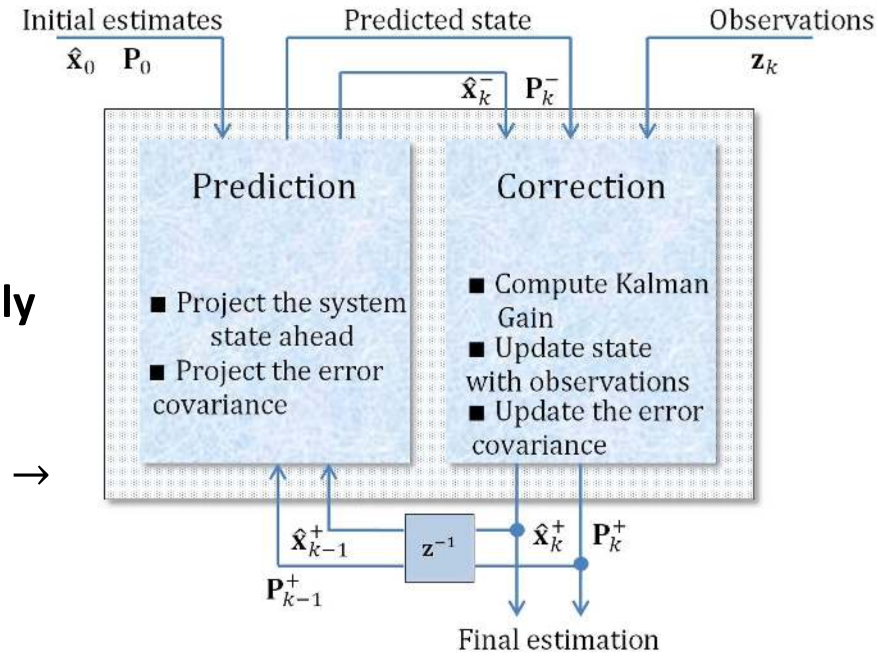
- **R**eceiver **A**utonomous **I**ntegrity **M**onitoring (**RAIM**)

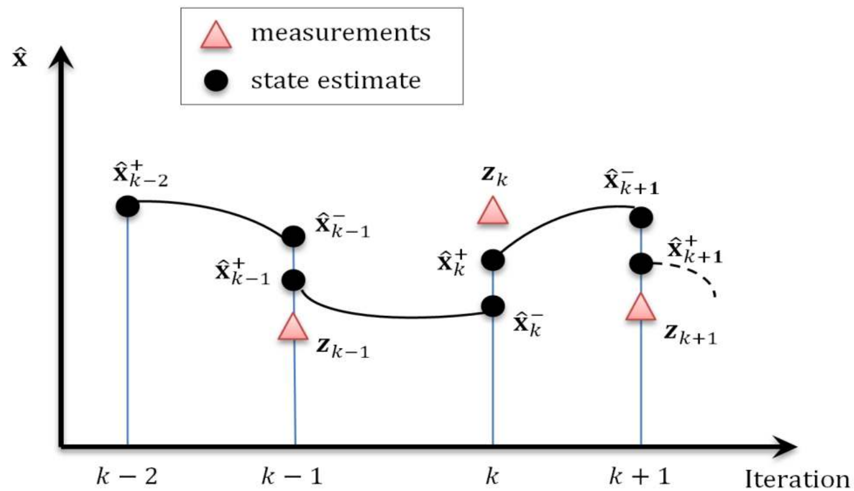
Kalman Filtering for Sensor Fusion

- **Standard approach for multi-sensor fusion** and navigation

- Incorporate of all the available information (uncertainties, noise statistics, dynamical models, kinematic constraints) in a **statistically consistent way**

- **K**alman **F**ilter (**KF**) is valid for linear problems → **E**xtended & **U**nscented **KF** (**UKF, EKF**)





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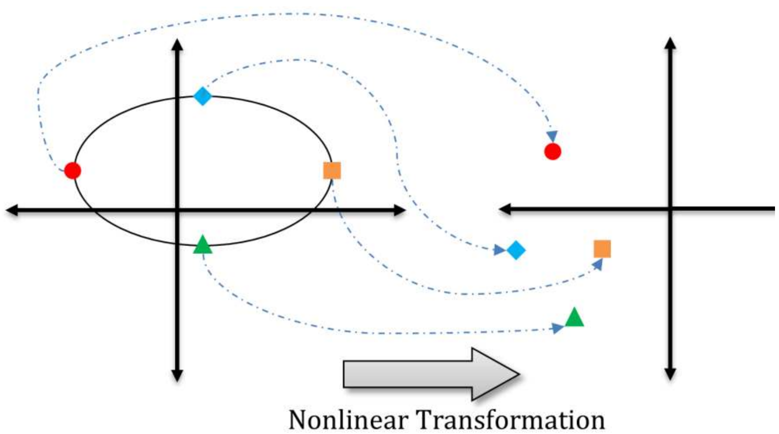
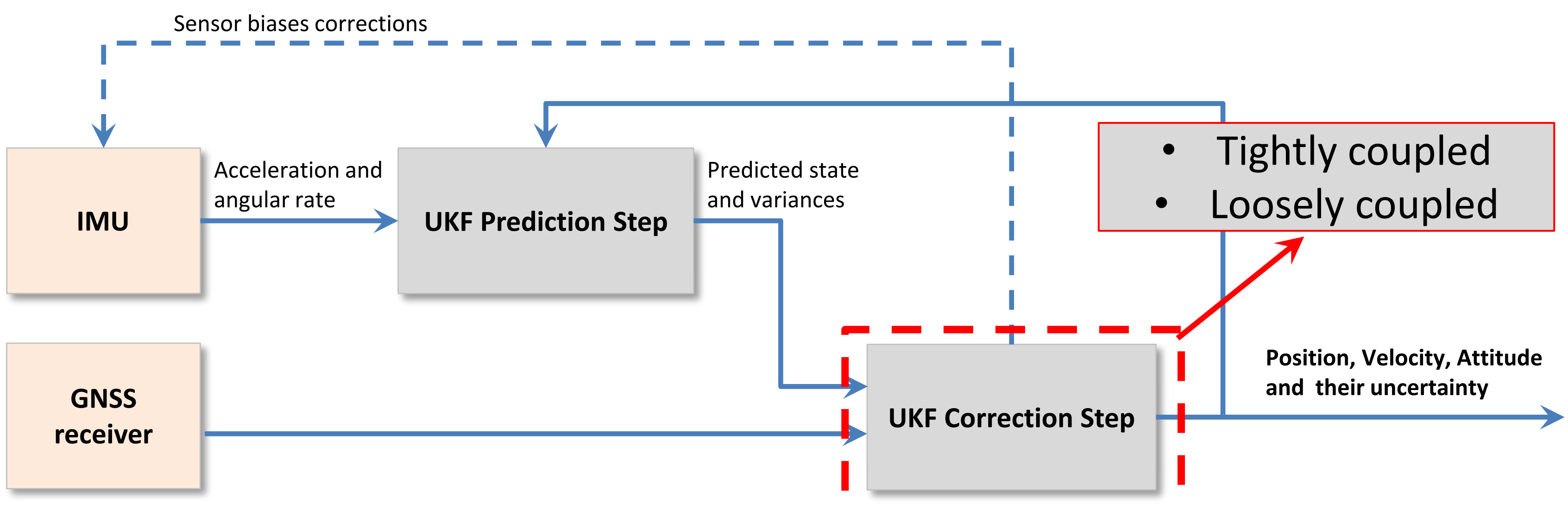
UKF for IMU/GNSS Navigation



- The state is represented by a set of *sigma points* → propagated through the nonlinear functions
- The mean and covariance of the solution are reconstructed back from the *sigma points*
- **Attention**: this is not a Monte Carlo method!



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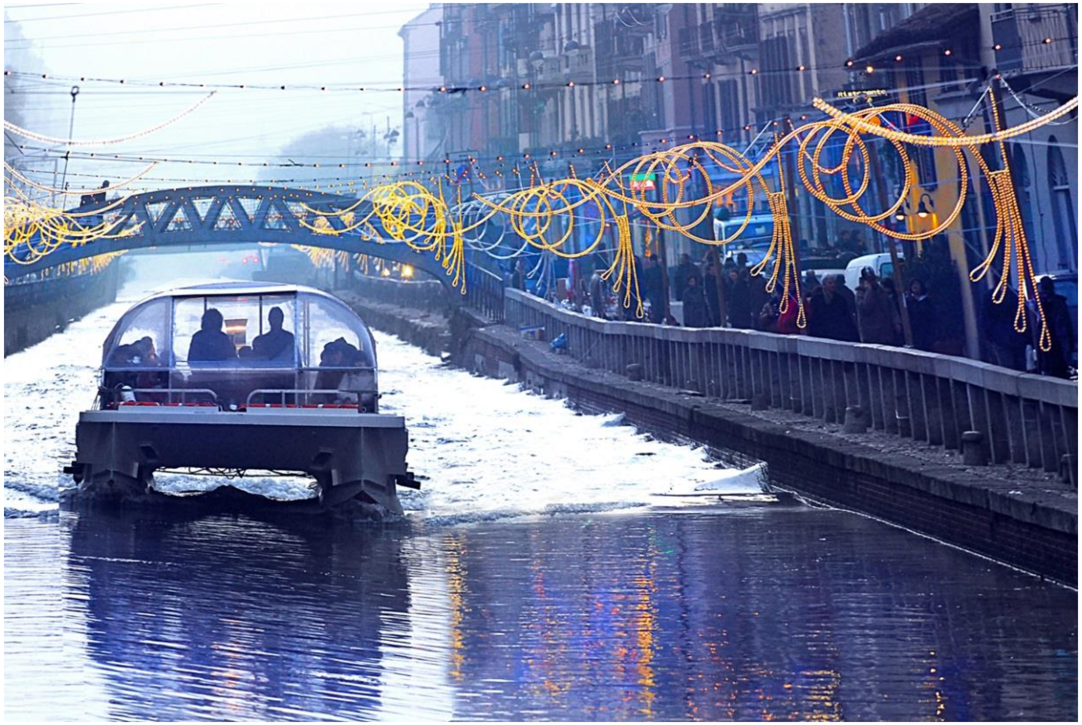

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Experiment Setup

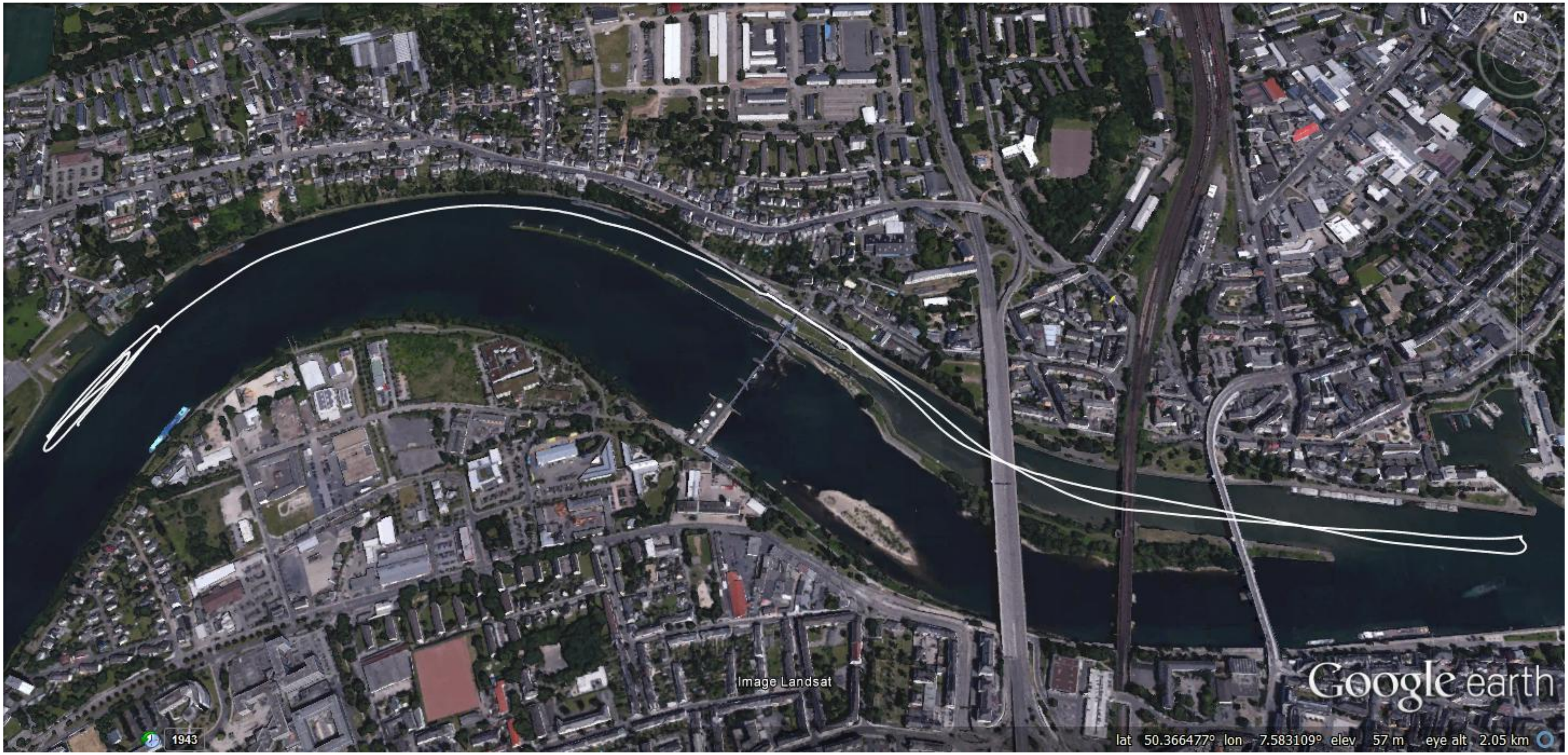
- The test scenario is the Moselle River in Koblenz (Germany)

- Vessel “MS BINGEN” performed 8 – shaped trajectory passing under the bridges

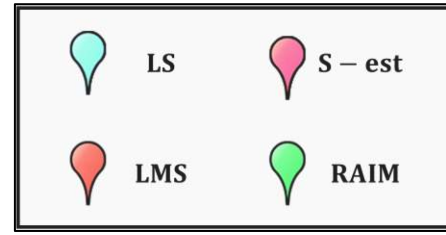
Equipment of vessel:

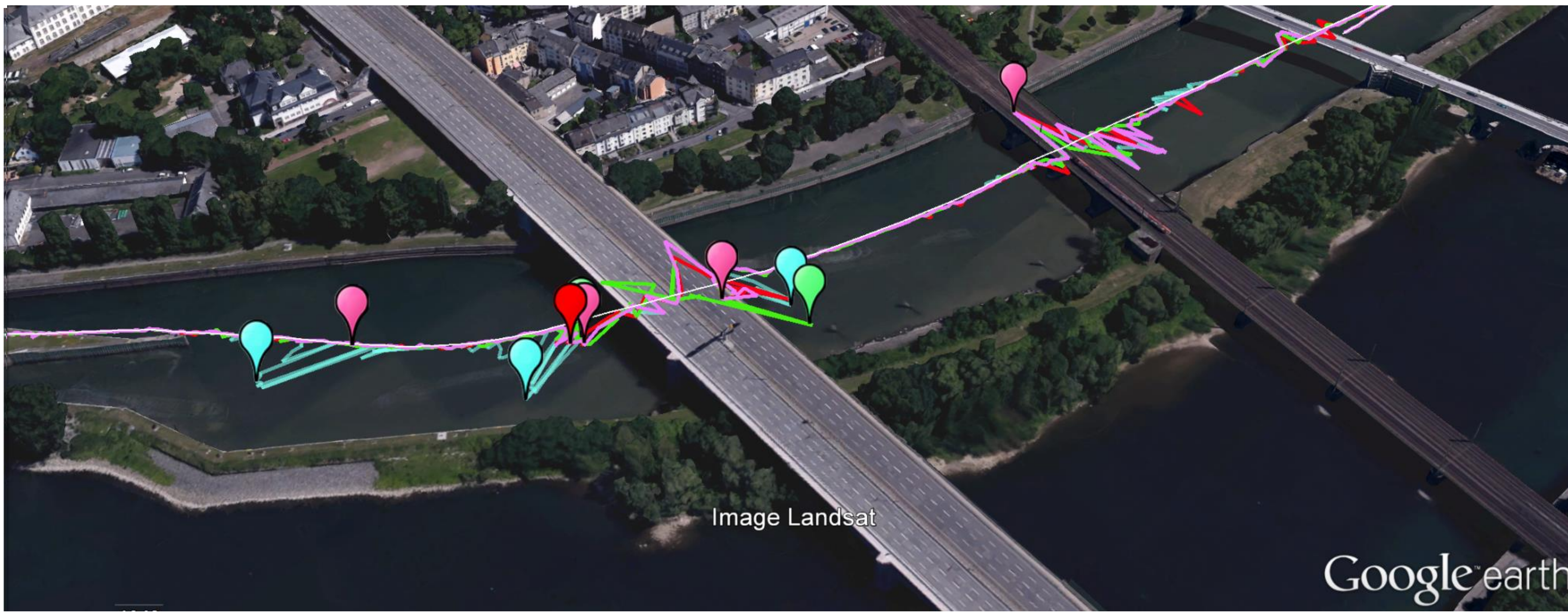
  - 3x – GNSS antennas, update rate 1 Hz
  - 1x – inertial sensors: gyroscope and accelerometer , update rate 200 Hz

Moselle River Scenario



Robust Method Comparison





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Discussion on Robust Estimation

Statistics on the Robust Methods performance

Method	Mean [m]	RMS [m]	Max [m]
SPP	2.9	4.5	50.7
S	2.4	3.4	34.0
LMS	2.4	3.4	34.9
RAIM	2.3	3.0	45.4

- ✓ Robust techniques perform better than regular **S**ingle **P**oint **P**ositioning (**SPP**)
- ✓ The mean error is reduced and the maximum error is 15 m smaller

- LMS and S estimator have a similar performance **but…**
  - LMS requires higher computation
  - LMS has a low Gaussian efficiency

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UKF Performance

- Comparison of the different UKF designs:
  - **Tightly Coupled UKF**

State for the Tightly Coupled Architecture UKF

State	Covariance	Variable	Symbol	Coordinate System
1:4	1:3	Attitude Quaternion	q	From B-frame to ECEF
5:7	4:6	Velocity	v	ECEF
8:10	7:9	Position	p	ECEF
11:13	10:12	Gyroscope Offset	b_ω	B-frame
14:16	13:15	Accelerometer Offset	b_a	B-frame
17	16	Clock offset	$c\delta t$	-
18	17	Clock rate	$c\dot{\delta} t$	-

  - **Loosely Coupled UKF** + a) classical LS b) robust scheme

State for the Loosely Coupled Architecture UKF

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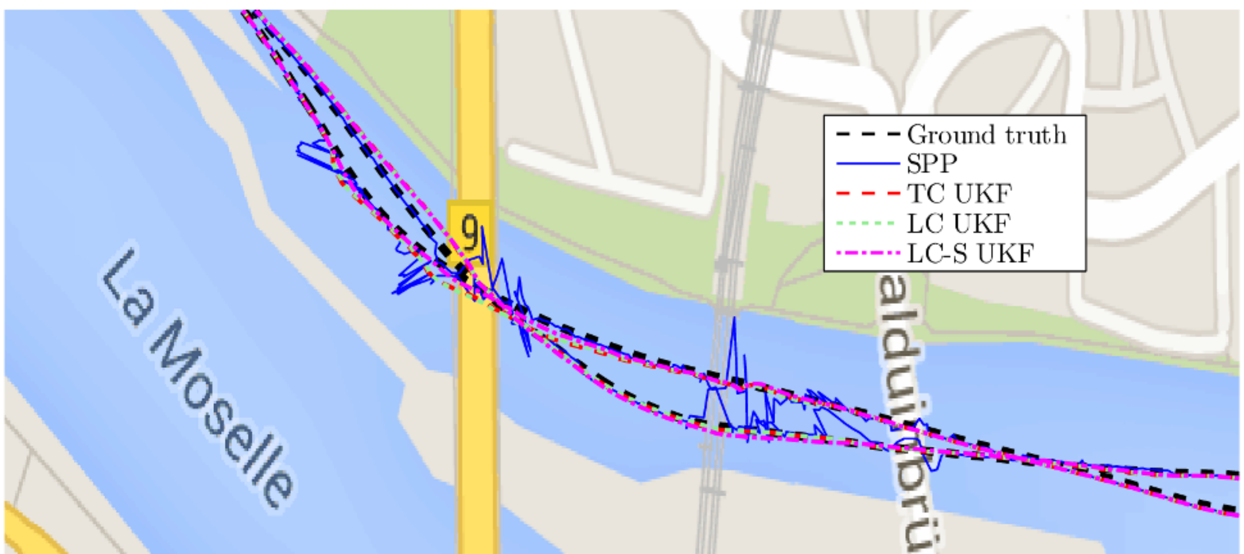
UKF Performance Discussion

Statistics on the KF performance

Method	Mean [m]	RMS [m]	Max [m]
SPP	2.9	4.5	50.7
TC UKF	3.0	3.8	18.3
LC UKF	3.0	3.70	17.0
LC-S UKF	2.3	2.6	9.1

- ✓ Kalman filtering provides a smooth position solution → largest errors are eliminated
- ✓ The inclusion of robust estimator → significant improvement in the position error



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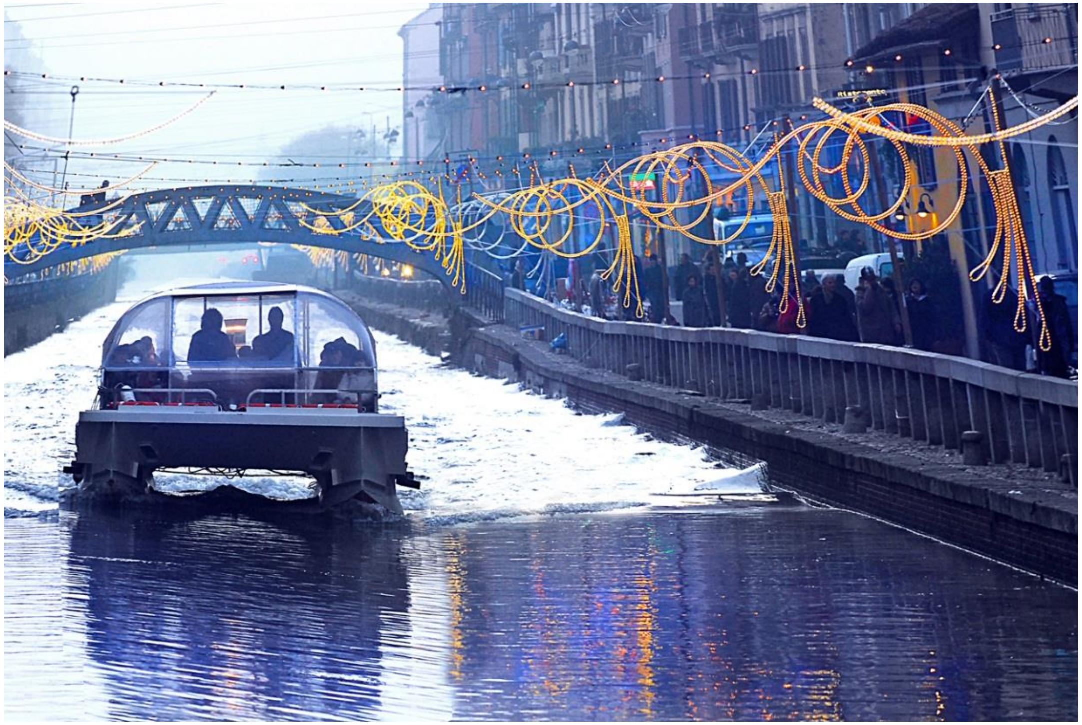

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Conclusions

- Review on the techniques for GNSS fault mitigation
- Integrated navigation fusing IMU+GNSS sensors using UKF
- Evaluation of the algorithms using real data
    - ✓ Promising performance improvement vs. classical LS
    - ✓ Great benefits of the use of robust schemes + KF

Future Work

- Extension to **M**ulti – antenna, **M**ulti – constellation, **M**ulti – frequency (**MMM**)
- Robust schemes lack any kind of integrity monitoring → user gets warned if position estimation is not reliable
- Implementation of the robust estimation in the tightly coupled UKF


Thanks for your Attention
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