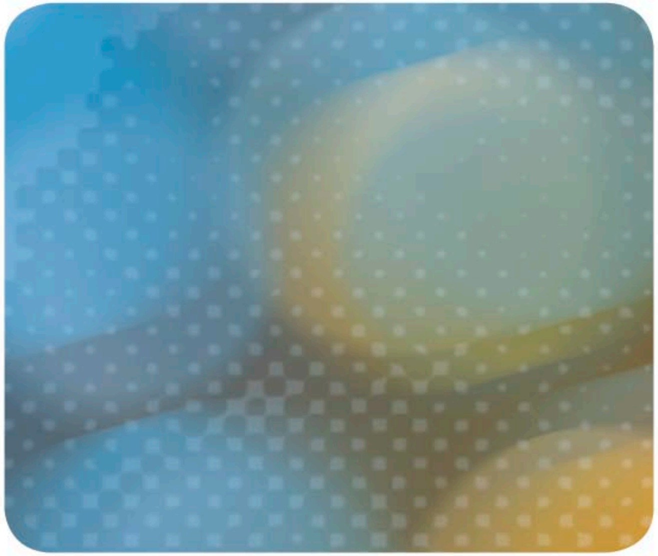
FFI Forsvarets forskningsinstitutt

Note 1: This is a short (20 pages) tutorial. An extended (57 pages) tutorial that also includes Kalman filtering is available at
http://www.navlab.net/Publications/Introduction_to_Inertial_Navigation_and_Kalman_Filtering.pdf

Introduction to Inertial Navigation (INS tutorial – short)



Tutorial for:
Geodesi- og Hydrografidagene 2005, Hoenefoss, Norway

Kenneth Gade, FFI
(Norwegian Defence Research Establishment)

Note 2 (from June 2016):
An important topic that is not covered by these tutorials is presented at
www.navlab.net/nvector

Here program code for Matlab, C#, C++, Python and JavaScript is available for download as well

To cite this tutorial, use: Gade, K. (2005): *Introduction to Inertial Navigation.* Tutorial for Geodesi- og Hydrografidagene 2005, Hoenefoss, Norway

Navigation

Navigation:

Estimate the position, orientation and velocity of a vehicle

Inertial navigation:

Inertial sensors are utilized for the navigation

Inertial Sensors

Based on inertial principles, *acceleration* and *angular velocity* are measured.

- Always relative to *inertial space*
- Most common inertial sensors:
    - *Accelerometers*
    - *Gyros*

Accelerometers

By attaching a mass to a spring, measuring its deflection, we get a simple accelerometer.

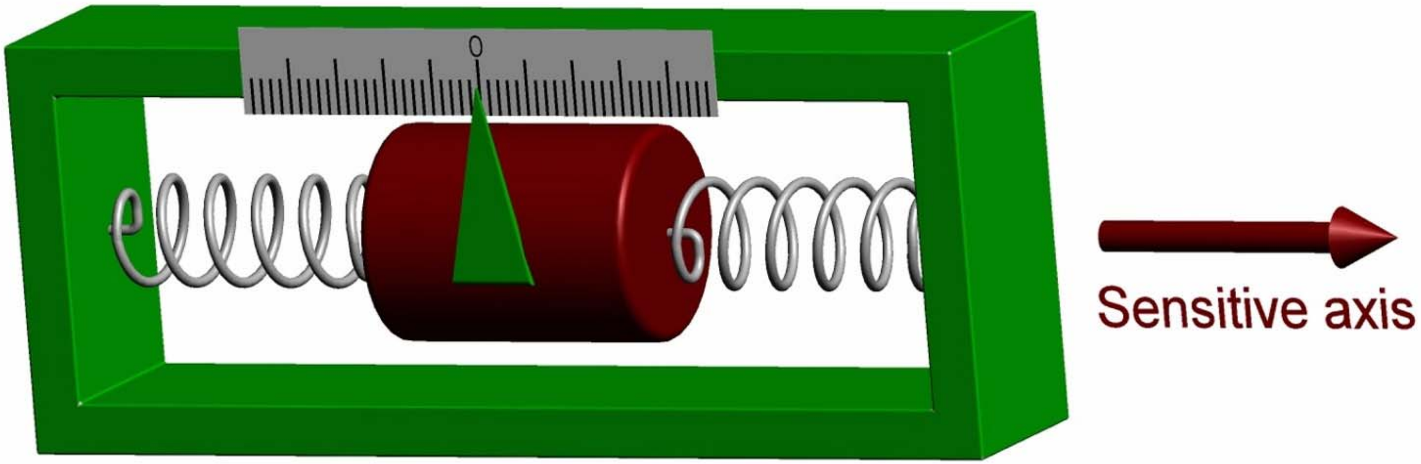


Figure: Gade (2004)

Accelerometers (continued)

- Gravitation is also measured (Einstein's principle of equivalence)
- Total measurement called *specific force*
- Using 3 (or more) accelerometers we can form a 3D specific force measurement: $\boldsymbol{f}_{IB}^{B}$

This means: Specific force of the body system (*B*) relative inertial space (*I*), decomposed in the body system.

Gyros

Gyros measure angular velocity relative inertial space: $\boldsymbol{\omega}_{IB}^{B}$

Measurement principles include:

Spinning wheel

- Mechanical gyro

Sagnac-effect

- Ring laser gyro (RLG)
- Fiber optic gyro (FOG)

Coriolis-effect

- MEMS
- “Tuning fork”
- “Wine glass”

Figure: Caplex (2000)

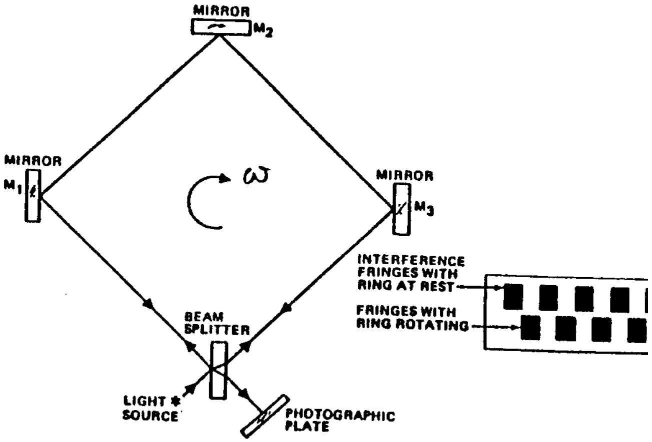


Figure: Bose (1998)

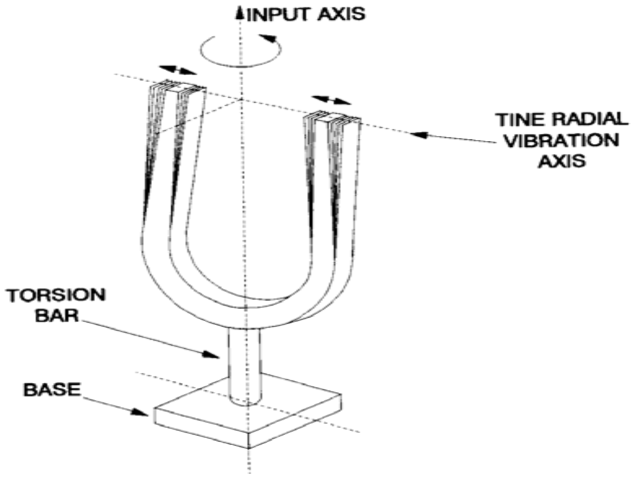


Figure: Titterton & Weston (1997)

IMU

Three gyros and three accelerometers are normally combined in an inertial measurement unit (IMU)

Example:

Honeywell HG1700 ("medium quality"):

- 3 accelerometers, accuracy: 1 mg
- 3 ring laser gyros, accuracy: 1 deg/h
- Rate of all 6 measurements: 100 Hz

Foto: FFI

Inertial Navigation

An IMU (giving $\boldsymbol{f}_{IB}^{B}$ and $\boldsymbol{\omega}_{IB}^{B}$) is sufficient to navigate relative to inertial space (no gravitation present), given initial values of *velocity, position* and *attitude*:

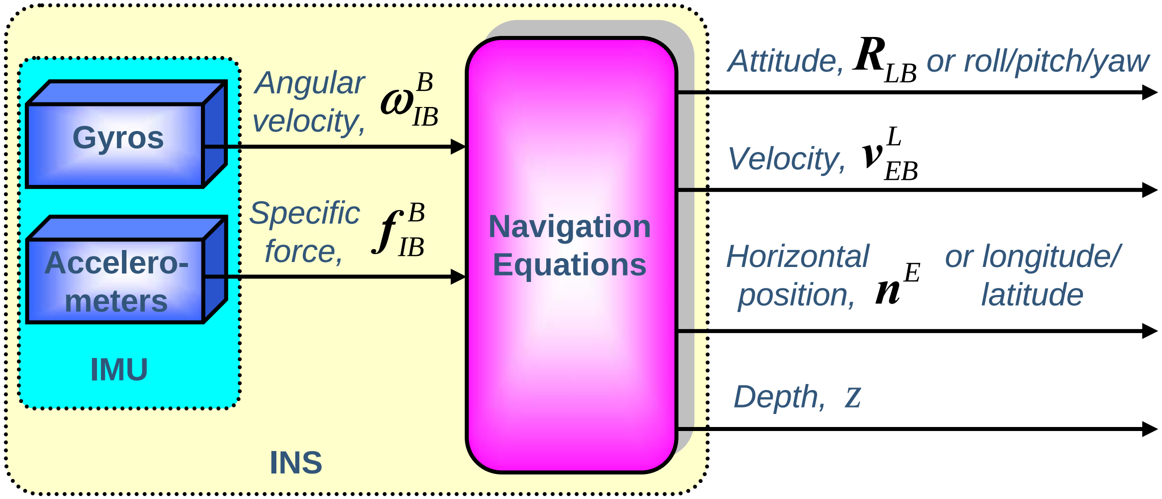
- Integrating the sensed acceleration will give velocity.
- A second integration gives position.
- To integrate in the correct direction, attitude is needed. This is obtained by integrating the sensed angular velocity.

In *terrestrial navigation* (close to the Earth) we compensate for gravitation, and rotation of the Earth

Equations integrating the gyro and accelerometer measurements into velocity, position and orientation are called *navigation equations*

Inertial Navigation System (INS)

The combination of an IMU and a computer running navigation equations is called an *Inertial Navigation System (INS)*.



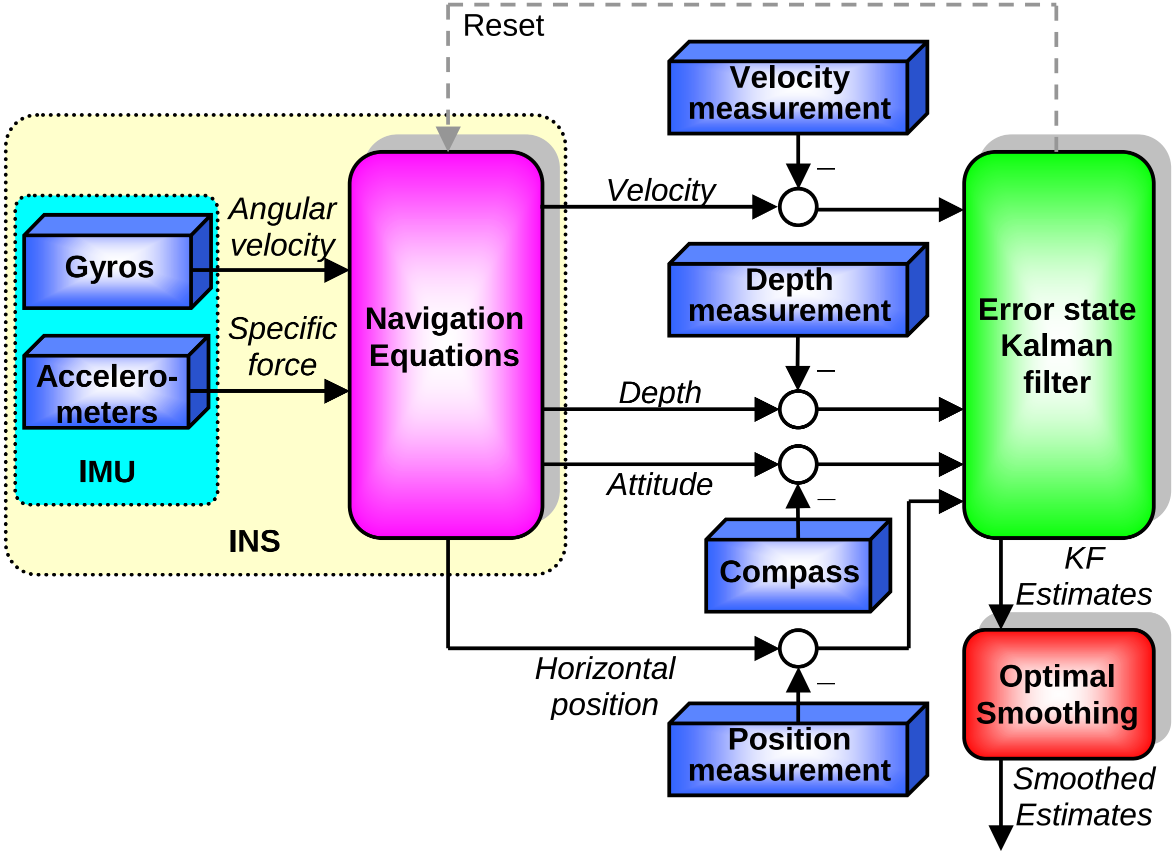
Due to errors in the gyros and accelerometers, an INS will have unlimited drift in velocity, position and attitude.

Categorization:
IMU technology and IMU performance

Class	**Position performance**	**Gyro technology**	**Accelerometer technology**	**Gyro bias**	**Acc bias**
”Military grade”	1 nmi / 24 h	ESG, RLG, FOG	Servo accelerometer	< 0.005°/h	< 30 µg
Navigation grade	1 nmi / h	RLG, FOG	Servo accelerometer, Vibrating beam	0.01°/h	50 µg
Tactical grade	> 10 nmi / h	RLG, FOG	Servo accelerometer, Vibrating beam, MEMS	1°/h	1 mg
AHRS	NA	MEMS, RLG, FOG, Coriolis	MEMS	1 - 10°/h	1 mg
Control system	NA	Coriolis	MEMS	10 - 1000°/h	10 mg

Aided inertial navigation system

- To limit the drift, an INS is usually aided by other sensors that provide direct measurements of for example position and velocity.
- The different measurements are blended in an optimal manner by means of a *Kalman filter.*



The INS and aiding sensors have complementary characteristics.

Optimal Smoothing

Optimal estimate when also using future measurements

Smoothing gives:

- Improved accuracy
- Improved robustness
- Improved integrity
- Estimate in accordance with process model

Example from HUGIN 1000:

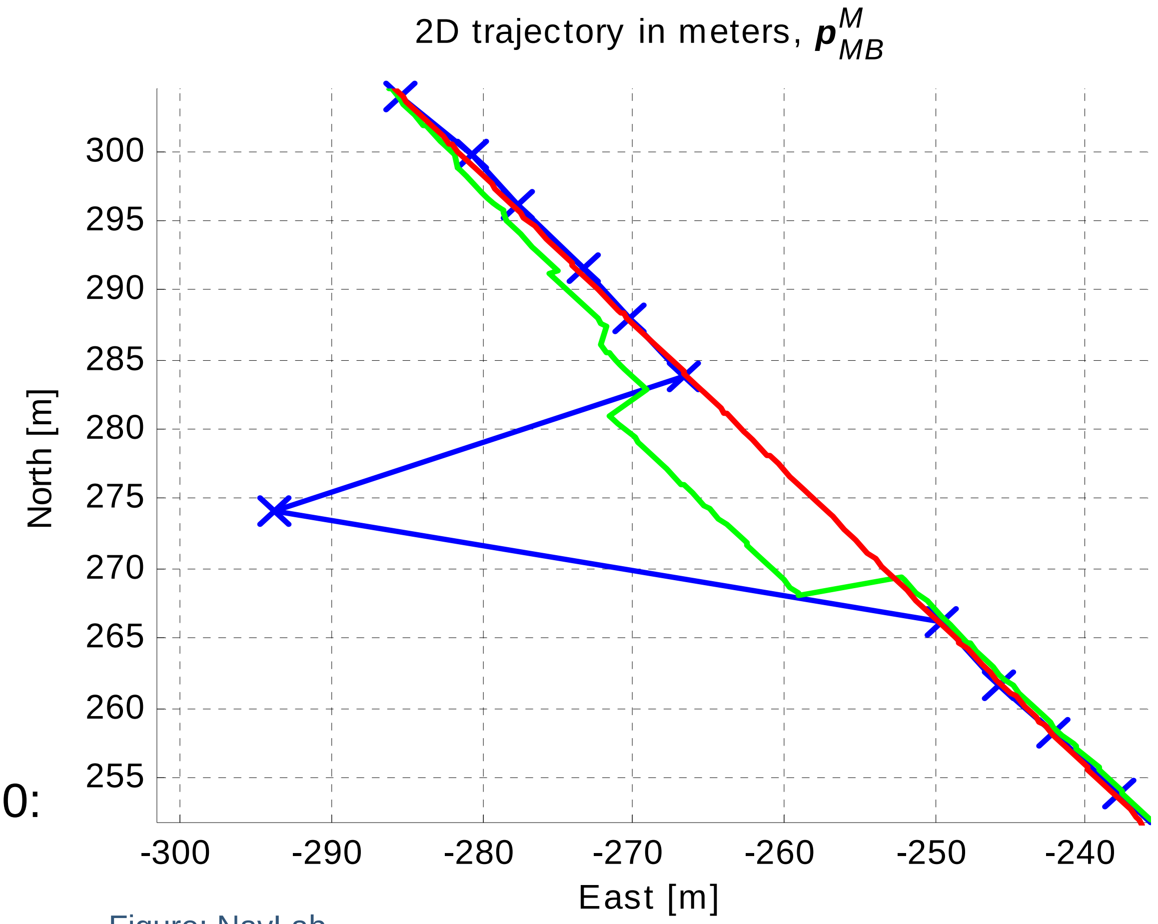


Figure: NavLab

Typical position estimate example (simulation)

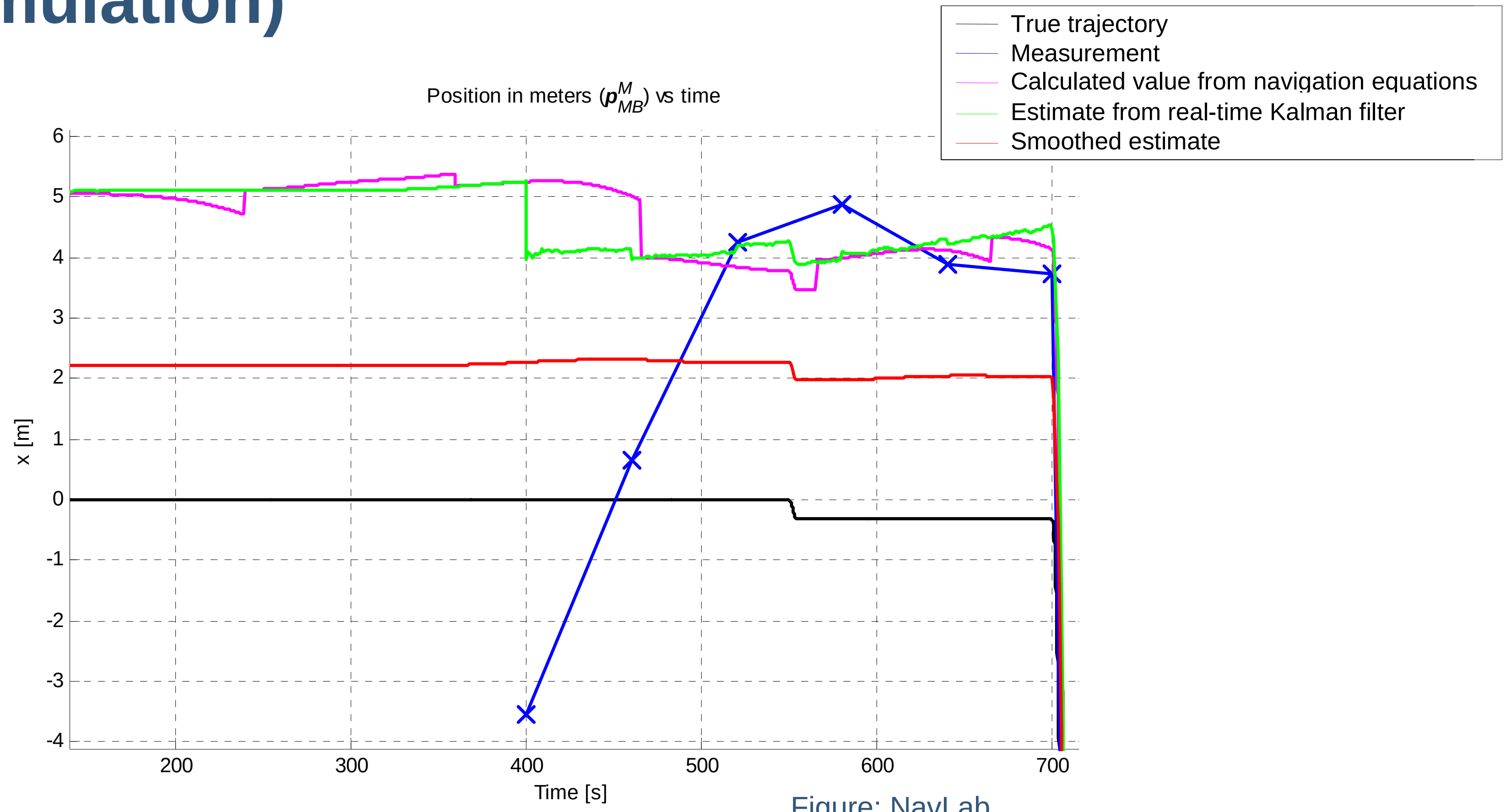


Figure: NavLab

Position measurement total error: 5 m (1 σ)

Navigation equation reset ca each 107 sec

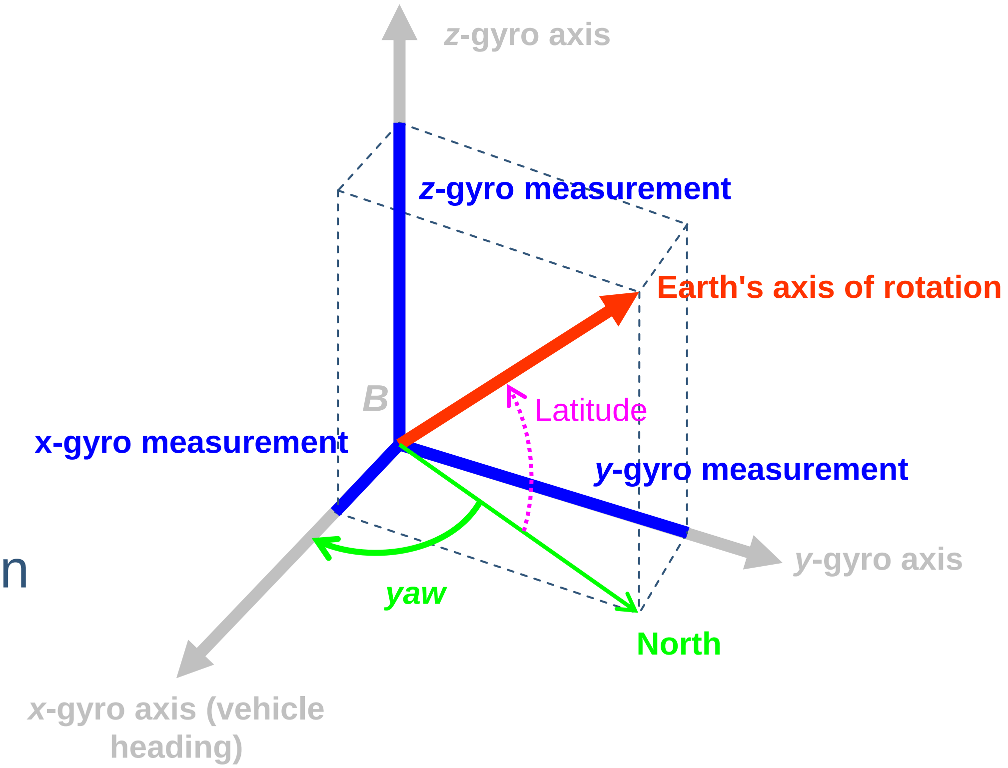
Gyrocompassing

Gyrocompassing

- The concept of finding North by measuring the direction of Earth's axis of rotation relative to inertial space $\vec{\omega}_{IE}$
- Earth rotation is measured by means of gyros

- An optimally designed AINS inherently gyrocompasses optimally when getting position or velocity measurements (better than a dedicated gyrocompass/motion sensor).

Static conditions, *x*- and *y*-gyros in the horizontal plane:



What is NavLab?

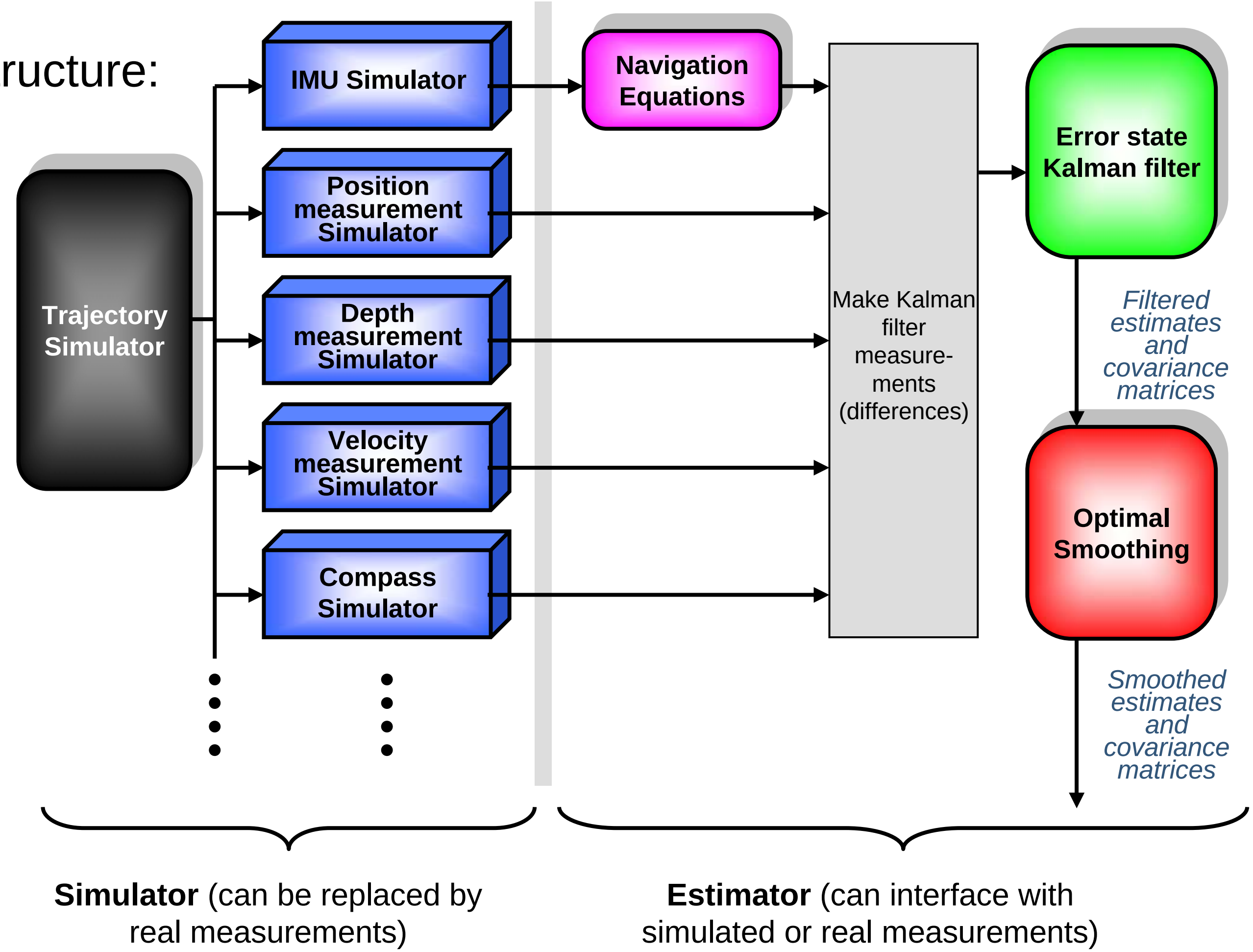
NavLab (Navigation Laboratory) is one common tool for solving a variety of navigation tasks.

Development started in 1998

Main focus during development:

- Solid theoretical foundation (competitive edge)

Structure:



Trajectory Simulator

IMU Simulator

Position measurement Simulator

Depth measurement Simulator

Velocity measurement Simulator

Compass Simulator

Navigation Equations

Make Kalman filter measure-ments (differences)

Error state Kalman filter

Filtered estimates and covariance matrices

Optimal Smoothing

Smoothed estimates and covariance matrices

Simulator (can be replaced by real measurements)

Estimator (can interface with simulated or real measurements)

Simulator

- Trajectory simulator
  - Can simulate any trajectory in the vicinity of Earth
  - No singularities

- Sensor simulators
  - Most common sensors with their characteristic errors are simulated
  - All parameters can change with time
  - Rate can change with time

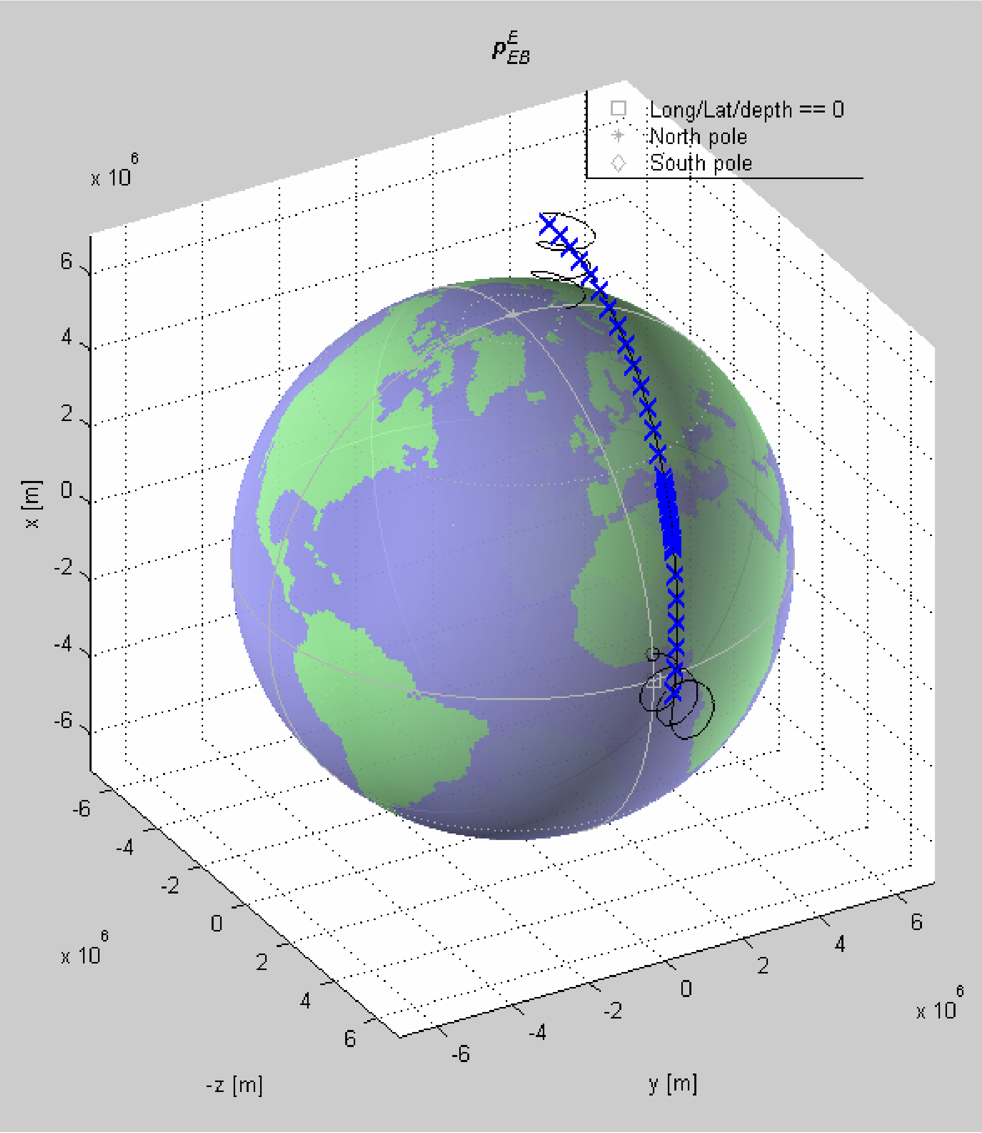


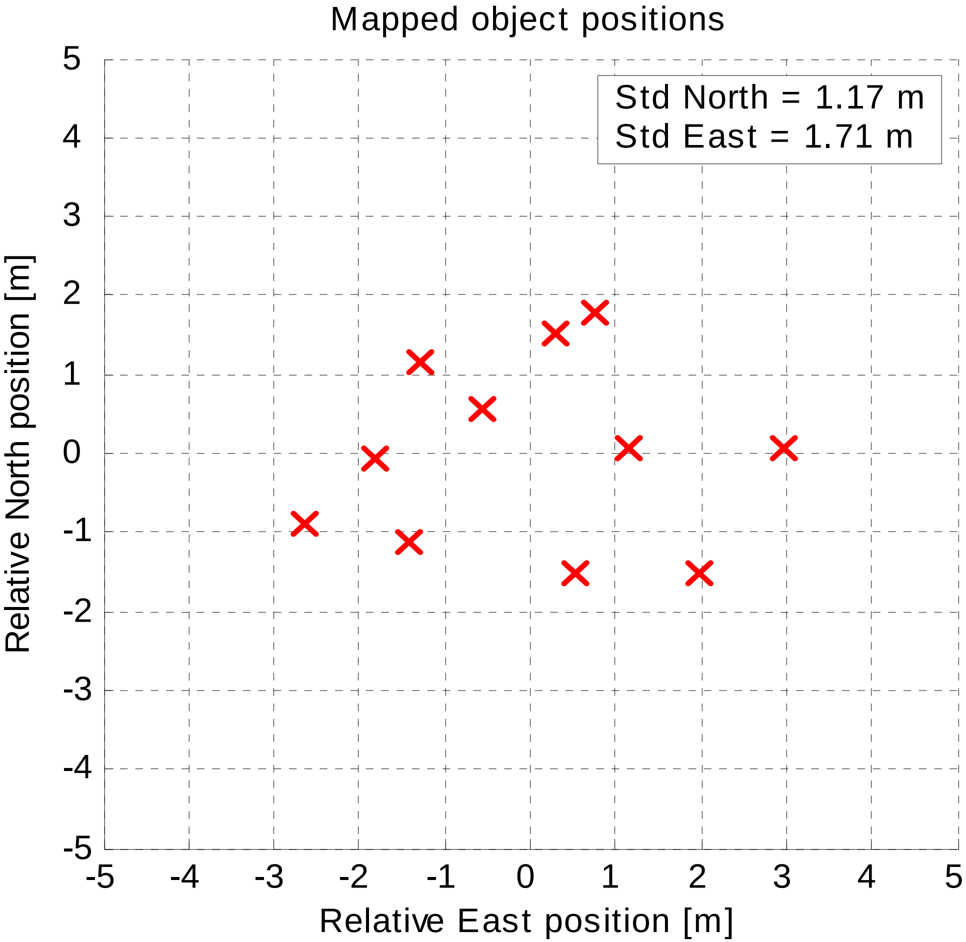
Figure: NavLab

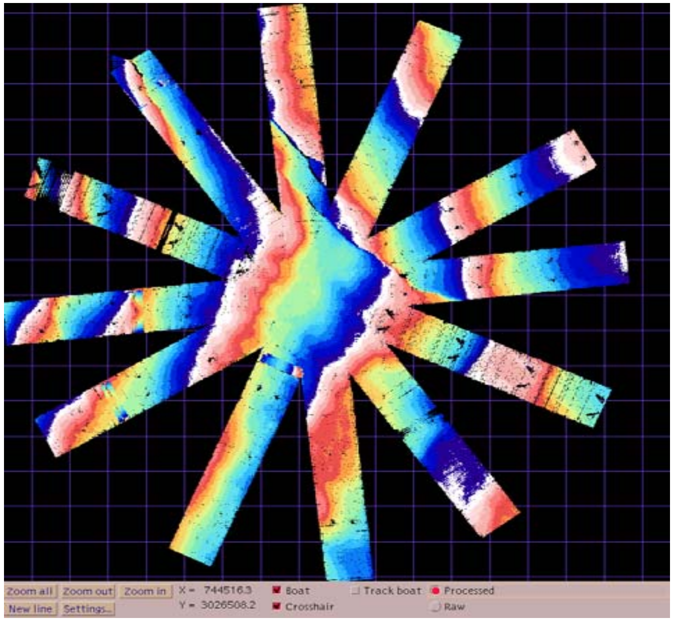
Verification of Estimator Performance

Verified using various simulations

Verified by mapping the same object repeatedly

HUGIN 3000 @ 1300 m depth:

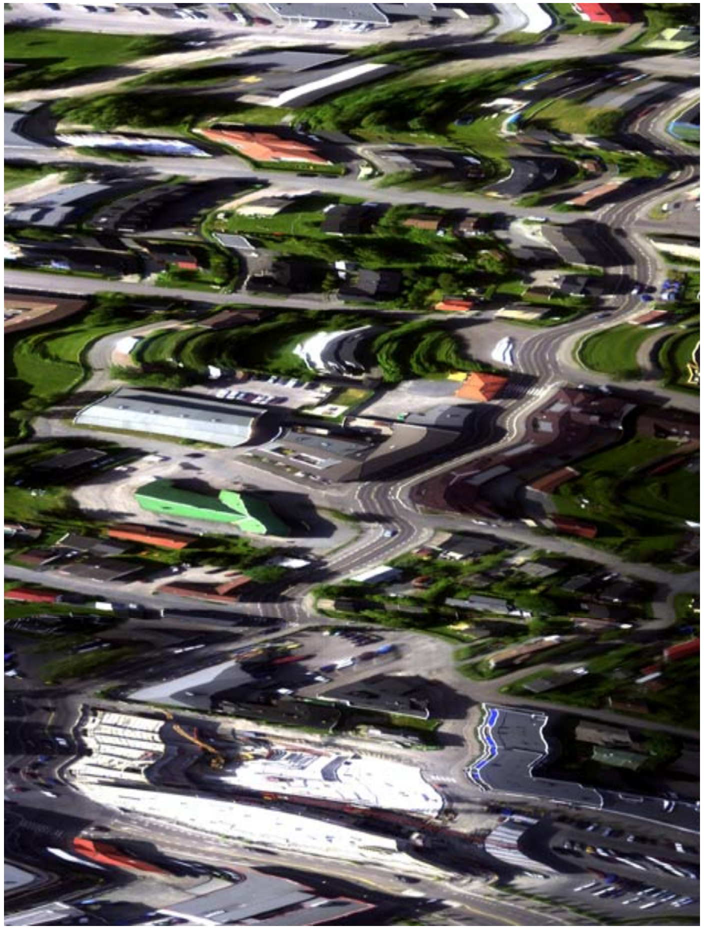




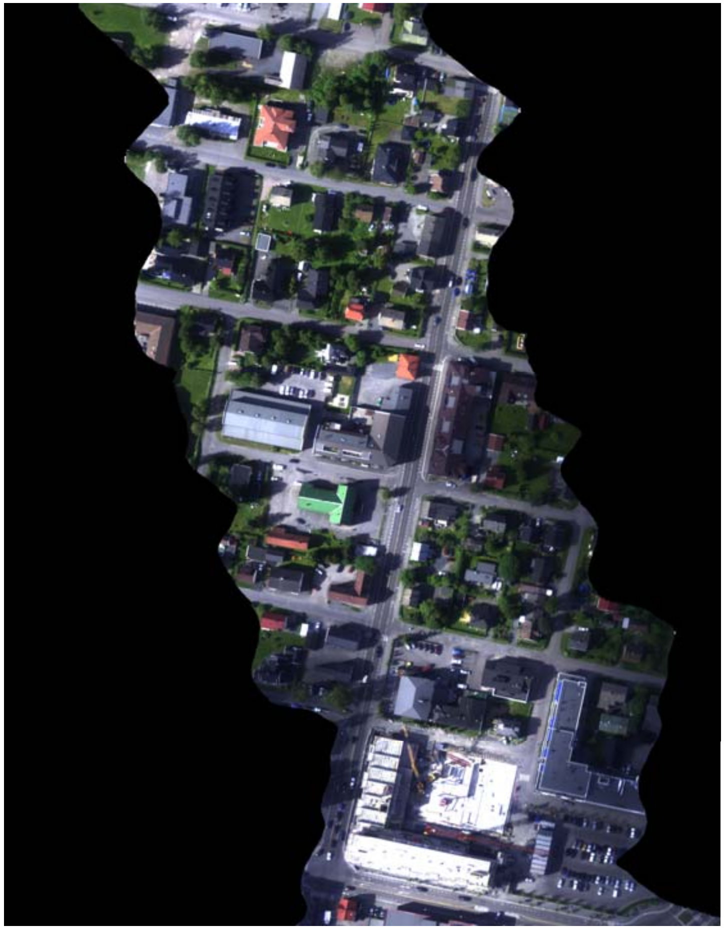
X = 744516.3
Y = 3026508.2
☑ Boat
☑ Crosshair
☐ Track boat
● Processed
○ Raw

Navigating aircraft with NavLab

- Cessna 172, 650 m height, much turbulence
- Simple GPS and IMU (no IMU spec. available)



Line imager data



Positioned with NavLab (abs. accuracy: ca 1 m verified)

NavLab Usage

Main usage:

- Navigation system research and development
- Analysis of navigation system
- Decision basis for sensor purchase and mission planning
- Post-processing of real navigation data
- Sensor evaluation
- Tuning of navigation system and sensor calibration

Users:

- Research groups (e.g. FFI (several groups), NATO Undersea Research Centre, QinetiQ, Kongsberg Maritime, Norsk Elektro Optikk)
- Universities (e.g. NTNU, UniK)
- Commercial companies (e.g. C&C Technologies, Geoconsult, FUGRO, Thales Geosolutions, Artec Subsea, Century Subsea)
- Norwegian Navy

Vehicles navigated with NavLab: AUVs, ROVs, ships and aircraft

☞ For more details, see www.navlab.net

Conclusions

- An **aided inertial navigation system** gives:
  - optimal solution based on all available sensors
  - all the relevant data with high rate

  Compare this with dedicated gyrocompasses, motion sensors etc that typically gives sub-optimal solutions, often with a subset of data
- If real-time data not required, **smoothing** should always be used to get maximum accuracy, robustness and integrity