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Tuesday, June 18, 2013

1 pm – 2:30 pm PST
2 pm – 3:30 pm MST
3 pm – 4:30 pm CST
4 pm – 5:30 pm EST
8 pm – 9:30 pm UTC

GNSS/INERTIAL INTEGRATION:
APPLYING THE TECHNOLOGIES

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WELCOME TO:

GNSS /Inertial Integration: Applying the Technologies

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Andrey Soloviev
Principle
Qunav

Xavier Orr
Lead Software Engineer
Advanced Navigation Pty Ltd

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Moderator: Mark Petovello,
Geomatics Engineering, University of Calgary, Contributing Editor at *Inside GNSS*

Co-Moderator: Mike Agron, Executive Webinar Producer

Who's In the Audience?

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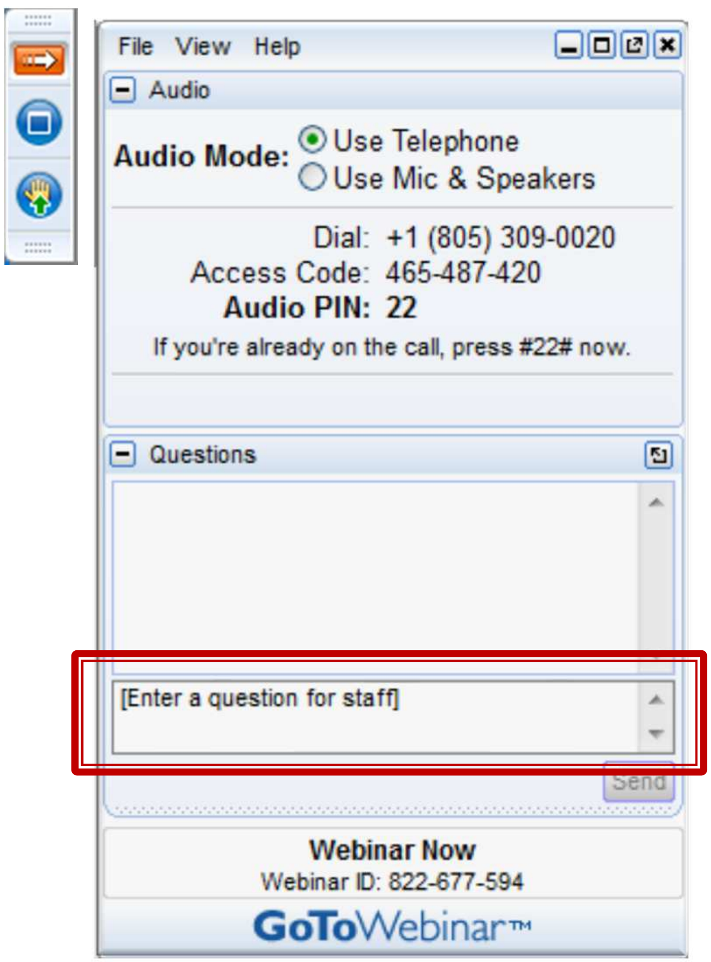
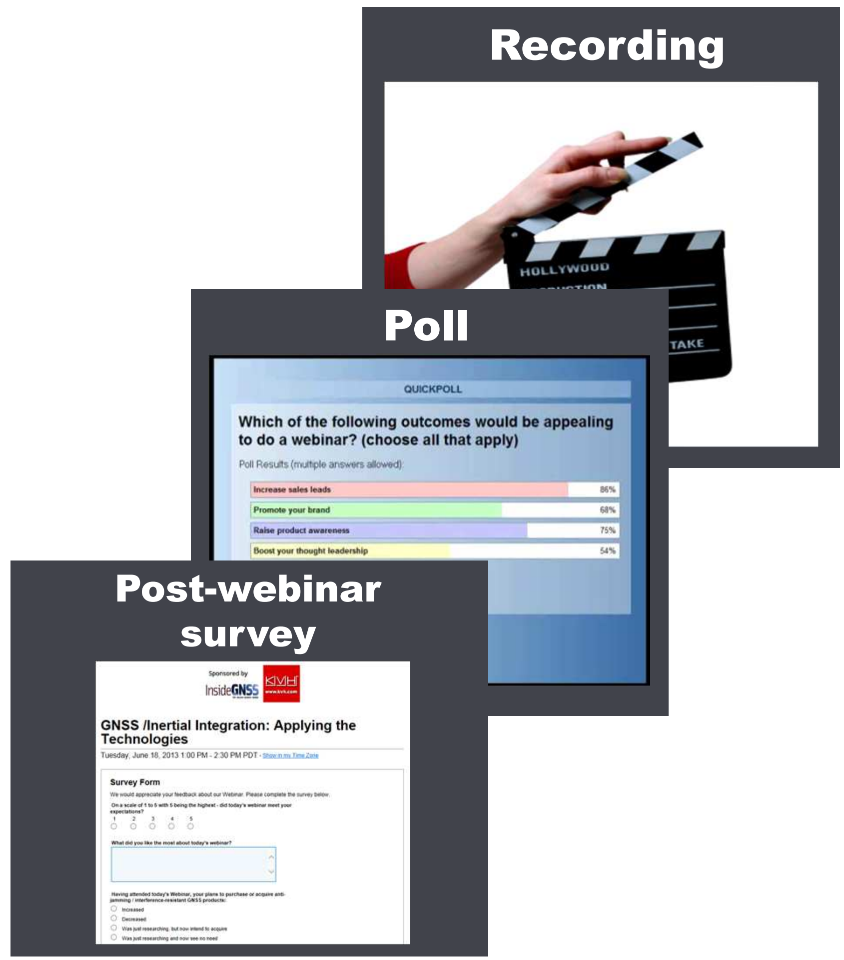
A diverse audience of over 700 professionals registered from 59 countries, 31 states and provinces representing the following roles:

- **15%** Professional User
- **19%** GNSS Equipment Manufacturer
- **19%** Product / Application Designer
- **22%** System Integrator
- **25%** Other

Housekeeping Tips

How to ask a question





Welcome from *Inside GNSS*

Richard Fischer

Director of Business Development

Inside GNSS

A word from the sponsor

Jay Napoli

Vice-President, FOG & OEM Sales

KVH Industries, Inc.

GNSS/Inertial Integration

Mark Petovello

Geomatics Engineering
University of Calgary
Contributing Editor

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The GNSS/INS Webinar Series to Date

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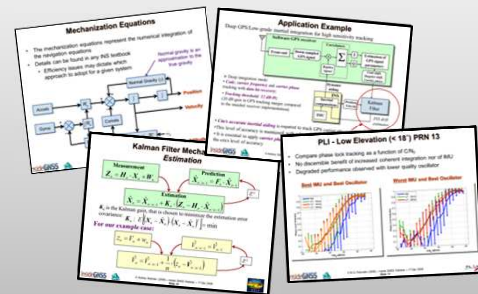
Dec '09: "Nuts & Bolts"

- Key inertial equations
- Integration concepts & equations
- Demonstrate possible results



Feb '12: "Filling in the Gaps"

- Select an integration strategy
- Practical considerations
- Sensor characterization

Today: "Applying the Technologies"

- Trends
- Key challenges
- Applications
- Beyond GNSS/INS
- And more…

Past webinars available at: http://insidegnss.com/webinars

Poll #1

- What would you say is the greatest challenge with integrating GNSS/INS? (select one)

1. Modeling the inertial errors
2. Identifying good/bad GNSS data
3. How to integrate other sensor data
4. Selecting architectures for GNSS/INS integration

Featured Presenter

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Andrey Soloviev
Principle
Qunav

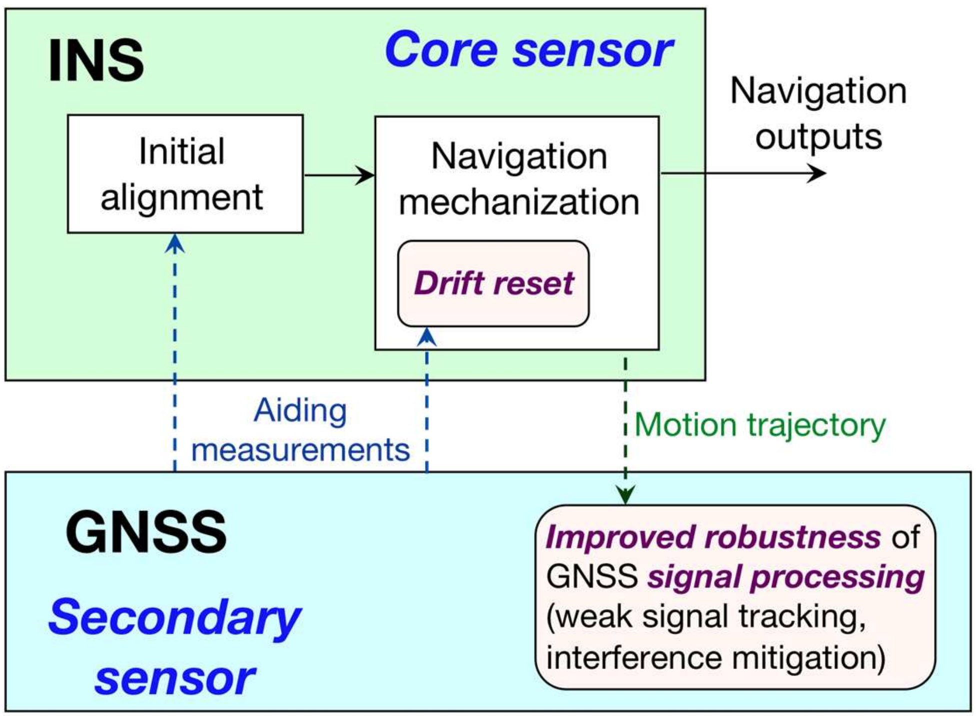
Overview of GNSS Inertial Integration

Andrey Soloviev
Principle
Qunav

Technology Overview

Combination of ***complementary features*** of ***GNSS*** and ***Inertial***

Integration of ***self-contained*** but ***drifting*** inertial
with GNSS that is ***drift-less*** but ***susceptible to interference***



Current Status

Wide range of GNSS/Inertial products

Examples:

- Embedded GPS/INS (EGI) for military applications

  Limitations: Use of relatively high grade, expensive inertial units

- GNSS/Inertial products for ground and aerial applications

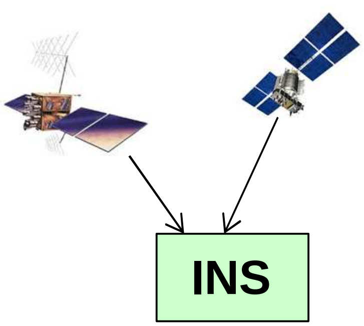
  Limitations: Some designs have limited capabilities in GPS denied environments

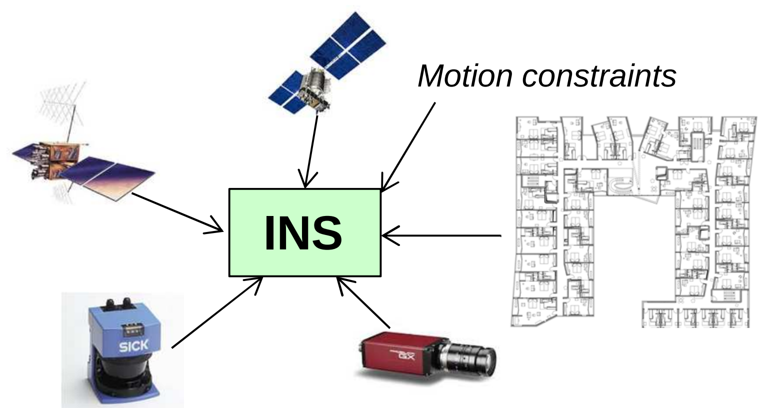
Development Trends

From high-grade inertial products to low-cost sensors (e.g., consumer-grade)

From open-sky environments to urban canyons, indoors and underwater

From GNSS/INS to INS/GNSS+





What is the Right Integration Approach

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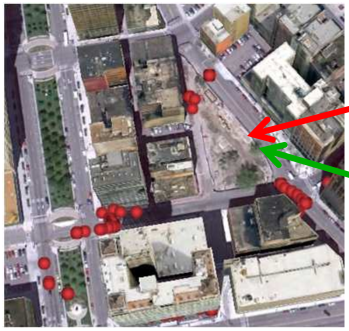
- **Loose Integration**: Fusion of ***navigation solutions***
- **Tight Integration**: Fusion of ***navigation measurements***
- **Deep Integration**: Integration at the ***signal processing level***

Loose integration has limited capabilities in GNSS-challenged environments

Example: sparse GNSS position fixes in urban canyon



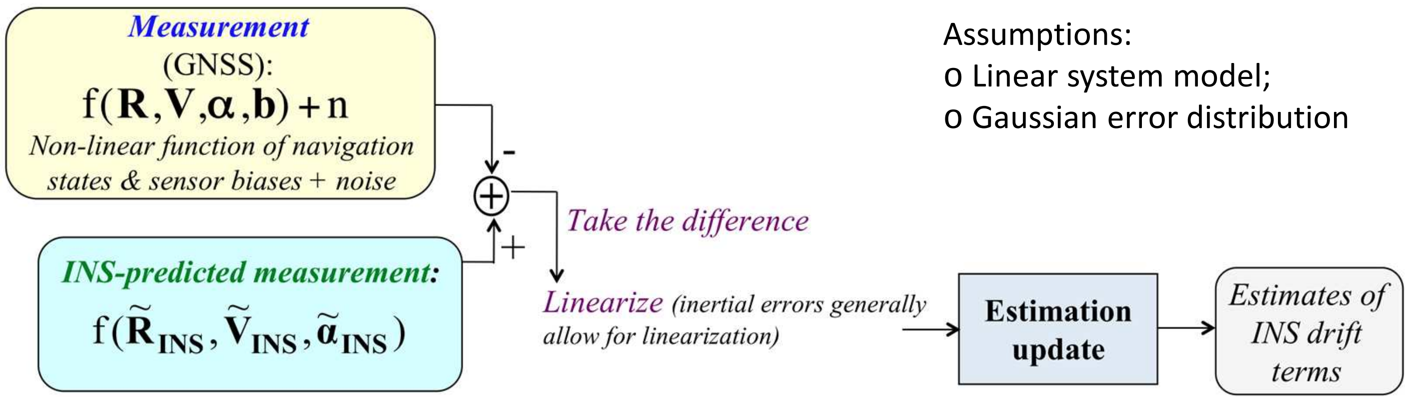
No GNSS data for loose integration

Some data may be still available (e.g. 2-3 satellites) for tight and deep modes

Tight and deep integration are more suitable for GNSS-challenged environments and integration of inertial with other sensors

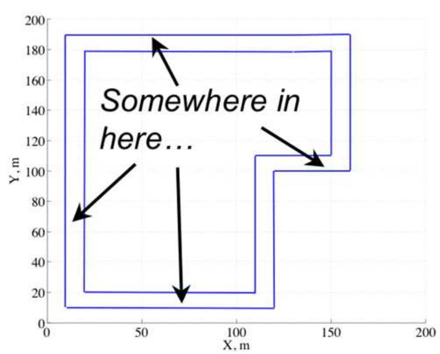
Data Fusion Tools

GNSS/Inertial: Complementary Extended Kalman Filter



Assumptions:
- Linear system model;
- Gaussian error distribution

INS/GNSS+: Kalman filter is not necessarily the best option and the use of nonlinear filtering techniques may be required



Example: A constraint that the platform stays within the hallway can be directly incorporated using ***particle filters***

Featured Presenter

Xavier Orr
Lead Software Engineer
Advanced Navigation Pty Ltd

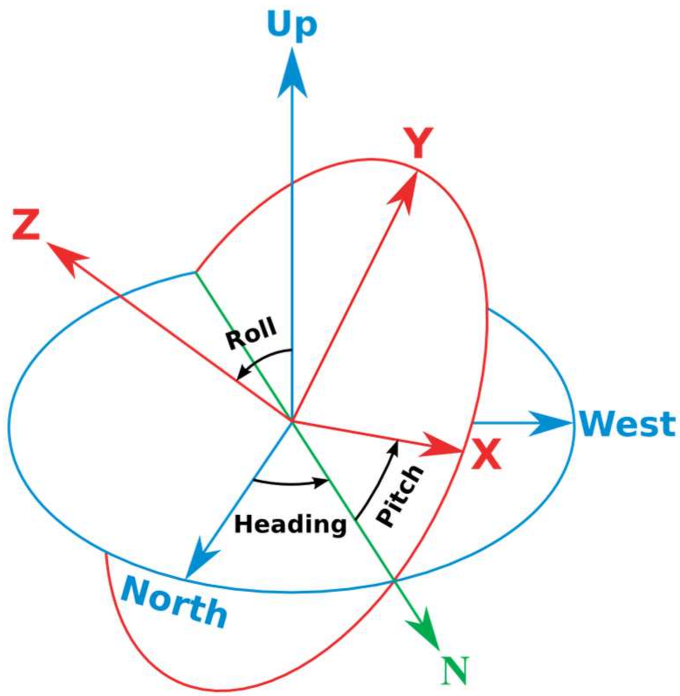
Integration Challenges

Xavier Orr
Lead Software Engineer
Advanced Navigation Pty Ltd

Introduction

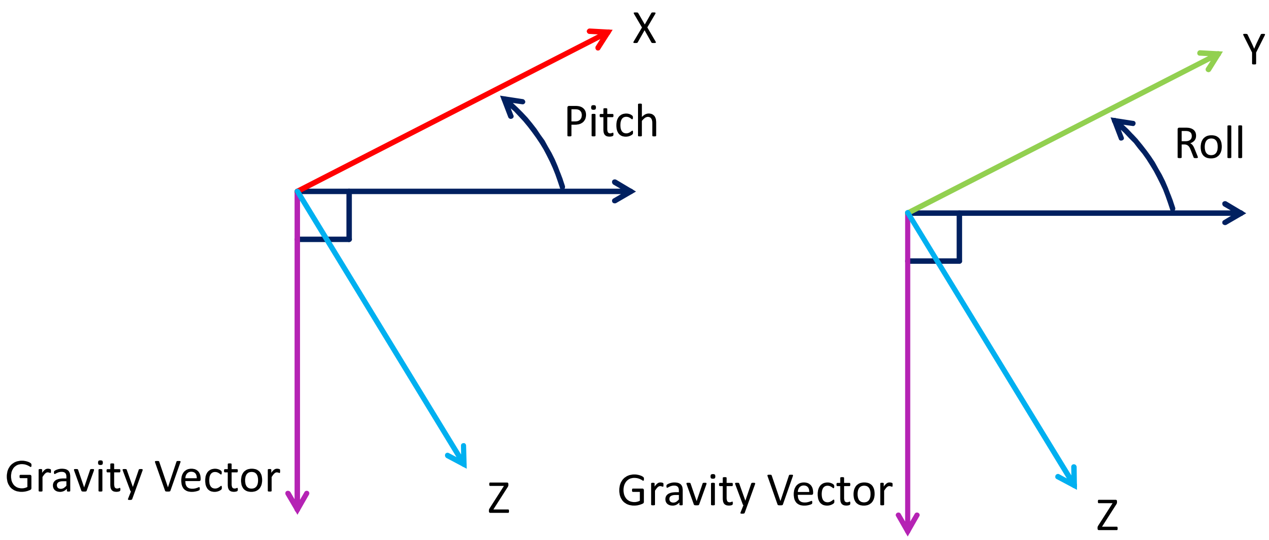
- Aim to produce inertial navigation system with superior dead reckoning
- Advanced north seeking capability
- Price target of under USD 30,000

Orientation Accuracy



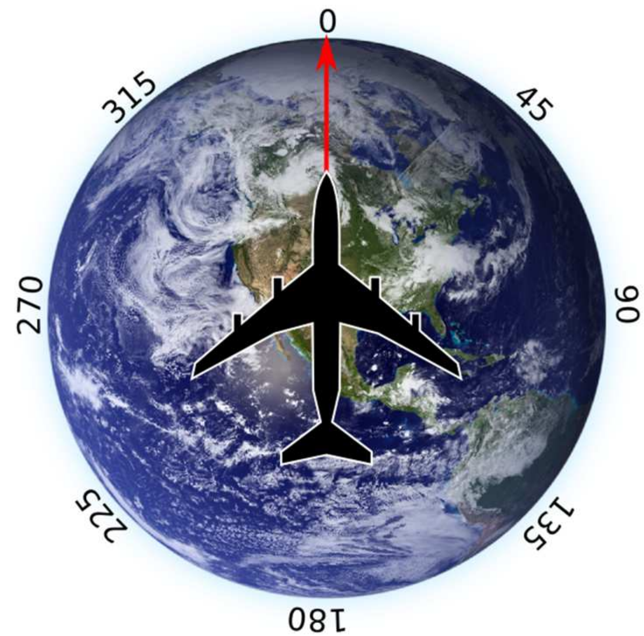
- For long term dead reckoning, highly accurate orientation is essential
- Orientation is tracked from gyroscopes and corrected for errors from gravity vector and other sources

Orientation Accuracy



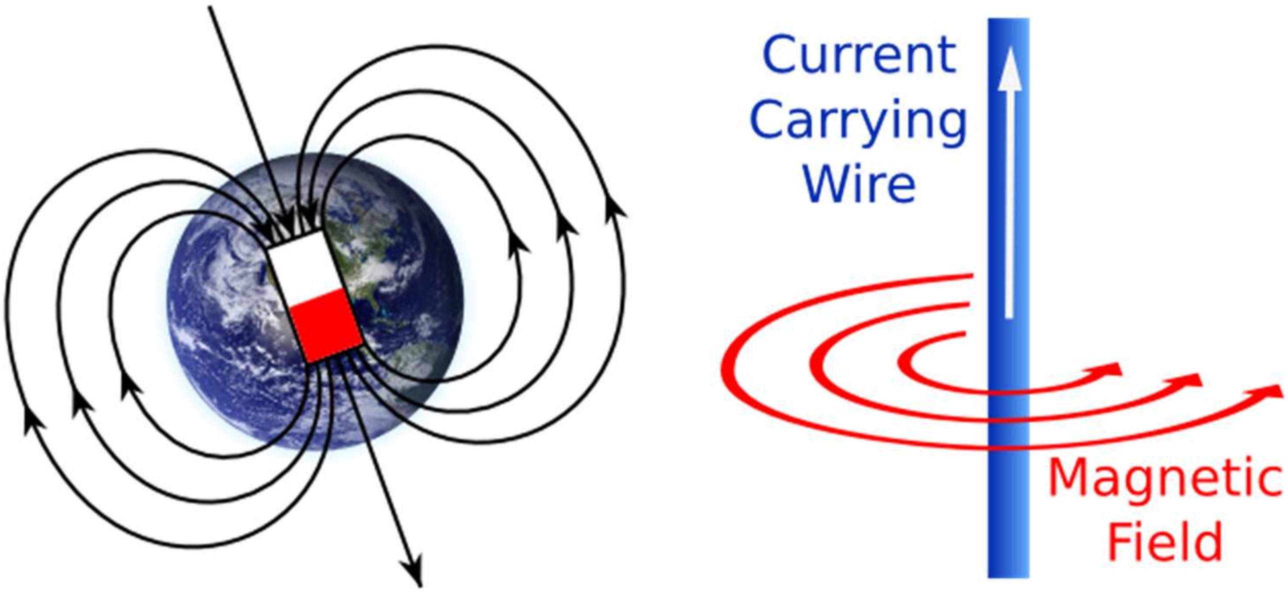
- High accuracy gyroscopes with very high bias stability are essential to maintain orientation accuracy
- Accelerometers with high bias stability are essential to provide a reference for the level orientation (gravity vector)
- Heading is more complicated

Heading



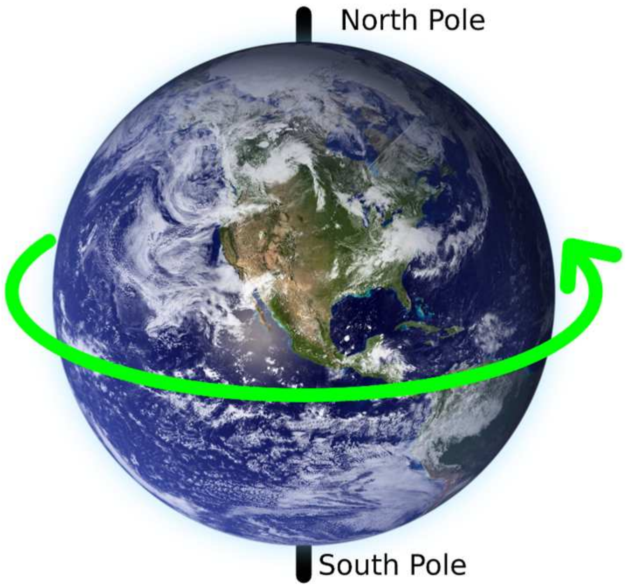
- Possible sources of heading are GNSS velocity, magnetometers, north seeking gyro-compassing and external references
- Magnetometers and north seeking gyro-compassing are the only always available sources

Magnetic Heading



- Magnetic heading is prone to interference, particularly in today's high tech environments
- Magnetic heading is not good for a high accuracy absolute reference, but good for a relative reference

North Seeking Heading



- Gyroscopes can detect the earth rotation rate
- Have to separate earth rotation from gyroscope bias, noise and other error sources
- Accurate north seeking gyro-compassing requires high bias stability gyroscopes

Commercially Available IMUs

- After market research KVH Industries 1750 IMU found to provide best commercial gyroscopes available
- Excellent gyroscope bias stability of 0.05 degrees/hour well suited to provide high accuracy orientation and north seeking
- Very low bias accelerometers in 1750 allows for fast initialization

Initial Alignment and Motion Constraints

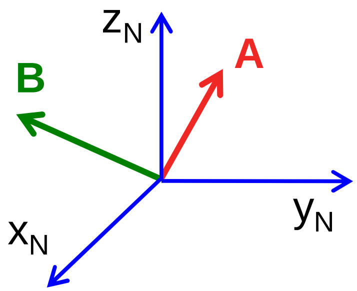
Andrey Soloviev
Principle
Qunav

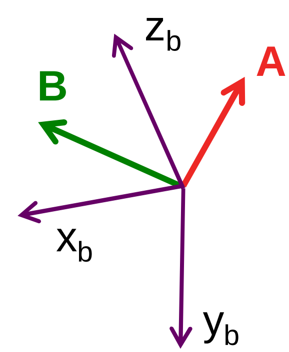
Initial Alignment: Attitude Initialization

- Motivation: INS is a dead-reckoning solution that needs to be initialized
- Position and velocity initialization is straightforward when GNSS is available

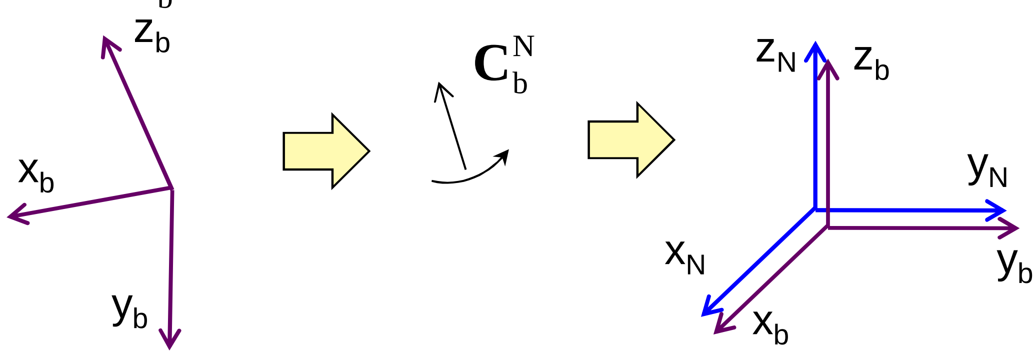
- ***How to initialize the attitude*?**

  We need two know <u>*projections of two non-collinear vectors*</u> (**A** and **B**) in ***navigation-frame*** and INS ***body-frame***





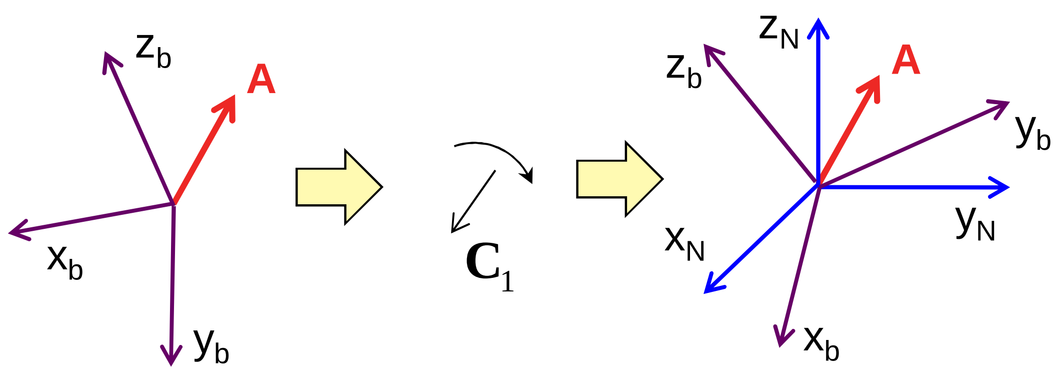
Then find a rotation $\mathbf{C}_b^N$ that aligns body-frame and navigation-frame vectors' projection



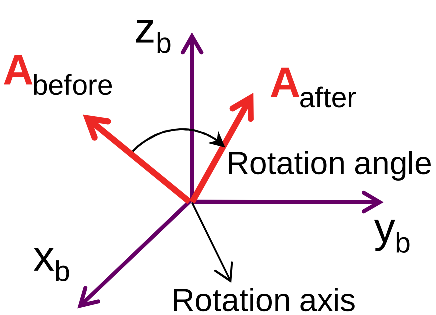
Alignment Sequence

- Step 1: Align vector A

  Computationally rotate body-frame such that projections of vector **A** are aligned with its navigation-frame projections



Body-frame view

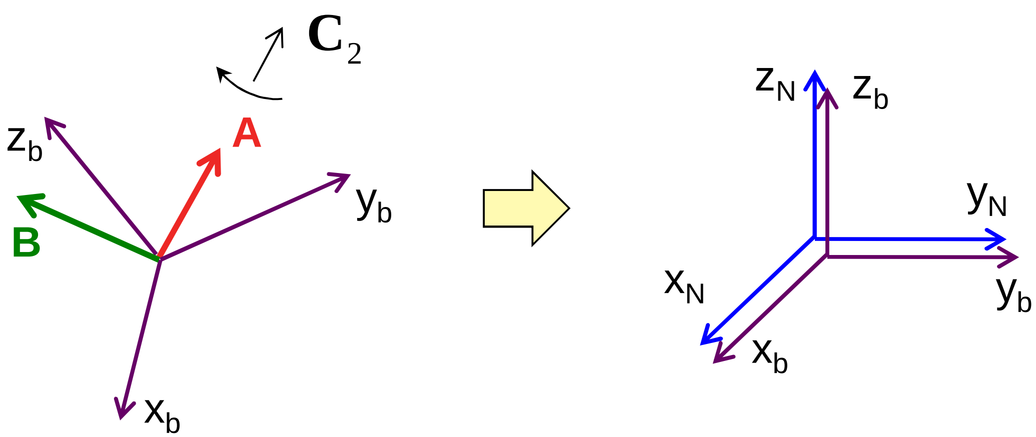


After that, body-frame is still not completely aligned with the navigation frame as there is a rotational degree of freedom around vector **A**

Alignment Sequence

- Step 2: Align vector B

Computationally rotate body-frame (from its new orientation) around vector A such that projections of vector **B** are aligned with its navigation-frame projections



Initial orientation

$$\mathbf{C}_b^N = \mathbf{C}_2 \cdot \mathbf{C}_1$$

Initial Alignment: Which Two Vectors To Use?

- Classical approach

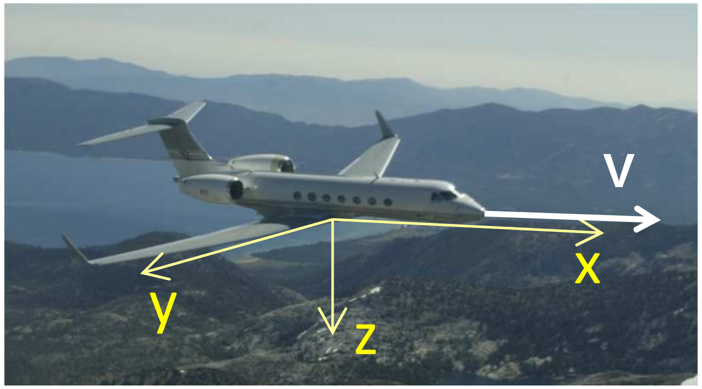
  Vector 1: Acceleration due to gravity:
  - Known in navigation-frame (gravitational model);
  - Measured in body-frame (accelerometers)

  Vector 2: Earth rate:
  - Known in navigation-frame (based on initial position);
  - Measured in body-frame (gyros)

  Requires high-grade gyros since the Earth rate is 15 deg/hr

- Alternative approach for lower-grade inertial sensors

  Vector 2: Velocity vector:
  - Navigation-frame: measured by GNSS;
  - Body-frame: assumed to be aligned with the front axis of the vehicle



Another option: use of magnetometers

Use of Motion Constraints: General Approach

Use as additional measurement(s) for the complementary Kalman filter

Motion constraint (which is generally a non-linear function of navigation and motion states)

$$f(\mathbf{R},\mathbf{V},\alpha,\mathbf{a},\mathbf{w})=0$$

INS-predicted value:

$$f(\hat{\mathbf{R}}_{\mathbf{INS}},\hat{\mathbf{V}}_{\mathbf{INS}},\hat{\alpha}_{\mathbf{INS}},\hat{\mathbf{a}}_{\mathbf{INS}},\hat{\mathbf{w}}_{\mathbf{INS}})$$

Linearize (inertial errors generally allow for linearization)

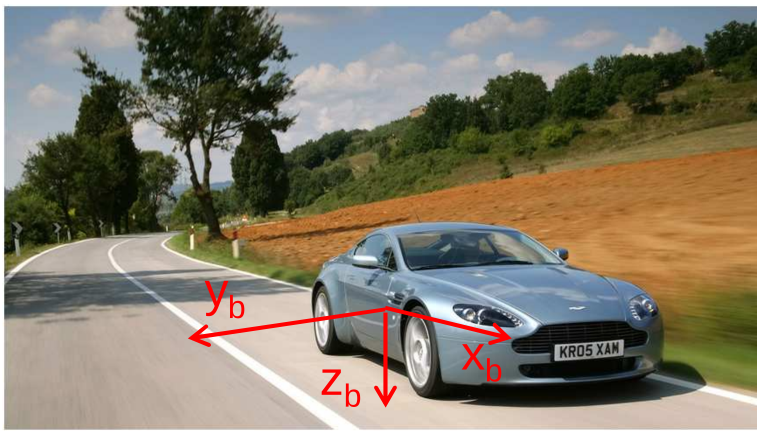
Kalman filter estimation update

Estimates of INS drift terms

Use of Motion Constraints: Example

Automotive application

Zero cross-track velocity



$$V_{y_b} = 0$$

Motion constraint

$$\begin{bmatrix}0 & 1 & 0\end{bmatrix} \cdot \hat{\mathbf{C}}_N^b \cdot \hat{\mathbf{V}}_{INS}$$

Projection on y_b-axis

Coordinate transformation from navigation into body frame

Linearization

Velocity error · *Cross product* · *Attitude error*

$$\begin{bmatrix}0 & 1 & 0\end{bmatrix} \cdot \hat{\mathbf{C}}_N^b \cdot \delta\mathbf{V}_{INS} + \begin{bmatrix}0 & 1 & 0\end{bmatrix} \cdot \hat{\mathbf{C}}_N^b \cdot \mathbf{V}_{INS} \times \delta\boldsymbol{\theta}_{INS}$$

Kalman filter measurement observable

Ask the Experts – Part 1

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Lead Software Engineer
Advanced Navigation Pty Ltd

Jay Napoli
Vice-President, FOG & OEM Sales
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Poll #2

Which types of IMU technologies have you had the MOST experience with? (Choose One)

1. MEMS
2. RLG (Ring-laser Gyros)
3. FOG (Fiber Optic Gyros)
4. Electro-mechanical
5. Not sure or none

GNSS/INS Implementation

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Advanced Navigation Pty Ltd

Spatial FOG

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Finished Integrated Product

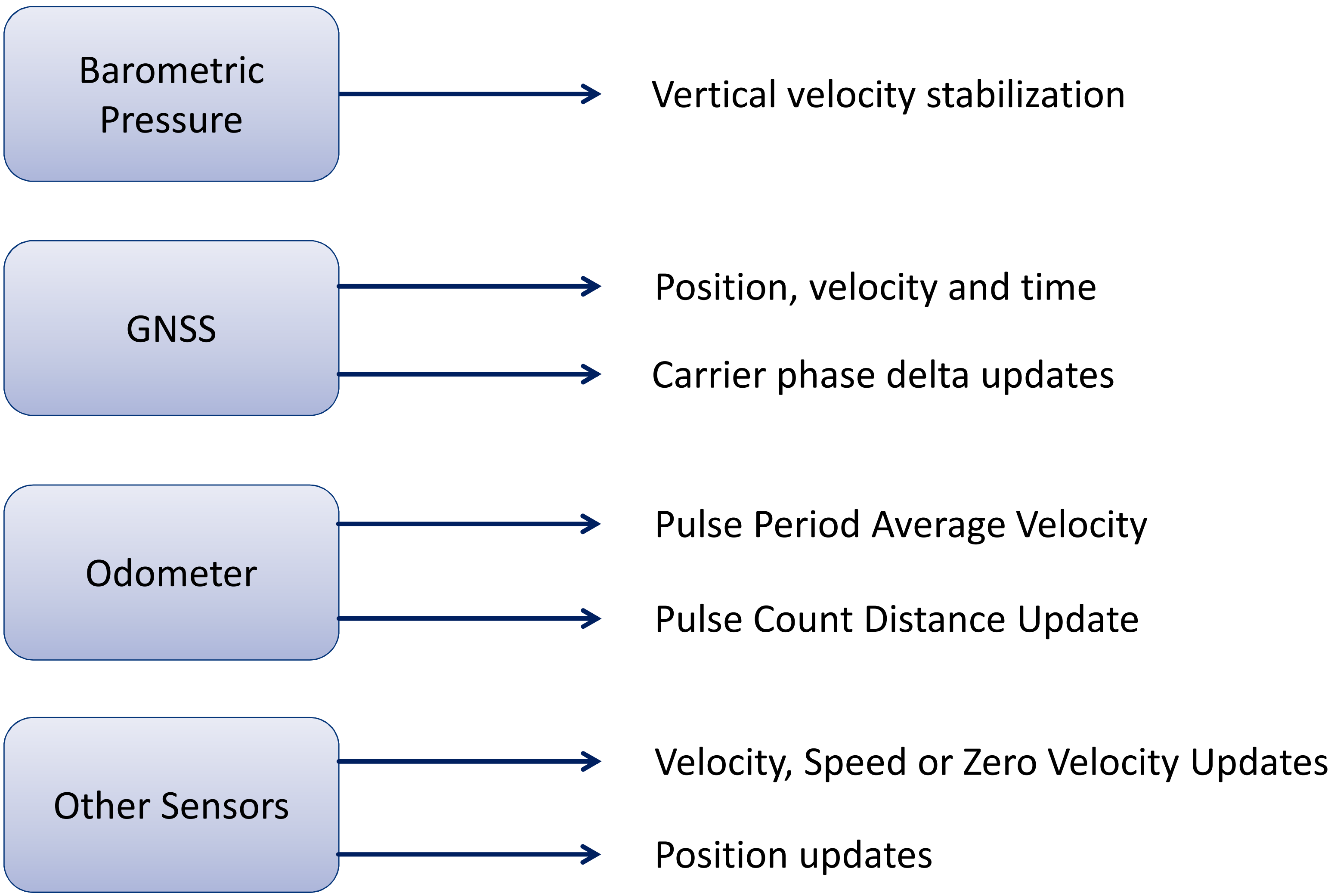
Sensors

Accelerometers
- Body Acceleration
- Gravity Vector Reference
- Motion Analysis

Gyroscopes
- Angular Velocity
- North Seeking Gyrocompass
- Motion Analysis

Magnetometers
- Speed up initial heading alignment
- Zero yaw rate updates help track gyroscope bias

Sensors

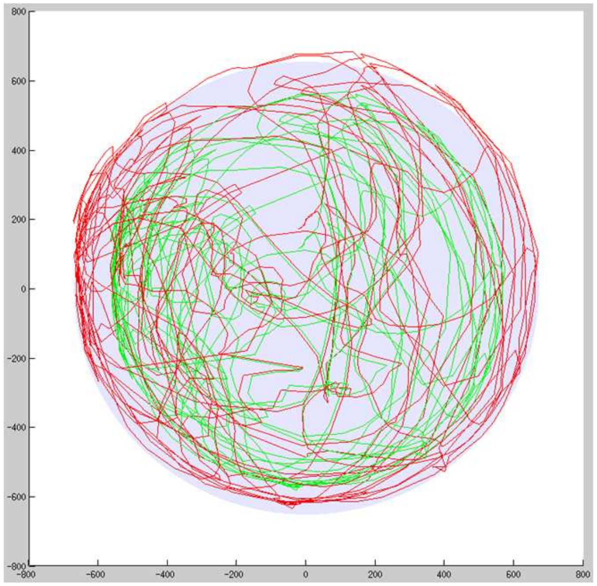


Barometric Pressure
Vertical velocity stabilization
GNSS
Position, velocity and time
Carrier phase delta updates
Odometer
Pulse Period Average Velocity
Pulse Count Distance Update
Other Sensors
Velocity, Speed or Zero Velocity Updates
Position updates

Filter

- Multiple simultaneous correction sources used
- Filter tracks history of correction standard deviation and predicts future correction standard deviation
- Attitude corrections based on gravity vector can introduce error
- To reduce this, the filter predicts and compensates for linear accelerations
- Balancing inertial bias tracking and north seeking is the biggest challenge

Magnetometers

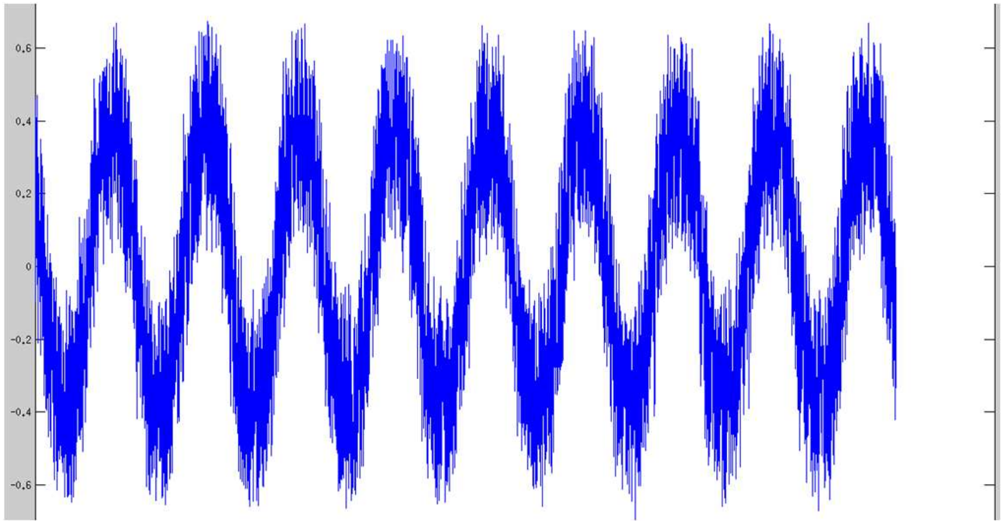


- Automatic magnetic calibration
- Magnetometers speed up north seeking initialization
- During operation magnetometers used primarily for zero yaw rate updates to assist in tracking Z axis gyroscope bias
- This makes the system immune to magnetic interference

GNSS

- GNSS provides position, velocity and time during normal operation
- When a fix is not possible carrier phase delta is used for velocity updates
- Tightly coupled but completely GNSS independent architecture
- RTK available for applications requiring high accuracy positioning
- RAIM FDE for safe operation

Motion Analysis



- Analyses patterns in inertial data
- Zero velocity updates
- Zero yaw rate updates
- Speed prediction for forward driving vehicles under GNSS outages

Hot Start

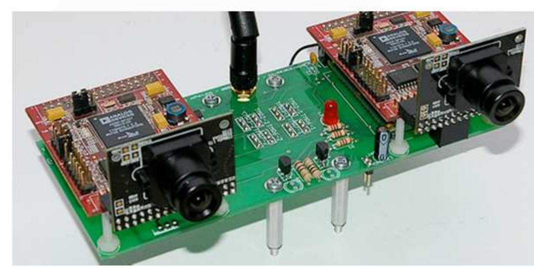
- Previous position, velocity, heading and bias model retained for very fast INS start
- Time tracked with RTC
- Almanac, ephemeris, position and time sent to GNSS receiver for hot start
- Hot start allows for high accuracy orientation quickly
- Ideal for vehicles that don't move when powered down
- Fast recovery from power outages

Timing & Update Rate

- Timing is critical for INS
- High update rate reduces integration and other errors but requires a lot of computing power and careful balancing of resources
- To achieve this we designed our own safety oriented real time operating system
- Direct Memory Access (DMA) is the key to balancing resources and achieving accurate timing
- Powerful processor with Floating Point Unit and lots of RAM required

External Data

- Delay estimation
- Standard deviation estimation
- External navigation aids
  - Local RF positioning systems
  - Rangefinders (Laser, ultrasonic, IR)
  - RFID position tags
  - WiFi
  - Vision and stereo vision
  - Stereo audio
  - SLAM



Land, Air & Marine Applications

- Navigation through GNSS outages and jamming
- Navigation in tunnels, indoor environments and around structures obstructing satellite view
- Beneficial for aircraft to maintain navigation through rolls that can cause degraded GNSS visibility
- Safety conscious autonomous vehicles

Subsea Applications

- Subsea versions specially designed and optimized for underwater navigation
- High level of motion constraints allows for superior navigation performance underwater

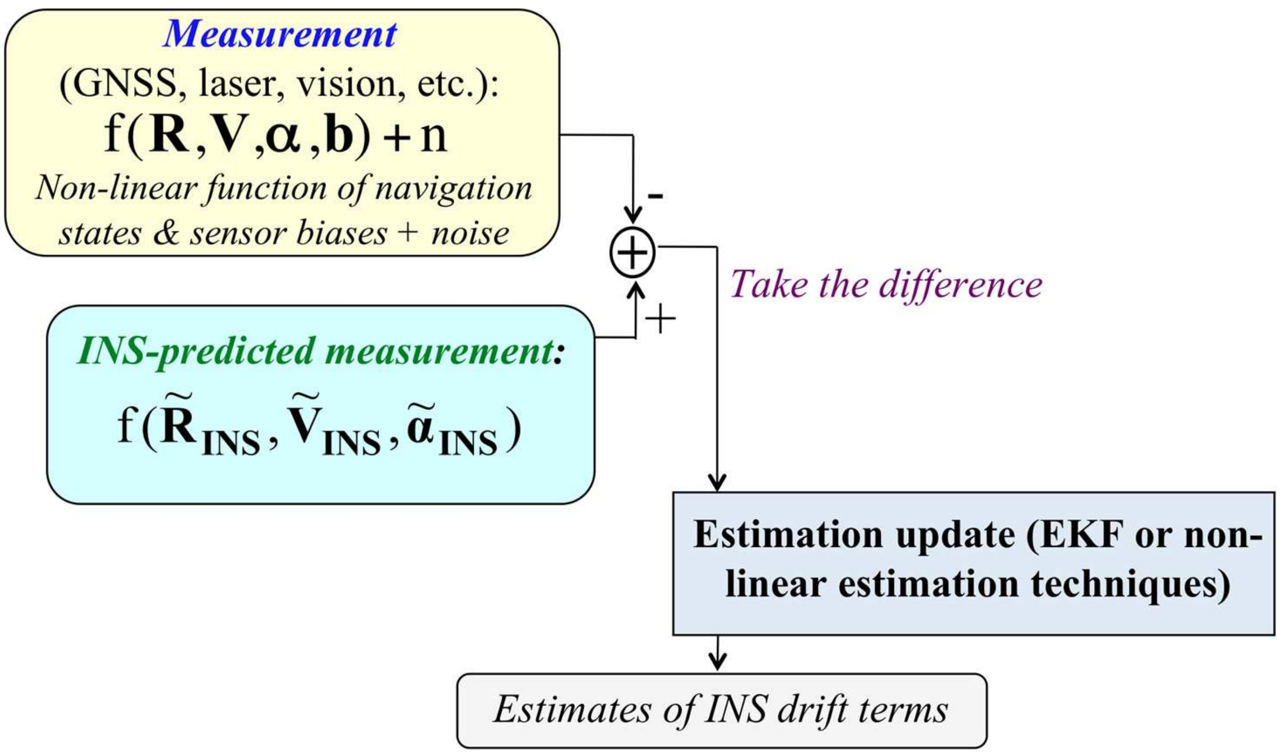
Beyond GNSS/INS Integration

Andrey Soloviev
Principle
Qunav

Generic Integration Approach

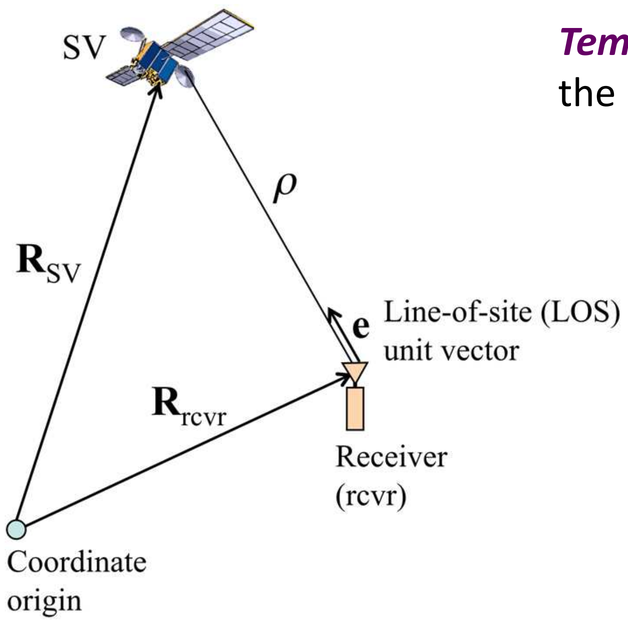
• INS is a core sensor;

• Other sensors provide reference data (when available) to reduce drift in inertial navigation outputs



Example Case Study 1

- How to extend GNSS/INS integration principles to include other sensors?
- Example: Integration of inertial and GNSS carrier phase



Temporal phase changes are applied as ***measurement observables*** of the Kalman filter to eliminate integer ambiguities

$$\Delta\varphi = \varphi(t_n) - \varphi(t_{n-1}) = \Delta\rho + \Delta\delta t_{rcvr} + \eta$$

$$\downarrow$$

$$-(\mathbf{e}, \Delta\mathbf{R})$$ ← Delta position or position change

$$\downarrow$$

Represented in a generic format:

$$\Delta\varphi = \mathbf{H}_{proj}\Delta\mathbf{R} + \mathbf{D}_{proj}\mathbf{b} + \eta$$

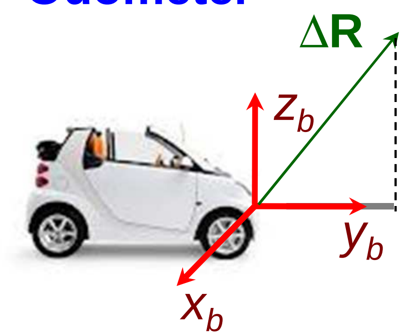
Projection matrices ($\mathbf{H}_{proj}$, $\mathbf{D}_{proj}$)

Bias states ($\mathbf{b}$)

Example Case Study 2

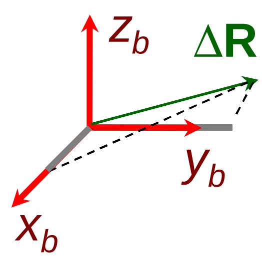
The same generic format can be applied ***for integration with other sensors*** whose measurements are related to position change (**ΔR**)

Odometer



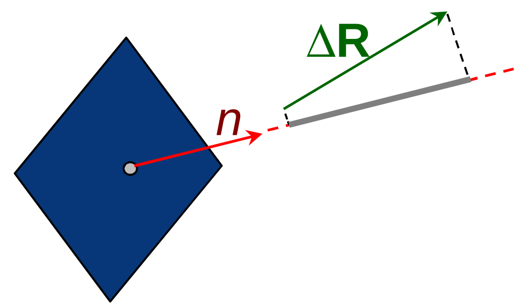
Position change projected onto forward axis

2D lidar



Position change projected onto x and y axes of the body-frame

3D lidar



Position change projected onto a normal vector of a planar surface extracted from lidar image

The integration software ***can fully utilize GNSS/INS development results***, the developer just needs to select different projection matrices.

Non-Linear Filtering Techniques

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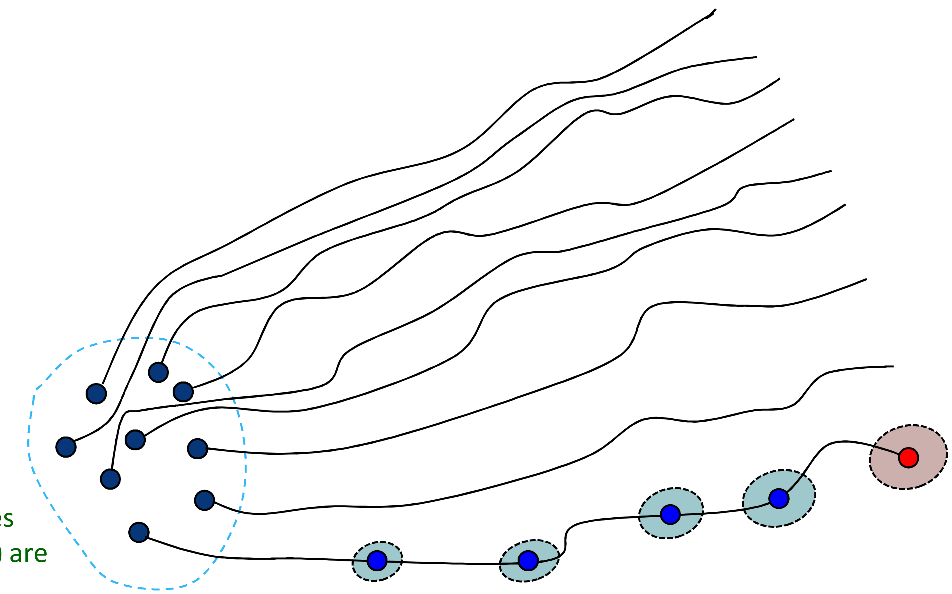
- ***Extension*** of the EKF to support ***non-linear aiding measurements:***

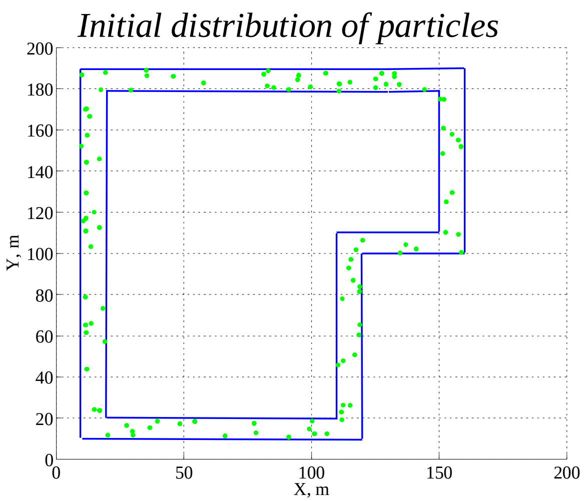
  Example: Map-matching (hallway layout, Wi-Fi fingerprinting)

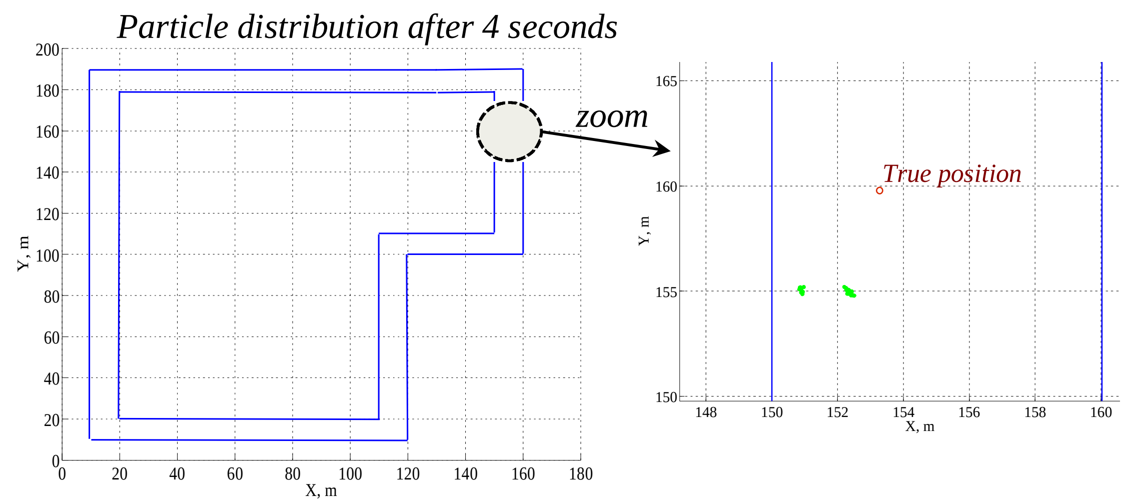
- For integration with INS, the extension is based on a ***marginalized particle filter*** (MPF):
  - The *estimation space* is partitioned into *linear* and *non-linear sub-spaces*;
  - Optimal *EKF* estimation is applied for the *linear sub-space*;
  - Monte-Carlo approximation (a.k.a *particle filter*) is used for the *non-linear sub-space*;



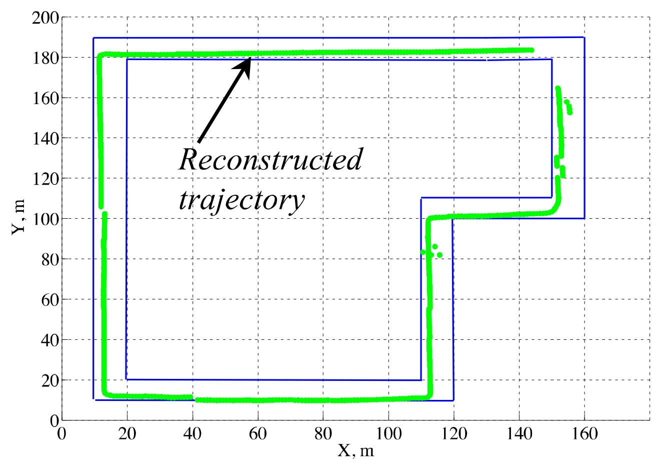
Example Simulation Results

- Integration of low-cost MEMS inertial, Vision, partial GPS (2 visible SVs) and a hallway layout





Performance of the marginalized particle filter



Poll #3

What challenges, if any, have you experienced with IMU technology? (Select all that apply)

1. Performance/accuracy limitations
2. Data communications
3. Size or weight
4. Interface connection issues
5. None

Next Steps

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Contact Info:

- **For more information visit:**
  www.kvh.com/1750imu

- **Email specific questions to:** Sean McCormack: smccormack@kvh.com

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Ask the Experts – Part 2

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