The Promise of MEMS to The Mobile Mapping Community

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Agenda

- Mobile Mapping Systems (MMS)
- Progress of Georeferencing
- The Direct Georeferencing Model
- The Potential of MEMS Sensors
- Sensors and Integration Problems
- Achievable Accuracies for Land MMS
- Potential for Airborne MMS
- Summary

Mobile Mapping Systems (MMS)

- The idea of MMS, i.e. mapping from moving vehicles, has been around for at least as long as photogrammetry has been practiced.
- About 15 years ago, advances in **satellite positioning and inertial technology** made it possible to think about mobile mapping in a different way. Instead of using ground control as reference for orienting the images in space, trajectory and attitude of the imaging platform could now be determined directly.
- Hand in hand with this development went the change from **analog to digital imaging/mapping techniques** – a change that has considerably accelerated over the past few years.

Progress of Georeferencing

Indirect Georeferencing

Ground Control Points (GCPs) were the only required source of information for providing the georeferencing parameters and suppressing undesirable errors through AT.

1960-1970

GPS-AT

- The start of direct determination of exterior orientation parameters in aerial photogrammetry
- The first investigations to use GPS for the determination of the projection centers in AT

1980 - 1990

Direct Georeferening

- The first implementation of the DG concept for Land Mobile Mapping at the UofC and OSU in early 1990s.
- The first sale of a DG product for commercial airborne mapping applications in1996 by ApplAnix Corp, Canada.

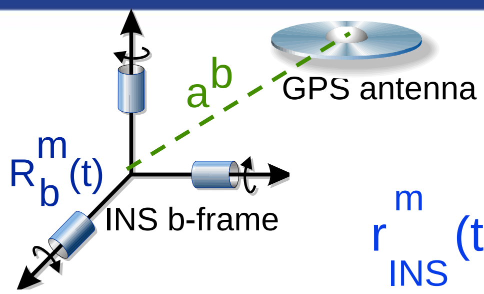
1990 - date

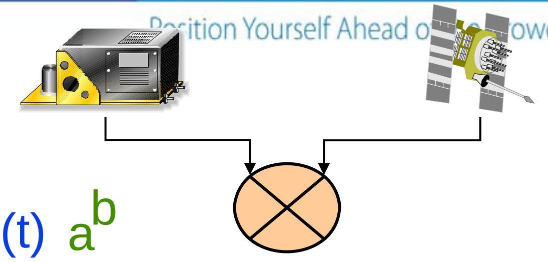
Elements of MMS

Mobile Mapping Systems

- **Navigation Sensors**
  - GNSS
  - Inertial Sensors
  - Nav Aids
- **Remote Sensing Sensors**
  - Digital Cameras
  - Laser Scanners
  - Other Sensors
- **Platforms**
  - Land
  - Airborne
  - Portable
- **Applications**
  - Mapping
  - DTM
  - GIS

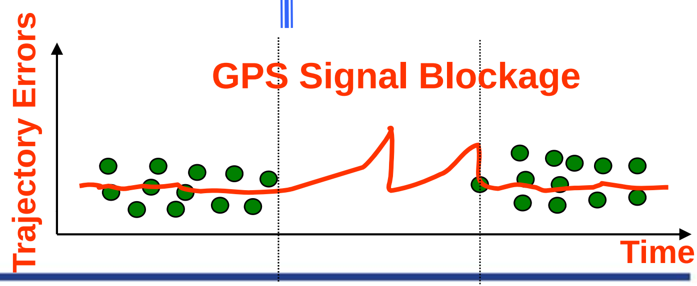
Why - GPS / INS Integration



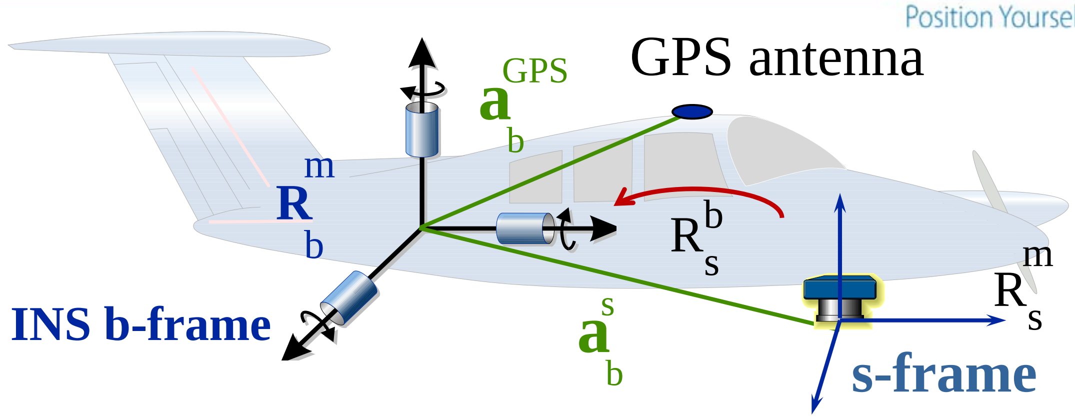


$$r_{INS}^m(t) = r_{GPS}^m(t) - R_b^m(t)\ a^b$$

GPS	INS
• High Position Accuracy	• High position and attitude accuracy in the short term
• Uniform Accuracy	• Accuracy function of time
• Interpolation needed (1-20 Hz)	• No interpolation needed (50 - 200 Hz)
• Cycle slip problems	• Continuos trajectory



Principle of Direct Georeferencing



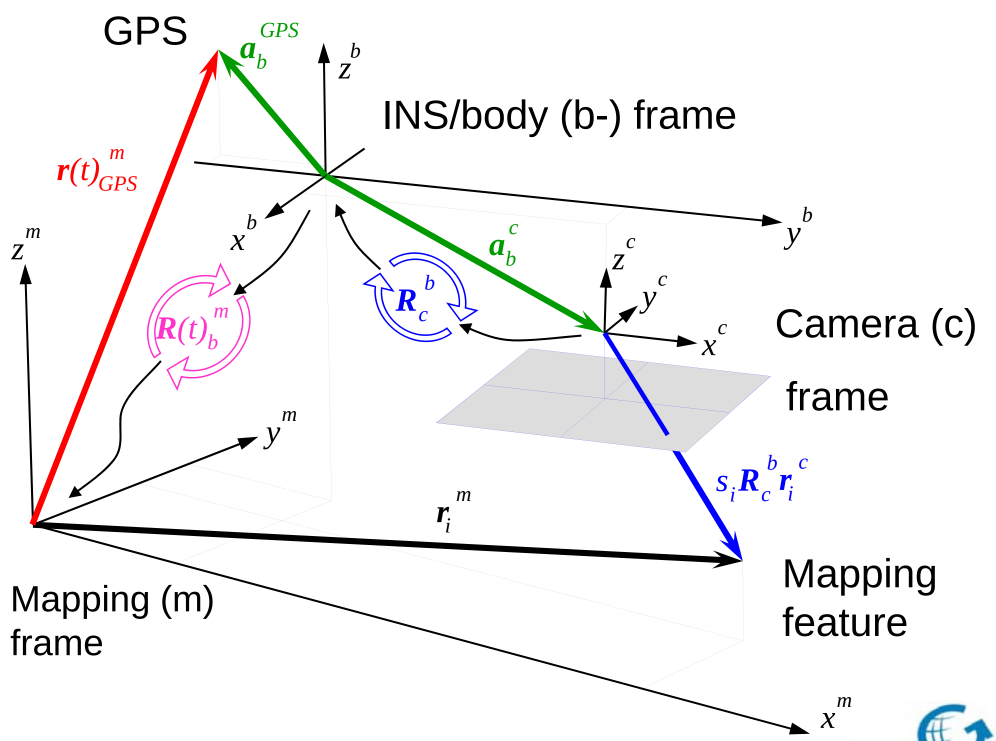
$$r_i^m = \boxed{r_s^m} + \mu_i \boxed{R_s^m} r_i^s$$

$$\boxed{r_s^m = r_b^m + R_s^m a_b^s}$$

$$\boxed{R_s^m = R_b^m R_s^b}$$

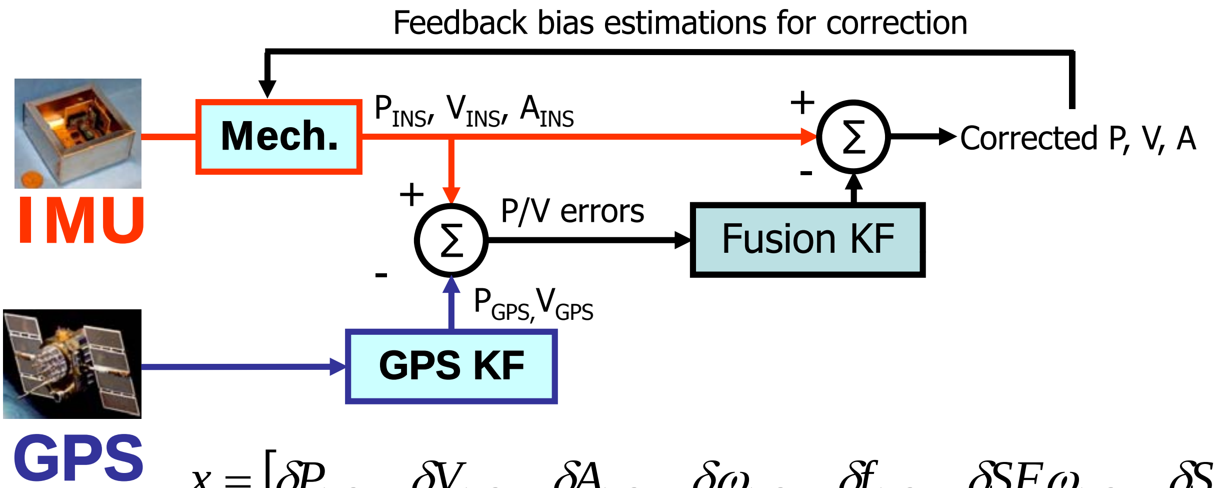
Georeferencing – Coordinate Frames

$$\boldsymbol{r}_i^m = \boldsymbol{r}(t)_{GPS}^m + \boldsymbol{R}(t)_b^m \left(s_i \boldsymbol{R}_c^b \boldsymbol{r}_i^c + \boldsymbol{a}_b^c - \boldsymbol{a}_b^{GPS} \right)$$



GPS/INS Integration

- Combining INS & GPS signals
  - Kalman filter typically used (optimal if certain assumptions are met)
  - Many integration strategies (loose, tight, deep)
- Filtering and prediction for the loose EKF (15 or 21 state):



$$x = [\delta P_{1x3} \quad \delta V_{1x3} \quad \delta A_{1x3} \quad \delta\omega_{1x3} \quad \delta f_{1x3} \quad \delta SF\omega_{1x3} \quad \delta SFf_{1x3}]^T$$

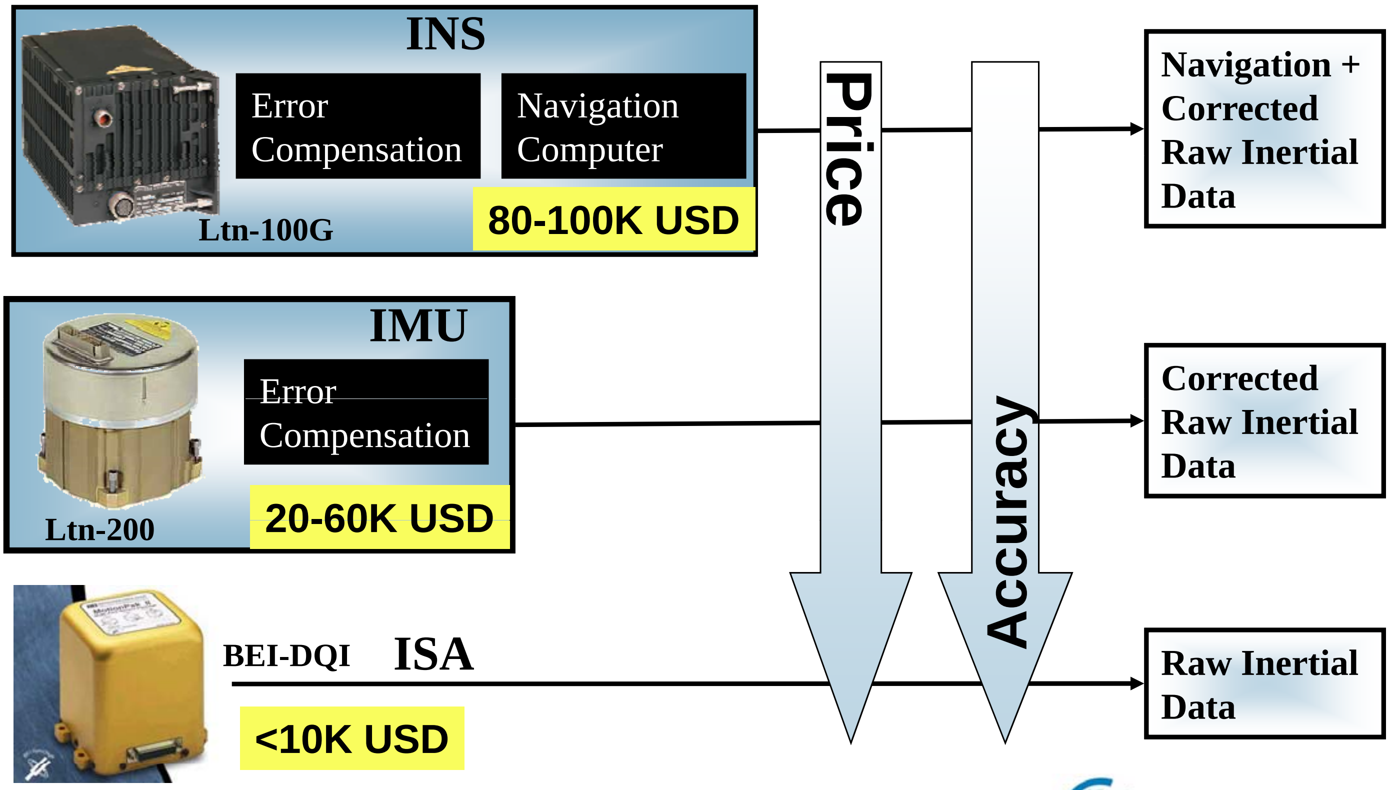
Land Based MMS

- Example – VISAT™
  - Navigation-grade INS - **$100,000 (30% of budget)**
  - Dual-frequency GPS - $20,000
  - Van - $30,000
  - Computer, 8 cameras, etc. - $$$

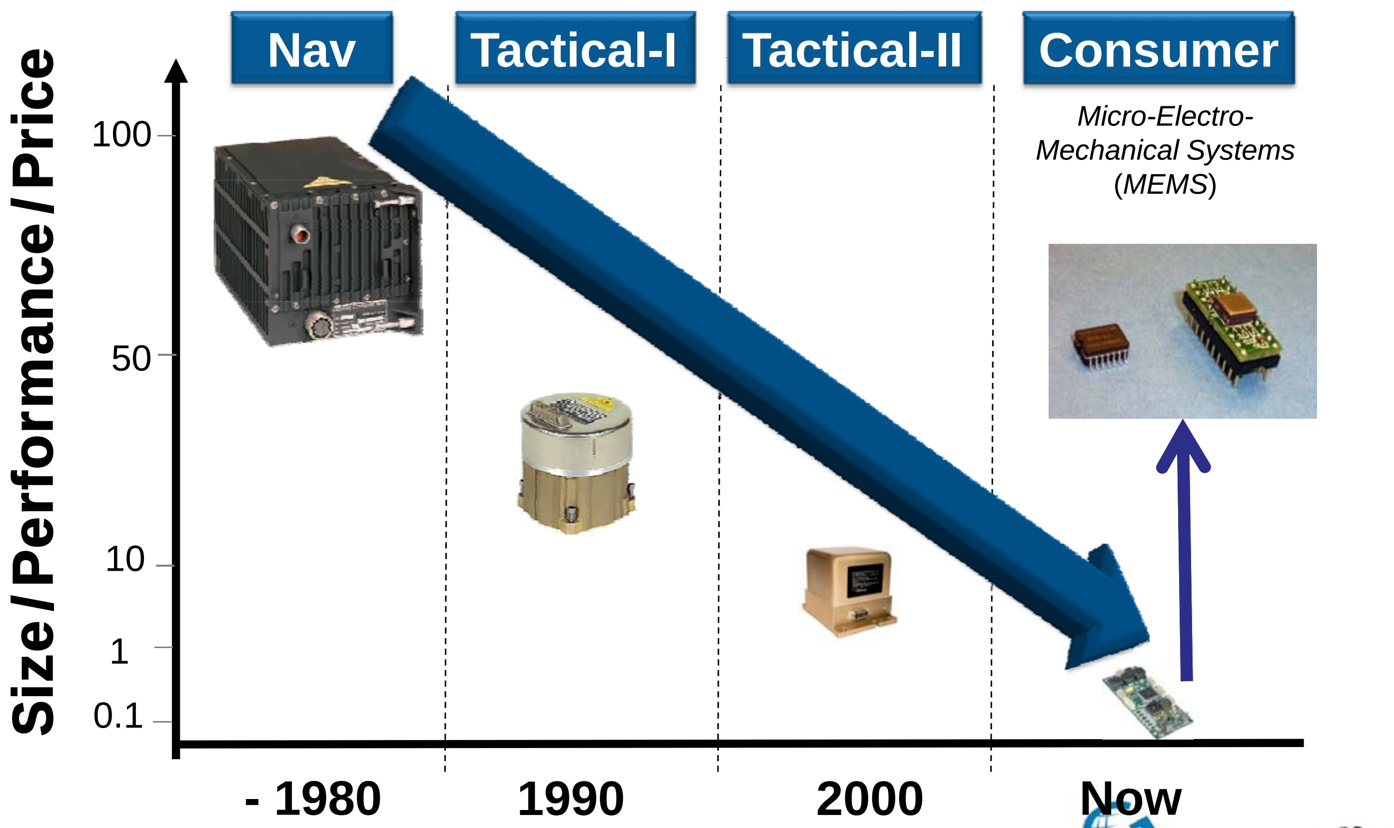
> $300,000

⌘ Widespread adoption of current systems has been limited by their high cost

Inertial Technology

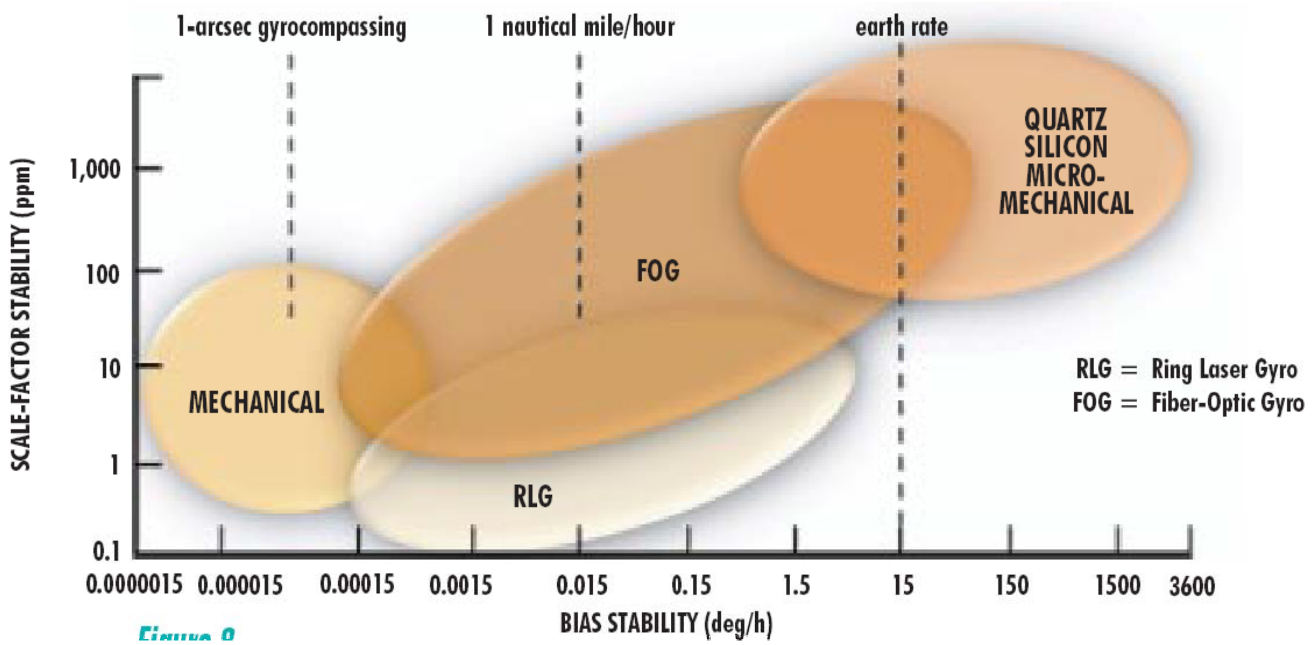


Roadmap of Inertial Technology

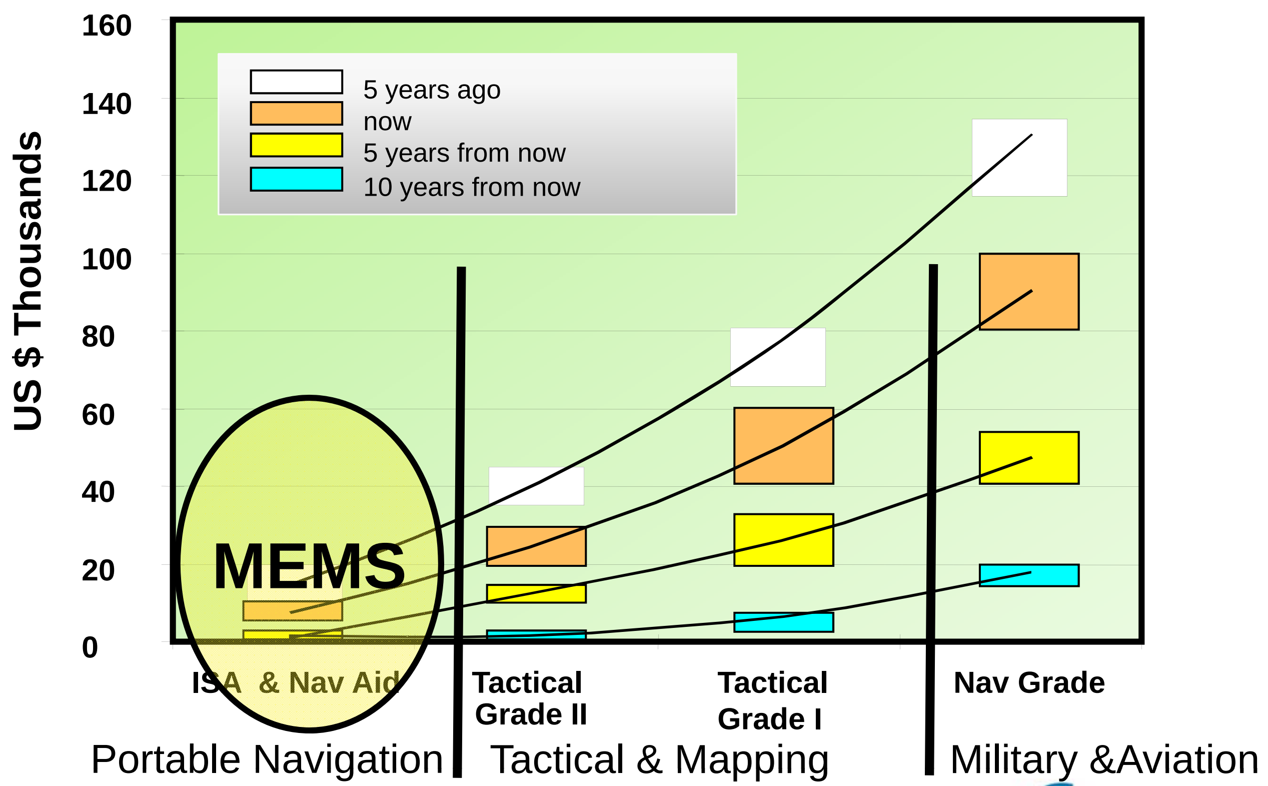


Performance of Gyro Technologies

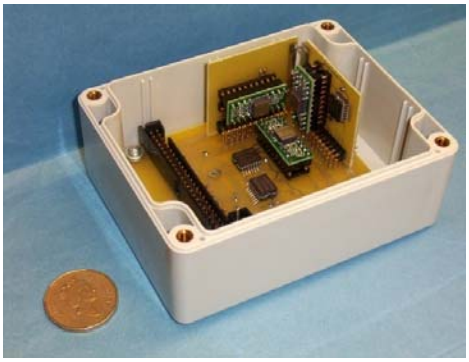
- Performance of Gyro Technologies is usually described by the bias and scale factor stability



INS – Price Roadmap



MEMS IMU - An Example



UofC IMU - Developed by employing off-the-shelve MEMS sensors with an average sensor cost 60$

	ADI Gyro (ADXRS150EB)	ADI Accel. (ADXL105A)
Range	± 150 deg/s	± 5 g
Cross-axis Sensitivity	± 1 deg	± 1 deg
Bias error	± 24 deg/s	± 2500 mg
Bias instability (100 sec) *	0.01 deg/s	0.2 mg
Scale factor error	± 10%	± 10%
Price**	USD 10	USD 2.5

- Advantages
  - Low cost
  - Small size
  - Low power
- Disadvantages
  - Large bias and SF error
  - Thermal drift

MEMS IMU – Lab Calibration

- Bias
- Scale factor
- Cross-axis

Error Model for Calibration (Gyros)

$$\begin{bmatrix} U_x \\ U_y \\ U_z \end{bmatrix} = \begin{bmatrix} k_{xx} & k_{xy} & k_{xz} \\ k_{yx} & k_{yy} & k_{yz} \\ k_{zx} & k_{zy} & k_{zz} \end{bmatrix} \cdot \begin{bmatrix} \omega_x \\ \omega_y \\ \omega_z \end{bmatrix} + \begin{bmatrix} U_{0x} \\ U_{0y} \\ U_{0z} \end{bmatrix}$$

Effects of calibration

	Before	After
Bias	< 25 deg/s < 2500 mg	< 0.5 deg/s < 6 mg
Scale Factor	< 10 %	< 0.1 %
Cross-axis	< 1.0 deg	< 0.2 deg

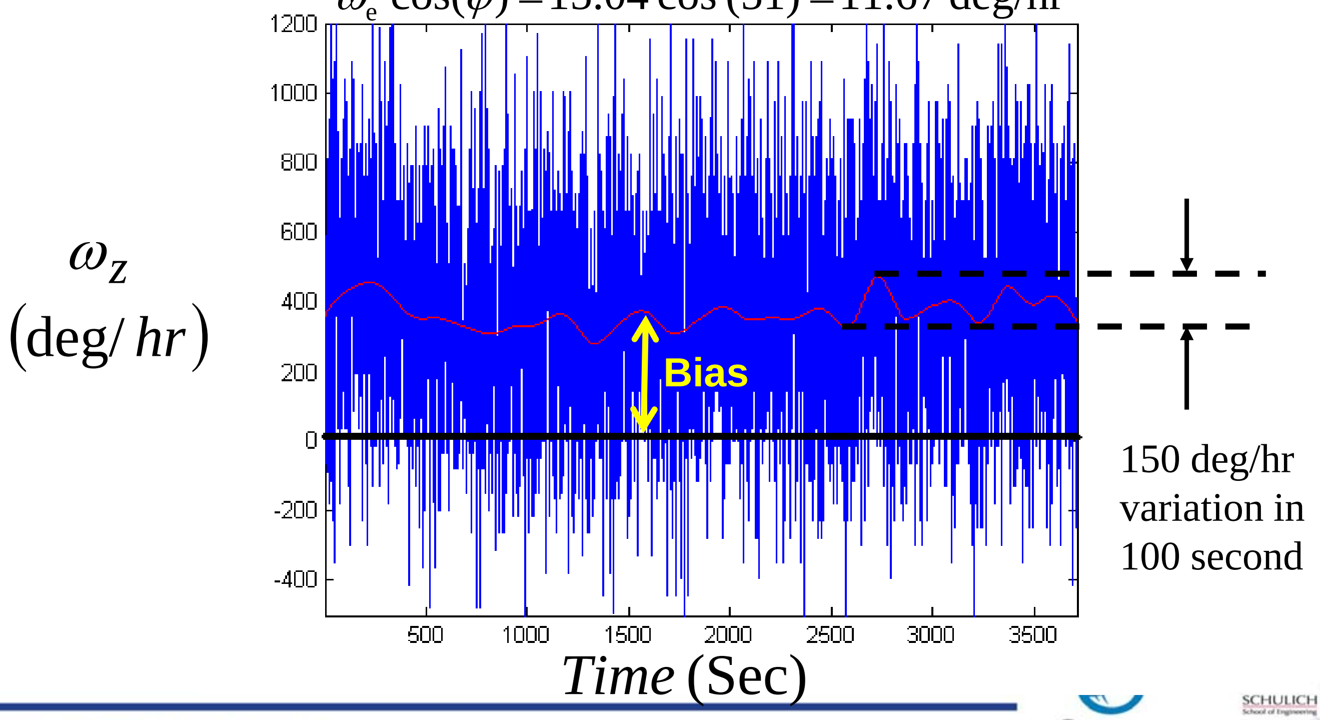
Problems with MEMS Sensors

- Most of the inadequacies are related to the sensors performance:
  - MEMS-based inertial sensors suffer from relatively poor signal to noise ratio (i.e. high noise level).
  - MEMS-based inertial sensors experience high thermal drift characteristics that may jeopardize the overall accuracy of the navigation systems.
  - MEMS-based inertial sensors have a significant run-to-run bias instability terms.
- The net effect is that the accuracy of a stand alone MEMS-based INS may deteriorate very quickly upon the absence of the GPS signal.

Problems with MEMS Sensors

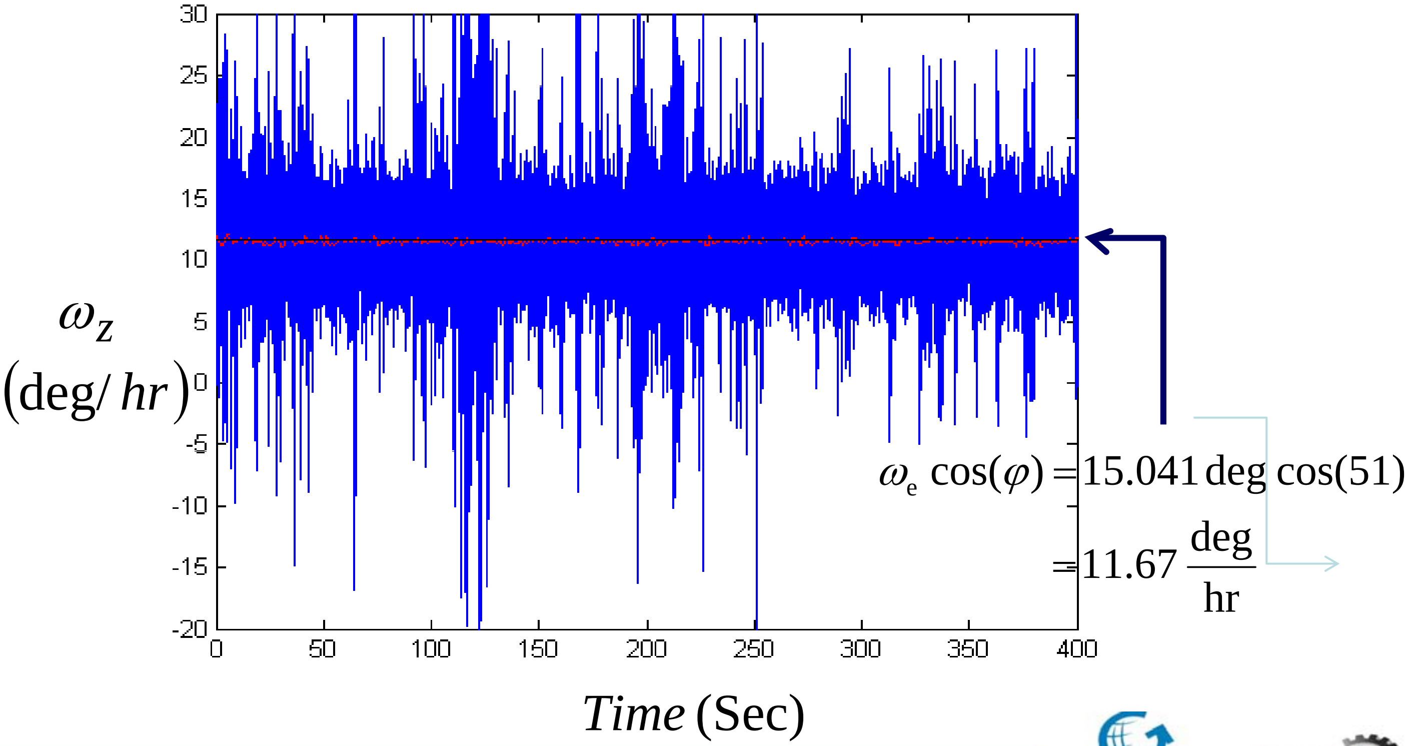
- Example: A MEMS-based gyro along the vertical direction – theoretical measurement = $\omega_e \cos(\varphi)$

$$\omega_e \cos(\varphi) = 15.04 \cos(51) = 11.67 \text{ deg/hr}$$



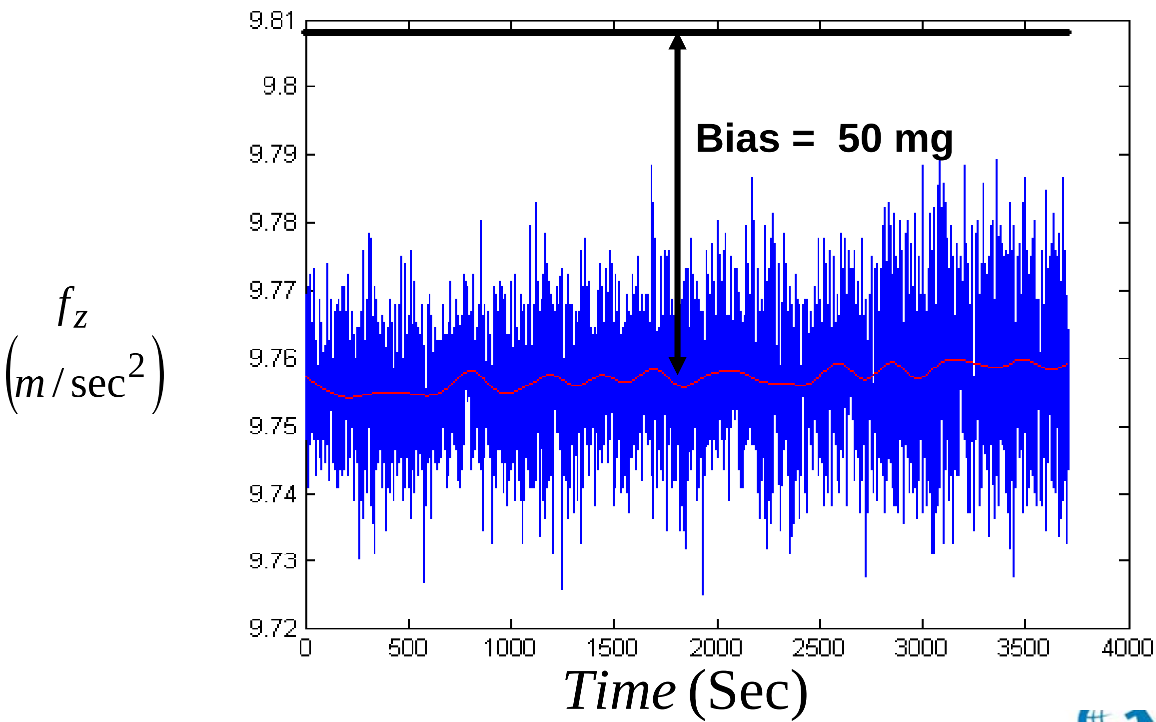
Problems with MEMS Sensors

- Comparison to a Tactical Grade Gyro Performance



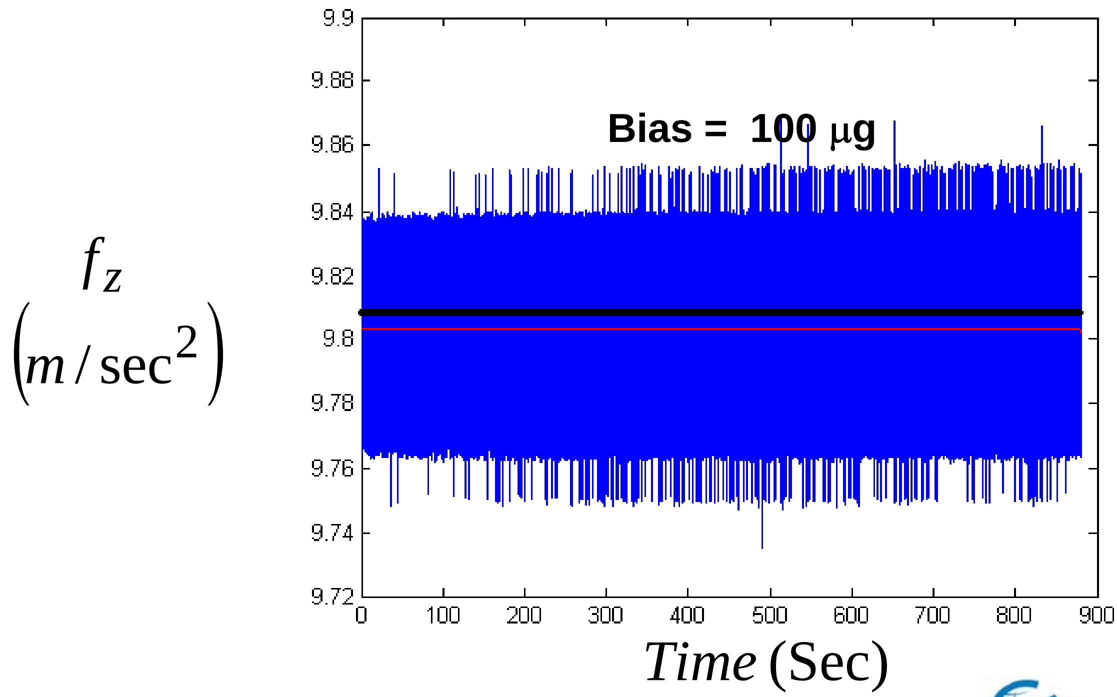
Problems with MEMS Sensors

- Example: A MEMS-based Accelerometer along the vertical direction



Problems with MEMS-based INS/GPS

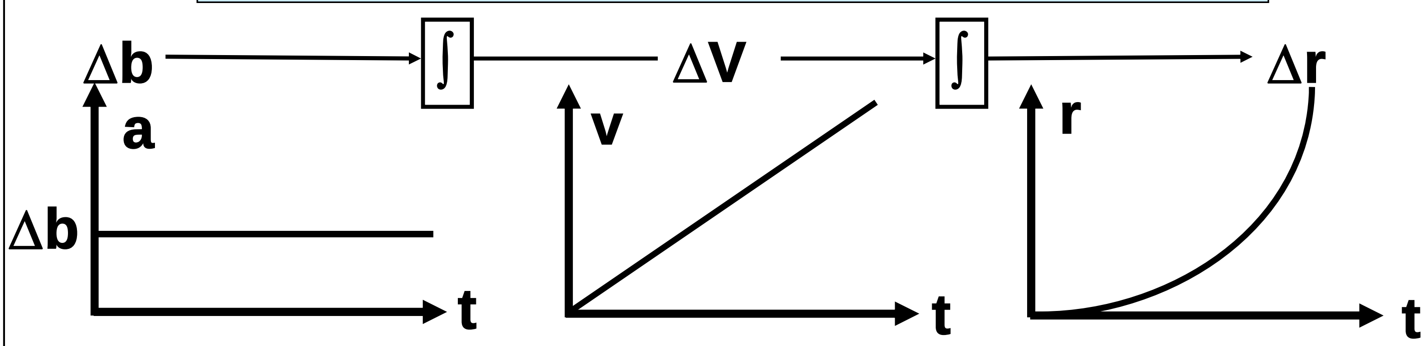
- Comparison to a Navigation Grade Accel



Effect of Inertial Sensor Errors on Navigation Parameters

- An uncompensated accelerometer bias error will introduce.
  - An error proportional to t in the velocity
  - An error proportional to t^2 in the position.

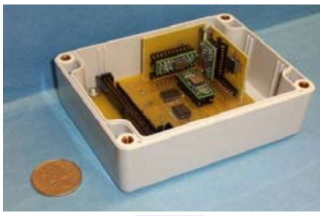
$$v = \int b_f \, dt = b_f \, t \Leftrightarrow p = \int v \, dt = \iint b_f \, t \, dt = \frac{1}{2} b_f t^2$$

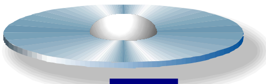


Error in position due to an uncompensated accelerometer bias of 100 μg (10^{-4} g ≈ 10^{-3} m/sec²) can introduce positional error in 60 sec = ½ * 10^{-3} *$(60)^2$ =1.8 m

Possible Improvement of MEMS Sensor Performance

- Multi-level Wavelet Decomposition:





Multi-level Wavelet Decomposition

Inertial Navigation Algorithm

Integration Algorithm (Kalman Filtering)

Position
Velocity
Attitude

Possible Improvement of MEMS Sensor Performance

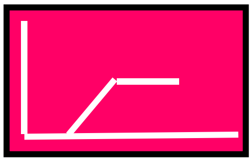
- Multi-level Wavelet Decomposition:

Inertial Sensor Measurement

Single Decomposition level

Low Pass Filter

High Pass Filter

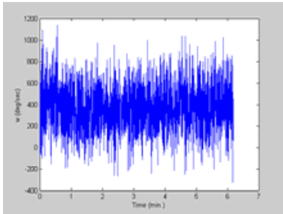


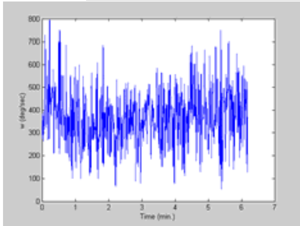
Approximation

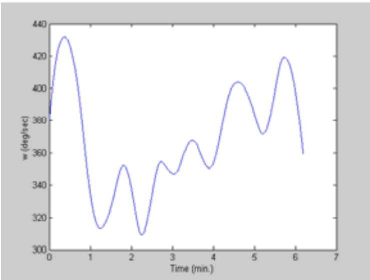
Details

Possible Improvement of MEMS Sensor Performance

- De-noising Inertial sensor signal utilizing Multi-level Wavelet Decomposition:







Inertial Sensor Measurement

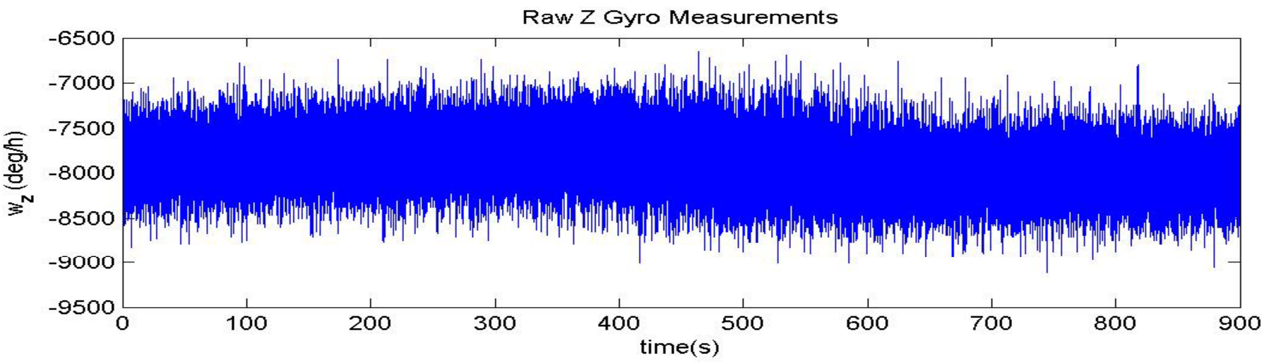
A1 D1

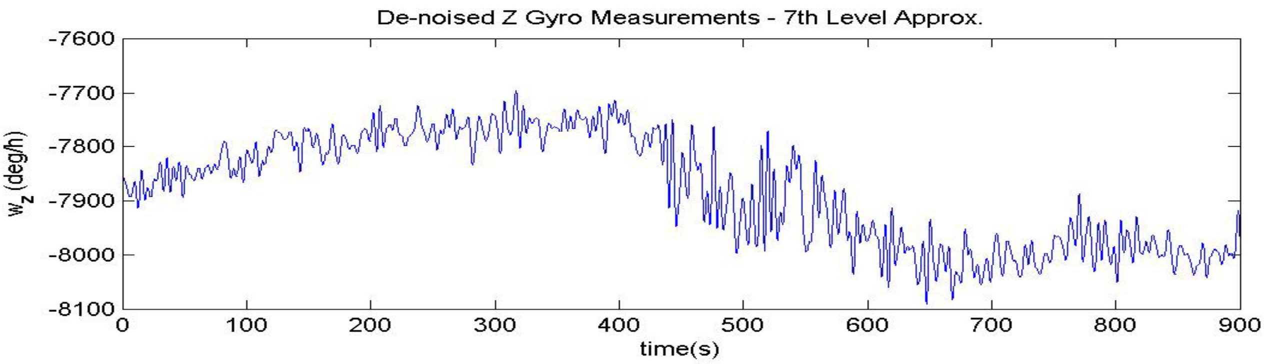
A2 D2

A3 D3

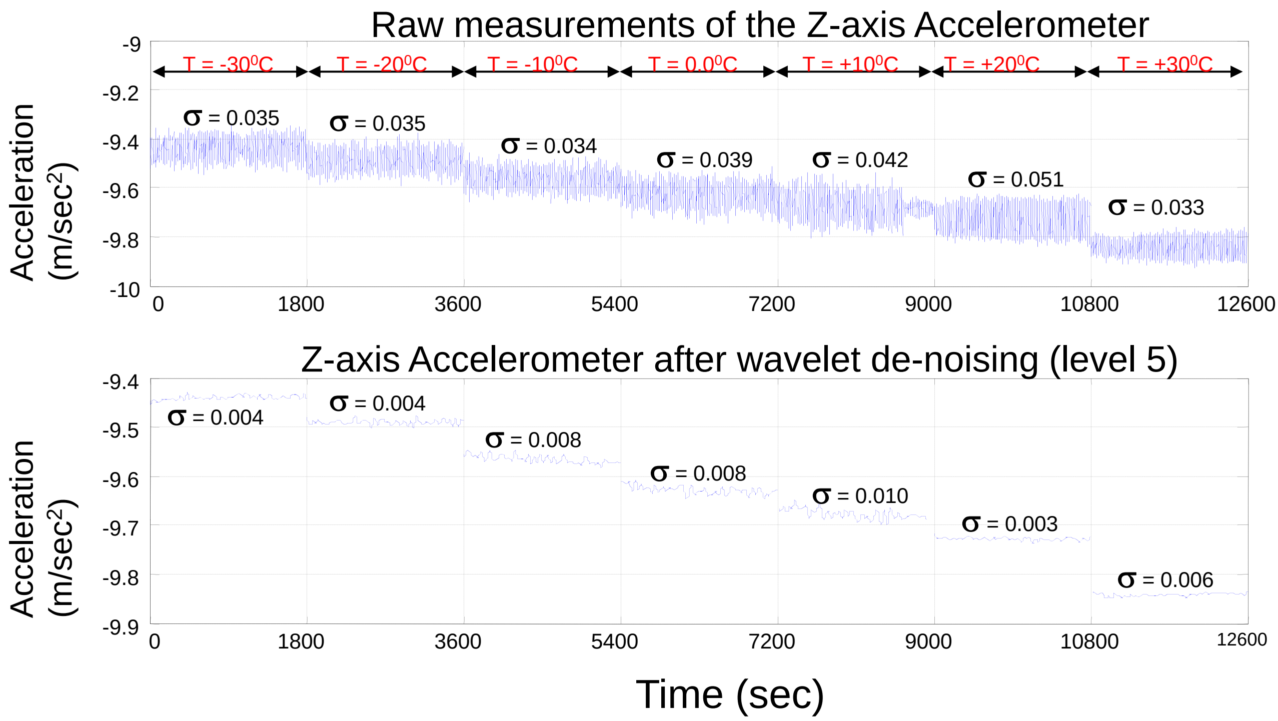
A8 D8

Wavelet De-noising – Z Gyroscope Measurements





Problems with MEMS Sensors



Extracting the thermal trend of Z-accelerometer output using Wavelet de-noising

Possible Ways to Improve the Positional Accuracy?

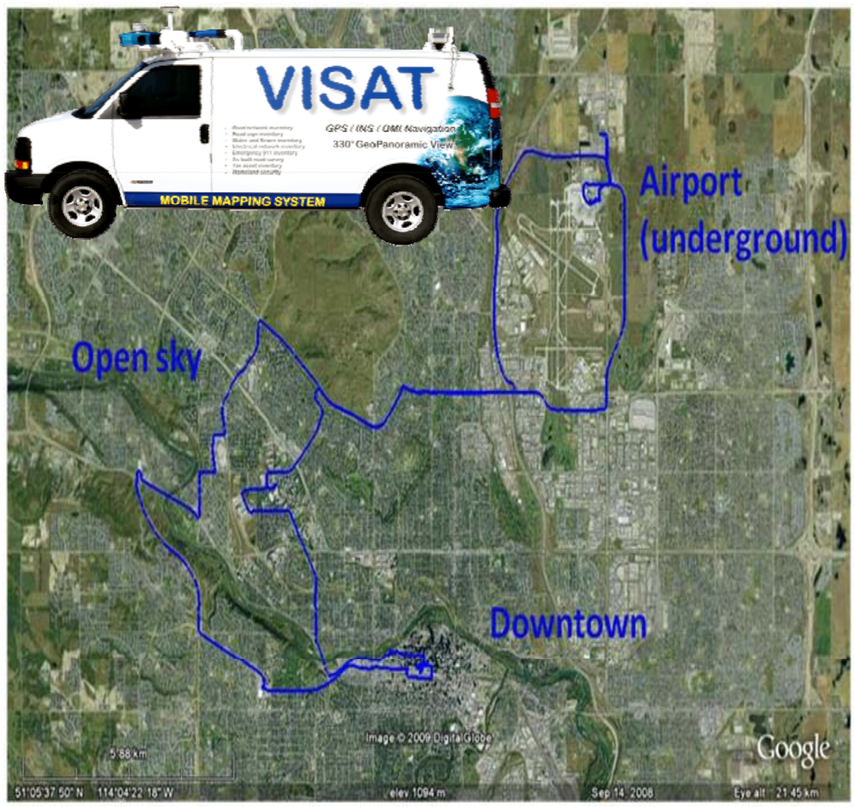
- **Improvement the performance at the integration filter level**
  - Use of velocity aiding in body frame
    - Zero Velocity Update (ZUPT) when possible
    - Non-holonomic constraints
    - Odometer
  - Advanced Algorithm
    - Unscented Kalman filter (UKF)
    - Integration of EKF/UKF and Artificial Neural Network (ANN)
  - Backward Smoothing

Achievable Accuracy

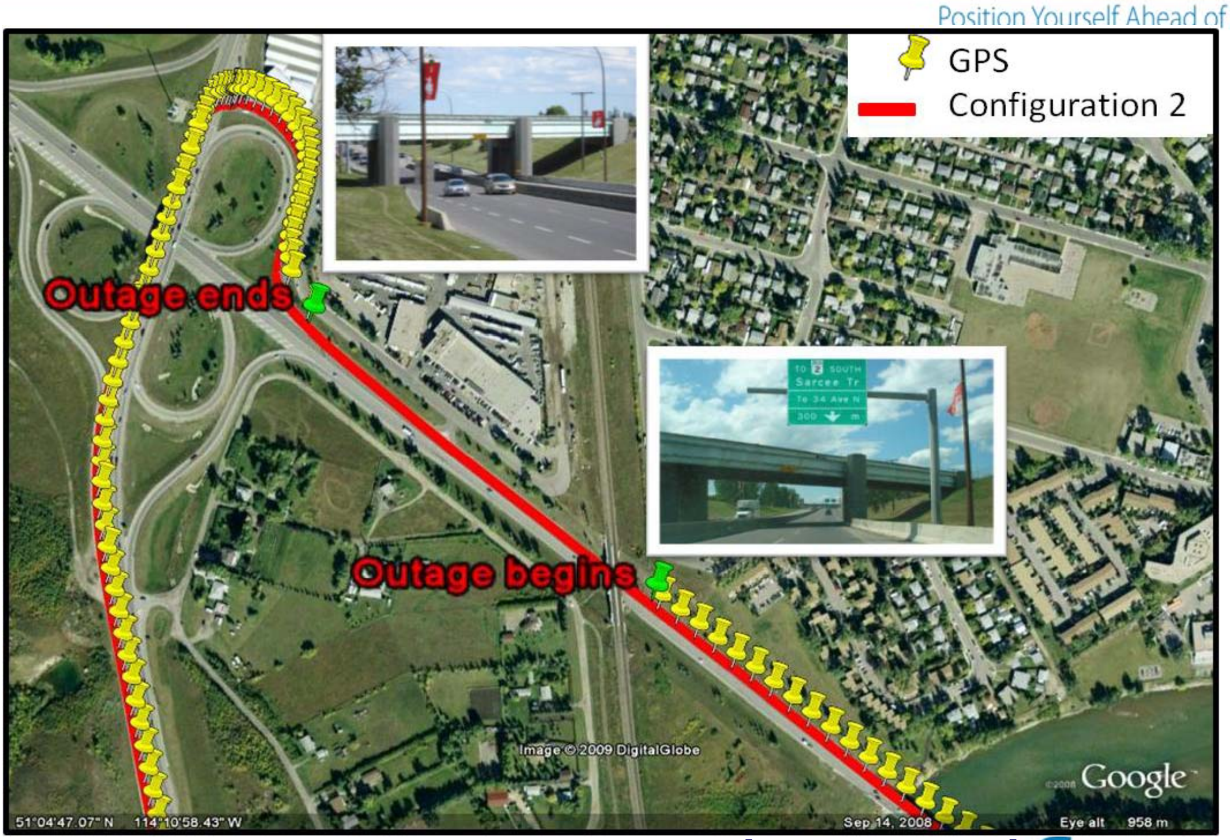
Inertial Systems
- Honeywell CIMU (Reference System)
- Litton L200 IMU
- ADI - S16365 IMU

GPS
- NovAtel OEM4
- UbBlox (HSGPS)

Nav Aid
- Odometer



Test Environment

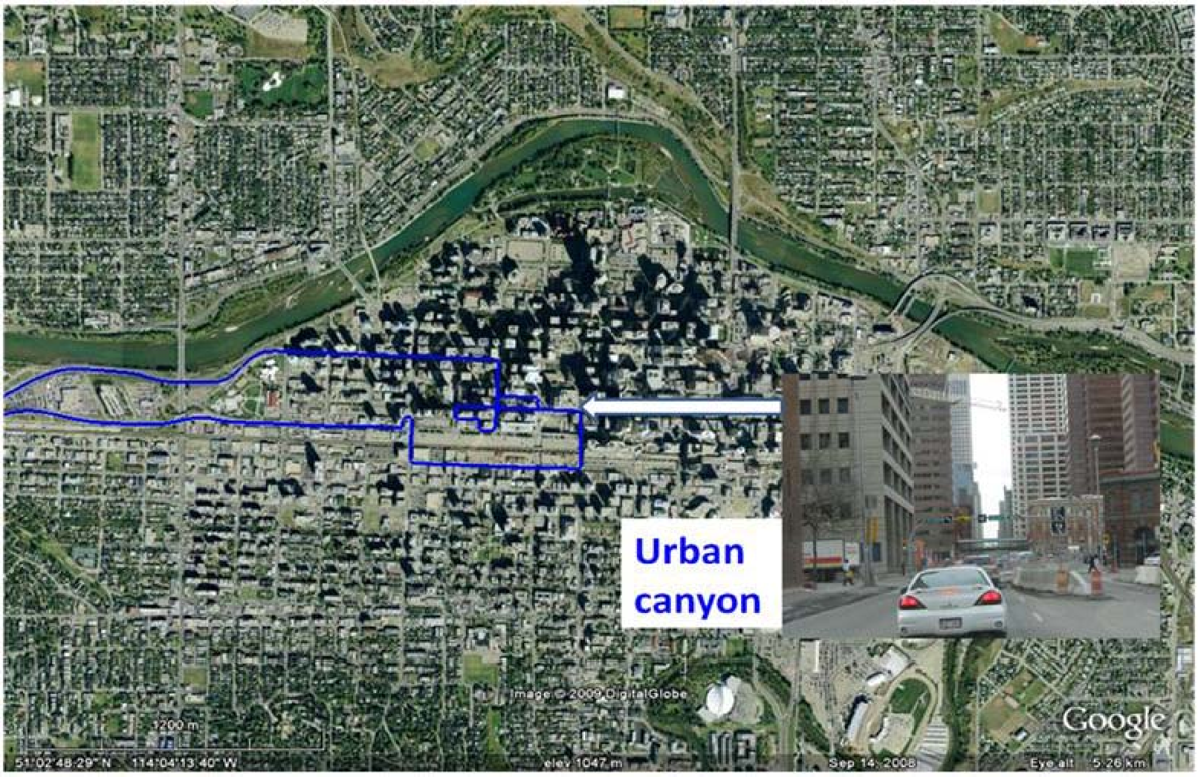


Frequent GPS outages (10 – 60 sec)

Test Environment

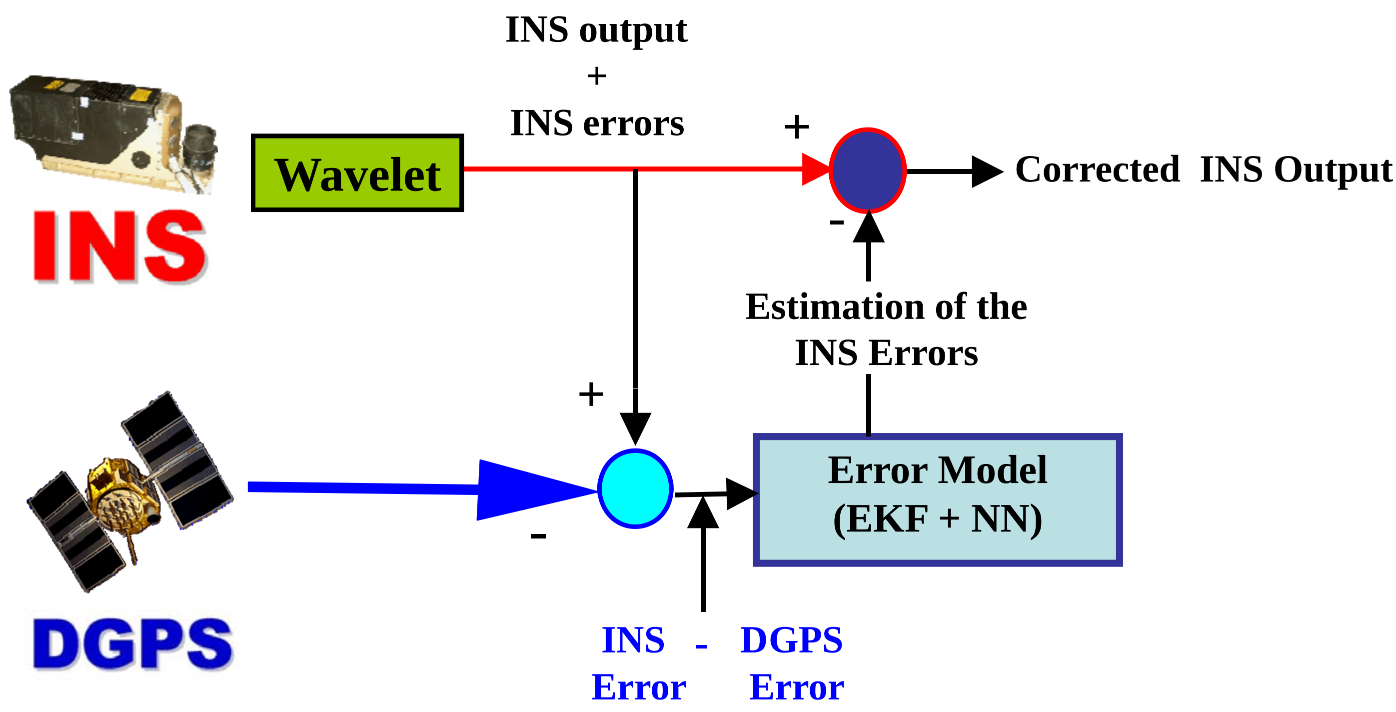
Long GPS outages (200 sec)

Test Environment



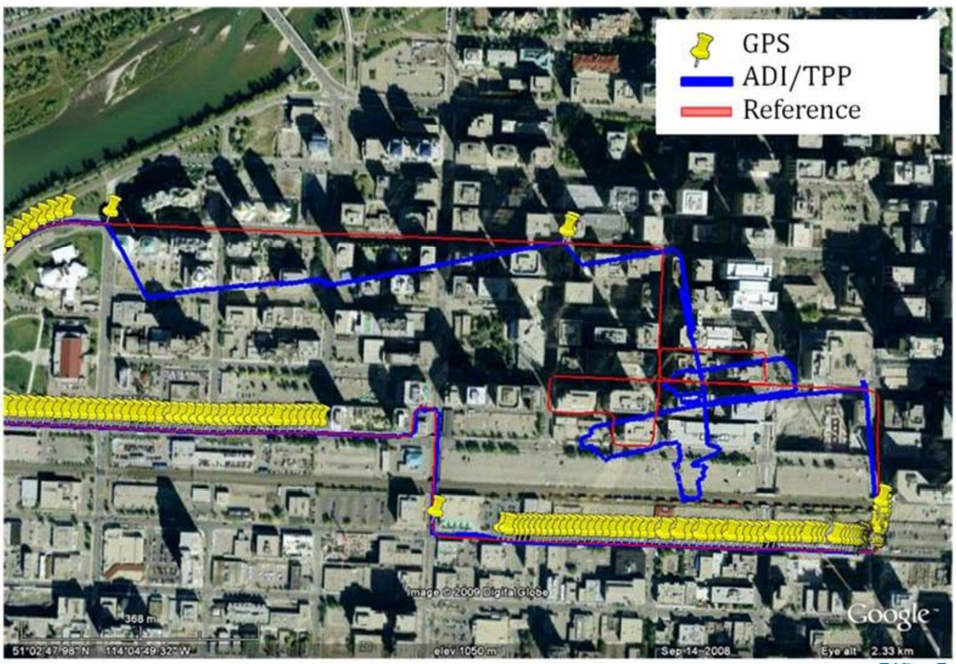
Very Long GPS outages (400 sec)

Integration Scheme



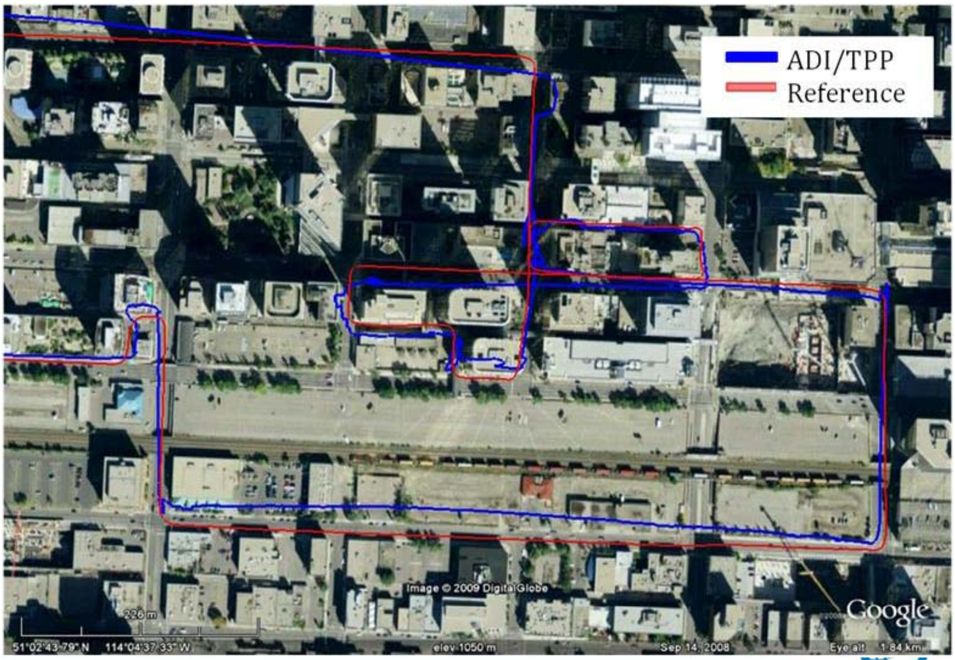
Forward Filtering

- Positional drift reaches 150m after 400 sec



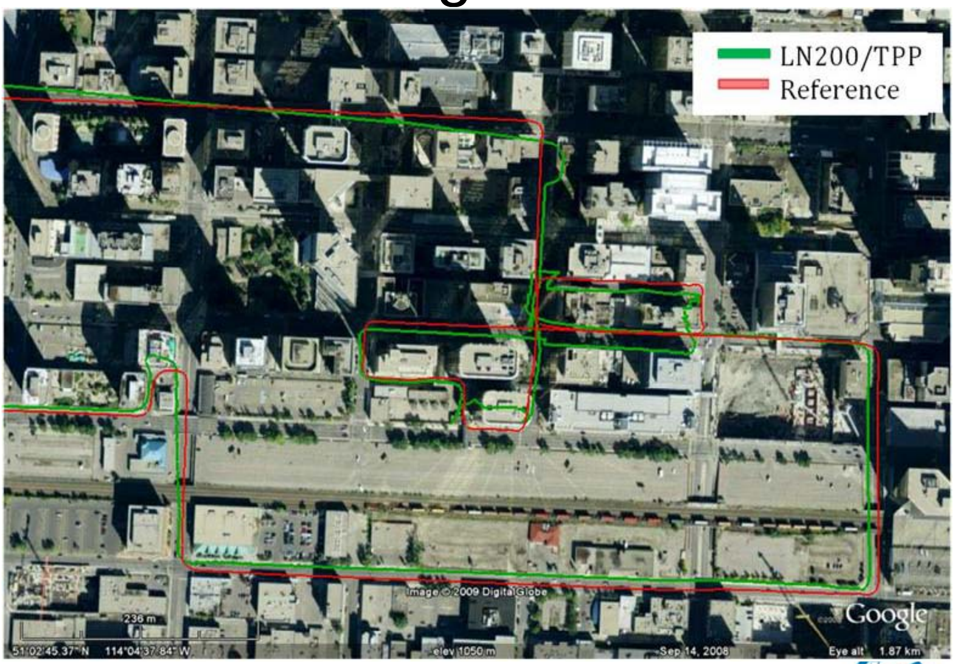
MEMS Backward Smoothing Solution

- Major improvement with average positional error in the 2-5 m level



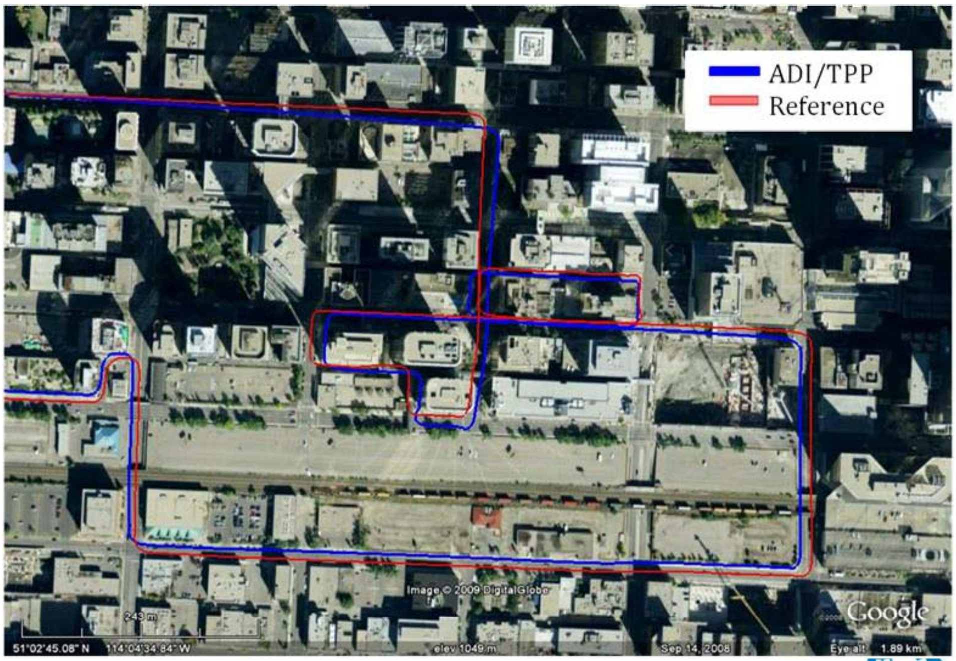
LN200 with Backward Soothing

- Similar performance to the MEMS backward smoothing solution



MEMS BS with Velocity Constraints

- Major improvement with average positional error in the 2 m level



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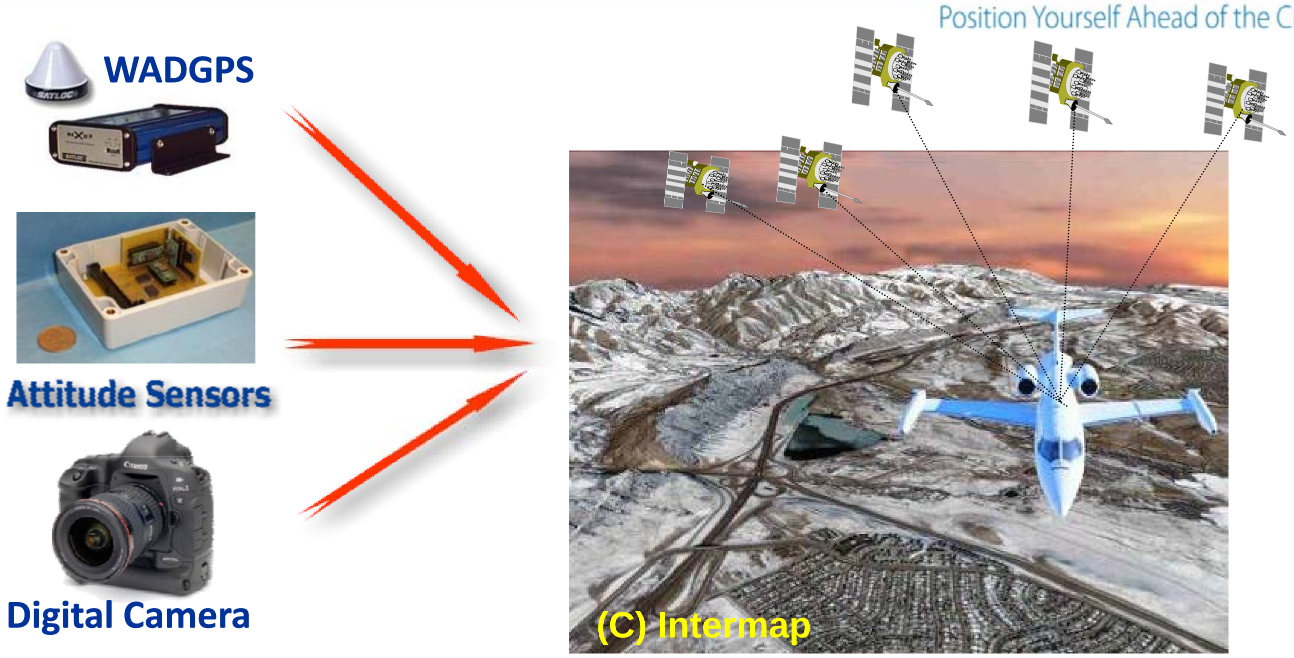
Performance of Low Cost Land MMS

Position Yourself Ahead of the Crowd

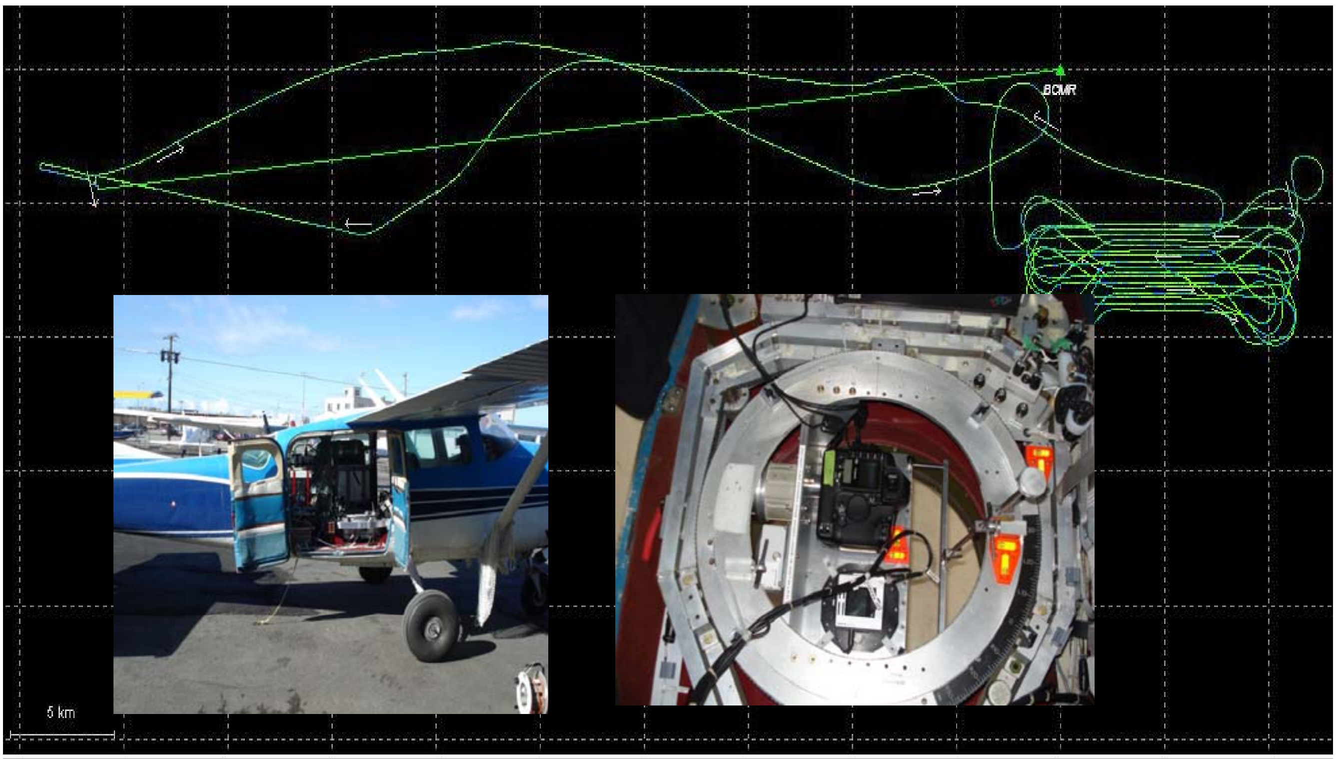
	Forward filtering	Backward Smoothing	Smoothing with non-holonomic constraints + Odometer
Position accuracy (RMS) with stable GPS update	1 m	0.5 m	0.1 m
Maximum position drift during GPS gaps	150 m	2.0 m	1.5 m
Attitude error in general (RMS)	1.5 deg	0.6 deg	0.35 deg
Maximum attitude drift with absence of kinematics	6.5 deg	1.6 deg	1.6 deg

Low Cost Airborne MMS

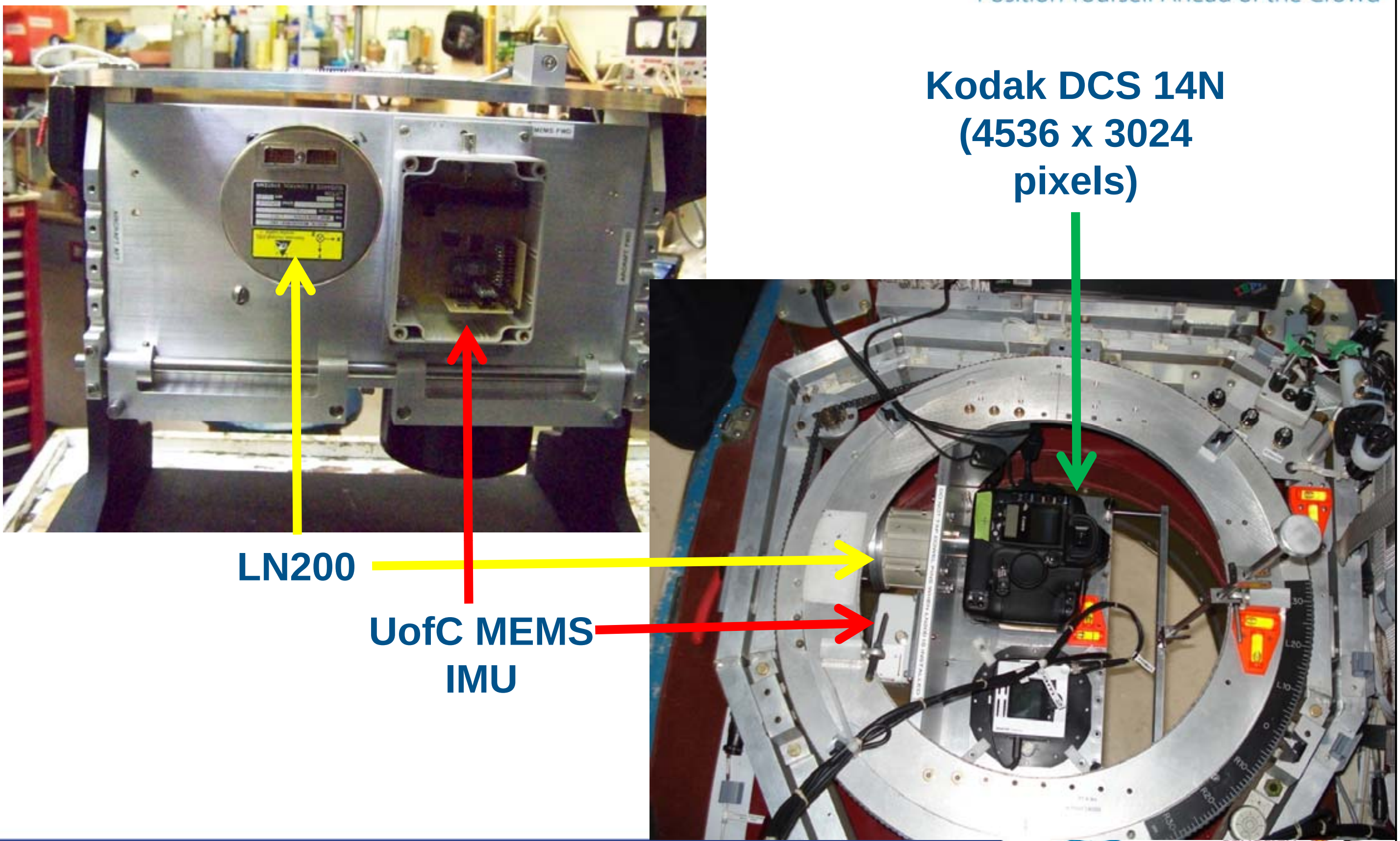


- Right of Way (ROW) mapping/monitoring of remote areas
- Minimal cost through the utilization of low cost components
- Operate without ground work → Lower cost

Low Cost Airborne MMS



Inertial Systems Setup



Performance of Low Cost Airborne MMS

Including all 16 Flight lines	Error Statistics (deg)			
	Mean	Min	Max	RMS
Roll	0.0	-0.75	1.21	0.28
Pitch	0.0	-1.15	1.07	0.44
Heading	0.2	-2.5	3.8	1.8

- The LN200/DGPS solution has been used as a reference
- The alignment of the MEMS IMU is based on static levelling (for roll and pitch) and 5-7 minutes on-the-fly alignment for heading estimation
- The average misalignment between the MEMS IMU and the LN200 (0.2, 0.3, and 1.2 deg) was removed when computing the mean values
- Promising results for Integrated Sensor Orientation

Summary

1. MEMS inertial navigation has shown promising performance today.
2. It will keep improving with the fast upgrading of the MEMS sensors in the market. The cost of the systems is also expected to drop down quickly with the blooming sensor manufacture.
3. Testing of MEMS-based IMU/GPS system with auxiliary velocity update can reach the requirements for land vehicle navigation and land based MMS systems.
4. Promising potential of using low-end MEMS inertial sensors for airborne MMS (e.g. Right of Way (ROW) of highways and Oil&Gas pipelines)

With the technology push and the market pull, MEMS inertial systems is going to reach the performance of Tactical Grade IMU Soon.

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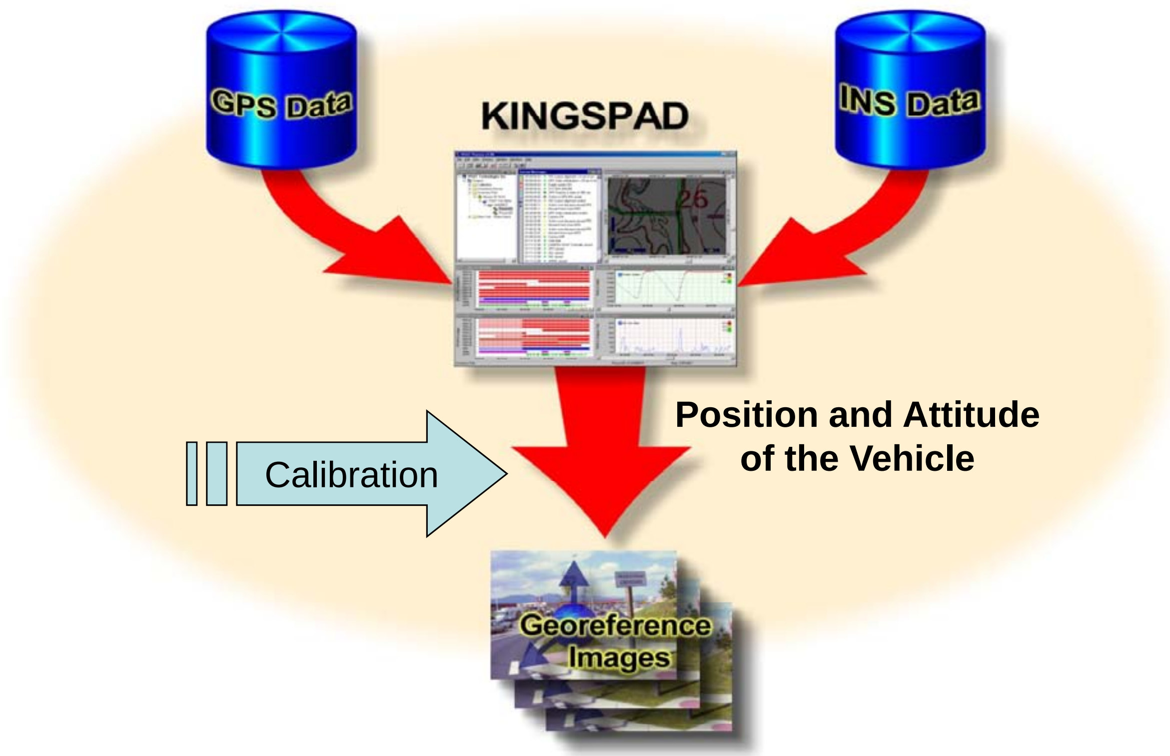
MMS – Georeferencing Processing Chain



Nonlinear Modeling – Unscented KF Concept

- The EKF approximates non-linear functions.
- The UKF approximates the Gaussian distribution using sigma points.
- Sigma points undergo the non-linear transformations (system/measurement).
- The mean and covariance are computed from the transformed sigma points.