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CASE STUDIES IN GNSS/INS INTEGRATION






Tuesday, December 15, 2015

WELCOME TO
Case Studies in GNSS/INS Integration

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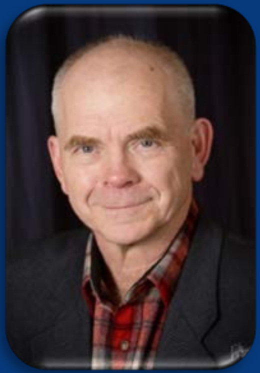
Co-Moderator: Lori Dearman, Sr. Webinar Producer

Who's In the Audience?

A diverse audience of over 500 professionals registered from 43 countries, 30 states and provinces representing the following industries:

- 23% System Integrator
- 19% Product/Application Designer
- 18% Professional User
- 15% GNSS Equipment Manufacturer
- 25% Other

Welcome from *Inside GNSS*



Glen Gibbons

Editor and Publisher
Inside GNSS

Welcome from *NovAtel*

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Case Studies in GNSS/INS Integration

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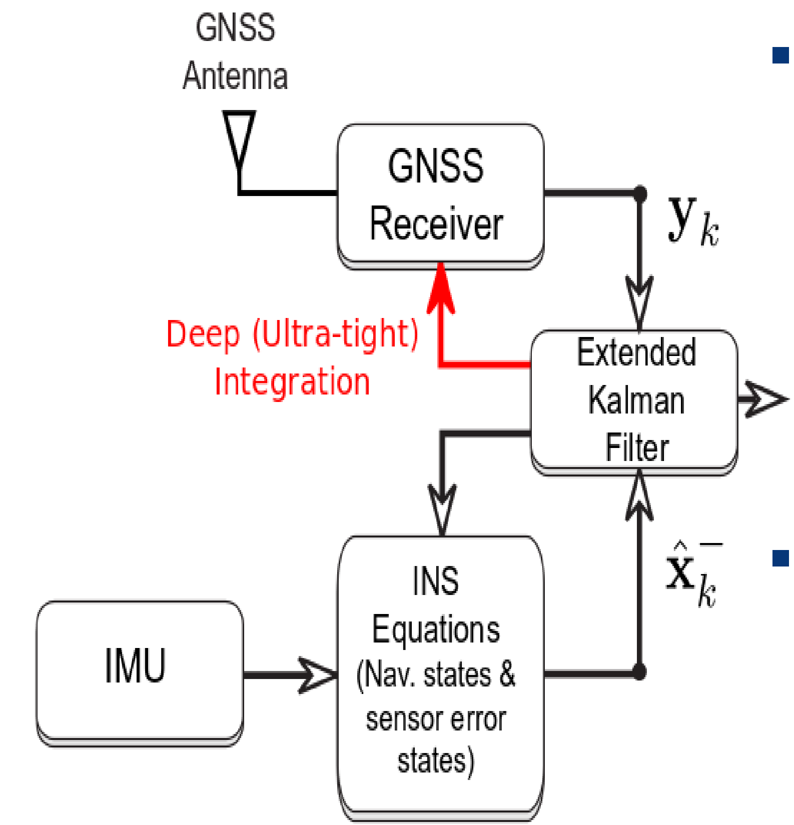
Mechanics Faculty
University of Minnesota

Poll #1

Which of the following are true of design requirements for an integrated GNSS/INS system? ***(Please select all that apply)***

- ***For a given hardware (GPS receiver and IMU) are independent of the application***
- ***For a given application are independent of the hardware used***
- ***Are "cast in stone" and never change once the design process starts***
- ***May be determined iteratively as the design process evolves.***
- ***All are true***

Generic GNSS/INS Filter



- Design process for two integrated INS/GNSS systems
  - GNSS + Tactical grade inertial sensors.
  - GNSS + Consumer (Automotive) grade inertial sensors.
- How and why are the integration architectures & design process different?

INS/GPS Integration In High Dynamic Environments

Modular System Design for a Range of High Dynamic Applications

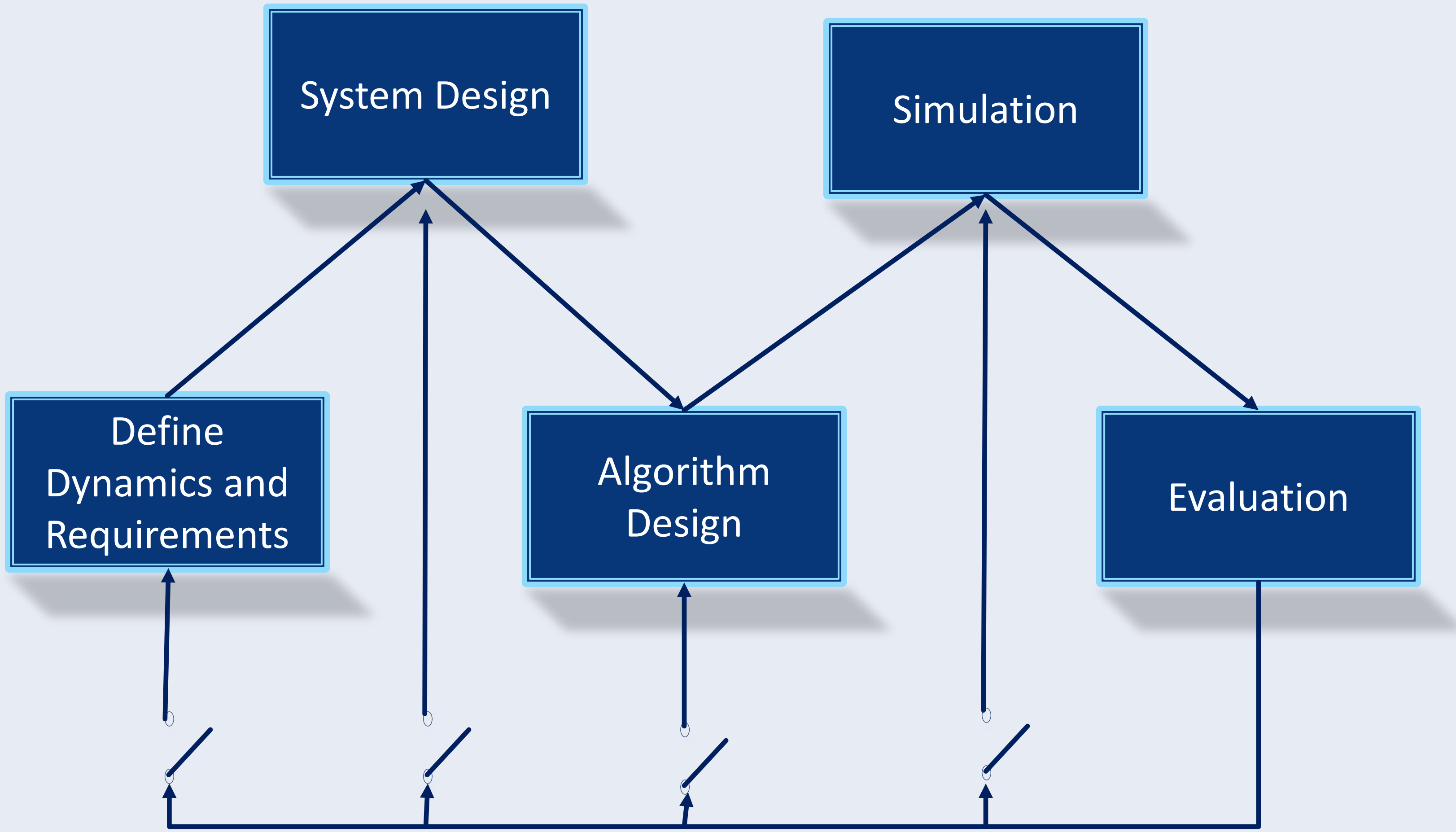
Thomas Jakel
Sr. Systems Engineer
Honeywell Sensor Guidance and Navigation COE

Introduction

•Produce an integrated inertial navigation system architecture which:

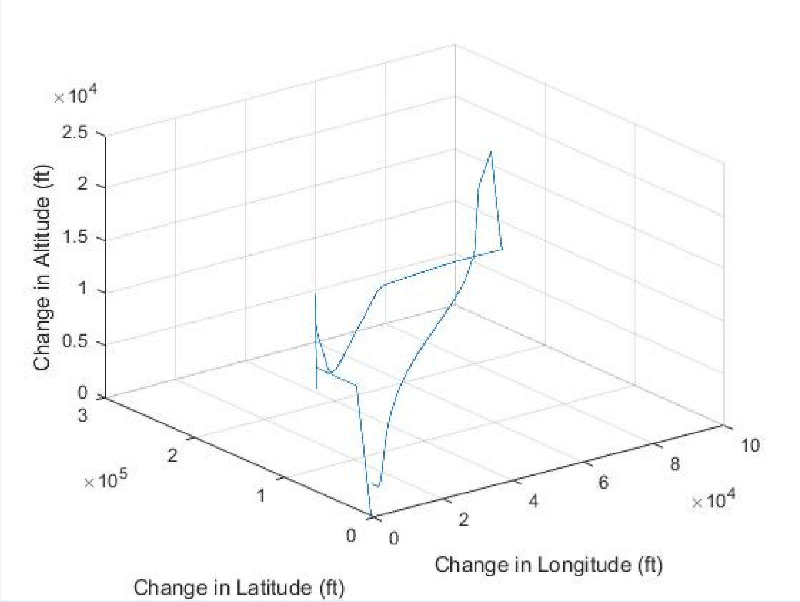
1) Is adaptable to various high dynamic applications
2) Minimizes free inertial drift during GPS outages
3) Is configurable to use various inertial measurement unit and GNSS types

Iterative Design Process



Define Dynamics

- Trajectory
  - Time history of 6 Degree of Freedom Motion
- Inertial Forces
  - Strapdown Navigation means sensors experience motion of the body with some attenuation due to mounting
  - Specific force modeling fidelity – tactical vs. navigation
  - Transport Rate
- High frequency dynamics
  - Vibration
  - Shock



Define Requirements

- SWAPC
  - Size, Weight, Power and Cost
- Dynamic Range and Bandwidth
  - Driven by platform dynamics
- Performance
  - Navigation Performance (Position, Velocity, and Attitude)
    - Circular Error Probability or Segment RMS Error

↓

- Performance
  - Inertial
  - Measurement (GNSS)
- Other Considerations
  - Reliability, Technology Readiness, and Ease of Adoption

Select Candidate IMUs

	HG1930	HG1900	HG1700	HG9900
Volume (in^3)	5	17	27	103
ARW (°/√hr)	0.09	0.06	0.125	<0.002
G_Bias (°/hr)	20	10	1	<0.003
G_BI (°/hr)	1.0	0.3	0.03	N/A
G_SF (ppm)	600	150	150	5
G_NO (µrad)	500	200	100	
A_Bias (mg)	5	1	1	<0.025
A_BI (mg)	0.3	0.05	0.05	<0.025
A_SF (ppm)	450	150	300	100
A_NO (µrad)	500	100	100	
Start Time (ms)	350	750	1500	
VRC (ug/g^2)	40	17	17	
Power (W)	2.6	3.5	6.5	<10

IMU Selection

- The HG1930 MEMS IMU has been successfully deployed on a wide range of guidance, navigation, control, and pointing applications on commercial and military platforms
- Extended operating range versions available
- Specified performance is over all environments – many of which are severe
  - Performance under benign conditions is even better
- Gyro rate limited ECCN 7A994 version
  - Entry in service late 2016

HG1930	CA50	BA50	AA50
Physical Parameters			
Volume (cubic inches)	< 5		
Weight (lbs)	< 0.35		
Power (Watts)	< 3		
Gyro Performance Overview			
Operating Range (dps)	1000		
Bias Repeatability (dph (1-sigma))	20	40	60
Bias In-run Stability (dph (1-sigma))	1	1.5	1.5
Scale Factor Repeatability (PPM (1-sigma))	600	800	1000
Scale Factor In-run Stability (PPM (1-sigma))	250		
Non-orthogonality (urad (1-sigma))	500	750	750
Angle Random Walk (deg/sqrt(hr))	0.125	0.125	0.175
Accelerometer Performance Overview			
Operating Range (g's)	30		
Bias Repeatibility (milli-g (1 sigma))	5	10	10
Bias In-run Stability (milli-g (1 sigma))	0.3	0.5	0.5
Scale Factor Repeatability (PPM (1-sigma))	750	1000	1000
Scale Factor In-run Stability (PPM (1-sigma))	150		
Non-orthogonality (urad (1-sigma))	500	750	750
Velocity Random Walk (fps/sqrt(hr))	0.3	0.3	0.4

Example Honeywell MEMS sensor technology

Navigation Algorithm Design

- Navigation Architecture centered around Strapdown Navigation and Extended Kalman Filter (EKF)
  - Proven navigation performance in past high dynamic applications
  - State Selection
    - PSI Error Model – Direct observation of Earth to Body states
    - Modeling of inertial sensor and measurement errors
    - Dynamics and observation dependent
  - Selectable Navigation Iteration Frequency
    - Modeling of transport rate and gravity

- GNSS measurements can be incorporated with different mechanizations
  - **Ultra-Tightly Coupled (UTC)**– Navigation solution drives the GPS receiver replicas (NCO)
  - Tightly coupled – Pseudorange and Deltarange incorporated as measurements to the EKF
  - Loosely coupled – Position and Velocity used as measurements in the EKF

GNSS Receiver Requirements - UTC

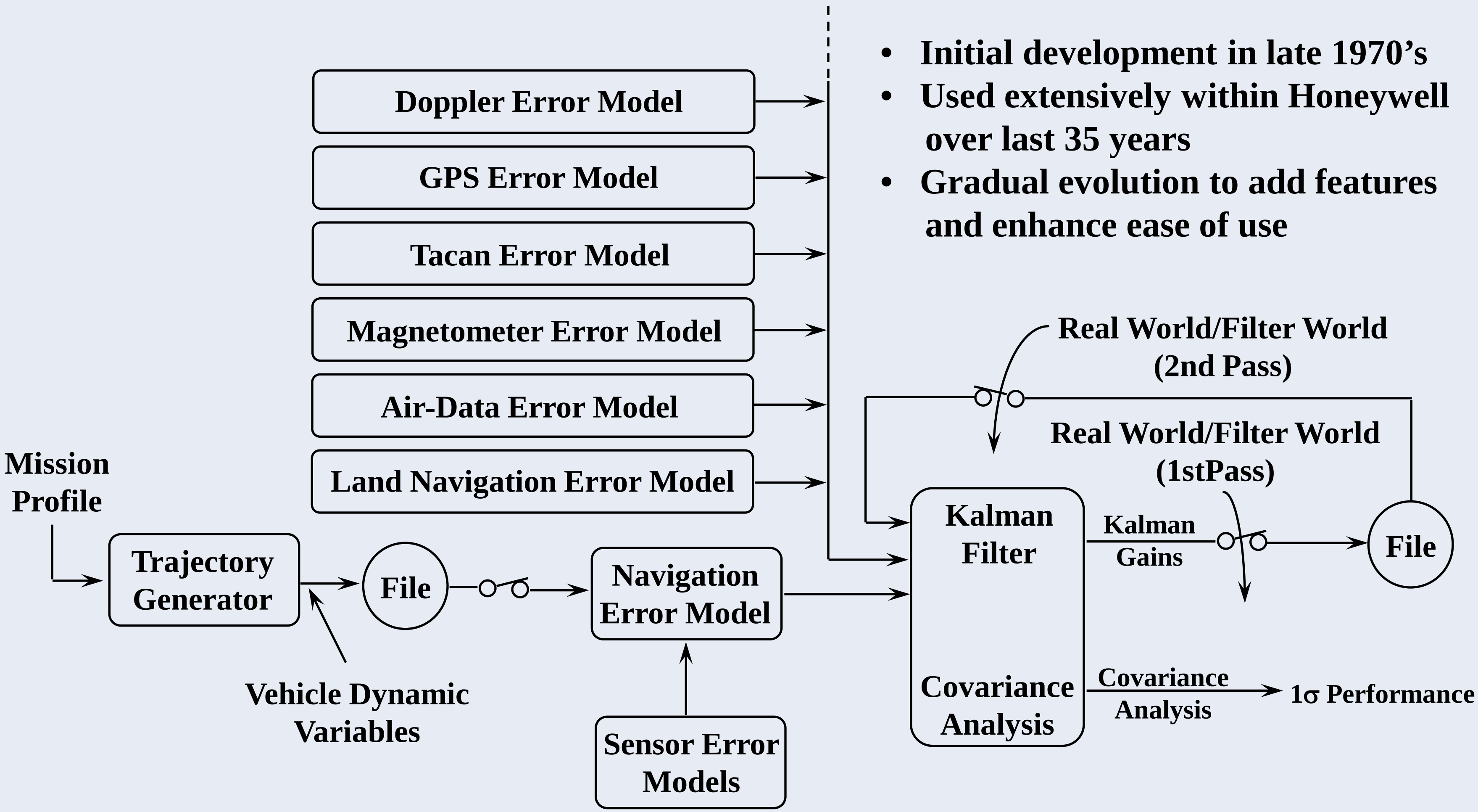
- Accept NCO commands from external sources
- Output *Is* and *Qs* at 50 Hz or greater (for signals with nav data on them)
- Bias estimation and application consistent with estimation performed in centralized EKF
- Small SWAP
- Oscillator Stability under dynamic conditions
- Receiver only needs to track the errors in the inertial solution
- Signal acquisition time may not be critical
  - Dependent on performance requirements post initialization

Simulation Tradeoffs

- Covariance simulation
  - Linear models of error characteristics
    - s = g(x)
  - Single run statistical assessment
- Time domain simulation
  - Non-linear models and events
    - y = f(x)
  - Direct visibility to application software implementation
    - Higher-order languages allow actual flight software to be simulated
      - Issue: Simulation is not usable until flight software is complete
  - Sensitive to signs and implementation
  - Monte-carlo provides statistical assessment

EKF State Selection – Covariance Analysis

- Initial development in late 1970's
- Used extensively within Honeywell over last 35 years
- Gradual evolution to add features and enhance ease of use



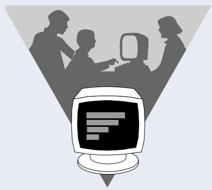
EKF State Selection Example

- Gyroscope Scale Factor
- Maneuver – 180° Roll
- No state in EKF – Scale Factor for HG1930 AA50 from Specification – 1000 PPM
  - Attitude Error = 1000 PPM * 10^-6 PPM/Part*180° = 0.18°
  - Velocity Error ≈ 0.18°*pi/180 rad/° * 9.81 = 0.03 m/s
- State in EKF – Estimated to Scale Factor In-Run from AA50 Specification – 250 PPM
  - Attitude Error = 250 PPM * 10^-6 PPM/Part*180° = 0.05°
  - Velocity Error ≈ 0.05°*pi/180 rad/° * 9.81 = 0.01 m/s
- Modeling Gyro Scale Factor State provides significant performance benefit
  - When trajectory excitation and measurement observability allow estimation

EKF State Selection – Available States

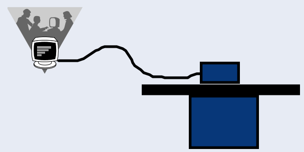
- Examples of inertial states modeled
  - Bias, Scale Factor, Repeatable Scale Factor Non-Linearity, Misalignment, Non-Orthogonality, Gyroscope G-Sensitivity
- Examples of GNSS Measurement States
  - Clock Drift, Clock Drift Rate, Range Bias, Oscillator G-Sensitivity
- State selection is a trade-off between performance and processing
  - Observability of states is trajectory dependent

Test Environments



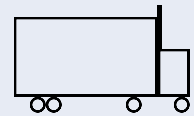
Off-line Simulation Tools

- Filter Design and Analysis
- Provides controlled and repeatable environment.
- Provides “user friendly” tools.
- Output information only as good as input drivers.



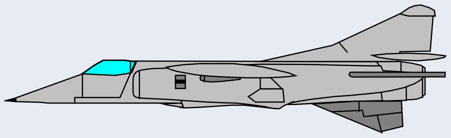
Laboratory Test

- Access to actual hardware and real-time software.
- Offers exposure to controlled environments
  - Temperature
  - Vibration
  - Humidity etc.



Van Test

- Access to low dynamic motion for visibility into timing errors etc.
- Cheaper than flight test.
  - Easy retest capability
- Good data collection/storage.



Flight Test

- True application environment

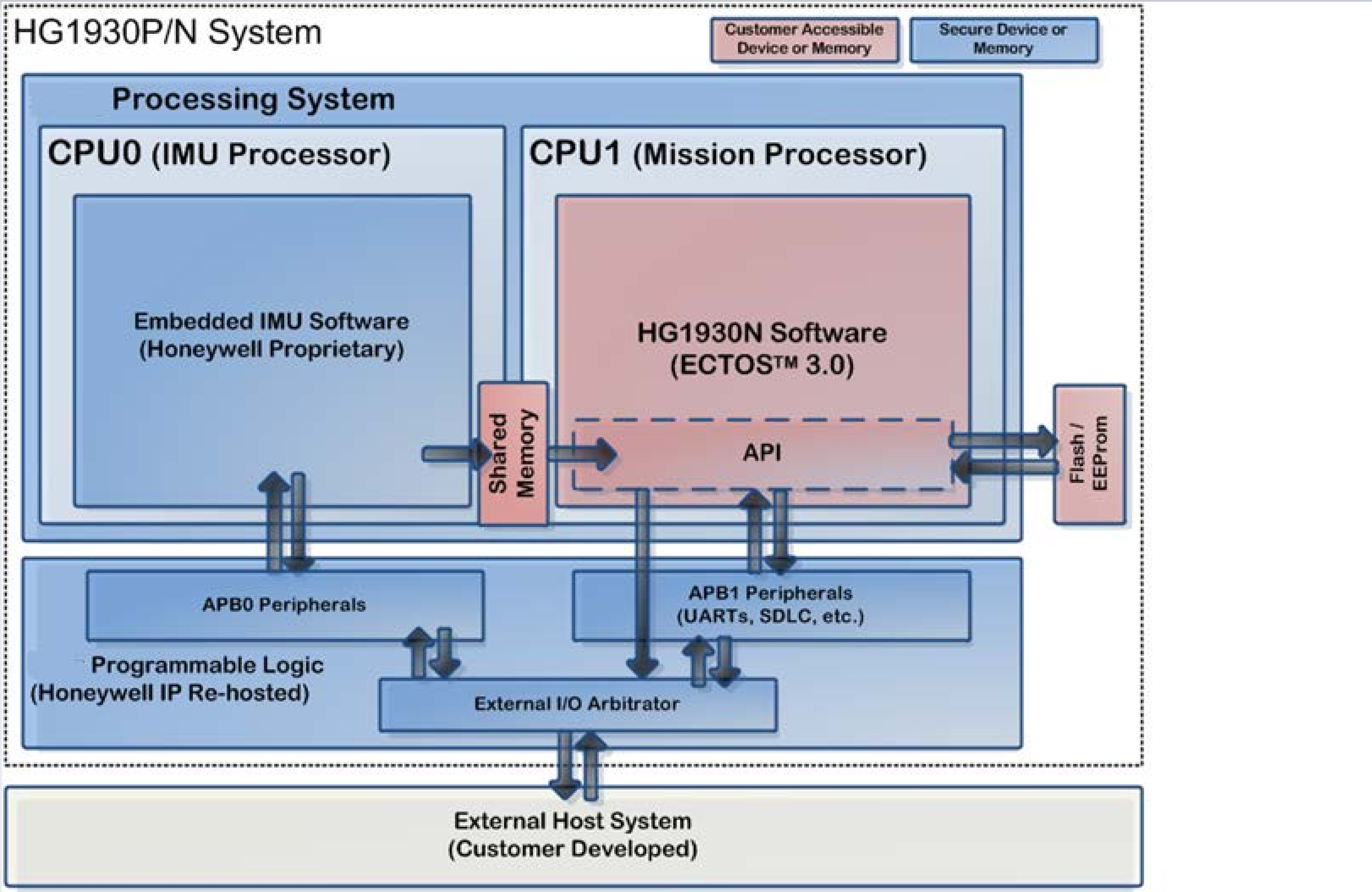
- Development utilizes all of the above environments
- Results from laboratory, van and flight test are fed back into off-line simulation tools to assist in analysis and provide better tools to use in the future.

Introduction to HG1930P/N

- Two new variants to the HG1930 family
  - HG1930P = Enhanced Processor
  - **HG1930N = Integrated Navigator**
- Small size, weight and power (SWaP)
  - HG1930 form factor
- Drop-in replacement of the HG1930 micro board
  - Multi-core System-on-Chip (SoC)
  - Secure dual processor architecture
- Flexible I/O options
- Honeywell MEMS sensors
  - Capable of using external IMU

Honeywell's new flexible low cost, small SWaP, MEMS INS

Dual Processor Architecture



Secure and open INS architecture

Flexible External I/O

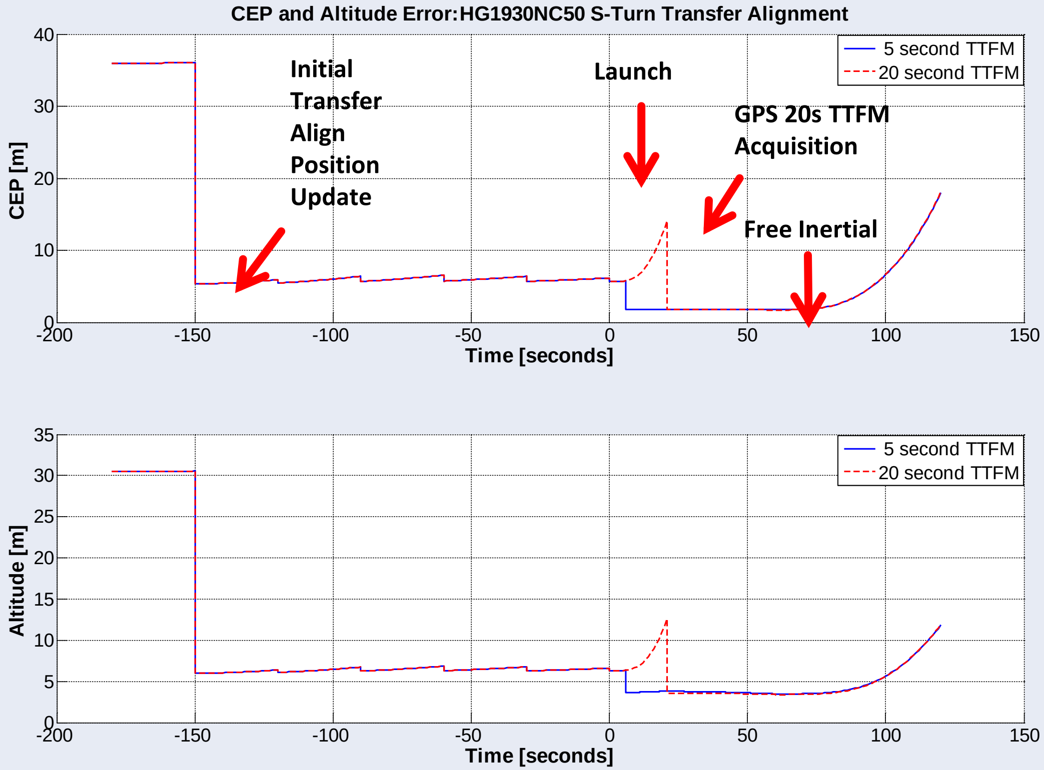
- 14 Pin Connector
- Design decision for volume, commonality of production and cost
- Mitigate limitations with configurability

- Up to 5 UARTs
  - 4 Mbaud capable – useful for low latency NCO commands
- SDLC port
- Additional pin options
  - Time Mark Input/Output
  - Discrete Input/Out
  - IMU Strobe/External Sync
- Both single-ended and differential signals supported on ports 3, 4 & 5
- Additional I/O supports varied Navigation usage

System Position Performance

- Navigation performance is expected to be similar to the Honeywell BG1930 GPS Aided Inertial Navigation System(INS).

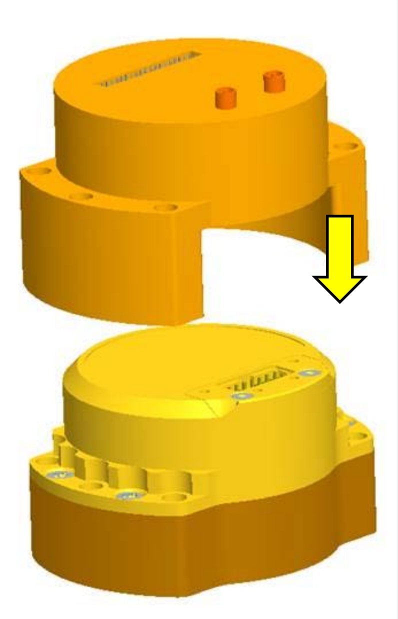
- **Preliminary simulation analysis shows comparable performance**



1 minute free inertial performance: 18 m CEP, 12 m Altitude Error (1σ)

Product Roadmap: Future Developments

- Top-hat options
  - Personality card
  - Federated GPSR
  - Other aiding sensors
  - Tailored for customer applications



- USB On-The-Go software
- Software services via a Platform API
- HG1930P/N concept to other Honeywell IMU product families, e.g., HG1900 and HG1700

System architecture supports hardware/software expandability

Takeaways

- INS/GNSS design for dynamic systems is an iterative trajectory dependent process
  - High fidelity simulations provide a low cost means to iterate on the design
- Modeling of inertial sensor error characteristics which are dynamics dependent is critical
- Selection of ultra-tightly coupled integration has significant design impact

References

- Groves, Paul D., Mather, Christopher J., Macaulay, Alex A., "Demonstration of Non-coherent Deep INS/GPS Integration for Optimised Signal-to-noise Performance," *Proceedings of the 20th International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS 2007)*, Fort Worth, TX, September 2007, pp. 2627-2638

- Buck, T. M., Wilmot, J., and Cook, M. J. (2006). A high G, MEMS based, deeply integrated, INS/GPS, guidance, navigation and control flight management unit. In Proceedings of IEEE/ION Position Location and Navigation Symposium Conference, San Diego, CA. IEEE/ION

Ask the Experts – Part 1

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Senior Systems Engineer
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Principal
QuNav

Name
Title
Organization

Poll #2

Which of the following are true about the INS mechanization used in an integrated GNSS/INS system?
(Please select all that apply)

- ***The same for a given application regardless of the quality of IMU used***
- ***The same for a given quality IMU regardless of the application in question***
- ***Always the same for a given quality IMU and GNSS receiver regardless of the application***
- ***Depend on the customer requirements***
- ***None are true***

GNSS/Inertial Integration for Land Vehicles

Andrey Soloviev
Principal, *QuNav*

Example Automotive Applications

- Navigation

Road-level accuracy

- Automotive safety:
  Connected cars

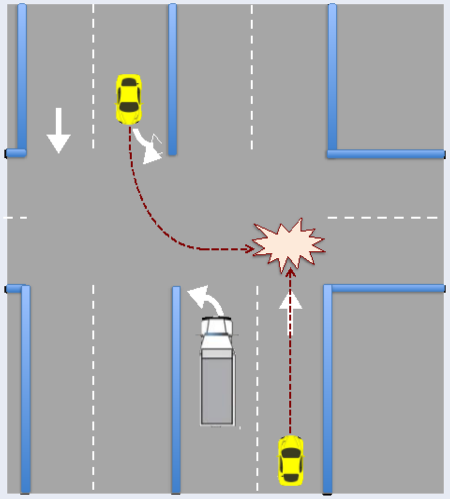
Lane-level accuracy

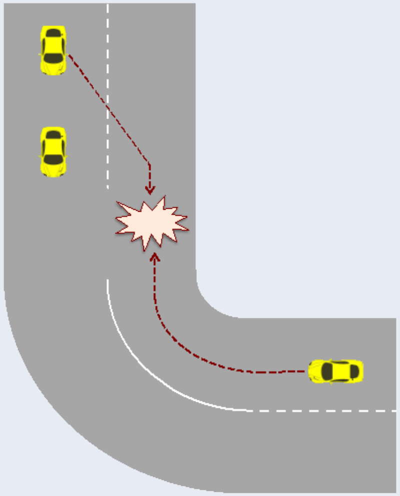
- Self-driving cars

Decimeter-level accuracy

... V2V ...

Next Gen Vehicle-to-Vehicle Communication



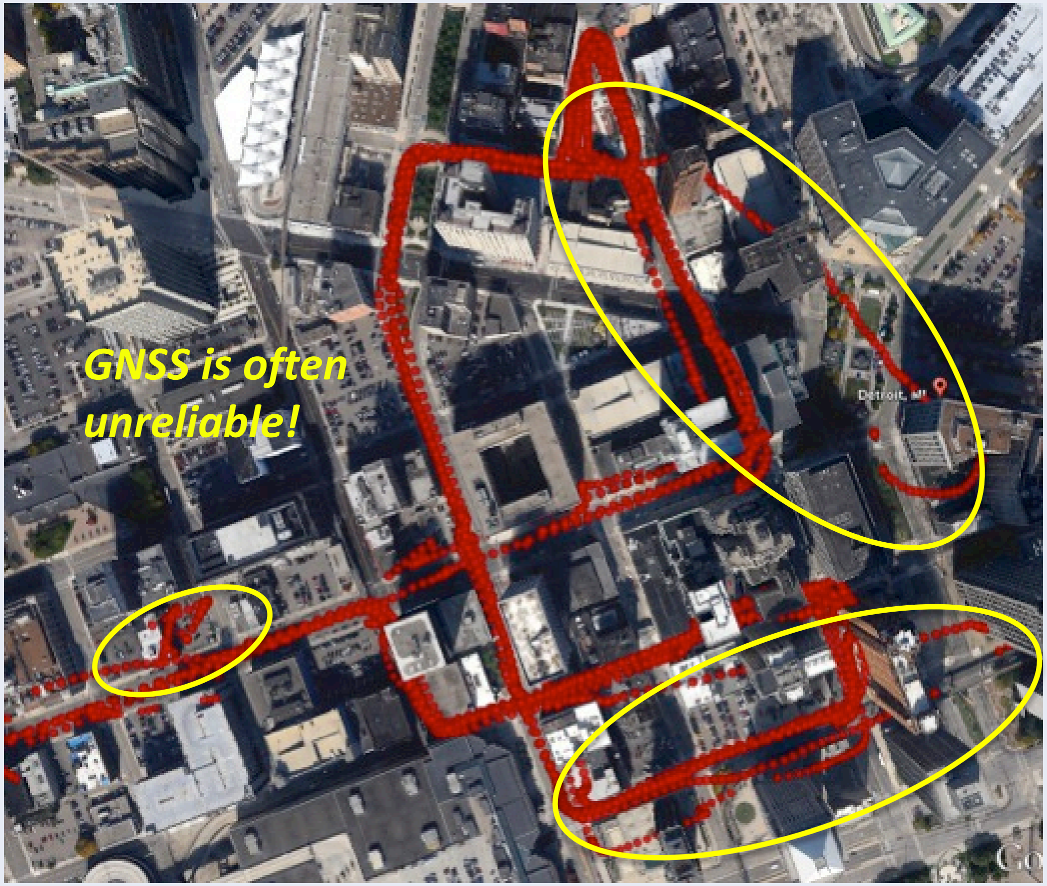


Operates in advisory mode

***No direct visibility* needed**

Preventing accidents using V2V **REQUIRES** lane level accuracy

Limitations of GNSS



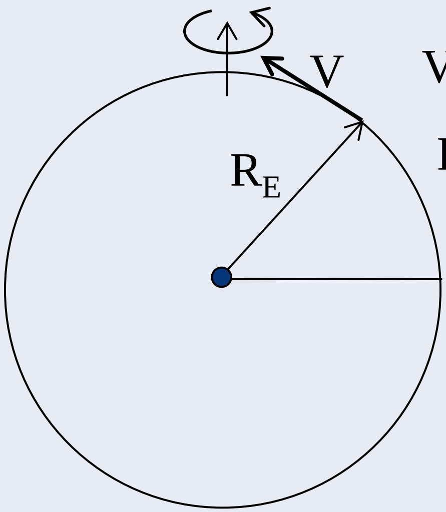
- GNSS is augmented with inertial sensors
- Consumer-grade inertial sensors must be used due to cost limitations
- Typical performance specs are:
  - 0.1 deg/s gyro drift (360 deg/hr)
  - 0.1 m/s^2 accelerometer bias

As compared to higher-grade inertials:

- ***Strapdown navigation mechanization*** is ***easier***: non-inertial effects and high-precision gravitation models do not have to be included)
- ***INS error model*** is ***easier***: high-order terms such as, for example, cross-axis sensitivity can be omitted
- The role of ***aiding data*** becomes much more ***critical***

Navigation Mechanization for Low-grade Inertial

- Non-inertial effects and sophisticated gravity models do not have to be considered since they are below the level of sensor biases



$V = 60$ mph $= 27$ m/s

$R_E = 6400$ km

Transport rate

$$\omega_{transport} = \frac{V}{R_E} = \frac{27}{6.4 \cdot 10^6} \sim 1\ \text{deg/hr}$$

Earth rate

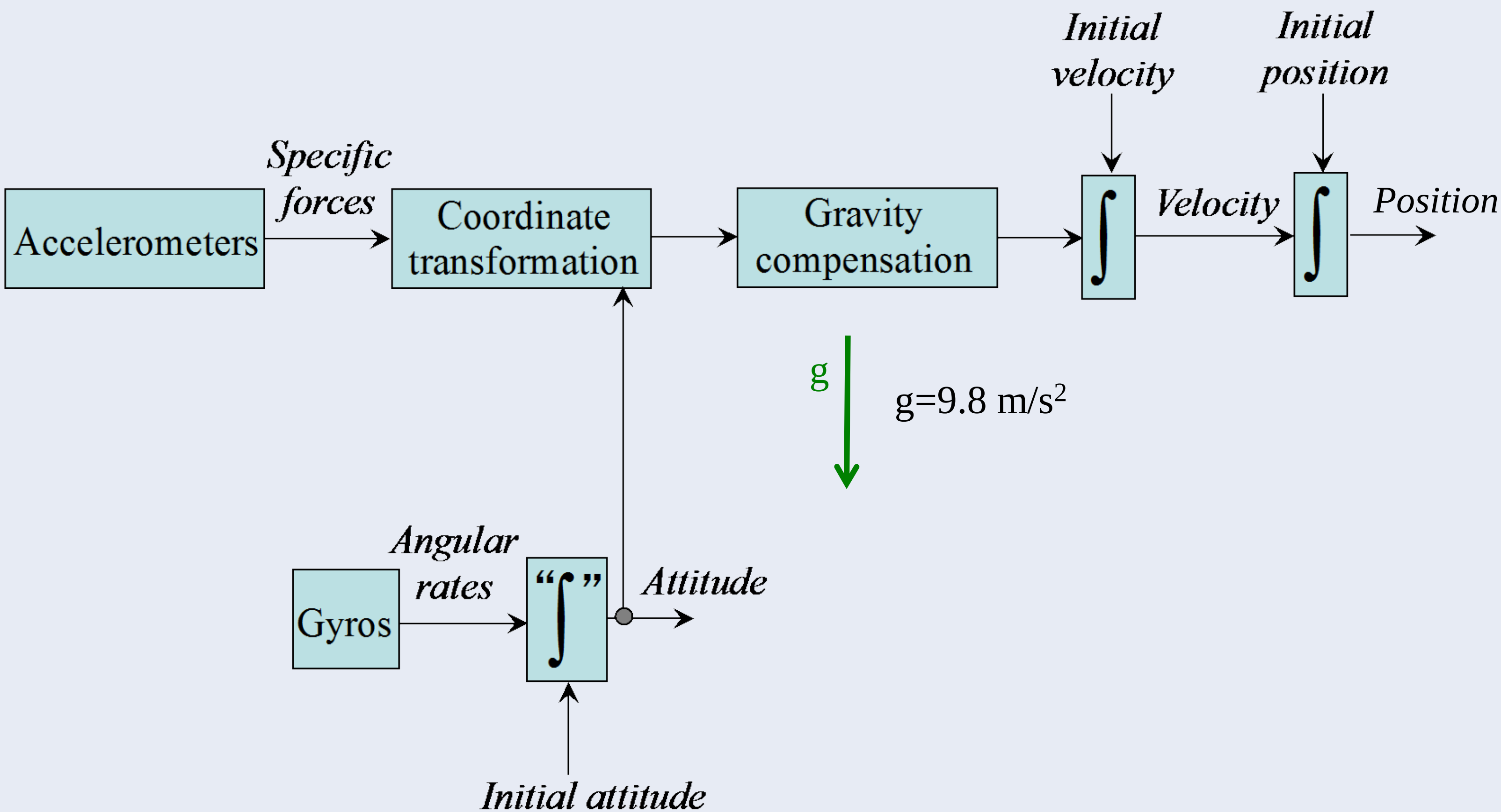
$$\Omega_{ie} = \frac{2\pi}{24 \cdot 3600} = 7.5 \cdot 10^{-5}\ \text{rad/s} = 15\ \text{deg/hr}$$

Typical gyro bias

~ 300 deg/hr

Navigation Mechanization for Low-grade Inertial

- This simplifies strapdown INS mechanization



Initial alignment for low-cost INS

- How to determine initial attitude?
- Traditionally, it is done based on gravitational acceleration and Earth rate
- However, low-cost gyros are not accurate enough to measure the Earth rate

Alternative alignment approach uses ***gravity*** and ***vehicle velocity***

- Navigation-frame velocity: measured by GNSS;
- Body-frame velocity: assumed to be aligned with the front axis of the vehicle

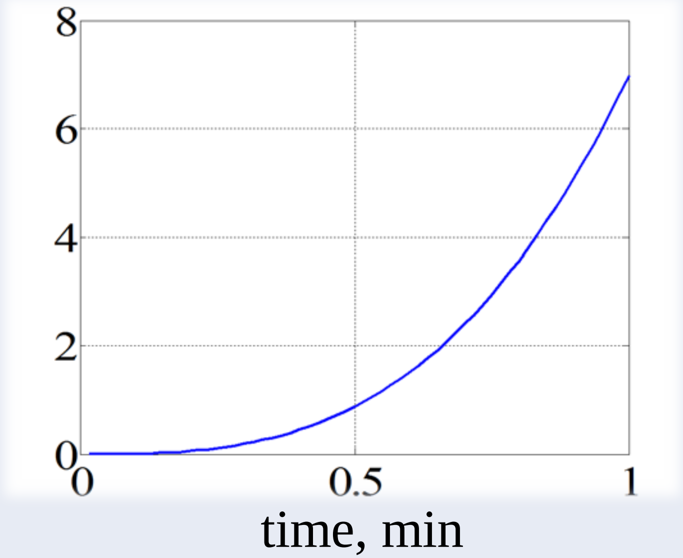
Integration with other sensors

- Stand-alone operation of INS is extremely limited

Example consumer grade IMU

MicroStrain
3DM-GX1

Position drift due to gyro drift, km



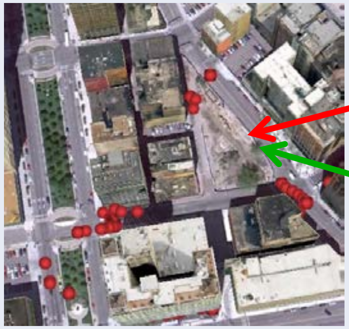
- Efficient integration with other sensors (including GNSS) is critical

What is the right integration mode?

- **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

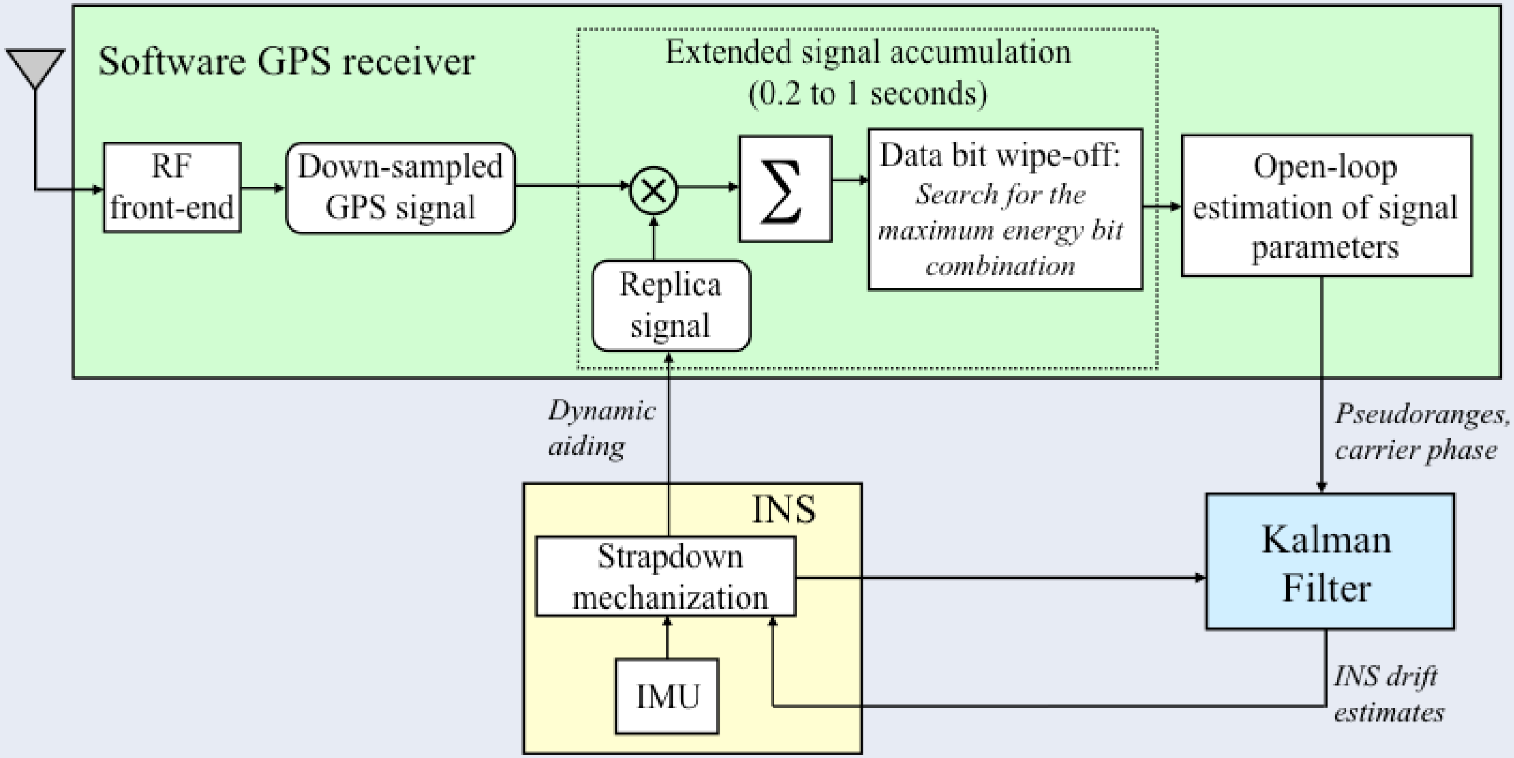
Example: sparse GNSS position fixes in urban canyon



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



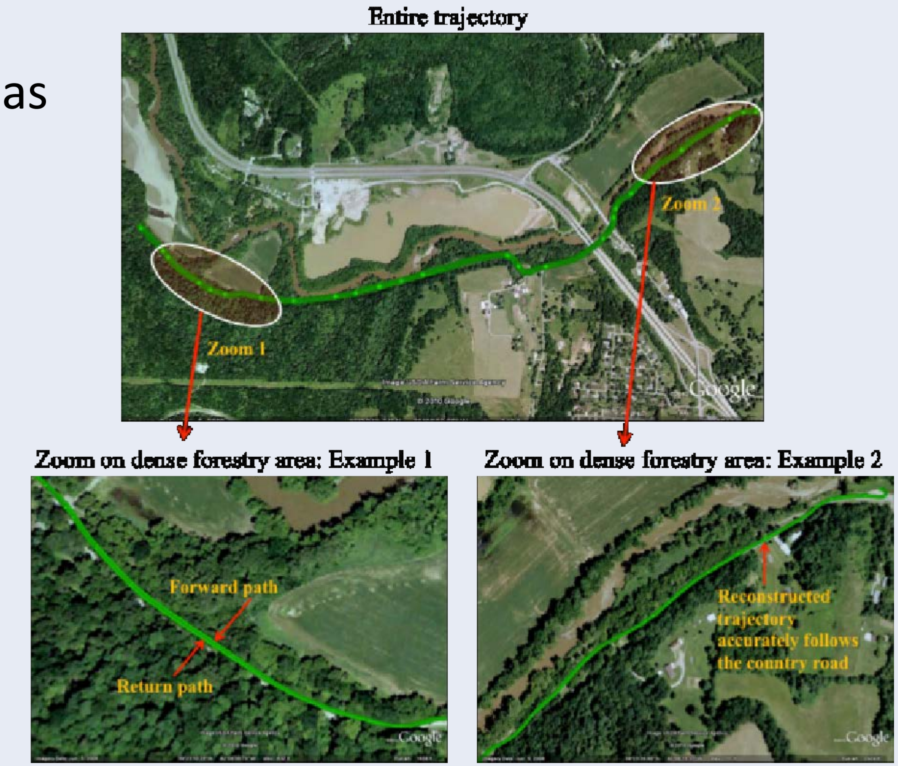
Key features:

- ***Sensor fusion at the signal processing level***;
- ***Inertial aiding of GPS signal accumulation***;
- Complete tracking status including ***tracking of the carrier phase***

Benefits of Deep Integration

- ***Deep integration*** recovers ***weak*** (attenuated) ***GNSS signals*** thus increasing the number of GNSS measurements
- It is ***beneficial*** in environments such as under ***dense tree coverage***

Example performance of deeply integrated GPS/INS under dense canopy



- However, it is very challenging to fully recover GNSS signals attenuated by buildings in dense urban environments

Which GNSS Measurements to Use?

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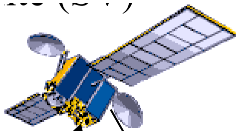
Carrier phase vs. pseudoranges:

- Carrie phase provides two-to-three orders of magnitude noise reduction;
- This significantly shortens noise averaging interval;
- ***The use of carrier phase is especially beneficial for integration with low-grade INS***:
  - Sensor errors change quicker than time intervals required to average pseudorange noise!

How To Apply Carrier Phase?

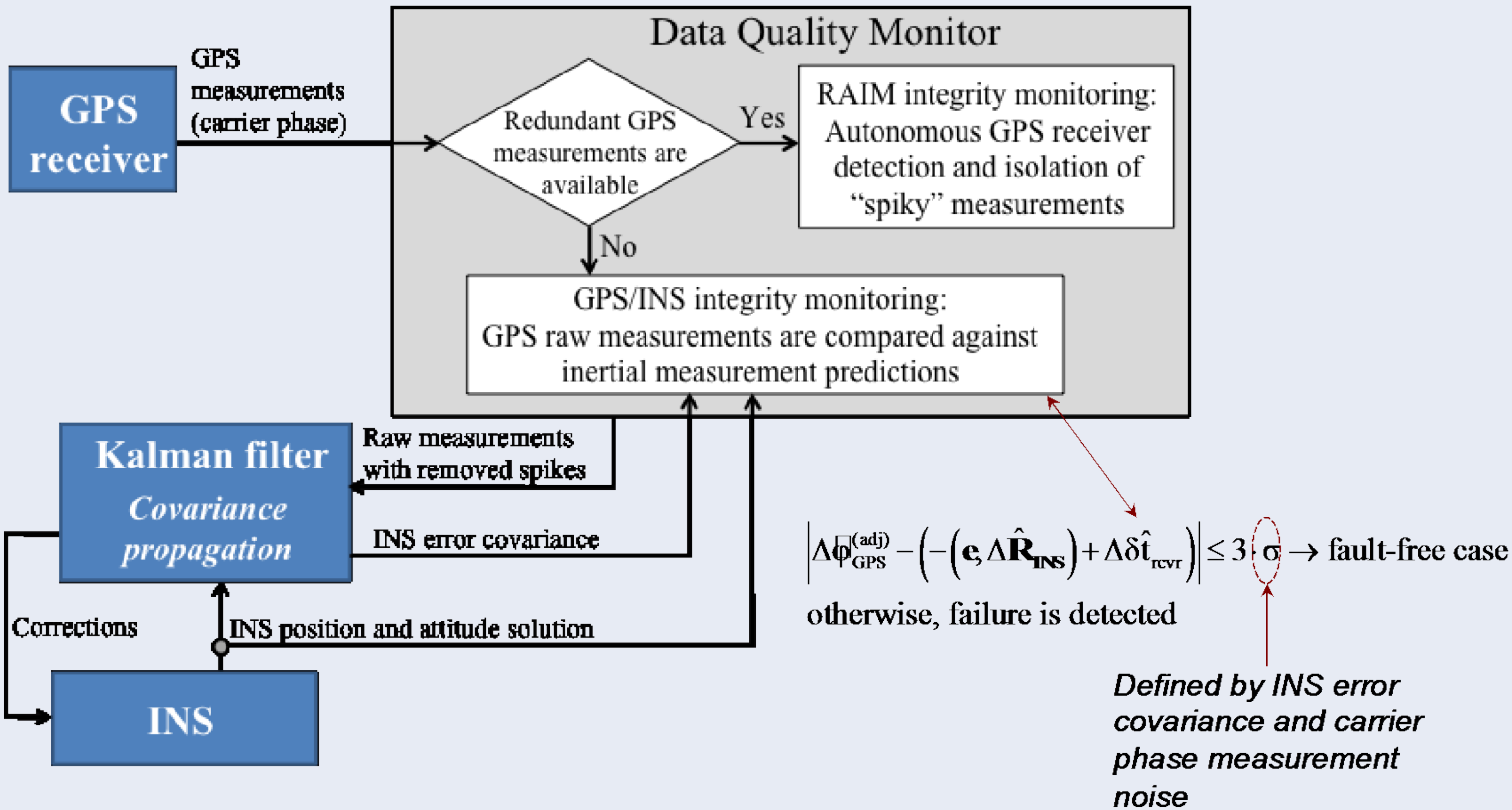


ging,
especially when a limited number of SVs is available

GNSS observables

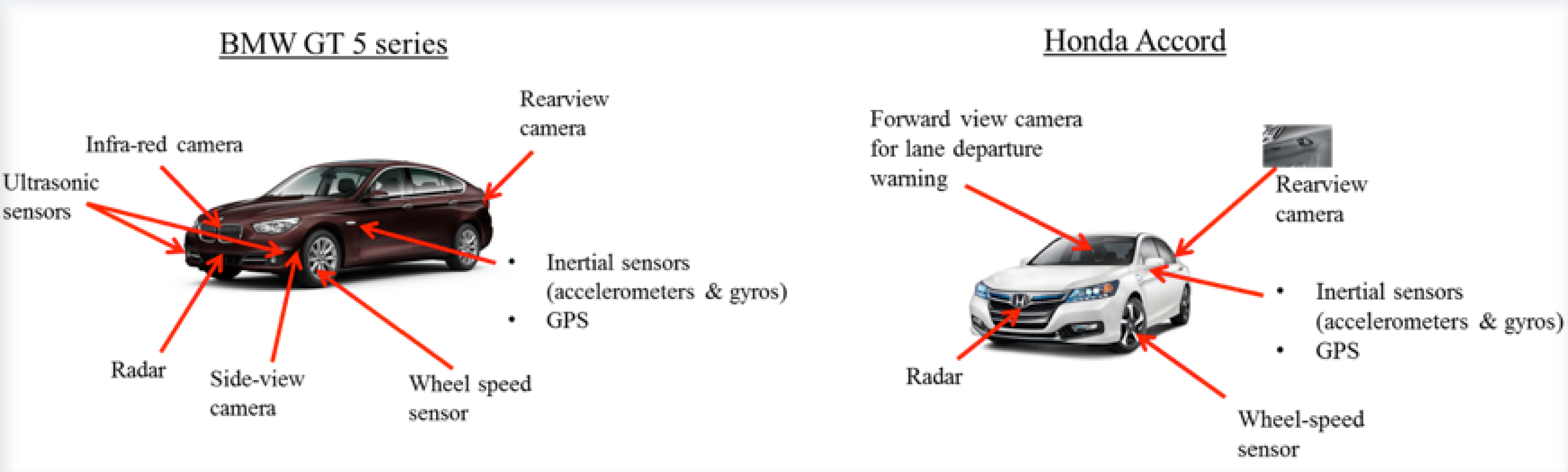
Measurement Quality Check

- Implementation of measurement quality control is critical to mitigate the influence of multipath



Addition of Other Sensors

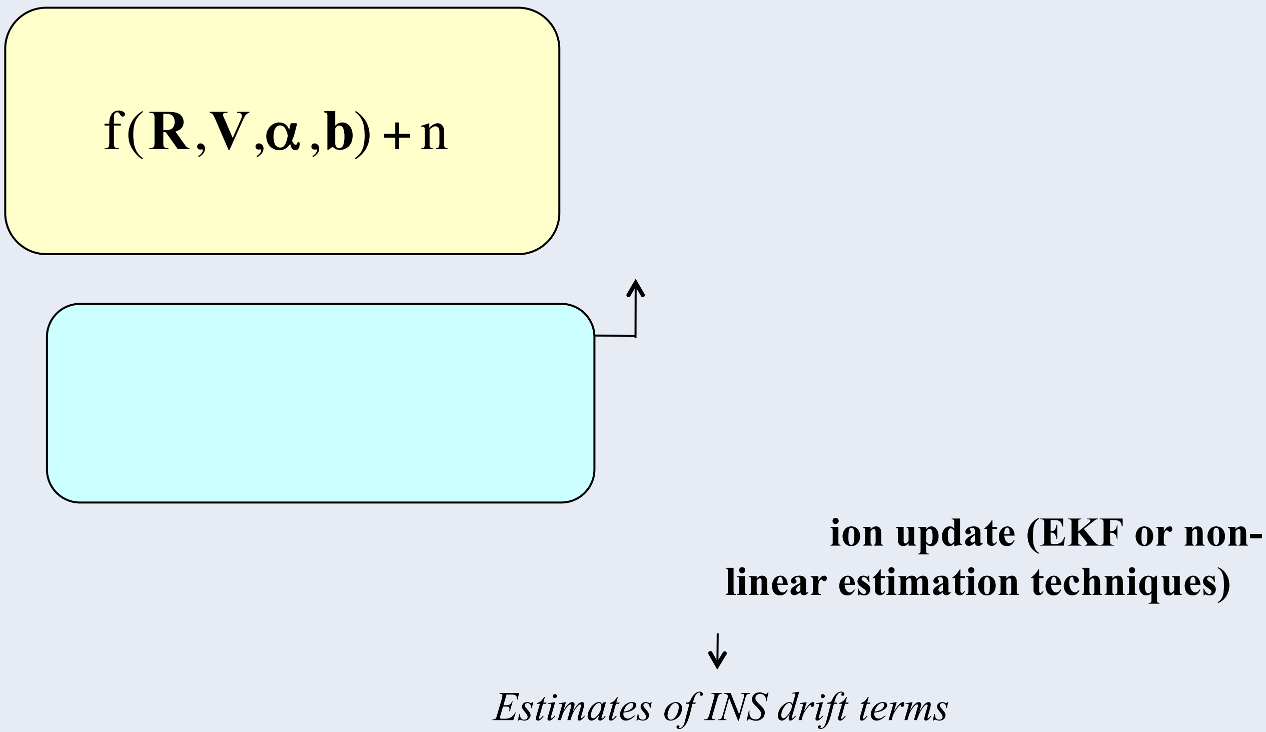
- Most modern cars have navigation-related sensors which are underutilized



- These sensors can be applied to improve performance of GNSS/INS in GNSS-challenged environments such as urban canyons

Addition of Other Sensors

- Generic integration approach
  - INS is a core sensor;
  - Other sensors provide aiding data for the inertial drift mitigation

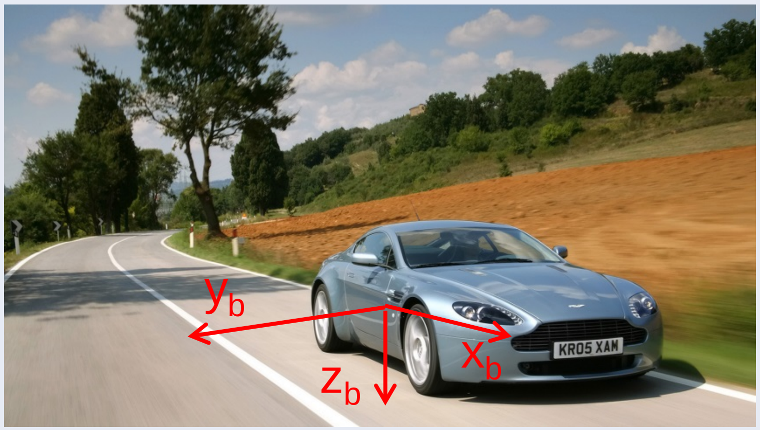


Example Implementation of GNSS/INS

- GNSS: GPS+GLONASS
- Tight coupling (carrier phase measurements are used)
- INS error model consists of 18 states including:
  - Position errors (3)
  - ***Position change errors*** (3)
  - Velocity errors (3)
  - Attitude errors (3)
  - Gyro and accelerometer biases (6)
- Use of other sensors:
  - Motion constraints (zero lateral and vertical velocity components in the body frame)
  - Monocular video camera

Motion Constraints

- Zero cross-track velocity
- Zero vertical velocity



$$V_{y_b} = 0$$

$$V_{z_b} = 0$$

Motion constraints

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

Projection matrix (H) — *Coordinate transformation from navigation into body frame*

Linearization

Velocity error — *Cross product* — *Attitude error*

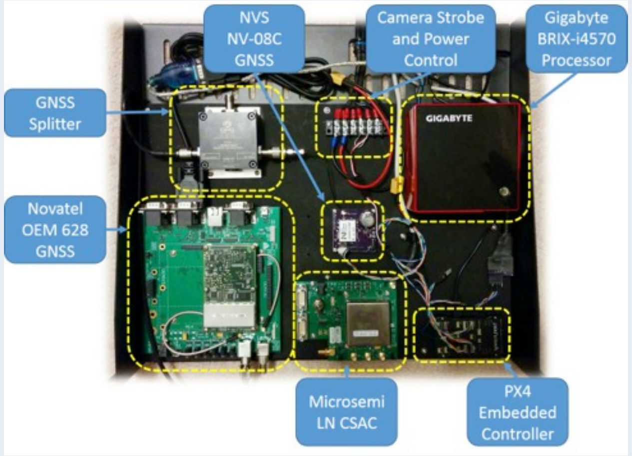
$$\begin{bmatrix}0 & 1 & 0\\ 0 & 0 & 1\end{bmatrix}\cdot \hat{\mathbf{C}}_N^b \cdot \delta\mathbf{V}_{INS} + \begin{bmatrix}0 & 1 & 0\\ 0 & 0 & 1\end{bmatrix}\cdot \hat{\mathbf{C}}_N^b \cdot \mathbf{V}_{INS} \times \delta\theta_{INS}$$

Kalman filter measurement observable

Experimental Setup

Test vehicle

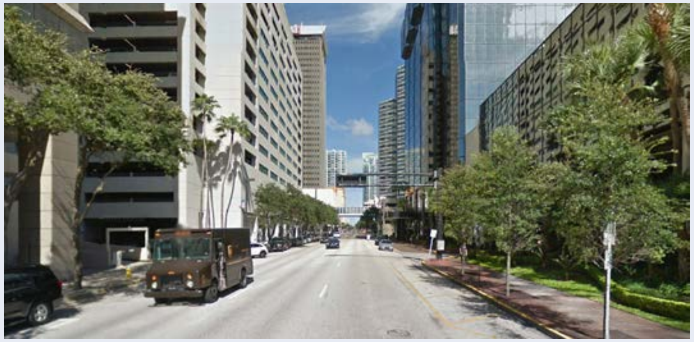
Sensor board



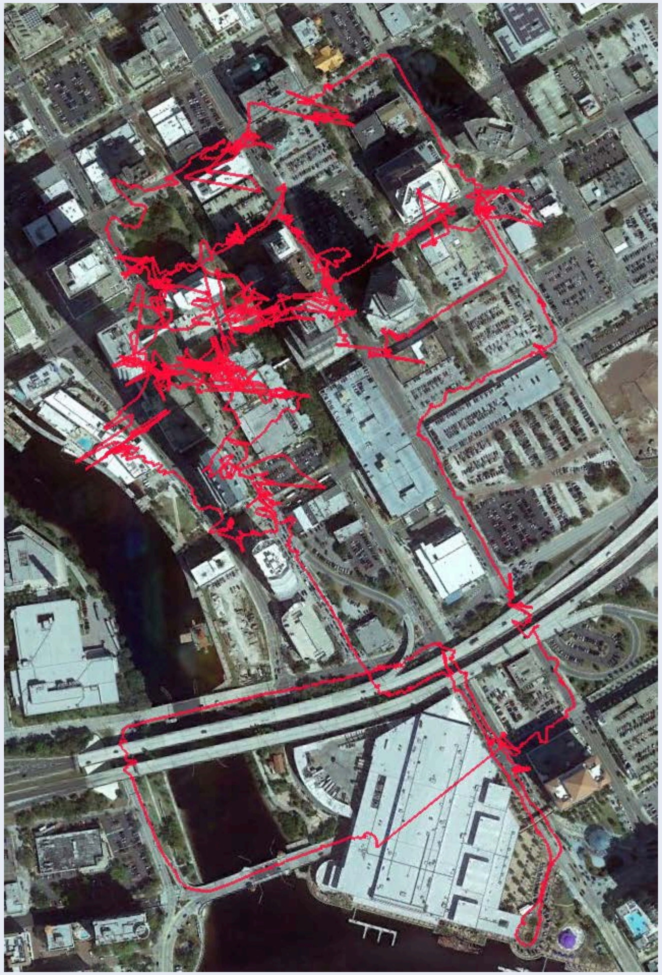
Vehicle mount

Example Test Scenario

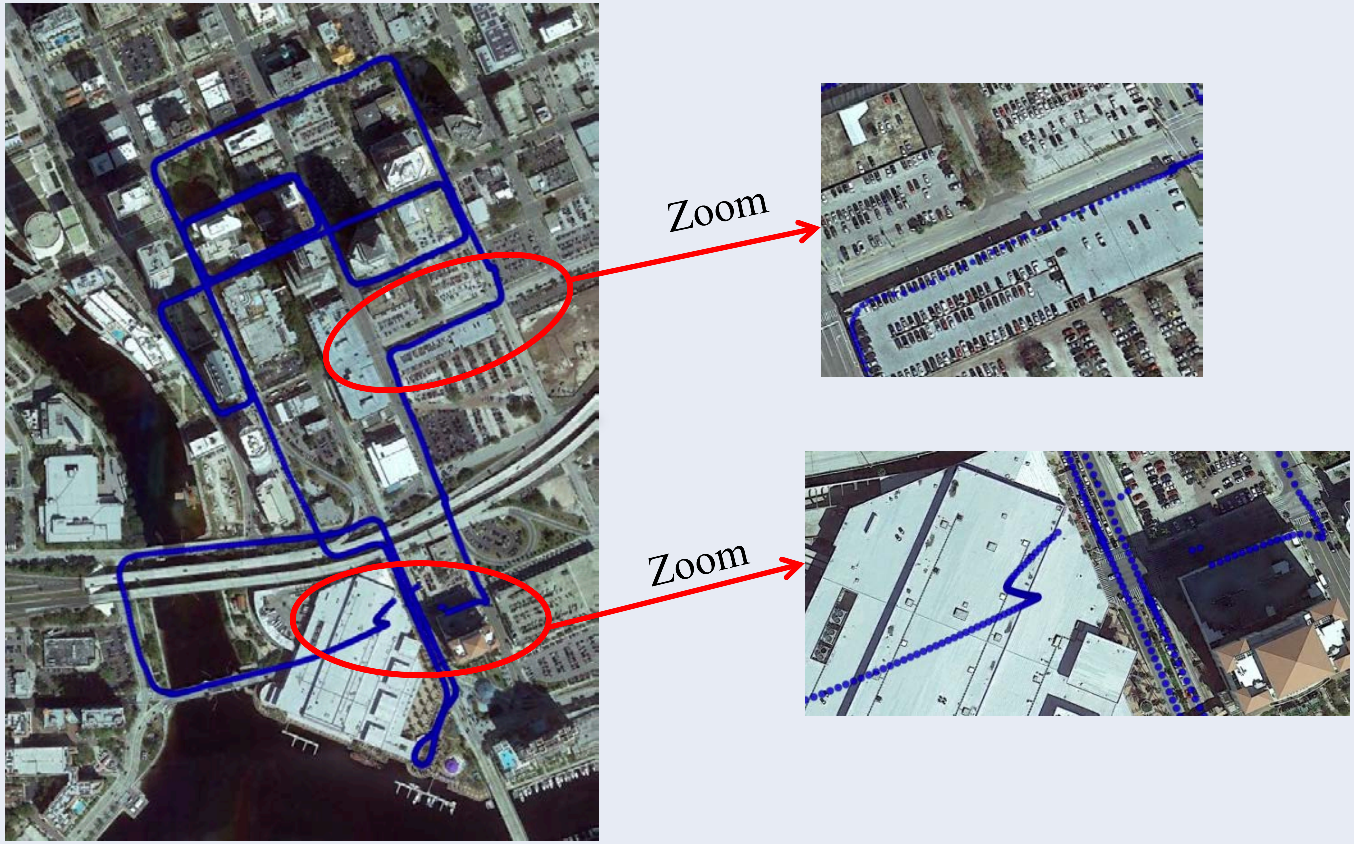
Downtown Tampa, FL



GNSS-only solution

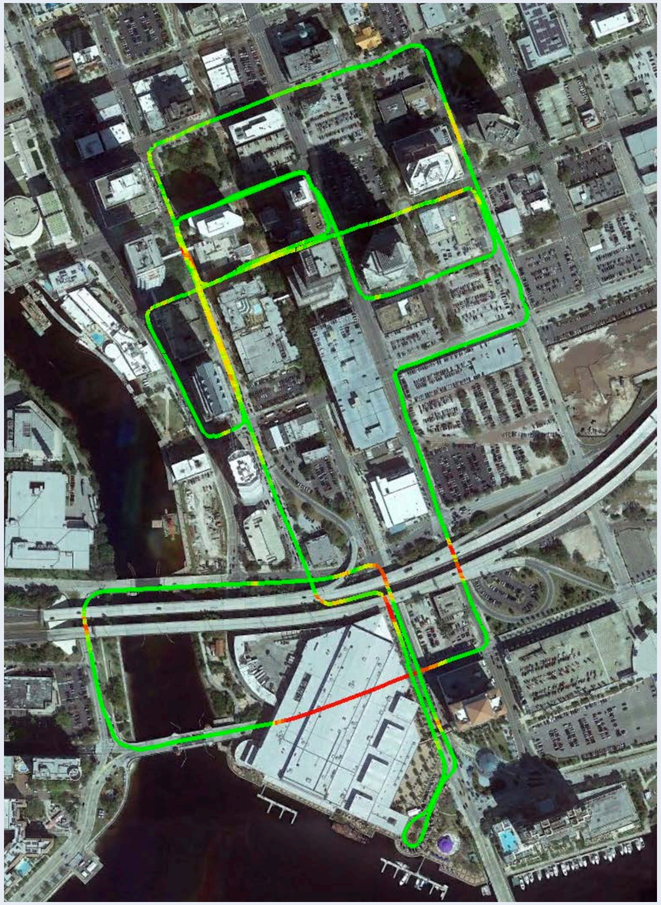


Performance of GNSS/INS



- ***Significant performance improvement*** as compared to GNSS
- However, ***some problem areas*** still ***remain***

GNSS, INS, Vision and Motion Constraints



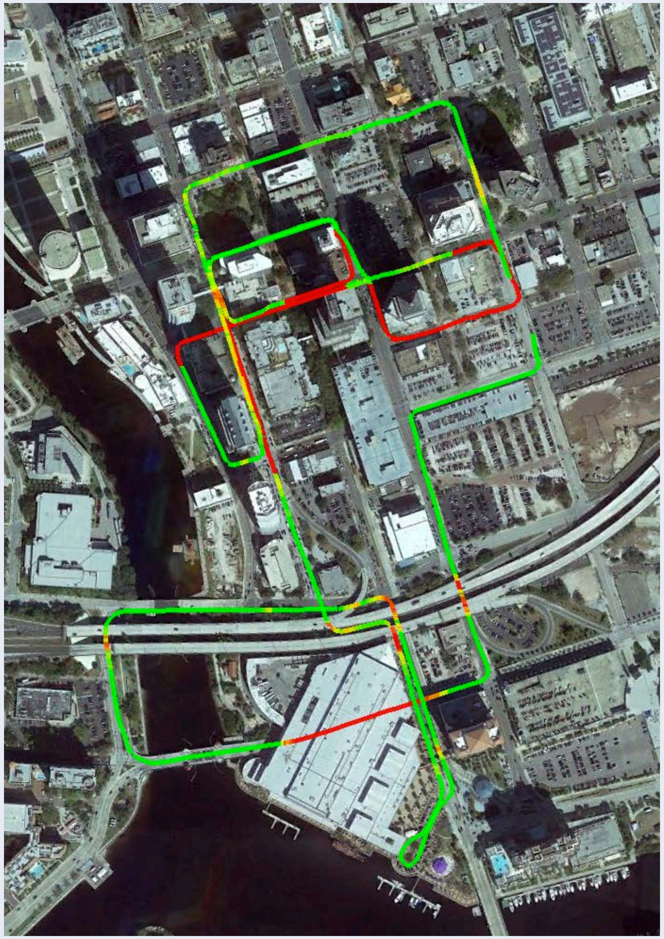
Complete GNSS outage

Zoom

Lane-level positioning accuracy is maintained!

GNSS, INS, Vision and Motion Constraints

Stressing the system with artificial GNSS outages



Complete GNSS outage

Lane-level positioning accuracy is still maintained!

Conclusion

- Integration with ***low-cost inertial sensors*** allows for ***simplification*** of ***inertial navigation mechanization*** and ***error propagation model***;
- However, proper use of ***aiding data*** is ***critical***;
- ***Tight or deep integration*** have to be used;
- ***Carrier phase measurements*** are ***most beneficial*** for mitigating the INS error growth;
- ***GNSS/Inertial*** generally does not support accurate positioning capabilities in challenging urban environments;
- ***Low-cost augmentation with other sensors*** enables ***accurate localization*** for all driving scenarios

Next Steps

- **Visit www.insidegnss.com/webinars** for a PDF of the presentations and a list of resources.
- Review the recorded version of today's webinar

Contact Info:

- **Novatel– www.novatel.com/**
- **Inside GNSS- www.insidegnss.com**

Poll #3

Do you believe advanced technologies i.e. chip scale atomic clocks and cold atom systems will eliminate the need for GNSS ? (please select one)

- *Yes*
- *No*
- *Probably*
- *Probably not*
- *Don't know*

Ask the Experts – Part 2

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