

InsideGNSS

GPS | GALILEO | GLONASS | BEIDOU

sponsored by  **NovAtel**

CASE STUDIES IN GNSS/INS INTEGRATION



Tuesday, December 15, 2015



WELCOME TO Case Studies in GNSS/INS Integration



Tom Jakel
Senior Systems Engineer
Honeywell Aerospace



Andrey Soloviev
Principal
QuNav

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*



Sheena Dixon
Product Manager
NovAtel

Case Studies in GNSS/INS Integration

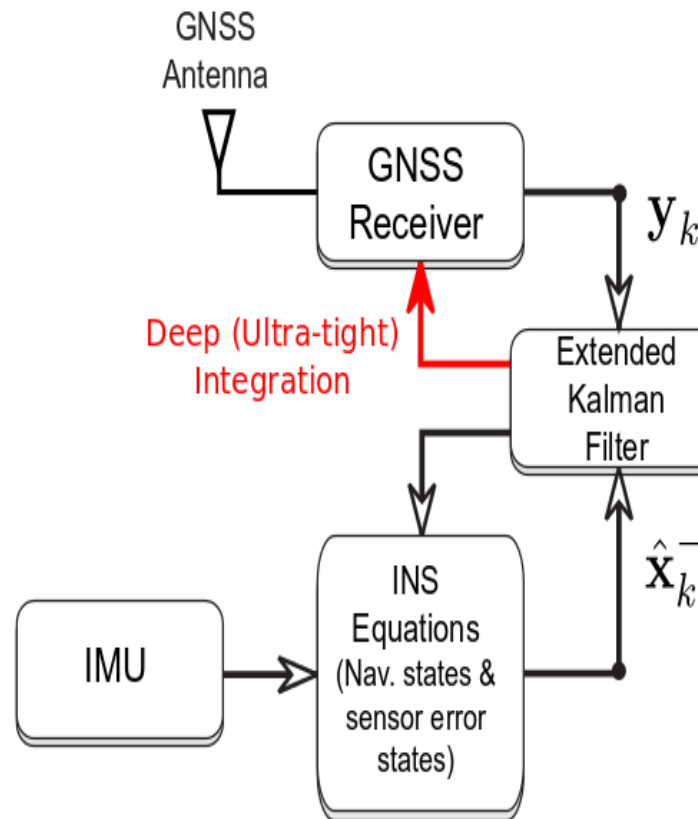


Demoz Gebre-Egziabher
Aerospace Engineer and
Mechanics Faculty
University of Minnesota

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*



- **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

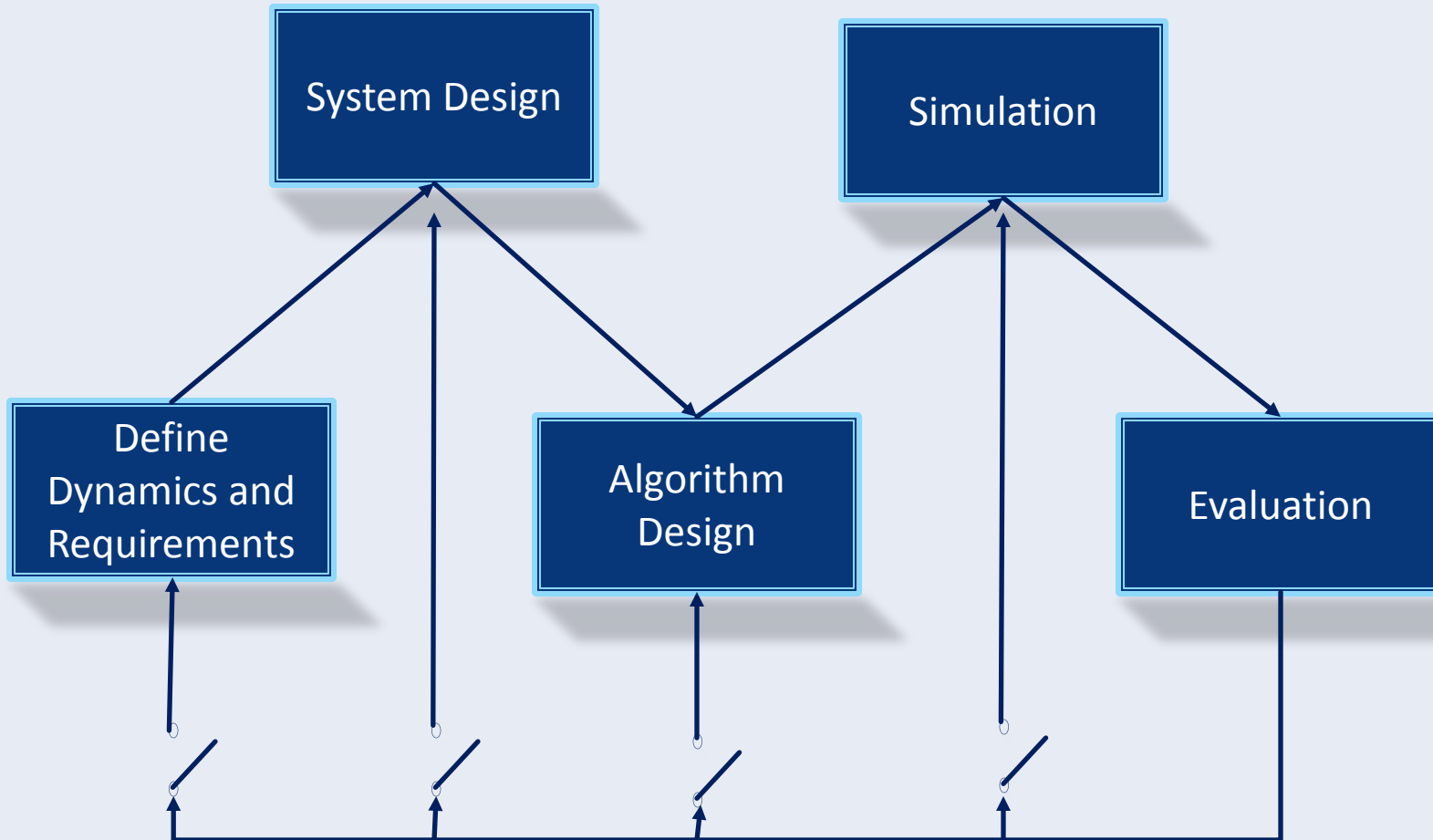
Modular System Design for a Range of High Dynamic Applications



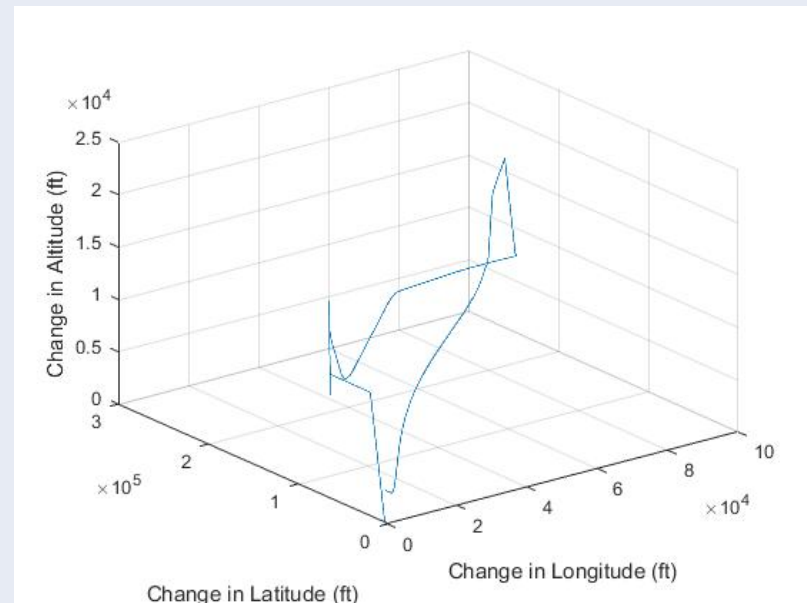
Thomas Jakel
Sr. Systems Engineer
Honeywell Sensor Guidance
and Navigation COE

- 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





- 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



- 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

	HG1930	HG1900	HG1700	HG9900
Volume (in³)	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/g²)	40	17	17	
Power (W)	2.6	3.5	6.5	<10

- 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 Repeatability (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

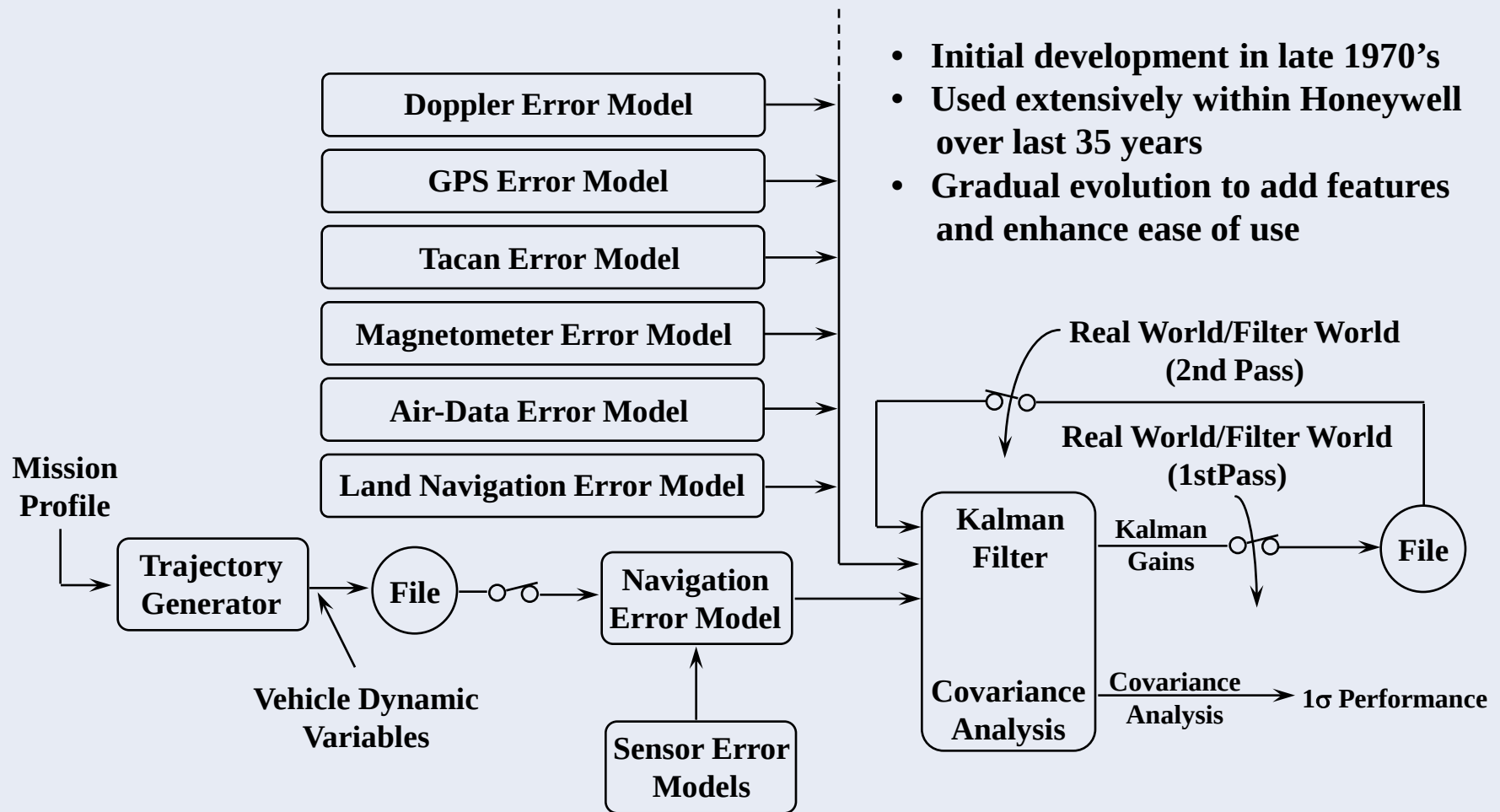
Example Honeywell MEMS sensor technology

- Navigation 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

- Accept NCO commands from external sources
- Output I_s and Q_s 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

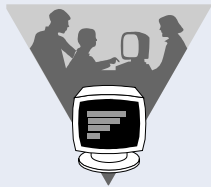
- Covariance simulation
 - Linear models of error characteristics
 - $s = g(x)$
 - Single run statistical assessment

- 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



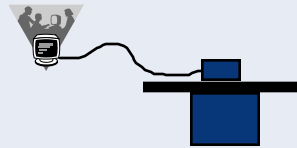
- Gyroscope Scale Factor
- Maneuver – 180° Roll
- No state in EKF – Scale Factor for HG1930 AA50 from [Specification](#) – 1000 PPM
 - Attitude Error = $1000 \text{ PPM} * 10^{-6} \text{ PPM/Part} * 180^\circ = 0.18^\circ$
 - Velocity Error $\approx 0.18^\circ * \pi / 180 \text{ rad/}^\circ * 9.81 =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

- 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



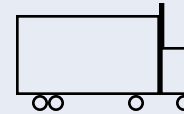
Off-line Simulation Tools

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



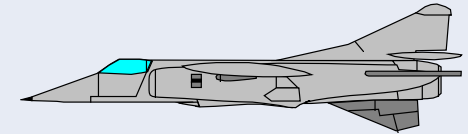
Laboratory Test

- 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

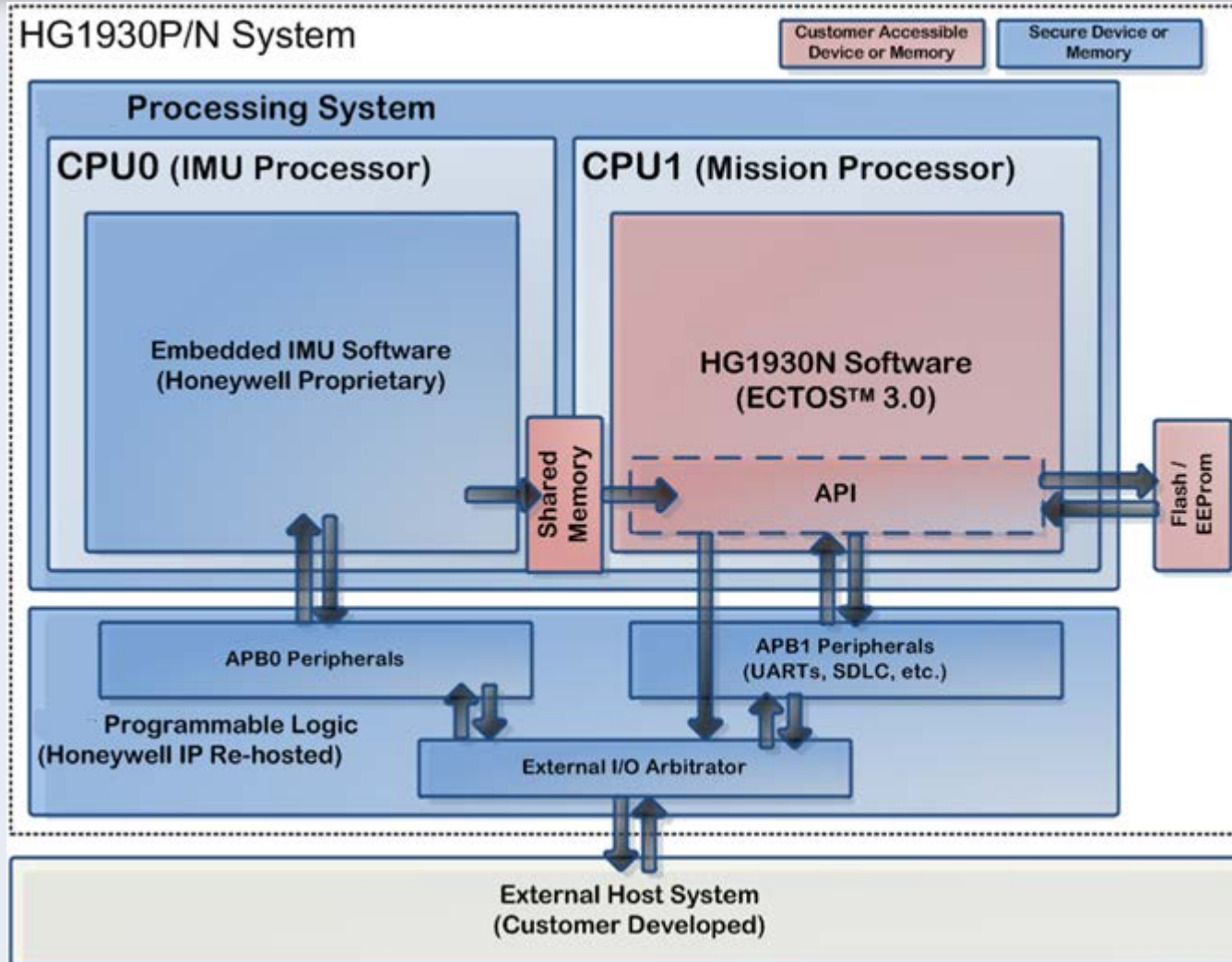
- True application environment

- 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.

- 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



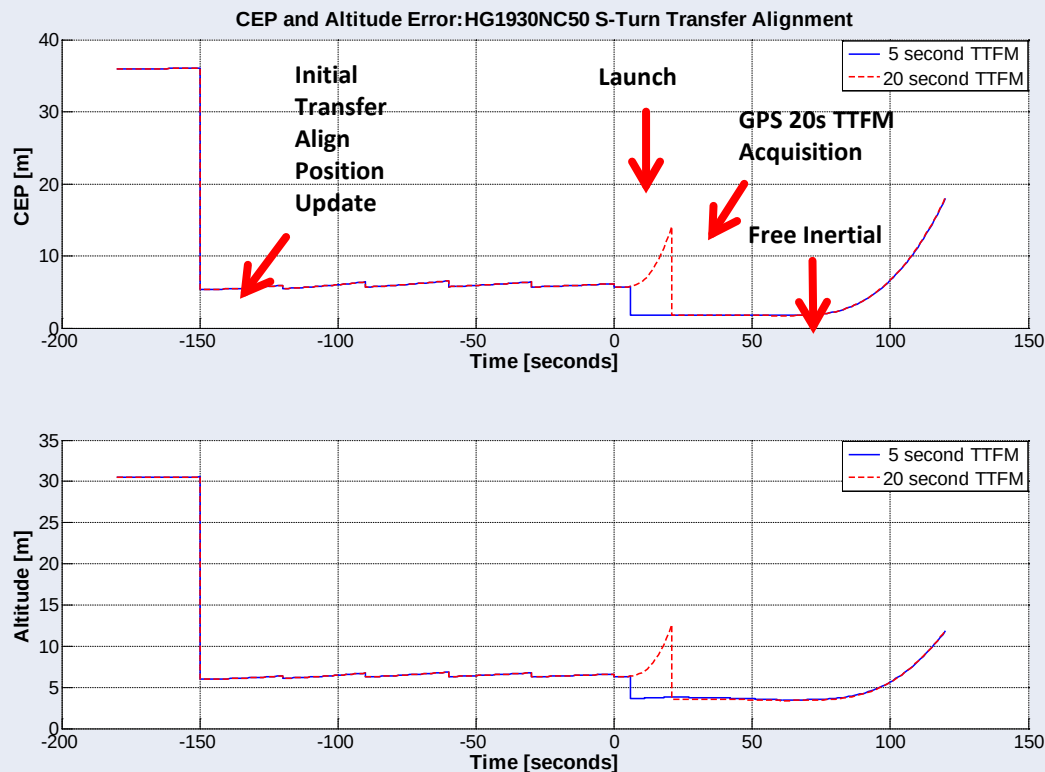
Honeywell's new flexible low cost, small SWaP, MEMS INS



Secure and open INS architecture

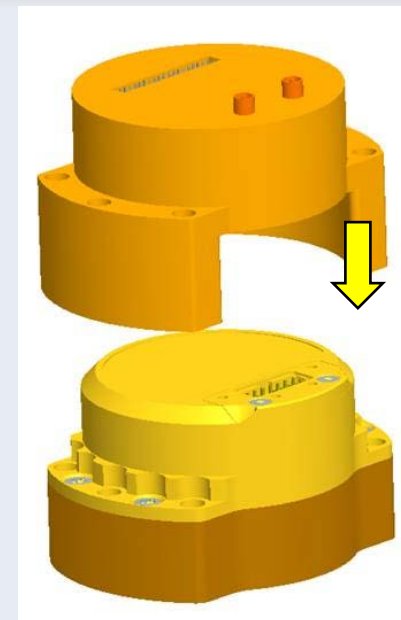
- 14 Pin Connector
- Design decision for volume, commonality of production and cost
- Mitigate limitations with configurability
- Up to 5 UARTs
 - 4 Mbaud capable – useful for low latency NCO commands
- SDLC port
- Additional pin options
 - Time Mark Input/Output
 - Discrete Input/Out
 - IMU Strobe/External Sync
- Both single-ended and differential signals supported on ports 3, 4 & 5
- Additional I/O supports varied Navigation usage

- 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)

- 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

- 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

- 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



Tom Jakel
Senior Systems Engineer
Honeywell Aerospace



Andrey Soloviev
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*

Navigation



Road-level accuracy

Automotive safety: Connected cars



Lane-level accuracy

Self-driving cars



Decimeter-level accuracy



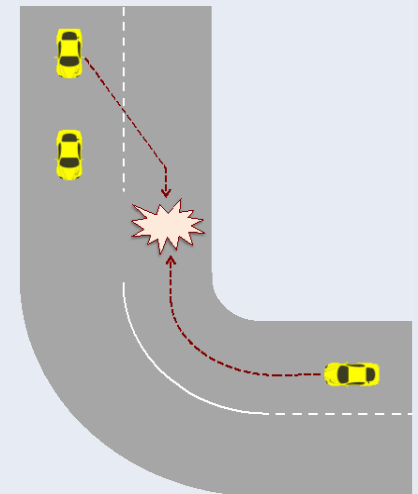
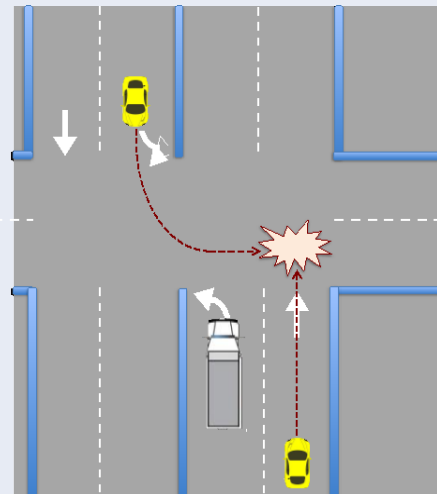
... V2V ...

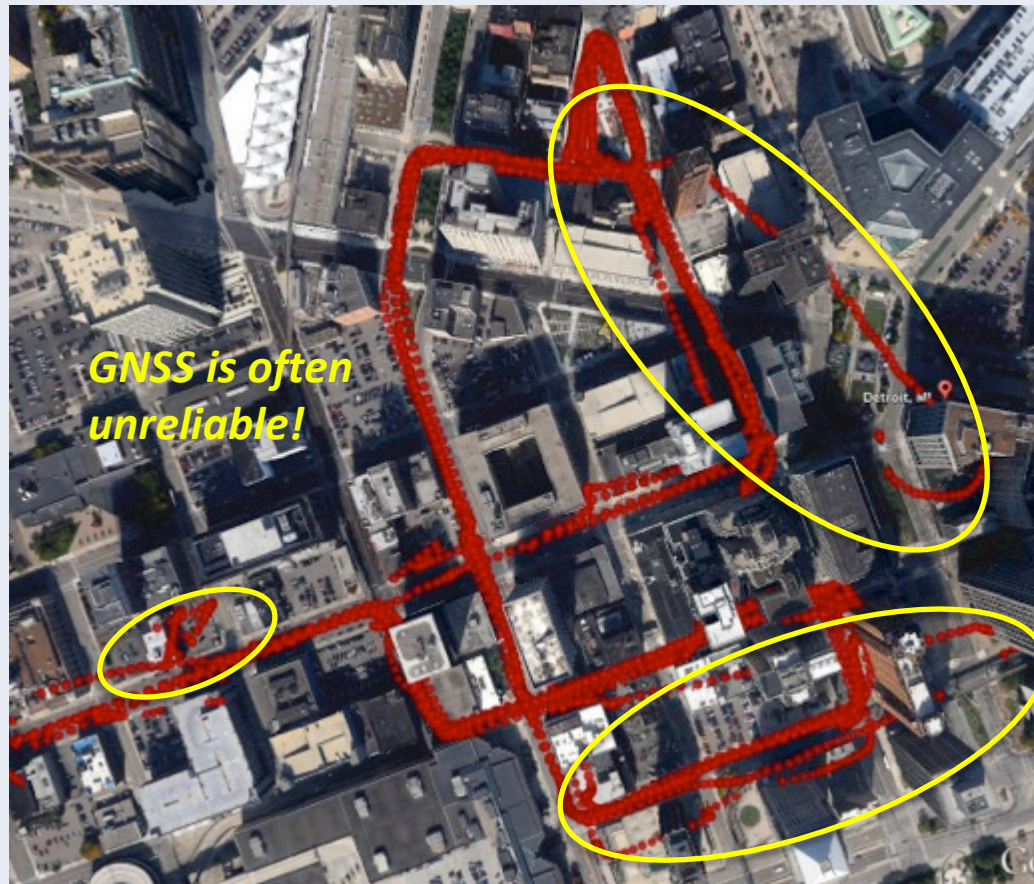
Next Gen Vehicle-to-Vehicle Communication

Operates in advisory mode

No direct visibility needed

Preventing accidents using V2V
REQUIRES lane level accuracy



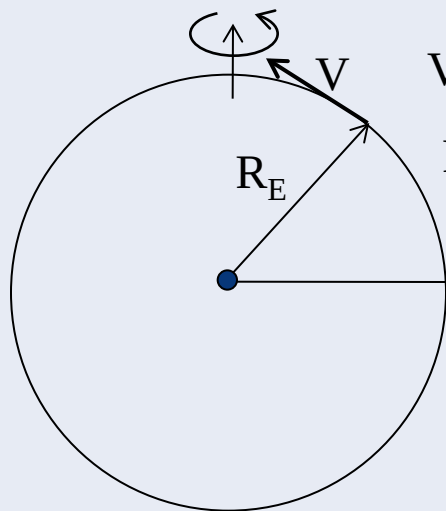


- GNSS is augmented with inertial sensors
- Consumer-grade inertial sensors must be used due to cost limitations
- Typical performance specs are:
 - 0.1 deg/s gyro drift (360 deg/hr)
 - 0.1 m/s² accelerometer bias

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**

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



$$V = 60 \text{ mph} = 27 \text{ m/s}$$

$$R_E = 6400 \text{ km}$$



Transport rate

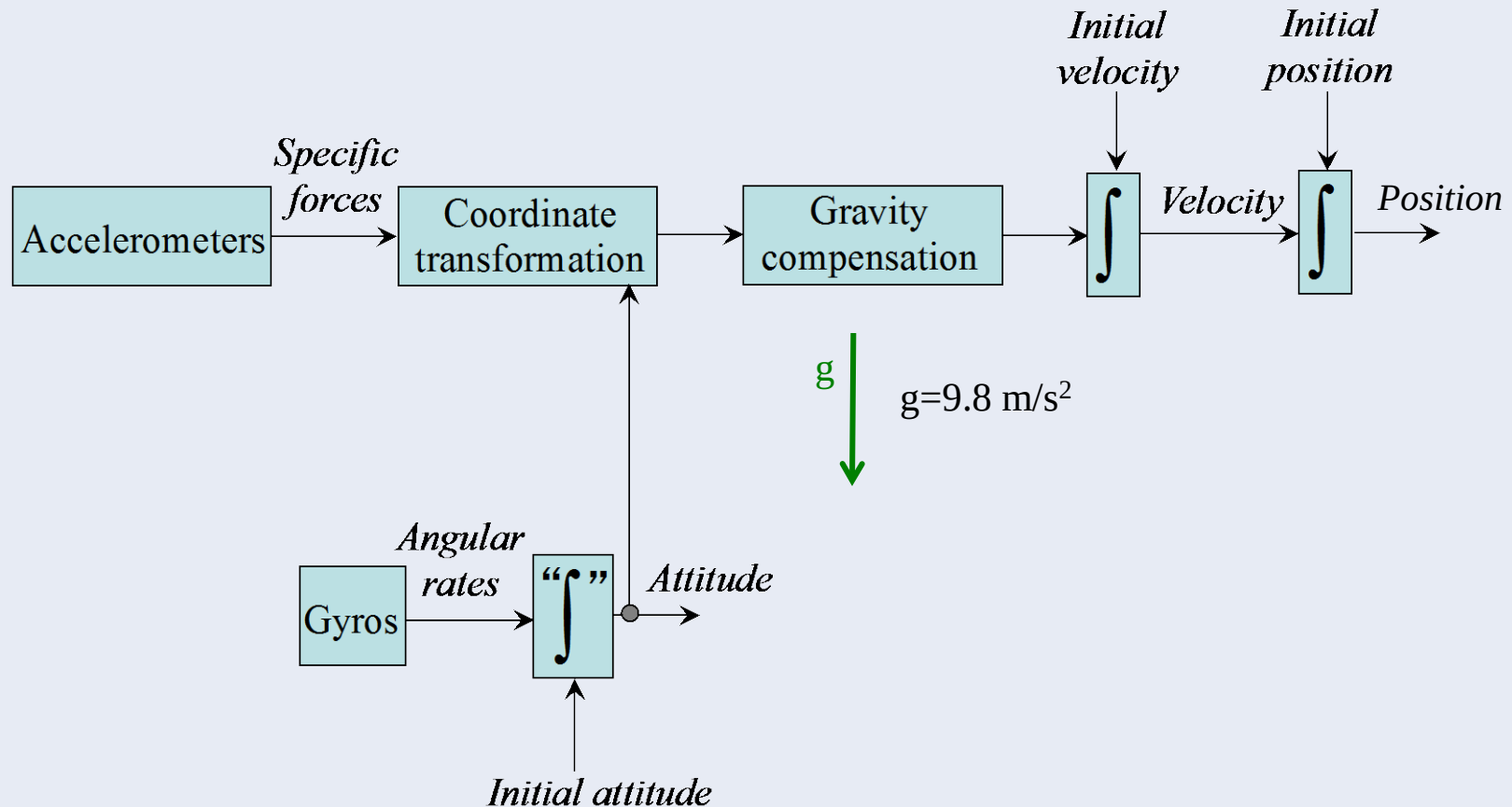
$$\omega_{\text{transport}} = \frac{V}{R_E} = \frac{27}{6.4 \cdot 10^6} \sim \underline{1 \text{ deg/hr}}$$

Earth rate

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

Typical gyro bias
 $\sim 300 \text{ deg/hr}$

- This simplifies strapdown INS mechanization



- 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*

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



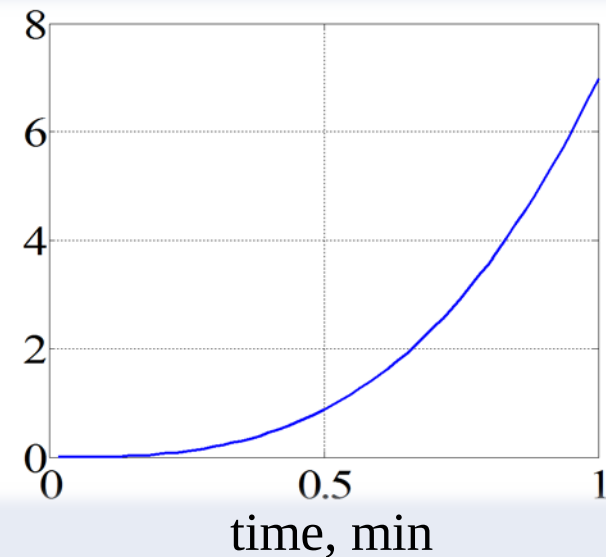
- Stand-alone operation of INS is extremely limited

Example consumer grade IMU



MicroStrain
3DM-GX1

Position drift due to gyro drift, km



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

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

Loose integration has limited capabilities in GNSS-challenged environments

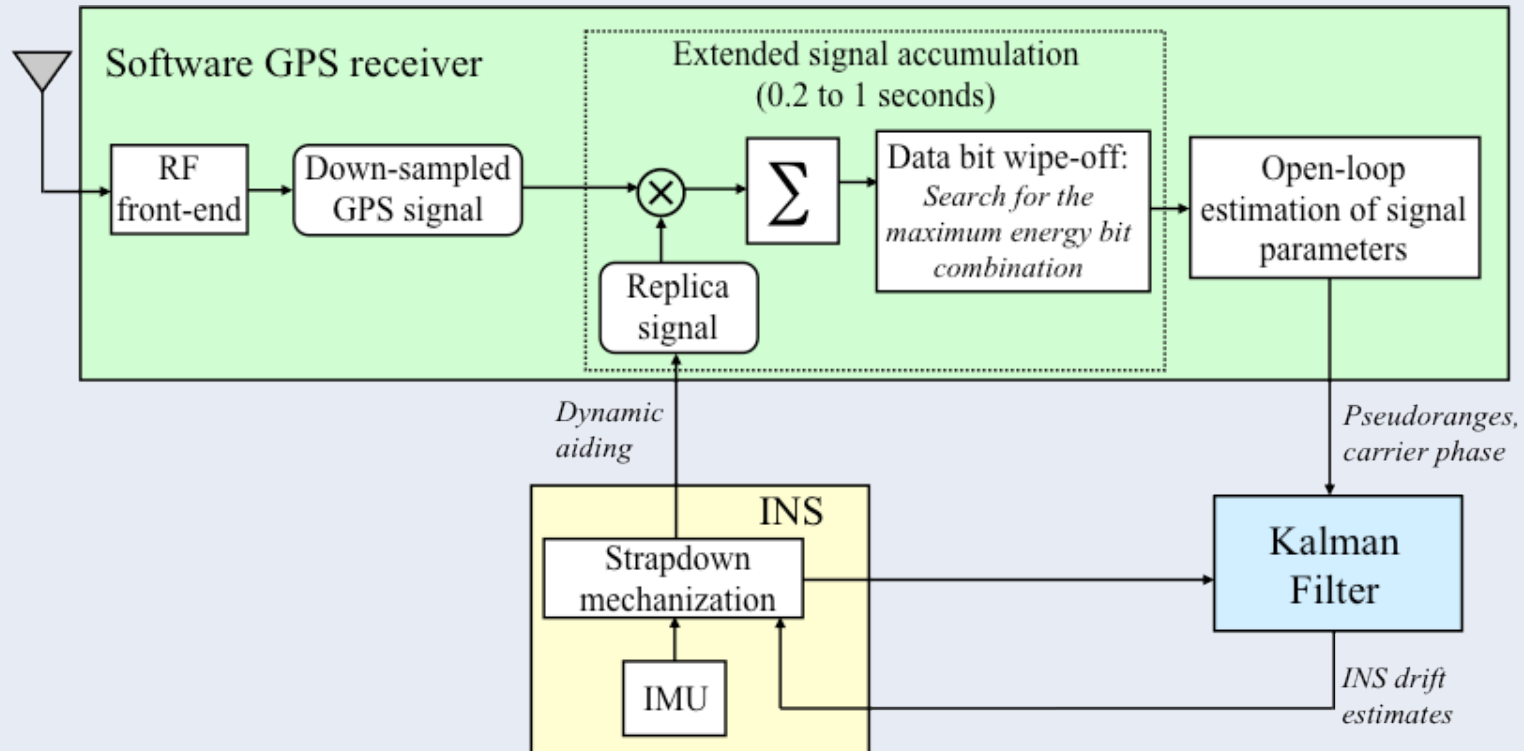
Example: sparse GNSS position fixes in urban canyon



No GNSS data for loose integration

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

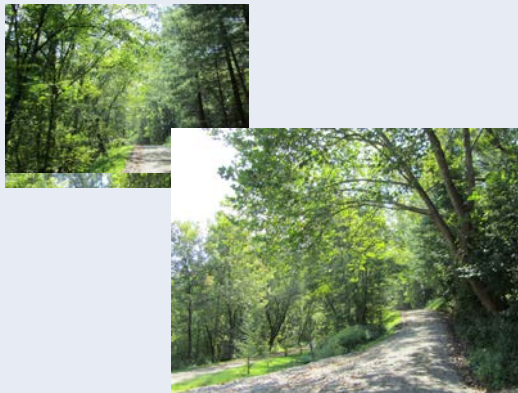
Tight and deep integration are more suitable for GNSS-challenged environments and integration of inertial with other sensors



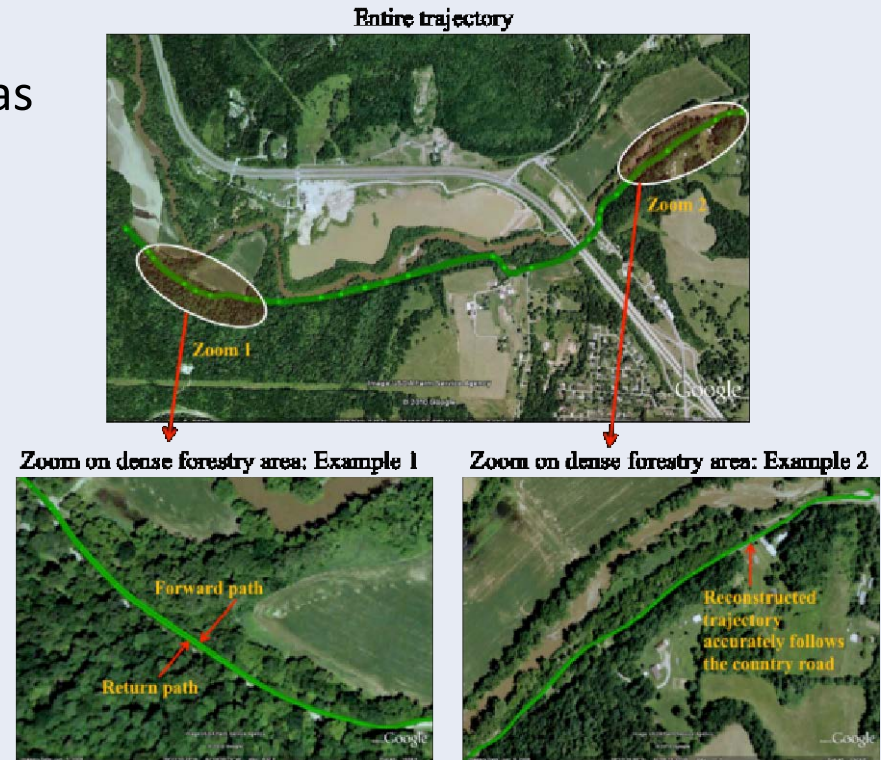
Key features:

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

- **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**



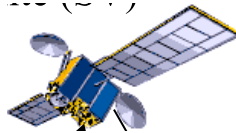
Example performance of deeply integrated GPS/INS under dense canopy



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

Carrier phase vs. pseudoranges:

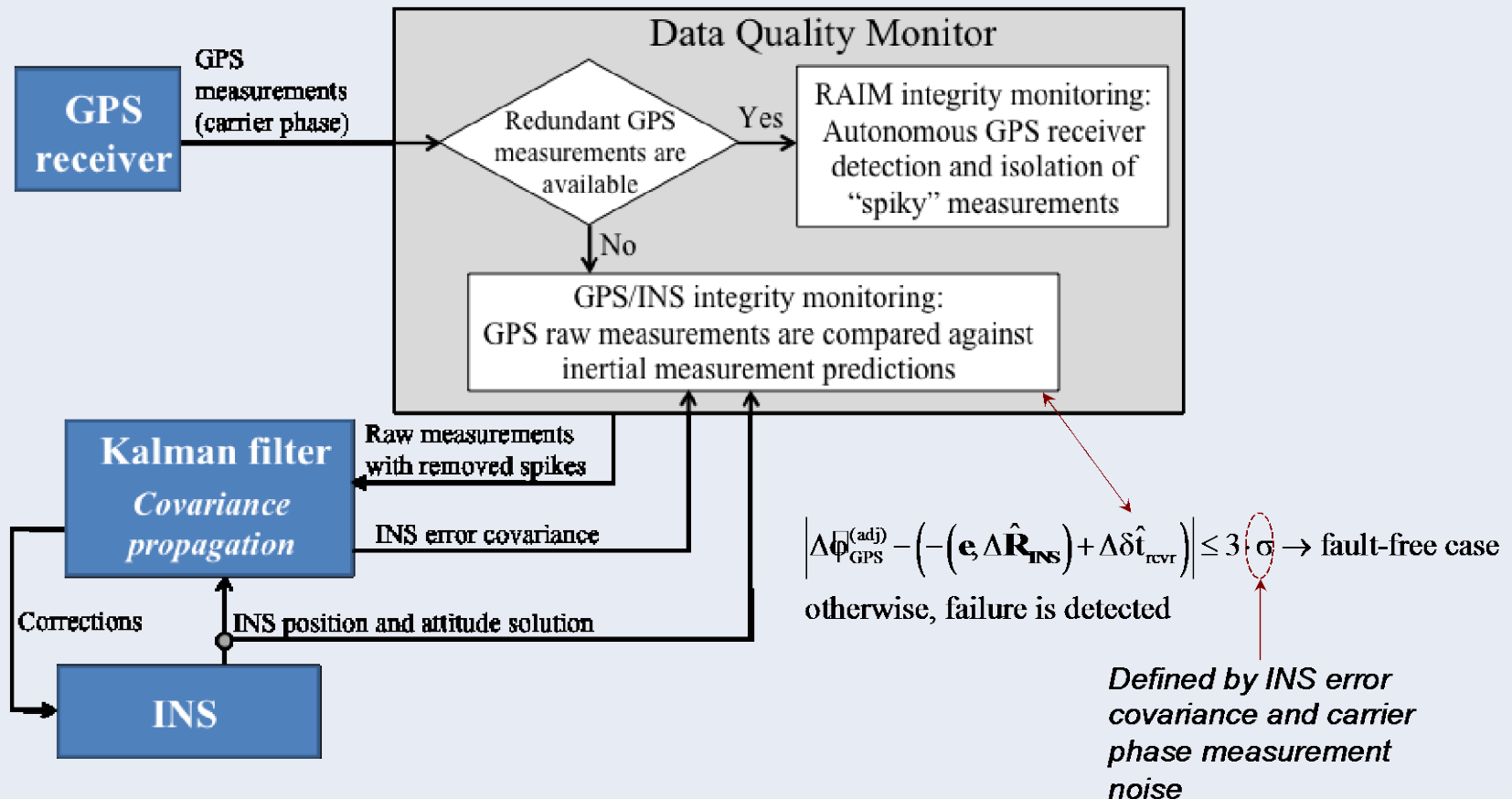
- o Carrier phase provides two-to-three orders of magnitude noise reduction;
- o This significantly shortens noise averaging interval;
- o ***The use of carrier phase is especially beneficial for integration with low-grade INS:***
 - ✧ Sensor errors change quicker than time intervals required to average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



especially when a limited number of SVs is available

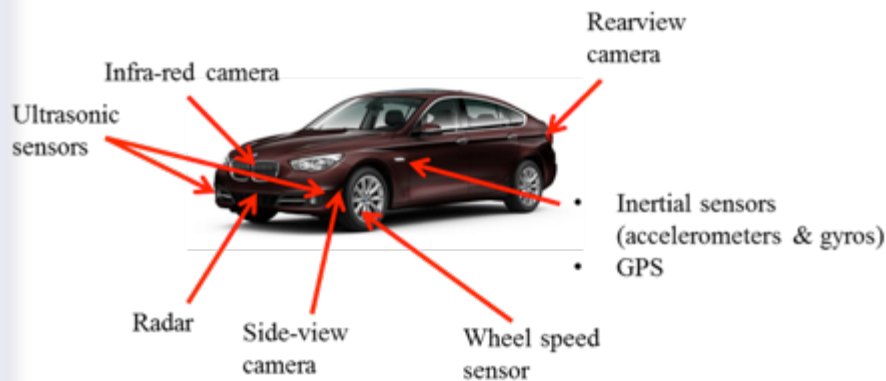
GNSS observables

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

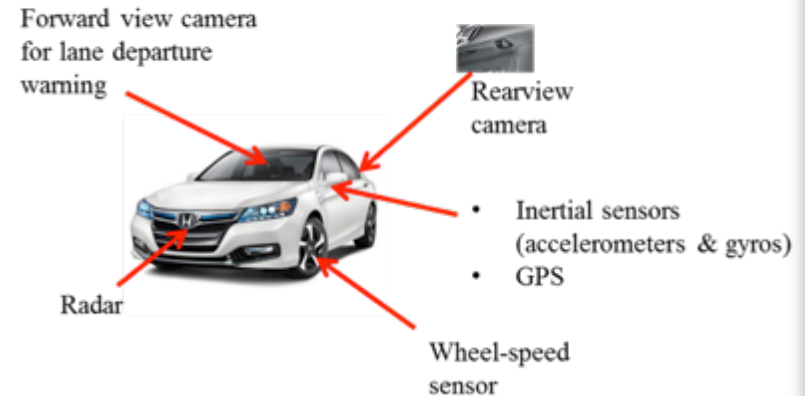


- Most modern cars have navigation-related sensors which are underutilized

BMW GT 5 series

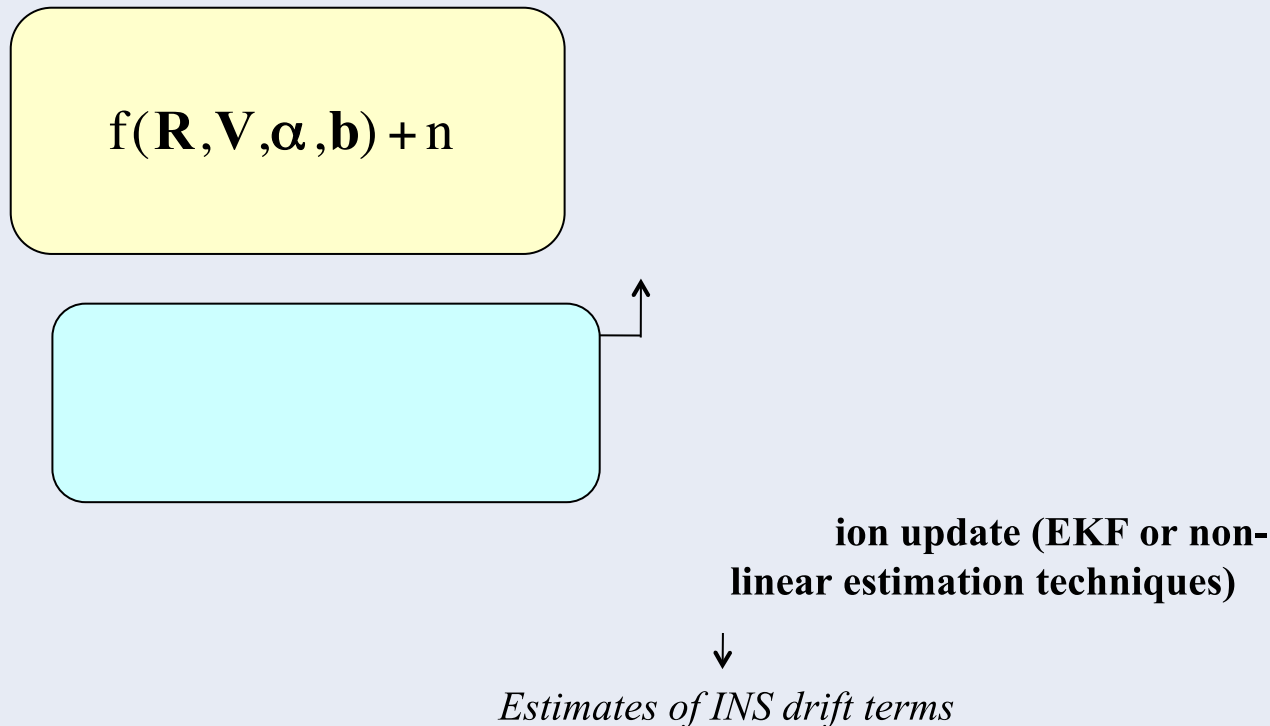


Honda Accord



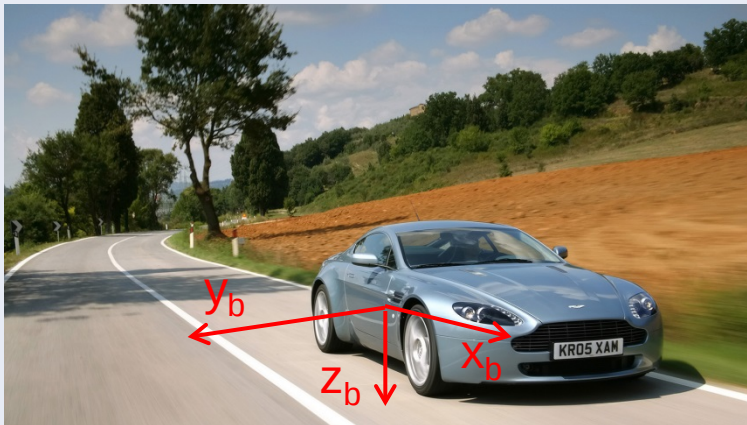
- These sensors can be applied to improve performance of GNSS/INS in GNSS-challenged environments such as urban canyons

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



- 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

- o Zero cross-track velocity
- o Zero vertical velocity



$$\mathbf{V}_{y_b} = 0$$

$$\mathbf{V}_{z_b} = 0$$

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

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

Velocity error Cross product Attitude error

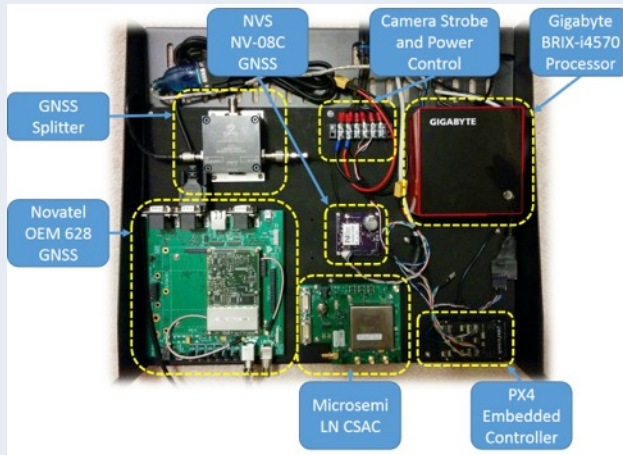


Kalman filter measurement observable

Test vehicle



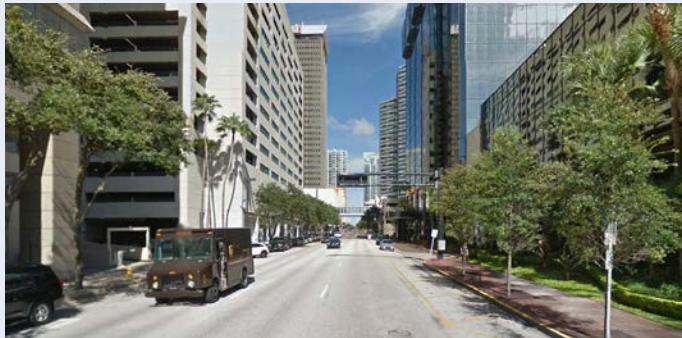
Sensor board



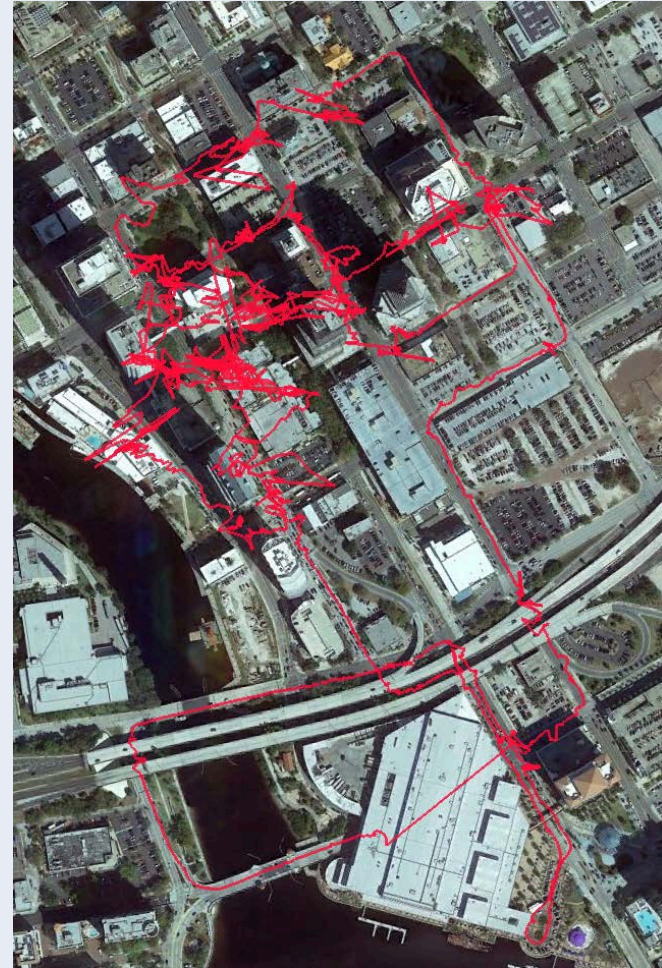
Vehicle mount

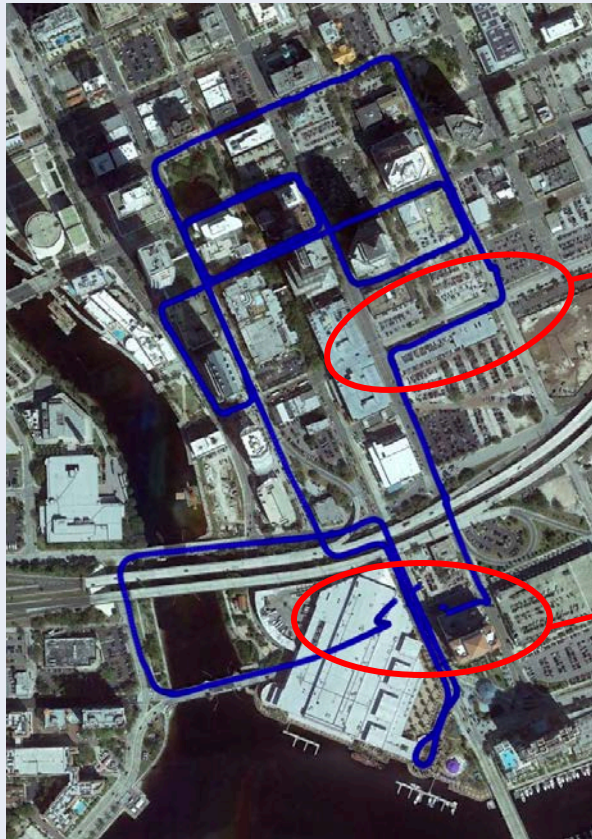


Downtown Tampa, FL



GNSS-only solution

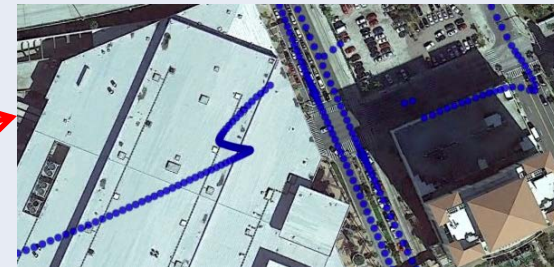




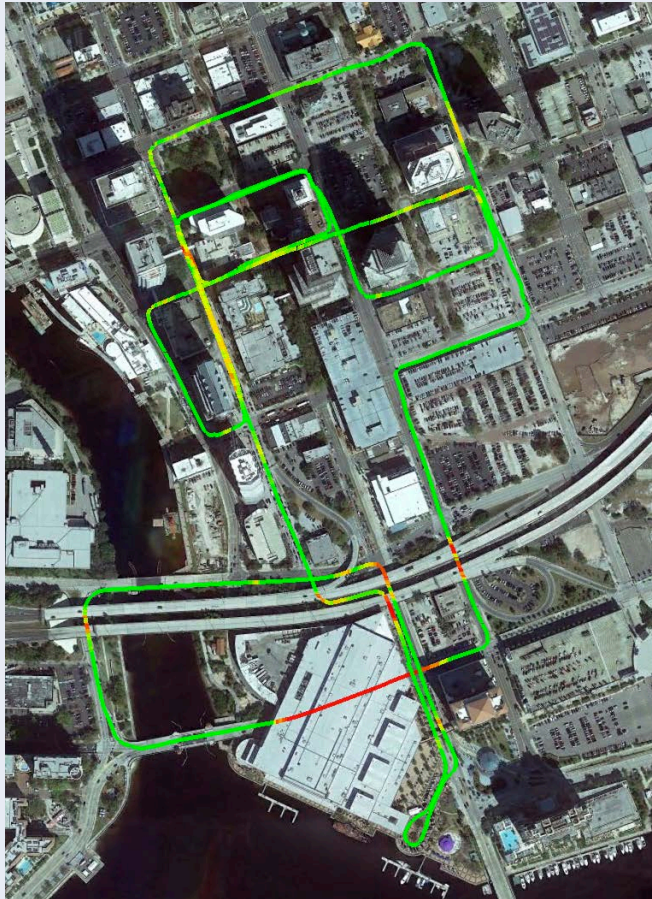
Zoom



Zoom



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



— Complete GNSS outage

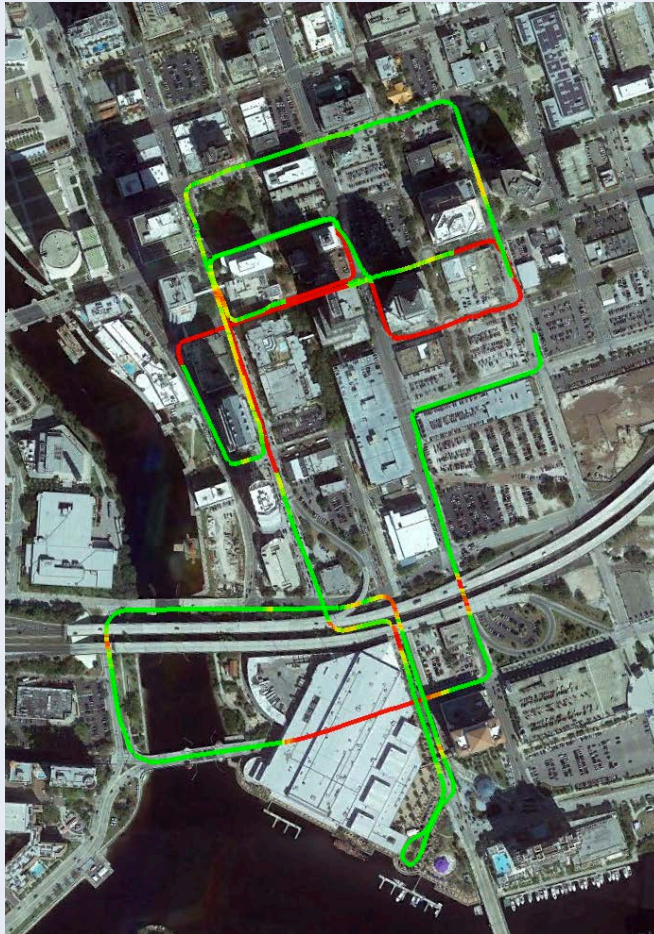


Zoom



Lane-level positioning accuracy is maintained!

Stressing the system with artificial GNSS outages



— Complete GNSS outage

Lane-level positioning accuracy is still maintained!

- 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

- 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



Tom Jakel
Senior Systems Engineer
Honeywell Aerospace



Andrey Soloviev
Principal
QuNav



Sheena Dixon
Product Manager
NovAtel

Inside GNSS @ www.insidegnss.com/
www.novatel.com/