DAY 1

AUTONOMOUS VEHICLE SAFETY: HOW TO TEST, HOW TO ENSURE

Tuesday June 16, 2020
WELCOME TO

Day 1: Autonomous Vehicle Safety: How to Test, How to Ensure

Co-Moderator: Lori Dearman, Executive Webinar Producer
Who’s In the Audience?

A diverse audience of over 650 professionals registered from 50 countries, representing the following industries:

22% Automotive
18% Research
13% University/Education
8% Transportation/Logistics/ Asset Tracking
8% Military and defense
4% Machine control/mining/construction
3% Precision Agriculture
24% Other
Welcome from *Inside Unmanned Systems*

Richard Fischer  
Publisher  
*Inside GNSS*  
*Inside Unmanned Systems*
A word from the sponsor

Natasha Wong Ken
Positioning Engine
Product Manager
Hexagon | NovAtel
Today’s Moderator

Alan Cameron
Editor in Chief
Inside GNSS
Inside Unmanned Systems
WELCOME TO

Day 1: Autonomous Vehicle Safety: How to Test, How to Ensure

Co-Moderator: Lori Dearman, Executive Webinar Producer
Poll #1: What type of GNSS vulnerabilities or failures are you most concerned about?

Poll Results (single answer required):

- Constellation failure - satellite or ground control segment: 9%
- GNSS Correction Network failure: 15%
- Atmospheric-induced failure - ionospheric storms, troposphere: 12%
- Receiver failure - hardware failure of design/mfr errors: 16%
- Spoofing/Jamming: 48%
High Precision Positioning in Automotive

Gordon Heidinger
Senior Engineering Manager Safety Critical Systems
Hexagon | NovAtel
Traditional Positioning in Automotive
Navigation for Mapping Applications

- **Several meters of accuracy**
  precision not required

- **Basic hardware and algorithms**
  no corrections or sensor fusion

- **No functional safety**
  not used to influence vehicle control

- **IMU data available but rarely coupled with GNSS**
  maximum cost effect
**Vehicle Level Positioning Needs**

**ADAS and Autonomous Driving Level**

Lane-level or better resolution

Helps allow vehicles to navigate safely, reliably and efficiently

Provides consistent performance across varying weather conditions
# Achieving Precise Positioning in Autonomous Solutions

<table>
<thead>
<tr>
<th>Feature</th>
<th>Added Ability</th>
<th>Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Enhanced Hardware</td>
<td>Multi-frequency</td>
<td>Several meters → one meter</td>
</tr>
<tr>
<td></td>
<td>Multi-constellation</td>
<td></td>
</tr>
<tr>
<td>Corrections Services</td>
<td>Satellite and Atmospheric Correction Data</td>
<td>One meter → decimeter</td>
</tr>
<tr>
<td>Advanced Software</td>
<td>Sensor Fusion</td>
<td>Increased Availability</td>
</tr>
<tr>
<td></td>
<td>Precise Positioning Algorithms</td>
<td>Rapid Convergence</td>
</tr>
</tbody>
</table>

Adding Sensor Fusion provides availability in non-open sky environments
**GNSS Corrections**

Two Methods of Enabling High Precision

**RTK (including Network RTK)**

- **Technology:** Corrects specific measurements
- **Implementation:** Direct, Network
- **Convergence:** 1 s, <10 s
- **2D Accuracy:** 1 cm + 1 ppm, 2 cm + 1 ppm
- **Coverage:** 40KM from base, Limited to Coverage Zone

**Precise Point Positioning (PPP)**

- **Technology:** Corrects for environment
- **Implementation:** Traditional, Fast
- **Convergence:** 18 min, <1 min
- **2D Accuracy:** 2.5 cm
- **Coverage:** Global

---

**Two-way data transfer**

(Corrections → Vehicle geo-location data)

**One-way data transfer**

(Corrections → Vehicle)

- **RTK software resolves the integer ambiguities in the carrier phase measurements**
- **Errors in satellite clocks are removed and errors in satellite orbits and the atmospheric effects on signal propagation are mitigated because the error sources are common to both receivers**
- **PPP filter algorithms in receiver estimates position, carrier phase ambiguities and other unknowns**
- **TerraStar provides precise satellite orbit and clock corrections**

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**Technology**

<table>
<thead>
<tr>
<th></th>
<th>Implementation</th>
<th>Convergence</th>
<th>2D Accuracy</th>
<th>Coverage</th>
</tr>
</thead>
<tbody>
<tr>
<td>RTK</td>
<td>Corrects specific measurements</td>
<td>Direct</td>
<td>1 s</td>
<td>1 cm + 1 ppm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Network</td>
<td>&lt;10 s</td>
<td>2 cm + 1 ppm</td>
</tr>
<tr>
<td>PPP</td>
<td>Corrects for environment</td>
<td>Traditional</td>
<td>18 min</td>
<td>2.5 cm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Fast</td>
<td>&lt;1 min</td>
<td></td>
</tr>
</tbody>
</table>
Improving Positioning Solutions for Mass Production

Traditional single frequency GNSS solution used today
- Accuracy of 5 to 15 m in the best conditions.
- Does not include any functional safety standards or protection level algorithms
- Only suitable for navigation

Dual frequency GNSS positioning solution with corrections services
- Improved position accuracy, availability and reliability
- Functional Safety
  - Certified Protection Level output
  - Complete integrity analysis
  - ASIL certified
  - ISO26262 functional safety compliance
  - Safety Certified Corrections Network

Emerging applications in automotive require increased performance
- V2V → 1.5 m 1σ
- AD/ADAS → < 1.0 m
Sensor Fusion at the Vehicle Level
Absolute Reference for Autonomous Technology

- GNSS & INS together provide the foundation for localization throughout different environments.
- GNSS provides absolute localization of a vehicle while other sensors are relative.
- Complimentary to other sensors, like cameras, Radar and LiDAR, providing precise timing.
- Robust sensor fusion based on a variety of inputs produces high availability with GNSS at the core.
## GNSS Positioning vs Other Sensors

<table>
<thead>
<tr>
<th>Few features</th>
<th>Adverse Weather</th>
<th>Dense Urban Environments</th>
</tr>
</thead>
<tbody>
<tr>
<td>✔️ GNSS</td>
<td>✔️ GNSS</td>
<td>✔️ Many objects easily seen</td>
</tr>
<tr>
<td>× Few objects to see</td>
<td>× Objects difficult to see</td>
<td>× GNSS Challenges</td>
</tr>
</tbody>
</table>

**Where relative positioning sensors fail, GNSS performs well.**

**Where GNSS struggles, relative positioning sensors perform well.**
System Architecture and Vehicle Integration
Production Representative Positioning Solution

Please Note: modules may not be represented in actual vehicle positions.
Validation of the Positioning Engine
Boundary Diagram Concept

<table>
<thead>
<tr>
<th>Value Ranges</th>
<th>Faults</th>
</tr>
</thead>
<tbody>
<tr>
<td>Satellite Geometry</td>
<td>Satellite failures</td>
</tr>
<tr>
<td>Multipath</td>
<td>Jamming/ Spoofing</td>
</tr>
<tr>
<td>Signal to Noise</td>
<td>Multipath beyond range</td>
</tr>
<tr>
<td>Satellite Count</td>
<td>Many more</td>
</tr>
</tbody>
</table>

Each input needs to be tested to the full functional limit while the output behavior is valid.

Each input failure mode needs to be considered.

All combinations of conditions are impossible to achieve with a finite amount of live testing.
Introduction to Integrity
The Study of How It Can Fail

Ground Segment Failures
(GNSS Constellation Provider)
- False Orbit Calculation

HW Failures
- Clock errors that are difficult to detect
- Evil waveform (correlation function)

Atmospheric Failures
- Ionospheric storms that are unstable and unpredictable
- Extreme tropospheric conditions

Difficult Multipath Conditions
- Conditions that are difficult to detect but still affect measurements

These failures are studied and accommodated for in algorithms generating the Protection Level output.

Commonly known errors as well as failures difficult to detect and model need to be accounted for and included.
Mathematics of Multipath

Example of a Difficult Error State

Typical or predicable GNSS error cases like multipath are not the problem.
Error cases and conditions difficult to detect and model must be accommodated for safety of life functionality.

Normal Gaussian Distribution
Not typical for GNSS position data

Very commonly known error state of multipath, (multi-modal)
Tails of the distribution are typically higher and farther out from Gaussian model

Normal Multipath Understanding

The situation of only the multipath signals being received is difficult to deal with.
PL output needs to accommodate this condition among other difficult error cases.

Difficult GNSS Error Cases
System and Vehicle Level Validation to Automotive Safety Standards

Represents a Billion Possible User Conditions and Faults

<table>
<thead>
<tr>
<th>Metric</th>
<th>ASIL-A</th>
<th>ASIL-B</th>
<th>ASIL-C</th>
<th>ASIL-D</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPF (Single Point Fault)</td>
<td>NA</td>
<td>&gt;90%</td>
<td>&gt;97%</td>
<td>&gt;99%</td>
</tr>
<tr>
<td>LF (Latent Fault)</td>
<td>NA</td>
<td>&gt;60%</td>
<td>&gt;80%</td>
<td>&gt;90%</td>
</tr>
<tr>
<td>Failure Rate</td>
<td>$10^{-6}$/hour</td>
<td>$10^{-7}$/hour</td>
<td>$10^{-7}$/hour</td>
<td>$10^{-8}$/hour</td>
</tr>
<tr>
<td>FIT (Failure in Time)</td>
<td>&lt;1,000</td>
<td>&lt;100</td>
<td>&lt;100</td>
<td></td>
</tr>
</tbody>
</table>

Autonomous Driving?

Please Note: modules may not be represented in actual vehicle positions.
Part I: Integrity for Precise Positioning in Automotive

Lance de Groot
Geomatics Lead
Safety Critical Systems
Hexagon | NovAtel
Quality Metrics for Positions

Typical quality metric for GNSS is estimated accuracy

Based on propagation of variance
Quality Metrics for Positions

Typical quality metric for GNSS is estimated accuracy

Based on propagation of variance

Confidence ellipse
Quality Metrics for Positions

Typical quality metric for GNSS is estimated accuracy
Based on propagation of variance
Confidence ellipse

Does not reflect faults in measurements
Quality Metrics for Positions

Typical quality metric for GNSS is estimated accuracy

Based on propagation of variance

Confidence ellipse

Does not reflect faults in measurements

For high integrity, we use a protection level (PL)

Estimate of the maximum possible error in the position
  • Considers possible measurement faults
  • Makes no claim about distribution of error
Terms in Integrity

**Protection Level**: estimate of the maximum possible error in the position
- Output from positioning

**Alert Limit**: The maximum error the system can tolerate
- Part of system design

**Integrity Risk**: Probability that the true error exceeds the PL
- Safety requirement

**Availability**: Probability that the PL <= AL
- Performance requirement
Required Performance

- No fixed standard

- Performance and safety requirements depend on application and safety concept

  Potential alert limits
  - Geogating, HD map initialization: Several metres
  - V2V: ~1 metre
  - AD, ADAS: sub-metre

- Availability on the order of 90 - 99%

- Integrity risk depends strongly on safety concept
  - May range from $10^{-3}$/h to $10^{-8}$/h
  - Compare to ISO-26262 hardware failure rates
    - $10^{-7}$/h at ASIL B/C, $10^{-8}$/h at ASIL D
    - Not necessarily the integrity risk for a positioning system
How to Account for Failures?

Ground Segment Failures (GNSS Constellation Provider)
- False Orbit Calculation

GNSS Correction Network (Hexagon)
- Reference station failures
- Server failures
- Corrections generation failures

HW Failures
- Clock errors that are difficult to detect
- Evil waveform (correlation function)

Atmospheric Failures
- Ionospheric storms that are unstable and unpredictable
- Extreme tropospheric conditions

Difficult Multipath Conditions
- Conditions that are difficult to detect but still affect measurements

Receiver Failure
- Hardware failure
- Design/Manufacturing errors

Spoofing
- Jamming

Data Corruption
- Spoofing

Customer Servers

Hexagon Servers

Ionospheric storms that are unstable and unpredictable

Extreme tropospheric conditions
Fault Tree Analysis

Fault tree analysis shows how risk is allocated throughout the system

Risk from each failure can be independently assessed

Total risk is summed from all sources to show that requirement is met
Individual Failure Sources

Contribution of each individual failure is the product of:

- Probability of failure
- Probability of mis-detection for each mitigation method

Probability of failure is based on analysis of the error source

Mitigation effectiveness based on analysis and testing

- Primarily testing through simulation due to low probability of occurrence

Some errors can only be mitigated at the user, e.g.

- Multipath
- HW failure (GNSS or IMU)
Ask the Experts Part I

Autonomous Vehicle Safety: How to Test, How to Ensure

Co-Moderator: Lori Dearman, Executive Webinar Producer
What level of positioning accuracy do you think autonomous driving requires?

Poll Results (single answer required):

- 0 – 10 cm: 32%
- 10 – 50 cm: 49%
- 50 cm – 1 Meter: 17%
- Greater than 1 Meter: 2%
Part II: Integrity for Precise Positioning in Automotive

Lance de Groot
Geomatics Lead
Safety Critical Systems
Hexagon | NovAtel
Mitigation at the User: RAIM

Fault tolerance in GNSS uses Receiver Autonomous Integrity Monitoring (RAIM)

Originally developed for the aviation industry

Techniques can be adapted to land based applications

A few differences:

- Environment, e.g. more multipath
- Corrections
- Sensor fusion
- Ambiguity resolution
- Use of carrier phase and inertial measurements requires a filtered solution

Fault in pseudorange

Effect on filtered position

T\text{ persistence}
CRAIM Techniques

No standardized approach yet for carrier phase RAIM

Residual based approaches consider faults in measurement domain
   Similar to classical aviation RAIM

Solution separation observes impact of faults in position domain
   Similar to ARAIM

Figure source: Brenner, M., 1996. Integrated GPS/inertial fault detection availability. Navigation, 43(2), pp.111-130
Sample Results – Open Sky Kinematic

Industrial district near Calgary airport

Automotive grade hardware:
- Dual frequency antenna
- GNSS receiver

Hexagon’s PPP algorithm and TerraStar X corrections
Sample Results – Open Sky Kinematic

<table>
<thead>
<tr>
<th>Percentile</th>
<th>50</th>
<th>68</th>
<th>95</th>
</tr>
</thead>
<tbody>
<tr>
<td>2D Error (m)</td>
<td>0.19</td>
<td>0.20</td>
<td>0.23</td>
</tr>
<tr>
<td>HPL (m)</td>
<td>0.78</td>
<td>0.83</td>
<td>1.04</td>
</tr>
</tbody>
</table>
Impact of GNSS Outages

- GNSS outages cause carrier phase ambiguities to reset.
- This causes a jump in the PL.
- Sensor fusion helps to bridge these gaps.
Sample Results – Overpasses
Freeway in California

SAFETY AND INTEGRITY

THE NOVATEL POSITIONING ENGINE ALSO DELIVERS PROTECTION LEVEL OUTPUTS.
Testing For GNSS Integrity

Automotive safety deals with extremely low probabilities of failure, e.g. 0.000001%

Can we prove this with live testing?

A fleet of 100 vehicles driving 24/365 at 25 mph must drive for:

• 12.5 years with no failures to show AVs are as good as human drivers (95% confidence)
• 400 years with failures to show AVs are roughly as good as human drivers (95% confidence)

This is clearly impractical.

Testing For GNSS Integrity

Instead, we must force faults to occur (e.g. a 15 m pseudorange fault on one SV)

Techniques
- Manipulation of input data
- Simulation – the next topic

Step  
Ramp  
Transient
Validating performance of Safety critical autonomous vehicle PNT systems

Ajay Vemuru
Product Manager - PNT
Spirent Communications
Redefine Validation statement

Required Performance

- Potential alert limits
  - Geogating, HD map initialization: Several meters
  - V2V: ~1 meter
  - AD, ADAS: sub-metre

- Availability on the order of 90 - 99%

- Integrity risk depends strongly on safety concept
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    - Not necessarily the integrity risk for a positioning system

Challenges

- Faults in PR
- GNSS outage
- …
**PNT Methods**

**Common Navigation Solutions**

- **Vision System**
  - Weather
  - Low light
  - Dirt
  - Incomplete lane markings

- **Radar**
  - Obstructions like
    - Dirt
    - Ice
    - Snow

- **LiDAR**
  - Weather
  - Dirt
  - Low feature areas

- **GNSS**
  - Urban canyons &
  - Interference
  - GNSS outages

**CAV Sensor Types and Challenges**
GNSS Outages

- GLONASS Suffers Temporary Systemwide Outage
  - Outages continued for more than 10 hours, with the Russian GLONASS monitoring center showing satellites in unhealthy statuses: “failure” and “illegal ephemeris. [source: InsideGNSS April 3, 2014]

- GPS Experiences UTC Timing, IIF Satellite Launcher Problems
  - Although the core navigation systems were operating normally, the coordinated universal time (UTC) timing signal was off by 13 microseconds, which exceeded the design specifications and affected some timing user equipment [source: InsideGNSS January 28, 2016]
GNSS Challenging Environments

- Overpasses
- Garages
- Multilevel roads
- Urban canyon

Source: Google images
# IMU Grades

<table>
<thead>
<tr>
<th>Example Application Area</th>
<th>Navigational Grade</th>
<th>Tactical Grade</th>
<th>Commercial Grade</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>High precision applications such as geo-referencing</td>
<td>Applications with short time stability needs such as Mapping</td>
<td>Low cost navigation such as automotive</td>
</tr>
<tr>
<td>Gyro drift</td>
<td>&lt; 0.01°/hr</td>
<td>1-10°/hr</td>
<td>0.1°/sec</td>
</tr>
<tr>
<td>Accel bias</td>
<td>&lt;100µg</td>
<td>1-5µg</td>
<td>100-1000µg</td>
</tr>
<tr>
<td>Cost</td>
<td>~$100,000</td>
<td>~$2000 - $50,000</td>
<td>~$1 - $50</td>
</tr>
</tbody>
</table>

IMU Parameters to be modelled

- Deterministic errors
  - Bias stability
  - Scale factor
  - Axis Misalignment

- Stochastic errors
  - Angle/velocity random walk noise

- A typical land-based vehicle has more than one inertial sensor, in a cluster or as independent sensors to sense vehicles long track and cross track dynamics
Impact of wrongly tuned IMU

A wider spread of the fault case positions (red) vs. the nominal case (green) over the 5 passes through this section.

Drive through an urban canyon, and the effect of having the IMU being noisier than it should be is very pronounced.

Thanks to Hexagon | NovAtel for providing these results.
Use Case: Impact of IMU Axis-mismatched

Position Errors - Vertical, 2D, 3D

Thanks to Hexagon | NovAtel for providing these results


**Odometry**

- There is a current trending of using any and everything possible to improve the position accuracy, availability and integrity.

- Wheel ticks, steering angle, ...

- Wheel ticks come in two major flavors:
  - Absolute wheel ticks
  - Differential wheel ticks (over front wheels, rear wheels or all four)

Plot source: “Robust Odometry using Sensor Consensus Analysis”, Andrew W. Palmer and Navid Nourani-Vatani
Validation of PNT system

- GNSS Simulation
  - PR ramp/Atmosphere/Orbit errors/Multipath/Jamming/...
- Accel & Gyro
  - Bias/ARW/VRW/...
- Mag & Baro
  - Scale factor/noise/...
- Odometry (wheel sensors)
  - Scale factors/noise/

Trajectory information

UDP/RF (conducted or radiated)
- UDP/SPI/CAN/I2C
- UDP or CAN

Sensor Fusion
How Simulation works

Truth From PosApp → Systematic Errors and White Noise → Band Limiting → Quantisation

ψ → 3-axis Mag Simulation → \( m_E^n \) → Systematic Errors and White Noise → \( m^b_m \) → Quantisation → \( \tilde{m}_{mq}^b \)

\( f, \omega \) → \( \tilde{f}, \tilde{\omega} \) → Quantisation

\( \Psi \) → Magnetic Anomaly

\( m^n_A \) → \( \tilde{f} \) → Compass → Quantisation

\( \tilde{\psi}_{mb}, \tilde{\psi}_{nb} \) → (\( \tilde{\phi}_{nb}, \tilde{\theta}_{nb} \)) → Quantisation

\( \tilde{\psi}_{mbq}, \tilde{\psi}_{nbq} \) → (\( \tilde{\phi}_{nbq}, \tilde{\theta}_{nbq} \))
Simulation Credibility

INERTIAL SENSOR SIMULATION

- QinetiQ/ UK Ministry Of Defense (MOD) paper & results
  - A series of logical investigative steps, described in this paper, has provided firm evidence that STANAG 4572 and the Spirent implementation of it meet the MOD’s requirement of not introducing a radial position error growth of greater than 1.8 metres/hour, when a perfect IMU is simulated.

GNSS SIMULATION

- Italdesign – leading automotive design company
  - **Objective:** To create an integrated system for testing connected autonomous vehicles (CAV) during their development
  - **Method:** Integrated hardware-in-the-loop (HIL) testing using Spirent’s GSS7000 and SimHIL application programming interface (API)
  - **Benefit:** CAV developers can reduce their product development times with greater confidence in the positioning accuracy of their vehicles

“Hardware-In-The-Loop Testing of the NATO Standardisation Agreement 4572 Interface Using High Precision Navigation Equations”, R.J. Handley, R.F. Stokes, J. Stevenson, QinetiQ, United Kingdom J.I.R. Owen, Dstl, United Kingdom
Better tuning of fusion filters—Simulation

Simulation as an effective tool:

- Simulate trajectory with realistic vehicle dynamics
- Simulate Orientation
- Simulate mismatch

Above all provides ground truth
What type of IMU errors are you most concerned about?

Poll Results (single answer required):

<table>
<thead>
<tr>
<th>Error Type</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bias stability</td>
<td>44%</td>
</tr>
<tr>
<td>Scale factor</td>
<td>4%</td>
</tr>
<tr>
<td>Axis misalignment</td>
<td>19%</td>
</tr>
<tr>
<td>Angle/velocity random walk noise</td>
<td>33%</td>
</tr>
</tbody>
</table>