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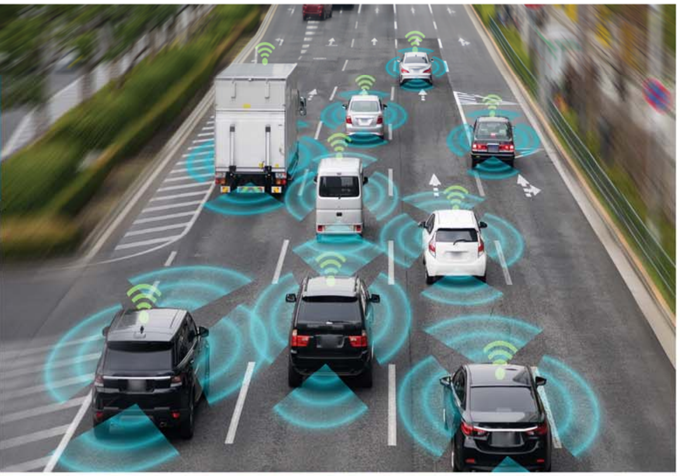

DAY 1

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

Alan Cameron
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Product Manager - PNT
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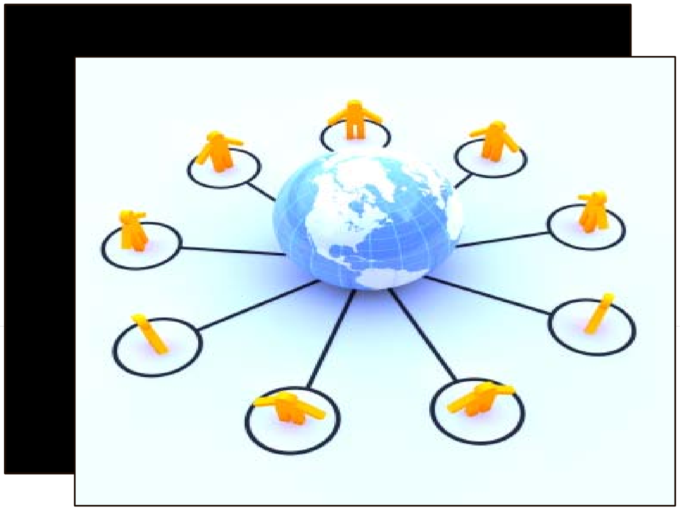
Co-Moderator: Lori Dearman, Executive Webinar Producer

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
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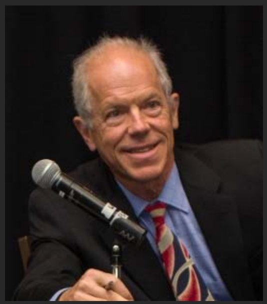

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QUICKPOLL

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

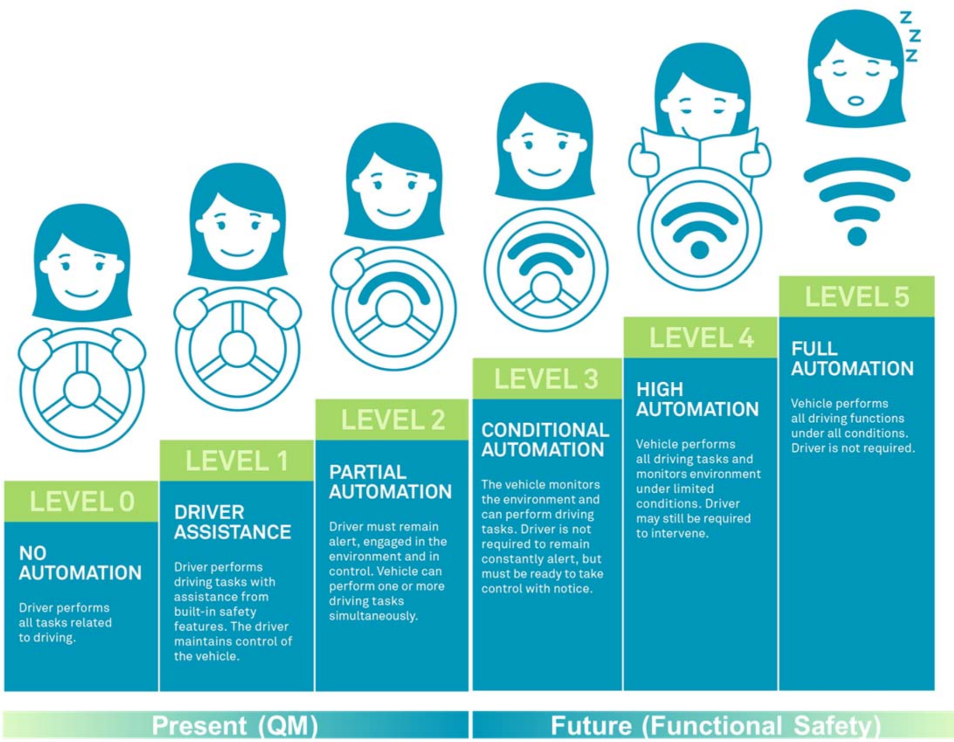
Basic hardware and algorithms
no corrections or sensor fusion

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

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Achieving Precise Positioning in Autonomous Solutions

Feature	Added Ability	Performance
Enhanced Hardware	• Multi-frequency • Multi-constellation	Several meters → one meter
Corrections Services	• Satellite and Atmospheric Correction Data	One meter → decimeter
Advanced Software	• Sensor Fusion • Precise Positioning Algorithms	Increased Availability Rapid Convergence

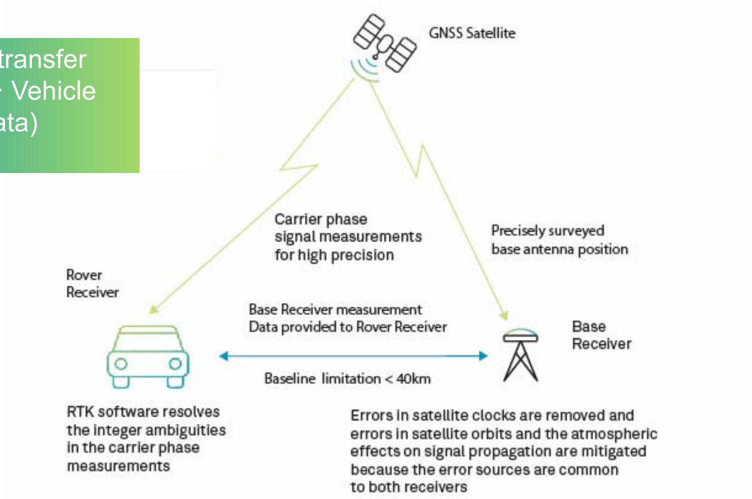
Adding Sensor Fusion provides availability in non-open sky environments

GNSS Corrections

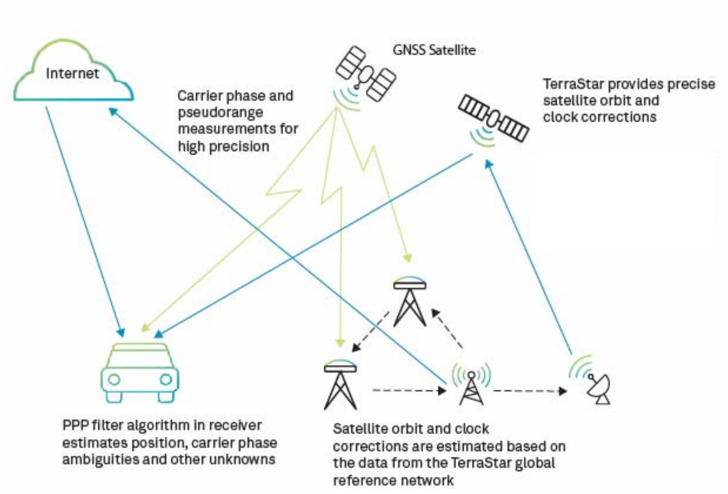
Two Methods of Enabling High Precision

RTK (including Network RTK)

Two-way data transfer (Corrections → Vehicle geo-location data)



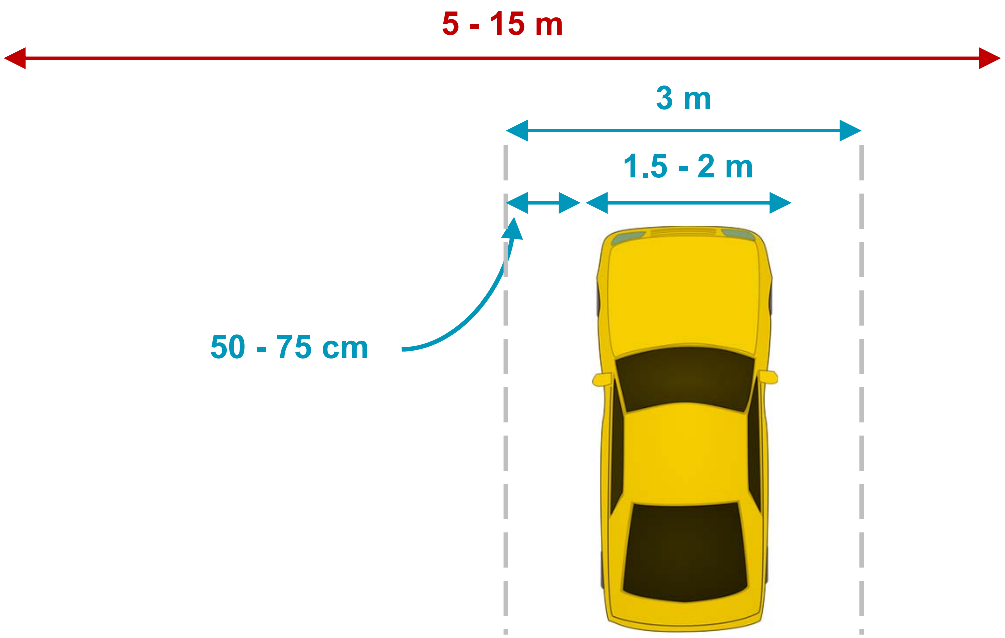
Precise Point Positioning (PPP)



One-way data transfer (Corrections → Vehicle)

Technology		Implementation	Convergence	2D Accuracy	Coverage
RTK	Corrects specific measurements	Direct	1 s	1 cm + 1 ppm	40KM from base
		Network	<10 s	2 cm + 1 ppm	Limited to Coverage Zone
PPP	Corrects for environment	Traditional	18 min	2.5 cm	Global
		Fast	<1 min		

Improving Positioning Solutions for Mass Production



Emerging applications in automotive require increased performance

V2V → 1.5 m 1σ **AD/ADAS → < 1.0 m**

Traditional single frequency GNSS solution used today

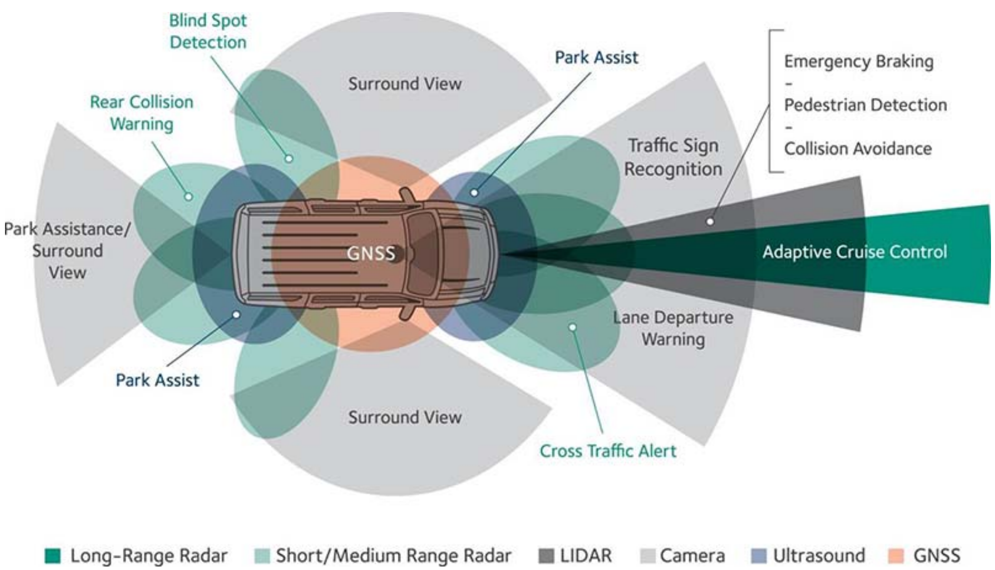
- Accuracy of 5 to 15 m in the best conditions.
- Does not include any functional safety standards or protection level algorithms
- Only suitable for navigation

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

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

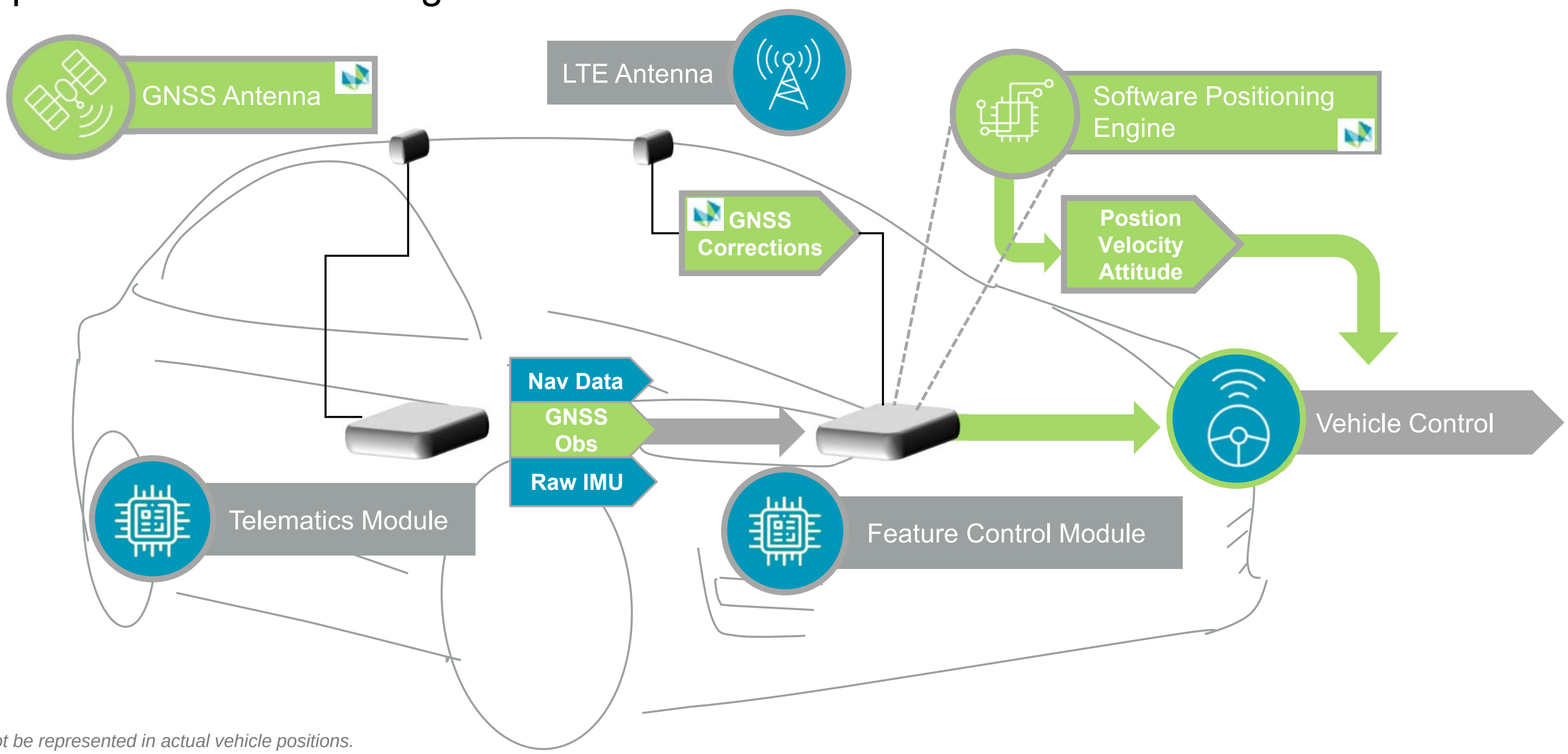
Where relative positioning sensors fail, GNSS performs well.

Where GNSS struggles, relative positioning sensors perform well.

Few features		Adverse Weather		Dense Urban Environments	
✓	✕	✓	✕	✕	✓
GNSS	Few objects to see	GNSS	Objects difficult to see	GNSS Challenges	Many objects easily seen

System Architecture and Vehicle Integration

Production Representative Positioning Solution

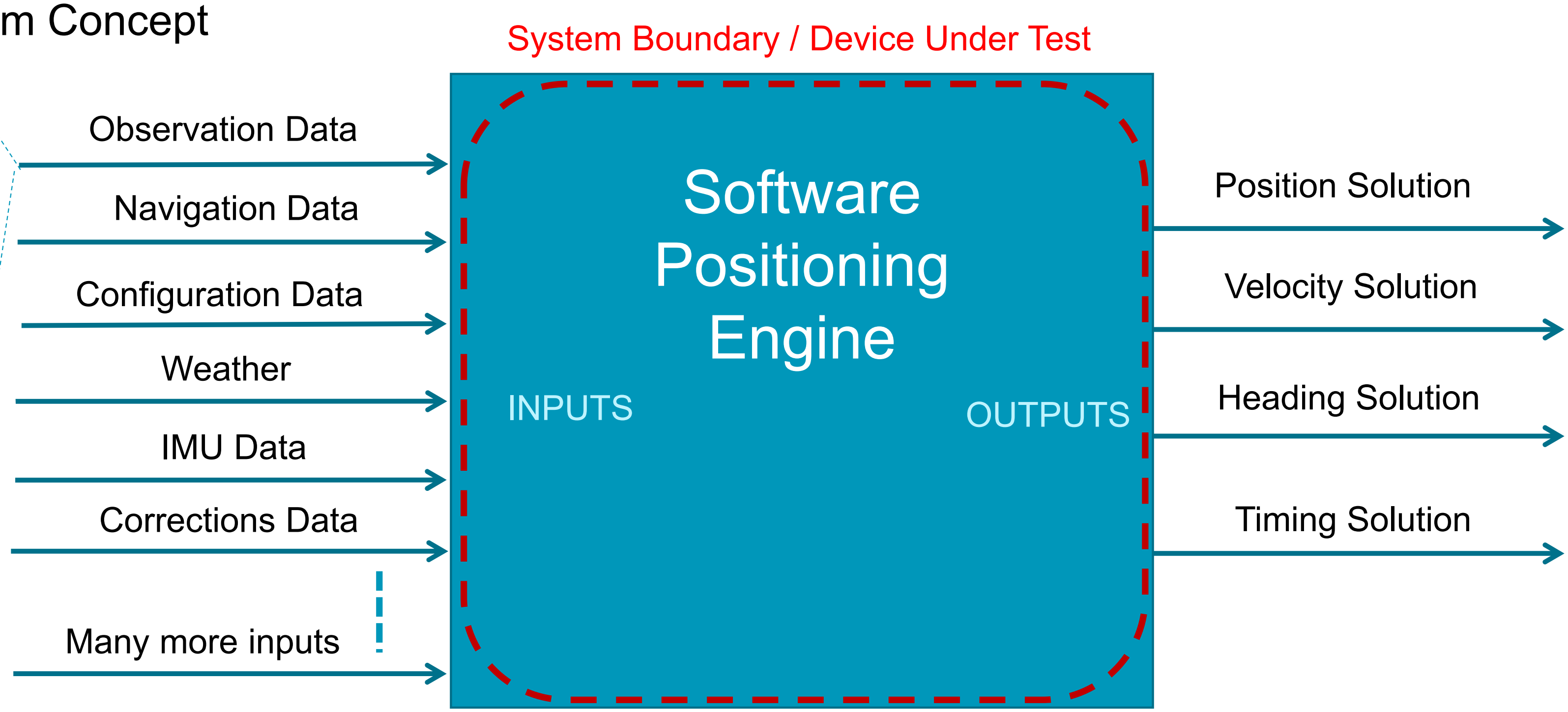


Please Note: modules may not be represented in actual vehicle positions.

Validation of the Positioning Engine

Boundary Diagram Concept

Value Ranges	Faults
Satellite Geometry	Satellite failures
Multipath	Jamming/ Spoofing
Signal to Noise	Multipath beyond range
Satellite Count	
Many more	



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

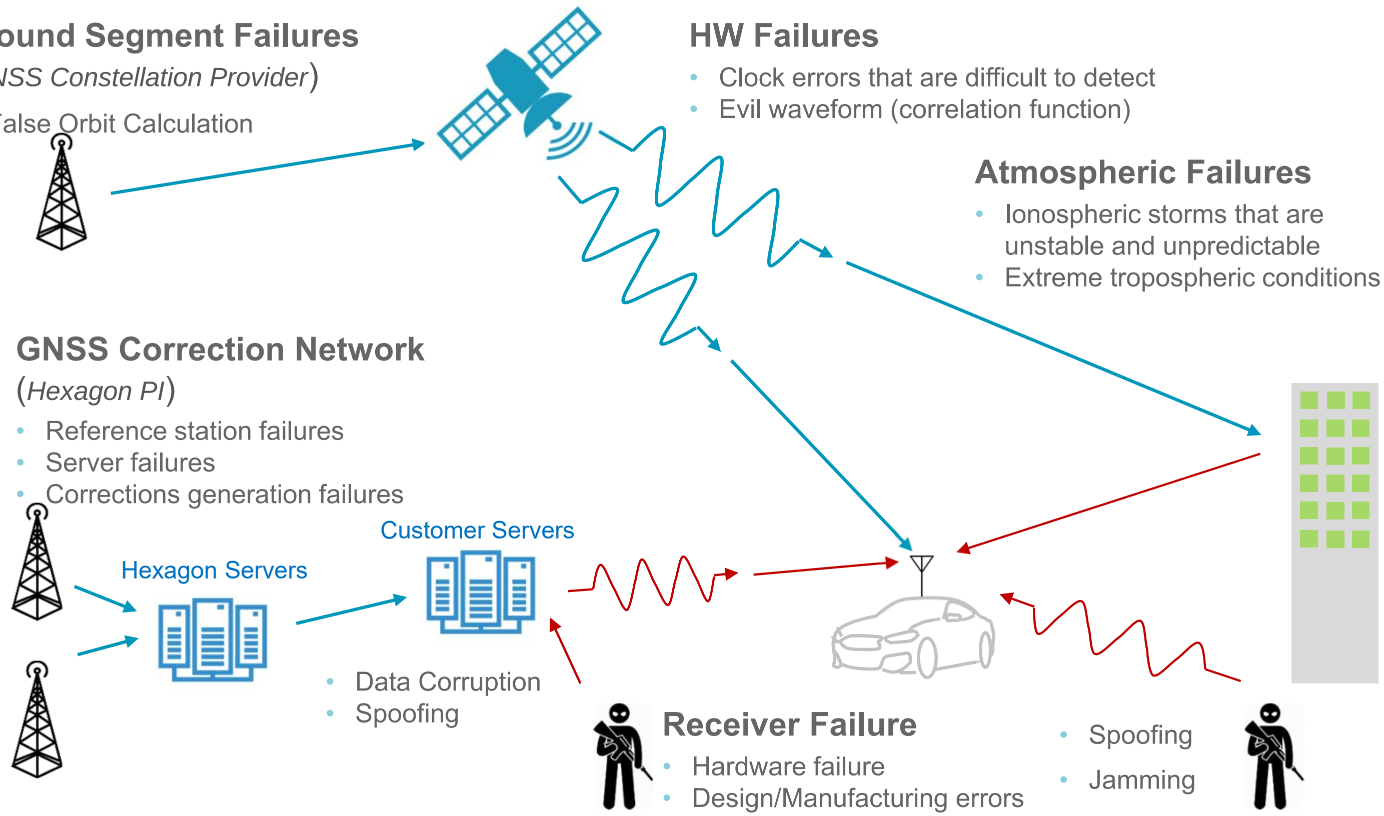
- Clock errors that are difficult to detect
- Evil waveform (correlation function)

Atmospheric Failures

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

GNSS Correction Network
(*Hexagon PI*)

- Reference station failures
- Server failures
- Corrections generation failures



- Data Corruption
- Spoofing

Receiver Failure

- Hardware failure
- Design/Manufacturing errors

- Spoofing
- Jamming

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.

Difficult Multipath Conditions

- Conditions that are difficult to detect but still affect measurements

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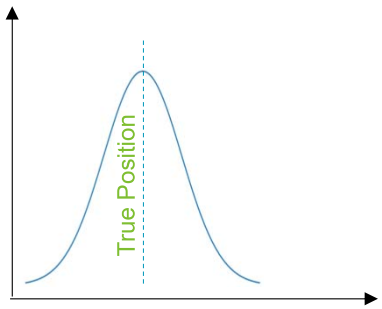
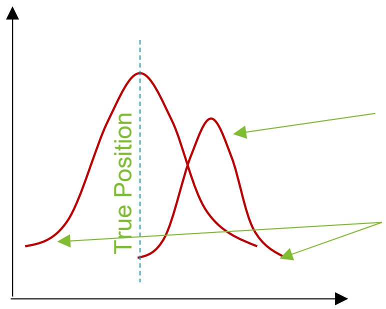
Mathematics of Multipath

Example of a Difficult Error State



Normal Gaussian Distribution

Not typical for GNSS position data



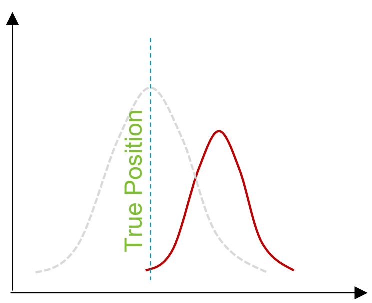
Very commonly known error state of multipath, (multi-modal)

Tails of the distribution are typically higher and farther out from Gaussian model

Normal Multipath Understanding

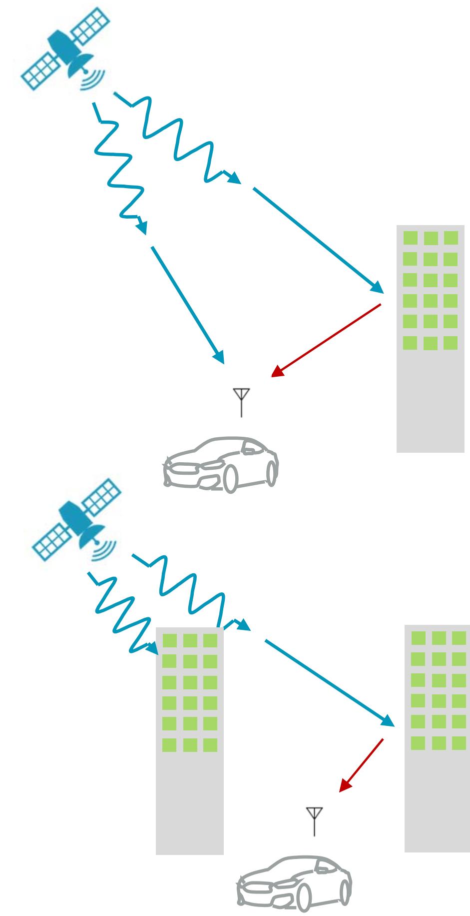
Typical or predicable GNSS error cases like multipath are **not** the problem.

Error cases and conditions difficult to detect and model must be accommodated for safety of life functionality.



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



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System and Vehicle Level Validation to Automotive Safety Standards

Represents a Billion Possible User Conditions and Faults

	ASIL-A	ASIL-B	ASIL-C	ASIL-D
SPF (Single Point Fault) Metric	**NA**	**>90%**	**>97%**	**>99%**
LF (Latent Fault) Metric	**NA**	**>60%**	**>80%**	**>90%**
Failure Rate	**10^{-6}/hour**	**10^{-7}/hour**	**10^{-7}/hour**	**10^{-8}/hour**
FIT (Failure in Time)	**<1,000**	**<100**	**<100**	

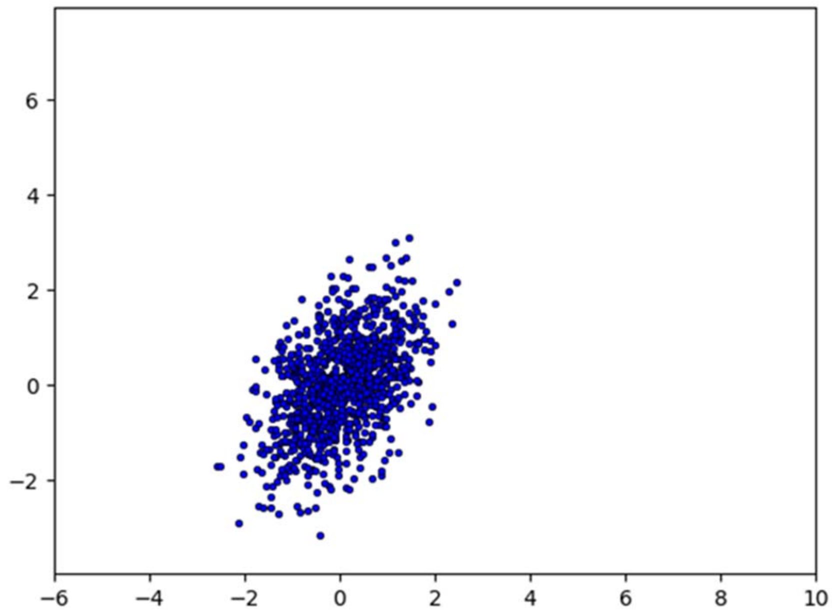
Autonomous Driving?

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

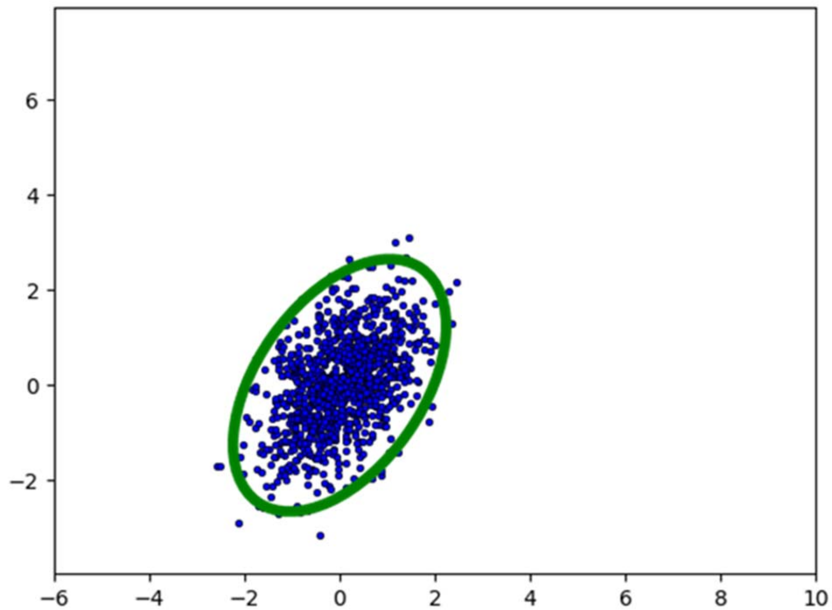
Quality Metrics for Positions



Typical quality metric for GNSS is estimated accuracy

Based on propagation of variance

Quality Metrics for Positions

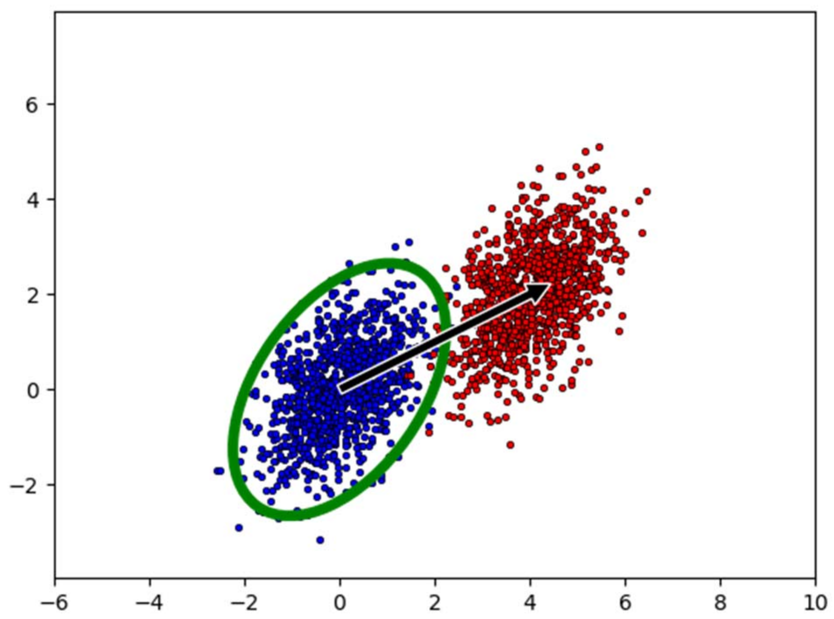


Typical quality metric for GNSS is estimated accuracy

Based on propagation of variance

Confidence ellipse

Quality Metrics for Positions

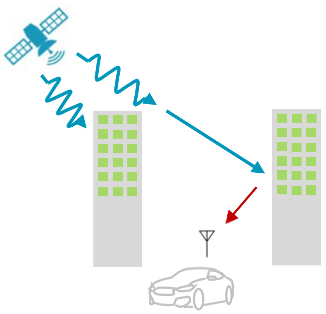


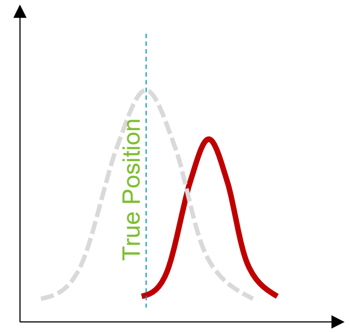
Typical quality metric for GNSS is estimated accuracy

Based on propagation of variance

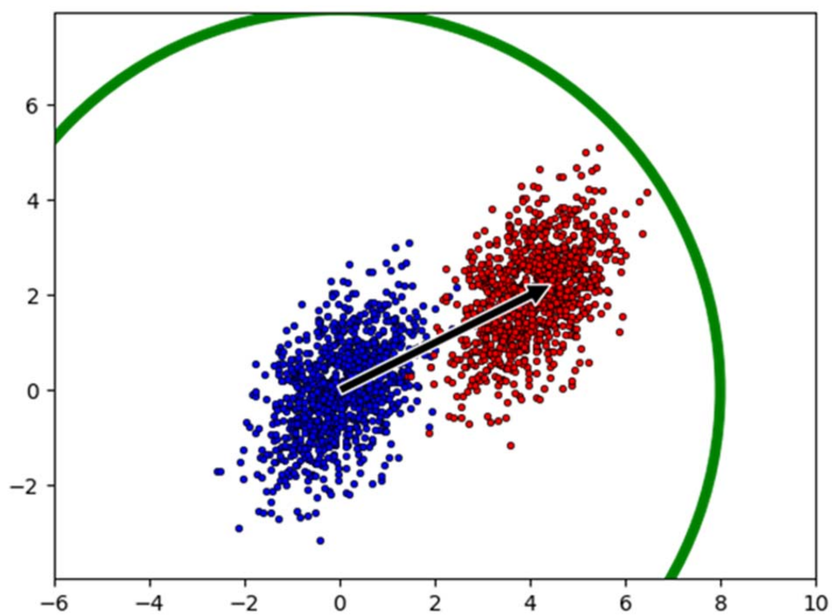
Confidence ellipse

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

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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

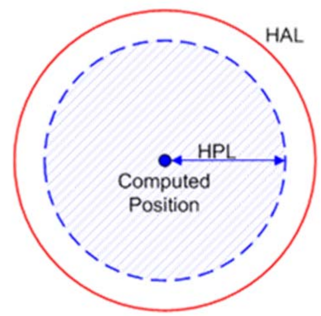
- Part of system design

Integrity Risk: Probability that the true error exceeds the PL

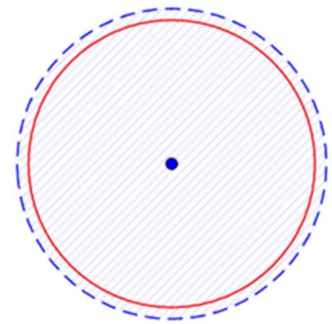
- Safety requirement

Availability: Probability that the PL <= AL

- Performance requirement



Position Valid



Position Invalid

Required Performance

No fixed standard

Performance and safety requirements depend on application and safety concept

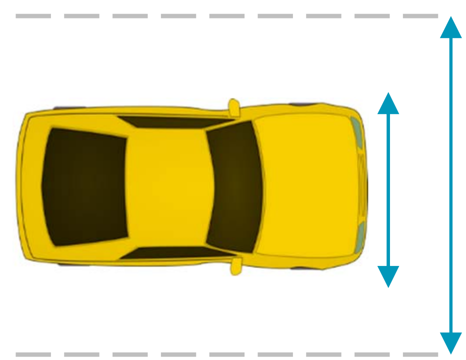
Potential alert limits

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

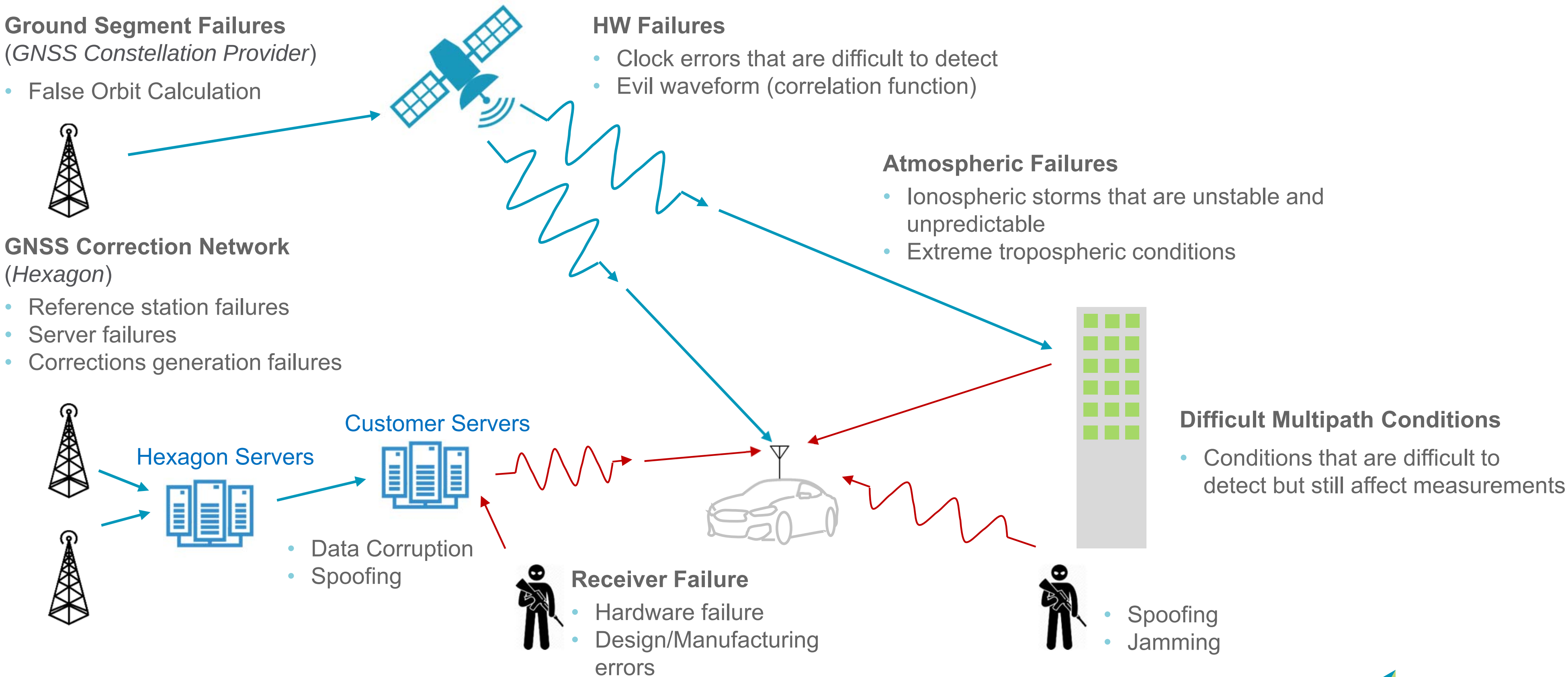
Availability on the order of 90 - 99%

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?

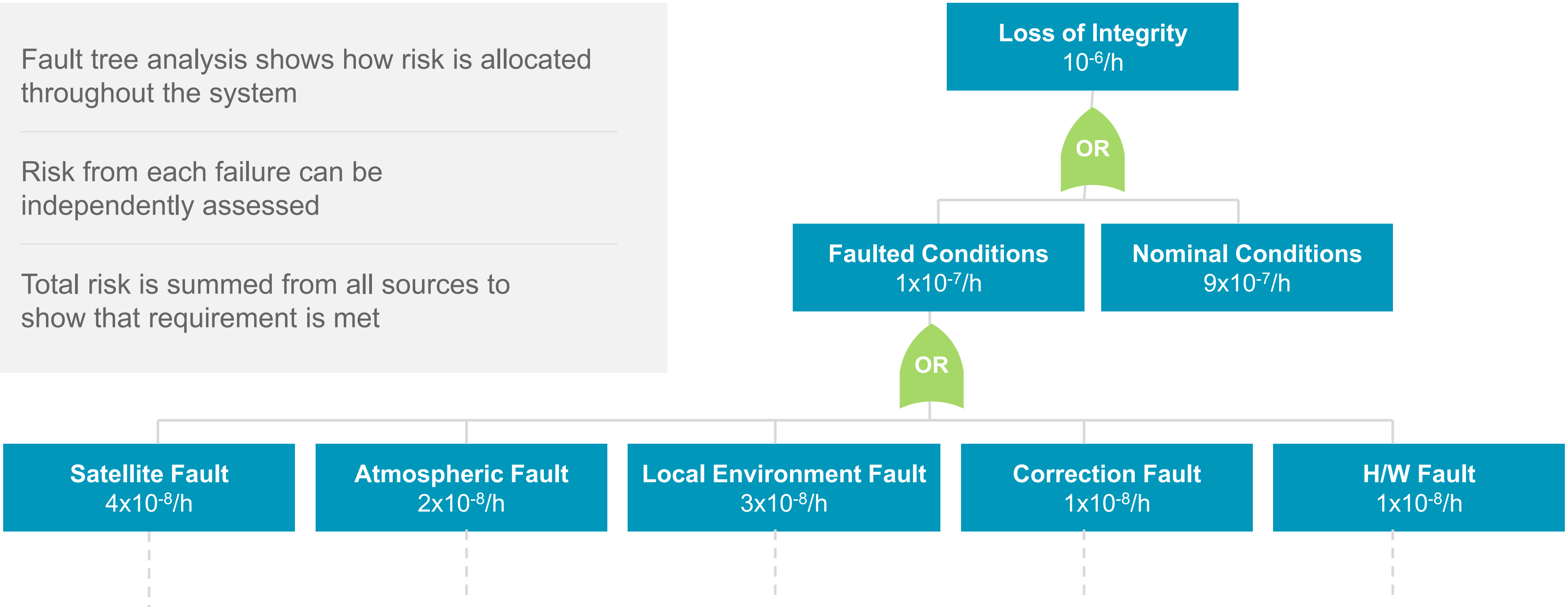


Fault Tree Analysis

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

---

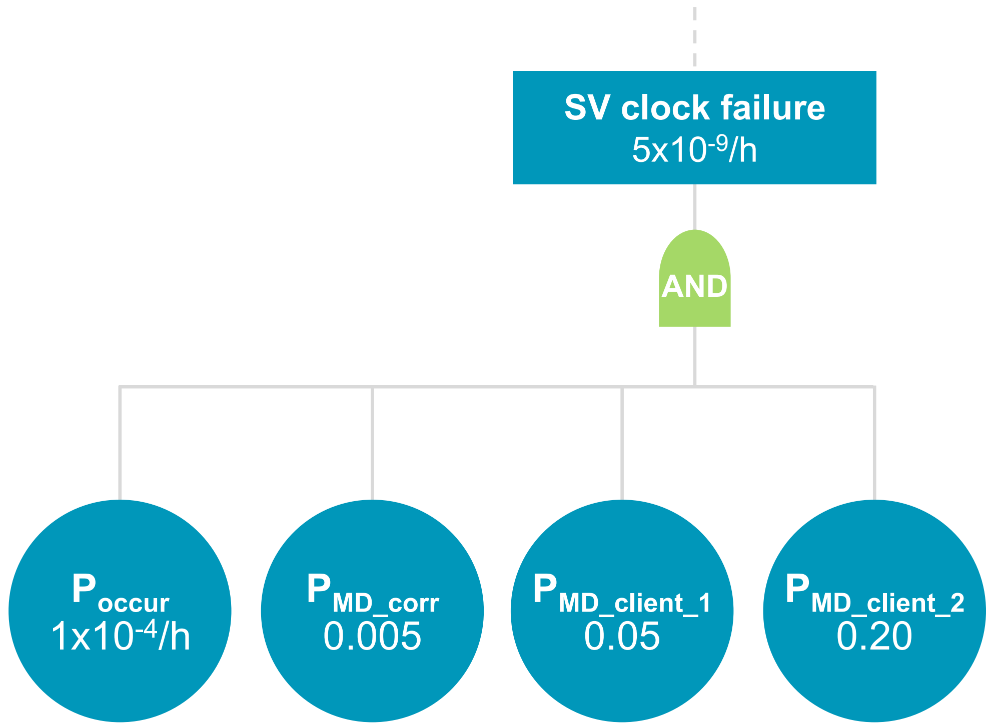
Mitigation effectiveness based on analysis and testing

- Primarily testing through simulation due to low probability of occurrence

---

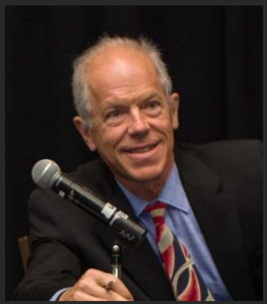
Some errors can only be mitigated at the user, e.g.

- Multipath
- HW failure (GNSS or IMU)



Ask the Experts Part I

Autonomous Vehicle Safety: How to Test, How to Ensure



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QUICKPOLL

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

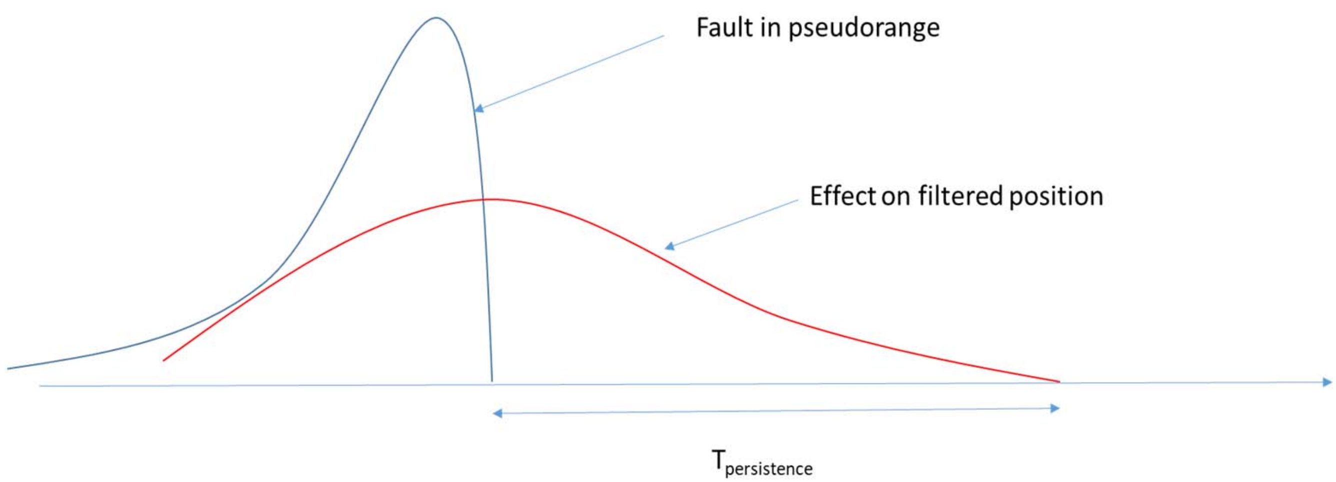
Fault tolerance in GNSS uses Receiver Autonomous Integrity Monitoring (RAIM)

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



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

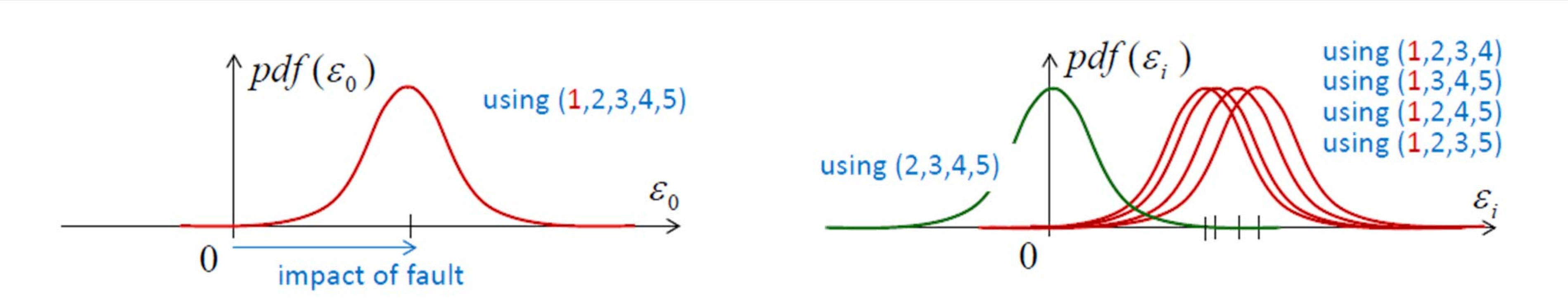


Figure source: Brenner, M., 1996. Integrated GPS/inertial fault detection availability. Navigation, 43(2), pp.111-130

Sample Results – Open Sky Kinematic

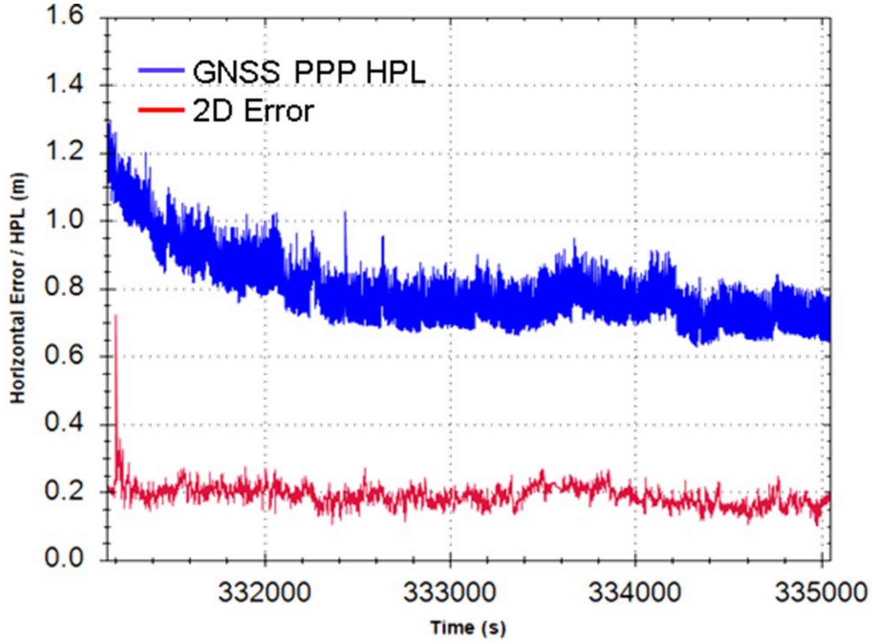
Industrial district near Calgary airport

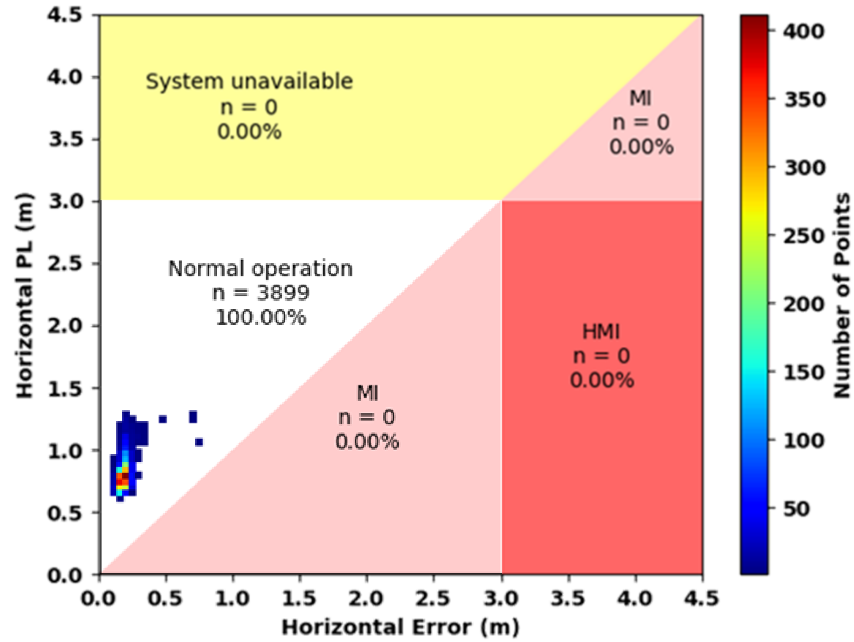
Automotive grade hardware:

- Dual frequency antenna
- GNSS receiver

Hexagon's PPP algorithm and TerraStar X corrections

Sample Results – Open Sky Kinematic





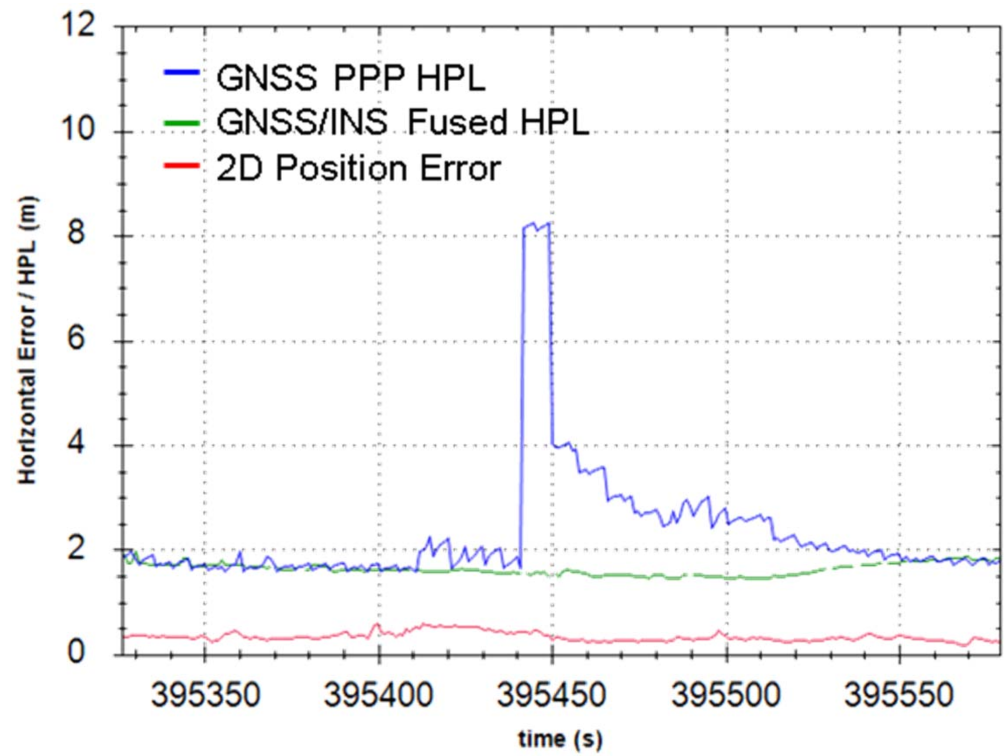
Percentile	50	68	95
2D Error (m)	0.19	0.20	0.23
HPL (m)	0.78	0.83	1.04

Impact of GNSS Outages

GNSS outages cause carrier phase ambiguities to reset

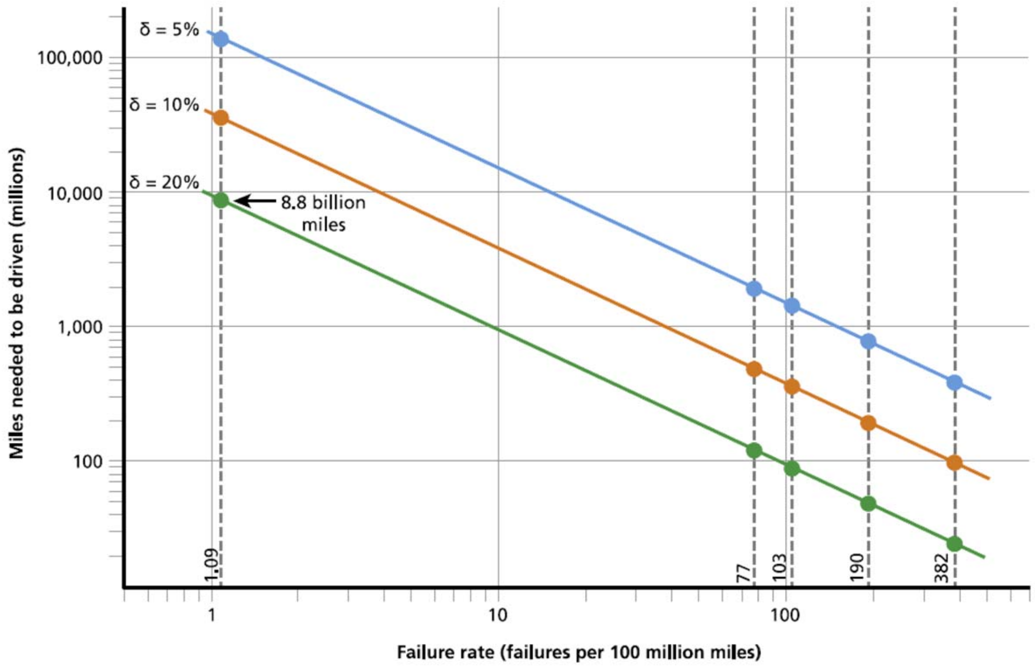
This causes a jump in the PL

Sensor fusion helps to bridge these gaps



Sample Results – Overpasses
Freeway in California

Testing For GNSS Integrity



Source: Kalra, N. and Paddock, S.M., 2016. Driving to safety: How many miles of driving would it take to demonstrate autonomous vehicle reliability?. *Transportation Research Part A: Policy and Practice, 94,* pp.182-193

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)

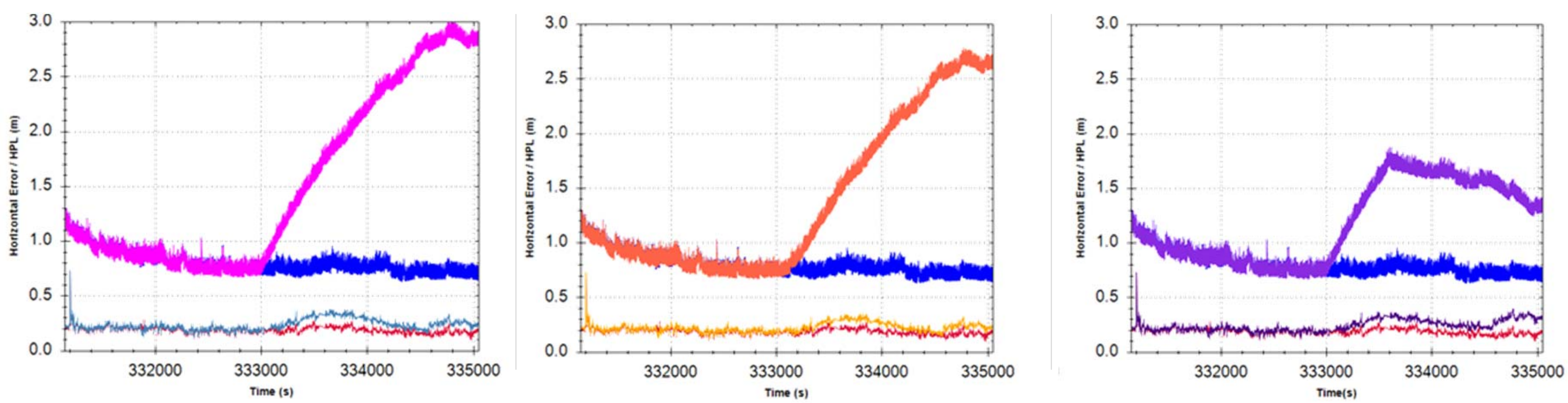
This is clearly impractical.

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

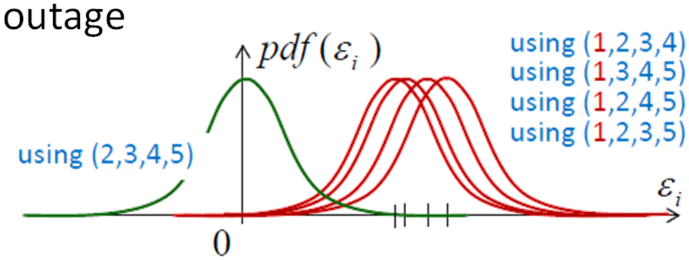
Redefine Validation statement

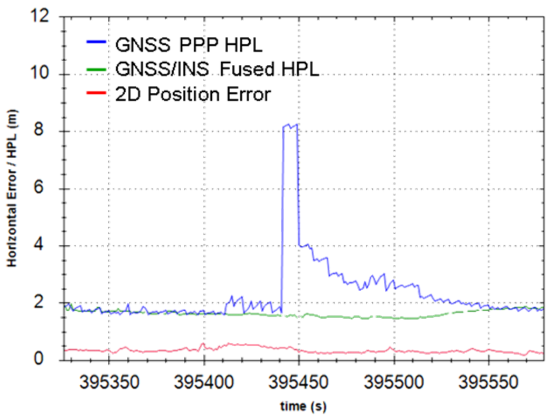
Required Performance

- 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
  - 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

Challenges

- Faults in PR
- GNSS outage
- …

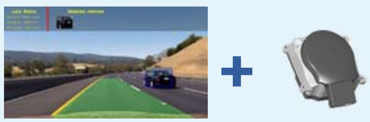




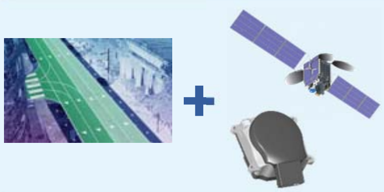
spirent Promise. Assured.

PNT Methods

Common Navigation Solutions



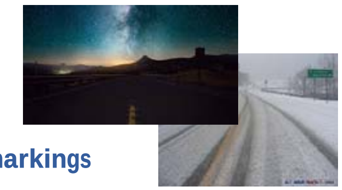
Vision System + Radar

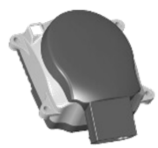


CAV Sensor Types and Challenges

Vision System

- Weather
- low light
- Dirt
- incomplete lane markings



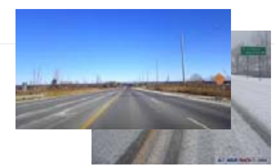


Radar

Obstructions like
- dirt
- ice
- snow

LiDAR

- Weather
- dirt
- low feature areas



GNSS

- Urban canyons &
- Interference
- GNSS outages

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

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

Source: "Inertial sensors technologies for navigation applications: state of the art and future trends", Naser El-Sheimy and Ahmed Youssef, 2020

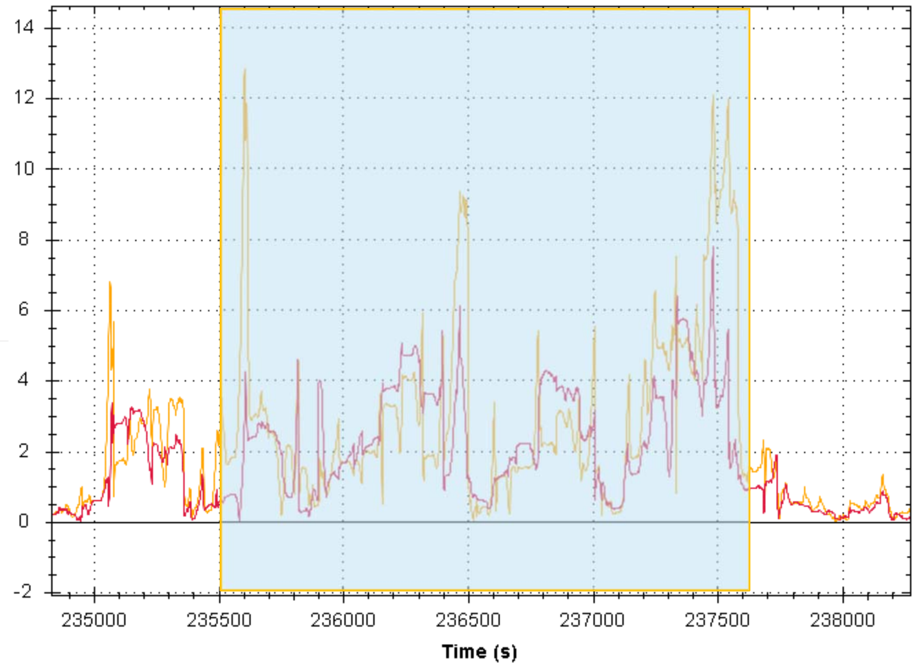
IMU Parameters to be modelled

- 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

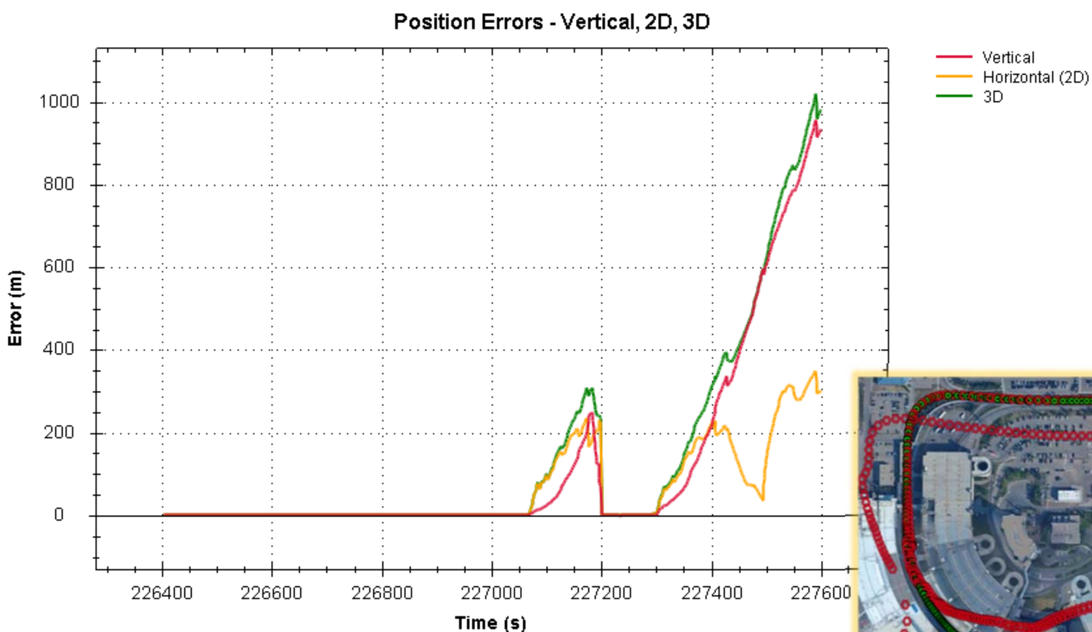
A wider spread of the fault case positions (red) vs. the nominal case (green) over the 5 passes through this section

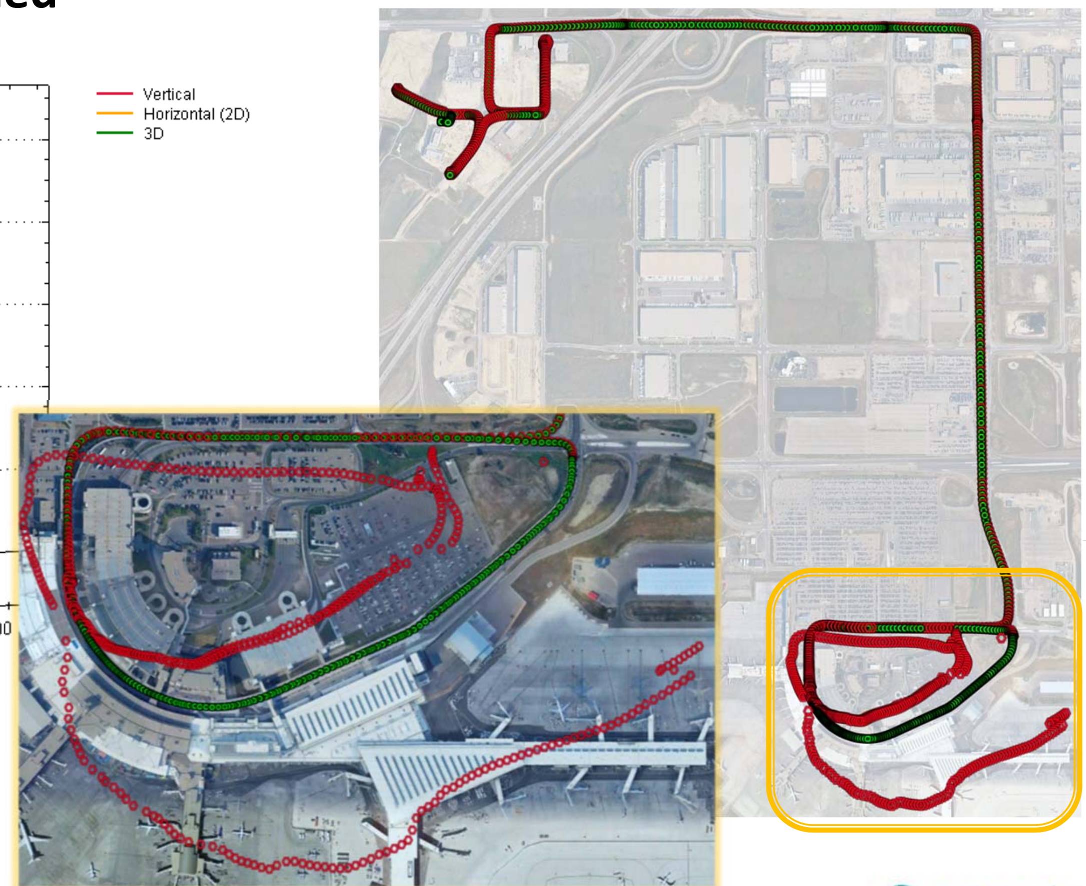
Drive through an urban canyon, and the effect of having the IMU being noisier than it should be is very pronounced



Thanks to Hexagon | NovAtel for providing these results

Use Case : Impact of IMU Axis-mismatched

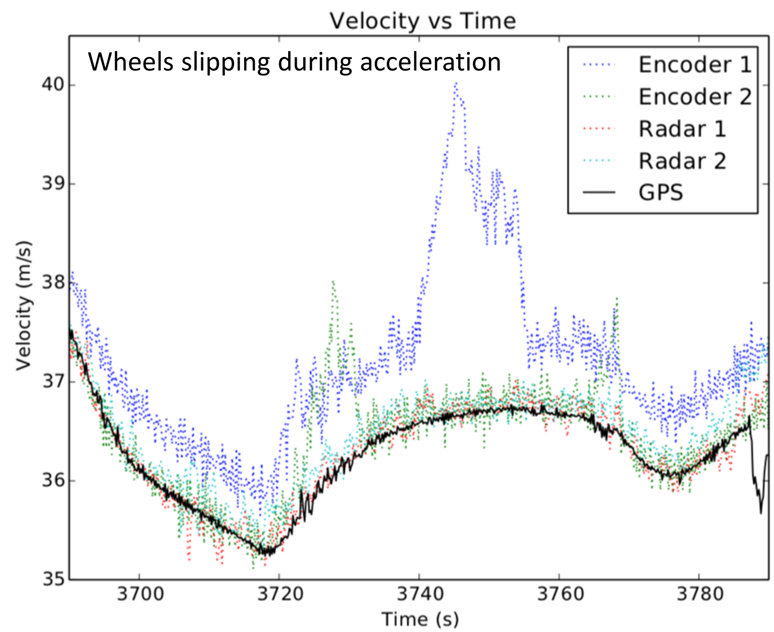




Thanks to Hexagon | NovAtel for providing these results

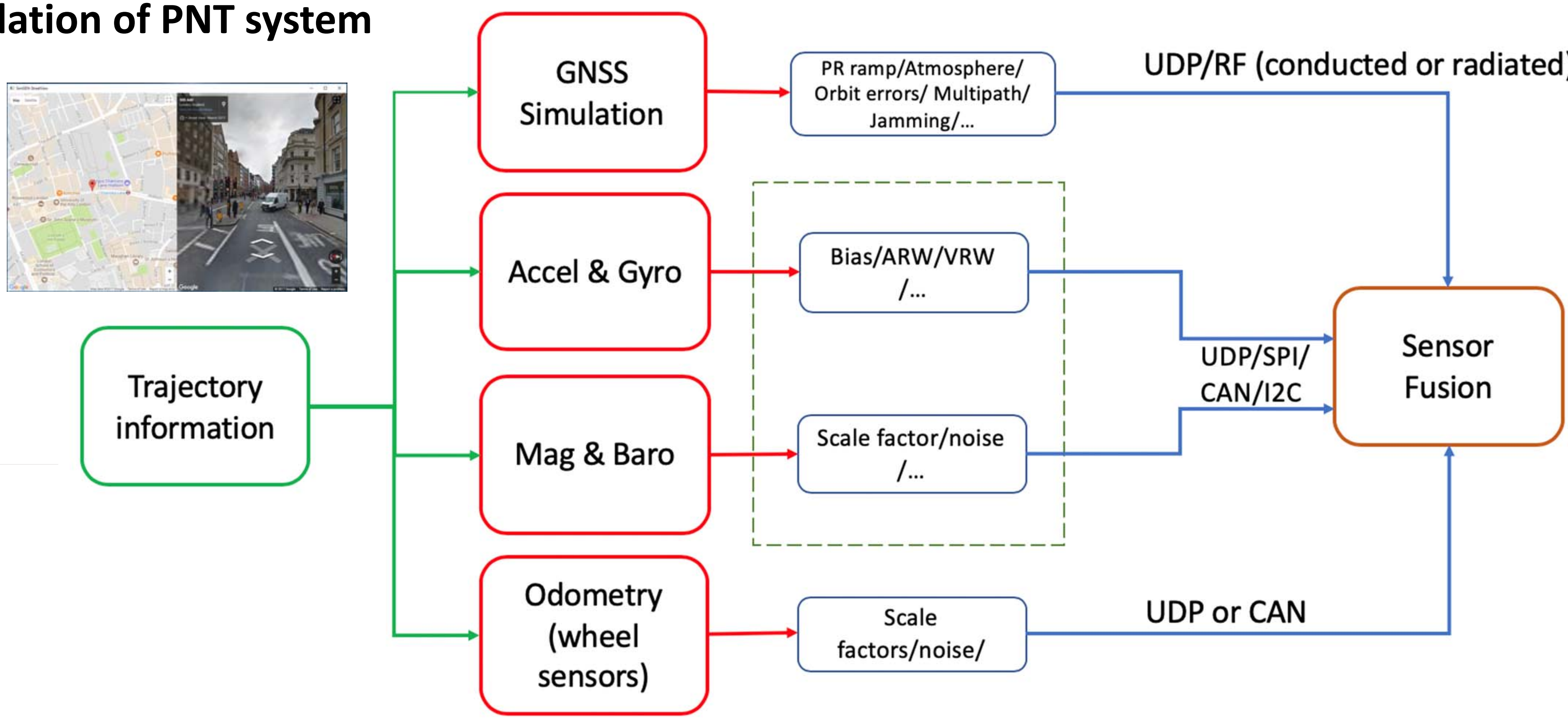
Odometry

- 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)

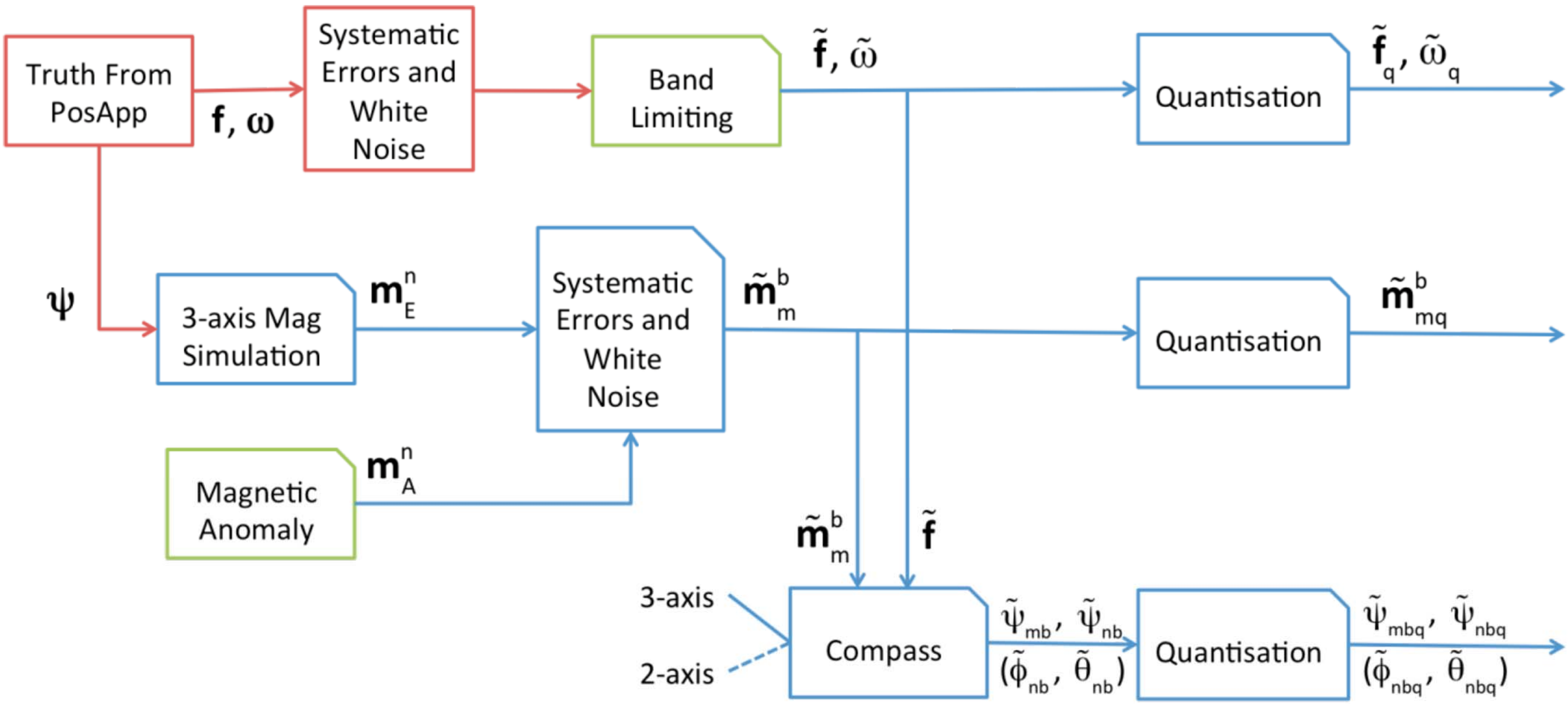


Plot source: "Robust Odometry using Sensor Consensus Analysis", Andrew W. Palmer and Navid Nourani-Vatani

Validation of PNT system



How Simulation works



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.

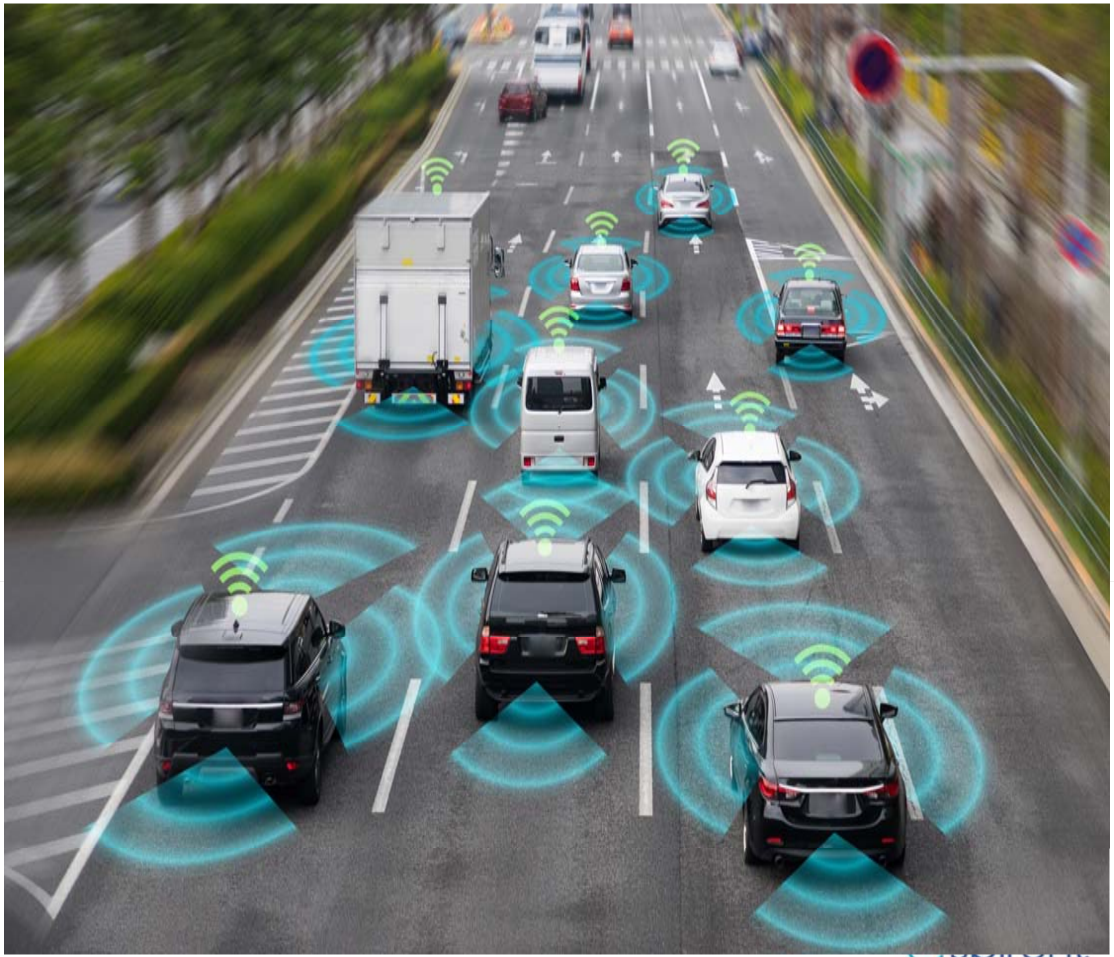
GNSS SIMULATION

- 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

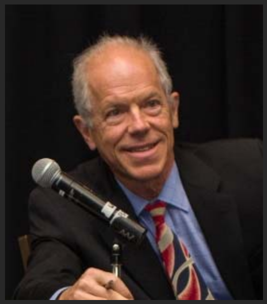
QUICKPOLL

What type of IMU errors are you most concerned about?

Poll Results (single answer required):

Bias stability	44%
Scale factor	4%
Axis misalignment	19%
Angle/velocity random walk noise	33%

Ask the Experts



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