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INSIDE ENGINEERING, POLICY AND PRACTICE

WEBINAR AND VIRTUAL WORKSHOP:

ON THE ROAD TO AUTONOMY

Wednesday, Dec 12, 2018

10 a.m. PST • Noon CST • 1 p.m. EST
6 p.m. BST • 7 p.m. CEST

WELCOME TO

On the Road to Autonomy

Demoz Gebre-Egziabher
Professor
Aerospace Engineering and Mechanics
University of Minnesota

Terry Lamprecht
Director of Products
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Samer Khanafseh
Research Assist. Professor
Manager
Illinois Institute of Tech.
TruNav LLC

Co-Moderator: Lori Dearman, Executive Webinar Producer

Who's In the Audience?

A diverse audience of over 480 professionals registered from 52 countries, representing the following industries:

24% GNSS equipment manufacturer

16% System Integrator

14% Professional User

11% Product/Application Designer

9% Government

26% Other

Welcome from *Inside Unmanned Systems*

Richard Fischer
Publisher
Inside GNSS
Inside Unmanned Systems

A word from the sponsor

Natasha Wong Ken
Product Manager
Safety Critical Systems
NovAtel, part of Hexagon's Positioning Intelligence Division

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Poll #1

How critical do you think the GNSS component is compared to other autonomous driving sensors (I.e. LiDAR, Radar, Camera, etc...)?

A. Most Important
B. Very Important
C. Somewhat Important
D. Not Important at All

Today’s Development Platforms

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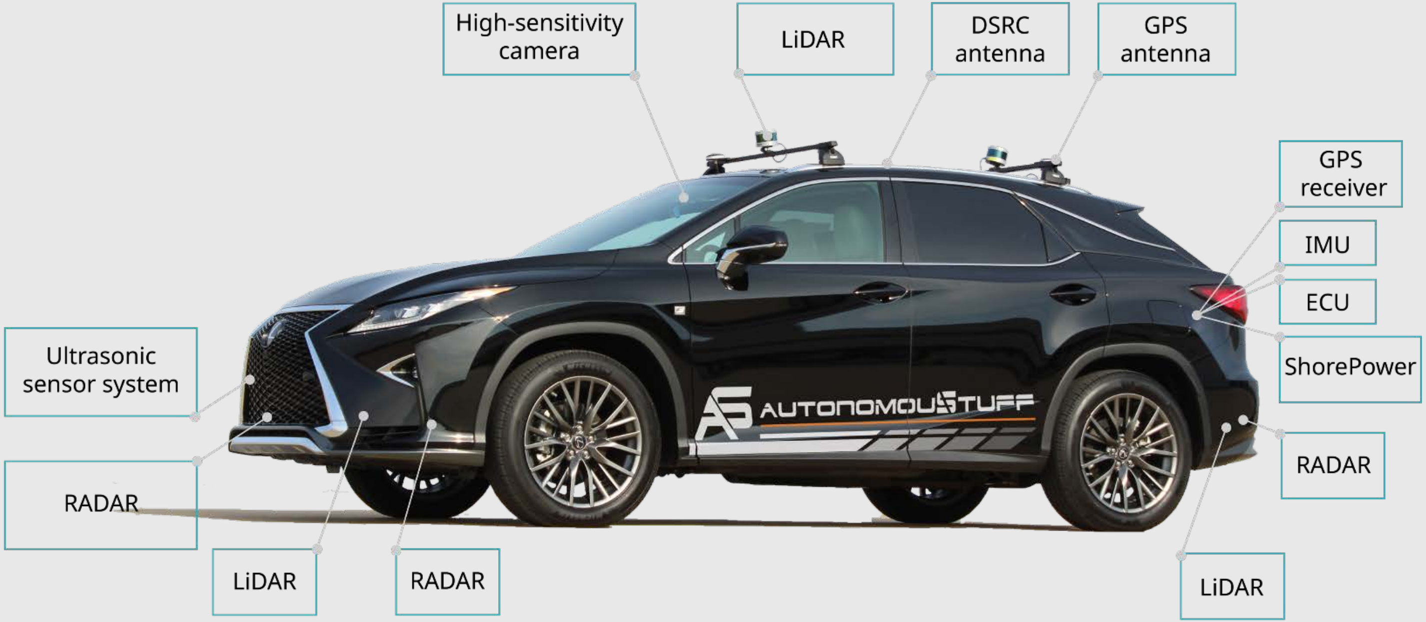
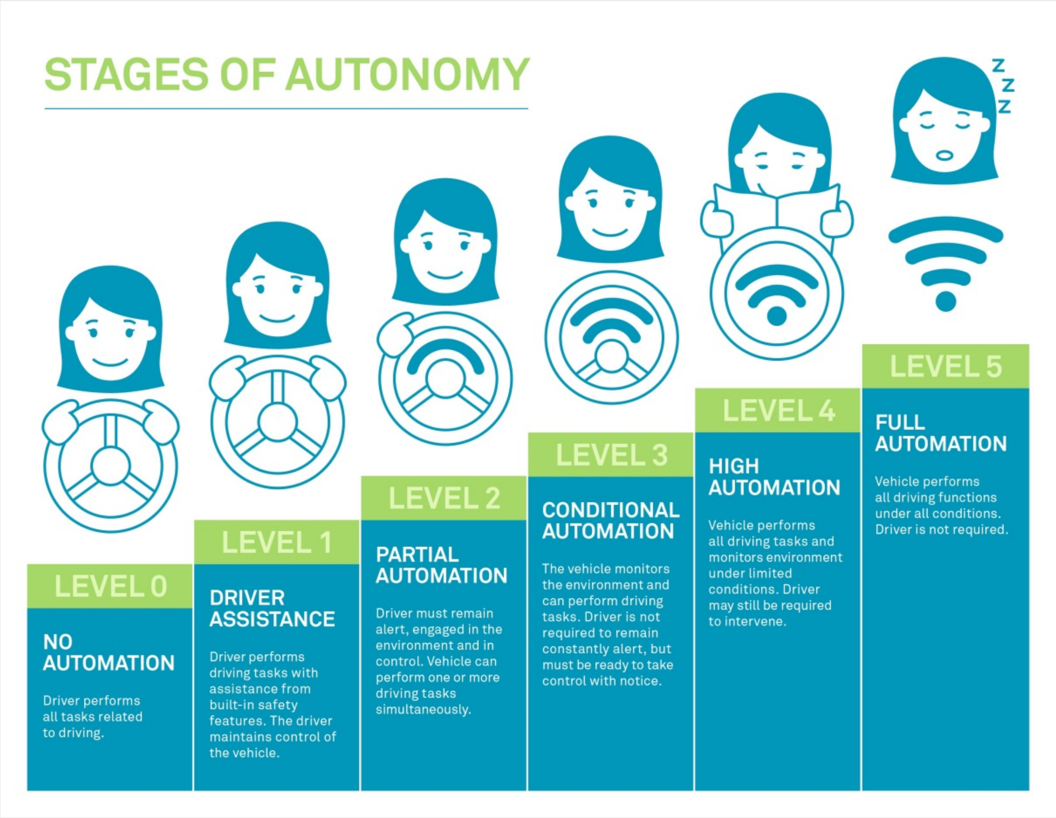
AUTONOMOUSTUFF

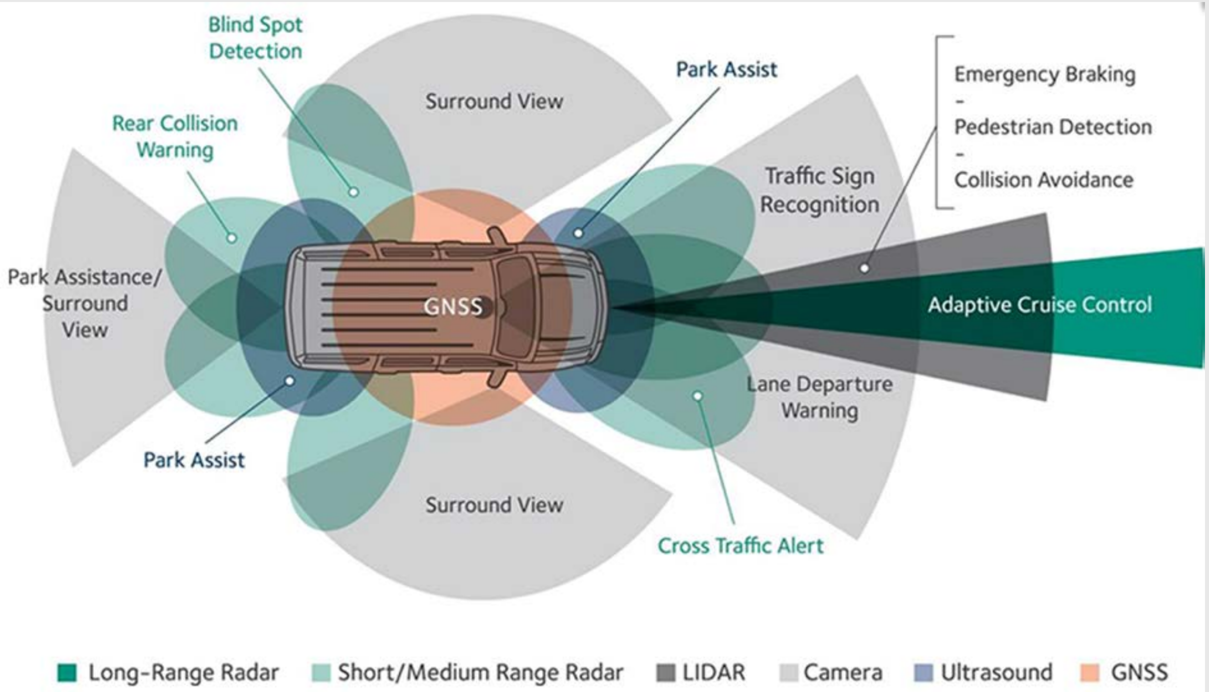
Terry Lamprecht
Director of Products and New Technologies
AutonomouStuff

Today’s Development Platforms

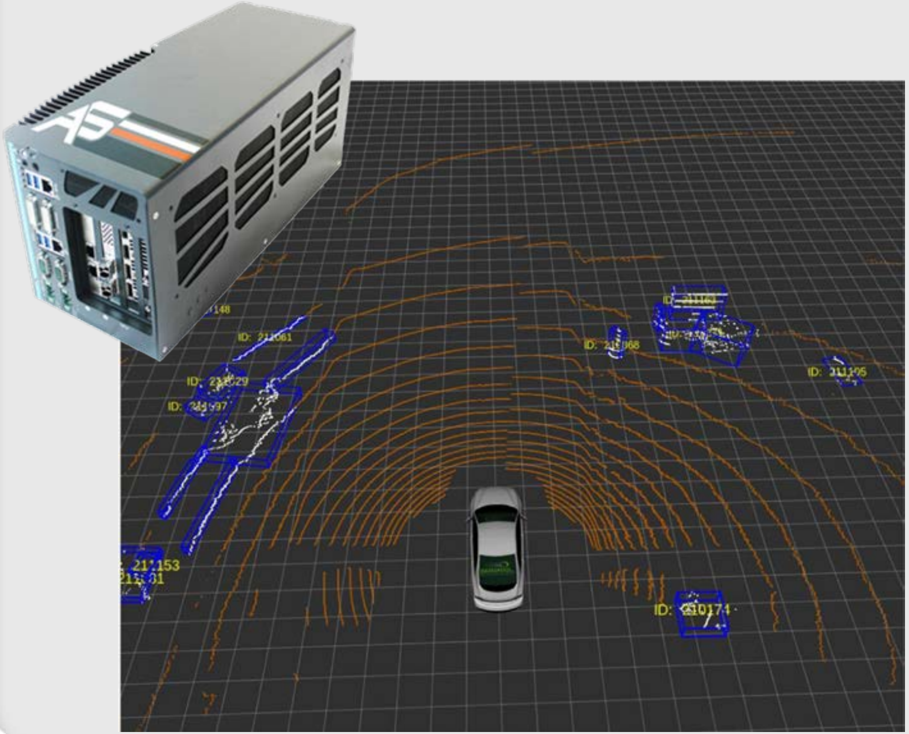



STAGES OF AUTONOMY
Z
Z
Z
LEVEL 0
NO AUTOMATION
Driver performs all tasks related to driving.
LEVEL 1
DRIVER ASSISTANCE
Driver performs driving tasks with assistance from built-in safety features. The driver maintains control of the vehicle.
LEVEL 2
PARTIAL AUTOMATION
Driver must remain alert, engaged in the environment and in control. Vehicle can perform one or more driving tasks simultaneously.
LEVEL 3
CONDITIONAL AUTOMATION
The vehicle monitors the environment and can perform driving tasks. Driver is not required to remain constantly alert, but must be ready to take control with notice.
LEVEL 4
HIGH AUTOMATION
Vehicle performs all driving tasks and monitors environment under limited conditions. Driver may still be required to intervene.
LEVEL 5
FULL AUTOMATION
Vehicle performs all driving functions under all conditions. Driver is not required.

Current ADAS Solutions



Compute Solutions



- Middleware
  - ROS
  - Others
- Industrial vs embedded computing

Cons:

- Power requirements
- Heat dissipation
- Robustness

Poll #2

What do you think the biggest barrier is to widespread production of autonomous vehicles? (select your top two)

a) *Public Safety*
b) *Cost*
c) *Regulation*
d) *Infrastructure*
e) *Technology Limitations*

RADAR

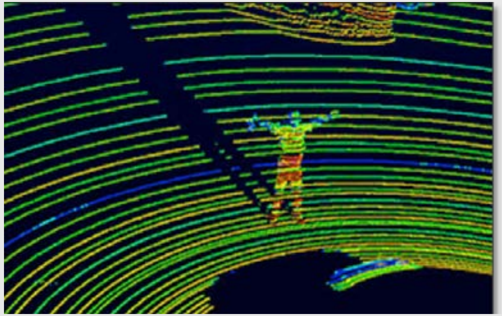
Pros:

- Automotive production volumes
- Robust design
- Reliable detection

Cons:

- Current bandwidth/resolution

LiDAR



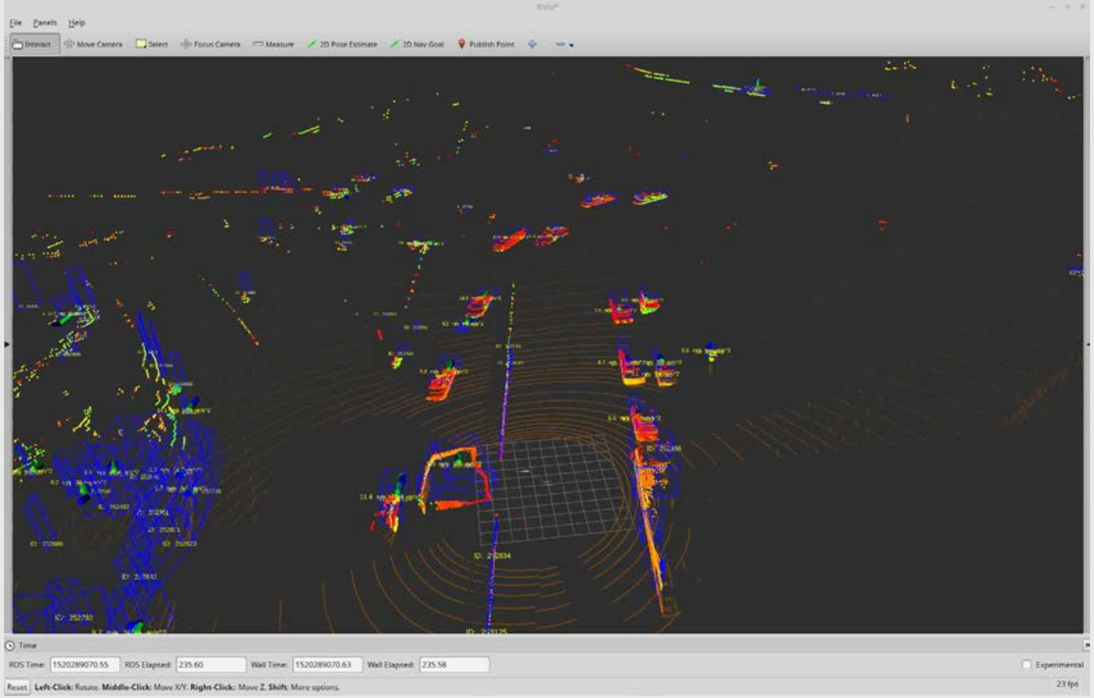
Pros:

- High resolution
- Fast update rate

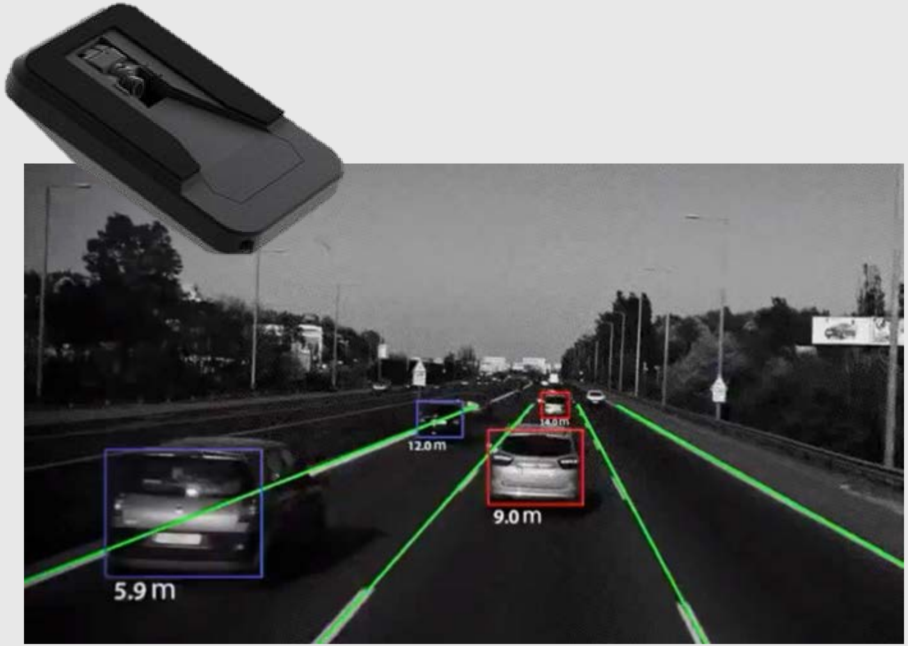
Cons:

- Price
- Environmental obscurants
- Mechanical designs
- Solid state design delays

LiDAR Object Processing



Vision



Pros:

- Good for lane detection
- Preferred method of classification

Cons:

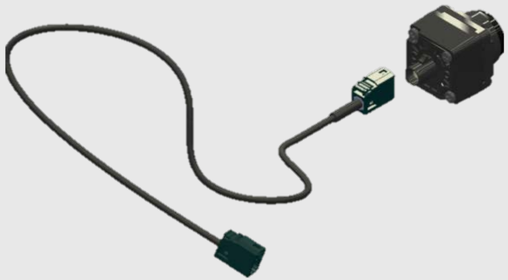
- Raw images produce huge amounts of data
- Needs quality lane markings
- Needs proper illumination

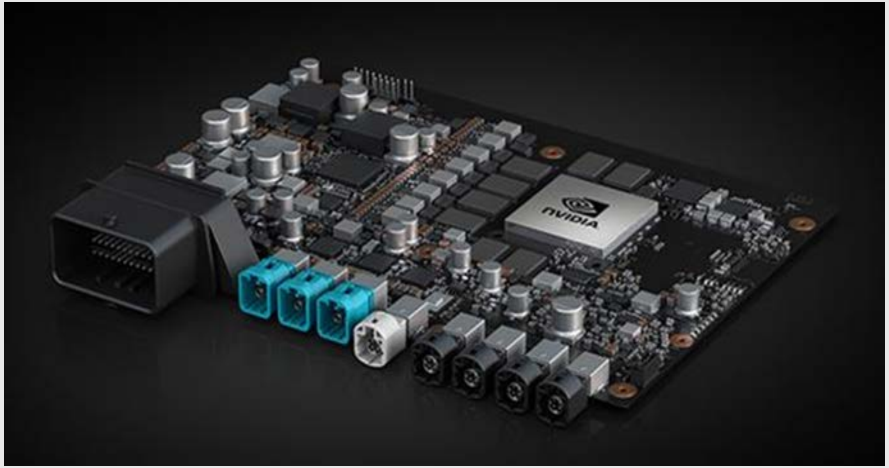
Vision

Thermal Vision Advantages:

- Nighttime driving
- Better visibility during rain, fog, smoke and dust

Parallel/Centralized Processing

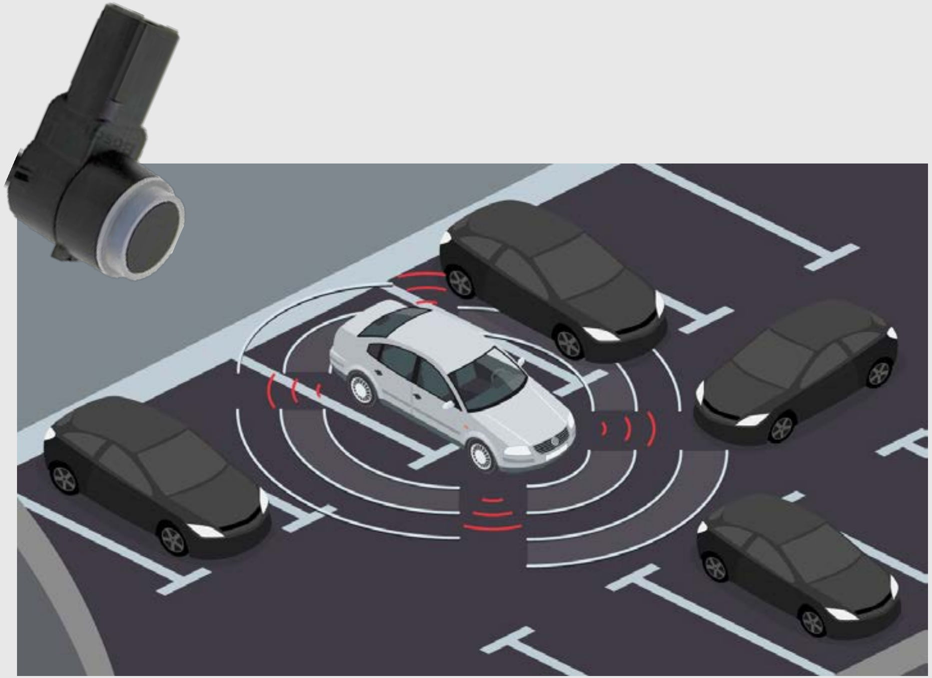




Pros:

- Enables easier sensor fusion
- Lower cost at high volumes
- Application specific processing

Ultrasonic



Pros:

- Low cost
- Reliable/robust sensing

Cons:

- Extremely short range

Today’s GNSS Ground Truth Systems

Pros:

- Extremely accurate
- Tightly coupled systems Provide adequate position in a variety of difficult scenarios

Cons:

- High cost
- Complex systems

Poll #3

What level of positioning accuracy do you think autonomous driving requires?

- ***A. 0 – 10 cm***
- ***B. 10 – 50 cm***
- ***C. 50 cm – 1 Meter***
- ***D. >1 Meter***

Precise Positioning for Automotive with Mass Market GNSS Chipsets

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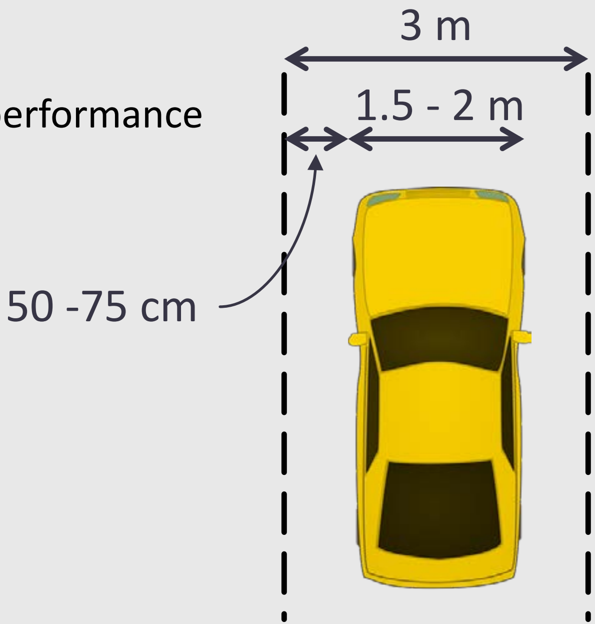
Lance de Groot
Senior Team Lead, Geomatics – Safety Critical Systems
NovAtel, part of Hexagon's Positioning Intelligence Division

Introduction

- Production GNSS in automotive today
  - L1 only pseudorange solution
  - Several metres of error
- Emerging applications in automotive require increased performance
  - V2V → 1.5 m 1σ[1]
  - AD/ADAS → < 1.0 m
- How to get there?
  - Multi-frequency mass-market chipsets recently announced
  - High precision carrier phase positioning algorithms



[1]NHTSA V2V Notice of Proposed Rulemaking (2127-AL55)

High Precision Positioning – Two Techniques

- RTK (including Network RTK)
  - Works by differencing measurements between rover and base to remove errors
  - Regional solution
  - Requires ~20-50 km station spacing
- PPP
  - Works by providing corrections for all error sources
  - Global solution, with regional atmospheric corrections
  - Regional requires ~100-300 km station spacing
- Our approach for automotive is PPP
  - One way data transfer
  - Less infrastructure
  - Globally consistent solution a benefit for implementation, safety

	RTK	PPP
Orbit	✓ and ✗	✓
Antenna phase centre offset	✓	✓
Antenna phase centre variations	✓	✓
Antenna phase wind-up	✗	✓
Clock corrections	✗	✓
Group delay differential	✗	✓
Relativity term	✗	✓
Ionospheric delay	✗	✓
Tropospheric delay	✓	✓

Chipsets Under Test

- We tested four current mass market chipsets

Chipset	Frequencies	Constellations
A	L1 Only	GPS/GLO
B	L1/L2	GPS/GLO/GAL
C	L1 Only	GPS/GLO
D	L1/L5*	GPS/GLO/GAL

A and B: Same manufacturer

*L5 not supported by corrections employed

- Some chipsets are not released
- Performance in this study may not reflect final performance

Measurement Noise

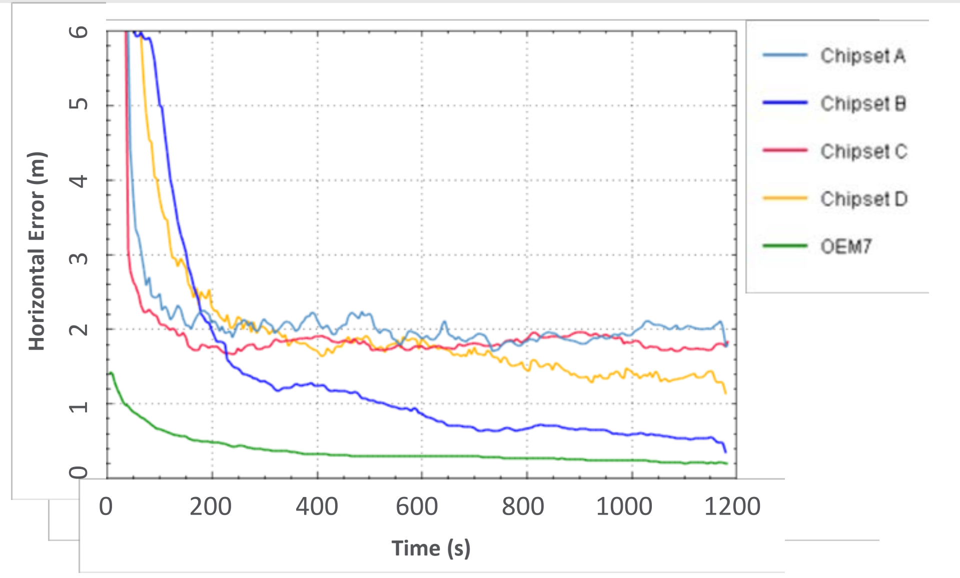
- Measurement noise measured with static zero-baseline double difference test

	Code Phase Standard Deviation (cm)		Carrier Phase Standard Deviation (mm)	
	GPS L1 C/A	GLS L1 CA	GPS L1 C/A	GLS L1
Chipset A	15	29	1.7	2.0
Chipset B	26	52	1.8	2.3
Chipset C	16	33	0.7	2.2
Chipset D	49	57	3.3	4.7
NovAtel OEM7	5	4	0.5	0.6

- Mass-market chips have 3x to 14x code noise compared to a survey grade receiver
- Will impact PPP convergence performance
- Wider correlator spacing is also more susceptible to multipath
- Phase noise also greater; no significant impact expected

Static Convergence – Global Corrections

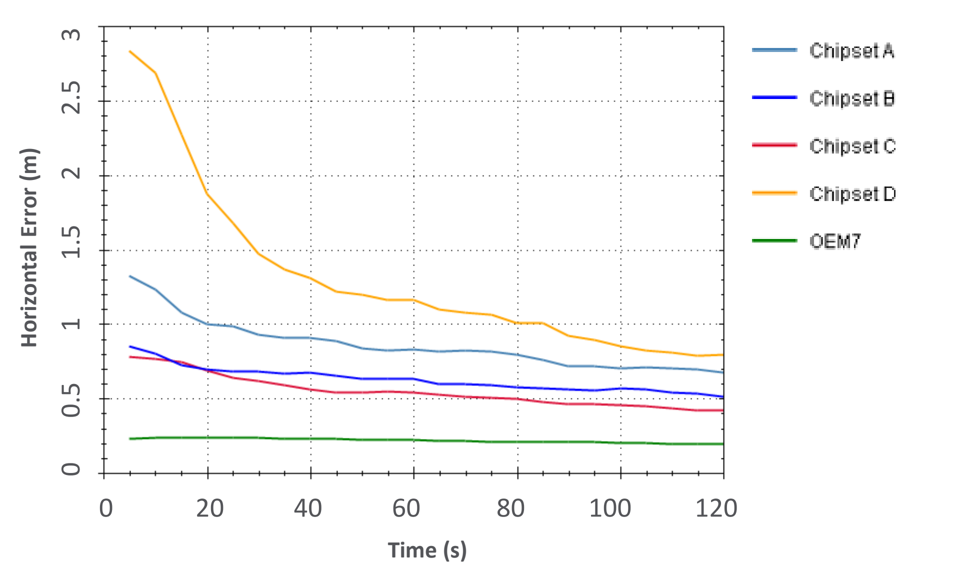
- Convergence tested in offline processing with simulated filter resets
- Horizontal 95% convergence performance with TerraStar-C corrections



- ~9 minutes to reach 1m for dual frequency, > 20 minutes for single frequency
- Not acceptable for automotive applications

Static Convergence – With Regional Corrections

- TerraStar-X is a future TerraStar service with enhanced convergence performance
- Provides regional ionosphere corrections



- Sub-metre performance now achieved in 30s for most chipsets
- Feasible for automotive

Ask the Experts – Part 1

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PART II
Precise Positioning for Automotive with Mass Market GNSS Chipsets

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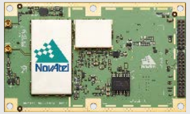
NovAtel, part of Hexagon's Positioning Intelligence Division

Kinematic Performance – Test Setup

Prototype L1/L2 Automotive Grade Antenna

A	B	C
L1 only	L1/L2	L1 only

Truth System



OEM729

+

uIMU

+

GPS-702GGL

Inertial Explorer

Position accuracy (m) RMS		Velocity Accuracy (m/s) RMS		Attitude Accuracy (degrees) RMS		
Horizontal	Vertical	Horizonal	Vertical	Roll	Pitch	Heading
0.01	0.02	0.010	0.010	0.005	0.005	0.009

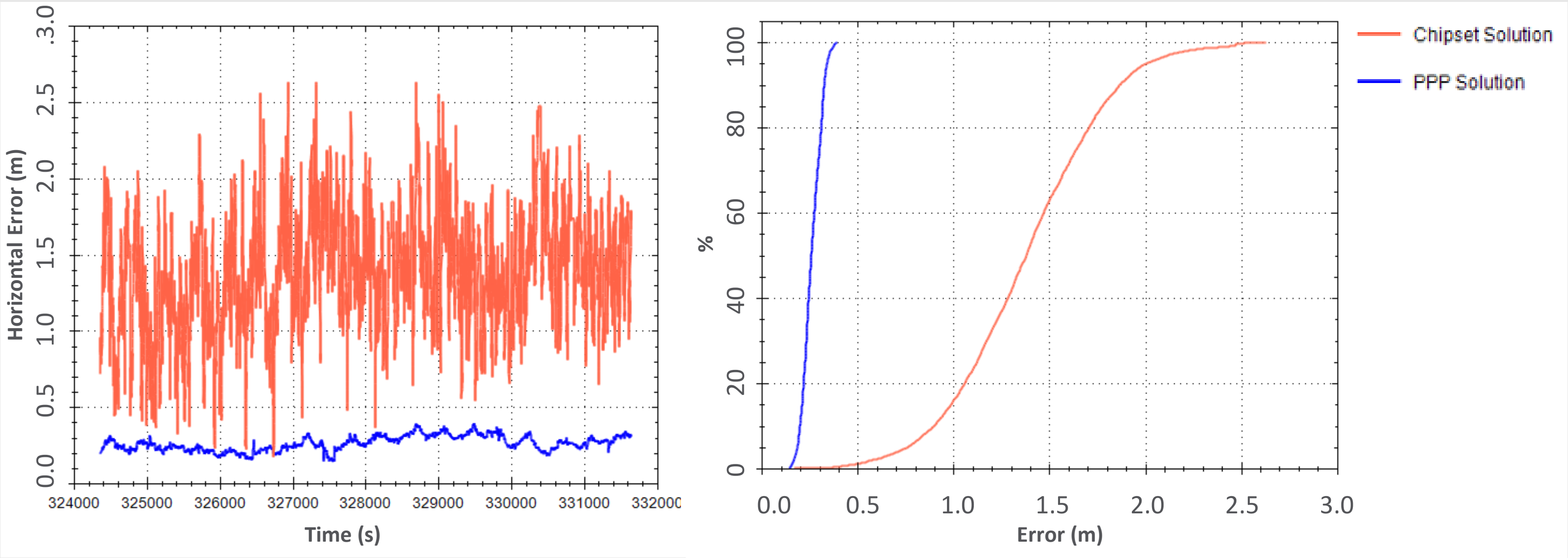
Kinematic Performance – Open Sky Trajectory

- Industrial district north of Calgary airport
- Mix of 1-2 storey warehouses, controlled access freeway

Photo credits: Google Earth, Google Streetview

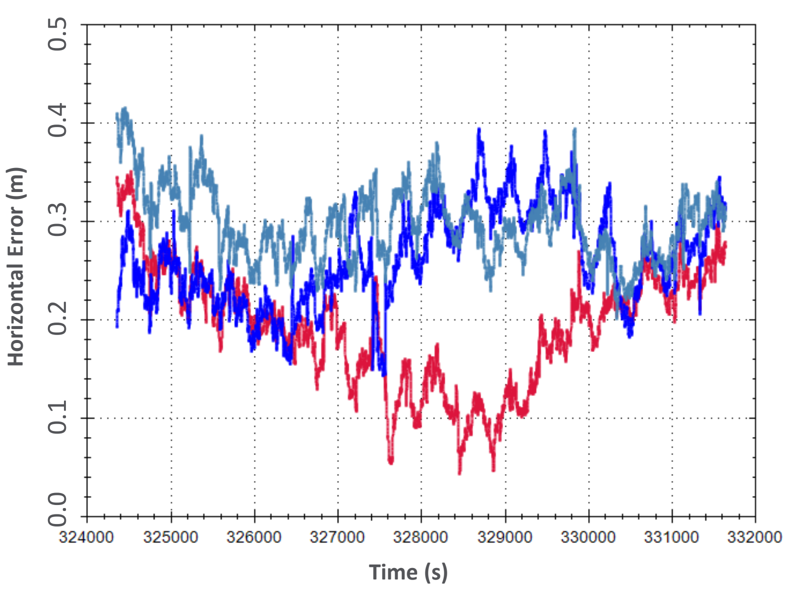
Improvement from Precise Algorithms

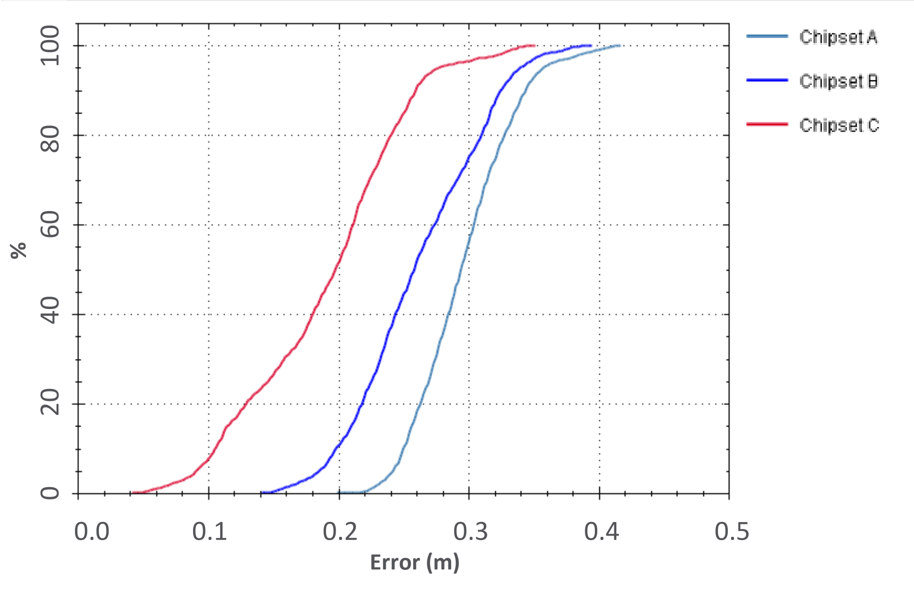
- On-board SBAS corrected code solution Chipset B vs. PPP solution with TerraStar X corrections and the same measurements



- PPP solution has a 64 - 93% improvement over on-board solution under open sky at 95%

Kinematic Performance – Open Sky Results





- Horizontal 95% error from 28 cm to 36 cm
- Viable for AD/ADAS applications

Kinematic Performance – Highway, Frequent Overpasses

- Route spans two primary controlled access freeways in Calgary
- Open sky punctuated by frequent overpasses

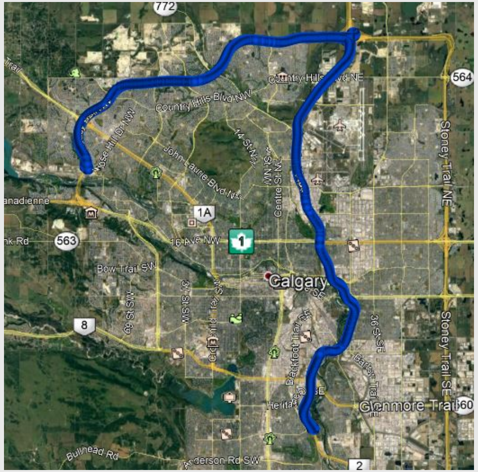
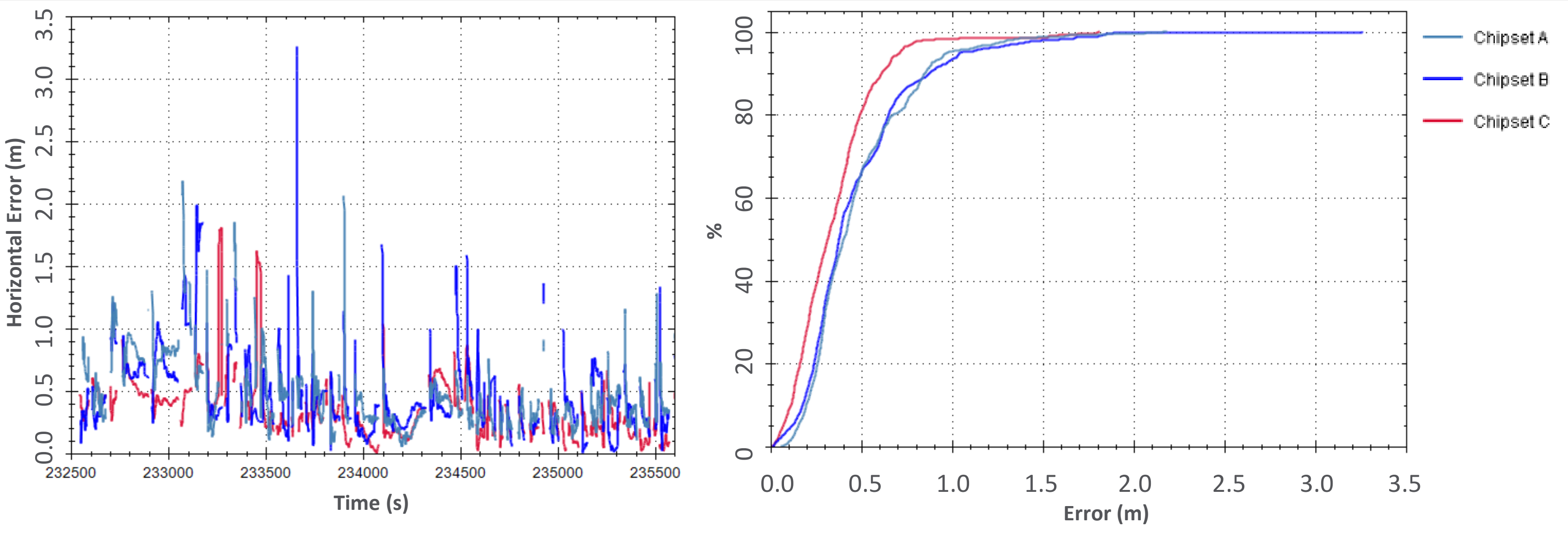


Photo credits: Google Earth, Google Streetview

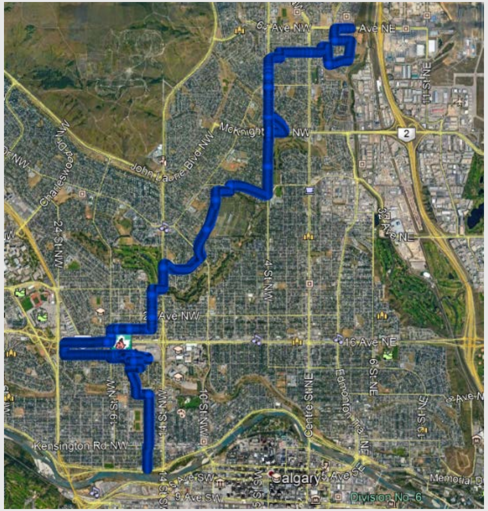
Kinematic Performance – Highway, Frequent Overpasses



- Horizontal 95% error from 71 cm to 105 cm
- Error is dominated by re-convergence following outages
- Benefits available from integration with IMU or other relative positioning sensors

Kinematic Performance – Suburban Trajectory

- Residential neighbourhoods
- Detached houses, condominiums, foliage
- Fewer total GNSS outages than highway, more partial outages



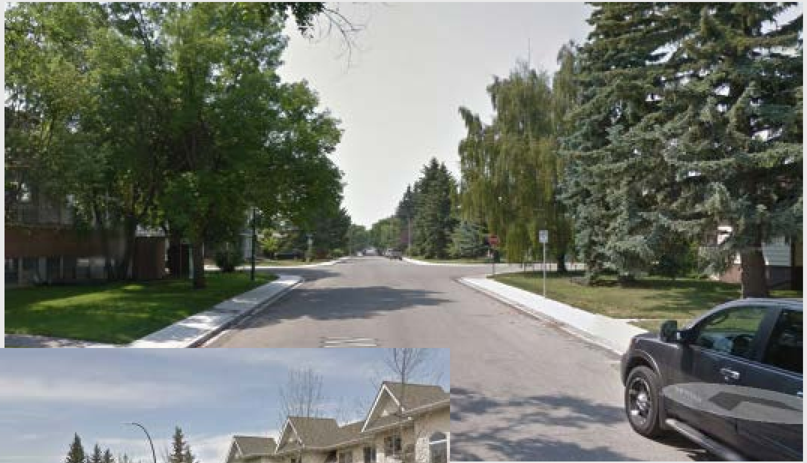
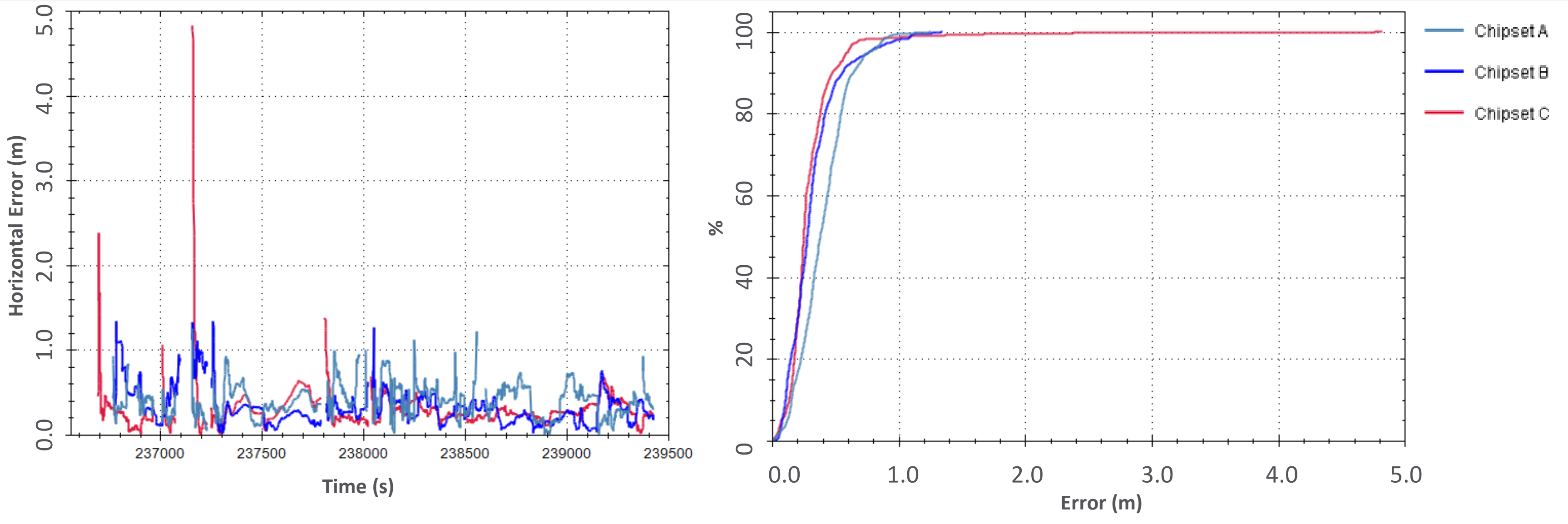


Photo credits: Google Earth, Google Streetview

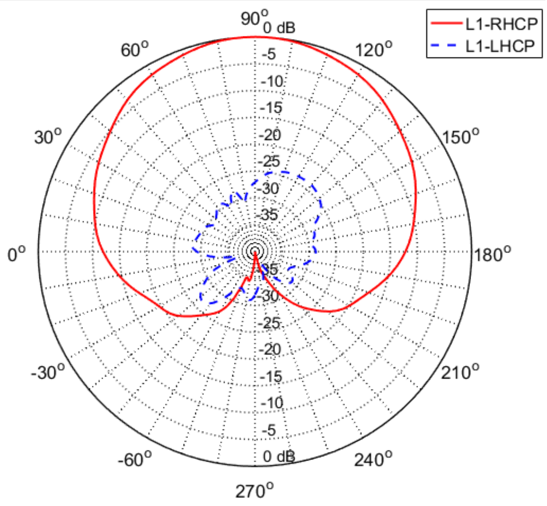
Kinematic Performance – Suburban Results



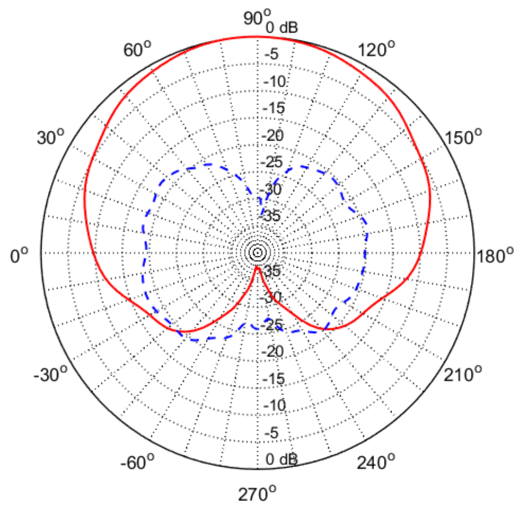
- Horizontal 95% error from 60 cm to 77 cm
- Steady state error is slightly higher than highway, reflecting worse environment

Mass-market Antennas

- Mass-market and automotive grade antennas also expected to have performance tradeoffs
- Smaller elements, ground planes



GPS-702-GG



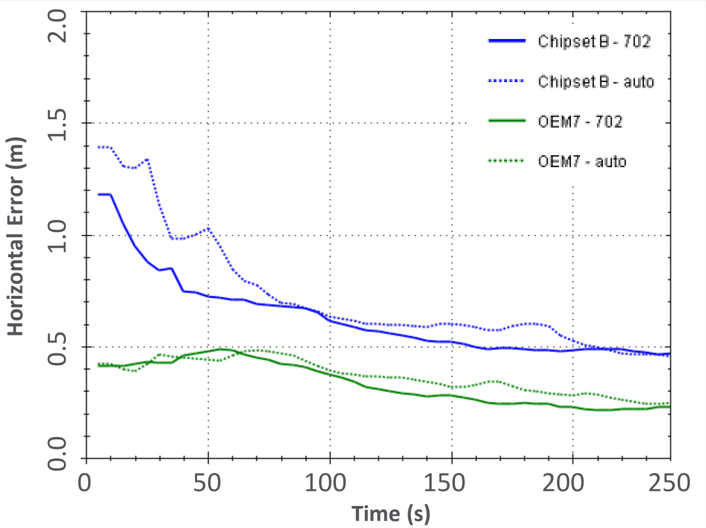
Automotive Grade Prototype

- More gradual roll-off at low elevation, lower axial ratio

Antenna impact

- Static moderate multipath test
- Survey and automotive grade antenna
- Survey grade and mass market chipset

68% horizontal convergence



- Mass-market chipset performance degrades more with automotive grade antenna
- Consistent with wider correlator spacing
- Antenna selection is likely more important with mass-market chips

Conclusions

- Hexagon PI software positioning engine with TerraStar X corrections with mass market chipsets is a viable solution for emerging automotive applications
- Ionospheric corrections are necessary to achieve desired PPP convergence performance
- Antenna selection is important with mass market chipsets

Poll #4

In your opinion, what is the biggest risk to integrity?

A. *Interference*

B. *Jamming and Spoofing*

C. *Data Security*

D. *GNSS Measurement Errors*

Safety of Autonomous Systems

Samer Khanafseh
Research Assist. Professor / Manager
Illinois Institute of Tech. / TruNav LLC

System Reliability

- Motivation for autonomous driving has been its safety compared to manned driving
  - Expectation is that autonomous driving will provide lower fatality rate
  - Currently, it is estimated that there is one fatality rate per 100,000,000 miles driven (the statistics has been computed based on several years)

- Does not imply that autonomous systems* can be allowed to be tested, and to count the fatality rate!
  - There should be enough reliability already built-in to the safety of the autonomous driving system
  - Certain design requirements and safety standards with documentation of the system proof-of-safety should be made in front of a certification entity (just like obtaining a driving license)

- It is not enough to demonstrate the system* safety case through testing and demos only
  - Were there enough tests? did the tests cover all scenarios that may arise? were those tests independent? any assumptions used? Can the likelihood of “hazardous” or “catastrophic” events be quantified beforehand?

* System(s) in this context: Guidance, **Navigation** and Control

Safety in Aviation Application

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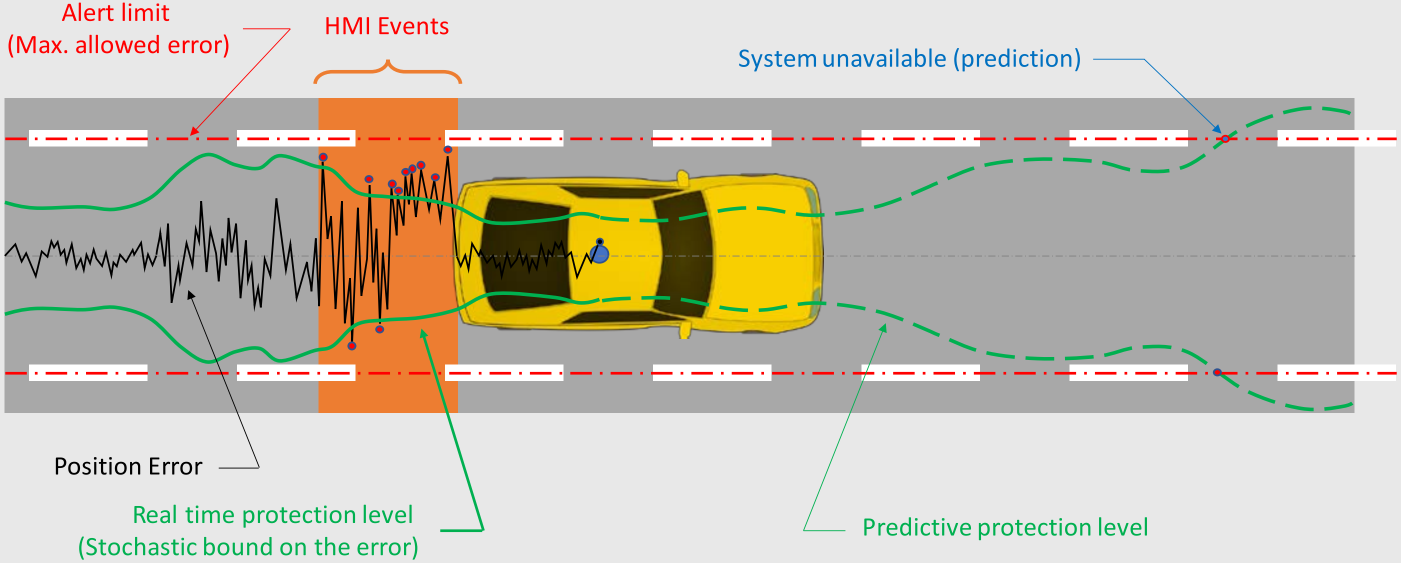
- Propose borrowing some concepts from the aviation industry in proving the design safety
- In addition to *accuracy*, system ***<u>Integrity</u>*** *Continuity* and *Availability* are measures of the system performance:
  - *Integrity risk: a measure of how much can we trust the position provided by the Navigation system*
  - Evaluated system integrity risk and the required value are application dependent:
    - Will a wrong position estimate cause any financial or life risk? Will an interruption to the operation/false-alarm cause any financial or life risk?
    - If so, then we need to provide a level of acceptable likelihood for a wrong position/interruption (stochastically and practically, zero probability is NOT an answer)
    - The required values are usually extracted from system engineering analysis.
    - Threats that are sufficiently likely to occur will require a monitor to mitigate the threat effects.

Integrity Risk Evaluation

- Example case of integrity risk I_R and its relation to the protection level PL.
  - The requirements are usually provided as an allowable alert limit AL and integrity risk $I_{R,req}$

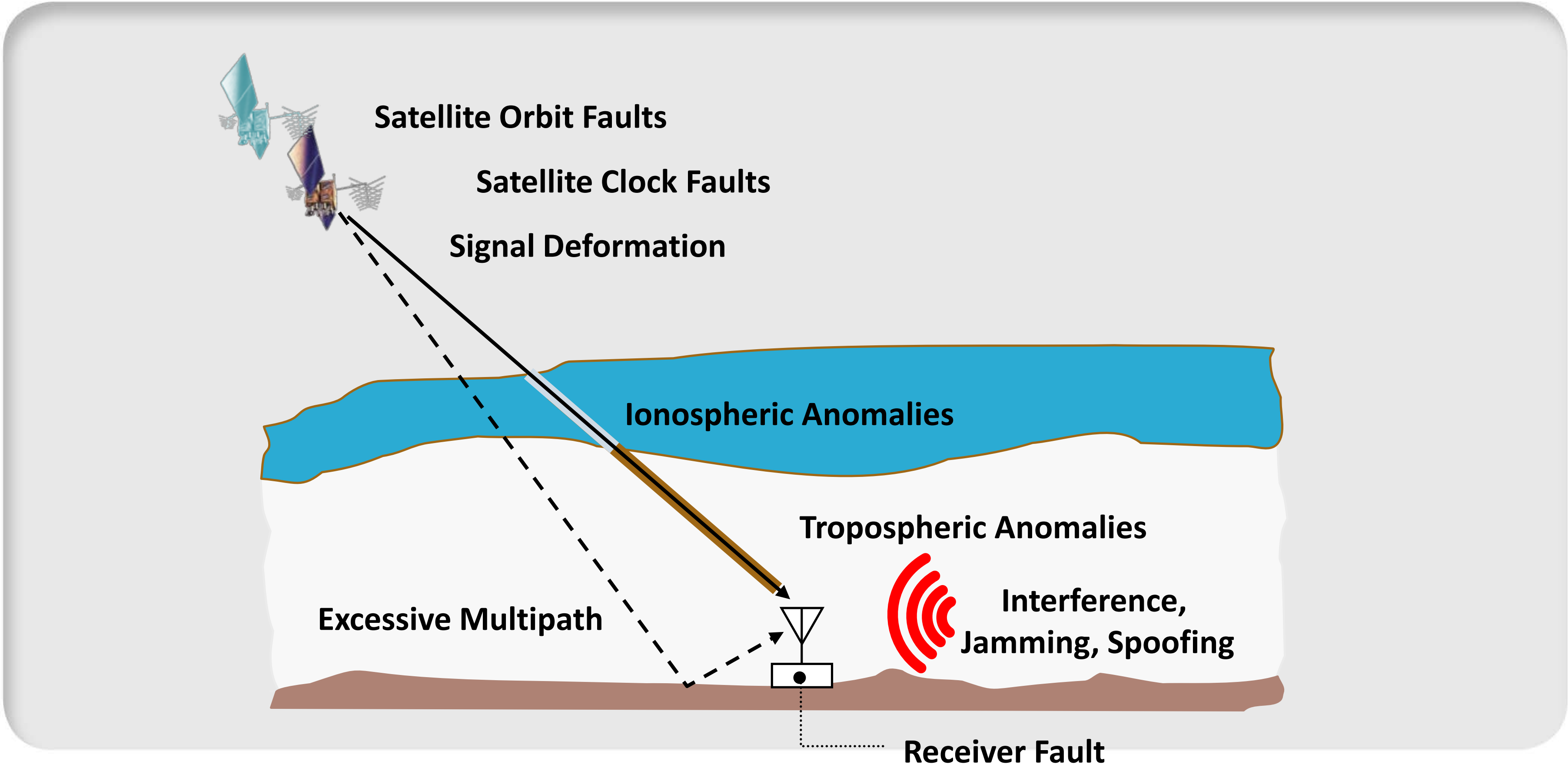
    $$I_R = P\{|\hat{x}_H - x_H| > AL\} \leq I_{R,req} \;\; (10^{-6} \; for \; example) \quad \Rightarrow \;\; PL = P^{-1}_{|\hat{x}_H - x_H|}\{I_{R,req}\}$$
  - Hazardous Misleading Information (HMI) event occurs when the position estimate error > PL



Key Aspects of Navigation System Integrity

- In designing a high integrity system, you need to analyze and address every system node for threats (faults)
  - Construct a fault tree or integrity risk tree
- Each threat or fault needs a threat model: likelihood, magnitude, profile, effect on the measurement, etc.
- Detection, monitoring, error bounding approaches are some of the techniques used for mitigation such that the total integrity risk meets the required value
  - Threat models and mitigation techniques depend on the positioning system (e.g. DGPS, RTK, and PPP)
- For example, for GNSS, we look at every possible fault from signal generation all the way to position estimation.

GPS Faults/Vulnerabilities



Fault mitigation

- Need to design monitors to detect faults and mitigate the threat. In designing a monitor, utilize
  - Threat model
  - Physics of the threat
  - Redundancy (satellite, sensor, etc)
- Need exclusion routines to distinguish the source of fault and exclude it
  - And potentially recovery logic (when the threat is over)
- In **most cases** a design that is tuned to provide high precision or accuracy doesn't necessarily translate to the highest integrity
  - In many cases, it is the opposite, and in others evaluating the integrity risk is quite complex or infeasible
  - E.g. fine tuning the estimator parameters to get high accuracy results of experiments is not considered an advisable approach from an integrity perspective.

Example: Multipath Error Modeling [1]

- In evaluating the integrity risk for autonomous vehicle applications, it is important to provide conservative error models (overbounding from a stochastic point of view).
- Automotive GNSS systems need to account for MP,
  - Multipath (MP) can occur due to signage, overpasses, trucks, etc.
  - Constraint: can't use other systems to detect changes in MP environment,
  - Need to bound the error under worst case environment.

[1] Khanafseh et al. "GNSS Multipath Error Modeling for Automotive Applications," *Proc. of the 31st ITM ION GNSS+ 2018*, Miami, Florida, Sept. 2018, pp. 1573-1589.

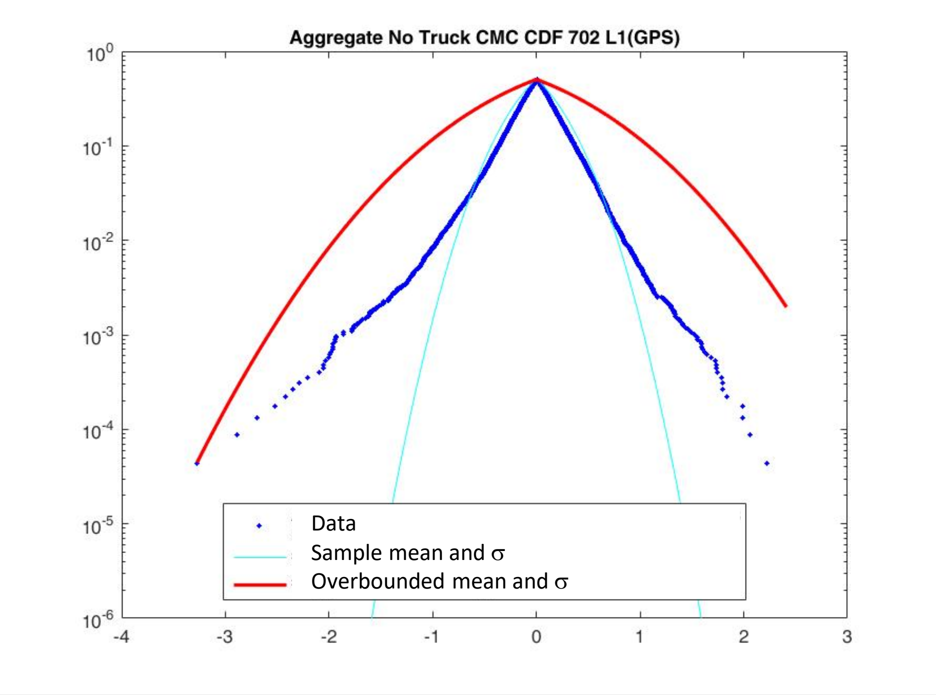
Study Objectives and Procedure

- Mitigation technique: provide GNSS error models under conditions representative of automotive environment,
  - Intended for navigation integrity and continuity risk evaluation.
  - The provided error models cover multifrequency multi-constellation code and carrier phase GNSS measurements under static and dynamic multipath environments
  - We characterized the errors by
    - Mean and standard deviation of a bounding Gaussian distribution
    - The autocorrelation time constant of the measurement errors.

[1] Khanafseh et al. "GNSS Multipath Error Modeling for Automotive Applications," *Proc. of the 31st ITM ION GNSS+ 2018*, Miami, Florida, Sept. 2018, pp. 1573-1589.

CDF Bounding

- For linear (or linearized) estimators, it has been shown that if the cumulative distribution function (CDF) of the actual measurement errors could be overbounded, then the actual estimate error CDF would be overbounded by that of the convolution of the bounding measurement error CDFs.
  - Find a Gaussian CDF with a mean and standard dev. that bounds the empirical distribution
  - With NovAtel's collaboration, we are running data collection campaigns to provide bounding multipath error models.



Integrity of GPS vs Other Systems

- **Recall that the integrity of GNSS has been scrutinized like no other sensor/system**
  - It had to go through brutal certification procedures through FAA and ICAO, because it has been proposed as replacement for current systems in terminal, approach and landing phases of civil aircraft
  - But the takeaway is to apply the lessons learned in aviation to autonomous driving field
- **Any other navigation system/sensor has fault modes and sources (Inertial Units, LIDAR, Radar, Vision, etc.)**
  - E.g. search for "fooling computer vision" will show results analogues to GNSS spoofing
- **Where "we" are now:**
  - At Illinois Institute of Tech, we are implementing similar concepts to prove the safety of Hexagon's design
  - At TruNav, we provide tailored high integrity and accuracy evaluation schemes for different designs

For More Information

SPAN Land Vehicle Performance Analysis Paper:

NovAtel's SPAN Land Vehicle Performance Analysis

Hexagon PI Papers:

https://hexagonpositioning.com/tech-talk/papers

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Ask the Experts – Part 2

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