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INSIDE ENGINEERING, POLICY AND PRACTICE

WEBINAR AND VIRTUAL WORKSHOP:
BEYOND GNSS: A SYSTEM OF SYSTEMS. TESTING SOLUTIONS FOR AUTONOMOUS VEHICLES AND ROBOTICS

Weds, July 25, 2018

10 a.m. PDT • Noon CDT • 1 p.m. EDT
6 p.m. BST • 7 p.m. CEST

WELCOME TO

Webinar and Virtual Workshop:

Beyond GNSS: A System of Systems. Testing Solutions for Autonomous Vehicles and Robotics

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

Matthew Spenko
Associate Professor
The Robotics Lab
Illinois Institute of Technology

Curtis Hay
Technical Fellow
General Motors
GPS & maps
VEC East

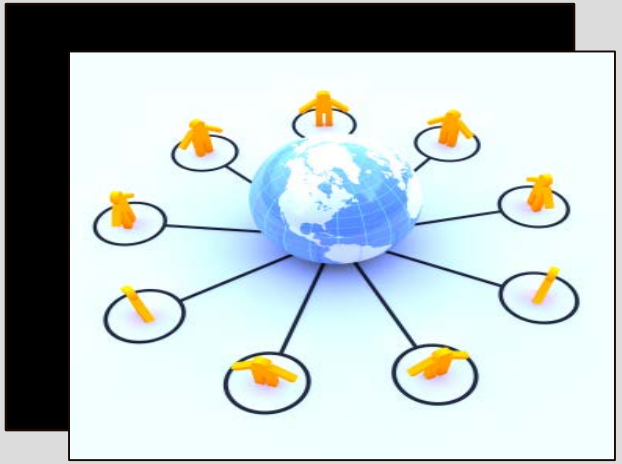
Chaminda Basnayake
Principal Engineer
Market Development
Locata Corporation Pty Ltd

Co-Moderator: Lori Dearman, Executive Webinar Producer

Who's In the Audience?

A diverse audience of over 350 professionals registered from around the globe, representing the following industries:

- **20% GNSS equipment manufacturer**
- **18% System Integrator**
- **17% Product/Application Designer**
- **11% Professional User**
- **11% Government**
- **23% Other**



Welcome from *Inside GNSS*

Richard Fischer
Publisher
Inside GNSS
Inside Unmanned Systems

Welcome from *our sponsor*

Ajay Vemuru
Strategy and Business Development
Positioning and Navigation
Spirent

Legacy

Spirent has been providing GNSS simulators for over 30 years, and this remains at the heart of what we do.

Nobody supplies more GNSS signals than Spirent.

Services Framework

In addition to test equipment, Spirent also offers a range of services to support the widest range of customers and challenges.

PNT

Spirent supplies test and evaluation solutions that provide coherent emulation of whatever combination of signals and sensors are required. To do so we work with industry leaders across the sector to provide integrated solutions.

Our Vision

Our aim is to provide Solutions to PNT test challenges that are realistic and support multiple signals and sensors – Beyond GNSS. We do this through internal development and by partnering or integrating with industry leading solutions.

Calnex NSL VECTOR dSPACE carSIM MECHANICAL SIMULATION IPG AUTOMOTIVE

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

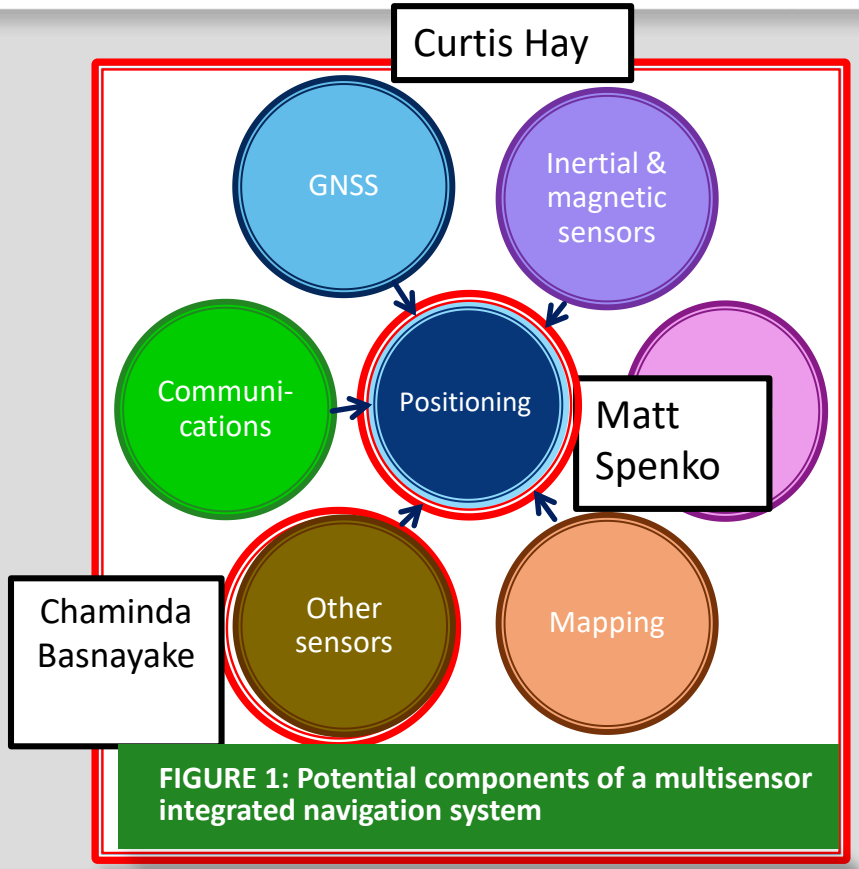


FIGURE 1: Potential components of a multisensor integrated navigation system

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Poll #1

Experimentally validating the performance of safety-critical autonomous vehicle PNT system will require: (select one)

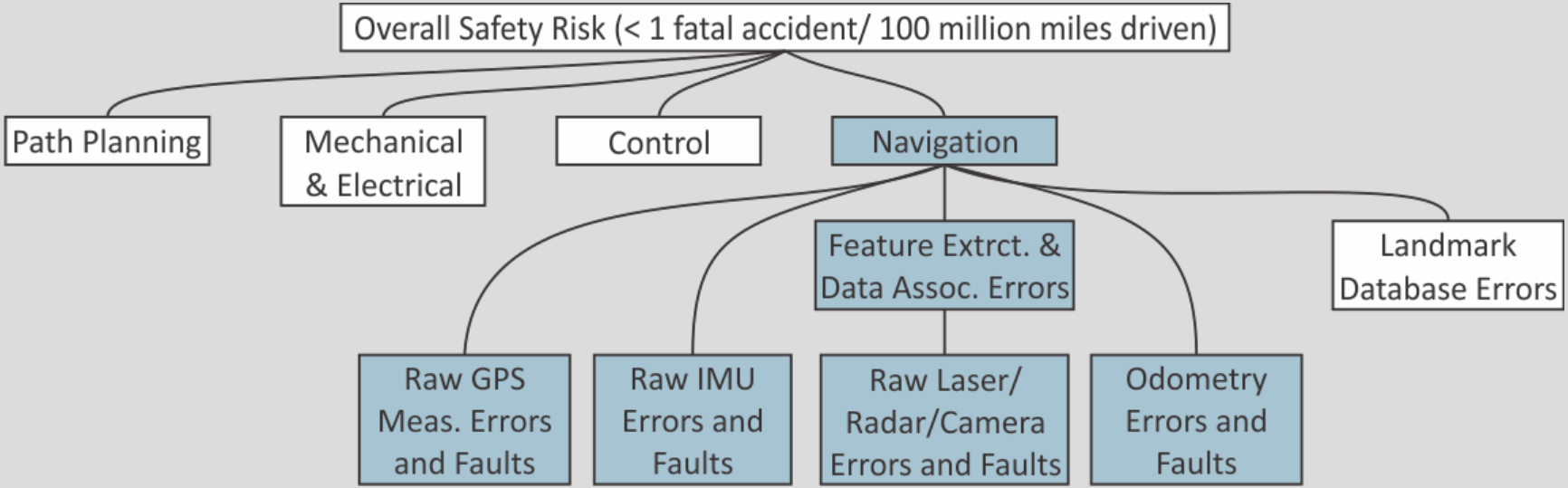
a) *A month's worth of data*
b) *A year's worth of data*
c) *10 years' worth of data*
d) *Can all be done in simulation*

Navigation Safety for Mobile Robots

Matthew Spenko
Associate Professor
Illinois Institute of Technology

The Robotics Lab @ Illinois Tech

Mobile Robot Safety Components



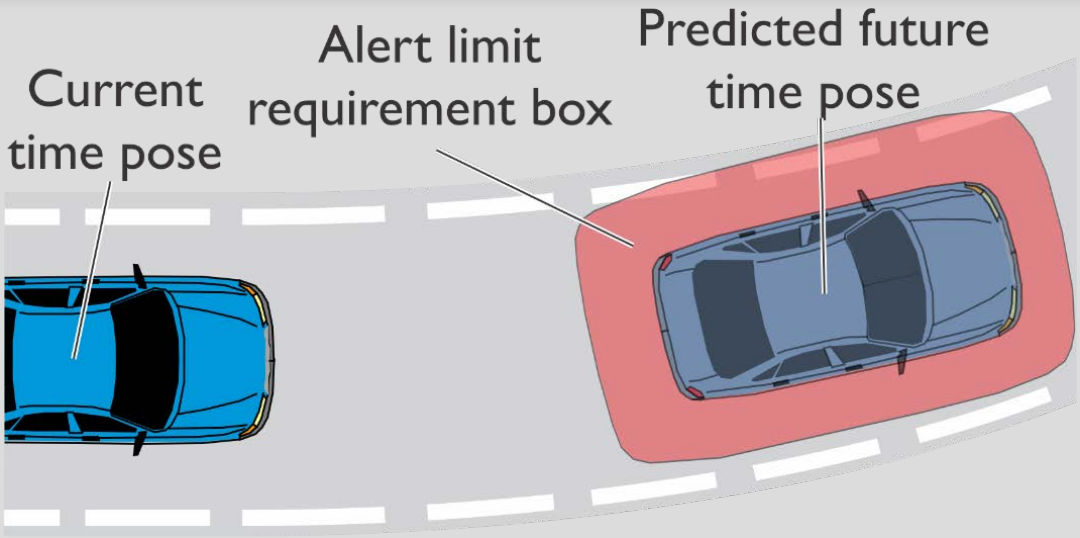
Can We Prove it Experimentally? [Kalra, 2016]

How many miles would have to be driven without failure to demonstrate with 95% confidence that the failure rate is…	Miles
less than current	275 million
20% better than current	11 billion

- Aviation industry
- Guarantee integrity–measure of trust in a sensor's information

[Kalra, 2016] – Kalra and Paddock "Driving to Safety: How many miles of driving would it take to demonstrate autonomous vehicle reliability" Rand Corporation, 2016

Adopting Aviation Safety Methods to Terrestrial Robots

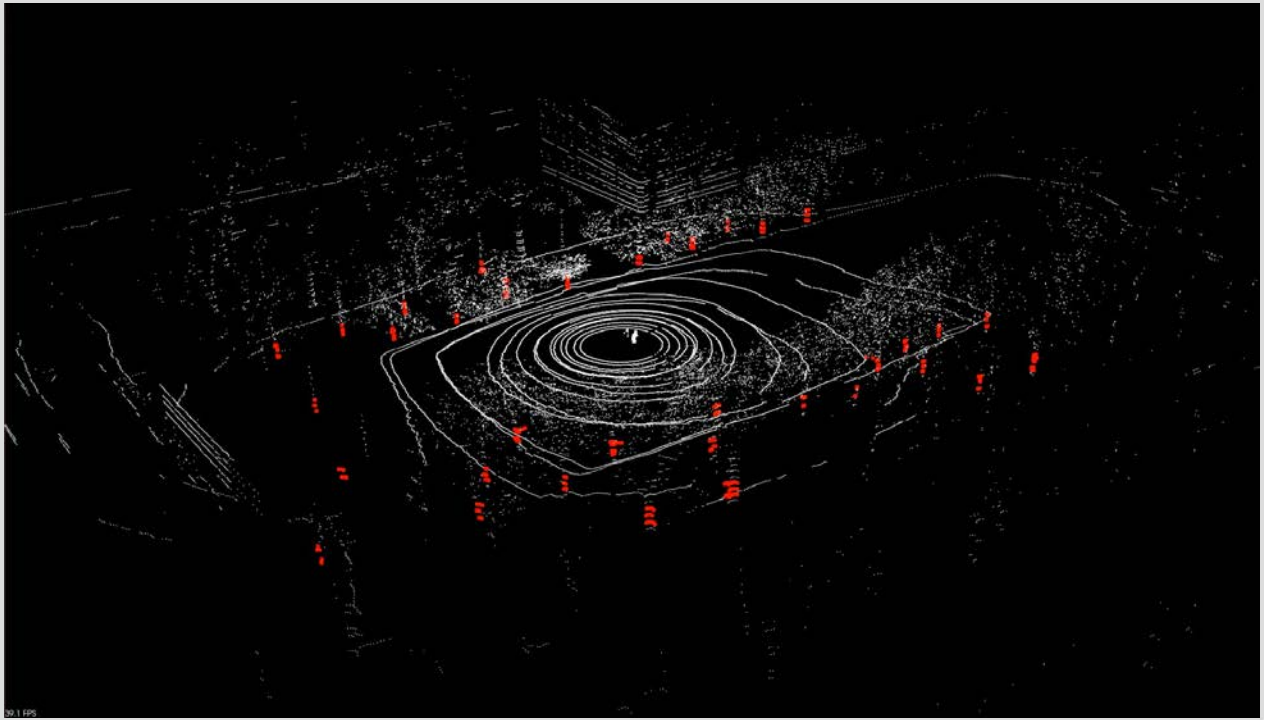


Challenge	Need
GNSS-alone is insufficient	Multi-sensor system
Not only peak in safety risk at landing	Continuous risk monitoring
Unpredictable measurement availability	Prediction in dynamic environment

[LAAS] RTCA SC-159, "Minimum Aviation System Performance Standards for the Local Area Augmentation System (LAAS)," Doc. TCA/DO-245, 2004.

Feature Extraction and Data Association

Extracted features (trees) in red



Data Association

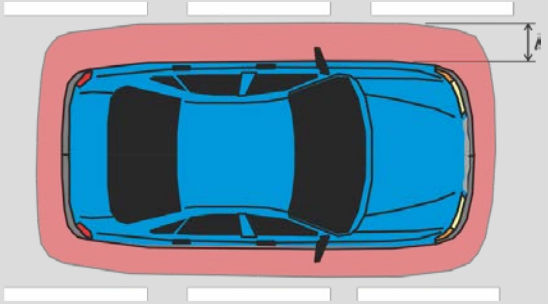
- Landmarks faults
  - Feature faults – landmark is associated to a wrongly extracted feature
  - Misassociation – a landmark is associated with a feature correctly extracted from a different landmark

Obscured posts because of construction could cause possible *feature fault*

Landmarks too close together could cause *misassociation*

How Do We Evaluate the Probability of Misassociation?

- Probability of Hazardous Misleading Information



- Evaluated under fault-free, or correctly associated (CA) and faulted, or incorrectly associated (IA) conditions
- Impossible to evaluate exactly, instead bound as:

$$P(HMI) \leq 1 + (P(HMI|CA) - 1)P(CA) \equiv \breve{P}(HMI)$$

Solvable from covariance of Kalman filter update

??

Upper bound set by safety requirements

Calculating the Probability of Correct Association

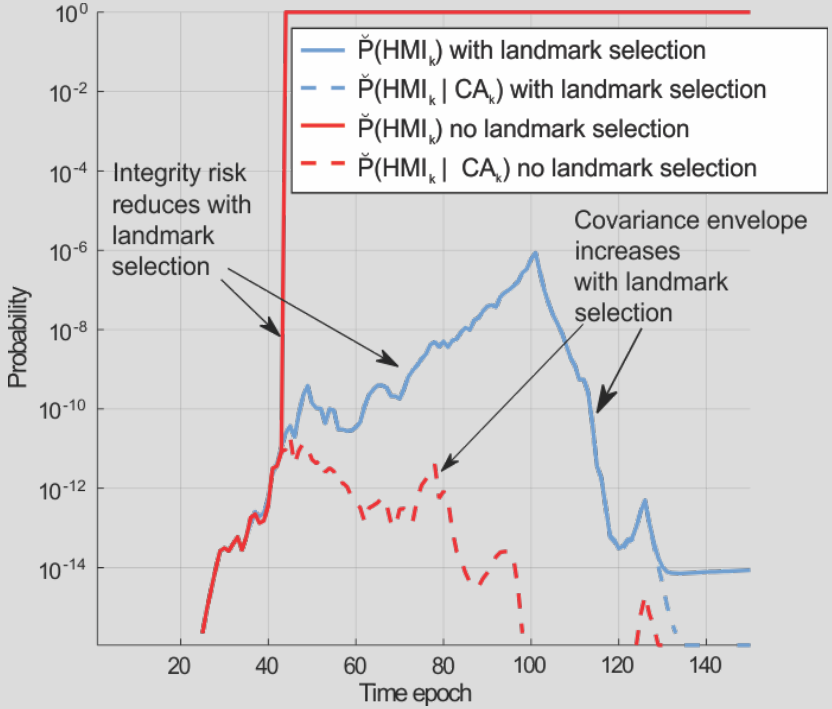
$$\breve{P}(CA_k) \propto 1 - n_{FoV} + \left(1 - \frac{I_y}{n_{FoV}}\right) \sum_{l=1}^{n_{FoV}} \mathrm{X}^2_{m+m_F} \left[\frac{1}{4} \|\mathbf{y}_l^*\|^2_{\mathbf{Y}_{i_l}^{-1}}\right]$$

Number of landmarks in the field of view. More landmarks is worse

More landmarks is better

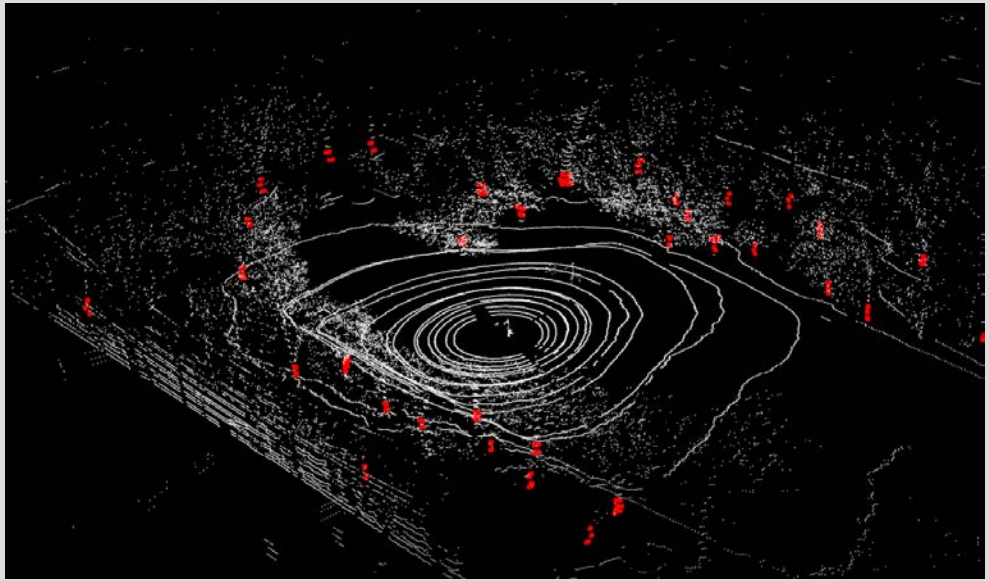
Accounts for the separation among landmarks. More separation is better

Landmark Selection

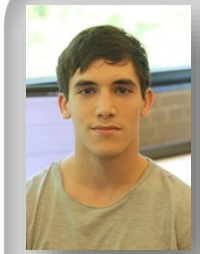


Conclusions

- Integrity important for ubiquitous robots
- Incorrect associations between features and landmarks
- Require landmarks to be plentiful and well-separated
- Must remove ill-separated landmarks



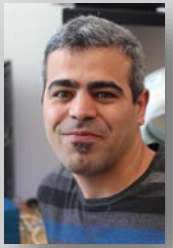
Acknowledgments



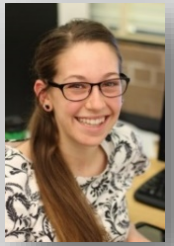
Guillermo Arana Ph.D. Student

Osama Hafez Ph.D. Student

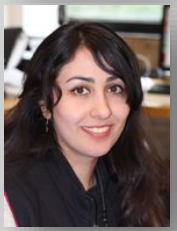
Dr. Aiva Simaite Postdoctoral scholar



Vahid Alizadehyazdi Ph.D. Student



Brigitte Temple Undergraduate Researcher



Neda Karimi-mohamadi Ph.D. Student

THE UNIVERSITY OF ARIZONA

Prof. Mathieu Joerger

Mohammad Amin Karimi Ph.D. Student

Koki Tanaka Ph.D. Student

Elizabeth McQueney Undergraduate Researcher

NSF

Perception ROBOTICS

OnRobot

NASA

JPL Jet Propulsion Laboratory

Sensors for Autonomous Vehicle Localization

Curtis Hay
Technical Fellow
GPS & Maps, VEC East
General Motors

OUR VISION

At General Motors, we envision a future with zero crashes, zero emissions and zero congestion:

Zero crashes to save lives

Each year close to 1.25 million people die in car crashes around the world, 40,000 in the United States alone. More than 2 million people are injured. Human error is a major contributing factor in 94 percent of these crashes.

Zero emissions to leave our children a healthier planet

Vehicles release almost 2 billion tons of carbon dioxide into the atmosphere every year.

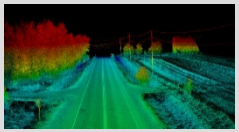
Zero congestion to give our customers back their precious time

In the United States, commuters spend about a week of their lives in traffic each and every year. That's a week not spent with those we love, doing what we want to do and being where we want to be.

Autonomous Vehicle Sensor Characteristics

	Sensor	*Pros*	*Cons*
Perception Vehicle Reference Frame	Radar	Relatively Low Cost Good Ranging Accuracy	Cannot Detect Road Markings
	Lidar	Highly Accurate Ranging	Higher Cost Less Effective in Featureless Areas Typically Requires Lidar Map as Reference
	Camera	Lower Cost Good Object Detection	Less Effective in Featureless Areas Less Effective in Snow, Darkness
Absolute Localization Global Reference Frame	HD Map	Excellent Accuracy (< 10 cm 95%)	Requires Continuous Updates High Acquisition Costs
	Motion Sensors (Gyro, Accel, Wheel Ticks)	Lower Cost	High Drift Rate for MEMS Sensors
	GNSS (GPS, GLONASS, Galileo)	Lower Cost Global Availability	Poor Performance in Urban Areas, Tunnels

Autonomous Vehicle Sensor Fusion



Lidar

Cartesian Vectors
Reflected Intensity

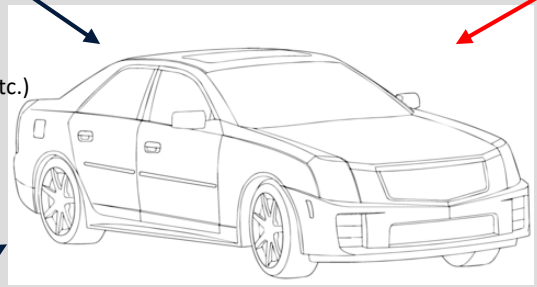
Corrected through PPP/RTK
Lat, Lon, Speed, Heading, Elevation
Quality Metrics

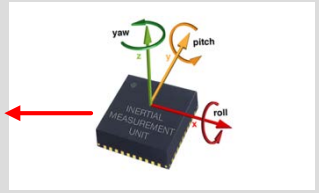
GNSS

Tight Coupling with GNSS measurements
(code, carrier, Doppler, range residuals, etc.)
Vehicle attitude (roll, pitch, yaw & rates)

Camera

Object Data
(Lane Markings, Signs, etc.)





IMU

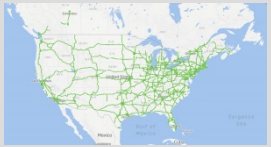
Long range, short range
Front, Side, Rear
Permanent and stationary objects

Radar

Sensor Fusion

- Deeply integrated
- Input quality characterization
- Integrity monitoring
- Reference frame alignment
- Vehicle position state estimation (translation, rotation)

Road attributes aligned to global reference datum
Usually surveyed in advance with Lidar/Camera and RTK



Precise Map

Vehicle Control

- Path planning
- Steering and braking

Perception Sensors
Vehicle Reference Frame

Absolute Localization Sensors
Global Reference Frame
(e.g., ITRF-2000, WGS-84)

Ask the Experts – Part 1

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Professor
Aerospace Engineering and Mechanics
University of Minnesota

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Associate Professor
The Robotics Lab
Illinois Institute of Technology

Curtis Hay
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Principal Engineer
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Locata Corporation Pty Ltd

Moderator: Demoz Gebre-Egziabher

Poll #2

Compared to aviation systems, the reliability requirements of PNT systems for autonomous ground vehicle are expected to be:

1. *More stringent*
2. *Less stringent*
3. *Equally stringent*

Practical Considerations for AV Test & Development

Curtis Hay
Technical Fellow
GPS & Maps, VEC East
General Motors

Potential Connectivity Applications for AVs

GNSS Corrections

- *Low rate (< 2 kbps)*
- *Delivered through satellite L-band or mobile IP*
- *Clock, orbit, ionosphere, troposphere state corrections*
- *Required for confident lane identification and sensor redundancy*
- *Sub-meter (2-sigma) target for autonomous vehicles*

Precise Map Updates

- *Periodic updates to vehicle database*
- *Delivered through mobile IP or Wi-Fi*
- *Lane markings, road attributes, construction areas*

Remote Diagnostics

- *Autonomous vehicle health and status telemetry*
- *Valuable for engineering continuous improvement*

Over-the-Air Software Updates

- *Improve customer experience*
- *Improve performance and fix bugs*

Live Advisor Services

- *Navigation routing, emergencies, peace of mind*

Super Cruise (ADAS)

Cadillac CT6 with Super Cruise

- Internal combustion engine
- Hands Free Lane Centering on highways
- Retail Availability: Q4 2017
- Optional Feature
- 0-90 mph on precisely interstate highways
- Driver attention required

Ongoing Industry Challenges

Precise localization within geodetic reference frame requires:

- Precise map
  - Transition to Crowd Sourcing
- High accuracy GNSS
  - Improved operation in urban areas (opportunity to include camera video in GNSS/IMU filter)
- Improved IMU
  - Low gyro bias drift rate, low angular random walk

Efficient testing:

- Apply modeling and simulation when feasible
- Increased importance of OEM leading technology development (versus suppliers)

Hardware in the Loop (HIL) Testing

Some Active Safety and AV development might benefit from HIL testing:

- Production camera, map database, fusion computer, steering, braking
- Time synchronized components for real-time operation
- Vehicle motion simulator to generate translation/rotation
    - GNSS simulator slaved to vehicle motion
    - Can be used to test map matching function
    - Camera video generated with artificial environment

Difficult, imperfect and expensive– but valuable for efficient validation.

Locata – Your Own GPS

Local Ground-Based Replica of GPS-Style Positioning

Chaminda Basnayake, PhD
Principal Engineer – Market Development
Locata Corporation Pty Ltd

SPIRENT Communications
InsideGNSS
inside unmanned systems

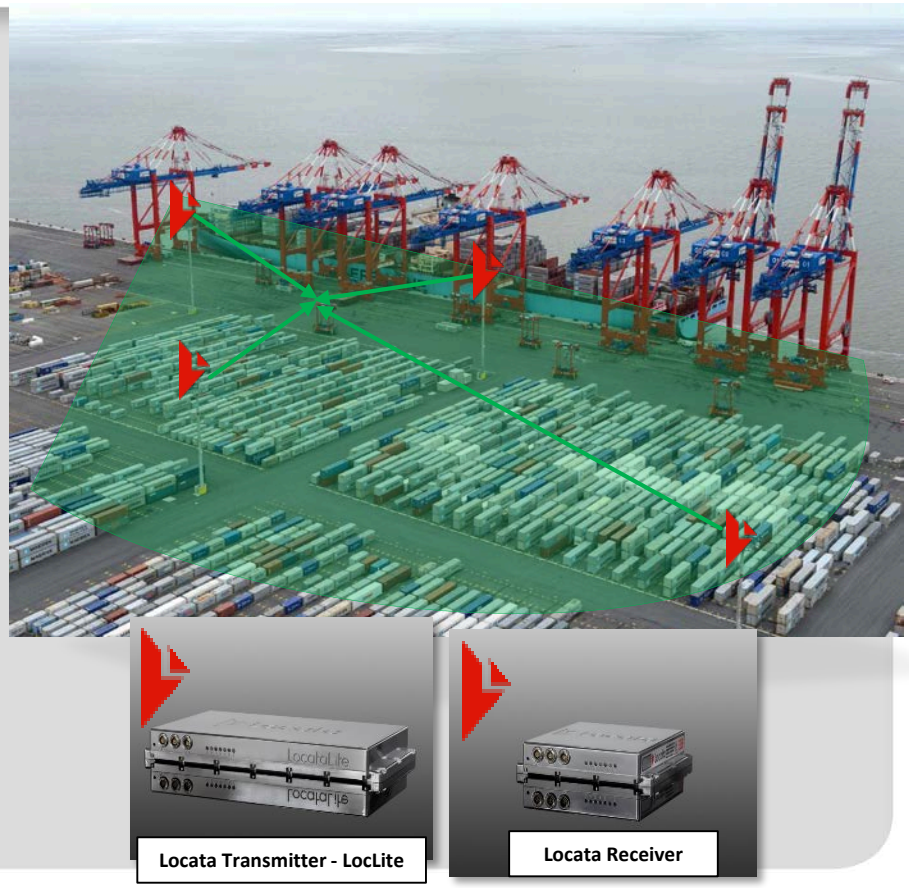
Courtesy of Inside Unmanned Systems magazine, Winter 2015

What is Locata?

- Locata is like your own local GPS
  - Uses terrestrial transmitters (LocLites) that act like satellites
  - Capable of GNSS RTK performance
    - Open sky, indoor, sever multipath, jamming/spoofing
  - Can be the core system in a *System of Systems*
    - Just like GNSS is for many systems
- We enable automated driving, control, path following
  - Automotive safety testing
    - Vehicle positioning & control
  - Port automation
    - Automated straddle carriers & machinery
  - Mining, military
    - Precise positioning & autonomous machinery

Locata Basics

- Designed as a Line-of-Sight system just like all GNSS
  - Same visibility requirements as GNSS
    - Customizable accuracy & reliability (no time variation)
- LocLites transmit GNSS-like signals
  - Works in 2.4 GHz (FCC & EC compliant)
    - Much stronger signals compared to GNSS
    - Ranging signal & nav data (up to 4 per LocLite)
  - All LocLites time synchronized
- Locata does not use atomic clocks
  - Uses a proprietary technology called ***TimeLoc***
    - A LocLite *TimeLoc* to another to nano second precision
    - All LocLites time sync to a master LocLite
  - A master LocLite can synch to GPS time
- Locata receiver works similar to a GNSS receiver
- Operation with severe multipath or indoor



Automotive Safety Testing – Locata as a Local GNSS

- Vehicle Research Center (VRC) – Insurance Institute for Highway Safety (IIHS)*
  - Rates safety of all vehicles that enter NA market
- IIHS LocataNet covers both IIHS test tracks
  - Locata is the reference system used for IIHS testing
    - Open/outdoor track - 100 x 600 m
      - LocataNet operational since 2016
    - Covered track 100 x 200 m
      - LocataNet operational since 2018
      - No GNSS RTK under the cover
- Requirements
  - Better than 10 cm (95 %)
  - High repeatability / predictability
    - Fair comparison across vehicle makes and models
  - Plug-and-play with test equipment meant for GNSS
- Uses
  - Test vehicle and target (vehicle, pedestrian, cyclist) positioning
  - Automated path following and target control

* https://www.youtube.com/watch?v=xl4eJUOSMBQ&t=185s

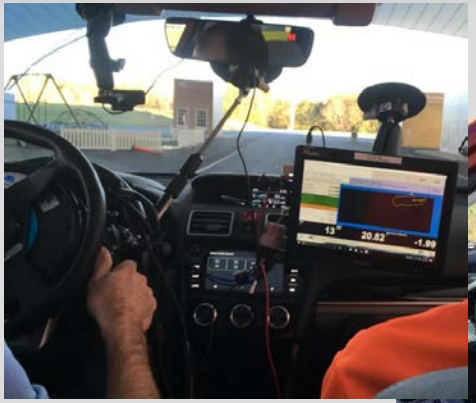
Automotive Safety Testing – Locata as a Local GNSS

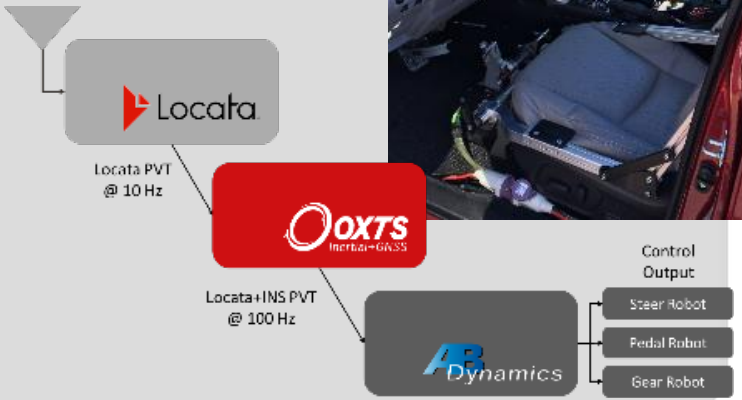
LocataLite Site

Vehicle Research Centre (VRC) in Virginia
Run by the Insurance Institute of Highway Safety (IIHS)
Open & Covered Test Tracks Positioning using Locata

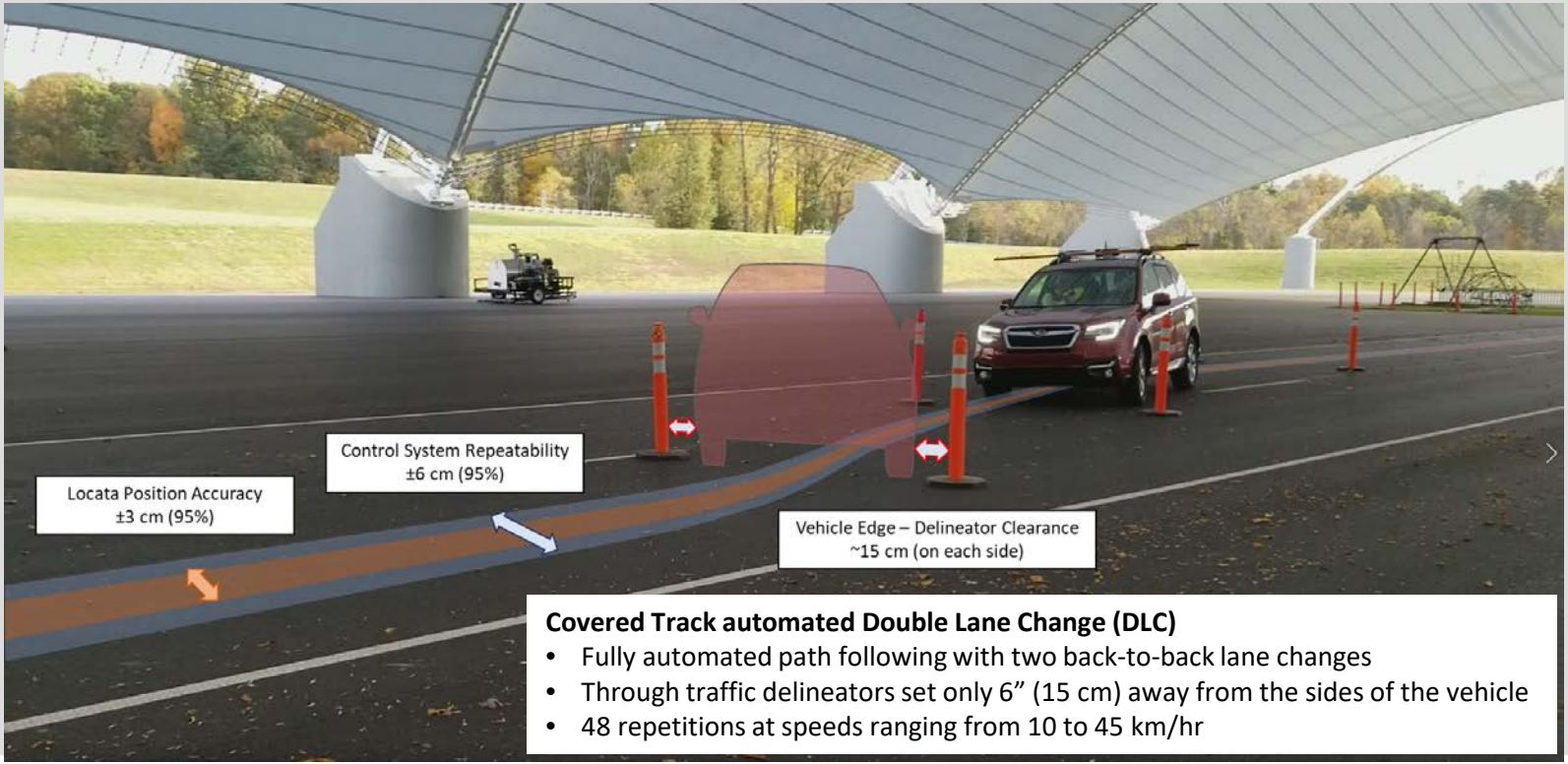
Precise Path Following @ VRC

- IIHS is automating test vehicle and target driving
  - Eliminates the driver dependency of the test
    - Precise control of time, speed, and path
- Automation demonstrated with a drop-in automation kit
  - Control equipment from AB Dynamics (www.abdynamics.com)
    - Steering robots (with manual override)
    - Acceleration and brake robots (with manual override)
  - Locata & INS integration by Oxford Technical Solutions (OxTS)
    - Locata output identical to a survey grade RTK GPS/GNSS unit
    - Generates 100 Hz control input from Locata 10 Hz
  - Positioning powered by Locata
    - Single antenna feeding PVT
    - Secondary antenna to verify Locata position accuracy (fixed baseline)





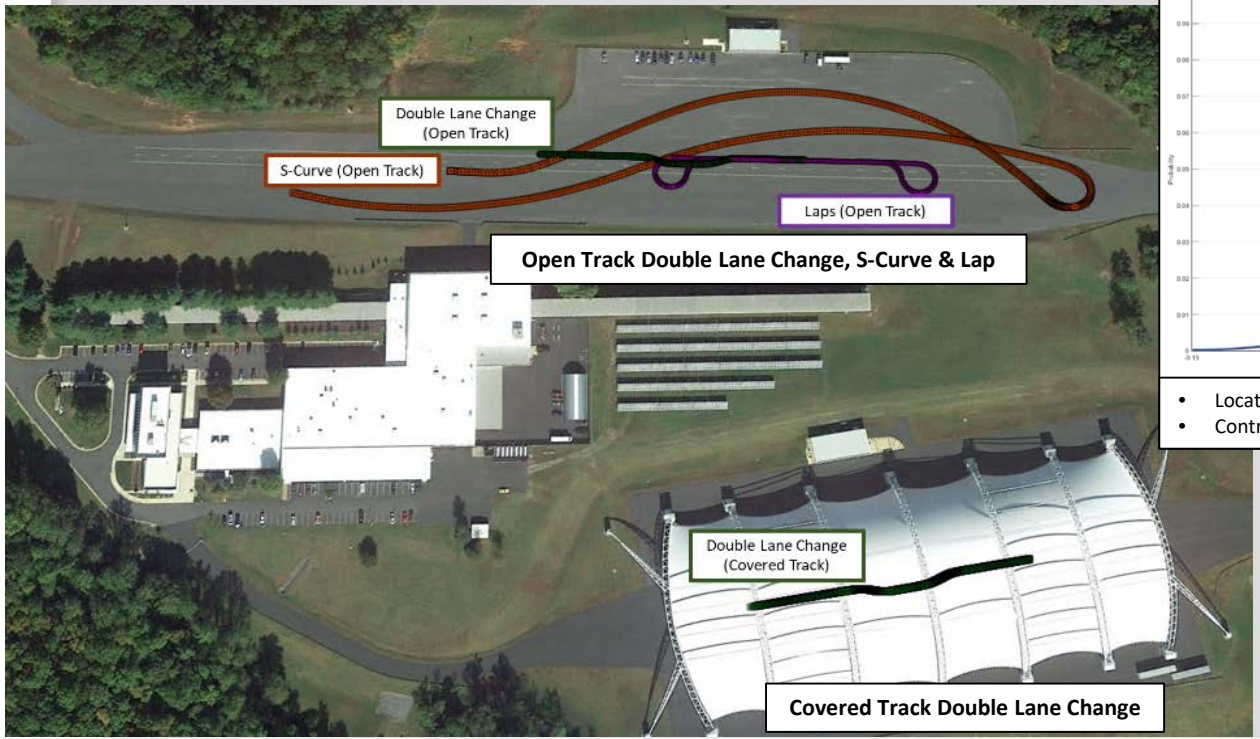
Precise Path Following @ VRC

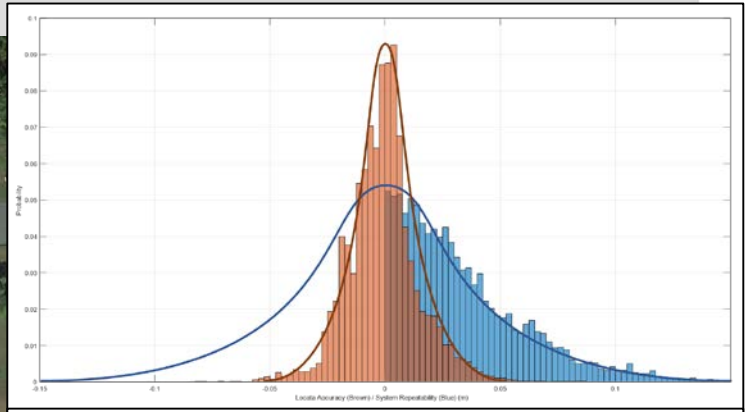


Covered Track automated Double Lane Change (DLC)

- Fully automated path following with two back-to-back lane changes
- Through traffic delineators set only 6” (15 cm) away from the sides of the vehicle
- 48 repetitions at speeds ranging from 10 to 45 km/hr

Precise Path Following @ VRC





- Locata Position Accuracy: ± 3 cm (95%)
- Control System Output Repeatability: ± 6 cm (95%)

Automation in Deep Pit Mines – Locata as a GNSS Augmentation

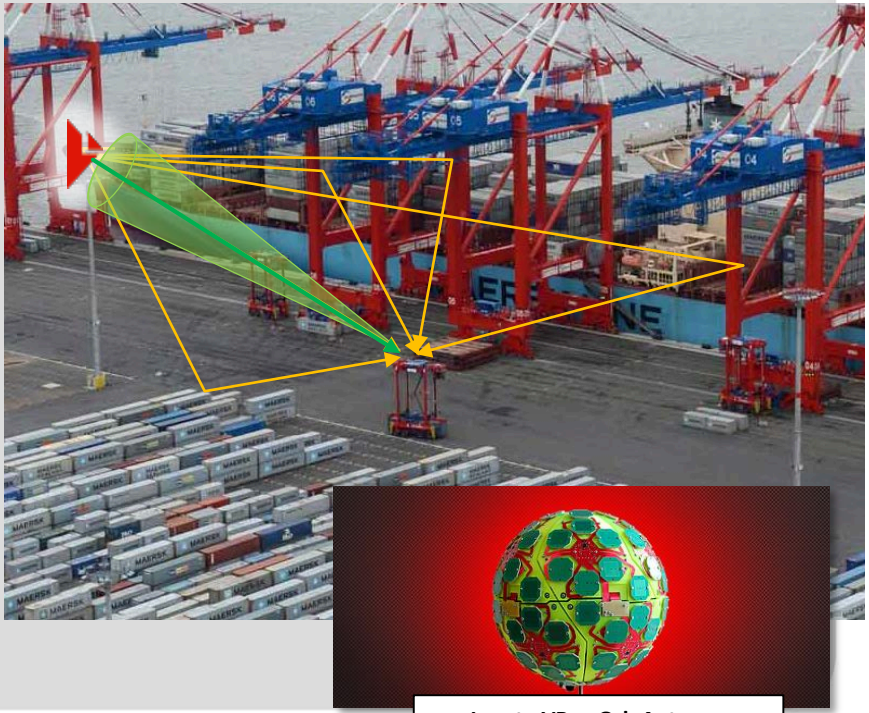
- Positioning system for automated machine control
  - Deep pit mines are somewhat similar to urban canyons
    - Limited sky view
      - Particular close to the walls where drill rigs operate
    - Operations stop when good GNSS geometry is not available
  - High availability, reliability and accuracy required
- Commercial GNSS+Locata product from Leica
  - Jigsaw Positioning System (JPS)
  - Locata integrated with GNSS
    - Portable JPS units & Locata receivers at the mine edge
  - Gives better accuracy
    - More signals
    - Better geometry
- Newmont Boddington Mine - First Locata deployment
  - Service availability improvement from ~75% (GNSS) to ~98%*

Leica Jps - Powered by Locata at Boddington Gold Mine Western Australia

* http://www.locata.com/wp-content/uploads/2012/09/**International-Mining**-Sept-2012.pdf

Working with Multipath - Locata Correlator Beamforming (CBF)

- Key to Locata performance in multipath-rich environments
  - Ten years of R&D + dozens of patents
  - VRay Orb antenna
    - Same standard Locata receiver
    - Collection of patch antennas digitally sampled in sequence
- Delivers cm-level accuracy where GNSS fails
  - Enables the formation of *millions* of Beams per second
  - Direct signal can be identified & tracked
- Proven technology deployed in port automation
- CBF applies equally to GNSS multipath mitigation
  - Published results from USAF Institute of Technology*



Locata VRay Orb Antenna

* Gunawardena, Sanjeev, Raquet, John, Carroll, Mark, **Correlator Beamforming for Multipath Mitigation in High-Fidelity GNSS Monitoring Applications**, *Proceedings of the 2017 International Technical Meeting of The Institute of Navigation*, Monterey, California, January 2017, pp. 1173-1188

Automation in Ports – Locata as a Precise Local System

- Locata is a key enabler in port automation
  - Autonomous control of straddle carriers (Level 5)
    - Locata VRay technology enables precise control (3 cm 95%)
    - Operate side-by-side with traditional manually operated machines
      - Speeds of up to 40 km/hr & able to stack up to 4 containers
      - Certified to meet EU Safety Standards
  - Becoming standard port technology with multiple OEMs
  - Other logistics handling operations to follow
- Locata offers many advantages to port operators
  - Unprecedented level of accuracy & reliability
    - GNSS multipath is a huge challenge, solved by VRay
    - Embedded markers, targets insufficient, complicated and costly
  - Flexibility
    - Modify paths, areas without infrastructure modifications
    - Change can be made in a running port
- LocataNets getting deployed in multiple ports globally
  - Port of Auckland, NZ will be commissioned late 2018*

A-STRAD Automated Straddle Carrier

* Konecranes A-STRAD: https://www.youtube.com/watch?v=4QOsSFaHZ3w&t=10s

Locata as a Local GNSS – In a GNSS Denied Environment

- USAF White Sands Missile Range LocataNet
  - Network covers 1,200 sq miles
    - 20 permanent monument sites
  - Operational since 2016
    - A sole-source contract to maintain & upgrade through 2025
- Locata used as the core non-GPS positioning system
  - Precision PNT with & without GPS in heavily jammed scenarios
  - Feeds into their **Ultra High Accuracy Reference System** (UHARS)
- Designed for aircraft testing (up to 30K ft MSL)
  - Can be configured to support ground test vehicles
  - USAF published results from validation flight tests
    - Position Accuracy: 6 cm (horizontal) & 15 cm (vertical) rms*
    - Acquisition: ~ 62 km range & over 500 km/hr*

USAF White Sands LocataNet
Declared "operational"
February 2016

746th Test Squadron Test Aircraft with Locata Receiver

Locata Antenna

* https://newatlas.com/locatanet/25628/

Locata Enables New Possibilities – with & without Infrastructure

- **With Locata Infrastructure**
  - Standalone or as a GNSS augmentation
  - **Reaching new markets**
    - Frequency flexible next generation
    - Integration with GNSS


MINING


MACHINE CONTROL


MILITARY


CONTAINER TERMINALS


WAREHOUSES


FIRST RESPONDERS


INDUSTRIAL APPLICATIONS


UNDERGROUND INFRASTRUCTURE

- **Without Locata Infrastructure**
  - **Correlator Beamforming for GNSS**
    - Better performance – accuracy & reliability
  - **TimeLoc - Precise Time Synchronization Using RF Signals**
    - Nano second level time synch via RF


REFERENCE NETWORKS


MONITORING


AUTONOMOUS VEHICLES


NETWORK SYNCHRONIZATION


LOCAL TIMING NETWORKS


CONNECTED VEHICLES

Poll #3

In addition to GNSS and other sensors for absolute localization, what are the most important perception sensors for autonomous vehicles? (top two)

A. Radar

B. LiDAR

C. Camera

For More Information

- Visit www.insidegnss.com
- Watch a CAV Testing - Tools Integration video
  - https://wi.st/2JRUsCu
- Connect with Spirent via LinkedIn
  - https://www.linkedin.com/showcase/spirent-positioning/
- Contact Info
  - Ajay Vemuru
    Ajay.Vemuru@spirent.com
  - Chaminda Basnayake
    chaminda.basnayake@locata.com
  - Matthew Spenko
    mspenko@iit.edu
  - Curtis Hay
    Curtis.1.hay@gm.com

Ask the Experts – Part 2

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

Matthew Spenko
Associate Professor
The Robotics Lab
Illinois Institute of Technology

Curtis Hay
Technical Fellow
General Motors
GPS & maps
VEC East

Chaminda Basnayake
Principal Engineer
Market Development
Locata Corporation Pty Ltd

www.insideunmannedsystems.com
www.insidegnss.com
www.spirent.com