

# Robust GNSS+: PNT Innovation for Autonomous Vehicles

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# Background – PNT (1)



- Global Navigation Satellite Systems (GNSS) are the primary sources of Positioning, Navigation, and Timing (PNT) information worldwide
- State-of-the-art in GNSS research is focused on jamming and spoofing threats, and integrating sensor positioning to enable precise and trustworthy PNT even in GNSS denied environments

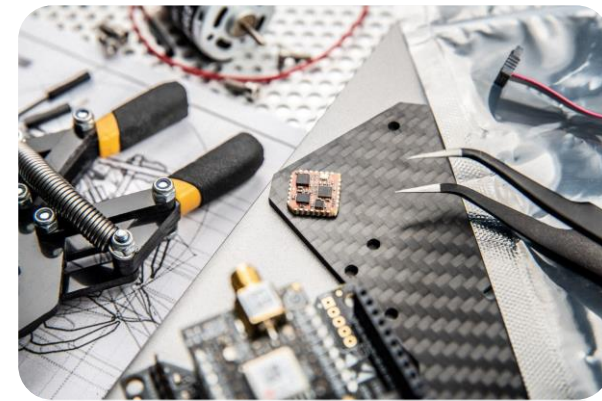
# Background – PNT (2)

- Visual localisation has progressed rapidly in the last few years with increased demand stemming from AR, autonomous vehicles, robotics
- Visual sensor technology for localisation is based on a range of technologies, including stereo cameras, depth-sensing cameras (e.g. time-of-flight sensors) and monocular cameras accompanied with depth-reconstructing algorithms
- With depth information, localisation can be performed either by simultaneous localization and mapping (SLAM), or by relying to the existence of a global map

Cheng J. et al (2022). [A review of visual SLAM methods for autonomous driving vehicles](#). *Engineering Applications of Artificial Intelligence*, Elsevier, Vol. 114



# Background – PNT (3)

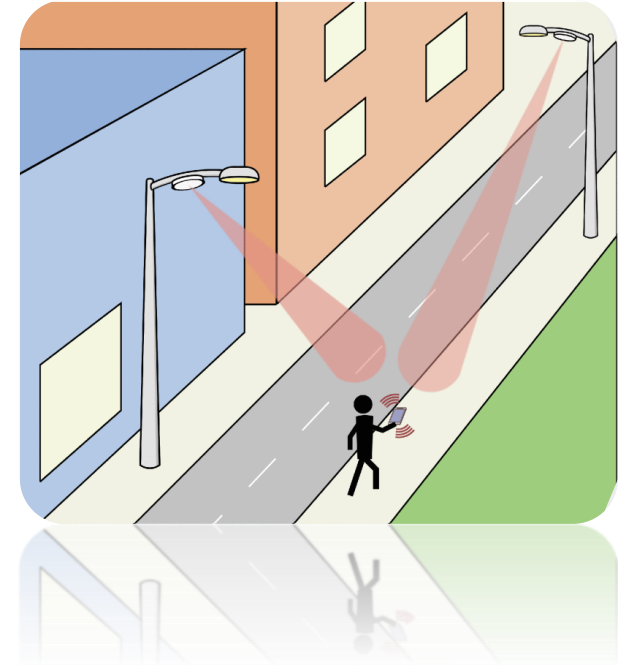


Source: [Xsens](#)

- Inertial sensors, i.e., gyroscopes and accelerometers, are a classical means of navigation and immune to environmental disturbances.
- Recently, the development of microelectromechanical system (MEMS) technology has brought inertial sensors to IoT devices and consumer products
- Magnetometers have significance in the form of a compass, but they are sensitive to local anomalies in the ambient magnetic field.
  - However, the magnetic field can be mapped and used for positioning. Alternatively, it is possible to apply SLAM methods to leverage the local magnetic field for positioning purposes
- Quantum technology is foreseen to bring the next revolution in the field of inertial navigation by improving the measurement performance over current state-of-the-art optical sensors

# Background – PNT (4)

- Positioning is an integral part of the 5G mobile networks. Positioning use cases are moving from customer segments towards industrial segments including autonomous traffic and smart logistics.
- RF technologies like 5G Standalone (SA) and Non-Standalone (NSA) operating at FR1 and FR2 frequency bands & C-V2X Wi-Fi or 5G technologies will open new possibilities for collaborative and co-operative positioning
- Alternative RF technologies such as Bluetooth, LPWANs, UWB, and active RFIDs need to be considered to offer seamless communications and positioning across indoor and outdoor environments

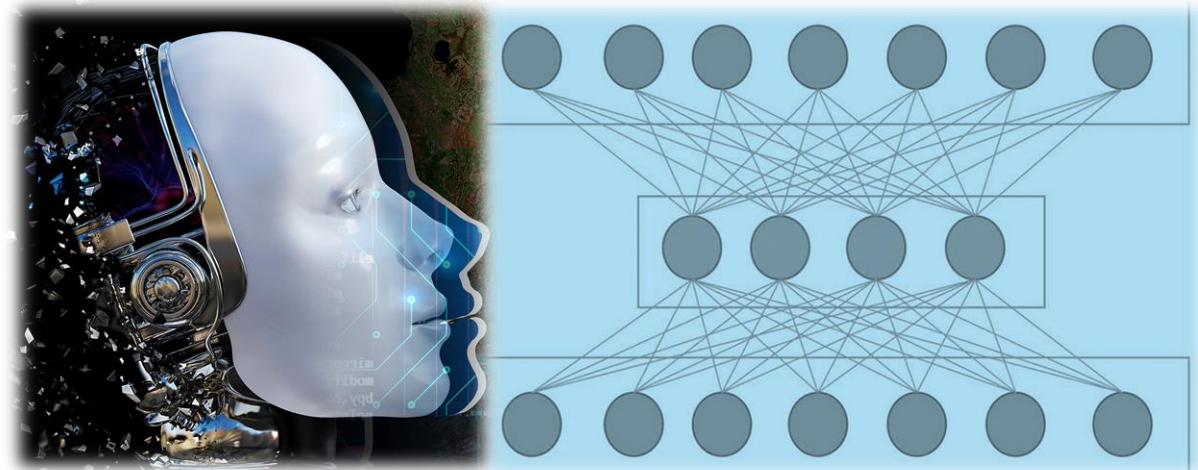


Source:  
M. Koivisto et al. (2017), Joint Device Positioning and Clock Synchronization in 5G Ultra-Dense Networks. *IEEE Transactions on Wireless Communications*, vol. 16, no. 5, pp. 2866-2881, May 2017,

C-V2X = Cellular-Vehicle to everything  
FR1 < 7,125 GHz  
FR2 > 24,250 GHz  
UWB = Ultrawide band  
LPWAN = low-power wide-area network

# Background – PNT (5)

- Many of the positioning problems essential require information fusion: combining of signals from different sensor systems to support decision processes
- Many information fusion algorithms have their foundations in statistical estimation theory (e.g. Kalman filters, particle filters)
- A new challenge is to combine the model-based approaches with emerging data-based approaches such as deep learning



# Background – autonomous vehicles

- The vehicles will transform step by step to become more autonomous, the pace of change depending on the degree of freedom (1D-2D-3D movement) and the complexity of their operating environment
- Several positioning and localization techniques needed for increasingly autonomous vehicles
- Automated road vehicles need to operate safely and smoothly in environments where also vulnerable road users and manually driven vehicles exist
  - This requires that the other road users' intentions are anticipated based on tracking them
  - Tracking algorithms are based on object recognition and fusing data between all information available from environment perception devices and vehicle positioning and inertial data



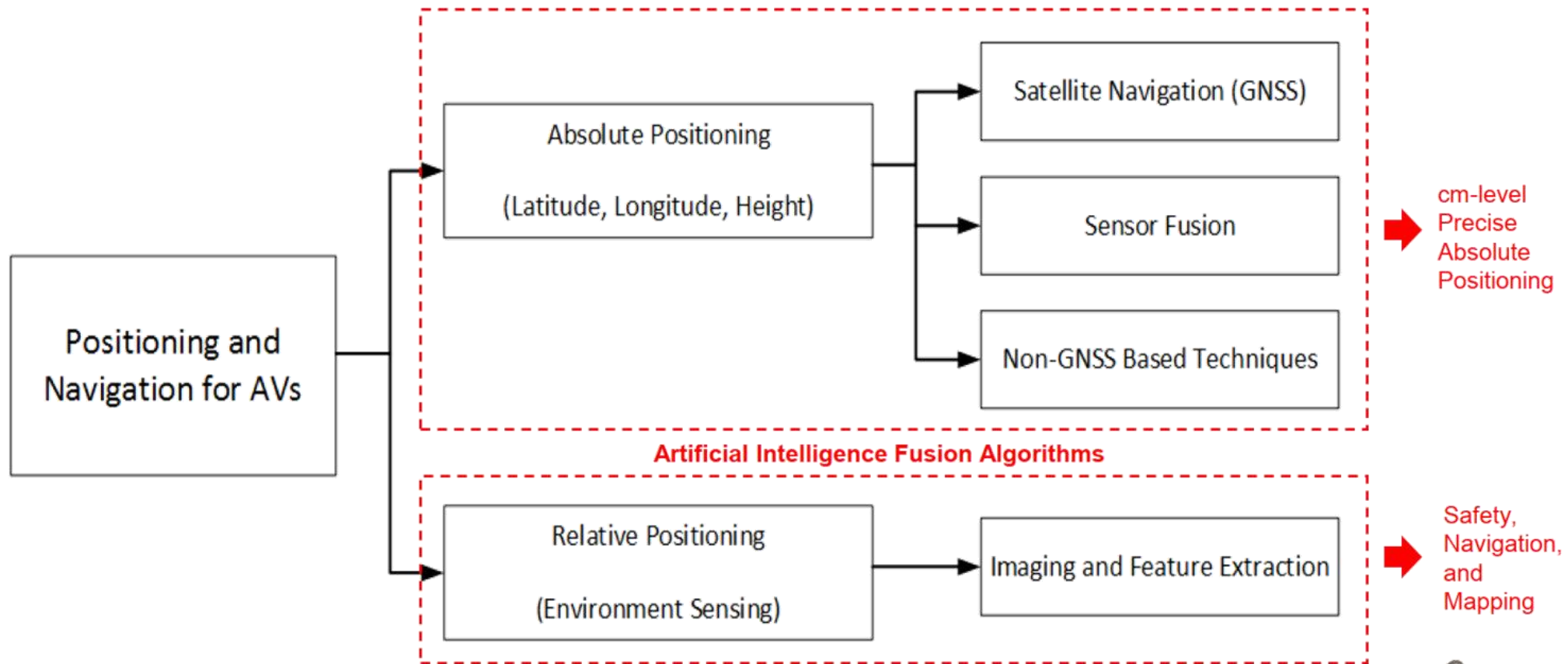
Source: ESA

# How does an autonomous vehicle 'think'?

- Where am I?
- What is around me?
- Where is my destination?
- What is the best way to reach my destination while avoiding local obstacles?



# Positioning and navigation in autonomous vehicles (AVs)



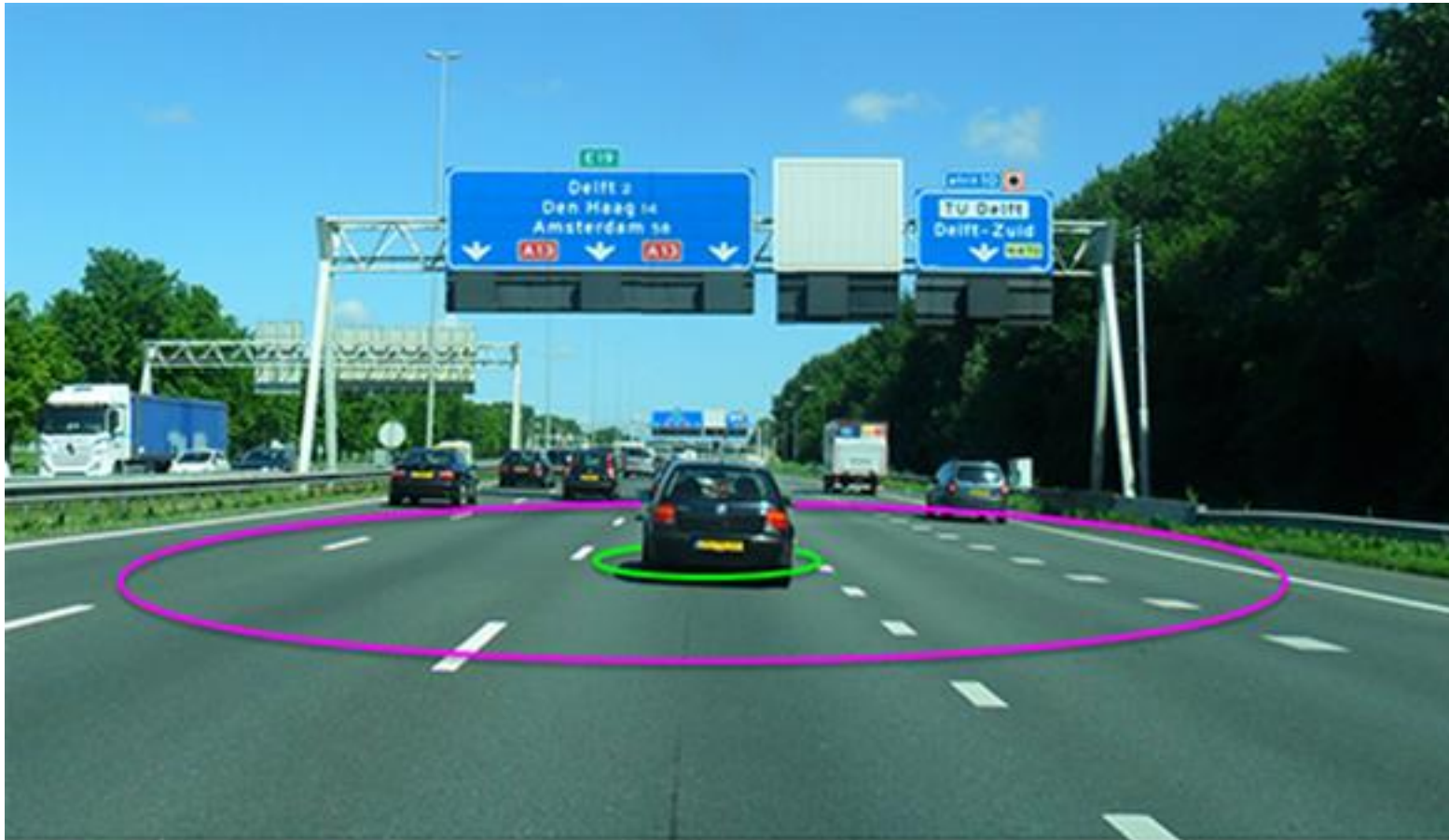
# User requirements for absolute positioning in autonomous driving

|  | Availability | Positioning accuracy                          | Timing accuracy  | Integrity message | Robustness vs. spoofing                  | Detection of GNSS interferences |
|--|--------------|---|------------------|-------------------|--|---------------------------------|
| Safety critical - traffic and safety warning | > 99.5%      | < 3 metres (horizontal)                       | < 1 second       | Required          | Robustness vs. spoofing threats required | Required                        |
| Safety critical - automated driving          | > 99.9%      | < 20 cm (horizontal)<br>< 2 metres (vertical) | < 1 micro second | Required          | Robustness vs. spoofing threats required | Required                        |
| Payment critical                             | > 99.5%      | < 3 metres (horizontal)                       | < 1 second       | Required          | Authentication message required          | Required                        |
| Regulatory critical                          | > 99.5%      | < 5 metres (horizontal)                       | < 1 second       | Required          | Authentication message required          | Required                        |
| Smart mobility                               | > 99.5%      | < 5 metres (horizontal)                       | < 1 second       | Required          | Authentication message required          | Required                        |

\* **European GNSS Agency**, 'Report On Road User Needs And Requirements - Outcome Of The European GNSS' User Consultation Platform', GSA-MKD-RD-UREQ-233537, Issue/Revision: 1.0, 18/10/2018.



# Precise positioning for road transport



- Road-level Accuracy**
- Lane-level Accuracy**

\* Figure - courtesy TU Delft

# GNSS position computation strategies

| Method  | SPP                                    | DGNSS                                | SBAS                     | RTK                                    | PPP-RTK  | PPP  | HAS (SL1/SL2)  |
|---|--|--------------------------------------|--------------------------|--|--|--|--|
| Observable  | Code                                   | Code                                 | Code                     | Carrier                                | Carrier  | Code /Carrier  | Code /Carrier  |
| Positioning   | Absolute (in the GNSS reference frame) | Relative                             | Relative                 | Relative                               | Absolute (in the tracking network reference frame) | Absolute (in the tracking network reference frame)                               | Corrections: PPP - orbit, clock, biases (code and phase) using Open format similar to Compact-SSR (CSSR) |
| Comm Link   | No                                     | Yes                                  | Yes (GNSS like)          | Yes                                    | Yes  | Yes  | Yes: Galileo E6B using 448 bits per satellite per second / terrestrial (internet)                        |
| Single Frequency (SF)<br>Dual Frequency (DF)<br>Triple Frequency (TF)<br>Multi Frequency (MF) | SF or DF                               | SF                                   | SF current<br>DF planned | Mostly DF                              | (SF) DF or TF                                      | (SF) DF or TF  | MF: E1/E5a/E5b/E6;<br>E5 AltBOC L1/L5;<br>L2C  |
| Time To First Fix (TTFF)  | Rx TTFF                                | As SPP + time to receive corrections | As DGNSS                 | As DGNSS + time to resolve ambiguities | Faster than PPP, but slower than RTK               | As RTK, but time to estimate ambiguities is significantly higher (more unknowns) | Convergence time: 300 s to 100 s   |
| Accuracy Horizontal   | 5-10 m DF<br>15-30 m SF                | 1 m to 5 m                           | 1 m                      | 1 cm + 1ppm baseline                   | 10 cm  | 10 cm to 1 m   | 20 cm  |
| Coverage  | Worldwide                              | Up to 100 Km                         | Up to 1000 Km            | Up to 10 Km                            | Regional   | Worldwide  | Worldwide  |

*EUSPA:*

*GNSS User Technology Report 2020. Available: [https://www.euspa.europa.eu/simplecount/pdf/tracker?file=uploads/technology\\_report\\_2020.pdf](https://www.euspa.europa.eu/simplecount/pdf/tracker?file=uploads/technology_report_2020.pdf)*

*Galileo High Accuracy Service. 2020. Available: [https://www.gsc-europa.eu/sites/default/files/sites/all/files/Galileo\\_HAS\\_Info\\_Note.pdf](https://www.gsc-europa.eu/sites/default/files/sites/all/files/Galileo_HAS_Info_Note.pdf)*

# Arctic-PNT Innovation Platform - SNOWBOX

Arctic-PNT project

- Accuracy
- Availability

of PNT in the Arctic

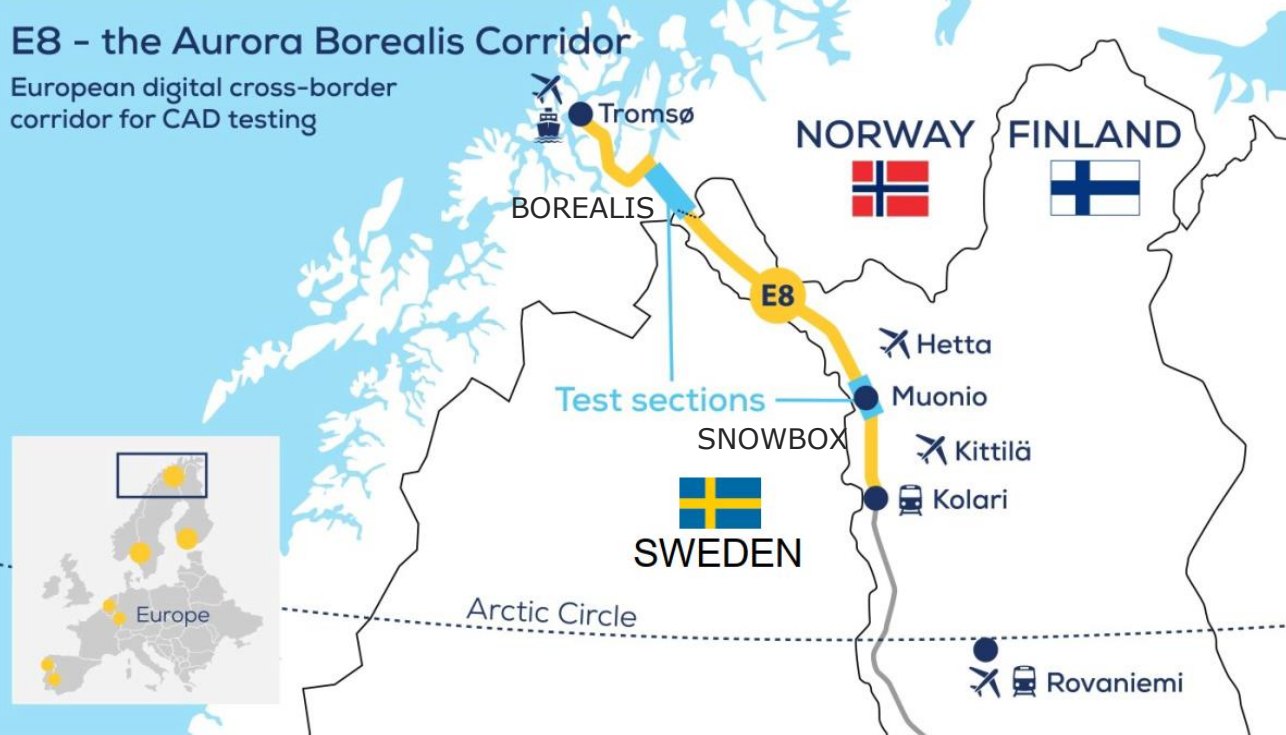
- Funding by ESA Express Procurement Plus, until Aug 2019
- With FGI-NLS Dept. of Geodesy



[www.arctic-pnt.org](http://www.arctic-pnt.org)

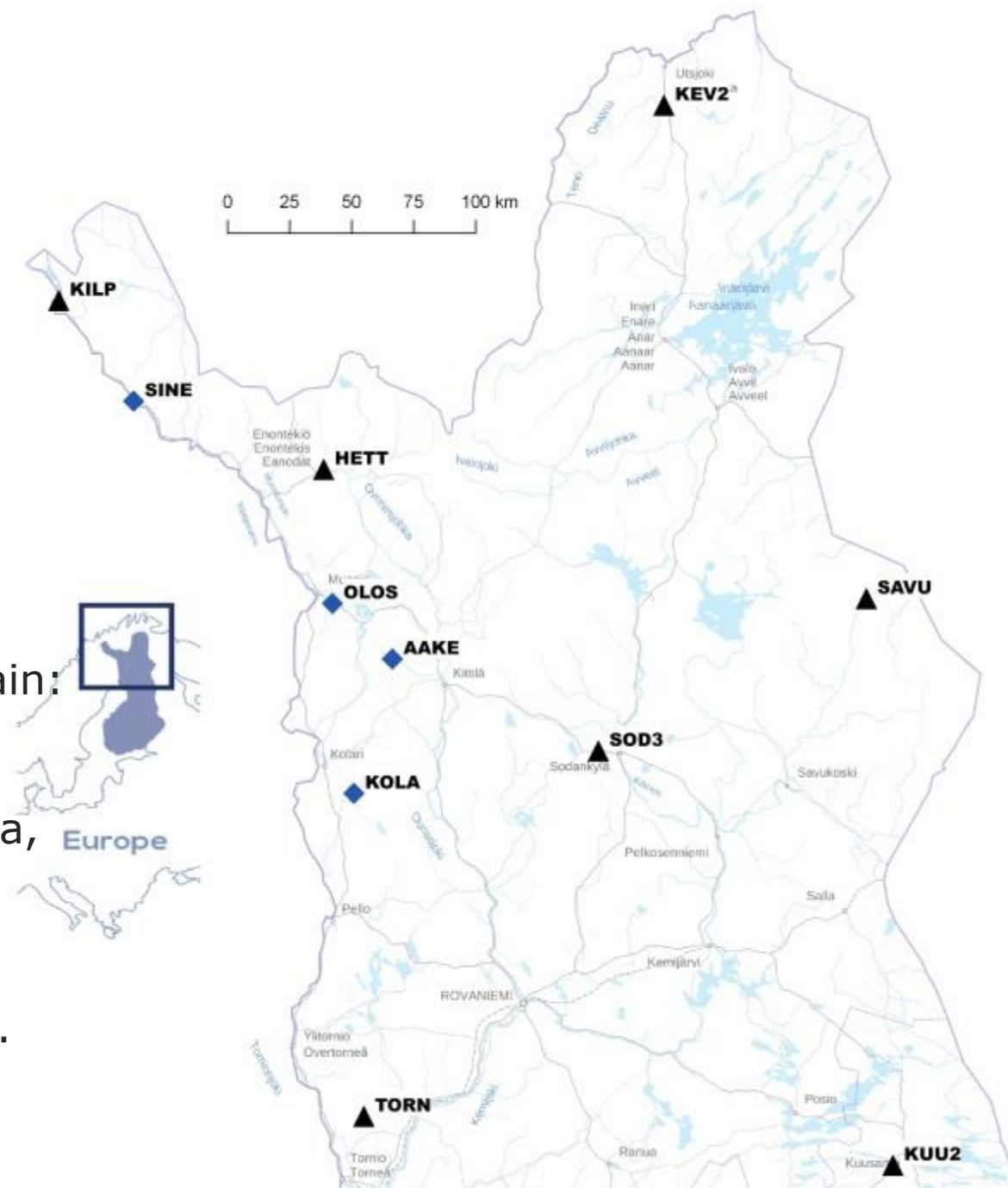
## E8 - the Aurora Borealis Corridor

European digital cross-border corridor for CAD testing

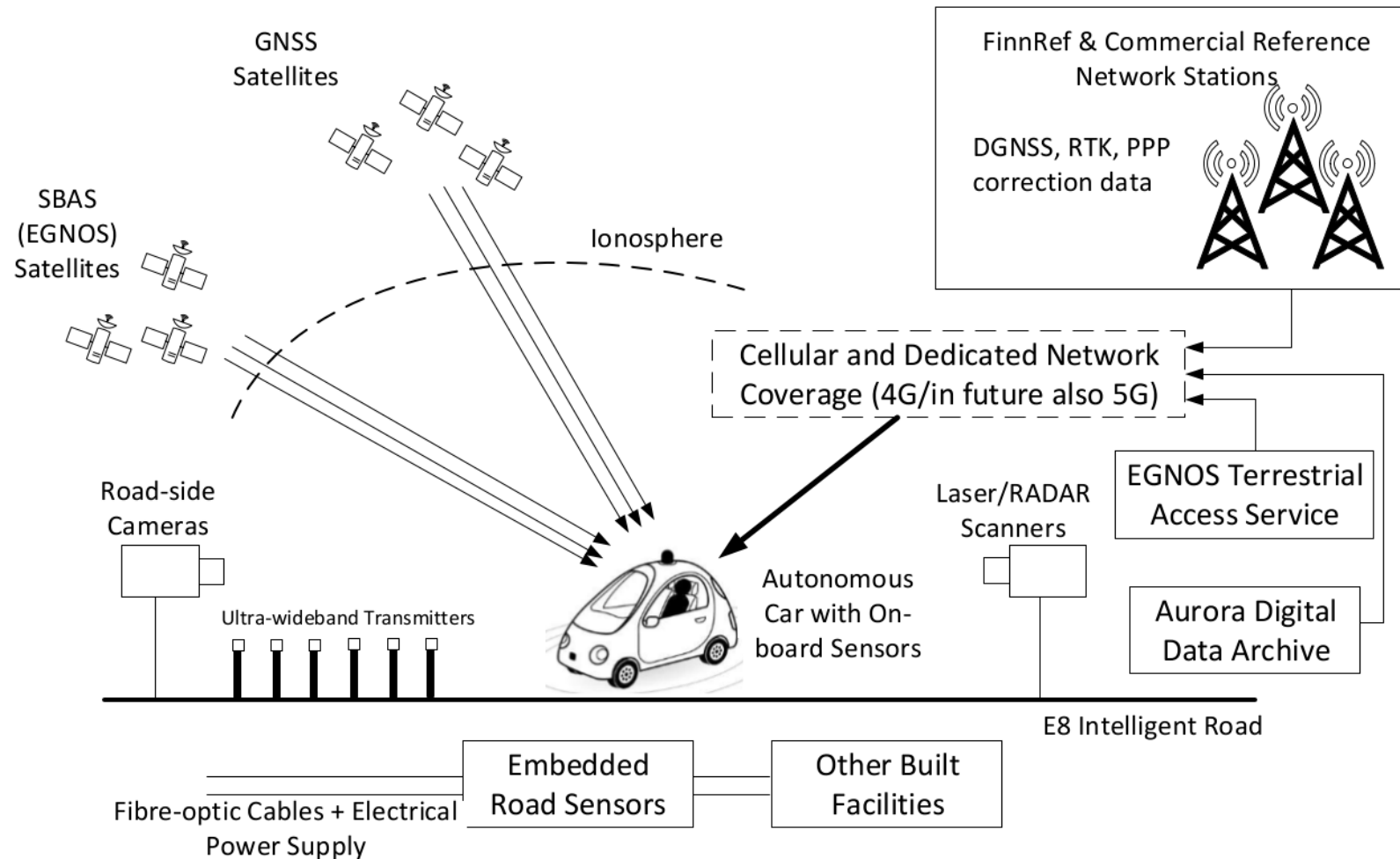


The Aurora SNOWBOX system included means to obtain:

- GNSS and EGNOS,
- 5G,
- Vehicle sensor (wheel sensors, inertial sensors) data,
- Camera data,
- Laser scanning data,
- FinnRef reference network data,
- Assess available communication links and 3D maps.

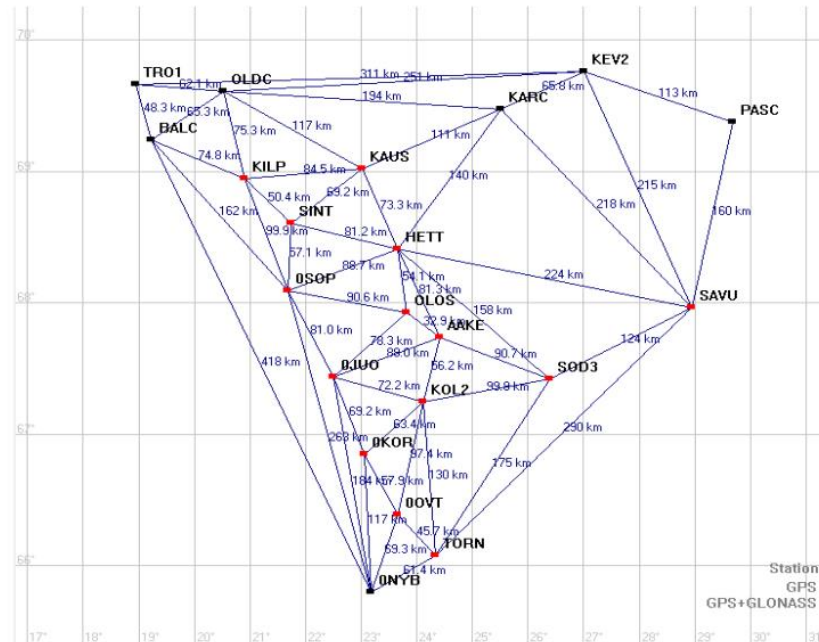


# INFRASTRUCTURE AT SNOWBOX



# FINNISH FINNREF CORRECTION SERVICE AT SNOWBOX

- Realtime corrections service prototype with tailored GNSS network
  - Finland + Sweden + Norway stations
  - Galileo, GPS, GLONASS multi-frequency
  - Network-RTK corrections with TopNet service



We utilized the infrastructure support provided by Snowbox, including the FinnRef GNSS reference stations around the test area, to collect positioning data.



# Commercial case at SNOWBOX: Sensible4 Ltd. (1)

## FOUR MODULES OF AUTONOMOUS DRIVE

### POSITIONING MODULE

Provides accurate position and angle of the vehicle, without support from the infrastructure. Positioning is based on proprietary probabilistic mapping algorithms.

### OBSTACLE DETECTION AND TRACKING MODULE

Detects, identifies, tracks, and predicts the behavior of others in traffic. Provides situational awareness to the vehicle and also acts as an emergency stop if needed, with so-called Reactive Layer.

### PLANNING AND CONTROL MODULE

Use information from the Positioning Module and Obstacle Detection and Tracking Module to driving route planning and control of the vehicle. The virtual driver of the vehicle.

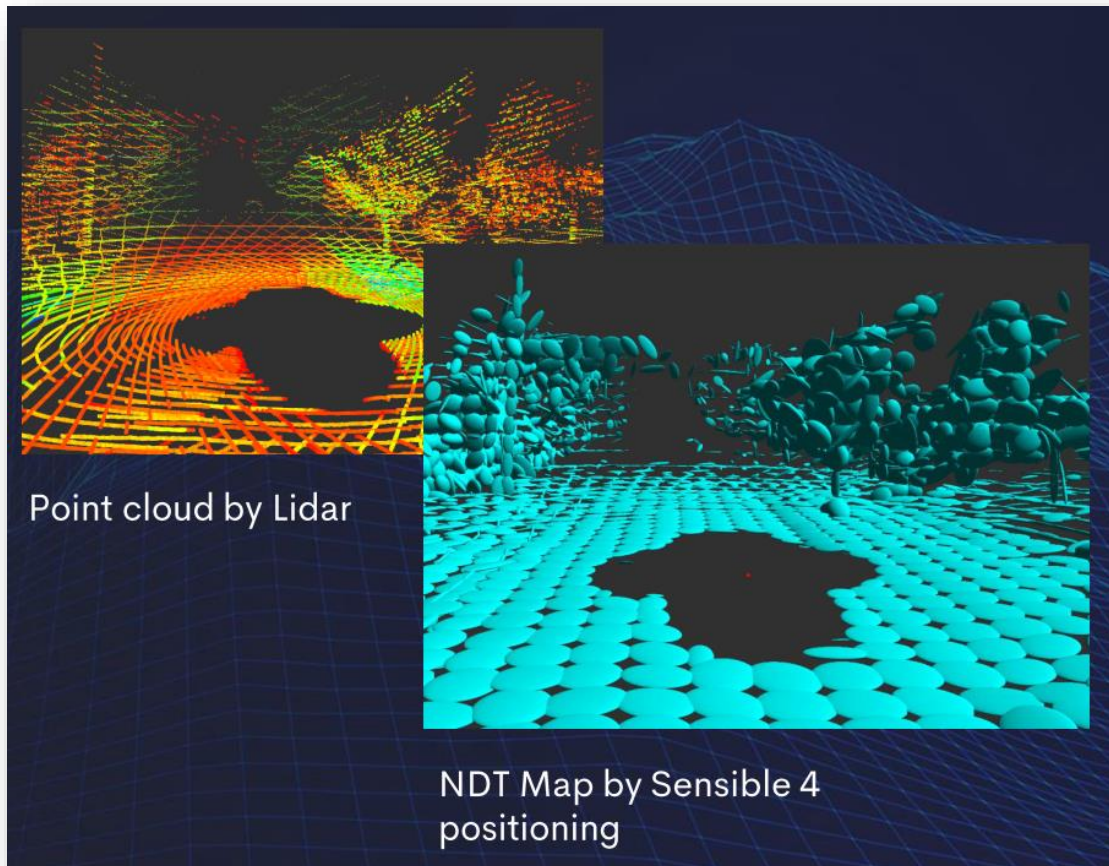
### FLEET OPERATIONS MODULE

Provides the way for self-driving vehicle to handle unexpected events with the help of human remote operator. Also provides software API to manage autonomous vehicles as part of a transportation fleet.

# Commercial case at SNOWBOX: Sensible4 Ltd.

(2)

Sensible4's positioning via LiDAR, radar, assisted GNSS and inertial measurement systems & probabilistic mapping



Point cloud by Lidar

NDT Map by Sensible 4 positioning

NDT = Normal Distributions Transform



An aerial photograph of a snowy, forested landscape in the Arctic. A road winds through the center, and a river flows on the left. The sky is overcast with a hint of sunset or sunrise. The text "Autonomous Driving in the Arctic" is overlaid in the center.

# Autonomous Driving in the Arctic

67.9553° N — 23.6841° E

# What are the topical research questions in PNT for Autonomous Vehicles?

- How to make satellite-based positioning and other localisation solutions trustworthy and robust enough for positioning of autonomous vehicles with centimeter-level accuracy?
- Are the complementary positioning, localisation and ranging technologies fulfilling their promises and how to improve their usability for the purpose?
- How to fuse the location information accurately, robustly and securely to be resilient against intentional and unintentional interference, poor integrity, blockage and sensing errors?
- How to apply position and timing information in vehicle and other mobility applications for improved operational environments for autonomous things?

# Robust PNT for self-driving cars (1)

- Resilient PNT consists of two steps
  - Authenticate the GNSS signals
    - Spoofing detection and mitigation
  - Prevent denial of PNT
    - Coupling GNSS with inertial sensors etc
    - Utilizing multi-element antennas
- Typical PNT setup for self-driving cars include multi-antenna GNSS, radar units, stereo cameras, lidar, inertial sensors, communication
  - "Robust GNSS+"

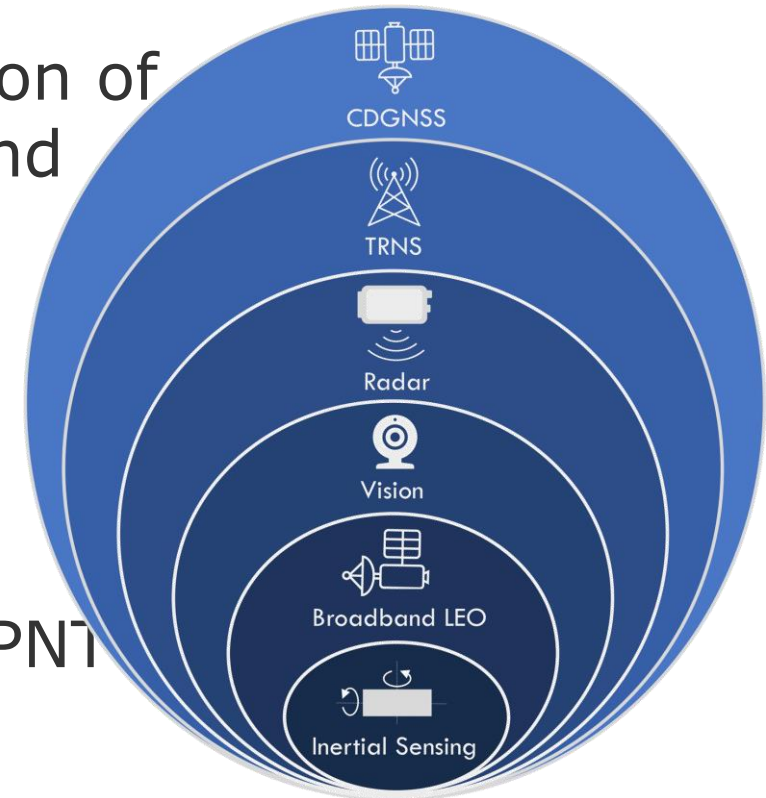


<https://group.volvocars.com/company/innovation/autonomous-drive>

# Robust PNT for self-driving cars (2)

Robust perception is critical for reliable navigation of autonomous systems, for collision avoidance, and for timing coordination

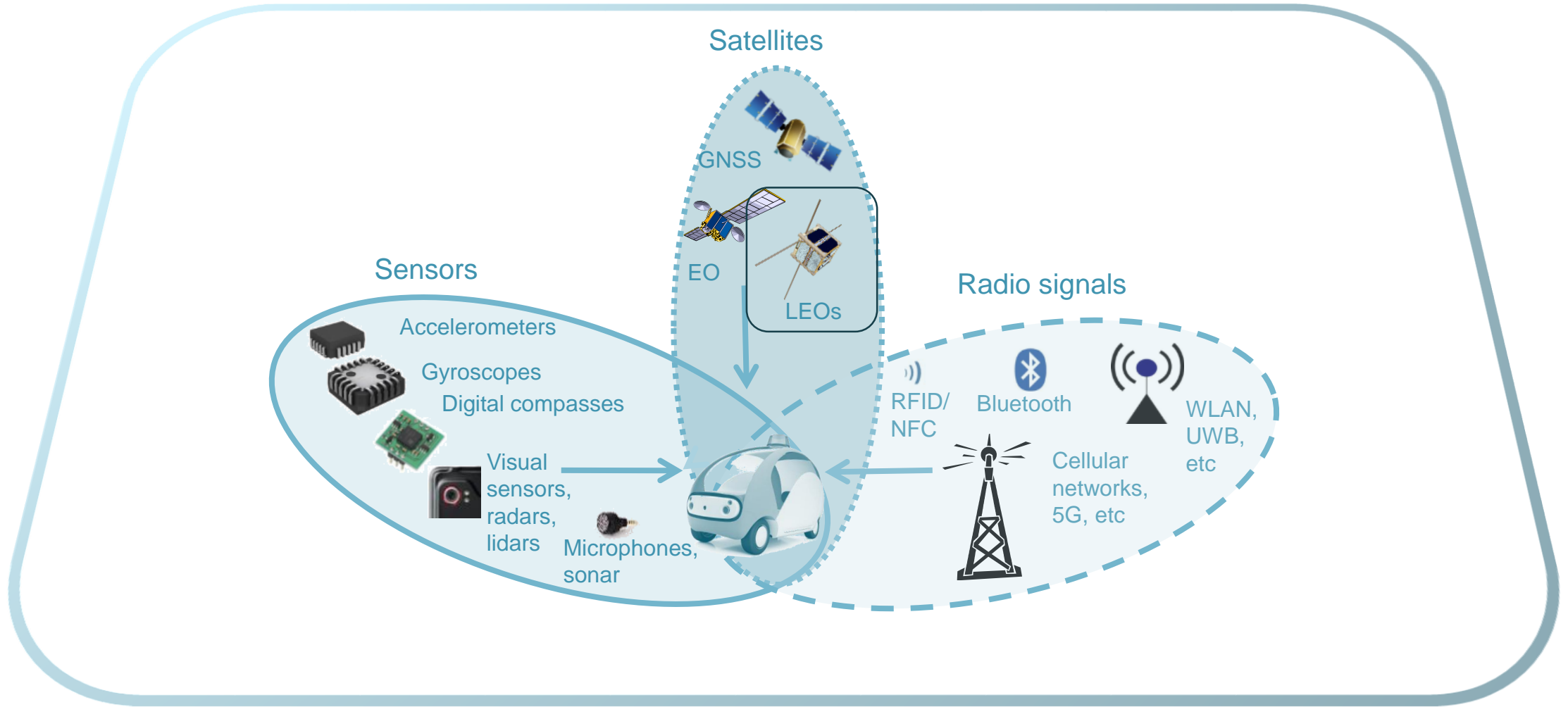
- Precision Vision-Based Sensing
- Radar-Based Odometry
- Urban PNT with Terrestrial Radio
- Massive signals-of-opportunity utilization for PNT
- Mega-LEO constellation exploitation for PNT



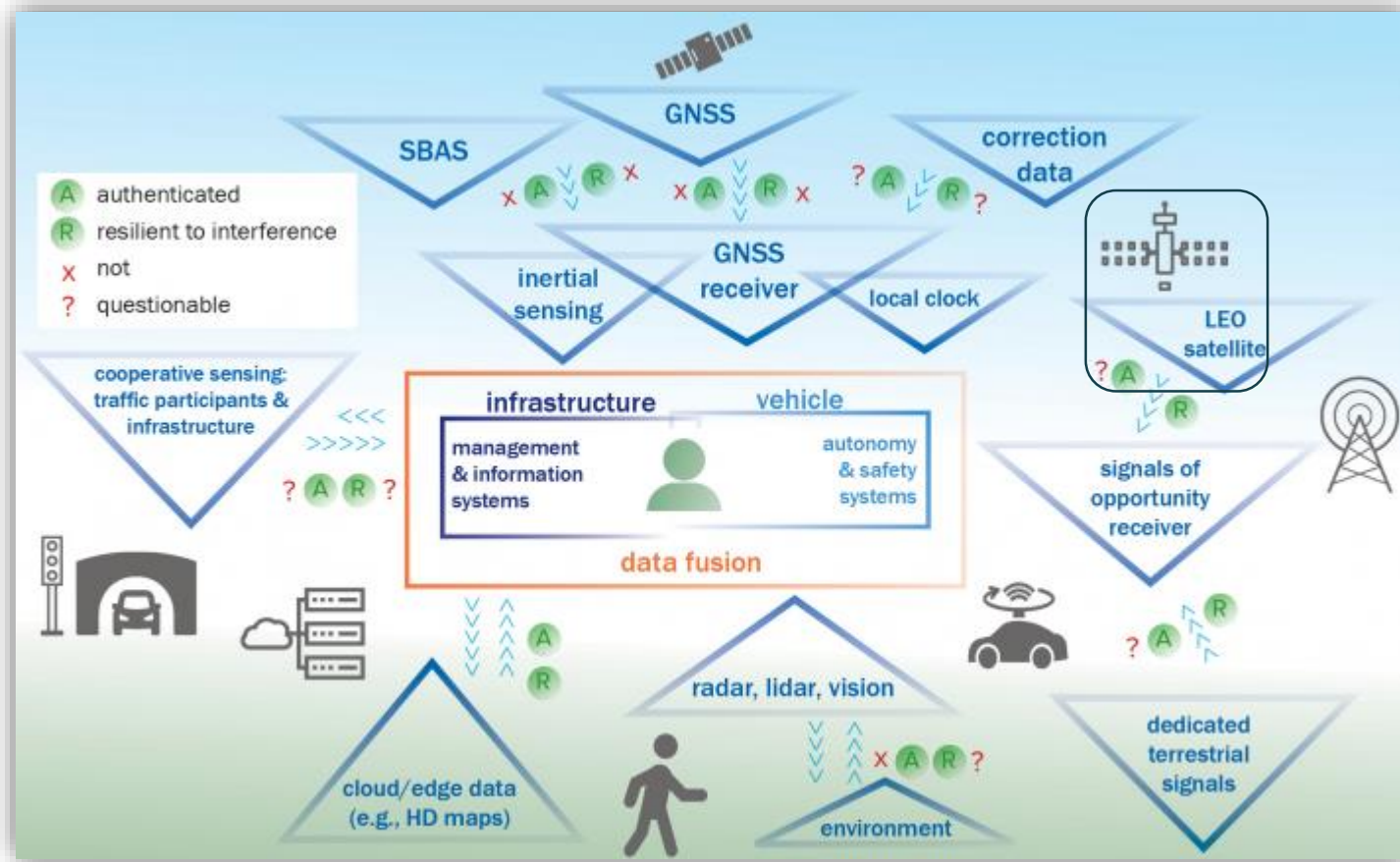
Source: Dr. Todd Humphreys,  
[Radionavigation laboratory](#),  
The University of Texas at Austin

# Comparison of commonly used localisation approaches

| Sensor/technology        | Advantages   | Disadvantages  |
|--------------------------|--|--|
| <b>Wheel Odometry</b>    | Simple to determine position/ orientation<br>short term accuracy<br>Allows high sampling rate and Low-cost solution            | Position drift due to wheel slippage<br>Error accumulation over time<br>Velocity estimation requires numerical differentiation that produces additional noise                          |
| <b>INS</b>               | Provides both position and orientation<br>Not subject to interference outages  | Position estimation requires second-order integral<br>Have long-term drift errors  |
| <b>GNSS</b>              | Provides absolute position with known value of error<br>No error accumulation over time  | Unavailable in indoor, underwater, and close areas<br>Affected by RF interference  |
| <b>Ultrasonic Sensor</b> | Provides a scalar distance measurement from sensor to object<br>Inexpensive solution   | Reflection of signal wave is dependent on material or orientation of obstacle surface<br>Suffer from interference if multiple sensors are used<br>Low angular resolution and scan rate |
| <b>Laser</b>             | Similar to sonar sensors but high accuracy and scanning rate<br>Return the distance to a single point or an array of distances | Reflection of signal wave is dependent on material or orientation of obstacle surface<br>Expensive solution  |
| <b>RADAR</b>             | Immune against poor weather conditions<br>Can be operated in low-texture environment   | Affected by outliers and non-flat terrain  |
| <b>Visual Odometry</b>   | Images contains meaningful information<br>Provide high localization accuracy and Inexpensive solution                          | Requires sophisticated images-processing algorithms<br>High computational cost to process images   |



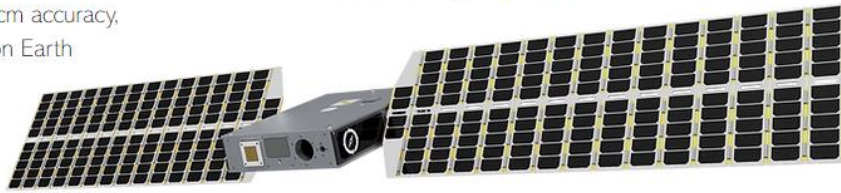
# Future vision example for highly automated transportation systems



The Ohio State University's CARMEN: [Center](#) for Automated Vehicles Research with Multimodal AssurEd Navigation

# LEO PNT (Pulsar) by Xona Space Systems

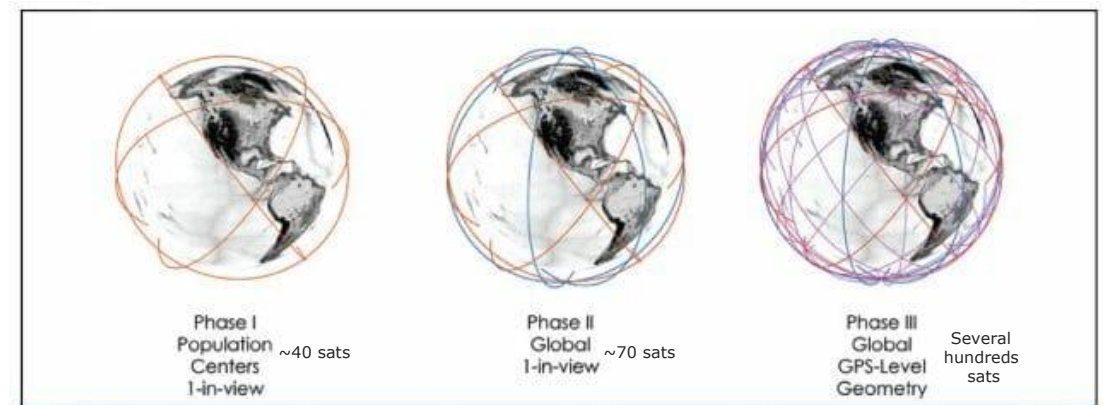
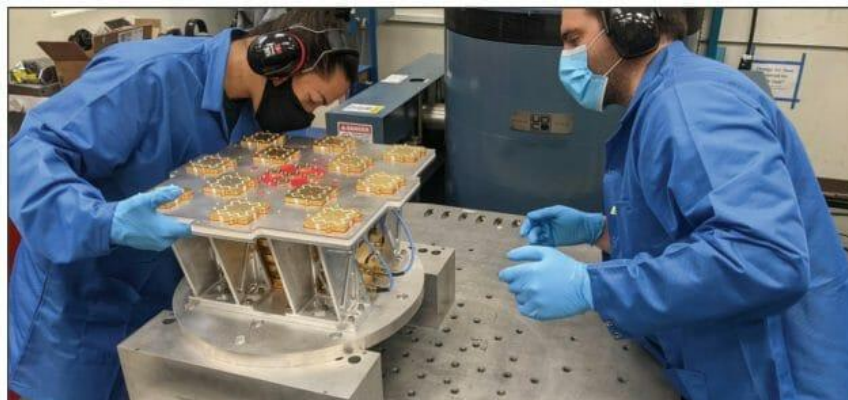
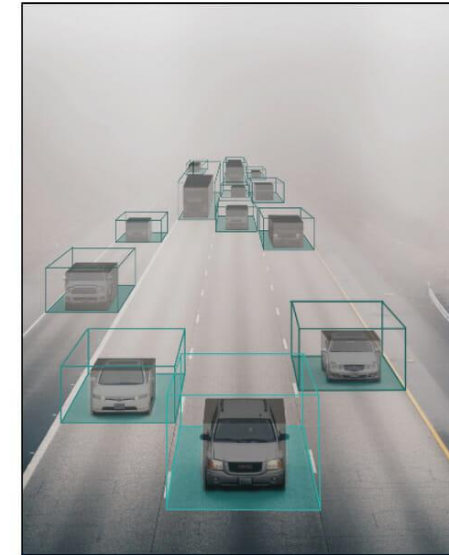
- Rapid <10cm accuracy, anywhere on Earth
- Low-cost LEO satellites enable affordable global services



- Designed to integrate into simple, low-cost user equipment

- Powerful & secure signal with exceptional interference and multipath mitigation capability

- Can both enhance legacy GNSS and operate fully independent



T. Reid (2020). [Commercial LEO PNT for Autonomy](#). Stanford Centre for PNT Symposium. Oct 2020. Xona Space Systems.

Launching Xona's Ravens: Commercial Satnav from LEO (2022). [Inside GNSS](#), May 18, 2022

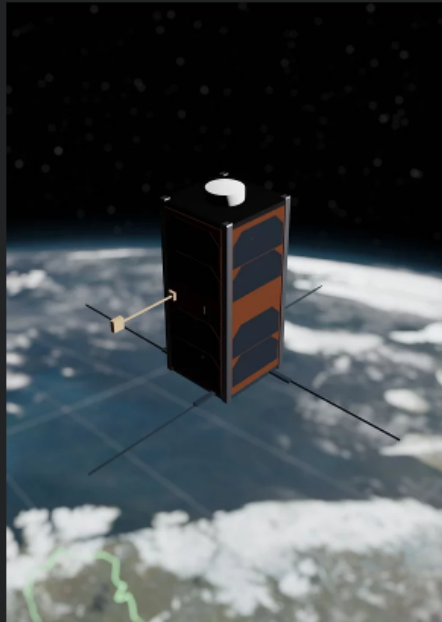
# LEO PNT by Geely Future Mobility Constellation

- Automaker Geely plans a future 240-satellite Geely Future Mobility Constellation to provide centimeter-accurate precise positioning and connectivity\*
  - In June 2022, nine Geespace satellites launched into low Earth orbit to support navigation and autonomous driving for automaker Geely
  - Plans for expanding global coverage after 2026

\*Location Business News, June 8, 2022



# LEO PNT in the Finnish INCUBATE project (2021-2024)



## INdoor navigation from CUBesAte TEchnology

The INCUBATE project aims at promoting the exploitation of LEO small satellites for precise position, navigation, and timing (PNT) information in challenging conditions and how these can be obtained in indoor environments.

Precise position, navigation, and timing (PNT) information and location-based services are crucial in various societal sectors, such as transportation and logistics, agriculture and forestry, mapping and surveying, industrial activities, search and rescue, as well as consumer smartphone applications. There is a lack of high-precision, sub-meter-level global positioning seamlessly available for outdoor and indoor navigation. Satellite navigation signals from Global Navigation Satellite Systems (GNSS) such as GPS signals are so weak, that they cannot be used reliably where they are obstructed such as indoors or in concrete, urban canyons.

The INCUBATE project aims at:

- promoting the exploitation of LEO small satellites for PNT in challenging conditions
- we will investigate how LEO-based PNT can be obtained in indoor environments
- we will optimize the signals and receivers both by improving the utilization of existing LEO's and also by the design of a new small satellite and payload into both new and existing LEO satellites to be able to define and test the performance required for accurate indoor PNT.

### 01 What is a LEO satellite?

Low Earth Orbit (LEO) satellites orbit at a lower attitude than traditional satellites, generally lower than 2000 Km. Compared to traditional Middle Earth Orbit (MEO) satellites, LEO are significantly smaller and generally don't have an atomic clock.

### 02 What are the advantages of LEO satellites?

LEO satellites have a lower launch cost, can allow denser constellations and the received signal on Earth is stronger compared to e.g. GNSS signal.

### 03 What are the challenges of LEO satellites?

As LEO satellites don't have an atomic clock, synchronization is still an open challenge. Also, as their orbital period is a couple of hours, a single satellite is visible in a given area only for a few minutes.

### 04 How are LEO satellites and positioning related?

Due to their stronger signal and denser constellation, it is believed that LEO satellites have great potential for positioning, especially in indoor spaces, where GNSS signal is generally not available. However, there are still challenges to be solved, such as clock synchronization and limited visibility. These are central themes investigated in the INCUBATE project.



# INCUBATE

## GOALS OF INCUBATE

WE AIM AT PROMOTING THE EXPLOITATION OF LEO SATELLITES FOR POSITIONING, NAVIGATION, AND TIMING (PNT) IN CHALLENGING CONDITIONS.

### 1. DESIGN

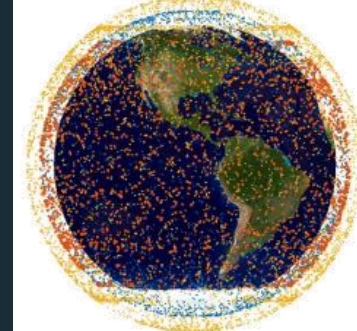
We will design system architecture and payload into both new and existing LEO satellites to be able to define and test the performance required for accurate indoor PNT.

### 2. OPTIMIZE

We will optimize the signals and receivers both by improving the utilization of existing LEO's, and by the design of *a new small satellite*.

### 3. VALIDATE

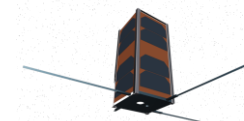
We will validate our approach by focusing on mathematical, analytical and simulation aspects leveraging on real signals from existing constellations as signals of opportunity and taking advantage of a Finnish-Swedish LEO satellite mission, the **KvarkenSat**, that will have GNSS payload (among others)



Starlink **blue**  
Kuiper **red**  
OneWeb **yellow**



FinnPNTSat



KvarkenSat

# Thank you!



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