FocalPoint

# The impact of S-GNSS® Auto in challenging environments

Featuring award-winning Supercorrelation™ technology

Automotive Trial Results
Phase 2

# About the paper

This paper assumes that the reader is already familiar with basic functionality of a GNSS receiver. If not, we recommend reviewing the References by Kaplan[1] or van Diggelen[2] to help familiarise yourself with the basics.

This report provides a top-level summary of the results from trials carried out in the UK and Germany in June 2024, made possible by funding received from ESA's Navigation Innovation and Support Program (NAVISP) to build a real-time S-GNSS® receiver.

This data is being tested and evaluated as part of a phased approach. Phase 1 consisted of 'pipe cleaning' testing across the UK. Phase 2 (covered in this report) presents results from Canary Wharf, London and Black Forest, Germany. Phase 3 will feature data from Japan and Korea, including more in-depth analysis.

[1] Kaplan, E.D. and Hegarty, C. eds., 2017. Understanding GPS/GNSS: Principles and applications. Artech house.
[2] Van Diggelen, F.S.T., 2009. A-GPS: Assisted GPS, GNSS, and SBAS. Artech house.

# About Supercorrelation™ technology

Supercorrelation™ is a software enhancement that operates between the correlators and the navigation engine. It provides enhancements to the code and carrier tracking functions, boosting the accuracy, sensitivity and integrity of the receiver by removing multipath interference and non-line-of-sight signals.

A Supercorrelation™-enabled Global Navigation Satellite System, known as an S-GNSS® receiver, is a patented technology that provides an upgrade to how GNSS receivers work by overcoming the common associated challenges including satellite multipath. This technology has facilitated the development of our S-GNSS® Auto product that has been designed to extend the availability and performance of ADAS in challenging scenarios, including urban and foliage heavy environments.

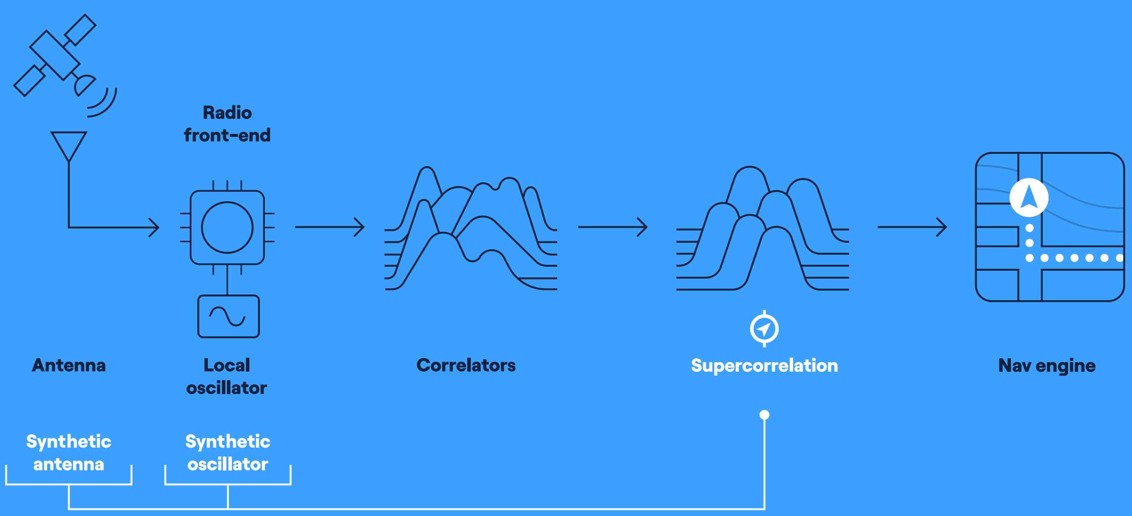


Figure 1 - An S-GNSS® Receiver

Supercorrelation™ operates between the traditional GNSS correlators and the navigation engine. It effectively creates a high performance synthetic antenna and synthetic oscillator, processing data from the correlators, mitigating multipath by removing NLOS signals. The impact of these corrections is improved sensitivity and accuracy for observables such as pseudorange and Doppler measurements.

# The role of GNSS in Automotive

GNSS has played a role in automotive systems for decades. The first GPS-based integrated satellite navigation system was introduced in 1990 by Mazda, in its high-end Eunos Cosmos car for the Japanese market.

Since then, in-vehicle sat-nav has advanced to the point where a GNSS receiver is now a standard component of vehicle infotainment systems, used not just for navigation but also for location-aware information services such as traffic and weather alerts.

But that's just the tip of the iceberg for GNSS in the modern vehicle. Today's vehicles often have more than one onboard GNSS receiver, with data feeding into as many as four functional areas.

## 4 functional use cases for GNSS

**Positioning information**

- Navigation
- Infotainment
- Fleet management
- Vehicle telematics

**Location-based services**

- Payments and tolling services
- Usage based insurance
- On-demand mobility services
- Over-the-air vehicle updates

**Driver assistance systems**

ADAS solutions such as

- eCall
- Intelligent speed assistance
- Combined ADAS services (e.g. Ford's Blue Cruise)
- Automated lane keeping systems

**Automated driving**

- Fully automated vehicles Level 3, 4 + 5

# What makes GNSS unique from the other sensors?

GNSS is the only PNT sensor that can provide an absolute rather than relative position. GNSS measurements therefore form a key input for real-time localisation, helping the ADAS to determine the vehicle's exact position and trajectory.

Once an absolute position is established via GNSS, the other PNT sensors can then position the vehicle within the lane to the required level of accuracy. These sensors enable the vehicle to detect and respond appropriately to obstacles and traffic infrastructure, and to make critical decisions around braking, indicating, turning, lane-changing and self-parking.

## Role of GNSS in High-Precision Positioning

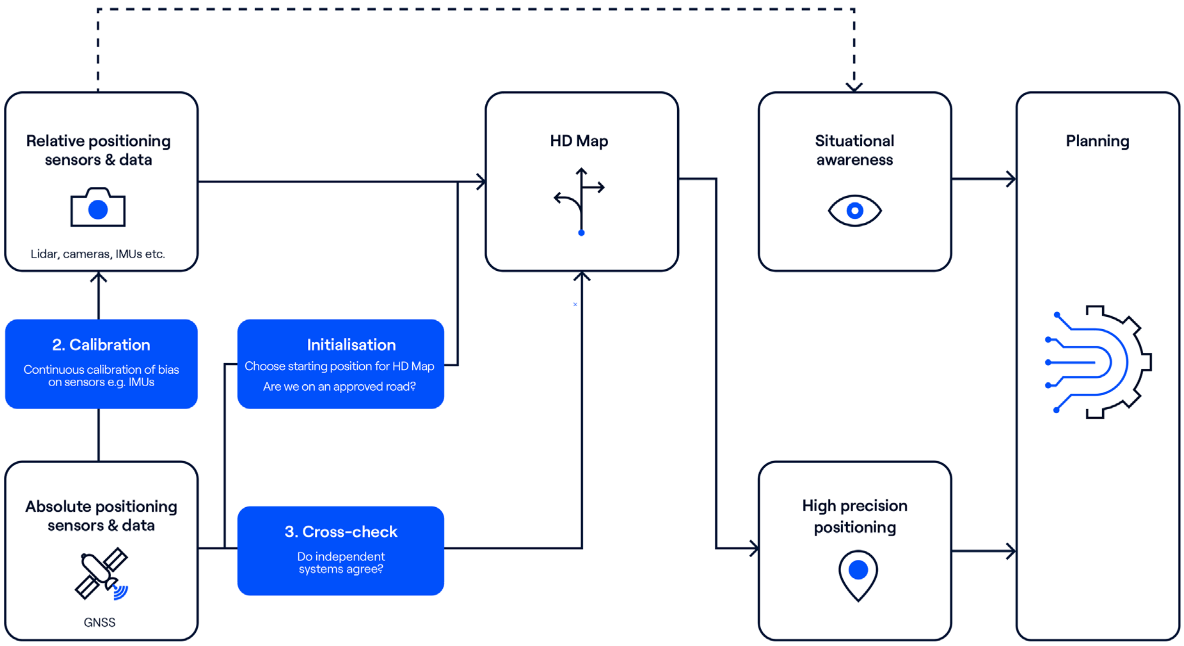


Figure 2 - The role of GNSS in high-precision positioning.

GNSS has 3 distinctive roles within the multi-sensor positioning system:

**Initialisation:** The global position provided by GNSS can be used to accelerate the vehicle control system's initialisation process. While HD maps can provide a high-accuracy position, they can only do so efficiently if they know the vehicle's starting location. Without that information, they would need to search the whole global database to find a match with what the camera and LiDAR are seeing: a time, data, and compute-intensive process.

**Calibration:** An accurate GNSS position can be used to calibrate other sensors to maintain their own accuracy. In particular, IMUs and MEMS sensors tend to accumulate biases over time that means their accuracy starts to drift. These sensors can be regularly re-calibrated by using the GNSS position to correct any biases that have crept in.

**Cross-check:** All sensors are susceptible to error, although the types of error differ depending on the sensor. ADAS and ADS systems compensate for this by continually cross-checking sensors against each other. If the GNSS position disagrees with an HD map position calculated using a camera, for example, it's a sign that something is wrong. GNSS is well suited to the role of cross-checking and flagging anomalous readings, as it is independent of other sensors and uses an entirely different data source—satellite signals from space.

# S-GNSS® Auto

S-GNSS® Auto unlocks the full potential of GNSS for automakers by providing a scalable software upgrade to ADAS and self-driving systems, extending its availability even in the presence of GNSS challenges. As a software product, it works in existing receivers and can even be used to update existing vehicles with OTA updates.

**The role of S-GNSS® Auto in Automotive**

**Extending the availability of ADAS**
Facilitating accurate GNSS inputs that automation systems can rely upon, only the desired, line-of-sight signals are used, by successful mitigating multipath in urban and high foliage environments.

**Enhancing cyber-security**
Malicious spoofed signals are rejected supporting ISO/SAE 21434 framework, including the rejection of external EMI interference.

**Optimising GNSS performance when using concealed antennas**
Synthesising a high performance antenna with a small, constrained or concealed antenna, end user motion facilitates an instant boost to GNSS performance.

**Improving GNSS for position and location-based services**

# About the Trials

## Testing S-GNSS® Auto, supported by ESA

ESA's Navigation Innovation and Support Program (NAVISP) plays a pivotal role in driving innovation within the European Positioning, Navigation, and Timing (PNT) landscape. Under the requirements of the European Space Agency (ESA) grant scheme, FocalPoint has developed an advanced Global Navigation Satellite System (GNSS) receiver to showcase its cutting-edge S-GNSS® Auto software to automotive OEMs.

Extensive urban driving trials were conducted in some of the most challenging environments, known for their notorious satellite multipath issues, due to dense modern skyscrapers and heavily forested areas. These trials aim to demonstrate that with the integration of S-GNSS® Auto, the persistent GNSS challenges faced by these manufacturers in their respective testing environments can be effectively overcome.

## How the trials were conducted

Using FocalPoint's bespoke hardware-plus-software trials platform, trials demonstrated the accuracy improvements in both the measurement (pseudorange and Doppler) and position domains (position and velocity). This platform was fixed to a vehicle and driven on fixed routes around the above locations. A survey-grade ground truth system logged the path travelled while the S-GNSS® receiver logged real-time data.

## S-GNSS® receiver architecture

The S-GNSS® receiver consists of three main elements: the hardware (including Radio- Frequency Front-End (RFFE) and processing unit), the Software-Defined Radio (SDR), and a Graphical User Interface (GUI).

# Hardware architecture

The design approach was to use Commercial-Off-The-Shelf (COTS) components for the hardware build, and perform Global Navigation Satellite System (GNSS) processing using a custom-built SDR receiver running on a processing module.

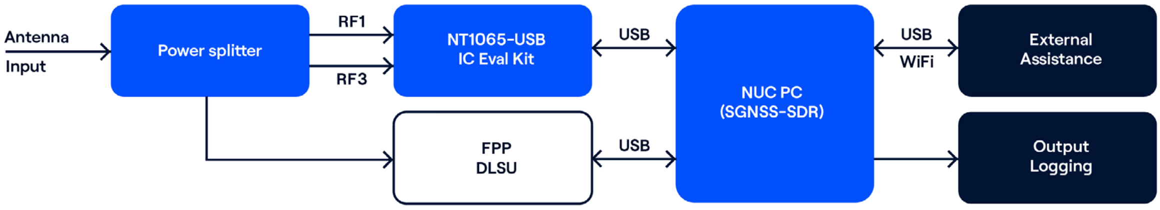


Figure 3 - The main building blocks of the S-GNSS® receiver hardware: the RFFE is an NTLab® NT1065-USB3 RF IC EVALUATION KIT; a Linux-based Next Unit of Computing (NUC) Personal Computer (PC) (Intel Rugged NUC 13 Pro NUC13ANFi7) is the processing unit, and an Focal Point Positioning (FPP) Inertial Sensor Data Logging and Streaming Unit (DLSU) is the inertial sensor data source.

The NTLab® NT1065-USB3 RFFE is configured for dual-band L1 and L5 operation. The DLSU contains a low-cost, consumer-grade Inertial Measurement Unit (IMU) and an F9T L1/L5 u-blox GNSS receiver. The u-blox receiver is used to time-stamp the inertial measurements.

# Software architecture

The custom-built S-GNSS® Software Defined Receiver (SDR) is designed to be fast and reliable. It can perform all vital GNSS processing, including acquisition, tracking, and Position, Velocity, and Time (PVT) calculation. Figure 3 shows the architecture of the SDR receiver.

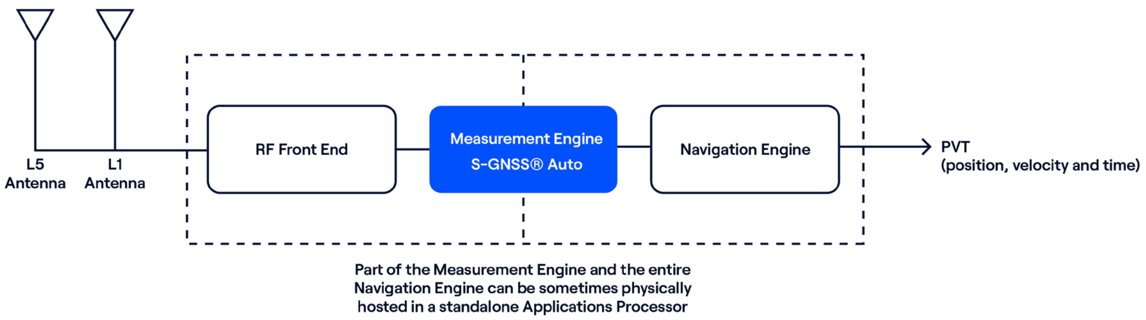


Figure 4 - Software architecture.

The current SDR can process GPS L1, GPS L5, Galileo E1, Galileo E5, Beidou B1 and Beidou B2 signals; however, it has a generalised architecture, which makes future extensions to other constellations and signals straightforward.

# Trialling demonstrator setup

A complete trialling hardware setup was constructed, consisting of the S-GNSS® receiver and a high-performance GNSS/INS ground truth reference system. These are rigidly fixed to a main board and housed in a car roof box along with the required antennas, RF cabling, power distribution and network routing. Power is supplied from a battery pack stored within the test vehicle, while a laptop also within the vehicle is used to control the trials hardware and handle data logging.

The complete setup inside the car roof box mounted on top of a car is shown in Figure 5 below, with Figure 6 detailing the open demonstrator and Figure 7 the demonstrator test vehicle during the trials at Canary Wharf, London.

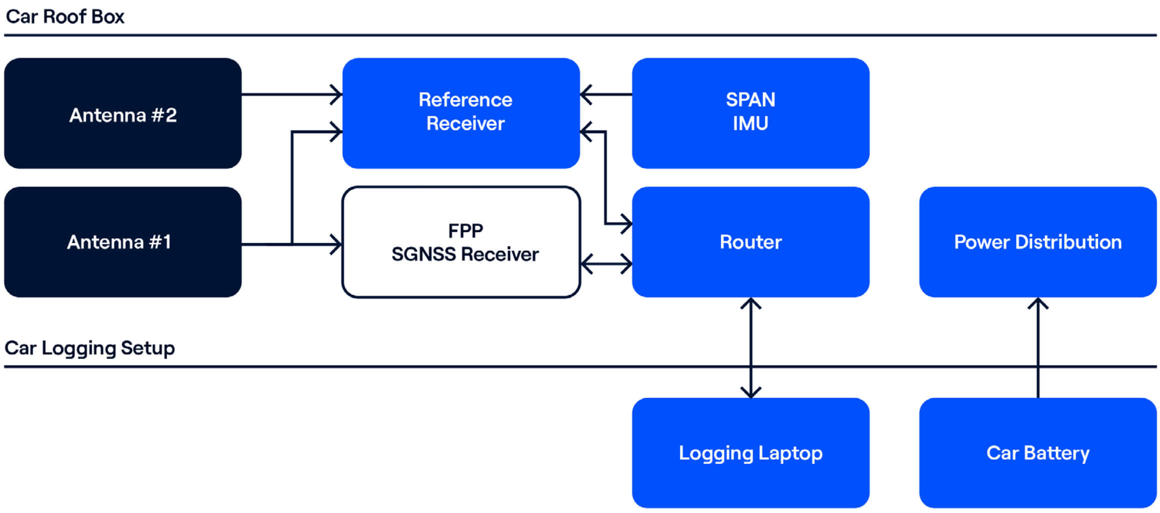


Figure 5 - Demonstrator setup.

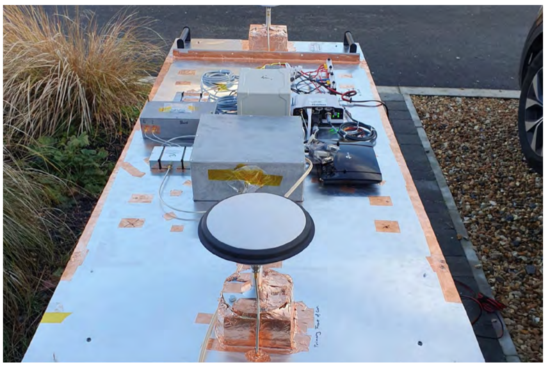

Figure 6 - Open demonstrator showing components and antennas.

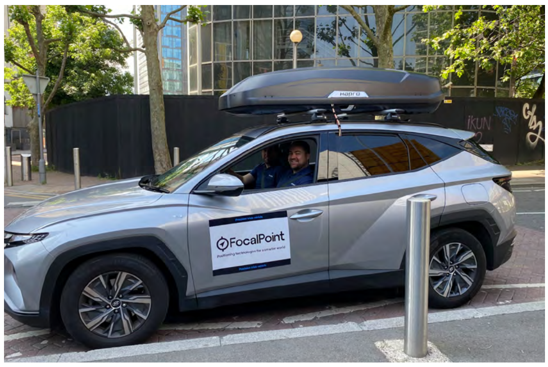


Figure 7 - Demonstrator test vehicle in Canary Wharf, London.

# Trial 1 Results: Canary Wharf, London

The following route was taken (Figure 8), involving 7 loops around the most dense urban environment London has to offer.

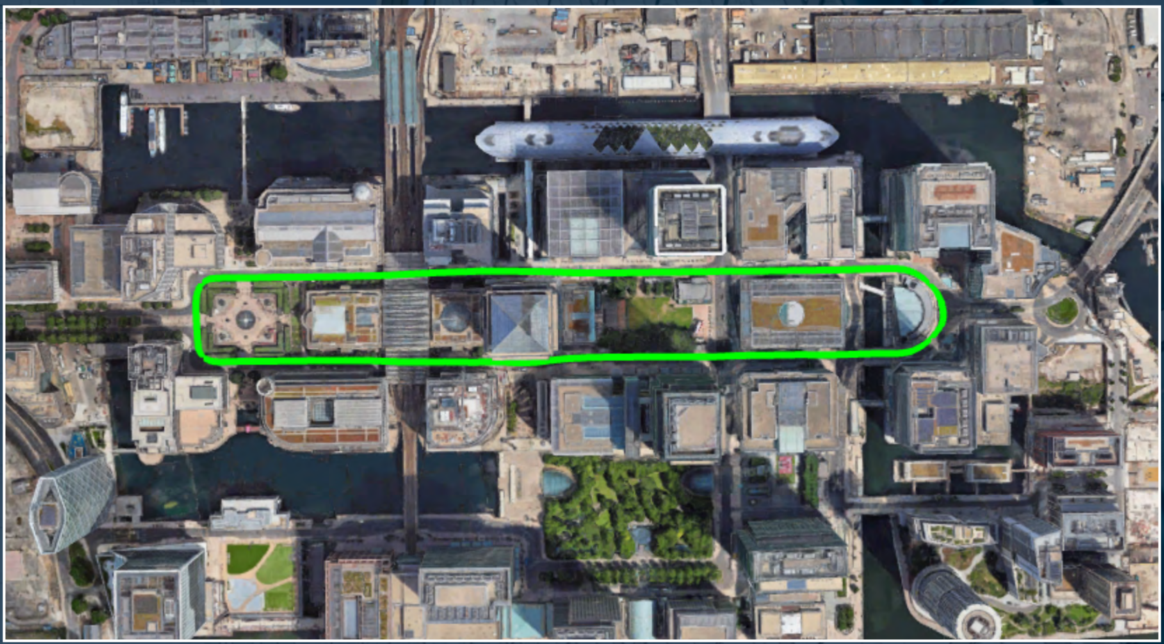

Figure 8 - Canary Wharf, London trail loop.

| 2D | S-GNSS® OFF | S-GNSS® ON | Error reduction | Multiple Improvement | Percentage Reduction |
|---|---|---|---|---|---|
| 90% | 6.17m | 3.49m | -2.68m | 1.8x | -43% |
| 95% | 8.8m | 4.13m | -4.67m | 2.1x | -53% |
| 99% | 13.13m | 5.17m | -7.96m | 2.5x | -61% |
| **3D** | | | | | |
| 90% | 8.89m | 3.61m | -5.3m | 2.5x | -59% |
| 95% | 12.07m | 4.24m | -7.83m | 2.8x | -65% |
| 99% | 14.98m | 5.31m | -9.67m | 2.8x | -65% |

Table 1 – Canary Wharf, London trial results for 2D (Horizontal) and 3D position errors and respective improvements with S-GNSS® Auto enabled.

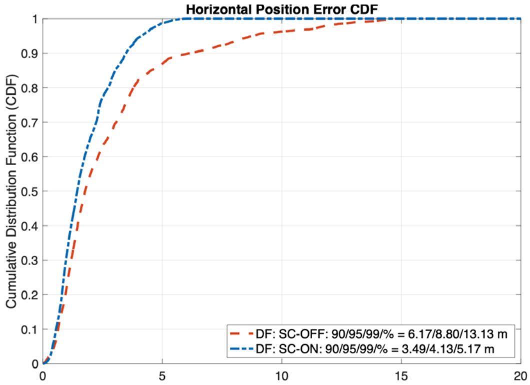


Figure 9 - Cumulative distribution function (CDF) graph of the horizontal position error for S-GNSS® on and off. Canary Wharf, London.

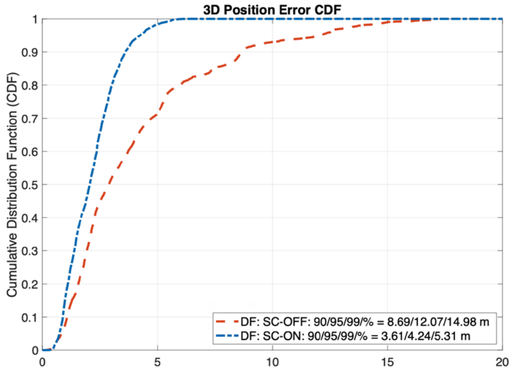


Figure 10 - Cumulative distribution function (CDF) graph of the 3D position error for S-GNSS® On and Off. Canary Wharf, London.

As shown in Table 1 and Figures 9 and 10, S-GNSS® Auto has improved the accuracy across all measures of position accuracy. The error statistics were calculated by comparing the positioning solution of the S-GNSS® receiver at each epoch to the ground truth solution. Highlighting the worst errors (99th percentile), we can see that S-GNSS® Auto was able to reduce them by 61% and 65% (2D and 3D respectively). This represents up to a 2.8x improvement of the GNSS performance when using S-GNSS® Auto in challenging urban environments.

Below are some highlights that show where the S-GNSS OFF line has been thrown off by multipath, and where S-GNSS® was able to dramatically improve the solution.

To provide a further proofpoint alongside the GNSS based ground truth, 360°video footage was captured during the trials, and screenshots of given moments are shown below.

Figure 11 - View from east to west of Canary Wharf, showing S-GNSS® OFF (red) diverging away from the ground truth (green) with supporting image from a mounted video camera showing the true location (right hand lane). S-GNSS® ON (blue) tracks the truth line closely.

Figure 12 - View into the south west corner of Canary Wharf, Lap 1, showing S-GNSS® OFF (red) away from the ground truth (green) with supporting image from a mounted video camera showing the true location (right hand lane). S-GNSS® ON (blue) tracks the truth line closely.

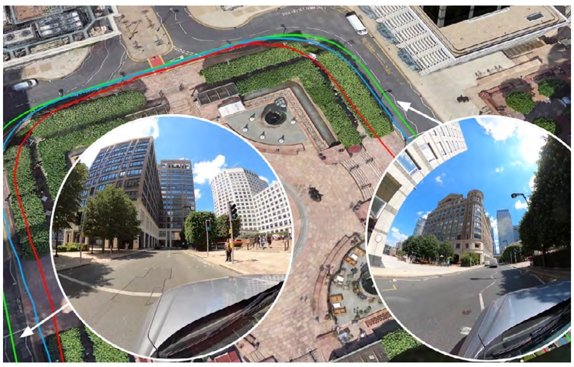

Figure 13 - View into the north west corner of Canary Wharf, Lap 2, showing S-GNSS® OFF (red) away from the ground truth (green) with supporting images from a mounted video camera showing the true location (right hand lane). S-GNSS® ON (blue) tracks the truth line closely.

Figure 14 - View into the north of Canary Wharf, Lap 2, showing S-GNSS® OFF (red) away from the ground truth (green) with supporting images from a mounted video camera showing the true location (right hand lane). S-GNSS® ON (blue) tracks the truth line closely.

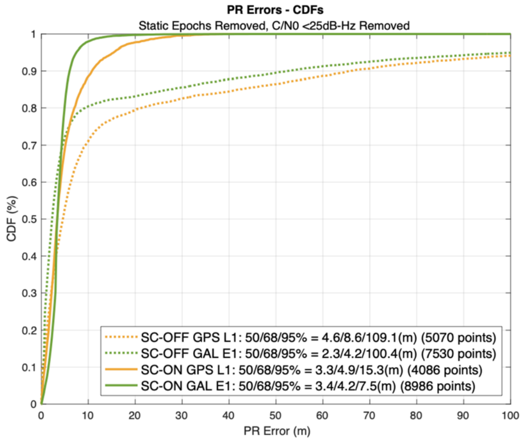


Figure 15 – CDF showing pseudorange errors for Galileo (E1) & GPS (L1) constellations with S-GNSS® OFF (dotted lines) and S-GNSS® ON (solid lines).

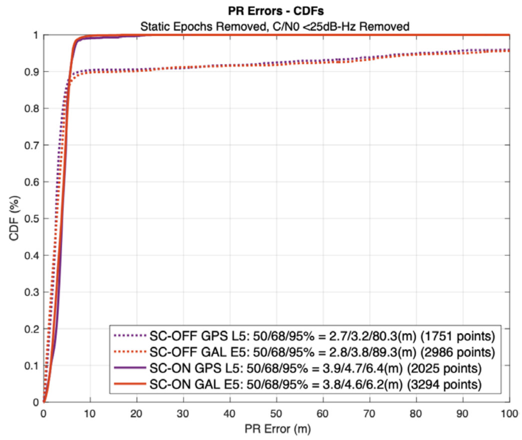


Figure 16 – CDF showing pseudorange errors for Galileo (E5) & GPS (L5) constellations with S-GNSS® OFF (dotted lines) and S-GNSS® ON (solid lines).

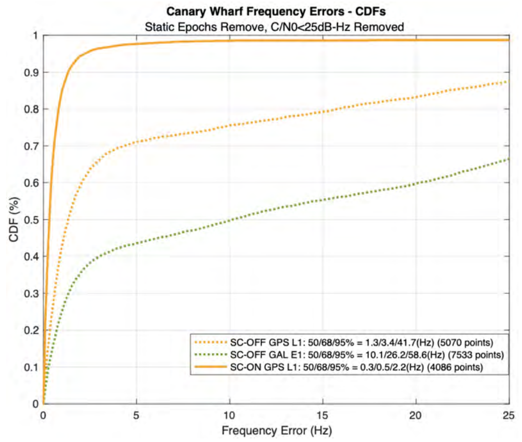


Figure 17 – CDF showing frequency errors for Galileo (E1) & GPS (L1) constellations with S-GNSS® OFF (dotted lines) and S-GNSS® ON (solid lines). *note: GAL E1 with S-GNSS® ON is not shown.

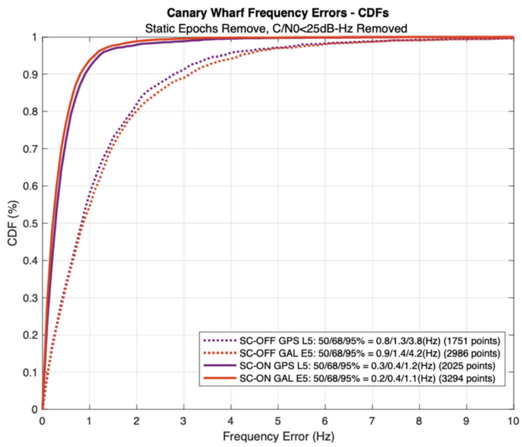


Figure 18 – CDF showing frequency errors for Galileo (E5) & GPS (L5) constellations with S-GNSS® OFF (dotted lines) and S-GNSS® ON (solid lines).

| PR | SC off | SC on | Error reduction | Multiple Improvement | Percentage Reduction |
|---|---|---|---|---|---|
| E1 | 100.4 | 7.5 | 92.9 | 13.4 | 93 |
| E5 | 89.3 | 6.2 | 83.1 | 14.4 | 83 |
| L1 | 109.1 | 15.3 | 93.8 | 7.1 | 86 |
| L5 | 80.3 | 6.4 | 73.9 | 12.5 | 92 |
| **Freq** | | | | | |
| E1 | 58.6 | NA | 39.5 | NA | 67 |
| E5 | 4.2 | 1.1 | 2.6 | 3.8 | 62 |
| L1 | 41.7 | 2.2 | 39.5 | 19.0 | 95 |
| L5 | 3.8 | 1.2 | 2.6 | 3.2 | 68 |

Table 3 – Results for Pseudorange (PR) and frequency errors and respective improvements. Canary Wharf, London.

As shown in Table 1 and Figures 15, 16, 17 and 18, Supercorrelation™ processing is shown to result in significantly lower pseudorange and frequency errors, which in turn enables the calculation of more accurate positions. The results demonstrate the significant benefits that S-GNSS® provides; particularly in challenging urban scenarios similar to the presented London dataset, in which severe multipath interference can result in large positioning errors for traditional GNSS processing.

# Trial 2 Results: Black Forest, Germany

The following route was taken (Figure 19), starting in the far west and travelling clockwise in an area renowned for its dense foliage. The three notable highlight areas are shown on the map.

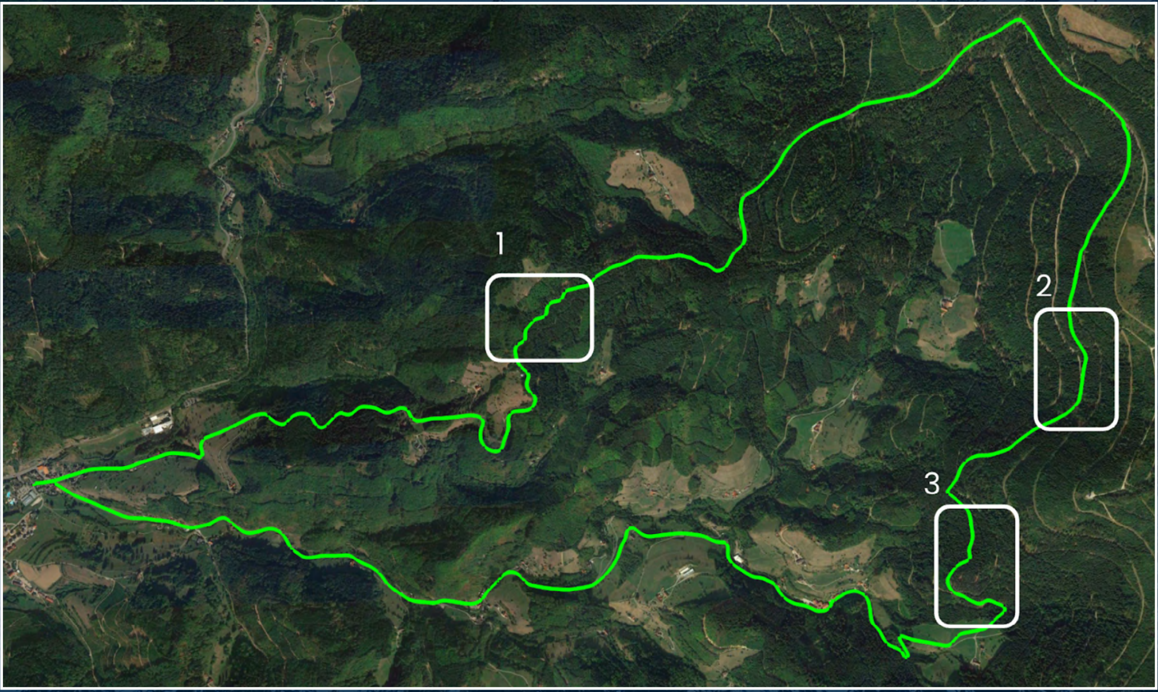


Figure 19 - The route taken around Black Forest, Germany - 17km east of Offenburg.

| 2D | S-GNSS® OFF | S-GNSS® ON | Error reduction | Multiple Improvement | Percentage Improvement |
|---|---|---|---|---|---|
| 90% | 7.93m | 4.07m | -3.86m | 1.9x | 49% |
| 95% | 11.37m | 4.53m | -6.84m | 2.5x | 60% |
| 99% | 20.94 | 5.65m | -15.29m | 3.7x | 73% |
| **3D** | | | | | |
| 90% | 15.28m | 6.15m | -9.13m | 2.5x | 60% |
| 95% | 17.21m | 7.37m | -9.84m | 2.3x | 57% |
| 99% | 22.83m | 10.73m | -12.1m | 2.1x | 53% |

Table 2 – Plot of 2D (Horizontal) and 3D position errors and respective improvements from Black Forest, Germany.

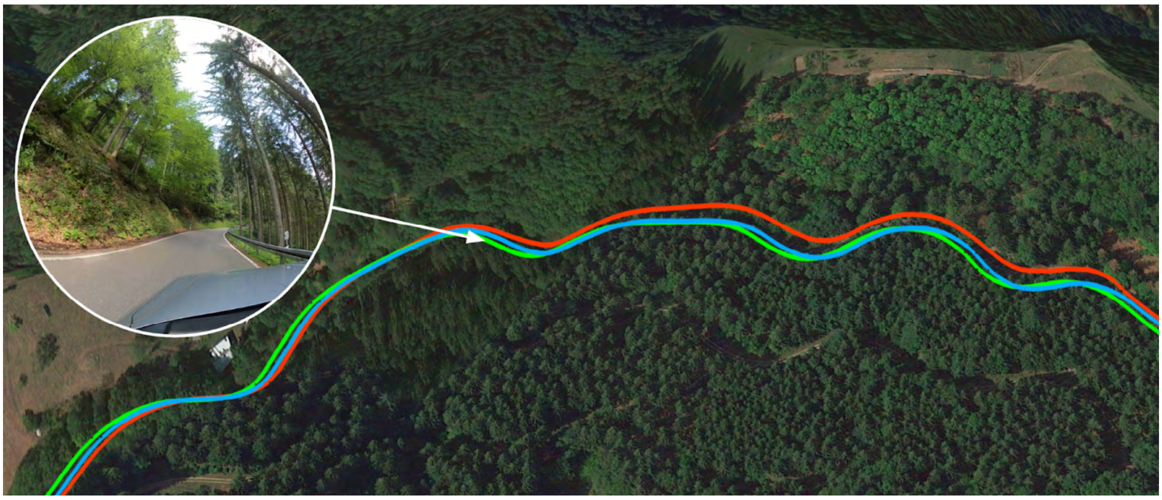

Figure 20 - Highlight 1 - along the north of the Black Forest route, shows S-GNSS® OFF (red) away from the ground truth (green) with supporting image from a mounted video camera showing the true location. S-GNSS® ON (blue) tracks the truth line closely.

Figure 21 - Highlight 2 - along the east of the Black Forest route, shows S-GNSS® OFF (red) away from the ground truth (green) with supporting image from a mounted video camera showing the true location. S-GNSS® ON (blue) tracks the truth line closely.

Figure 22 - Highlight 3 - along the south-east of the Black Forest route, showing S-GNSS® OFF (red) away from the ground truth (green) with supporting image from a mounted video camera showing the true location. S-GNSS® ON (blue) tracks the truth line closely.

As shown in Table 2 and Figures 20, 21 and 22, S-GNSS® Auto has improved the accuracy across all measures of position accuracy. Highlighting the worst errors (99th percentile), we can see that S-GNSS® Auto was able to reduce them by 73% and 53% (2D and 3D respectively). This represents up to a 3.7x improvement of the GNSS performance when using S-GNSS® Auto in challenging under-foliage environments.

| PR | SC off | SC on | Delta | Times | Percentage |
|---|---|---|---|---|---|
| E1 | 85 | 6.1 | 78.9 | 13.9 | 93 |
| E5 | 83 | 6.6 | 76.4 | 12.6 | 92 |
| L1 | 89.5 | 7.6 | 81.9 | 11.8 | 92 |
| L5 | 61.4 | 6.2 | 55.2 | 9.9 | 90 |
| **Freq** | | | | | |
| E1 | 3.4 | 1.4 | 1.5 | 2.4 | 44 |
| E5 | 3.1 | 1 | 2.1 | 3.1 | 68 |
| L1 | 3.5 | 2 | 1.5 | 1.8 | 43 |
| L5 | 3.1 | 1 | 2.1 | 3.1 | 68 |

Table 3 – Results for Pseudorange (PR) and frequency errors and respective improvements. Black Forest, Germany.

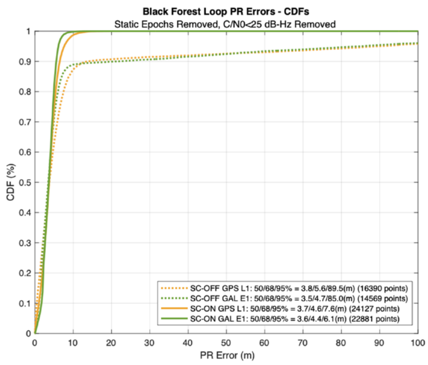


Figure 23 - CDF showing frequency errors for Galileo (E1) & GPS (L1) constellations with S-GNSS OFF (dotted lines) and S-GNSS® ON (solid lines). Black Forest, Germany.

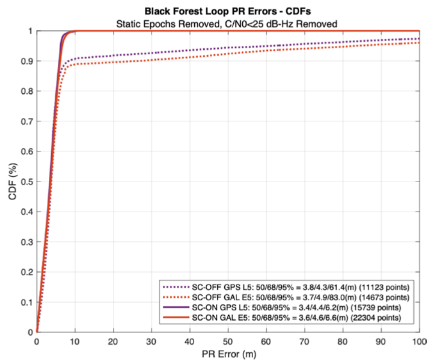


Figure 24 - CDF showing frequency errors for Galileo (E5) & GPS (L5) constellations with S-GNSS OFF (dotted lines) and S-GNSS ON (solid lines). Black Forest, Germany.

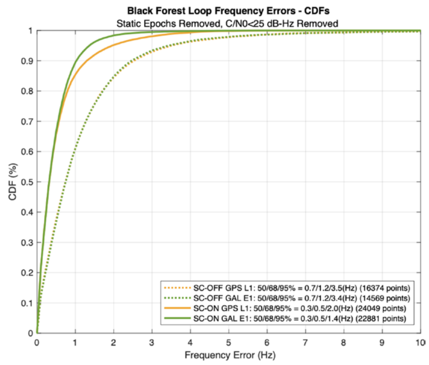


Figure 25 - CDF showing frequency errors for Galileo (E1) & GPS (L1) constellations with S-GNSS® OFF (dotted lines) and S-GNSS ON (solid lines). Black Forest, Germany.

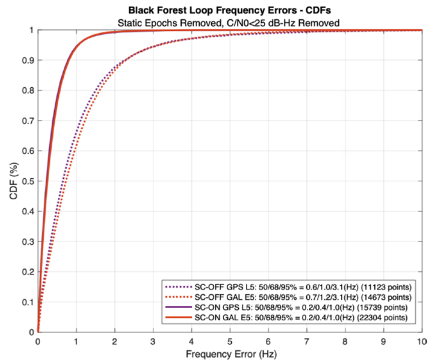


Figure 26 - CDF showing frequency errors for Galileo (E5) & GPS (L5) constellations with S-GNSS OFF (dotted lines) and S-GNSS ON (solid lines). Black Forest, Germany.

As shown in table 3 and figures 23, 24, 25 and 26, Supercorrelation™ processing is shown to result in significantly lower pseudorange and frequency errors, which in turn enables the calculation of more accurate positions. The results demonstrate the significant benefits that S-GNSS provides; particularly in challenging foliage scenarios seen in the Black Forest dataset, in which severe interference can result in large positioning errors for standard GNSS receivers.

# Sensitivity boost under foliage

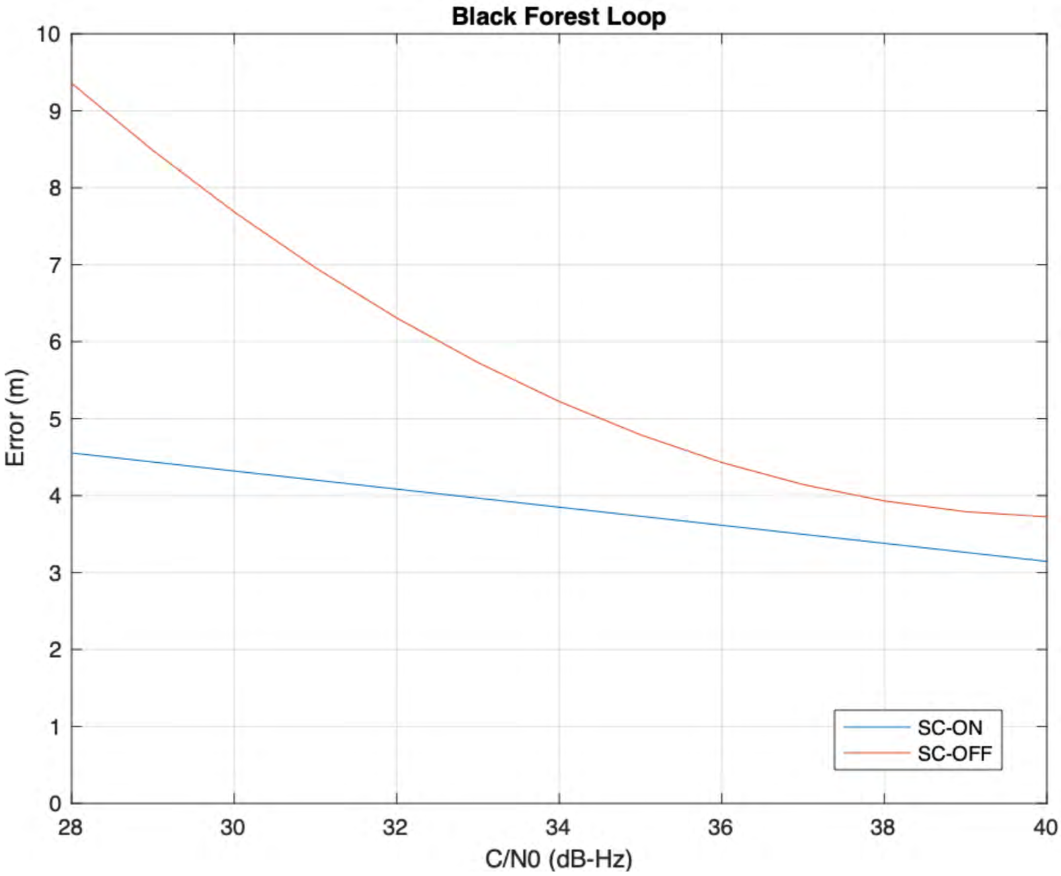


Figure 27 - CDF showing Position errors against C/N0.

Figure 27 shows how in the dense foliage environment of the Black Forest, as the signal strength is reduced, S-GNSS® Auto enables a much better Accuracy-to-C/N0 ratio. At the lower powers, the S-GNSS® OFF line shows a dramatic increase in error, while only a slight increase is seen for the S-GNSS® ON line. This represents the 'sensitivity boost' that S-GNSS® Auto enables: even with low signal powers, high accuracy is still possible.

# Industry impact summary

These results are representative from S-GNSS® Auto June 2024 trials in the UK and Europe and are representative of our global data collection campaign. They demonstrate that with S-GNSS® Auto integrated, GNSS accuracy is vastly improved, whereas without S-GNSS® Auto, accuracy is heavily impacted from satellite multipath and interference from tree foliage.

## Key trial findings with S-GNSS® Auto enabled

**2.5x**

2.5x improvement in accuracy in the dense urban environment of Canary Wharf, London (99th percentile of 2D position). This represents a reduction of 61% of error.

**3.7x**

3.7x improvement in accuracy under the dense foliage of the Black Forest, Germany (99th percentile of 2D position). This represents a 73% reduction of error.

**10x**

Over 10x improvement across GNSS measurements (pseudorange and frequency)across both trials. Pseudoranges were improved by 83-93% while frequency errors decreased by 44-95%.

# Why these results matter to automotive OEMs

For Automotive applications, specifically in ADAS/AVs, the key roles of GNSS are initialisation, calibration and cross-check. Upgrading with S-GNSS® Auto bring the following benefits to these functions:

**Initialisation:** The demonstrated improvement in accuracy, allows system initialisation to be faster and more reliable. Without S-GNSS® Auto enabled, automotive manufacturers would expect a longer search through HD maps to find a position match or even a mis-match due to a poor GNSS location. A mis-match could potentially result in a safety risk as road rules may be incorrectly applied.

**Calibration:** The more accurate a GNSS location, the faster and more accurate calibration of IMU. With corrected biases, IMUs become more useful in sensor fusion for multiple applications. With poor or slow calibration, the IMU's output is less trustworthy and less valuable. The improvement in calibration impacted by S-GNSS® Auto, could represent a cost efficiency, allowing OEMs to make improvements elsewhere in the vehicle.

**Cross-check:** The cross-check function is one that is vital for system safety. Checking the vehicle positioning against an independent source ensures any errors can be flagged and correcting action taken. Poor accuracy from GNSS can result in either false negative (fault incorrectly reported), which represent a user frustration or false positives (fault not detected), representing a safety concern. High accuracy GNSS enabled through S-GNSS® Auto, means this cross-check function is more robust, resulting in a better user experience and safer operation.

# Find out more about S-GNSS® Auto with Supercorrelation™

To register your interest in a summary of the full trial data from Korea and Japan or to trial S-GNSS® Auto, please get in touch at contact@focalpointpositioning.com with the subject line 'Trial'.

**For a more detailed overview of FocalPoint's Supercorrelation™ technology, please view:**

Supercorrelation technical overview white paper, March 2022.
Accessed: 13 May 2023 Online
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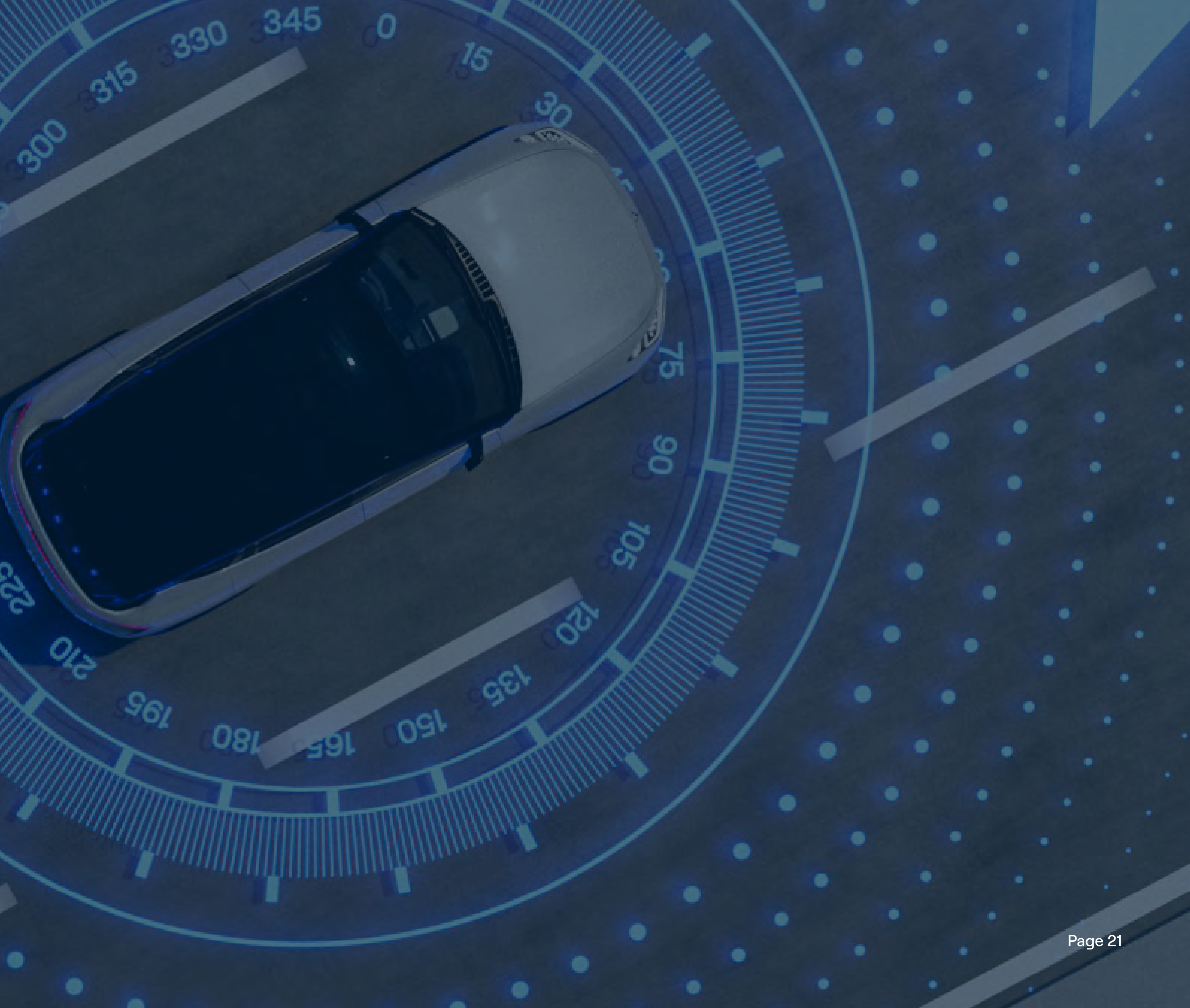

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