ESA NAVISP NEXTGEN GNSS ANTENNA PROJECT

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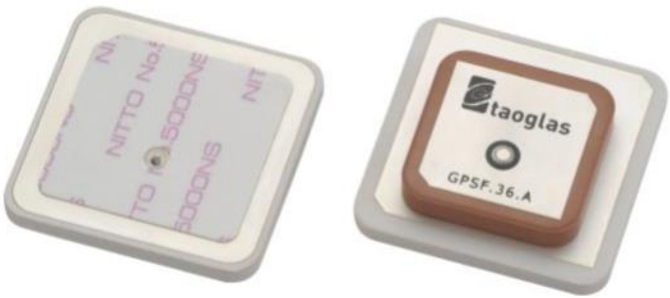
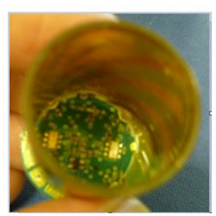
- Company context: how Helix Geospace was founded and a brief introduction to the present company.
- A discussion of the GNSS antenna technologies existing at the beginning of the project.
- The dielectric-loaded Hexafilar-Turnstile GNSS antenna that was proposed in the project.
- Solving manufacturing challenges.
- Trial samples and in-city car-trial validation.
- Discussion of drive-testing conclusions.
- Future product and marketing plans.
- Reflections on working with the ESA NAVISP funding and collaboration system.

Helix Geospace: History and Present

- Helix Technologies Ltd was founded in January 2017 as a startup operating within the ESA BIC (business incubation centre) in Harwell, United Kingdom.
- Helix Technologies Proposed the present NEXTGEN GNSS antenna project and the project commenced with an initial project start meeting that was held at ESA Noordwijk on the 17th January 2018.
- Construction of a pilot-plant within the Harwell leased facilities enabled the laser-lithography chemical processes review and identified the need for an additional toolpath generator software tool as required to meet accuracy requirements.
- Further accuracy improvements were required: additional metrology was included in the laser-imaging machine and an independent metrology booth to validate pattern print accuracies were implemented and project extensions. Both of these tools register to dielectric substrate three-dimension physical form using precision drives and vision systems.
- Final sample parts for validation were produced as input to the London validation drive-test trial that took place in September 2022.
- Today using the manufacturing processes and technology Helix Geospace employs 28 people making a portfolio of dielectric-loaded multi-filar helix antennas for GNSS and satellite communications terminals.

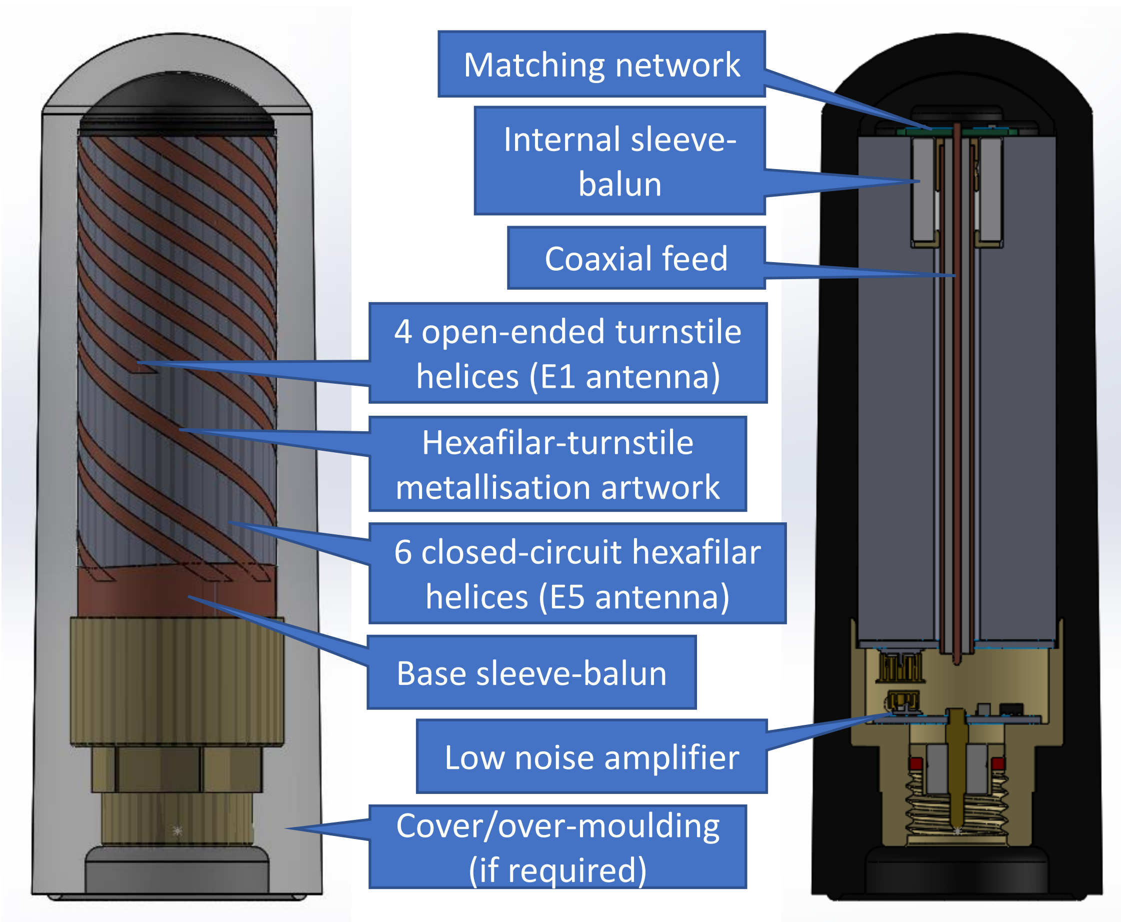
Antenna Technologies Existing at the Beginning of the Project: Multi-band GNSS.





- The Helix Geospace proposal correctly speculated that the movement towards autonomous vehicles (safety critical) will stimulate a trend towards multi-band GNSS and a demand for multi-band GNSS antennas.
- uBlox launches their F9 multi-band GNSS platform in 2018: the first mass-market multi-band chipset.
- At the beginning of the project there were two available classes of multi-frequency antennas:
  - Stacked-patch antenna: poor pattern performance, no independence from ground.
  - Air-loaded multifilar helix antennas: complex feed, large side and vulnerable to static electricity damage.
- At the commencement of the project it was speculated that the primary technology advance would be concerned with improvement of co-to-cross polarisation discrimination and consequential improvement in position accuracy in multipath environments.
- The NEXTGEN GNSS antenna was proposed as an electrically small (all dimensions being less than 0.07 times the carrier wavelength) which can provide sufficient gain times bandwidth to provide excellent positioning accuracy using the Galileo wide-band services.

Structure of the ESA NAVISP NEXTGEN GNSS

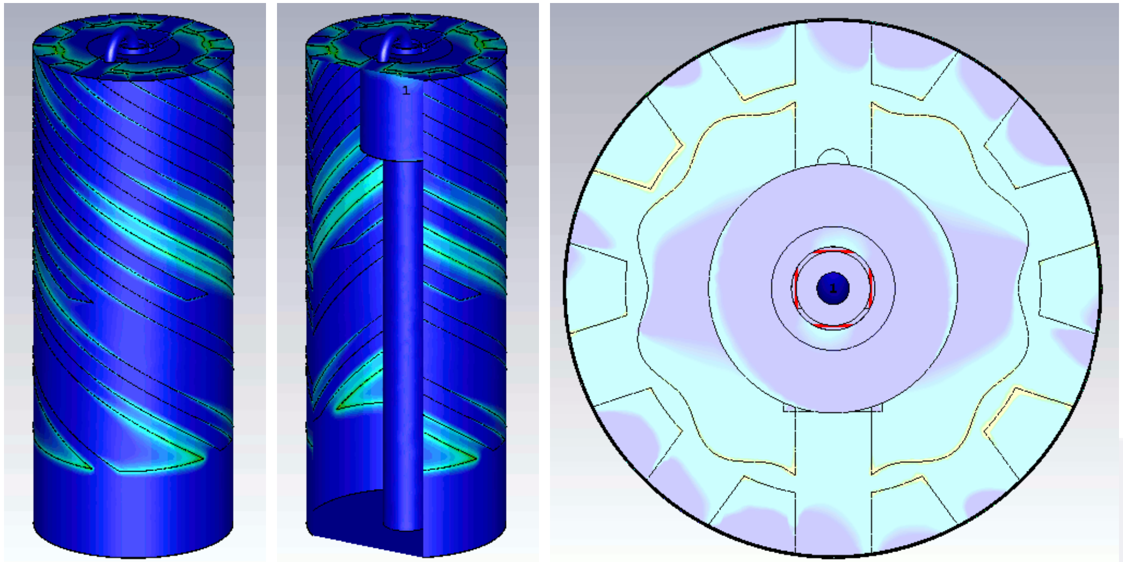


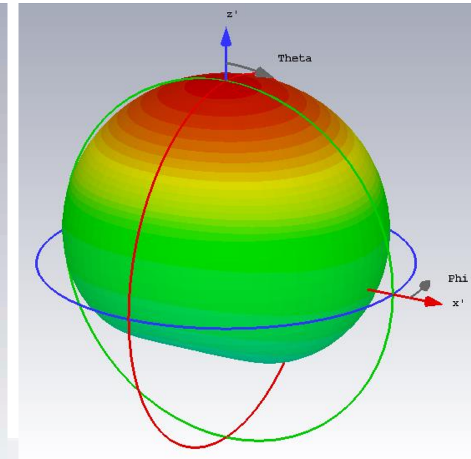
- Dual-band Galileo E1 and E5.
- Designed for high isolation from chassis-ground: feed-path contains two sleeve-balun (traps).
- Dielectric loaded for small electrical size and sharp focus (phase centre).
- Designed to provide the best gain bandwidth at Galileo E5 (to enable the GNSS receiver to take full advantage of the E5a+E5b AltBOC bandwidth).
- Hexafilar-turnstile architecture designed to provide high gain and efficiency at both GNSS frequencies (that are not harmonically related).
- This version is fitted with a low-noise amplifier and the over-moulding is designed to provide a water-seal.

Manufacturing Challenges

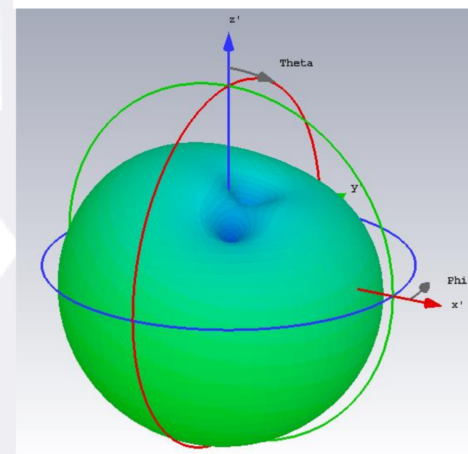
- Electrically small antennas can be separated into two classes:
  - Antennas which resonate with the device platform. These are not really small antennas because the radiating aperture encompasses the device chassis which is often/usually a large structure (in comparison with free-space carrier wavelength). Because radiating volume is large these parts have high gain and bandwidth and do not need to be accurately made.
  - Antennas which resonate independently of the device platform. These can only have high gain over a narrow bandwidth and therefore must be made accurately. The NEXTGEN GNSS antenna is a member of this class.
- The NEXTGEN GNSS antenna is such a small radiator that it must be made very accurately: otherwise manufacturing errors that are within achievable manufacturing process tolerances will cause the antenna to resonate out of the required GNSS signal band.
- As part of the NEXTGEN GNSS antenna project Helix Geospace developed a precise manufacturing process comprising of bespoke laser-lithography and metrology tools. The software tools that are necessary to manage image and to evaluate electrical performance were built as contract change note extensions to the original project as proposed.
- The NEXTGEN GNSS antenna is made using a process that adapts to measured dielectric properties of the specific dielectric core substrate that is patterned. This enables the manufacture of antennas to a tighter tolerance specification than would be possible using a build-to-drawing method.

Surface H-field at 1.17645GHz (Top Artwork From Top Underside) and Circular Polarisation Patterns





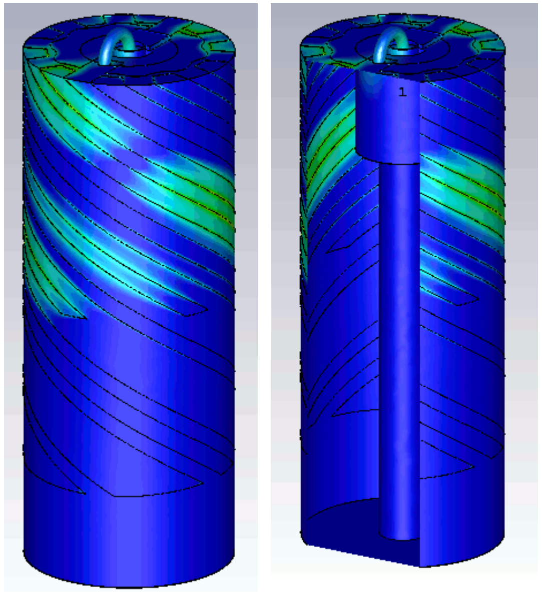
Right-Hand Circular Polarised gain pattern

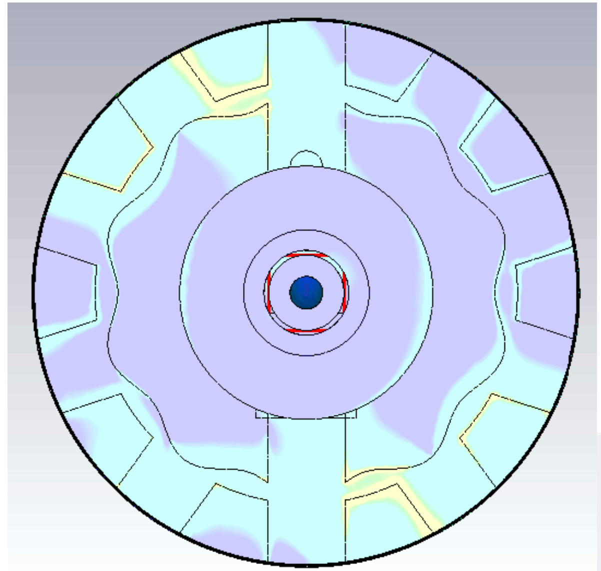


Left-Hand Circular Polarised gain pattern

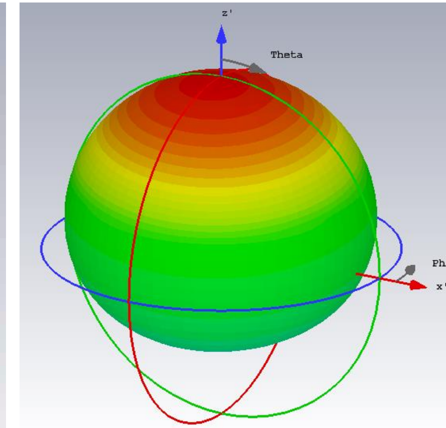
- Full-wave hexafilar-mode resonance: at Galileo E5a centre-frequency.
- Seeking to provide highest possible gain-bandwidth product at Galileo E5 frequency band: providing optimum navigation performance at the E5a+E5a AltBOC band.
- Predicts high co-to-cross polarisation discrimination above horizon.

Surface H-field at 1.575GHz (Top Artwork From Top Underside) and Circular Polarisation Patterns

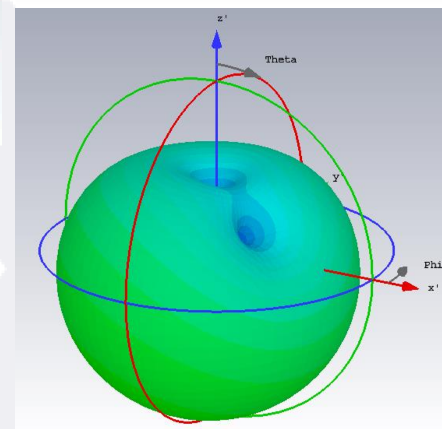




3λ/4 turnstile-mode resonance: at Galileo E1 centre-frequency.
Predicts high co-to-cross polarisation discrimination above horizon.

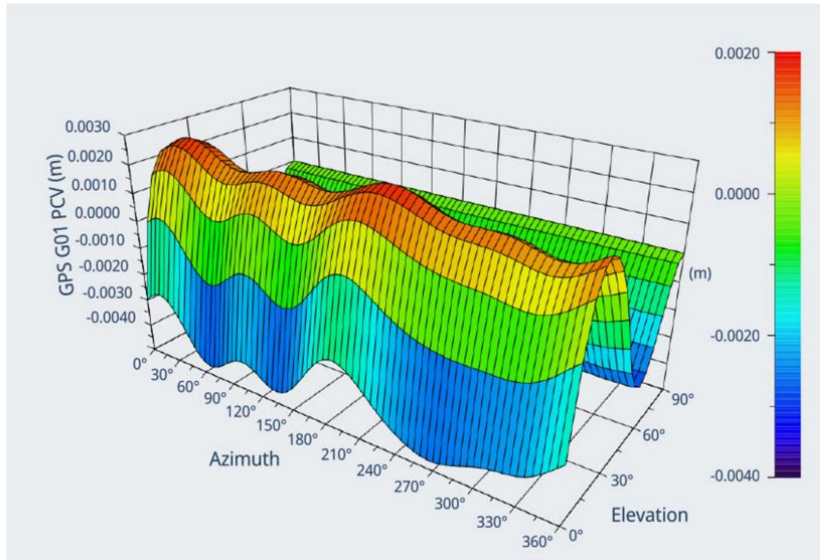


Right-Hand Circular Polarised gain pattern



Left-Hand Circular Polarised gain pattern

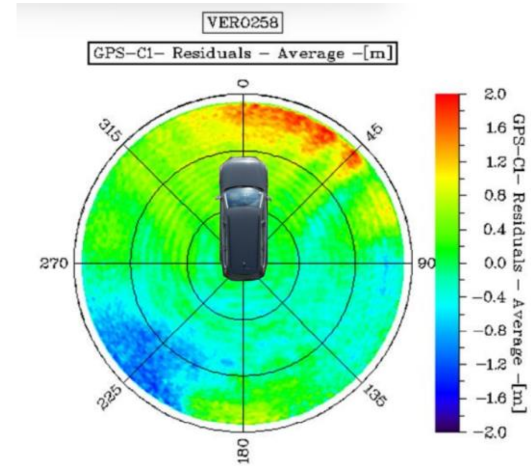
Performance of a Survey-Grade Antenna (Tripod Mounting)



Survey-grade antennas can be calibrated using a robot which moves the pointing direction of the antenna about the phase centre point. Any deviations of measurement range caused by attitude must be due to antenna phase-centre variations and these errors (recorded for all directions of arrival) can be subtracted from measurements.

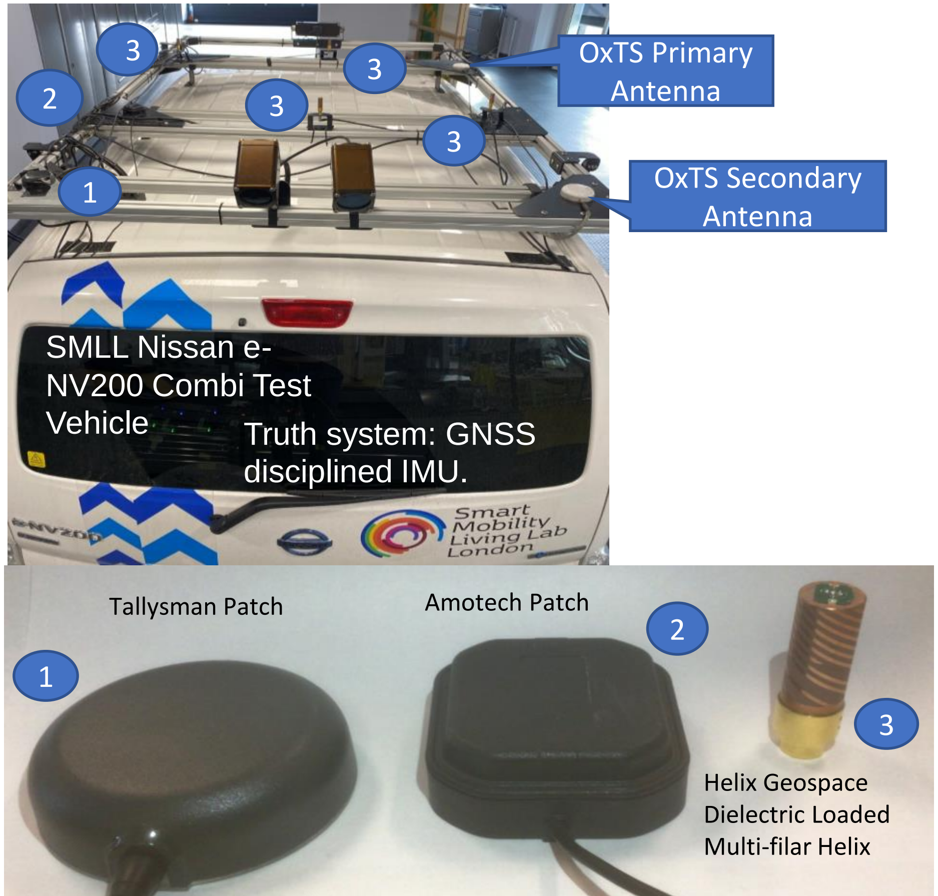
- Jannes B. Wübbena, A. N. (2022). GNSS Antenna Calibration for Cars – Challenges and Prospects. *ION GNSS+ 2022 (Conference Proceedings) 21st-23rd September*.

Range-error Calibration of a Patch Antenna on a Car Show That the Measurement Ambiguities Are as Big as the Car



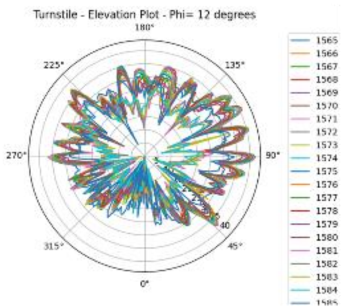
- A German company called Geo++ has published papers showing the corresponding measurement range ambiguity of a patch antenna installed in a shark's fin package when it is installed on a VW Passat car.
- Geo++'s apparatus shows that the position ambiguity of a patch mounted on a car is of the order of ±2 metres. Unsurprisingly this error is as big as the car. The experiment proves the conclusion that the radiating system of the **patch antenna on the car: is the car**!

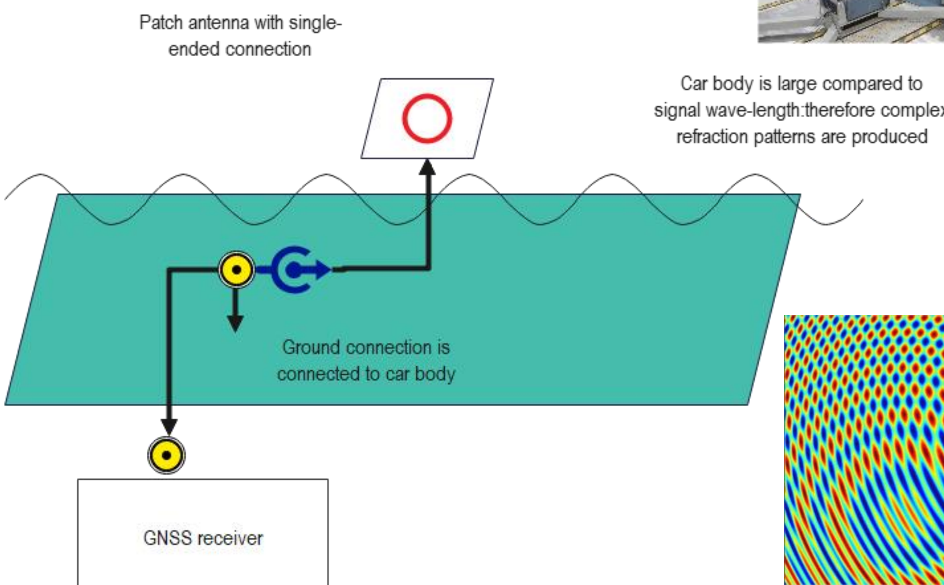
London Drive-Test Using Test Antennas on SMLL Test Vehicle.

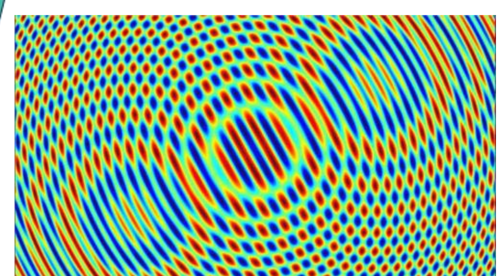


- Helix Geospace has proven that the use of a dielectric-loaded hexafilar-turntile antenna can solve this range-ambiguity problem at a cost and size that is much less than for a conventional survey-grade antenna.
- One test was carried out using the Smart Mobility Living-lab London test vehicle which allowed us to test two forms of stacked-patch multi-frequency GNSS antenna against the Helix Geospace hexafilar-turnstile format of antenna.
- This vehicle was driven round a set of challenging test-circuits in London. The measurements were evaluated against a measurement truth system that is manufactured by OxTS. This truth system is a high-quality vehicle tracker unit: a two-antenna GNSS disciplined inertial measurement unit (IMU).

Patch Antenna Interacting With the Metal Surface of the Vehicle.

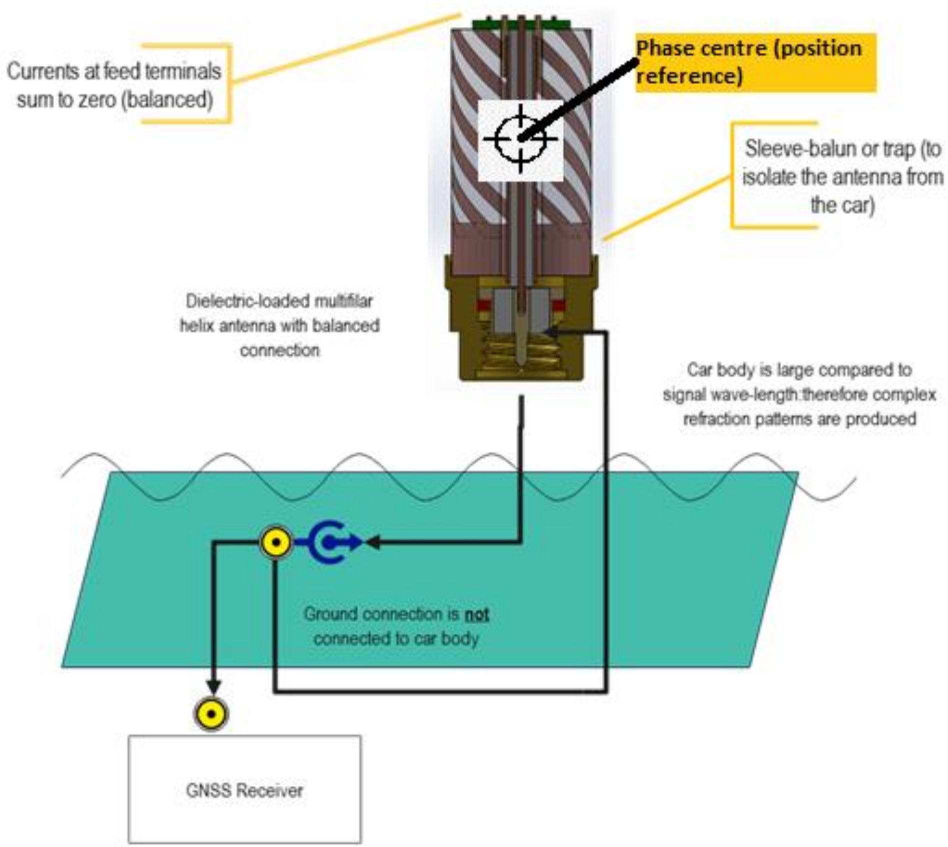






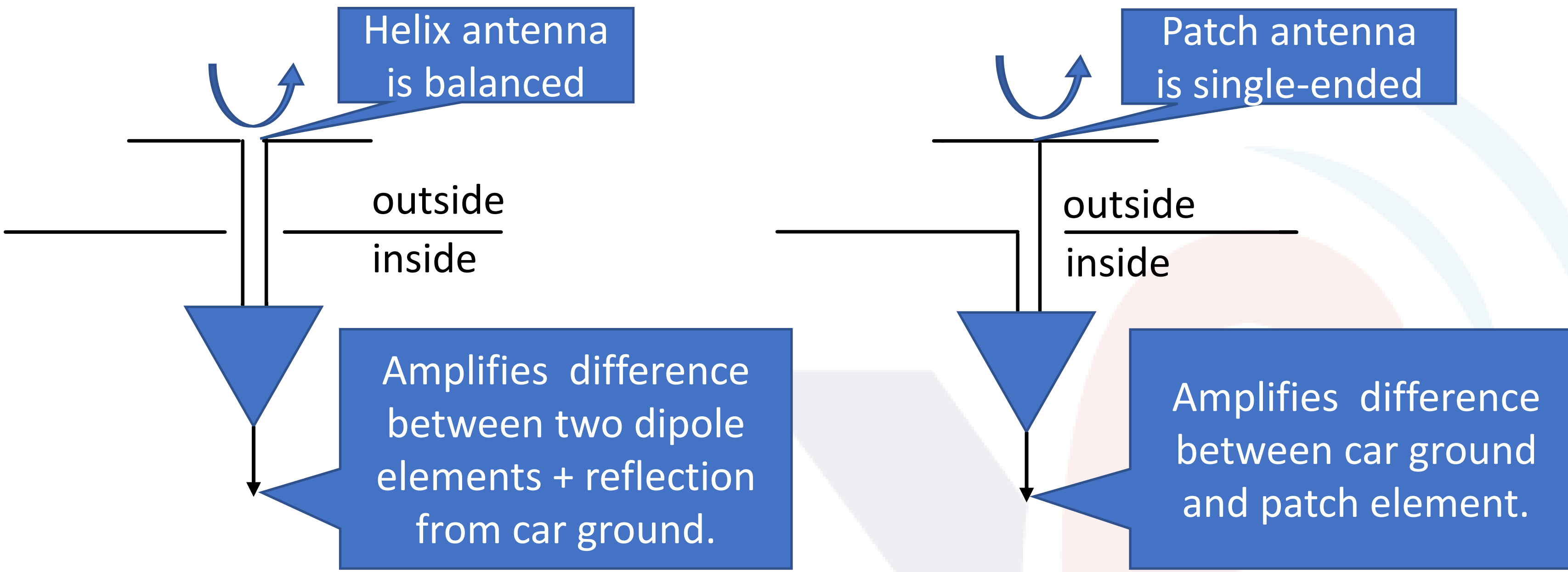
- A patch antenna mounted onto the SMLL test vehicle was tested in a large anechoic facility at Horiba Mira's facility near Nuneaton, England.
- These measurements demonstrate how the pattern response of the antenna is determined primarily by the large vehicle collecting surface which cause the pattern to have many peaks and nulls.
- In urban environments the propagation of signals is complex due to multipath. Interaction with a complex antenna pattern makes the signal processing unwieldy.

More Accurate Position When Antenna is Isolated from The Car



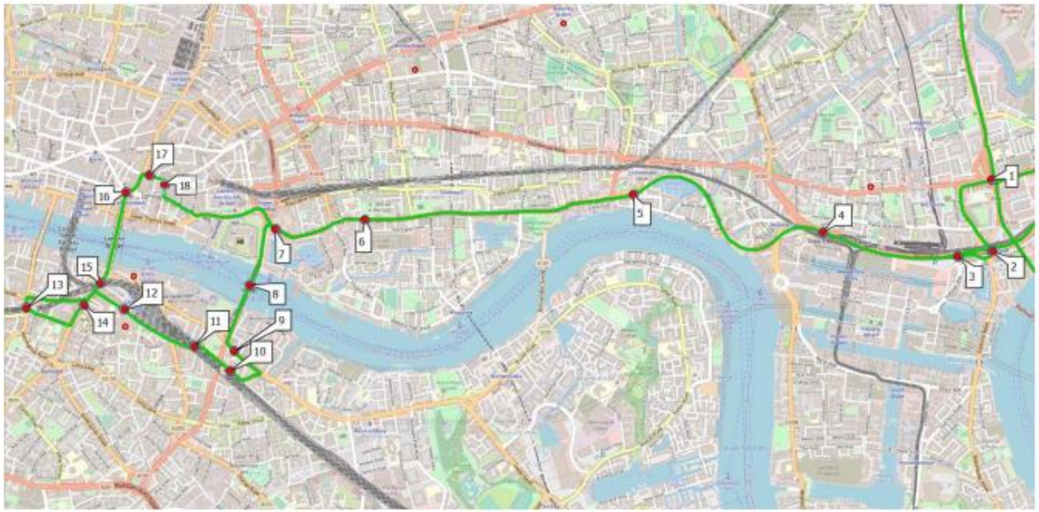
- Signal processing is greatly simplified when the antenna is designed to be isolated from the skin of the vehicle.
- This can be provided if the antenna is balance-fed so that the antenna currents at the two terminals to the radiating artwork sum to zero.
- If this is done it is certain that the phase-centre or focal-point lies between in the core of the antenna (ideally on it’s axis).
- The antenna can be receiving signals that are re-radiated from the car-body and these can combine constructively and destructively with the signals arriving directly from the satellites: the antenna pattern may have peaks and nulls. However the phase-centre can only be in the antenna core.
- A comprehensive solution must ensure that the combination of interfering waves can never be destructive. This can be done by shaping the ground-plane near to the antenna to emphasise constructive interference and placing an absorptive dam concentrically beyond that to attenuate reflections which could be destructive. This physical system need not be large because reflections rapidly become less intense with radial distance.

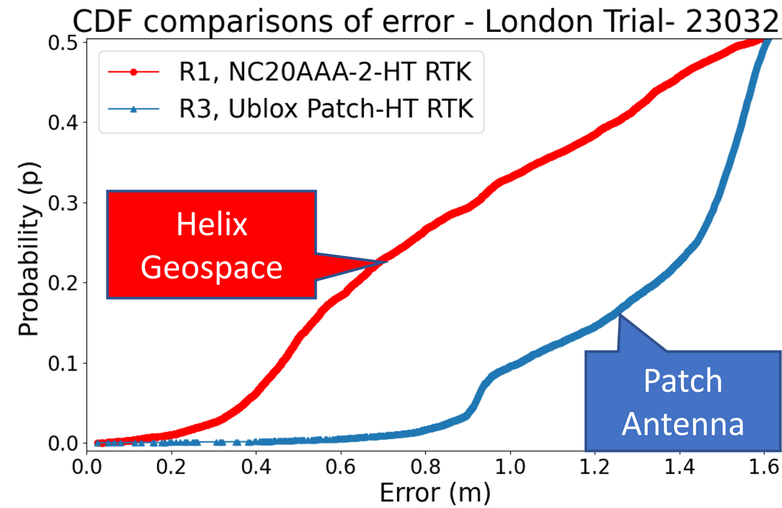
Calming the Installed Pattern: We want to try this.



- Complex pattern (antenna installed on a car) is a problem for high reliability navigation.
- The effect of reflections from the car body can be reduced using an area of sheet absorber material near the antenna. This can reduce the installed pattern ripple when the antenna is balanced like the Helix Geospace one.
- The single-ended (patch) cannot be isolated from the ground. Therefore the pattern ripple cannot be reduced.

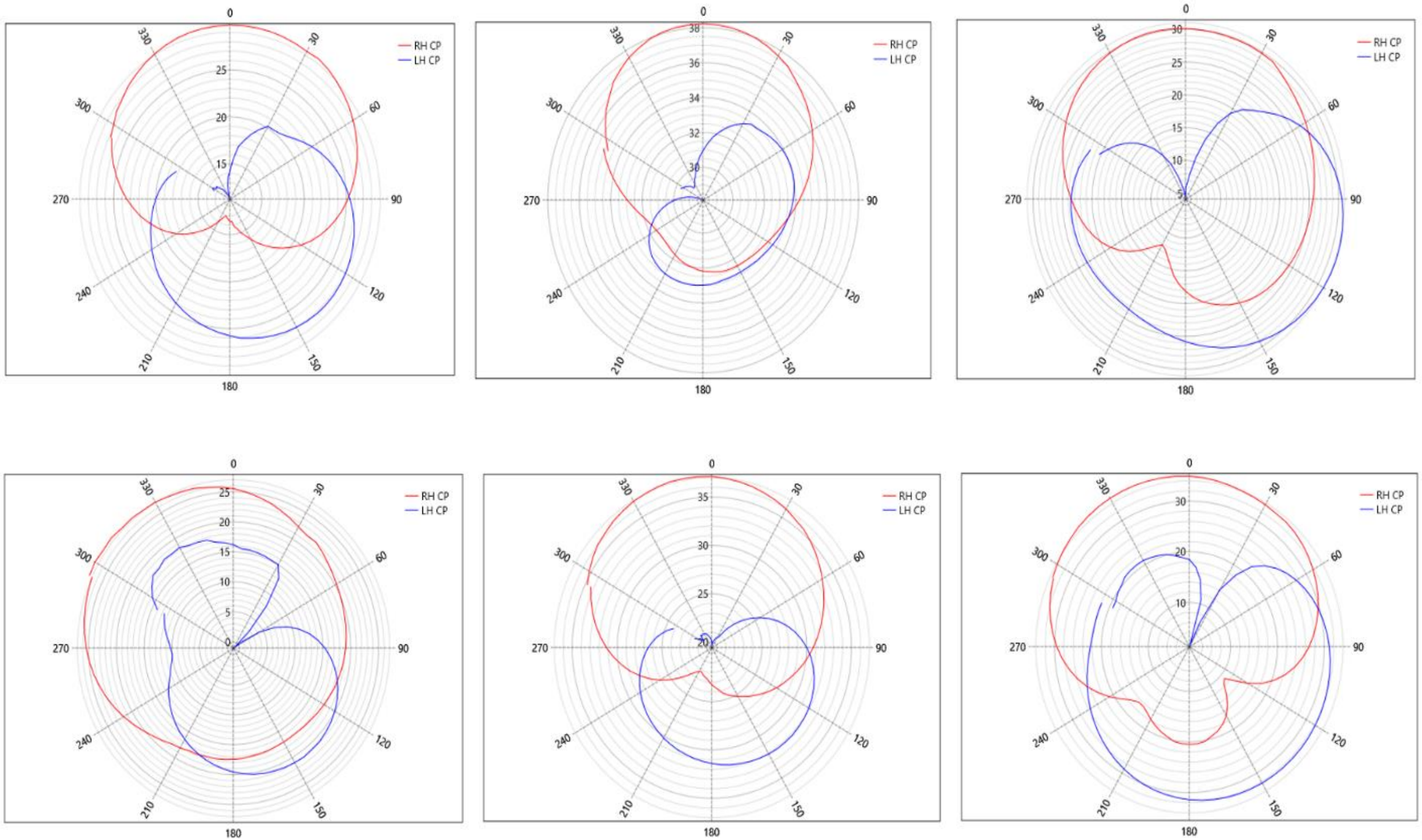
The Balanced Hexafilar Turnstile Antenna Demonstrates a Higher Probability of Small Errors.





- The poorer close-in accuracy of the patch antenna is known to be caused by GNSS measurement range ambiguities that are present when the single-ended antenna is installed on a car (Geo++ results shown previously).
- This result was compiled from a long test-drive in London. It is significant because there are of the order of a million data-points in this data-set.

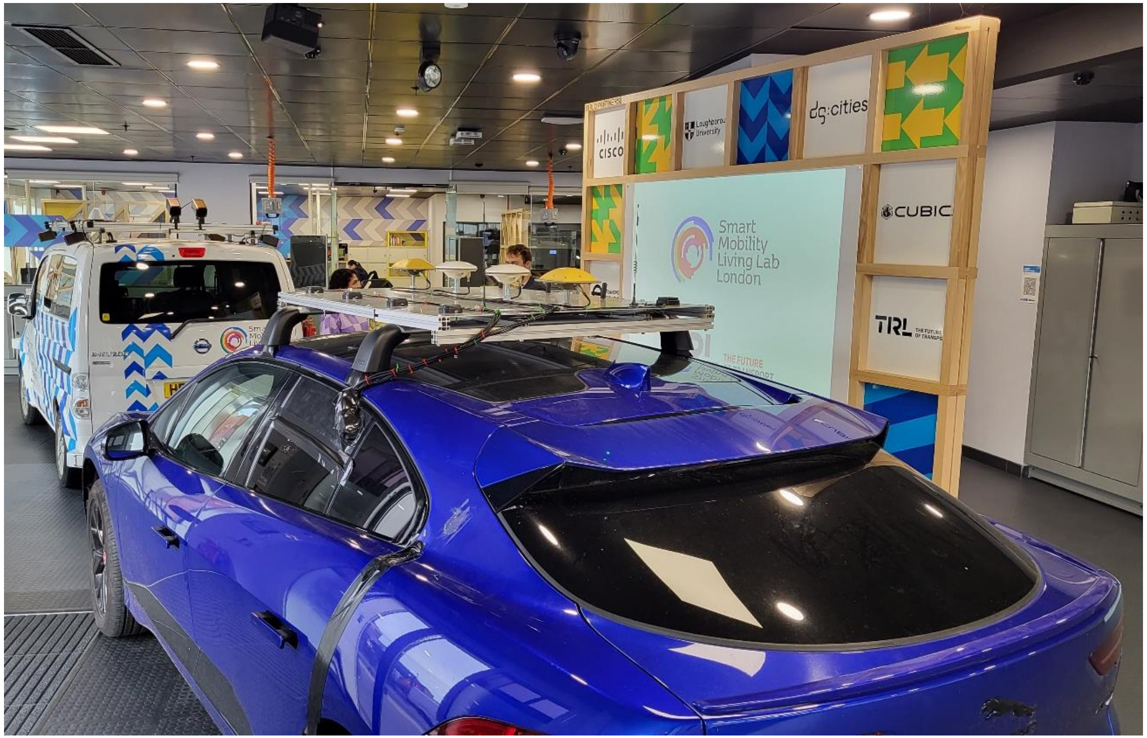
RH Circular-polarisation Performance of the Galileo E5a+E5b and E1 Antennas Used in the Drive-Test Trial



- Patterns are shown for E5a (left) E5b (middle) and E1 (right) centre-frequencies.
- Antenna above was used in “primary” antenna position and antenna below in “secondary” position.

Testing with The Vodafone Jaguar i-Pace Test-Car

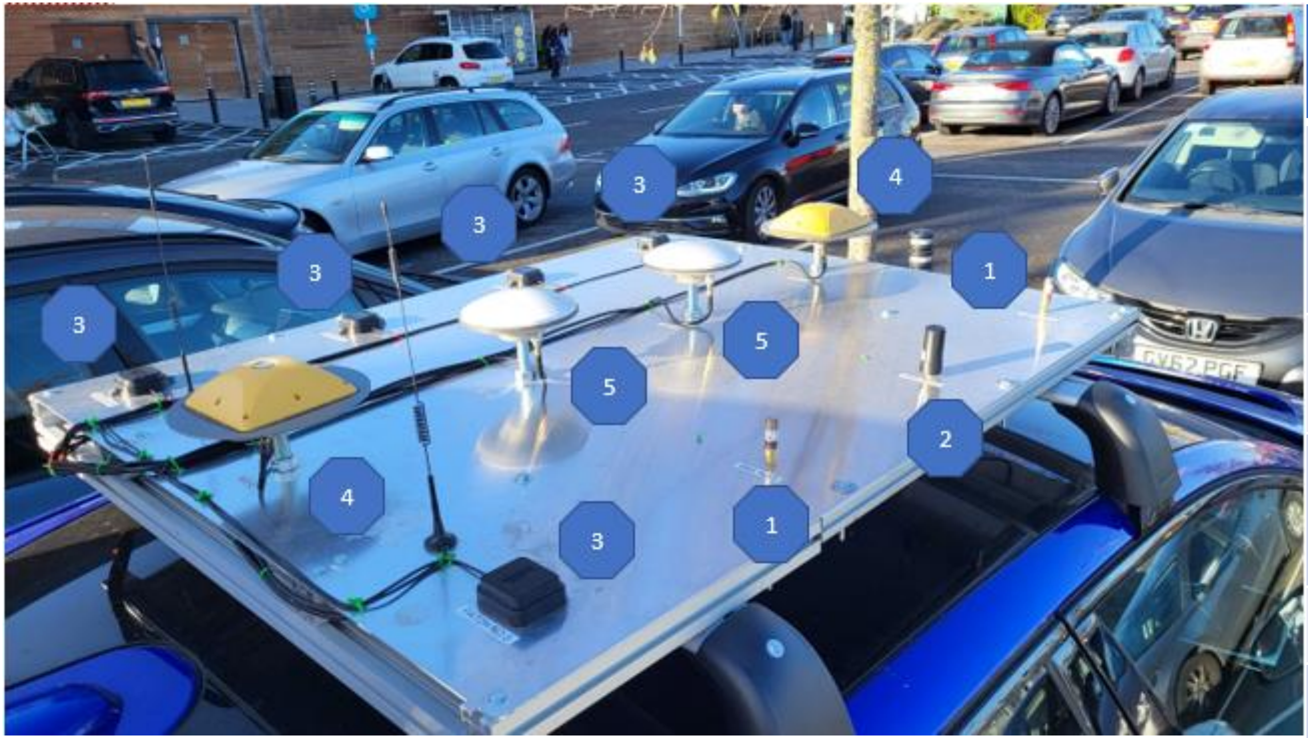
helix GEOSPACE



Helix Geospace wishes to acknowledge and express gratitude for the kind assistance given to the project by Vodafone. Vodafone's Edmund Wontner drove the vehicle and provided a huge amount of technical support.

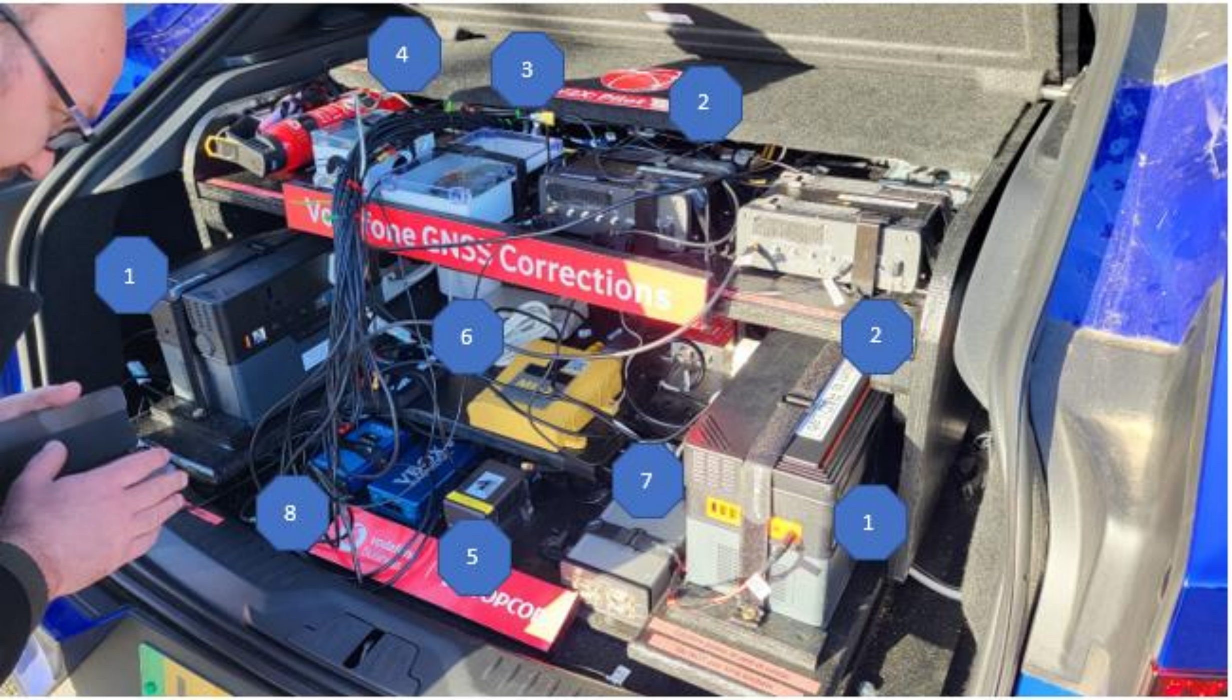
- The photograph shows the (blue) Vodafone car in the SMLL test facility in Woolwich.
- The antenna-farm ground-plane on the roof-rack of the car has positions for 12 GNSS antennas. In this configuration there are two-formats of survey quality antennas which can be used to provide the truth-system with the highest possible accuracy.
- To provide continuity with Helix Geospace's prior test-experience the testing followed the same urban test circuits as have been used in previous trials.
- The trial-car was driven by Vodafone personnel. Helix Geospace personnel assisted with the trial set-up but all GNSS equipment belonged to Vodafone (apart from the Septentrio AsterRx-i3 DPro+ unit.

Vodafone Jaguar i-Pace Test Car Antenna Farm



Type	Manufacturer	Format
1	Helix Geospace	Dielectric-loaded multifilar-helix E1/E5a+E5b with integrated balun/trap.
2	Beitian BT-560	Single-ended multi-filar helix antenna.
3	Amotech (uBlox evaluation kit)	stacked patch (two frequency bands)
4	TopCon FG-F1	Survey-grade antenna
5	Harxon GP1000	Survey grade patch antenna

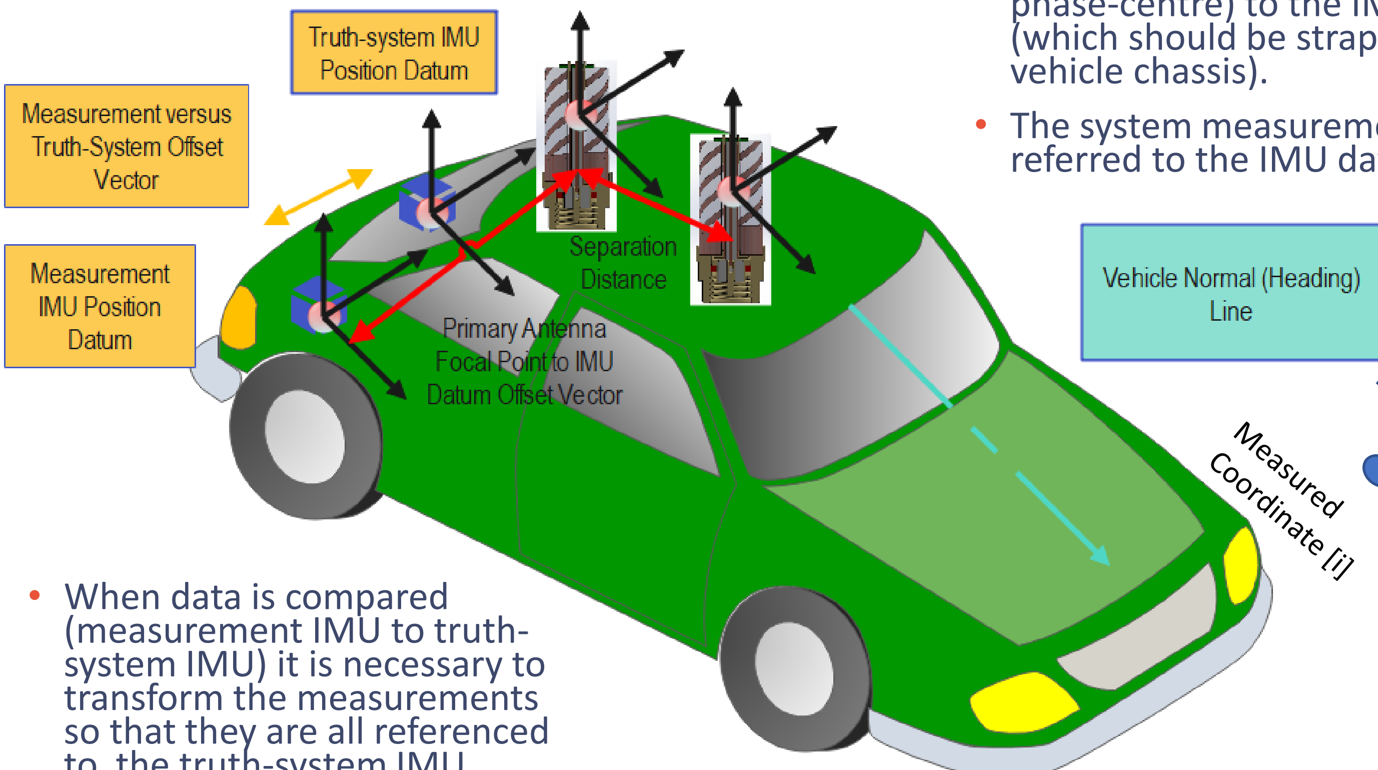
GNSS Systems Under Test.



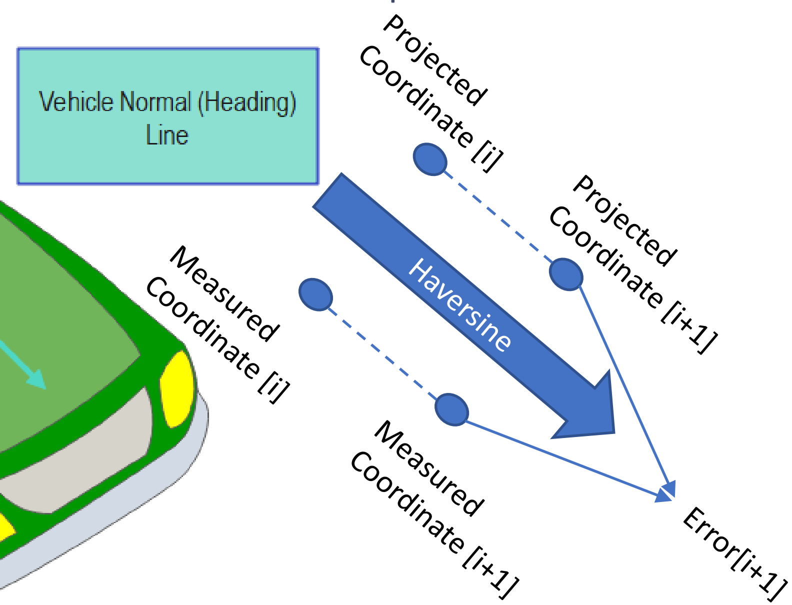
Equip	Manufact	Type / Format
1	X2	Equipment battery: multi-point mains inverter
2	SwiftNav	With integral IMU+RTCM corrections.
3	Quectel LG69T	Receiving RTCM corrections.
4	Ericsson uBlox	RTCM correction stream to 3GPP NLG standard.
5	Hexagon CPT7	Truth system with IMU: two HarxonGP1000 survey-grade antennas. RTCM corrections.
6	Topcon MR2	High-end multi-band receiver. RTCM corrections.
7	Septentrio AsterRx-i3 DPro+	This receiver was used with the NextGEN E1/E5a+E5b test antennas. Includes IMU + RTCM stream.
8	Racelogic VBOX + wheel-tick input.	This receiver can be integrated with IMU and RTCM corrections.

Measurement Datums and Vector Translations

- For a two-antenna system the antennas should be placed on or parallel to the vehicle normal line.

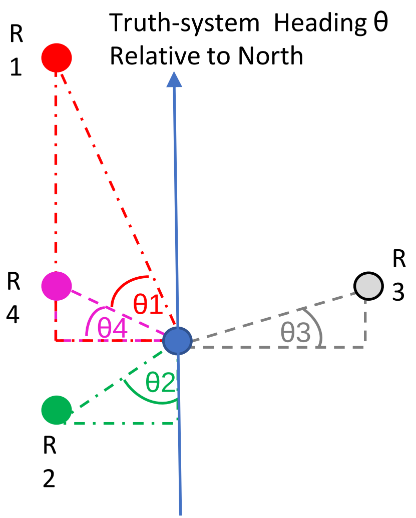


- When an IMU is used in the positioning system it must be set-up to project the GNSS measurements (referenced to the antenna phase-centre) to the IMU datum position (which should be strapped down to the vehicle chassis).
- The system measurements are then properly referred to the IMU datum point.



- When data is compared (measurement IMU to truth-system IMU) it is necessary to transform the measurements so that they are all referenced to the truth-system IMU datum.

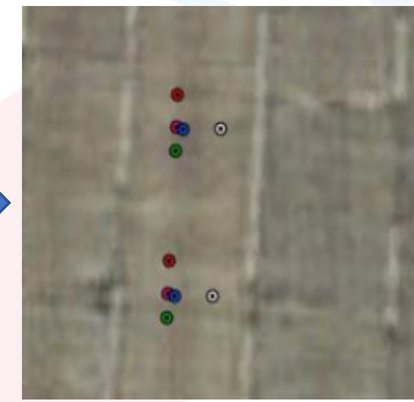
Software : Calculating expected position



Known Physical positions on vehicle

```
Import math
RE = 6371000  #Radius of Earth (meters)
For Each Time Frame [i]:
{
   For Each Rover [n]:
   {
       VOffset = cos(θ_OXTS + θ_[n]) * Resultant_[n]
       HOffset = sin(θ_OXTS + θ_[n]) * Resultant_[n]

       LatVector = VOffset / RE
       LonVector = HOffset / (RE * cos(pi * oxtsLat / 180))

       LatProjected[n] = (oxtsLat + LatVector*180/pi)
       LonProjected [n]= (oxtsLon +  LonVector*180/pi)

       Error [n]= Haversine(LatProjected[n],
LonProjected[n],                LatMeasured,[n]
LonMeasured[n])

   }
}
```

Adding truth-system heading to antenna position on vehicle and extrapolating co-ordinates

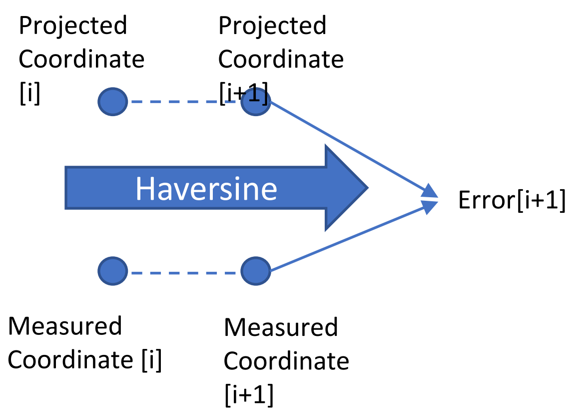


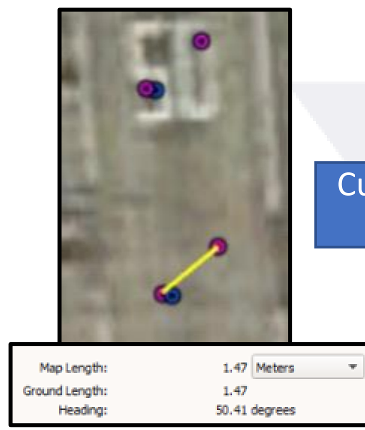
Project New Time-Varying Coordinates

Outputs (Overview)

GOAL: Interested in assessing the performance-quality of various hardware setups on various routes. This can be done by calculating **error** between **measured** and **projected** coordinates for each time frame for each rover. Calculating distance between 2 Latitude and Longitude coordinates can be done with a Harversine Formula which outputs a Great Circle Distance between coordinates on the surface of the Earth.

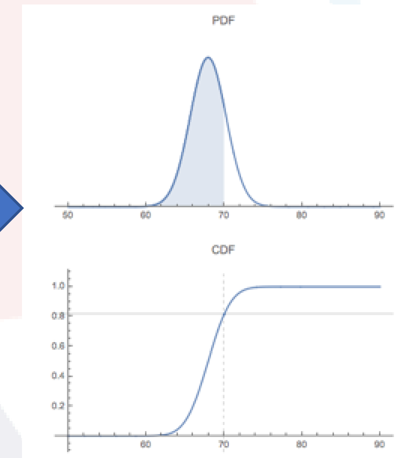
Error Distance = Haversine_Formula (Projected Coordinate – Measured Coordinate)



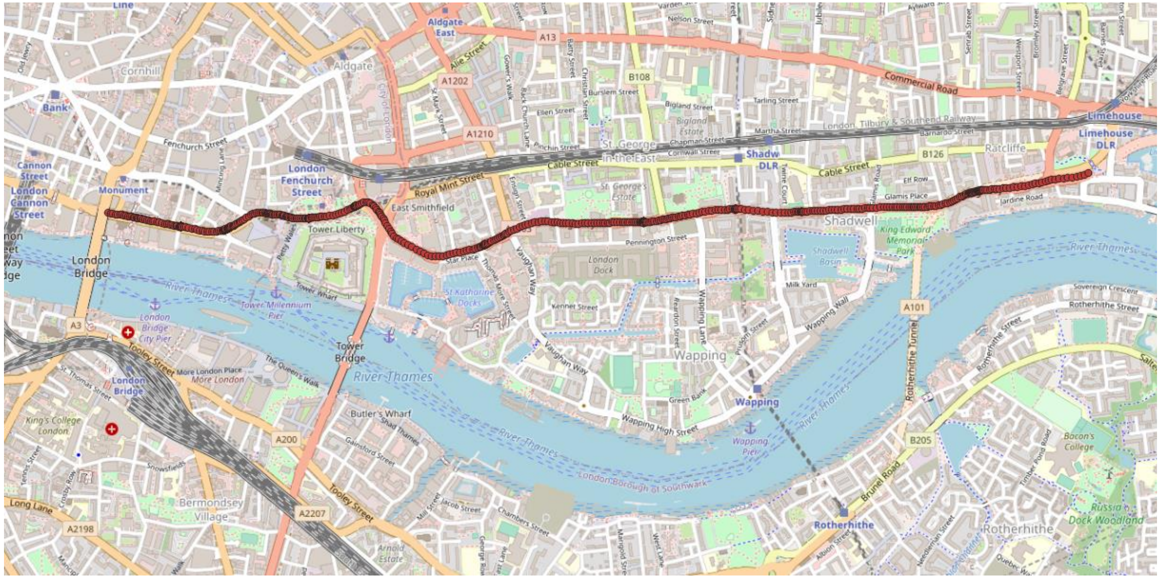


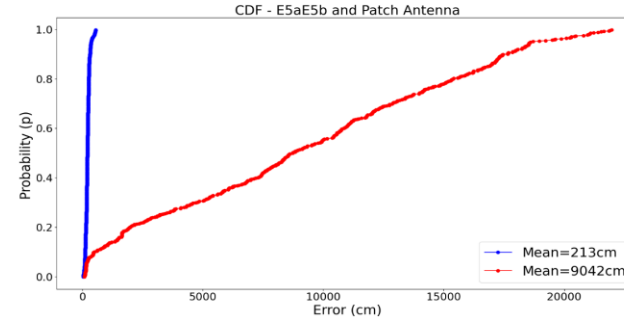
All Error results

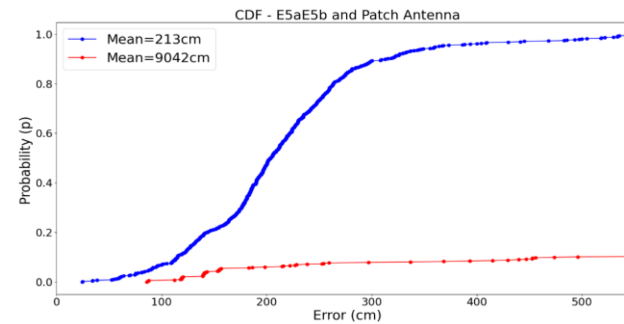
Cumulative Distribution Function



Urban Drive-Testing Results

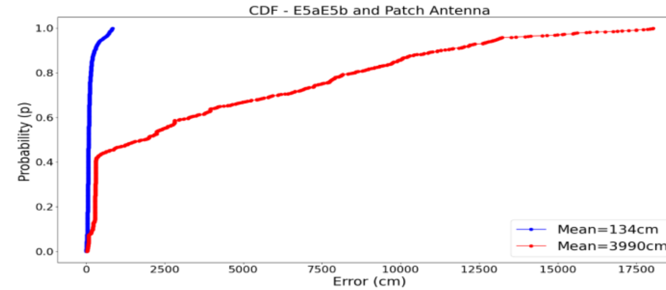


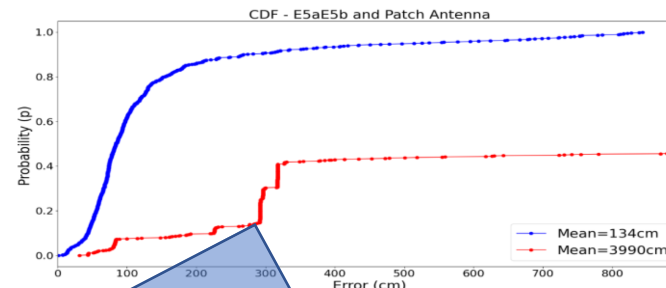




- This route passes large buildings and the Tower of London.
- The CDF response for the Septentrio AsterRx-i3 DPro+ operating with two NextGen ESA E1/E5a+E5b antennas (blue graph) shows relatively low errors (mean error =2.13 metres).
- The CDF response for the uBlox C100 operating with an Amotech stacked patch antenna (red graph) shows large errors (mean error = 90.42 metres).
- Clear advantage in favour of broad-band system (E5A+E5b versus C/A).

Urban Drive-Testing Results: 5 Changes of Direction





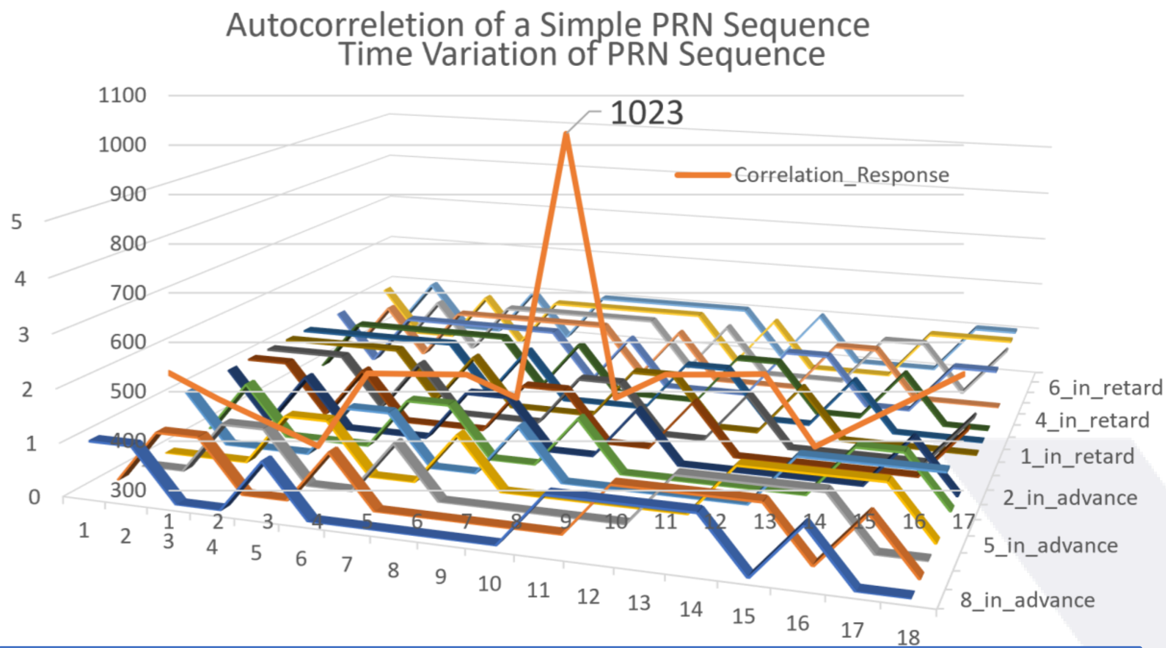
- This route passes the Shard (Britain's tallest building) and London Bridge railway station.
- The CDF of the narrow-band GNSS signals (red-curve) demonstrates much greater effect of large range-errors that are caused by multipath.
- The close-in errors portion of the CDF relating to the patch antenna (red-curve) has step inflections which are assumed to be related to 5 different orientations of the vehicle.

Steps could be due to range-measurement error differences due to antenna interaction with the car skin. Alternatively this may indicate that the offset from antenna to truth-system datum is set incorrectly and the error changes with different orientation with respect to geodetic-north heading.

A Typical Urban Scene With Re-radiation from Horizontal and Vertical Edges: the E5a+E5b Perspective

- E5a+E5b range errors due to multi-path are restricted to the time-interval of the E5a+E5b PRN autocorrelation.
- This region is a sphere of radius approximately 6 metres.
- Everything in relative movement.
- Many antennas/ signal sources and many reflections - constantly changing patterns of multi-path interference at receiving antennas.
- Reflections: “re-radiation” mainly from metal edges. Re-radiation maxima transverse to the directions of re-radiating edges.
- Polarisation of the re-radiated waves are sympathetic to the direction of the re-radiating edges.
- Horizontally and vertically polarised waves generally combine to form spinning waves.

Time/Distance Interval of the Code Correlation



> The primary effect of the higher code-bandwidth of the GNSS signal is that it can be used to bound the time-variation of delay reflections that can be included in a code-correlation window that is fixed in time by the first-to-arrive signal. Naturally these signals only have low noise if they have not been impacted by reflection delays that occur outside of this window.

- Consider a simple pseudo-random noise sequence of 1023 bits and sent 1.023MHz.
- This bit has a period of just less than 1μs and given that the speed of light is approx. $3x10^8$m/s an equivalent distance of approx. 293metres.
- This means that large multi-path reflections can be arrive within the bit period. Narrow correlator processing can be employed to estimate to peak of the first-to-arrive signal.
- Now consider a faster pseudo-random noise sequence of 10230 bits and sent at 10.23MHz.
- This bit has a period of just less than 0.1μs and an equivalent distance of approx. 29.3 metres.
- A correlator that is locked in time to receive the first-to-arrive signal will not see signals which arrive 0.1μs or 29.3 metres equivalent distance later.
- E5a+E5b AltBOC has greater code bandwidth than this.
- In our measurements we saw approximately 7metres maximum multipath error for extreme urban canyon environments.

Path to Market

datasheet *preliminary*
GPS L1/L5 Antenna

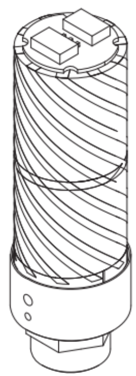
HXGL L1/L5 Antenna

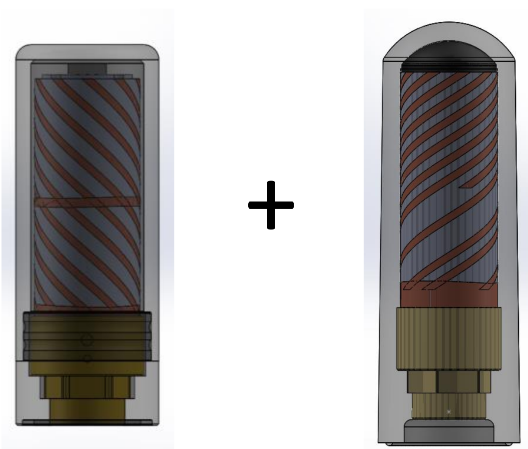
The Helix Geospace GPS L1/L5 Antenna is a dielectric loaded decafilar helix, which uses patented Dielectrix™ antenna technology to provide the highest available efficiency per unit of size/volume.

These antennas have excellent co-to-cross polarisation and therefore provide useful discrimination of multi-path (reflected polarisation-reversed) signals. They are balanced and isolated from platform ground, ensuring high immunity to common-mode noise and very low proximity de-tuning caused by nearby objects.

HDC Dielectrix antennas deliver predictable installed performance that belies the small size, due to operation of the dielectric-core material (patent-protected).

The product will be available encapsulated with an over-moulded protective radome, or unencapsulated as appropriate for direct integration into devices.





- From field-trials Helix Geospace has demonstrated that the wide-band E5a+E5b signal provides much higher positioning accuracy within the cityscape. It is likely that Galileo will become preferred over GPS and the E5/L5 signal will become the preferred cluster of GNSS signals.
- Helix Geospace is therefore determined to manufacture and sell E5/L1 multiband antennas that provide this solution.
- Production trials to make high quality hexafilar-turnstile parts have provided data that indicate that the hexafilar-turnstile artwork cannot, without further development, be reproduced at commercial yields.
- Therefore Helix Geospace is developing the market with a stacked decafilar product. The attached datasheet is being released to prospective customers and sample parts are being produced for customer evaluation.
- The hexafilar turnstile antenna is being refined further and is expected to uplift performance at E5. Helix Geospace is actively developing products for a market that is expected to develop quickly as the mature Galileo constellation demonstrates accuracy advantages to the market. This is expected to accelerate as the Galileo Has correction signal is to start being transmitted from the spacecraft.

Overall Project Conclusions

- This ESA NAVISP-EL2-013 "NEXTGEN GNSS ANTENNA" project has enabled the design, development and means of manufacture of an antenna which has the bandwidth in a small size to operate effectively with the Galileo wide-band GNSS signals such as E5a+E5b.
- The NextGen GNSS dielectric-loaded antenna has a phase centre that is independent of the vehicle and therefore the measurement range-ambiguities are minimized by the sharp antenna focus. Therefore the NextGen GNSS antenna can provide the 10 cm (2σ) accuracy that is required by the SAE but that the accuracy that is provided by an alternative single-ended antenna may be limited to the metre dimensions of the vehicle skin's radiation aperture.
- The NextGen GNSS antenna high cross-polar polarisation discrimination in the Galileo E5a+E5b and E1 bands of operation so that the reflections from cityscape objects causing polarisation reversal can be rejected. This is important because the sense of circular polarisation is reversed from right-hand to left-hand by the action of a planar reflector such as a steel and reflective glass constructed modern building surface.
- The NextGen GNSS antenna has been designed to optimise the bandwidth within a small antenna size envelope: breaking with the conventional wisdom that the performance of a GNSS antenna (in terms of gain/efficiency bandwidth) is enhanced by resonating with a ground-plane. In fact, the parameters that are more important for accurate navigation are concerned with sharp focus (low range-ambiguities) and high co-to-cross polarisation (high rejection of multi-path affected signals).
- The manufacture of small antennas providing wide-band GNSS operation relies on the implementation of an optimised matched-filter frequency-response and the accuracy of manufacture. There is no excess of bandwidth to accommodate manufacturing tolerances.
- The project has enabled the development of high-accuracy laser-lithography methods to facilitate manufacturing to higher performance than would be possible following nominal drawing dimensions. Some of these methods were not part of the original project proposal and were facilitated using project extension implemented through Contract Change Notices. Methods were developed for implementing and validating vision system-based methods for correcting imaging toolpath movements to measured part precession or runout present on a workpiece that is held in the chuck of the laser-imaging machine.
- These techniques are necessary for manufacturing these antenna products with a commercial yield and have been adopted in the GNSS manufacturing processes at Helix Geospace.

ESA NAVISP NEXTGEN ANTENNA: OVERALL REFLECTIONS

- It has been a very great privilege and also very rewarding to have worked with the ESA team on this exciting project.
- The scope of this project was very large: encompassing the creation of a new technology and a high-accuracy manufacturing process to make it. Additionally, the project some significant difficulties that were not anticipated arose and solutions needed to be made to overcome them. The ESA NAVISP demonstrated that it provides a funding mechanism that can support a project of this high scope.
- This ESA NAVISP funded project has enabled Helix Geospace to establish a technology and an application engineering insight that is world-leading in the sectors that it excels in. The funding system has the scale and flexibility to incubate complex new technology. For Helix Geospace this project has facilitated the commercial start-up of a new technology business that undertakes high-precision 3D metallization patterning using bespoke plant.
- Working with ESA also helps to nurture very high standards of attainment. The ESA NAVISP project supervision process is founded on the formal contractual approach which built the highly accomplished institution that ESA is today. At Helix Geospace we found that the respect we have for the traditions and attainments of ESA fueled the pride and ambition of our work.

- Helix Geospace is grateful for the steadfast support that the ESA team has provided supervising the project through a longer execution period than was expected. Thanks especially to ESA Technical Officer: Roberto Prieto Cerdeira who supervised this project throughout this extended time period despite being assigned to other projects within ESA.
- Helix Geospace also gratefully acknowledges the kind support of Vodafone (Edmund Wontner and Bob Banks) and also support from Smart Mobility Living-lab London SMLL (Oliver Howes).