Supercorrelation technical overview white paper

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About the paper

This paper assumes that the user is already familiar with basic functionality of a GNSS receiver. Good references to bring a user up to speed with receiver design before reading this white paper are Kaplan[1] or van Diggelen[2].

Introduction

Focal Point Positioning offers a portfolio of patented technology applicable to a wide variety of markets ranging from GNSS, Wi-Fi, cellular, satellite communications, and many others. This paper introduces and discusses the Supercorrelation technology implementation for GNSS receivers.

Supercorrelation boosts the performance of radio receivers

Supercorrelation is an additional software function 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 GNSS receiver is known as an S-GNSS™ receiver.

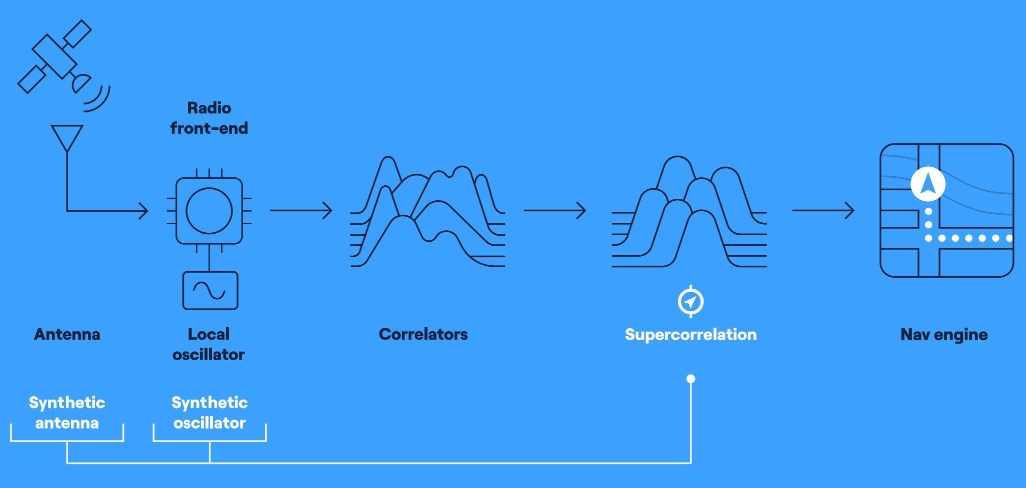

Figure 1 - An S-GNSS™ Receiver
Supercorrelation operates between the traditional GNSS correlators and the navigation engine. It effectively creates a high performance synthetic antenna and synthetic oscillator, processing data from the correlators, mitigating multipath by removing NLOS signals. The impact of these corrections is improved sensitivity and accuracy for observables such as pseudorange and Doppler measurements.

Supercorrelation benefits

Current generation GNSS receivers perform a small amount of coherent integration, typically less than 20 milliseconds, and then incoherently integrate further to boost sensitivity. The reasons for this are historical limitations of data modulation bits, crystal oscillator stability, and receiver motion during the integration period. FocalPoint's Supercorrelation technology overcomes these limitations to provide more than one second of coherent integration. It can do so even while undergoing complex motions and on low-cost hardware. The benefit is higher sensitivity coupled with unique multipath mitigation capabilities. This provides a high accuracy and high integrity solution for positioning in traditionally difficult environments. It also enables unique angle-of-arrival measurement capabilities only otherwise available from military-grade Controlled Radiation Pattern Antennas (CRPAs).

Multipath mitigation

The major problem with using incoherent integration instead of coherent integration is the increased susceptibility to multipath interference. Incoherent integration destroys the phase information stored within the captured data before combining it, resulting in line-of-sight (LOS) and non-line-of-sight (NLOS) signals accumulating within the same correlation peak, producing a distortion of the desired line-of-sight information. This distortion leads to erroneous pseudorange estimates, which in turn leads to erroneous position estimates.

Supercorrelation employs motion compensation of the correlation process itself to separate out the energy from different incoming directions by angle of arrival. This allows the LOS energy to be isolated and allows a LOS-only correlation peak to be formed, regardless of the number of incoming reflected signals at the same moment that would normally cause distortion of the desired correlation peak, as shown in Figure 2.

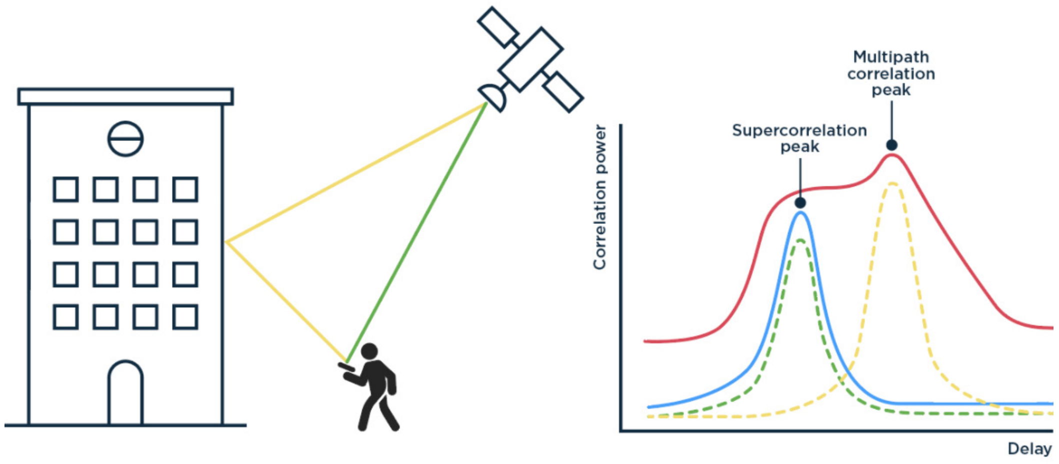

Figure 2 - Multipath Correlation Peak
The yellow line shows a reflected (NLOS) satellite signal and the green is a direct (LOS) signal. The red correlation peak shows a typical corrupted correlation peak resulting from multipath interference. The blue correlation peak shows the uncorrupted correlation peak tracked by Supercorrelation after rejecting any multipath interference which would otherwise obscure the LOS signal.

This provides uncorrupted pseudoranges for available satellites, leading to improvements in accuracy and integrity. Such improvements are equivalent to a "synthetic L5" software upgrade to an L1 receiver. The improvements in the accuracy and integrity of the observables for a Supercorrelating L1 receiver exceed the performance of an L5 receiver using traditional processing in urban environments.

Locking on to the line-of-sight signal

Supercorrelation is sensitive to angle of arrival, and can be used to track signals arriving from the known direction of the satellites in the sky. This property can be confirmed by assessing the "true shadows" that can be provided in urban environments by Supercorrelation. As the receiver passes buildings that obscure a given satellite, the C/N0 from Supercorrelation will vary from high values representative of open-sky power, down to just a few dB-Hz, as the Supercorrelator correctly tracks into the shadow of the building, as shown in Figure 3.

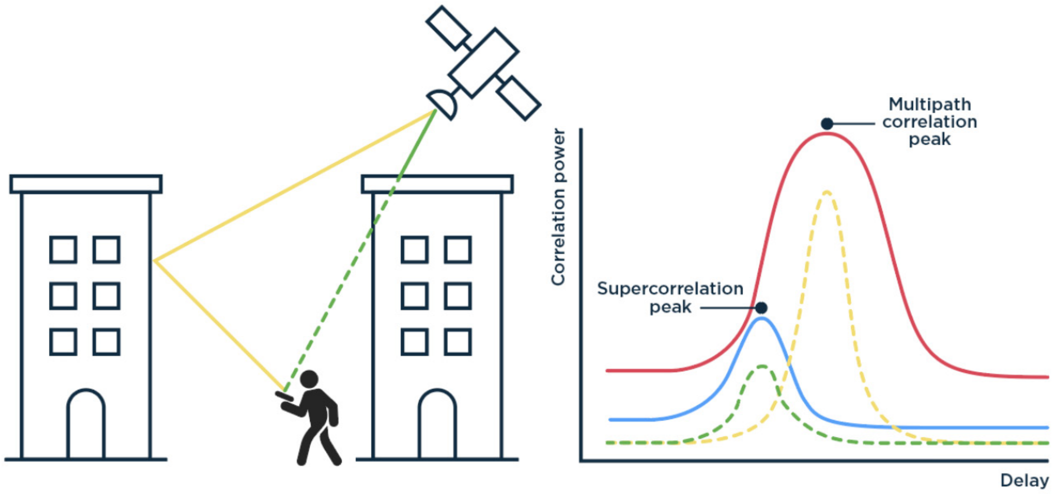

Figure 3 - Locking onto weak LOS
The LOS (green) signal is relatively weak due to the obstruction, but Supercorrelation enables the receiver to stay locked onto the weak LOS rather than the strong NLOS signal (yellow). A typical receiver will correlate its replica code strongly with the strong (but inaccurate) NLOS signal (red correlation peak), while a Supercorrelating receiver is able to correlate with the weaker LOS signal (blue correlation peak).

Often it is observed that traditional trackers will maintain a lock on a reflected signal during such obscurations, reporting incorrect pseudorange, Doppler, and C/N0 measurements within these building shadows. The Supercorrelator outputs will however provide correlation peaks corresponding to the correct pseudorange, Doppler, and C/N0 as the satellite moves in and out of occlusion. Supercorrelation is therefore ideal for shadow matching and 3D-Map-Aiding augmentation systems.

Spoofer immunity

The ability to reject NLOS signals also enables a Supercorrelating receiver to be immune to spoofing. As the spoofer will be unable to send false signals from the correct azimuths and elevations for each satellite, these signals will be filtered out, irrespective of their relative strength. FocalPoint has demonstrated this ability through a simulated trial, and real-world demonstration is possible with authorisation from the appropriate regulatory body.

Sensitivity boost

Supercorrelation processing enables very long coherent integration times. Typically 1 second is used; however FocalPoint has demonstrated successful integrations of 5 seconds on smartphone-based platforms. These long integrations are possible even while undergoing complicated user motions, such as walking or running. Coherent integration boosts the signal while attenuating the noise, whereas traditional incoherent integration boosts the signal and the noise by different factors. Supercorrelation therefore provides a boost in sensitivity, even when compared to receivers that are already performing 1 second of incoherent integration. Supercorrelation typically provides a 6dB - 10dB reduction in the receiver's noise floor, depending on the receiver settings, enabling the tracking of much weaker signals than is possible in standard GNSS receivers. Supercorrelation effectively provides a "synthetic antenna", increasing signal sensitivity and discriminating signals by their angle of arrival.

Summary of benefits

Supercorrelation enables strong reduction in multipath interference, sensitivity only to LOS signal components and an increase in receiver sensitivity. These benefits all work together to provide cleaner, stronger pseudorange and Doppler measurements. These in turn result in more accurate PVT estimates in the navigation engine. This is because Supercorrelation rejects NLOS signals when the LOS path is obstructed, whereas traditional processing will continue to process NLOS measurements, corrupting the PVT estimates.

How Supercorrelation works

A Supercorrelator is a complex phasor sequence which is designed to adjust the phases of a chain of GNSS PRN codewords, based on user motion with respect to the LOS. As a result, the Supercorrelator integrates strongly with the energy coming from a LOS satellite and attenuates energy coming from all other directions (e.g. NLOS). This provides unique multipath mitigation. The degree of multipath mitigation provided is a function of both the speed of the receiver through space (relative to the reflecting surfaces in the environment) and the coherent integration time.

In addition, the Supercorrelator also compensates for local oscillator (LO) variations which can affect all satellite signals. The Supercorrelation algorithms maintain an estimate of the receiver's LO variation in order to compensate for oscillator errors during each Supercorrelation period. This allows for low quality oscillators to be used, such as XOs and TSXs. The oscillator compensation technology effectively allows for a "synthetic TCXO" by improving the effective stability of lower-quality crystals.

The Supercorrelation algorithms also maintain an estimate of the receiver motion during the Supercorrelation period, and this estimate is typically provided with the assistance of inertial sensors. Low quality sensors can be used, such as those in smart-wearable devices. Supercorrelation can be used without any inertial sensor assistance at all for platforms with simple motion characteristics like cars and drones, but the sensitivity and computational load are improved if they are available.

In order to provide extended coherent integration times, either modern pilot signals should be used, or in the case of legacy signals with navigation bits or other data modulated onto the code sequence the navigation bits need to be stripped from the datastream. It is possible to strip the navigation bits through signal processing, but preferentially the navigation bits should be provided in an assistance data stream, predicted onboard, or a pilot signal should be used.

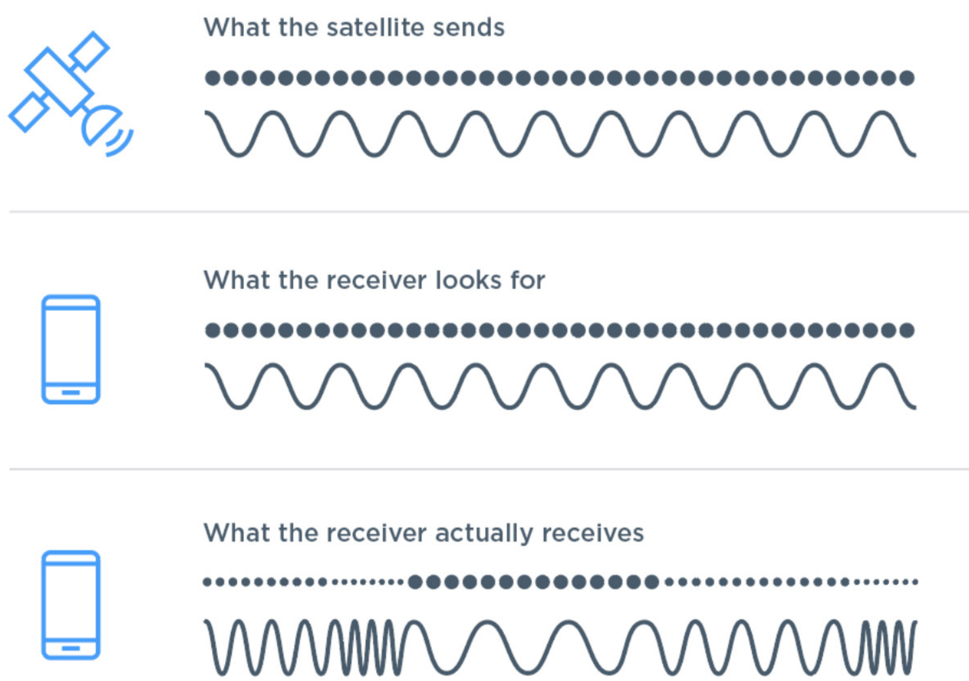

Figure 4 - Textbook Theory vs Real World
Ideally, the code frequency (represented by the dots) and carrier frequency (represented by the oscillating line) from a satellite remains constant over the coherent integration time interval and can be easily and accurately correlated with local signal replicas generated by the receiver. This is true for very short correlation times or static receivers with expensive oscillators. However for mobile low cost devices, the code frequency and carrier frequency detected by a receiver suffer perturbations due to Doppler, platform motions, oscillator variations, and other short-timescale nonlinear problems.

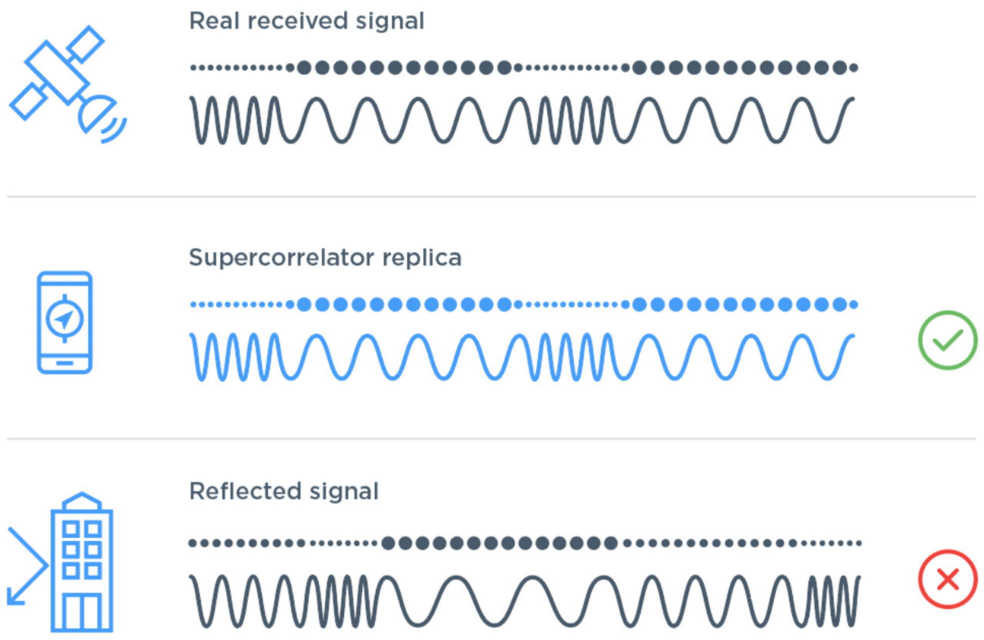

Figure 5 - Supercorrelation
Supercorrelation can generate an accurate replica which compensates for all of these issues. Reflected signals in the local environment suffer different code and carrier Doppler variations than the desired line-of-sight signal. This means that the Supercorrelator phasor that is created for a given satellite broadcast couples strongly to the desired line-of-sight version of the signal, but attenuates any reflected signals arriving from different directions.

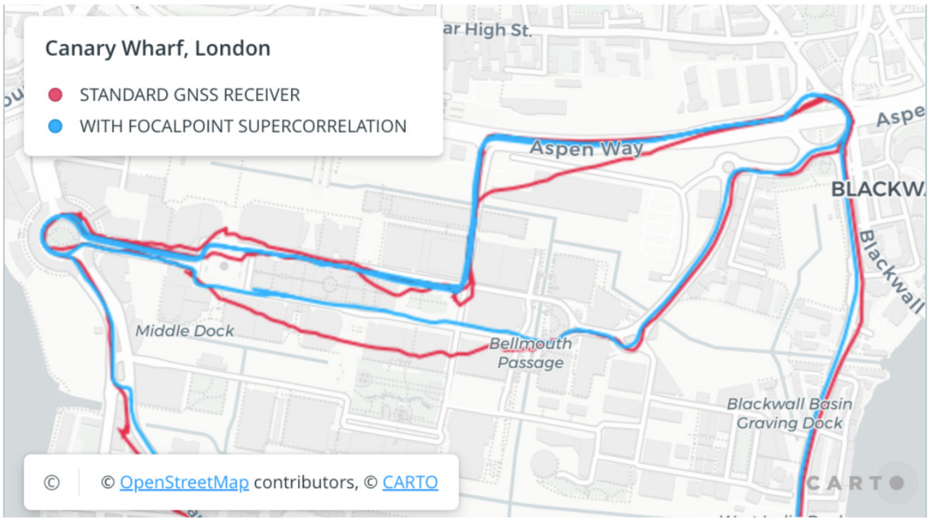

Figure 6 - S-GNSS™ performance
The result of Supercorrelation on positioning performance for a car driving in the urban canyons of Canary Wharf, London. The red line is a standard state-of-the-art vector tracking GNSS solution, and the blue line is the same positioning engine with Supercorrelation processing enabled. The effect of multipath interference is clear on the standard GNSS solution, where it cuts through buildings, whereas the S-GNSS receiver is able to ignore the NLOS and keep the true position on the road.

Skyscan

A Supercorrelator is tailored to couple strongly to energy from a given arrival direction through motion compensation. Skyscan is an optimised method of taking the current estimate of the user motion and producing a bank of Supercorrelators that effectively allow the receiver to scan the entire sky for incoming energy for each selected satellite PRN. This allows the receiver to not only confirm the availability of LOS energy but to separately measure the pseudorange and frequency associated with any reflected signal from the local environment. The output can be plotted to produce a map of the sky showing each PRNs signal power as shown in figure 7.

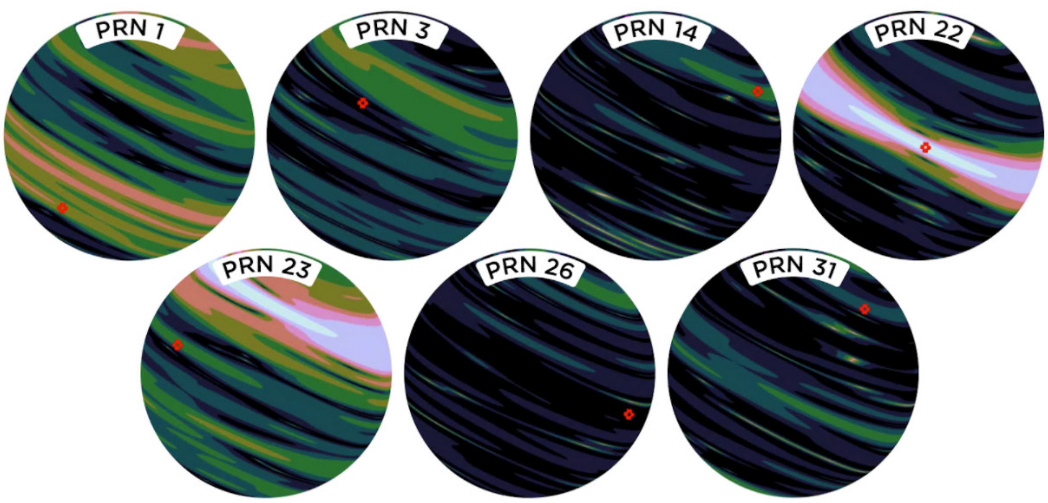

Figure 7 - SkyScan outputs
Example SkyScan outputs for each of the satellites in use during a moment within an urban canyon. Each disc is an azimuth-elevation plot of the sky, with a red mark showing the position of a given satellite (the PRN number is given in each title). The colours in the plots represent the energy being detected from all azimuths and elevations for each satellite. PRN 22 for example is a strong overhead satellite. PRN 23 however is exhibiting a strong NLOS signal on the north side of the receiver at moderate elevation, whereas only a weak signal is being detected from the true satellite direction in the West at moderate elevation. No line-of-sight energy is detectable at all for PRN 26, although there are more than three weak versions of the signal being received from the northern side at various elevations.

SkyScan processing can be used to unlock new capabilities or provide improvements to applications such as:

- **3D map-aiding**
  3DMA uses maps of building models to predict which satellite signals will be blocked by structures and therefore not visible by a receiver. This technique and similar "shadow-matching" schemes allows the receiver position to be better constrained using building models, but can be confused by reflected signals. SkyScan can unlock a much more powerful and hitherto impractical implementation of 3DMA in which Skyscan measurements of the reflected signals can be used directly in the calculation of receiver position and velocity[3].

- **Spoofer localisation**
  SkyScan data can reveal the azimuth and elevation of spoofers as they will show up as high power energy away from the satellite location.

- **Magnetic-free compass**
  The heading of the user through space (relative to true north) can be determined to an accuracy of a few degrees using SkyScan processing, through comparing known satellite positions against received signals. This potentially eliminates the need for a magnetometer depending on the application.

- **Passive radar**
  SkyScan data reveals the location of reflective surfaces in the environment, and can also be used to determine the extra path delay associated with those reflections. This data can be used as a form of passive radar.

Summary

Supercorrelation represents a new and significant improvement for GNSS receiver designs. The technology meets three of the most pressing needs in the modern navigation industry through its unique and patented angle of arrival sensing capability.

- Increased sensitivity and accuracy in dense urban environments
- Comprehensive multipath mitigation
- High position integrity

In addition the technologies stemming from Supercorrelation, such as SkyScan, unlock unique capabilities and applications that have been hitherto impractical or impossible on consumer devices.

Supercorrelation is available as a licensable software upgrade to modern smart devices with flexible deployment opportunities depending upon the customer requirement.

For further information and to trial the Supercorrelation technologies, please get in touch with Focal Point Positioning Ltd.

info@focalpointpositioning.com

References

[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.

[3] Groves, Zhong, Faragher and Esteves, Inside GNSS, 2021, Supercorrelation Plus 3D Mapping-Aided GNSS, www.insidegnss.com/supercorrelation-plus-3d-mapping-aided-gnss

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