Setup and Verification of a Multi-GNSS Over-The-Air Wave Field Synthesis Testbed

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***Abstract*—In this paper, we describe the principle, hardware/software setup, calibration and verification measurement results of a wave field synthesis (WFS) over-the-air (OTA) testbed for global navigation satellite systems (GNSS). It represents a new approach that, in contrast to conventionally conducted and open-field tests, realistically emulates real world scenarios under controllable and repeatable conditions. This enables the realistic comparison of receivers and algorithms especially for multi/beamforming antenna receivers as well as for receivers with integrated antennas. Having outlined the architecture and hardware setup of the WFS OTA testbed together with the GNSS constellation simulator, we describe the current 2D setup and the upcoming 3D installation. Then we discuss and present results of two different ways of calibration and validation carried out in the 2D setup: firstly, using an electromagnetic field probe, and secondly, using a commercial geodetic GNSS antenna with reference receiver in a 2.5D emulation.**

***Index Terms*—Satellite Navigation Systems, Global Positioning System, Over-the-Air Testing, Wave Field Synthesis**

I. Introduction

In contrast to conventionally conducted and open field device testing, the over-the-air (OTA) test represents a novel approach that allows, by the use of wave-field synthesis (WFS), the realistic emulation of real world scenarios under controllable and repeatable conditions inside an anechoic chamber, see Figure 1. The benefits of such a controlled test environment are the realistic performance assessment and the product evaluation of different wireless technologies, without the need for special frequency licensing or other interference restraints required for open field tests [1], [2].

Recently, interference mitigation techniques utilizing antenna arrays have attracted a lot of interest in global navigation satellite system (GNSS) applications. The main advantage of directional steerable antennas in GNSS systems is the suppression of jammers and spoofers as well as the higher reception signal quality in multipath fading channel environments. However, this advantage comes at the cost of increased device testing effort. In this regard, traditional device test measurement procedures such as the conducted measurement test are not able to cover the spatial dimension of the propagation channel as the air interface is bridged by cables towards the device tester. To cope with that issue, the two-stage conducted testing approach that includes the effects of the propagation channel and the antenna radiation pattern was developed, see [3]. However, a drawback of this procedure is the inaccessibility of small and compact antennas in integrated devices, as it is not always possible to access the antenna ports without destroying the device under test (DUT), or at least significantly altering its electromagnetic properties.

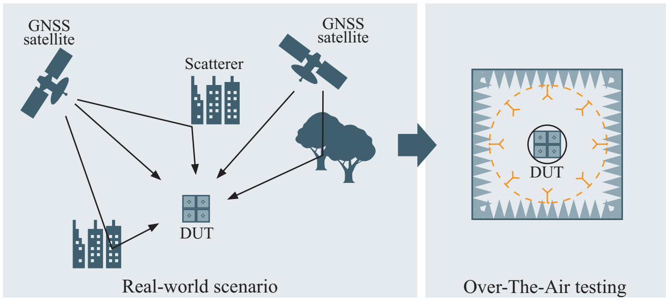

Fig. 1. Principle of Over-the-air testing inside an anechoic chamber

In comparison to the well-known methods for device testing, the wave-field synthesis (WFS) Over-The-Air (OTA) approach provides the opportunity to test a device in a holistic way [4]. The DUT is placed in an anechoic chamber surrounded by an antenna ring or (hemi)-sphere to recreate the electromagnetic environment virtually in the chamber, as depicted in Figure 1. The advantages of the OTA method are the following: The device can be tested without unmounting the device's antenna. Multiple devices of the same or of different types can be tested using exactly the same measurement environment. No electromagnetic disturbance from the outside to the test environment and vice versa has to be taken into account. Therefore, even classified signals, e. g., Galileo PRS or GPS PPS can be safely tested within the protected chamber as well as jamming and spoofing which are not allowed to be carried out in the free field without permission. Finally, the propagation channel conditions (e. g. multipath) of GNSS signals but also of jammers and spoofers can be emulated in great detail.

In 2013, the Facility for Over-the-air Research and TEsting (FORTE) was put into operation by Fraunhofer IIS [5]. It hosts two basic research platforms, a testbed for Satellite Communication on the Move (SOTM) terminals and an environment for Over-the-Air (OTA) testing of GNSS applications. Besides GNSS testing, the testbed also enables realistic radio channel emulation for LTE, LTE-A and cognitive radio, sensor

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networks, car-to-car and car-to-infrastructure communications.

This paper is organized as follows: Section II summarizes the identified applications for WFS OTA GNSS testing. Section III briefly summarizes the principle and setup of the FORTE WFS OTA system with its capabilities and limitations. The GNSS simulator that is connected to the WFS OTA is outlined, followed by the description of the antenna setup with the calibration procedure. Section IV describes the measurement setup and verification methodology of the current WFS OTA GNSS setup with their verification measurement results. Section V discusses the measurement results and performance comparisons to conventionally conducted GNSS RF constellation simulator tests. Finally, Section VI concludes the paper.

II. Applications for WFS OTA Testing

Today's mass-market GNSS receivers, e.g. contained in handheld mobile phones, are tested and verified for position accuracy, acquisition sensitivity, time-to-first-fix and other benchmarks, but not for their robustness against intentional interferences. Testing, qualification and certification—at least for safety-critical receivers—are regarded as a must and necessary to guarantee a certain minimum standard.

The WFS OTA approach provides a novel testing method for interference robustness assessments of GNSS receivers equipped with integrated antennas, or external ones, but especially with phased array antennas. The identified use cases for the WFS OTA testing range from GNSS device testing with classical open service GPS/Galileo signals to classified signals (e.g. GPS PPS or Galileo PRS) and different multipath propagation conditions that include jammers and spoofers. In the following subsections, the identified use cases for WFS OTA testing are described in detail.

A. Use Case 1: GNSS Receivers with Integrated Antennas

Smartphones, portable car navigation systems as well as highly integrated navigation devices (e.g. GPS Watch, handheld navigation receivers for outdoor activities, etc.) have an integrated GNSS antenna. Neither can an external GNSS antenna can connected to these devices nor can the internal antenna be separately measured and characterized. However, the antenna is a critical element for the overall receiver functionality, as the antenna design has a strong influence on the receiver sensitivity as well as the receiver's susceptibility in terms of multipath and interference suppression. A conventional cable-connected simulator cannot accurately test such an integrated system. With the aid of the WFS OTA testing approach, realistic end-to-end tests for GNSS DUT receivers equipped with integrated antennas can be performed "as it is" in a realistic and reproducible testing environment.

B. Use Case 2: GNSS Receivers with Array Antennas

In contrast to legacy mobile devices that encounter a harsh mobile channel environment, GNSS receivers are faced with intentional interferences. This is becoming a critical issue, as more and more GNSS receivers are used for security related applications. These are the traditional military GNSS services, flight approach and Ground Based Augmentation Systems (GBASs). But besides that, upcoming consumer applications may incorporate Advanced Driving Assistance Solutions (ADAS) up to automatic driving or guidance for vision impaired people. Moreover, the GNSS time is widely used for synchronization of distributed systems, e.g., mobile device base station networks, phase-synchronous current injection of decentralized power plants, and many more.

To provide protection against interferences, GNSS receivers equipped with phased array antennas can be a powerful solution. For instance, a very effective interference mitigation method is utilizing a Controlled Reception Pattern Antenna (CRPA). This type of phased array antenna places nulls in the direction of the interferer to protect the receiver from impairments. Commercial products are already available on the market, like the 7-element CRPA named GAJT from Novatel/Qinetiq [6].

A more sophisticated solution provides a beam-steering antenna, e.g. developed by the German Aerospace Center (DLR) within the BaSE project [7]. In this approach, several beams are steered in each direction of the satellite signals to be received. Due to the increased gain in a specific direction, possible interferences coming from other directions are attenuated. Moreover, such beam-steering antennas provide the possibility to detect spoofers: Typically, a spoofer broadcasts all signals from a single point in space, whereas the desired GNSS information is inherently linked to the spatial diversity of the satellite signals. By using a phased array antenna, the Direction of Arrival (DoA) can be estimated at the receiver side, independently from the transmitted GNSS message. This cross check enables effective spoofing detection [8].

To test GNSS receivers equipped with an array antenna, a simulator setup taking into account the spatial component of the channel must be used. This cannot be done with a conventional single RF-output GNSS constellation simulator, but with the WFS OTA testing approach as installed at FORTE.

C. Use Case 3: GNSS Receivers in High Dynamic Environments

The WFS OTA testbed emulates the physical direction of the received GNSS signals, multipath channel components and/or jammers by wave field synthesis. This approach allows for a continuous angular motion of the transmitter (satellite, jammer, and spoofer) in space. Moreover, huge dynamic range changes in terms of Doppler shift can be emulated (e.g. acceleration of a rocket or a plane) via WFS without the need of physically moving the DUT. If scenario coherent inertial data is required, the GSS9000 can be coupled with Spirent's SimInertial simulation system.

D. Use Case 4: GNSS Receivers with Classified Signals and/or Jammers

Conventional free-field test ranges like the GATE testbeds in Germany are not suited to test the receiver's robustness against interference. The operation of a powerful jammer or spoofer in an open field would also affect surrounding receivers and therefore requires a special frequency license to be legally authorized. Moreover, the testing, optimization, and verification of not yet certified receiver designs that incorporate classified signals (e.g. Galileo PRS or the GPS PPS) are generally not allowed in conventional free field testbeds, since stringent anti-tamper requirements and limitation of radiation have to be guaranteed.

Thanks to the anechoic chamber in which the WFS OTA testing is installed and the facility security clearances of the installation site, testing with both the military GPS signals as well as with the Galileo Public Regulated Service (PRS) signals are possible in the installation. Even high-power jammers can be used within the OTA's anechoic chamber without any harm to the outside environment.

III. Over-the-Air Testing for GNSS Systems

A. *FORTE WFS OTA Hardware Setup*

A WFS OTA testbed for emulating complex electromagnetic wave fields with signal bandwidths up to 80 MHz in the frequency range of 350 MHz to 3 GHz is operated at Fraunhofer IIS FORTE. The wave field impinging at the device-under-test (DUT) is generated as a coherent superposition of pre-defined, discrete plane wave components with certain directions, delays, amplitudes and phases that are radiated by several OTA illumination antennas. That way, an arbitrary multipath propagation channel and interference environment can be emulated at the DUT (e. g. a GNSS receiver).

Specifically, as shown in Fig. 2 and Fig. 3, the WFS OTA testbed consists of a GNSS radio frequency constellation simulator (RFCS) (Spirent GSS9000 TS788) as signal source, an OTA channel emulator, and 32 OTA illumination antennas surrounding the DUT. Up to 12 signals can be fed into the system. These signals can be individual GNSS satellite signals from the Spirent GSS9000 TS788 or radio frequency (RF) signals, e.g. of interferers. While the Spirent GSS9000 TS788 signals only need to be adapted in the format, the RF input signals are converted to digital base-band (DBB) signals by analog-to-digital down-converter (ADD) units. The DBB signals are then distributed to each of 16 FPGA Digital Signal Processors (FDSP). A single FDSP convolves all 12 input signals with the coefficients of the propagation channel model for the target scenario. The propagation channel model includes the complex WFS weights for each individual channel tap delay to control the direction of the multipath components. Note that the signal convolution can be accomplished either in the time or frequency domain. When performing the signal convolution in the frequency domain, the OTA testbed supports the emulation of channel impulse responses with an almost unlimited number of propagation paths. This means the emulated wave field is not restricted to a certain number of channel delay taps. Finally, the output signals of each FDSP are converted to the analog domain and mixed up to the operating frequency by the digital-to-analog up-converters (DAUs). Each DAU has two RF outputs, which add up, in total, to 32 analog output channels. Thus, each of the 32 output signals is a

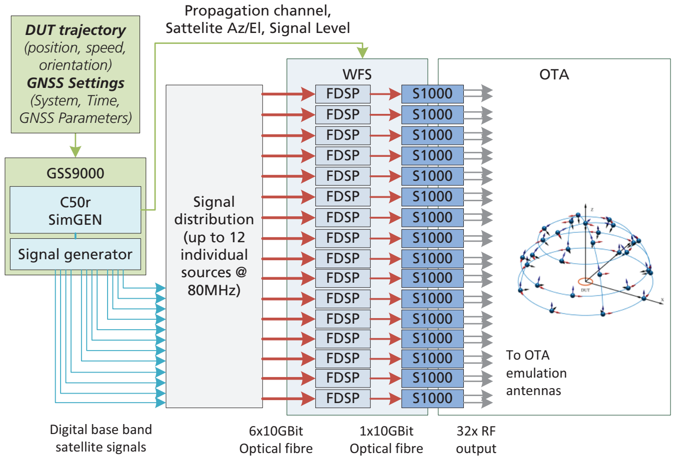


Fig. 2. FORTE 3D-WFS OTA schematic for GNSS testing

superposition of the 12 convolved input DBB signals. The output signals are fed into the 32 OTA emulation antennas. The antennas reproduce dual-polarization with perpendicularly arranged Vivaldi-horns to be able to emulate linear as well as left/right hand circular polarization (L/RHCP). The emulation antennas are placed in either a 2-dimensional or a spherical setup around the DUT. The maximum RF output power per channel is +10 dBm, resulting in a maximum of ≈-45 dBm at the DUTs position.

When using WFS for OTA testing, the maximum DUT size is restricted by the number of phase coherent hardware channels, the operating frequency, and the OTA emulation antenna constellation. Following the spatial sampling theorem for a 3-dimensional arrangement of OTA emulation antennas $D < \sqrt{M} \cdot \lambda/(2\sqrt{\pi})$, a maximum electrical size of the DUT with $D = 0.21\,\text{m}$ for an arrangement of $M = 16$ dual-polarized OTA emulation antennas can be achieved. Using $M = 32$ OTA emulation antennas, the possible electrical DUT diameter increases to $D = 0.30\,\text{m}$ [9]. In a 2-dimensional setup, we can achieve a maximum electrical DUT diameter of 0.48 m/0.73 m/0.97 m using the the spatial sampling equation for the 2D case $D = \lambda/2 \cdot M/\pi$ and $M = 16/24/32$ emulation antennas [10], [11].

B. *GNSS Emulator for WFS OTA Setup*

A "Tailored Solution" (TS) based on the new GSS9000 series of Spirent's high-end GNSS signal emulator was customized for Fraunhofer IIS. The so called GSS9000 TS788 was modified with specific digital I/Q output channels instead of the conventional composite analog RF output port. Each satellite's individual raw baseband signal (including navigation messages, PRN-codes, Doppler-offsets, and relative power adjustment between the signals but no noise) is digitally converted to the format used by the OTA channel emulator and fed into the signal distribution unit, as depicted in Figure 2. The information about the simulated satellites' positions and their respective power levels are streamed from the GSS9000 TS788 control PC running Spirent's SimGEN software via

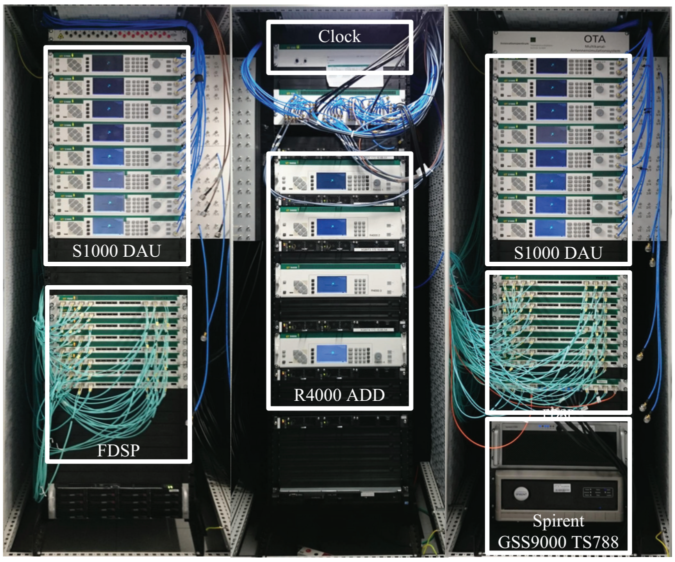


Fig. 3. FORTE WFS OTA channel emulator hardware

Ethernet and TCP/IP to the OTA control PC. The GSS9000 TS788 chassis contains two versatile signal generators where each one supports up to 8 satellite channels on one carrier frequency. The GSS9000 TS788 chassis is expandable to a maximum of 5 signal generators, allowing up to 40 satellites in view generated together. The current TS788 installation is able to simulate up to 16 GNSS signals and combinations of GPS, Galileo, GLONASS and BeiDou, including SBAS in two frequency bands at the same time.

With the currently realized OTA channel emulator, a maximum of 12 satellites either on one carrier frequency or 6/6 satellites on two carrier frequencies can be generated. The American NAVSTAR GPS L1, L2, L5 as well as the European Galileo E1, E6, E5, the Russian GLONASS G1, G2 and the Chinese BeiDou B1, B2 are currently supported. Some examples of supported carriers/systems for GPS and Galileo are:

- 12x Galileo E1 or 12x GPS L1
- 6x Galileo E1 + 6x Galileo E6
- 6x Galileo E1 + 6x GPS L1
- 6x GPS L1 + 6x GPS L2
- 6x Galileo E1 + 6x Galileo E5

where the Galileo E1 includes the E1A PRS (Public Regulated Service) together with the E1BC OS (Open Service), the E6 includes the E6A PRS and E6BC CS (Commercial Service) and the E5 provides the complete AltBOC signal for Galileo OS. Similarly, GPS L1 includes C/A, TMBOC and P-Code and L2 the P-Code including L2C.

The supported signal bandwidth for all channels and carrier frequencies is 60 MHz, providing sufficient bandwidth for the Galileo E5 AltBOC-signals as well as for all other GNSS signals defined, including classified ones like Galileo PRS and GPS SA/A-S / M-Code.

The GSS9000 TS788 simulator is equipped with a dedicated security module, and is licensed for classified Galileo PRS and GPS SAASM test campaigns.

C. WFS OTA Antenna Setup and Calibration Procedure

In the current WFS OTA setup, we use a 2-dimensional distribution of 24 OTA emulation antennas arranged in a full ring with a separation of 15 degrees. In this setup, we can achieve a maximum electrical DUT diameter of 0.73 m using the spatial sampling equation for the 2D case $D = {}^{\lambda}\!/_{2} \cdot {}^{M}\!/_{\pi}$ [10], [11].

To produce an accurate electromagnetic field at the DUT position, a calibration procedure has to be performed. This is necessary because each physical channel is w.r.t. its delay (mostly cable length and antenna position), attenuation (cable and antenna), free space attenuation (distance between antenna and optimization point). To identify the delay and attenuation contributions of each OTA emulation antenna at the sweet spot, an (x, y, z, ϕ) positioner carrying an electromagnetic field probe is used to measure the field at multiple positions inside the sweet spot with a spatial sampling less than ${}^{\lambda}\!/_{2}$. The resulting data structure is called the transfer matrix $\boldsymbol{X} \in \mathbb{C}^{N \times M}$, where N is the number of optimization points, and $M = 24$ is the number of OTA emulation antennas. The number of optimization points depends on the number of used OTA emulation antennas, and the electrical size of the DUT. Using 24 OTA emulation antennas, at least 24 optimization points have to be distributed in the desired sweet spot to achieve full rank of the transfer matrix.

A simplification can be made with the assumption that only antennas contribute to the resulting plane wave that lie in the vicinity of the wave origin. OTA emulation antennas having an angular distance $> \beta = 80°$ related to the incidence angle of the emulated plane wave are not used for the respective plane wave synthesis. This is realized via setting the transfer matrix elements to zero, which correspond to the unused OTA emulation antennas. Finally, using the transfer matrix, the antenna weights/steering vectors for the OTA emulation antennas for each individual delay path are obtained. A detailed description for the calculation is given in [9].

To evaluate the wave field quality, we utilize the error vector magnitude (EVM)

$$\mathrm{EVM}_{[\mathrm{dB}]} = 20 \cdot \log \left(\frac{\|\boldsymbol{e}_{\mathrm{synth}}(\boldsymbol{o}) - \boldsymbol{e}_{\mathrm{tgt}}(\boldsymbol{o})\|_2}{\|\boldsymbol{e}_{\mathrm{tgt}}(\boldsymbol{o})\|_2} \right), \quad (1)$$

where $\boldsymbol{e}_{\mathrm{synth}}$ is the synthesized field vector, and $\boldsymbol{e}_{\mathrm{tgt}}$ the targeted field vector at optimization position $\boldsymbol{o}$.

Figure 4 shows an error vector magnitude (EVM) simulation for a sweet spot diameter of $d_{\mathrm{SP}} = 0.2\,\mathrm{m}$ and $N = 14$ optimization points (black dots). The white circle surrounds the sweet spot area and the black line denotes the plane wave incidence angle for the simulation. The left subplot shows the magnitude of the resulting steering vector $\boldsymbol{s}$ for one emulated plane wave and the active OTA emulation antennas (blue dots), blue circles stand for inactive OTA emulation antennas. The simulation uses 11 active OTA emulation antennas. With an EVM value of $< -30\,\mathrm{dB}$ good wave field synthesis results are achieved.

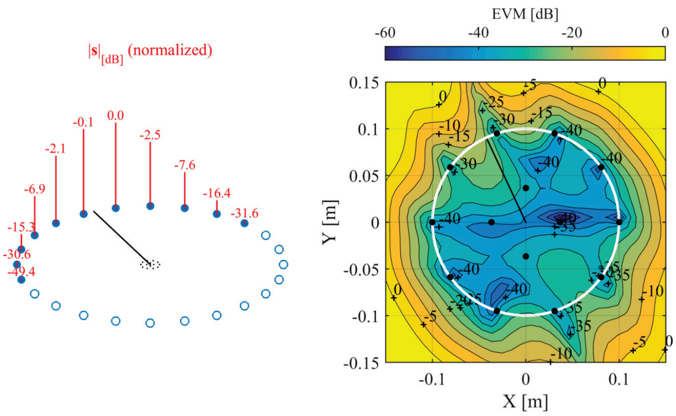


Fig. 4. EVM distribution inside sweet spot (white circle) having used 14 optimization points (black dots), $d_{\text{SP}} = 0.2\,\text{m}$. The red lines with according values depict the power contribution of the active OTA emulation antennas. The wave origin is depicted by the black line.

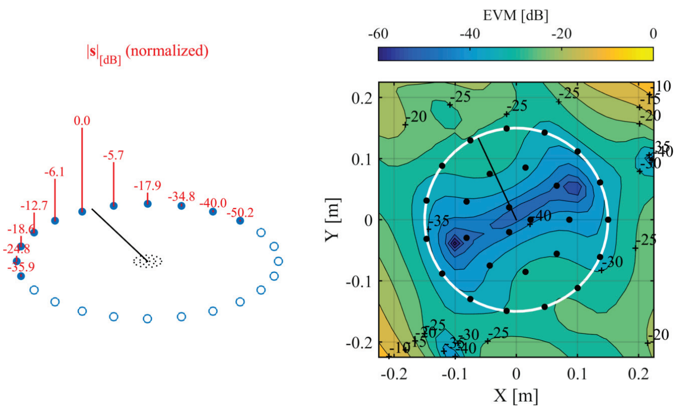


Fig. 5. EVM distribution inside sweet spot (white circle) having used 27 optimization points (black dots), $d_{\text{SP}} = 0.3\,\text{m}$. The red lines with according values depict the power contribution of the active OTA emulation antennas. The wave origin is depicted by the black line.

The initial measurements were conducted with the $d_{\text{SP}} = 0.2\,\text{m}$ configuration, as the geometrical size of the GNSS DUT (a geodetic multi-GNSS antenna) is in the same region. However, the first measurement results yielded a positioning bias of $\approx\ 0.5\,\text{m}$ (plot not shown here). The wave-field synthesis measurements were repeated using a larger sweet spot diameter of $d_{\text{SP}} = 0.3\,\text{m}$ and also having 27, instead of 14 optimization points, cf. Figure 5. The EVM distribution now shows better values, especially around the sweet spot borders. This is important because the electrical size of an antenna is usually greater than the geometrical one. This measurement configuration was used in the following for comparing the WFS OTA generated satellite signals with the conducted and the single-antenna ones.

IV. Verification Measurements

This chapter presents the methodology and verification results of the WFS OTA testbed (including the Spirent GSS9000 TS788) compared to conventional Spirent GSS9000 conducted measurements. The objective is to verify the simulations by

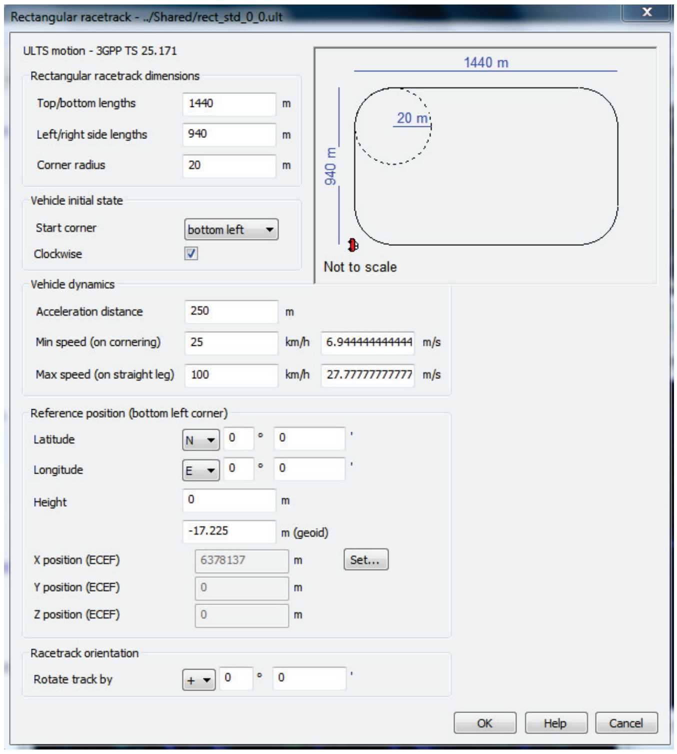


Fig. 6. Default race track scenario of Sprient's SimGen

comparing the positioning accuracy obtained by the WFS OTA method with the GSS9000 RFCS conducted measurements, which are generally accepted as accurate.

For a realistic end-to-end check, a professional geodetic GNSS antenna (*NavXperience 3G+C* multi-GNSS antenna) developed by Fraunhofer IIS [12], together with the GNSS reference receiver *Septentrio PolarRx4* were used. Two test scenarios were selected for the verification of the measurements.

- Static scenario: GPS L1 C/A only; Position lat/long 0°/0°; no atmospheric effects; default settings of Spirent's SimGen
- Race track scenario: GPS L1 C/A only; Position track around lat/long 0°/0°; no atmospheric effects; default settings of Spirent's SimGen, see Figure 6

Note that other GNSS signals or combinations can be simulated as well. As explained in Section III-B, the WFS OTA emulation does not depend on the chosen GNSS signals. Therefore, a GPS only scenario was selected without loss of generality.

The GNSS receiver was set to its default settings, except the intentional disabling of tropospheric and ionospheric corrections as no atmosphere was simulated. Moreover, the receiver was restarted (”soft reset” with deletion of every receiver internal setting except its configuration) before each measurement run. Each scenario was simulated for approx. 5 minutes. The receiver logged every measurement in the Septentrio Binary Format (SBF), which was then further processed in Matlab.

As depicted in Figure 8, the reception pattern of the geodetic

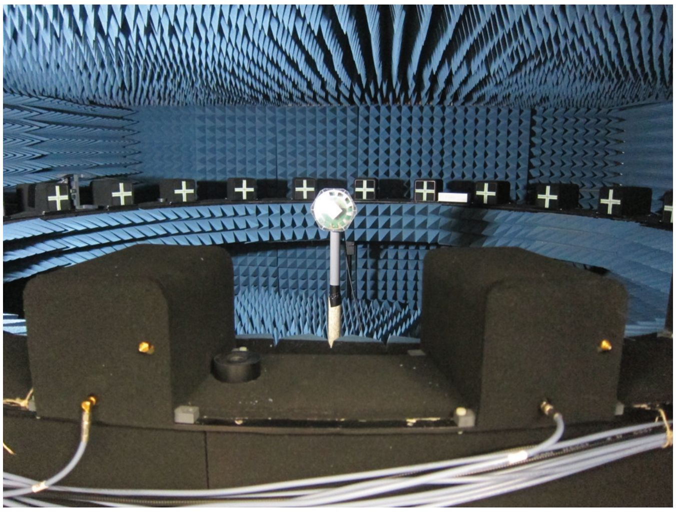


Fig. 7. WFS OTA setup with geodetic antenna

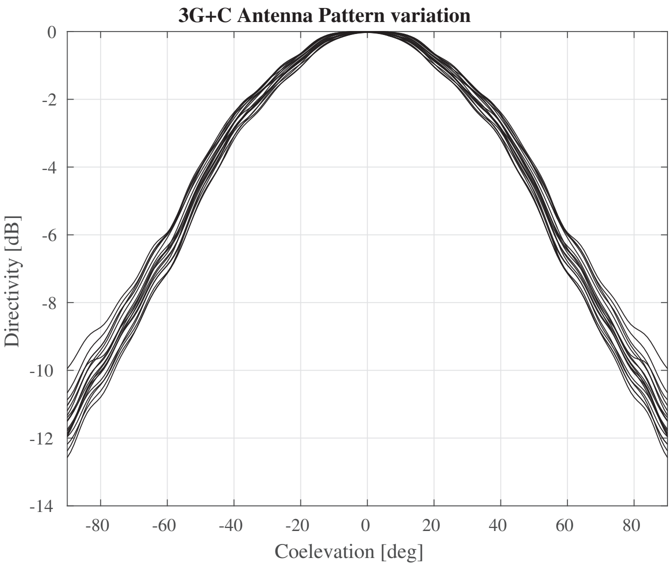


Fig. 8. Measured azimuth vs. elevation radiation patterns of the 3G+C antenna

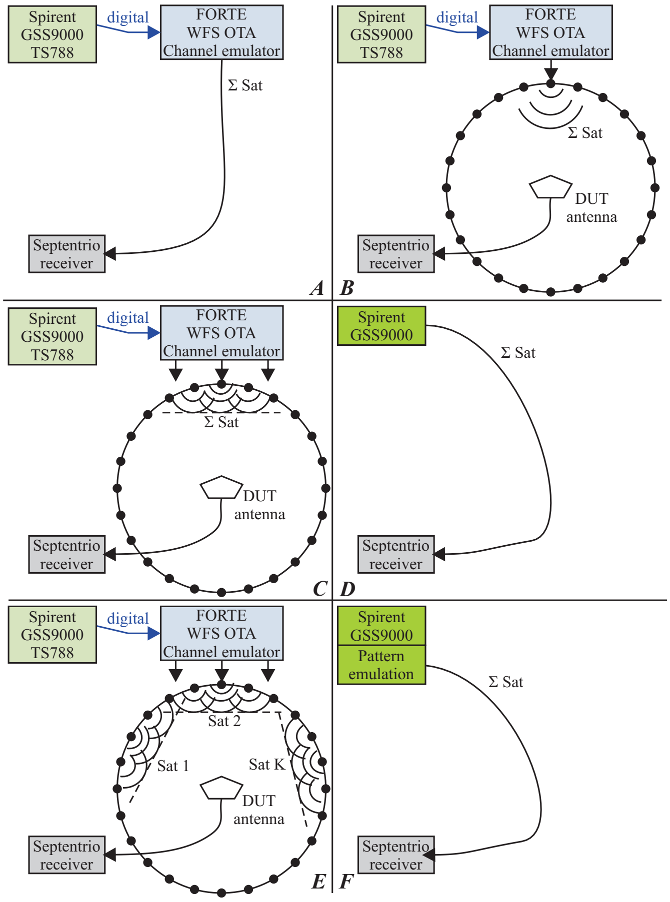


Fig. 9. Measurement setup

GNSS antenna is nearly identical in the azimuth plane, each black line denotes a pattern slice, step size 10° azimuth, but it provides a significant attenuation (due to multipath suppression) at elevation angles below 15°. Thus, a 2.5D simulation of a single GNSS antenna/receiver setup can be done in the 2D OTA ring by tilting the GNSS antenna by 90° relative to the OTA ring, as depicted in Figure 7. Then, all GNSS satellites' azimuth angles can be projected onto the 2D ring, emulating the GNSS satellites' elevation.

The satellites' elevation is emulated via the FORTE WFS OTA channel emulator. With this setup, a quasi 3D or 2.5D WFS OTA GNSS emulation can be performed. The GNSS signal is emulated and the reference receiver's output is used to assess the GNSS position.

To verify the measurements, six different setups were used for the emulation of the scenarios "static" and "race track". The positioning result plots shown in Fig. 11 and Fig. 12 provide the obtained mean with its 1-σ and 2-σ 2-D horizontal error with respect to the emulated lat/long 0°/0° position. For the dynamic scenario "race track", the reference was subtracted from the obtained position to show the 2-D horizontal error only.

In the following, we describe the six different measurement setups, which are depicted in Figure 9.

A. *TS788 Conducted Test*

As explained in the OTA GNSS emulator setup, the digital outputs of each simulated satellite are passed from the GSS9000 TS788 RFCS to the FDSPs. Here, the signal convolution takes place. In this first test, all incoming RFCS signals are digitally combined into a single digital composite signal, meaning that each satellite signal's steering vector is constant. This digital signal is then routed to one S1000 DAU's analog output and RF up-converters. Instead of using OTA emulation antennas for transmission, a direct cable connection to the GNSS reference receiver was used.

This test checks if all digital signals are handled correctly and are free of any (relative) latencies introduced by the WFS OTA testbed, which would directly lead to systematic position errors.

The positioning error for the two simulated scenarios in this configuration are depicted in Figures 11(a) and 12(a).

B. TS788 Single Emulation Antenna OTA

In this test, the same configuration as in the previously conducted one was used, but now the composite signal was transmitted "over-the-air" to the DUT using one single OTA emulation antenna directly facing the GNSS antenna, see Figure 7.

The results should be the same as for the conducted test before, if the influence of the transmission antenna and the anechoic chamber are negligible.

The positioning errors for the two simulated scenarios in this configuration are depicted in Figures 11(b) and 12(b).

C. TS788 Single-Directional WFS OTA

In this configuration, the WFS steering vector is calculated in a way that all GNSS signals are targeting the reception antenna from boresight single direction—thus from 90° elevation, see Figure 4.

In contrast to the previous composite single transmitter antenna test, several OTA emulation antennas are transmitting signals with the objective to form a plain wavefront from entering the reception antenna frontally. This is the first test of WFS, forming a sweet spot in the vicinity of the GNSS antenna. The results should be comparable to the single transmitter antenna test before. The positioning errors are shown in Figures 11(c) and 12(c).

D. GSS9000 - Conducted without Antenna Pattern Simulation

To verify the results of the TS788/WFS OTA, the same three verification measurements were carried out in a conducted way with the with a conventional RF-output Spirent GSS9000 simulator. The exact same scenario as for the TS788 WFS OTA configuration was used, however, the C/N0 settings had to be calibrated first, as discussed in the Subsection IV-G. No effects of the reception antenna were simulated at first, to have a fair comparison to the single direction tests. The results are shown in Figures 11(d) and 12(d).

E. TS788 Multi-Directional WFS OTA

In this configuration, the elevation of each emulated satellite signal was projected on the azimuth of the 2D-OTA constellation. This was done by using wave field synthesis, resulting in plane wave fronts from different angles of arrival within the emulation's sweet spot, where the antenna was located.

By simulating the different elevations, the antenna's reception pattern leads to significant attenuation e.g. for low elevation signals. This is the reason why the position is much less accurate as for all the measurements before, as shown in Figures 11(e) and 12(e).

F. GSS9000 - Conducted with Antenna Pattern Simulation

In the second run of the GSS9000 reference simulations, the GNSS reference reception antenna used was modeled in its level and phase patterns (see Figure 8) over elevation/azimuth and applied in the Spirent simulation setup. Precisely, the azimuth cut valid for the OTA 2.5D setup was used. The RFCS took the elevation dependent attenuation into account when generating a single RF output signal to the reference receiver.

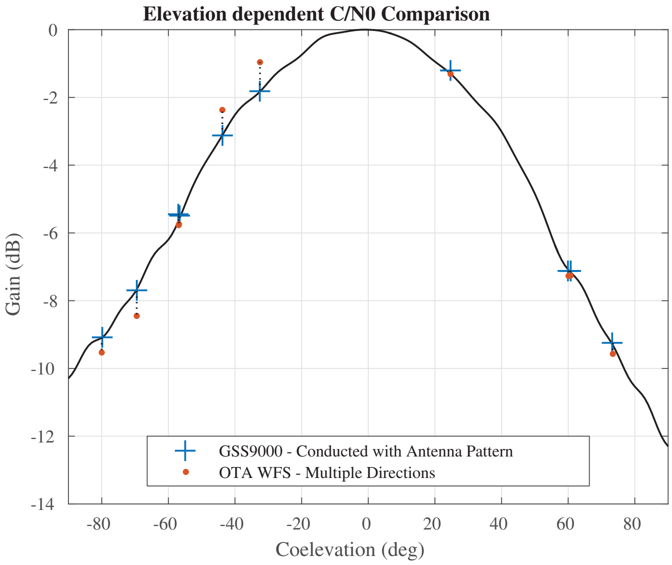


Fig. 10. Comparison of elevation-dependent C/N0 for static scenarios: conducted test with antenna model and GSS9000 vs. the multi-directional WFS OTA test; the black line denotes the antenna pattern gain

Figure 10 depicts the measurement and used GNSS reference antenna azimuth cut of the elevation depended attenuation. One can see that the "TS788 Multi-Directional WFS OTA" result leads to a simulation result that is very close to the model's prediction.

G. C/N0 Calibration

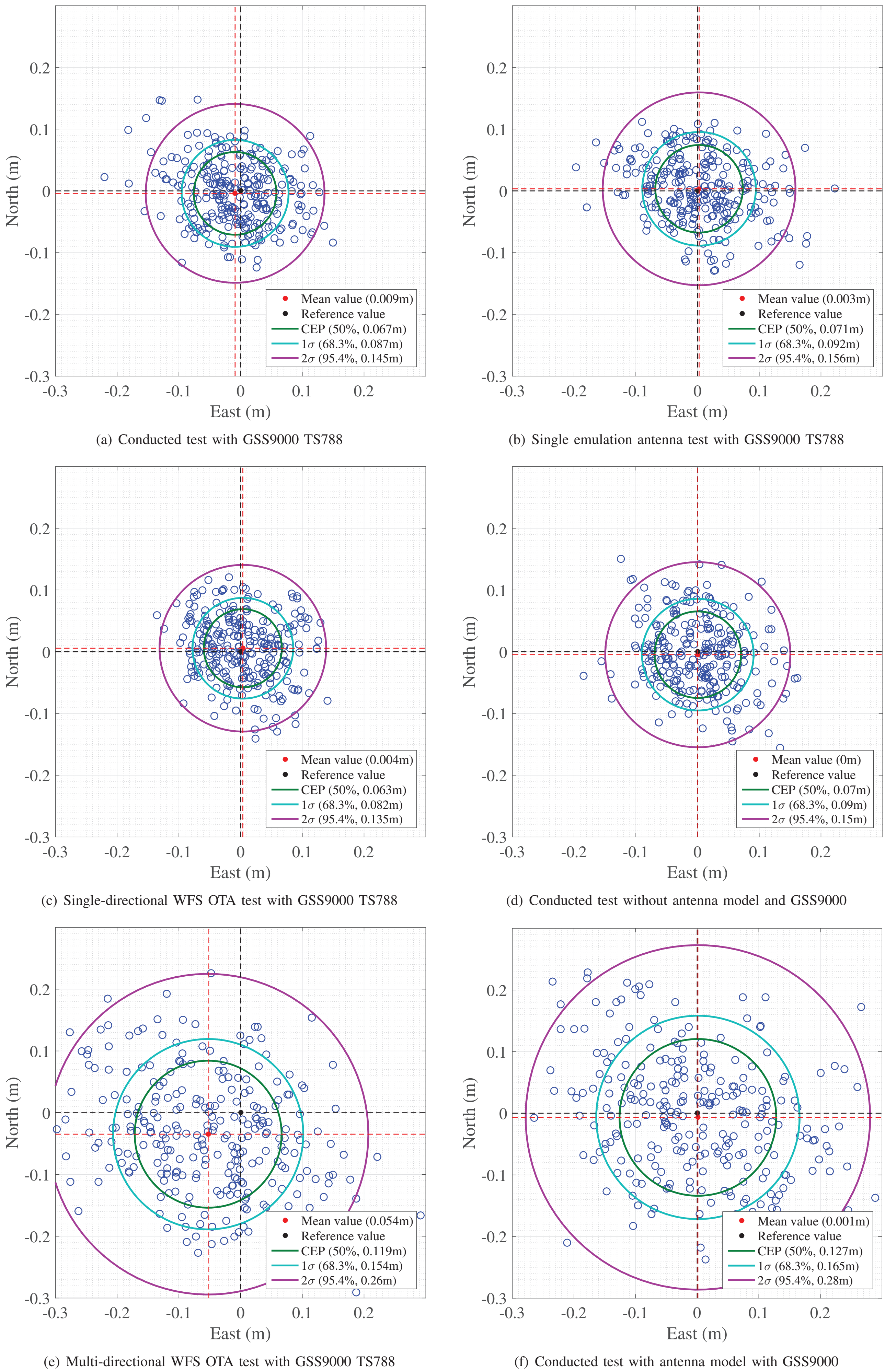
Since the GSS9000 TS788 emulates the signal power only relative to each satellite but does not set the overall noise level, the amplification gain of the WFS OTA's S1000 units set the simulation's absolute C/N0. A C/N0 of approx. 46 dBHz was arbitrarily chosen by adjusting the variable gain amplifier till this desired C/N0 was reported by the GNSS reference receiver.

For each test case, this C/N0 had to be manually calibrated, to obtain comparable position error results. Figure 13 shows the comparison of the measured C/N0 for one arbitrarily chosen satellite. The other satellites are similar in their C/N0 offsets between the measurement setups.

V. Discussion of the Results

To prove the accuracy and validate the new WFS OTA GNSS installation, each scenario was compared to a corresponding reference scenario, simulated with a conventionally conducted RF signal generator.

In a first test stage, one must ensure that the digital combination of the TS788 RFCS signals in the FDSPs work correctly. Any error (e.g. delays or asymmetry between the raw data inputs) would lead to systematic errors in all WFS OTA scenarios. In the first experiments, we had a constant bias of about 0.5 m in the WFS OTA measurements, that enabled



(a) Conducted test with GSS9000 TS788

(b) Single emulation antenna test with GSS9000 TS788

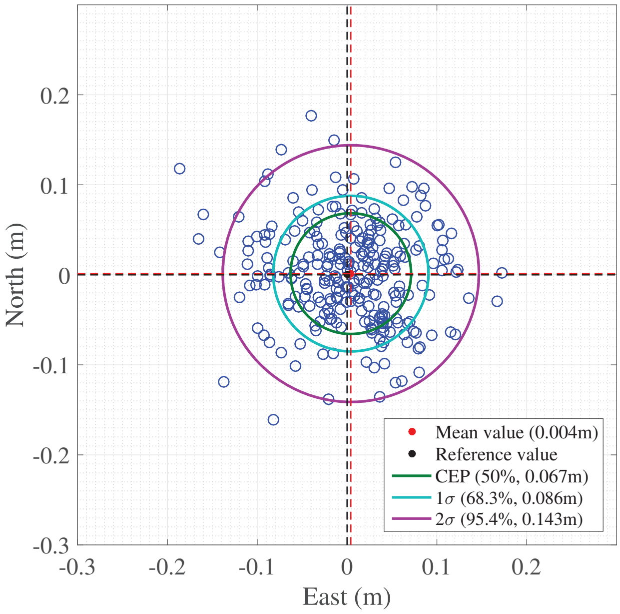
(c) Single-directional WFS OTA test with GSS9000 TS788

(d) Conducted test without antenna model and GSS9000

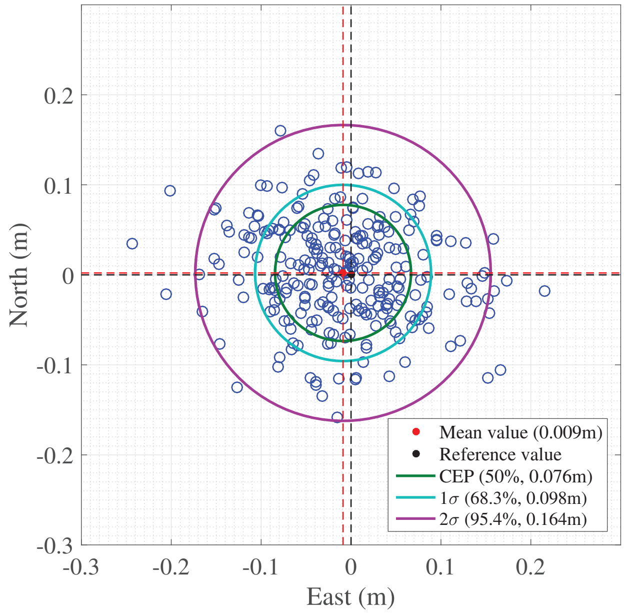
(e) Multi-directional WFS OTA test with GSS9000 TS788

(f) Conducted test with antenna model with GSS9000

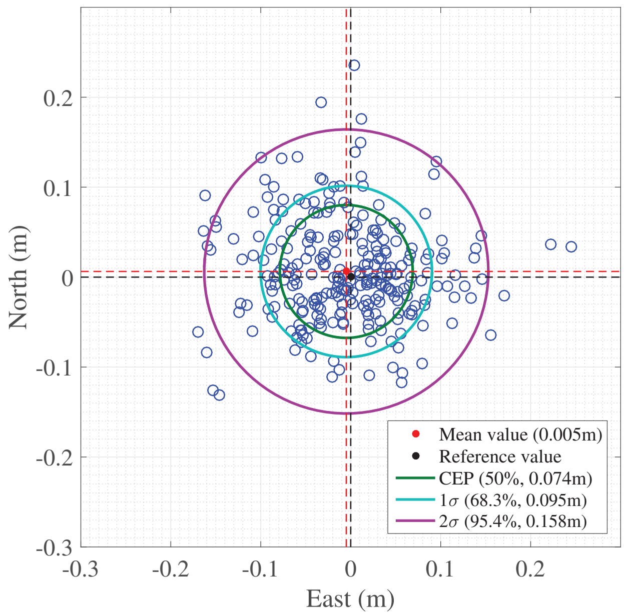
Fig. 11. Static scenario at lat/long 0°/0°



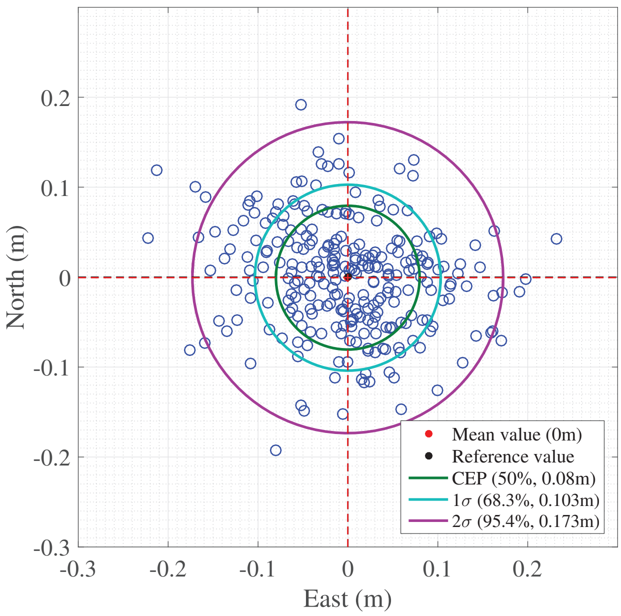
(a) Conducted test with GSS9000 TS788



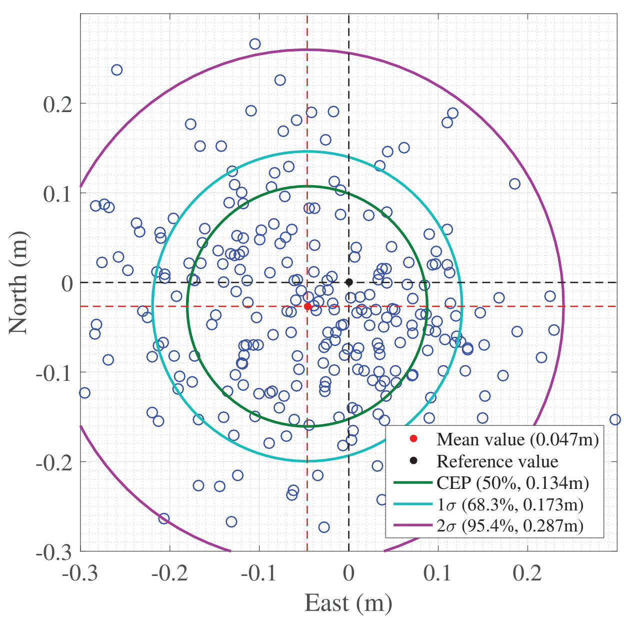
(b) Single emulation antenna test with GSS9000 TS788



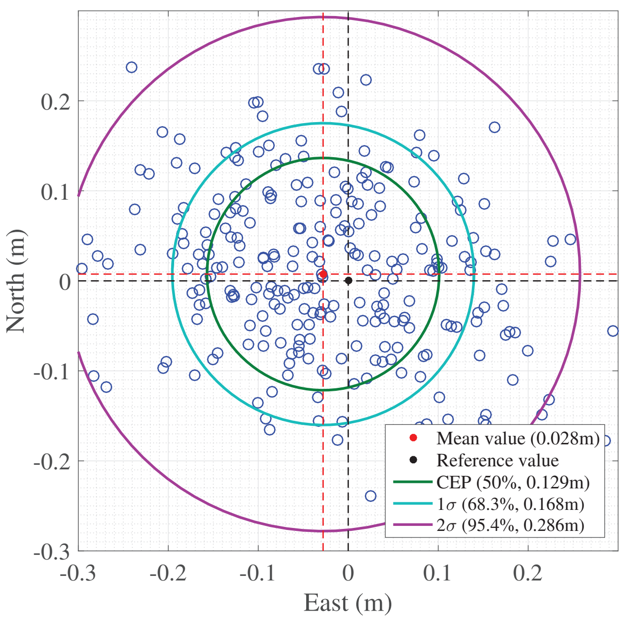
(c) Single-directional WFS OTA test with GSS9000 TS788



(d) Conducted test without antenna model with GSS9000



(e) Multi-directional WFS OTA test with GSS9000 TS788



(f) Conducted test with antenna model with GSS9000

Fig. 12. Race track scenario

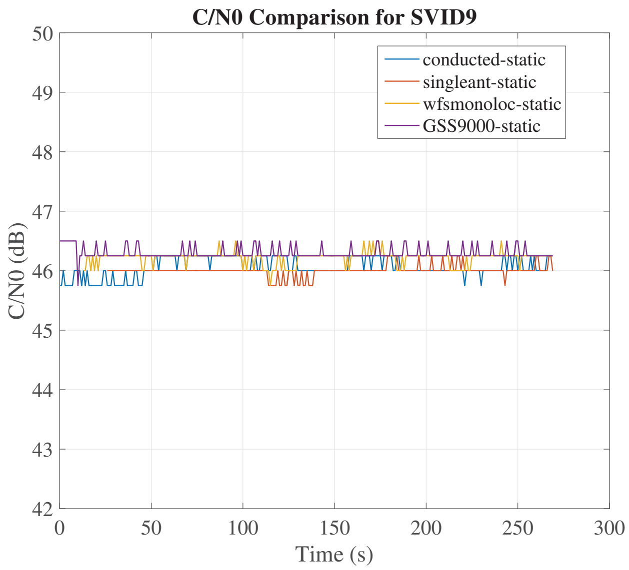


Fig. 13. Comparison of the absolute C/N0 of one, arbitrarily chosen satellite (SVID 9)

us to discover a delay bug in the FDSPs which was then resolved with a firmware update. Comparing the results of the WFS OTA (Figure 11(a) and Figure 12(a)) and the reference GSS9000 conducted tests (Figure 11(d) and Figure 12(d)), there are only slight variances of random and systematic positioning errors of less than centimeter level. Respecting the fact that these results are on the limits of the GPS L1 C/A resolution, one can say that the differences are not significant and the digital combination works correctly. The same holds for the single transmitter antenna test (Figure 11(b) and Figure 12(b)) as well as for the WFS OTA single direction scenario (Figure 11(b) and Figure 12(b)) where the resulting errors are nearly identical to the GSS9000 conducted reference results (Figure 11(d) and Figure 12(d)).

Transmitting the signals from multiple directions towards the receiver antenna results in additional attenuation, depending on the antenna level pattern and the angle of arrival, see Figure 8. To simulate comparable results one must also take the antenna level pattern into account. Since the WFS OTA scenario is 2.5D, this pattern should differ only between different coelevation angles for a single specific azimuth. We have taken a cut of the measured *NavXperience 3G+C* antenna level pattern, with respect to the orientation of the antenna in the anechoic chamber, to simulate the same scenario with the conducted GSS9000. Figure 13 shows the expected influence of the pattern on the C/N0. However, the results of the ”WFS OTA - Multiple Directions” test show some difference of up to 1 dB. One reason for this might be that the measurement level pattern used does not exactly match the specific *3G+C* antenna used in the experiment.

As in the previous scenario, the lower C/N0 for some satellites affects the variance of the positioning error. The results of both the WFS OTA multi-directional (Figure 11(e) and 12(e)) and the corresponding GSS9000 with antenna pattern (Figure 11(f) and 12(f)) measurement setups are quite similar in their variances. The higher variance is caused by the reduced C/N0 for the low elevation satellites. The systematic error in both cases results from the reduced C/N0 as well as from the antenna pattern phase variation that is only correctly accounted for in the OTA multiple directional WFS case. In conclusion, the few centimeters’ bias errors are negligible, and it is proved that the 2.5D WFS OTA works very well.

VI. Conclusion

In this paper, we described the general setup and principle of wave field synthesis over-the-air testing (WFS OTA) with emphasis on GNSS. Different tests to compare the WFS OTA GNSS's with a conventional GNSS simulator's results have been carried out and discussed. The non-WFS test results show the same performance as for the conventional GNSS simulator conducted ones. So do the single-directional WFS OTA ones, which validates the general WFS OTA GNSS installation.

The ”multi-directional WFS OTA” tests prove the capability of the WFS OTA to emulate the elevation of the GNSS satellites accurately – already in a 2D ring arrangement, if the DUT's elevation pattern is similar for different azimuth angles. We have shown that the positioning error due to the antenna pattern in phase and amplitude is accounted for during the OTA test. Therefore, receivers with integrated antennas can be tested more realistically in the WFS OTA, which would not be possible with conventional OTA single transmitter antenna tests when the antenna gain pattern is unknown.

For CRPA and beamforming antenna arrays that track the individual satellite in azimuth and elevation for a better interference mitigation (spoofer and/or multipath), a 3D WFS OTA emulation is mandatory. For the upcoming 3D WFS OTA setup, numerical simulations were performed and a 3D Lebedev grid arrangement with 29 circular polarized emulation antennas was analyzed. Simulations show that the WFS quality measurement in the error vector magnitude is constantly better than -30 dB compared to the ideal planar wave front for a DUT diameter of 0.3 m. This arrangement will be installed and tested in practice in the next step at the Facility for Over-the-air Research and Testing at Fraunhofer IIS. Similar verification measurement steps as carried out for this paper will be done in the fully 3D arranged WFS OTA anechoic chamber. Then also tests with GNSS array antennas and GNSS beamforming receivers will be performed to demonstrate the additional benefits that the WFS OTA GNSS provides.

References

[1] A. Rügamer, G. Del Galdo, J. Mahr, G. Rohmer, G. Siegert, and M. Landmann, “GNSS Over-the-Air Testing using Wave Field Synthesis,” in *Proceedings of the 26th International Technical Meeting of The Satellite Division of the Institute of Navigation (ION GNSS+ 2013), Nashville, TN, September 2013, pp. 1931-1943*, September 2013.

[2] G. Siegert, M. Landmann, A. Rügamer, F. Klier, J. Mahr, G. Del Galdo, and G. Rohmer, “Multi-directional Over The Air Testbed for Robustness Testing of GNSS Receivers against Jammers and Spoofers,” in *Proceedings of the 31st AIAA International Communications Satellite Systems Conference - ICSSC 2013*, 2013.

[3] M. Rumney, R. Pirkl, M. H. Landmann, and D. A. Sanchez-Hernandez, “MIMO over-the-air research, development, and testing,” *International Journal of Antennas and Propagation*, vol. 2012, 2012.

[4] R. K. Sharma, W. Kotterman, M. H. Landmann, C. Schirmer, C. Schneider, F. Wollenschläger, G. Del Galdo, M. Hein, and R. S. Thomä, “Over-the-air testing of cognitive radio nodes in a virtual electromagnetic environment,” *International Journal of Antennas and Propagation*, vol. 2013, 2013.

[5] W. Kotterman, M. Landmann, A. Heuberger, and R. Thoma, “New laboratory for over-the-air testing and wave field synthesis,” in *General Assembly and Scientific Symposium, 2011 XXXth URSI*, Aug 2011, pp. 1–4.

[6] Novatel/QinetiQ, “GAJT Anti-Jam Antenna,” http://www.novatel.com/products/gnss-antennas/gajt/, 2013.

[7] A. Rügamer, P. Neumaier, P. Sommer, F. Garzia, G. Rohmer, A. Konovaltsev, M. Sgammini, S. Caizzone, M. Meurer, J. Wendel, F. Schubert, and S. Baumann, “BaSE-II: A Robust and Experimental Galileo PRS Receiver Development Platform,” in *Proceedings of the 27th International Technical Meeting of the Satellite Division of the Insitute of Navigation, ION GNSS+ 2014*, September 2014.

[8] A. Konovaltsev, M. Cuntz, C. Haettich, and M. Meurer, “Performance Analysis of Joint Multi-Antenna Spoofing Detection and Attitude Estimation,” in *Proceedings of the 2013 International Technical Meeting of The Institute of Navigation, ION ITM 2013, San Diego, January 27-29*, 2013.

[9] C. Schirmer, W. Kotterman, G. Siegert, A. Rügamer, G. Del Galdo, A. Heuberger, and M. Landmann, “Accuracy of Realistic 3D Emulation Environments for GNSS and Multi-Satellite Receiver Testing,” in *Proceedings of the IEEE Sensor Array and Multichannel Signal Processing Workshop SAM’14*, 2014.

[10] P. Kyösti, T. Jämsä, and J.-P. Nuutinen, “Channel modelling for multiprobe Over-the-Air MIMO testing,” *International Journal of Antennas and Propagation*, vol. 2012, 2012.

[11] T. Laitinen, P. Kyösti, J. P. Nuutinen, and P. Vainikainen, “On the number of OTA antenna elements for plane-wave synthesis in a MIMO-OTA test system involving a circular antenna array,” in *Antennas and Propagation (EuCAP), 2010, Proceedings of the Fourth European Conference on*, 2010, pp. 1–5.

[12] A. Popugaev, R. Wansch, and S. Urquijo, “A Novel High Performance Antenna for GNSS Applications,” in *Antennas and Propagation (EuCAP), 2007, Processings of the Second European Conference on*, Nov. 2007, pp. 1 –5.