GNSS Over-the-Air Testing using Wave Field Synthesis

Alexander Rügamer[1], Giovanni Del Galdo[2], Johannes Mahr[3], Günter Rohmer[1], Gregor Siegert[2], Markus Landmann[2]
[1]*Fraunhofer Institute for Integrated Circuits IIS, Nuremberg, Germany*
[2]*Fraunhofer Institute for Integrated Circuits IIS, Ilmenau, Germany*
[3]*Technical University Ilmenau, Germany*

BIOGRAPHY

Alexander Rügamer received his Dipl.-Ing. (FH) degree in Electrical Engineering from the University of Applied Sciences Würzburg-Schweinfurt, Germany in 2007. Since the same year he works at the Fraunhofer Institute for Integrated Circuits IIS in the field of GNSS receiver development. He was promoted to Senior Engineer in February 2012. Since April 2013 he is head of a research group dealing with secure GNSS receivers and receivers for special applications. His main research interests focus on GNSS multi-band reception, integrated circuits and immunity to interference.

Giovanni Del Galdo received his Masters degree in 2005 in telecommunications engineering from the Politecnico di Milano and in 2007 his PhD from the Ilmenau University of Technology (TUI). He joined the Fraunhofer IIS and the International Audio Laboratories Erlangen as senior scientist. In 2012 he was appointed full professor at TUI as the head of the DVT Research Group, a joint activity between TUI and Fraunhofer IIS. His current research interests include the analysis, modeling, and manipulation of multi-dimensional signals, over-the-air testing for terrestrial and satellite communication systems, and sparsity reconstruction methods.

Johannes Mahr received his Master degree in Electrical Engineering from the University of Technology Ilmenau, Germany in 2012. Since that year he worked at the University department "Digital Broadcasting Research Laboratory". His main research interest was image based motion detection of vehicles. He was also working on the simulation of wave field synthesis at the Facility for Over the Air Research and Testing (FORTE) in Ilmenau.

Günter Rohmer received his Dipl.-Ing. degree in Electrical Engineering in 1988 and the PhD in 1995 from the University of Erlangen, Germany. Since 2001 he is head of a department at the Fraunhofer IIS dealing with the development of components for satellite navigation receivers, indoor navigation and microwave localization systems.

Gregor Siegert received his Dipl.-Ing. degree in Media Technology from the University of Technology Ilmenau, Germany in 2010. Since that year he works at the Fraunhofer IIS within the Project Group "Wireless Distribution Systems / Digital Broadcasting". He is mainly occupied with the Facility for Over the Air Research and Testing (FORTE). The Facility covers the test and development of satellite and terrestrial based communications systems under realistic but repeatable propagation conditions.

Markus Landmann received the Dipl.-Ing. and Dr.-Ing. (Ph.D.E.E.) degrees in Electrical Engineering from Ilmenau University of Technology (TUI), Germany, in 2001 and 2008 respectively. From 2001 to 2003 he worked as a research assistant and instructor at TUI. In 2004 he was developing advanced antenna array calibration methods and high resolution parameter estimation algorithm (RIMAX) for propagation studies at MEDAV Company. In 2005 he was visiting researcher and instructor at Tokyo Institute of Technology (Takada Laboratory) in the field of channel measurement and estimation techniques. From 2006 to 2008 he was finalizing his PhD thesis whilst a research assistant and instructor TUI. Between 2008 and 2009 his projects were in wireless propagation, channel modelling, and array signal processing for TUI and Tokyo Institute of Technology. In 2010 he started working for Fraunhofer IIS. He is mainly responsible for the Facility for Over the Air Research and Testing (FORTE).

ABSTRACT

This paper presents an over-the-air (OTA) wave field synthesis (WFS) system for test and certification of GNSS receivers. We discuss its application with respect to jammers, spoofers and classified signals and compare it to the state-of-the-art in GNSS receiver testing. Having outlined the OTA WFS system architecture, different test cases are described. We verify the emulated OTA environment on one selected test case in an experiment emulating a realistic GNSS signal and artificial jammers, while employing a 2x2 GNSS array antenna with a 4 channel receiver as de-

Proceedings of the 26th International Technical Meeting of the ION Satellite Division, ION GNSS+ 2013, Nashville, Tennessee, September 16-20, 2013

vice under test. The results in terms of direction of arrival estimation and jammer mitigation are finally presented to proof the concept and feasibility of the multi-directional over-the-air testbed. Moreover these results show the need for accurate jammer propagation modelling.

INTRODUCTION

Multiple-Input Multiple-Output (MIMO) Over-The-Air (OTA) testbeds are typically deployed for certification, performance testing and product evaluation of mobile devices utilizing broadband wireless technologies, e.g. Long Term Evolution (LTE) or LTE-Advanced. However, the demand for a reliable performance assessment of next generation Global Navigation Satellite System (GNSS) receivers is constantly increasing. In contrast to a mobile phone that encounters a harsh mobile environment only, GNSS receivers are also 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 of blind people. Moreover, GNSS time is widely used for synchronisation of distributed systems, e.g. of mobile phone base station networks, phase-synchronous current injection of decentralized power plants and many more.

Due to the inherently low power of GNSS signals (approx. -127 dBm received signal power on earth), the GNSS bands are dominated by white Gaussian noise. The noise is about a hundred to a few thousand times stronger than the GNSS signals themselves. As a consequence, the GNSS signals are extremely susceptible to all types of interferences. These interferences can be unintentional, e.g. the harmonics of certain oscillators that translate into single Continuous Wave (CW)-tones or multi-tones in the GNSS spectrum. However, there are also more and more intentional interferers readily available on the Commercial-Off-The-Shelf (COTS) market, mostly sold over the internet, even if their use is illegal in most countries. Whereas jammers are used for denial-of-service attacks, spoofers pose an even bigger threat, since they can intentionally lead a receiver to estimate a fake position and/or time without recognizing it. All of these interferences, unintentional or on purpose, have one aspect in common. Only a very small amount of output power is sufficient to exceed the thermal noise floor and therefore to effectively disturb the GNSS signals on the receiver side.

To provide protection against interferences, GNSS receiver using 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 impairment. Already commercial products are available on the market, like the 7-element CRPA named GAJT from Novatel/Qinetiq [1].

A more sophisticated solution provides a beamsteering antenna, e.g. developed by the German Aerospace Center (DLR) and used within the BaSE project [2]. In this approach, a beam is steered in each direction of the satellites to be received. Due to the increased gain in a specific direction, possible interferences coming from other directions are already attenuated. Moreover these beamsteering antennas give the possibility to detect spoofing. Typically, a spoofer broadcasts all signals from a single point in space, whereas the desired GNSS information is inherently linked to a spatial diversity of the satellites. 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 an effective spoofing detection [3].

Another non-antenna dependent defence against spoofers is to use encrypted signals. While the encrypted GPS PPS is intended for military use only, the Galileo system offers with its Public Regulated Service (PRS) an encrypted signal for civil usage not limited to military operations. Nevertheless, it is a classified signal. This could mean that the operation of non-certified PRS receivers is prohibited in an unprotected environment.

At the moment, mass-market receivers, e.g. shipped with smartphones, 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 is regarded a must and necessary to guarantee a certain minimum standard. Hence, the goal of this work is to develop a new testing method for interference robustness assessment of GNSS receivers using integrated antennas, external ones, but especially also receivers with phased array antennas. The test applications shall range from classical open service GPS/Galileo signals to classified signals (e.g. GPS PPS or Galileo PRS). To avoid inherent drawbacks of conventional approaches (e.g. conducted or free field tests), the method of choice is OTA testing under repeatable and shielded laboratory conditions. Special care will be taken for the emulation of the propagation conditions that jammers and spoofers are subject to.

First state of the art test setups for GNSS receiver testing are summarized. Then we introduce our multi-directional over-the-air testbed for GNSS receiver testing, whereas its test cases are discussed in following *Test cases* section. Finally, the proposed concept is proven and demonstrated with a directional GNSS test receiver setup before we draw conclusion.

STATE OF THE ART TEST SETUPS

Three different test setups can be distinguished and will be briefly described in the following. Furthermore, their usability w.r.t. the targeted application of GNSS robustness tests against interference is analysed.

Conducted tests

Conducted tests are regarded as the state-of-the-art. In these setups, a RF-GNSS constellation emulator is directly connected to the Device Under Test (DUT) bypassing the antenna. Such a RF emulator provides great advantages in the receiver development and verification phases and finally in performance evaluations. Moreover completely different scenarios in terms of satellite constellation used, dynamics of the movement, multipath environment and so forth can easily be set up and tested. However there are still several limitations. Firstly, the DUT as well as jammers or spoofers may have integrated antennas that make a direct connection impossible. Secondly, cable-connected tests bypass the antenna characteristics and therefore neglect its influence on the receiver performance. This is a major limitation for mass-market receivers with integrated antennas (e.g. smartphones) as well as for sophisticated beamforming receivers where the antenna(s) of the device are a critical factor in the performance evaluation.

Free field tests

To avoid the shortcomings of a conducted test, a free field test range is the common choice to evaluate receivers with their antenna. However, the test conditions are not really reproducible, which makes the direct comparison of different devices or algorithmic implementations difficult (e.g. the GNSS satellite constellations, weather conditions or multipath environment might vary between each test run). Additionally, no future or intentionally changed GNSS constellations can be simulated. To assess the robustness of a receiver, optimize its algorithms, or to certify its performance in presence of interferences a specially protected test range is necessary. Such protected ranges are available for military tests, e.g. in the missile test range Vidsel, Sweden [4] or at the White Sands Missile Range *JAMFEST* in New Mexico, USA [5]. Due to their military origin they are most often only temporally available and not always open for public or commercial usage. 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) are generally not allowed in conventional free field test beds, since stringent anti-tamper requirements and limitation of radiation have to be guaranteed. This issue was also identified in a study from 2009, which discussed the requirements and consequences if *GATE* was extended for Galileo PRS usage [6].

Uni-directional over-the-air tests

The OTA testing approach combines the advantages of both previous methods and overcomes their inherent drawbacks. In general the DUT is placed inside an anechoic chamber in which the real-world scenario, e.g. a GNSS receiver is subject to interference, is emulated via an OTA illumination antenna. A GNSS constellation simulator is used to generate arbitrary test signals and the receiver is tested together with its antenna(s). This approach provides a repeatable and fully controllable test environment, with no need for special frequency licensing or other anti-tamper restraints thanks to the anechoic chamber.

Currently, in the GNSS domain, these OTA setups are used mainly for Assisted GPS (A-GPS) testing of mobile phones, that employ integrated antennas for multiple services (e.g. LTE, WiFi, GPS, etc.). Different commercial GNSS OTA test systems are available on the market, e.g. from Spirent[1] or Agilent[2]. These systems only use a single transmission antenna to radiate the composite RF signal of all GNSS satellites and also the interferers to be simulated. However, this approach neglects the capabilities of beamforming antennas, that have a clear benefit in a real-world environment with multi-directional sources.

The consequent enhancement of these single transmitter uni-directional OTA testbeds is to use a dedicated transmit antenna for each satellite to be emulated in a certain constellation. This approach allows now testing of GNSS receivers that employ beamforming as it requires spatial array processing. First commercial solutions are available on the market, e.g. the GSS7790[3] from Spirent, intended for CRPA testing. In this setup the RF constellation simulator provides separated RF outputs for the satellites to be simulated. However, also this approach faces some limitations. Firstly, the physical setup of the transmit antennas has to be replicated in the anechoic chamber in such a way, that the intended scenario matches the actually emulated one. A change in the scenario constellation results in the need of a physical reordering of the transmit antennas to match the emulated satellite position in terms of azimuth and elevation. Secondly, the movement of the satellites is only simulated in the broadcasted navigation messages, i.e. the physical transmit antennas do not change their position over time. This may lead to problems in long term tests. Thirdly, the emulation of interference signals that are subject to multipath propagation is also limited to the physical

[1] http://www.spirent.com/~/media/Datasheets/Mobile/8100_AGPS_OTA_Test_Solutions_datasheet.pdf

[2] http://cp.literature.agilent.com/litweb/pdf/5990-4655EN.pdf

[3] http://www.spirent.com/~/media/Datasheets/Positioning/GSS7790.pdf

alignment of the transmit antennas and cannot be changed within the tests in an arbitrary way.

In general, a similar problem is present in the field of MIMO device testing in the communication area, e.g. for LTE mobile phones and systems. One approach used there to include the spatial interaction between antennas and radio environment is the application of Wave Field Synthesis (WFS) for testing wireless equipment. This is also known as Over-The-Air testing and is the technology of choice for testing the full potential of MIMO systems.

An OTA system with WFS can be regarded as an evolution of the previously described uni-directional OTA setups. Here, the physical direction of the received GNSS signals, multipath components or jammers are emulated with WFS. This approach also allows for a continuous angular motion of the transmitter (satellite, jammer, spoofer) in space. Moreover, huge dynamic changes, in terms of doppler shift, can be emulated (e.g. acceleration of a rocket or plane) via WFS without the need of physically moving the DUT.

To the authors' knowledge, the use of an OTA system employing WFS for GNSS testing has not been used nor described yet. In the following the paper discusses the architecture of an OTA system incorporating WFS for GNSS testing.

SYSTEM ARCHITECTURE OF THE MULTI-DIRECTIONAL OVER THE AIR TESTBED

Fraunhofer IIS operates a laboratory, called Facility for Over-the-air Research and Testing (FORTE) in Ilmenau, Germany. This facility hosts two research platforms in satellite and terrestrial communication, referred to as *SatCom* and *MIMO-OTA* testbeds. The MIMO-OTA research is mainly focussed at OTA test methodologies, Wave Field Synthesis, Cognitive Radio (CR) nodes and also evaluation of GNSS receivers. The benefits from this controlled test environment are clearly the accurate and reproducible performance assessments of wireless terminals equipped with multiple antennas. With the projected equipment, a state-of-the-art OTA installation is and will become available in near future (fully operational at the end of 2014/beginning of 2015).

Specifications of the complete OTA test laboratory

The connectivity of the OTA channel emulators produced by IZT GmbH will be 12×32 (12 input, 32 phase coherent physical output channels), currently 8×28 channels are supported. Every single physical channel (out of 12×32) is hereby convoluted with its unique channel impulse response controlling delay, phase and amplitude of the individual signals. Each of the 32 output signals is the superposition of the 12 convoluted input signals. The signal bandwidth supported is 80 MHz across a frequency range from 350 MHz to 3 GHz (for 4×4 channels up to 18 GHz). For CR and GNSS testing two frequency bands with larger separation can be used for emulation, but still with an instantaneous bandwidth of 80 MHz for each band. The maximum RF output power is +10 dBm. The generation of the delay characteristics can be accomplished by performing the convolution of the signal with the channel impulse response either in time or frequency domain.

In Figure 1 the general OTA test setup is depicted. Note, that in case of GNSS receiver evaluation the uplink path is not required and all available channels (12×32) are used to generate the GNSS downlink channel applying WFS. For WFS, each of the 28 (in future 32) available dual-polarized OTA illumination antennas radiate a signal with well-defined phase and a plane wave for a certain direction at the DUT, see Figure 3 for a visualization of this principle.

The convolution of the 12 input signals with the 12×32 complex impulse responses has to be performed in real time. By employing such a WFS the constituted wave field can be arbitrarily shaped to emulate real-world electro magnetic environments.

Adaptation of the OTA testbed for GNSS receiver robustness evaluation

In this paper the current communication-based installation is analysed and its suitability for GNSS testing is assessed, especially for scenarios involving interferences. The adapted OTA setup is depicted in Figure 2.

A tailored solution of a *Spirent* GNSS satellite constellation simulator generates an individual digital baseband output signal for each satellite to be emulated. Two carrier frequencies with up to 8 satellite channels are supported, expandable to max. 40 satellite channels. All GNSS are supported, namely GPS, Galileo, GLONASS and Beidou. Moreover, also the support of the encrypted Galileo PRS on E1 and E6 is foreseen. The maximal digital 3-dB bandwidth of each channel is 61 MHz which is even sufficient for the complete Galileo AltBOC signal.

The delay between the satellites and the DUT will be applied to the individual baseband signals of each satellite in the GNSS satellite emulator. A maximum of 12 baseband signals (e.g. 6 Galileo E1/E6) are streamed via optical 10 GBit/s links to the channel emulator consisting of a so called *FDSP* units, see Figure 2. This channel emulator adjusts the correct signal power of the simulated constellation according to the chosen propagation conditions. Another input to the OTA WFS are the spatial mapping parameters of each simulated satellite provided by a GNSS satellite emulator (in this case from Spirents *PosApp*). The RF output signals are finally radiated via the OTA illumination antennas that are surrounded by the shielded anechoic chamber.

In that way the realistic angular characteristic of the wave field for the DUT (e.g. a GNSS receiver with integrated

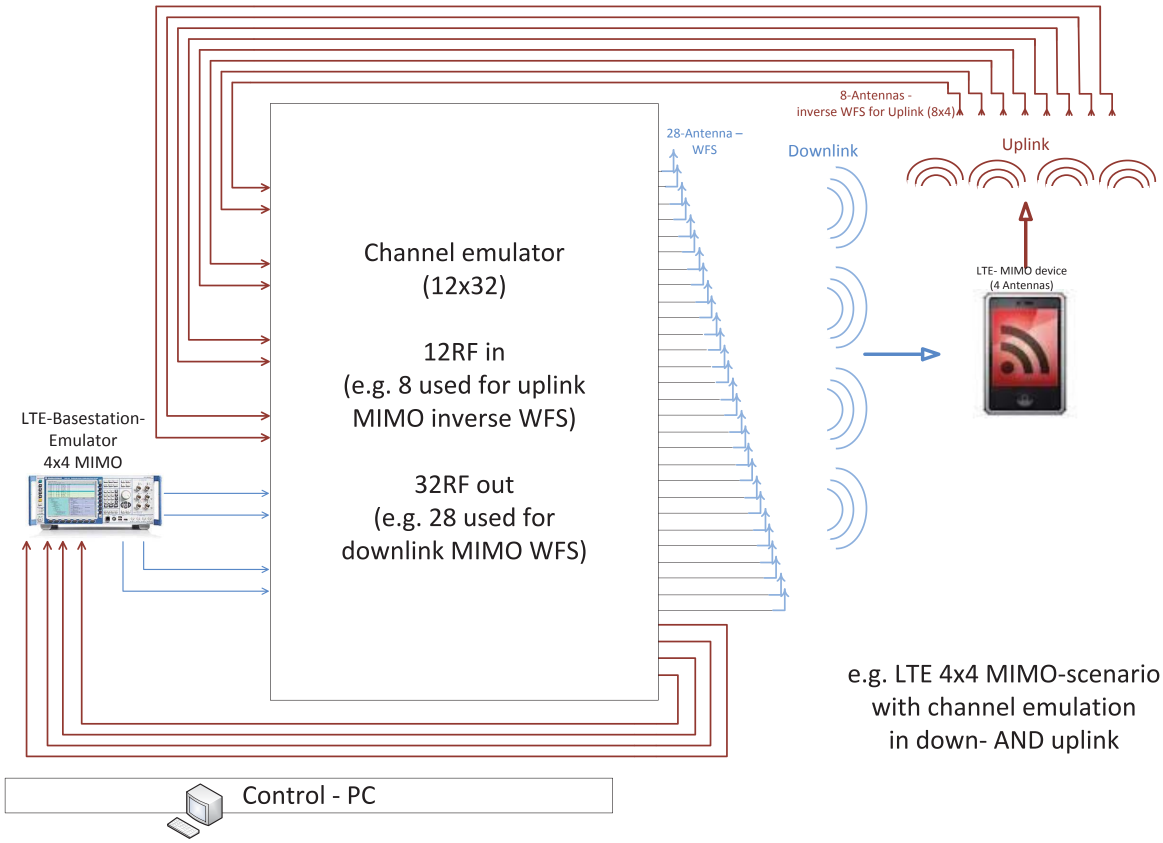


Figure 1: MIMO-OTA closed loop test setup.

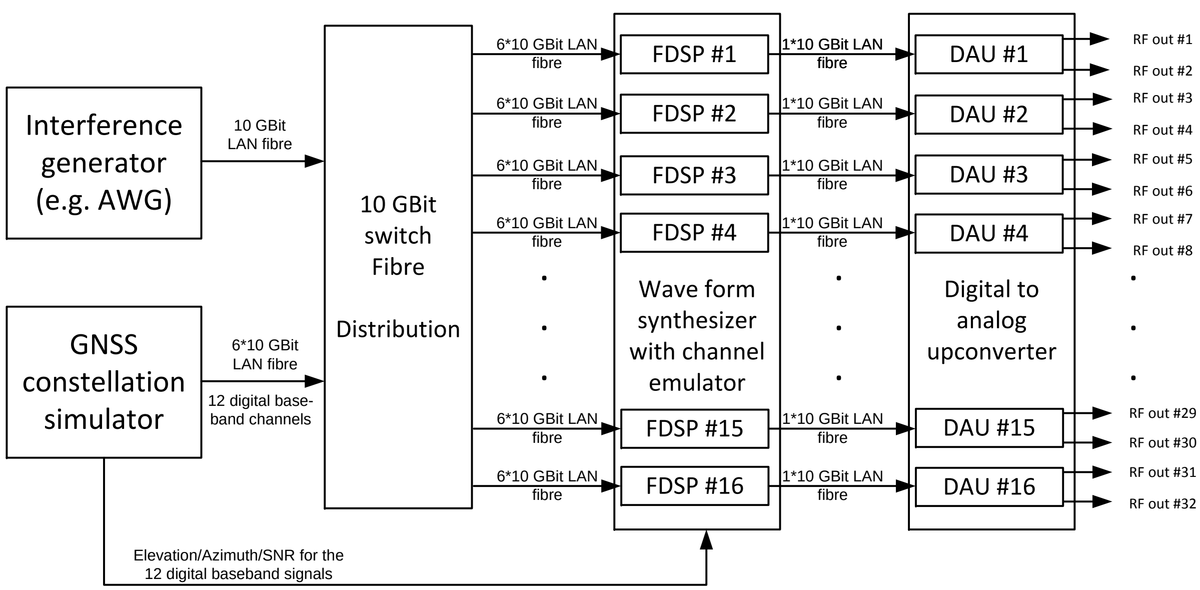


Figure 2: Detailed diagram of the OTA setup for GNSS receiver tests. A GNSS satellite simulator provides up to 12 streams in digital baseband. All of these inputs are distributed via fibre optic LAN to each of the 16 *FPGA-Digital Signal Processors* (FDSPs), where the actual signal convolution with the channel impulse response is performed. Each FDSP streams two composite digital output signals over LAN to its corresponding *Digital to Analogue Upconvertor* (DAU), which transmits the output signals via the OTA illumination antennas.

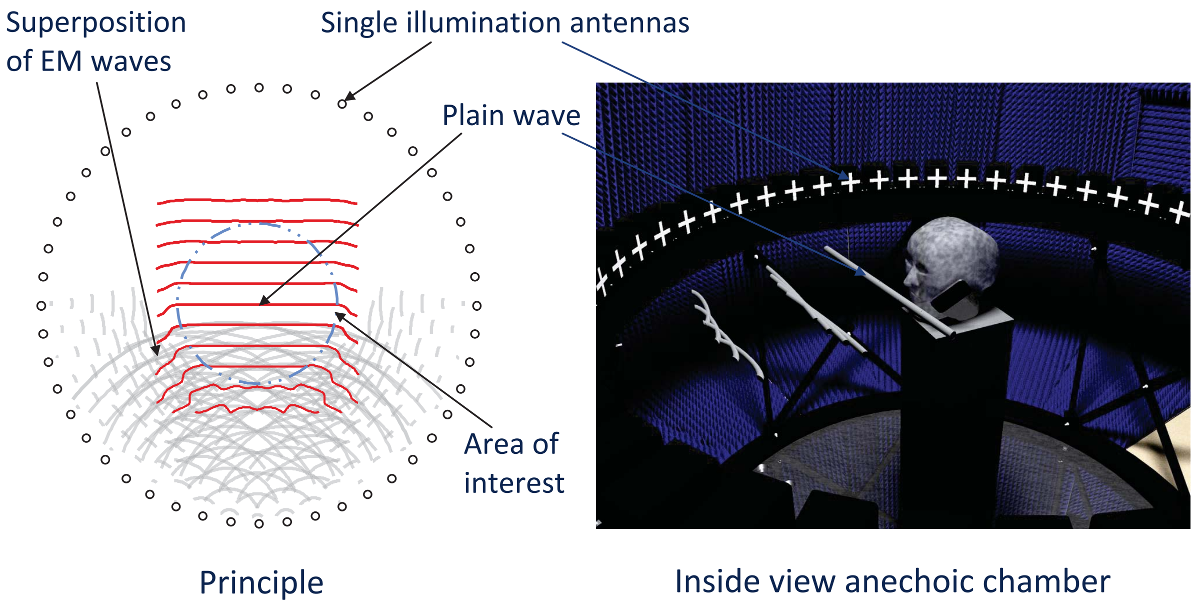


Figure 3: Principle of wave field emulation in OTA test system.

phased array antenna) including jammers and spoofers is emulated. Special care has to be taken for the emulation of the latter, as these interferers are usually subject to terrestrial channel effects, i.e. multipath propagation. In the worst case, a phased array based receiver might be able to null the LoS direction of an interferer, but a strong reflection from another Angle of Arrival (AoA) might also cause severe harm to the receiver positioning algorithm. The anechoic chamber, surrounding the OTA illumination antennas, provides an isolation of approx. 80 dB, making this testbed also suited to be used with classified signals (e.g. Galileo PRS). Moreover, also receivers which are not certified yet in their anti-tamper properties (e.g. within the development phase) can already be used for tests with their antenna in this protected environment.

The scientific and technological challenges of the adaptation of the OTA testbed to full GNSS needs, are the hardware and resource efficient spatial temporal emulation of the wave field for the GNSS satellites, as well as for jammers and spoofers. In the following different test cases will be discussed.

GNSS RECEIVER TEST CASES

In standard conducted tests GNSS receiver are most often qualified for parameters like acquisition time in cold/-warm/hot-start mode, acquisition and tracking sensitivity, time-to-first-fix and so forth. Additionally, there are tests defined against continuous wave and pulse interferences. But these interference tests are rather theoretical since they are quite abstract to the challenges in the real world. Since anti-jamming capability is getting more and more important an OTA setup provides much more possibilities of interference tests.

In general, the OTA system with its WFS can be used as an arbitrary waveform generator (AWG). This means that artificial jammer signals can be generated e.g. CW, swept-CW, narrow/wideband-noise, pulses, chirps with different parameters and power levels. Moreover, the anechoic chamber can be used to record real-world jammers and reuse them afterwards for the different test cases described in the following.

As mentioned before, array antennas are a promising way of interferer mitigation in GNSS processing. Since the accuracy of the WFS is, among other parameters, highly linked to the size of the array antenna under test, it is necessary to investigate the possible DUT diameters. Table 1 gives an overview of different array antennas available today with their diameters.

Test case 1: Jammer & spoofer emulation considering LoS only

This test case is designed to test GNSS receiver robustness against strong interferers (jammers and/or spoofers). The interferer's velocity and distance relative to the DUT can be controlled by the emulation environment. In this case, all GNSS signals are transmitted as composite signal via a single antenna. This means, the receiver's capability of spatial processing of the GNSS signal can not be tested – similar to the A-GPS test method described in Section *State-of-the Art*. However, the capabilities of the described OTA system can be fully used for jammer and/or spoofer emulation. By sweeping the interference signal in arbitrary horizontal directions (only 2D arrangements are taken into account at the moment) around the receiver up to extremely high dy-

Table 1: Overview of some available CRPA antennas

Manufacturer	Model	Nr of Elements	Diameter [mm]	Reference
AntCom	3-Element-5-Channel CRPA	3	120	[7]
AntCom	4-Element CRPA L1/L2 GPS	4	120	[7]
AntCom	5-Element-10-Channel	5	150	[7]
AntCom	7-Element CRPA	7	178	[7]
AntCom	15-Element-30-Channel CRPA	15	267	[7]
DLR	Galant	4	270	[3]
Novatel	GAJT	7	290	[1]
Satimo	CRPA	7	365	[8]

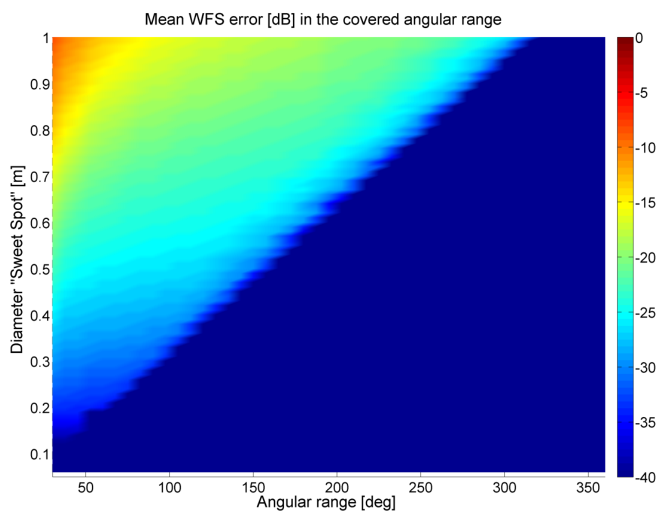


Figure 5: Comparison of mean error [dB] between WFS and optimum plane wave for aperture diameter (*sweet spot*) versus number of antennas. Note that for this simulation the angular spacing of the OTA antennas is set to the minimum value of 7.5 °, which gives a varying covered angular range for different numbers of antennas.

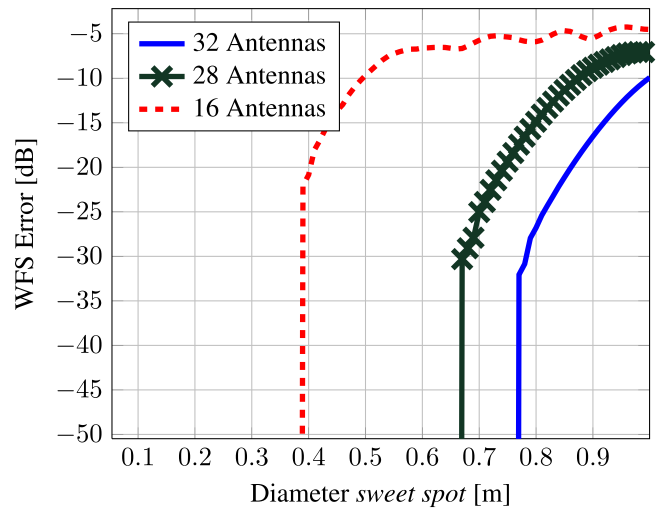


Figure 7: Comparison of mean error [dB] between WFS and optimum plane wave for different aperture diameters (*sweet spot*) and three different numbers of antennas (16, 28, 32). These results always correspond to an angular coverage of 360 °, i.e. the spacing between adjacent antennas varies for different numbers of antennas.

namics, the receiver's interference mitigation algorithms, e.g. adaption of the CRPA and interferer DoA estimation, can be challenged. The interferer is only simulated for Line of Sight (LoS), i.e. channel impairments are not simulated. This test scenario covers the minimum requirement of OTA GNSS robustness tests. Currently, the maximum number of uncorrelated interferences that can be emulated in parallel is 8 (in 2015 up to 12). The setup for this scenario is illustrated in Figure 4.

As the emulation accuracy depends on the size of the DUT, a simulation was performed to analyse the emulation error w.r.t. the DUT diameter and desired angular range. Figure 5 shows that with an increasing diameter of the DUT the emulation accuracy decreases. However, since GNSS receivers work at a very low SNR in the range of 0-30 dB even after correlation, an emulation accuracy larger than this range is not required. Due to the physical size of the used antennas, the minimum spacing between the OTA illumination antennas is 7.5 °. This means that the covered angular range is always the product of 7.5 ° times the number of antennas. From Figure 5 it can be seen that the full angular range of 210 °, which corresponds to 28 antennas, results in a maximum DUT diameter of 65 cm for 30 dB SNR and 80 cm for a SNR of 20 dB. If several jammers or spoofers have to be emulated with a larger separation than 210 °, this range can be subdivided resulting in an overall smaller maximum DUT diameter.

In comparison with the overview of the available GNSS array antennas in Table 1, the possible aperture diameter of 0.65 m is sufficient for all of the mentioned antennas in this simulated 2D arrangement with one interference source.

Test case 2: Jammer & spoofer with multipath propagation

The previous test case is somehow relevant to show the robustness of a GNSS receiver in a first step. However, in reality not only the LoS path between spoofer/jammer and

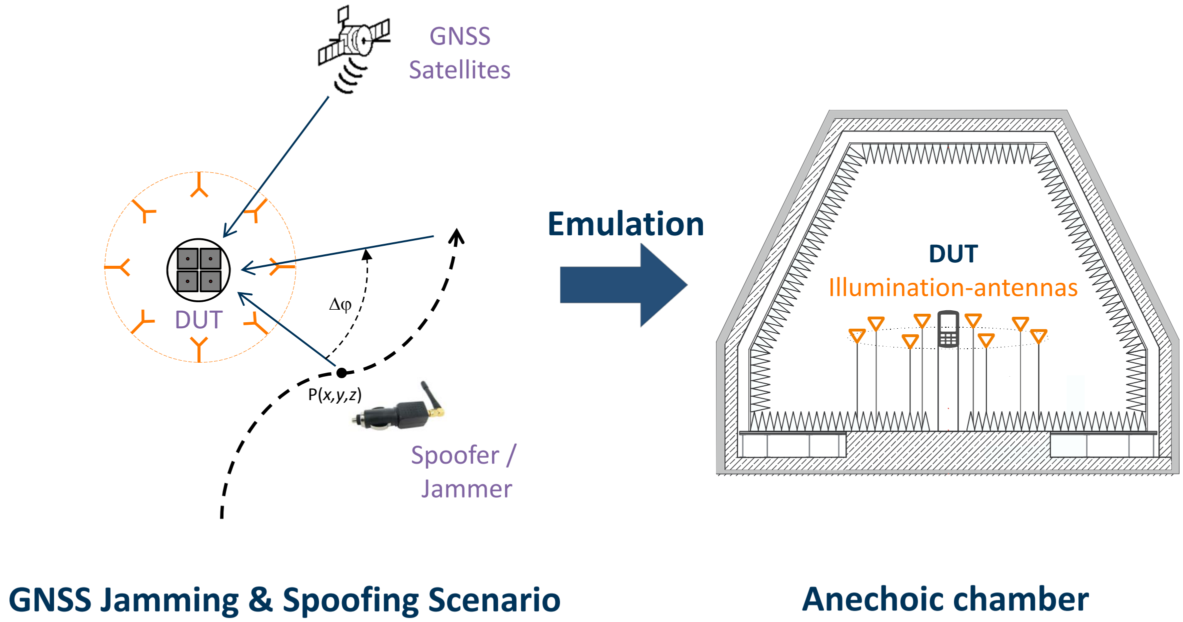


Figure 4: Test case 1, covering a moving interferer from LoS. The GNSS signal is radiated as composite signal.

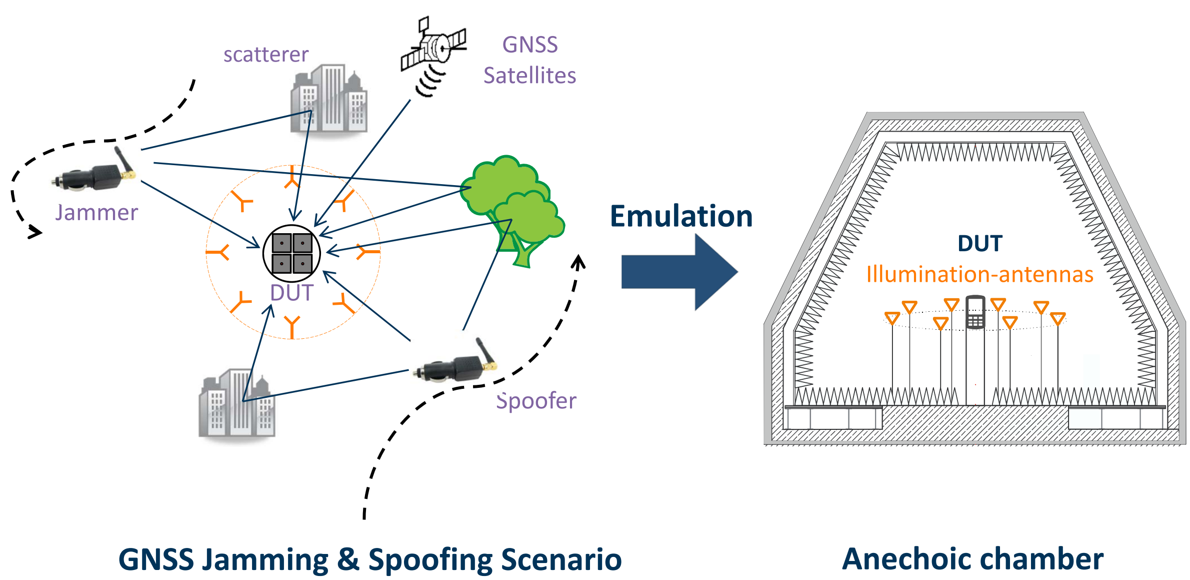


Figure 6: Test case 2, covering moving interferers that are subject to multipath propagation. Again, the GNSS signal is radiated as composite signal.

the DUT exists. An interferer is also subject to strong reflections and scatterers, leading to multipath propagation that may cause serious harm to the receiver, as the reflections can still be much stronger than the targeted GNSS signals. In consequence not only the direct path, but also the reflections have to be taken into account. In this case, the receiver's interference mitigation algorithms have to be capable of null steering to cancel interferences from multiple directions in a time variant channel. The test case that accounts for this is sketched in Figure 6. The generated multipath propagation is based on channel models that are used in mobile communications (e.g. WINNER channel model [9]) as the terrestrial channel between a jammer/spoofer and the GNSS receiver does not differ from the channel of any other mobile device. In contrast to the first test case the angular range to be covered has to be 360° in order to emulate a complete real-world scenario. In Figure 7 the WFS error considering the usage of 32, 28 and 16 OTA illumination antennas is shown. It can be seen that below a certain diameter the WFS is "infinitely" accurate, whereas above this threshold the resulting field is biased, i.e. the WFS accuracy becomes finite.

Test case 3: Jammer & spoofer in a dynamic multi-satellite GNSS emulation

The full three-dimensional emulation of the entire GNSS scenario, including the emulation of each individual GNSS satellite and its orbit, as is shown in Figure 8, is most challenging. However, it can be assumed that for one satellite the emulation accuracy of the WFS is the same as the simulations shown in the previous test cases. Based on these results a fixed constellation of satellites applying one or more OTA illumination antennas for each satellite is already possible. However, currently it is analysed in which way the OTA illumination antennas have to be placed in a three dimensional hemisphere to achieve a sufficient emulation accuracy for multiple satellites on changing orbit positions. The aim is to emulate up to 6 satellites on two frequency bands or 12 on one. As a jamming source in this scenario a commercially available *privacy protection device* could be used and placed anywhere in the anechoic chamber. Both GNSS beamsteering algorithms to track single satellites as well as the nulling of interferers can be tested. In a similar way, a potential spoofer can be simulated, by transmitting a composite GNSS signal from a single OTA illumination antenna.

PROOF OF CONCEPT WITH A DIRECTIONAL GNSS TEST RECEIVER

In this Section preliminary results with respect to test case 2 are presented. The goal is to prove the general test principle and the feasibility to test beamforming algorithms and receiver in this test environment.

In this test case, the ability of a beamforming GNSS receiver to track the individual GNSS satellites is neglected. Instead, the goal of this test is to assess the performance of interference mitigation. The target GPS signal was radiated as composite signal from a single OTA illumination antenna at 1575.42 MHz (L1 frequency band). From the array antenna's point of view, this target signal was radiated at an elevation of $\theta = 87^\circ$, since the array was placed normal to the OTA antenna plane (i.e. the arrays $x - y$ plane is the $z - y$ plane of the OTA illumination antenna ring).

The interferer was radiated from two different directions (see Figure 9). The main jammer was placed at an elevation θ of about 43°, with a transmit power of 15 dB above the desired Global Positioning System (GPS) signal. To simulate a strong reflection, the same interference signal was transmitted from $\theta = 30^\circ$, still 5 dB above the GPS signal. The total duration of interference was $\sim 5\,\mathrm{s}$, in which the GPS signal was completely jammed. In this scenario only a static environment was emulated, i.e. the jammers were not moving.

The GNSS beamforming test receiver comprised a 2×2 active antenna array in combination with four Universal Software Radio Peripherals (USRPs) [4]. All four signals from the antenna array were captured phase synchronously and digitized by the USRPs for post analysis and processing.

The GPS test sequence was obtained from the Spirent GNSS Simulator GSS8000[5], available at Fraunhofer IIS using the Flexiband USB recording front-end [10]. Both, GPS test signal and jammer were 5 MHz wide. The jammer itself was modelled as multi tone signal with 224 frequency bins, which leads to a period length of $44.8\,\mu s$. This test signal may oppose typical jammers, that can be classified as narrow-/wideband AWGN, chirped or pulsed signals. However, it was considerably chosen, as it is well suited for the characterization and comparison of all four antenna output channels.

DoA estimation

The key idea for OTA test methodologies is to emulate a plane wave inside the *sweet spot* surrounding the DUT for a virtual source from a specific direction. The direction of target signals or interferers has to be estimated by the receiver prior to either steering a beam towards the source or to null it. In case of GNSS receivers, the almanac of satellite positions supports the DoA estimation, but interferers have to be estimated based on the signal.

As discussed previously, the synthesized wave field may deviate to a certain extent from the ideal field, which automatically affects the DoA estimation of phased array antennas, since the wave will not be plane over the entire array aperture. With this test setup it shall be shown that the receiver's antenna array "sees" the same environment as intended. To estimate the AoA of the different sources, a

[4] https://www.ettus.com/product/details/UN210-KIT

[5] http://www.spirent.com/Products/GSS8000

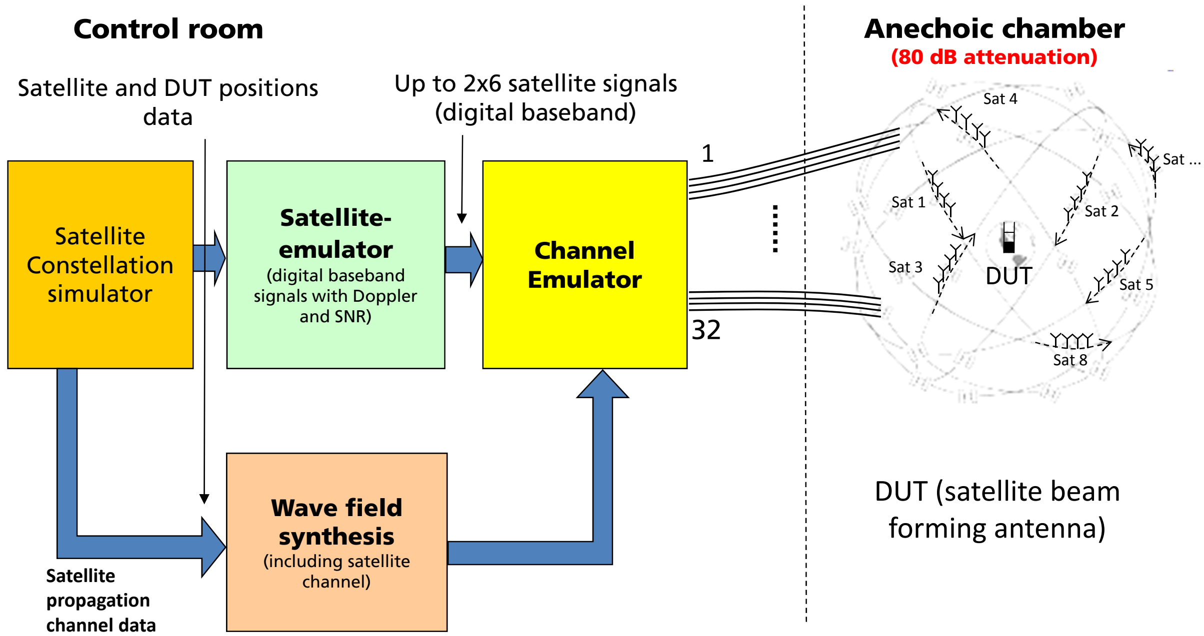


Figure 8: Test case 3, covering the emulation of a full multi-directional GNSS constellation and moving interferers that are subject to multipath propagation.

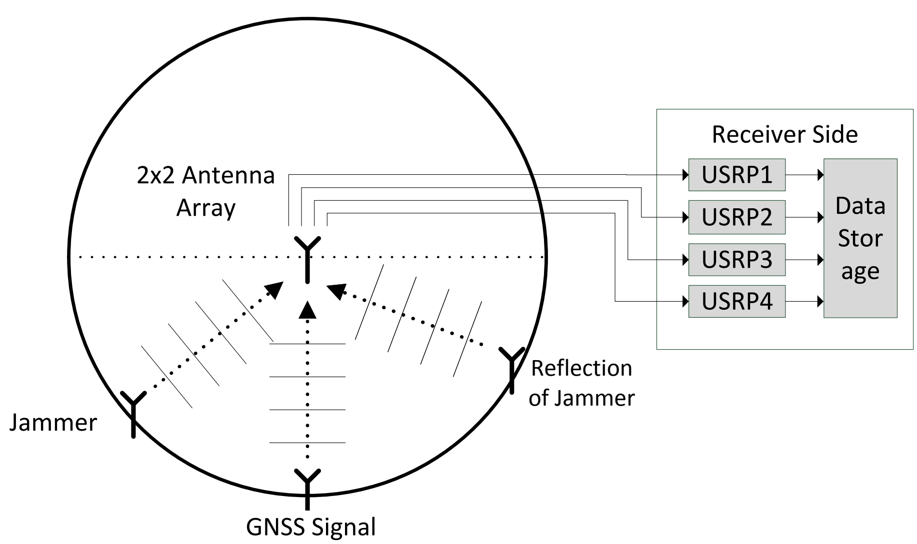
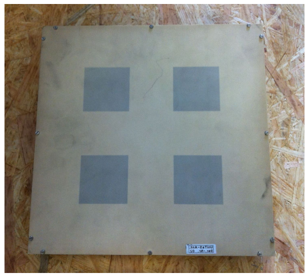


Figure 9: Test setup for test case 1. The target GNSS signal is transmitted as composite signal above the center of the receiver array antenna. The main interferer is radiated from the right side of the antenna, a strong reflection from the left side. All antenna channels are stored synchronously for post processing beamforming.



(a) Active 2×2 Antenna Array (see [3]).

(b) Setup with four USRPs, synchronized via PPS and an external reference clock.

Figure 10: Antenna Array and USRPs used for experimental setup.

maximum likelihood parameter estimation algorithm such as [11] was applied. Figures 11a to 11c show steered beams that result from the DoA estimation.

The best result is achieved for the main interferer, which is also the strongest source. The other two sources, GPS signal and interferer reflection, are estimated close to their actual angular position coordinate.

Mitigation of Interference

After DoA estimation of interferers an interference cancellation has to be performed. For that purpose, a beamforming technique known as *null steering* is typically applied. This means, that the N-element output of the antenna array has to be weighted in such a way, that the array response is minimum in the DoA of the interferer. In this case a linear constraint minimum variance (LCMV) approach was used. As shown in [12], the optimum complex weight vector $\mathbf{w}_{opt}$ can be obtained from Equ. 1.

$$\mathbf{w}_{opt} = \mathbf{R}_{xx}^{-1}\mathbf{C}\left(\mathbf{C}^H\mathbf{R}_{xx}^{-1}\mathbf{C}\right)^{-1}\mathbf{g} \tag{1}$$

In this context $\mathbf{R}_{xx}$ is the covariance matrix for the N-dimensional array output $\mathbf{x}(t)$ at a given time t. $\mathbf{C}$ is the constraint matrix containing the steering vectors of the beamformer for directions to suppress or to intensify. The obtained weight vector has to satisfy Eq. 2.

$$\mathbf{C}\mathbf{w}_{opt}^H = \mathbf{g} \tag{2}$$

The vector $\mathbf{g}$ contains the desired gain for the array response in a certain direction, i.e. 1 for the direction of the target signal and 0 for the interferer.

Following this approach two nulls were set to mitigate the interferers signals. Figures 12a to 12c show the results of beamforming and nullsteering for one time stamp of the sample data.

From Figure 12c it can already be seen that in this setup, the target direction is also slightly attenuated, when both directions of interference are nulled. This is surely due to the limited number of elements and also to the high elevation of the main interferer.

After computing the optimum weight vector for the N antenna outputs, the combined signal for all time instances of the sample data was obtained from Eq. 3.

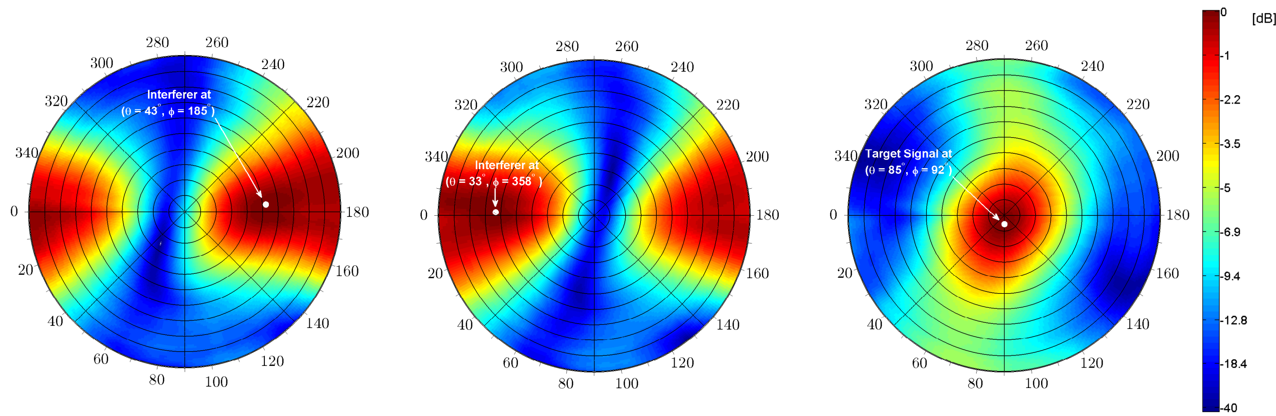
$$y(t) = \mathbf{w}_{opt}^H\mathbf{x}(t) \tag{3}$$

This signal was then replayed to a commercial uBlox5 GPS receiver, to get the GPS position estimate. In case of only one jammer (i.e. main jammer or its reflection) interfering with the GPS signal the interferer is successfully mitigated. Consequently, the GPS position estimate was valid also during the jammed sequence. The GPS receiver clearly fails to track the GPS signal, as soon as the jamming starts.

As was expected from Figure 12c, when jamming the GPS signal from multiple directions by means of a strong reflection of the jammer signal due to multipath propagation, the interferers could not be sufficiently suppressed for this specific constellation. This stresses the need for an accurate propagation channel simulation of interferers, currently most often not taken into account.

CONCLUSION

In this work a new approach for OTA GNSS receiver robustness tests against jammers and spoofers was presented. In a first test setup with a directional GNSS test receiver it was demonstrated that in contrast to open field test ranges, the OTA approach can be used to realistically emulate real world GNSS scenarios under controlled and repeatable laboratory conditions. This enables the direct and fair comparison of different algorithms and receivers as well as the identification of optimal receiver settings. Moreover receivers with array antennas as well as integrated antennas can be tested while fully accounting for the antenna influences. Thanks to the anechoic chamber in which the WFS is applied, jammers and spoofers can be operated without any constraints. Similarly, the testing of classified signals, like Galileo PRS, with non-certified receivers is feasible as

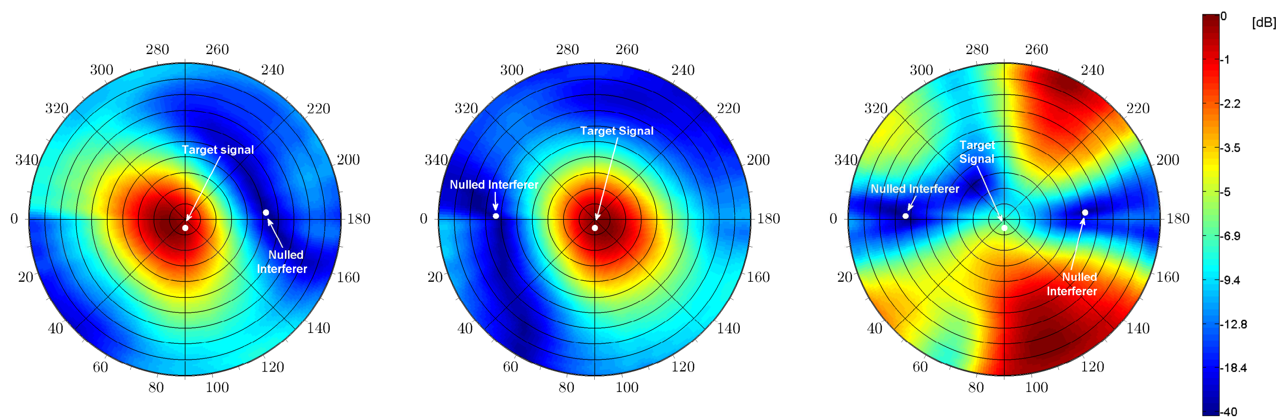


(a) Estimated direction of second interferer at $\theta = 33^\circ$ and $\phi = 359^\circ$.

(b) Estimated direction of main interferer at $\theta = 43^\circ$ and $\phi = 185^\circ$.

(c) Estimated direction of target signal at $\theta = 85^\circ$ and $\phi = 92^\circ$.

Figure 11: Results for DoA estimation of the interferer, its reflection and target signal.



(a) One null is steered to $\theta = 43^\circ$ and $\phi = 185^\circ$.

(b) One null is steered to $\theta = 33^\circ$ and $\phi = 358^\circ$.

(c) Two nulls are set simultaneously at ($\theta = 33^\circ$, $\phi = 359^\circ$) and ($\theta = 43^\circ$, $\phi = 185^\circ$).

Figure 12: Results for null steering of the array response.

the anechoic chamber inherently provides an excellent isolation to and from the outside world.

REFERENCES

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

[2] A. Rügamer, I. Suberviola, F. Förster, G. Rohmer, A. Konovaltsev, N. Basta, M. Meurer, J. Wendel, M. Kaindl, and S. Baumann, "A Bavarian Initiative towards a Robust Galileo PRS Receiver," in *in Proceedings of the 24th International Technical Meeting of the Satellite Division of the Insitute of Navigation, ION GNSS 2011, September 19-23, 2011, Portland, Oregon, USA*, September 2011.

[3] 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.

[4] FMV, "Vidsel, the natural first choice for real-world testing in europa, http://www.vidseltestrange.com/."

[5] E. Lagier, D. Craig, and P. Benshoof, "JAMFEST - A Cost Effective Solution to GPS Vulnerability Testing," *Journal of Global Positioning Systems*, vol. 3, pp. 40–44, 2004.

[6] T. Kraus, R. Bauernfeind, B. Eissfeller, S. Baumann, and B. Ott, "Test- und Entwicklungsumgebung für den Galileo Public Regulated Service (PRS)," in *in Proceedings of the DGON POSNAV 2009, October 27-28, 2009, Dresden*, October 2009.

[7] Antcom, "ANTCOM L1/L2 GPS CRPA Antennas." http://www.antcom.com/documents/catalogs/05_Antcom_CRPA_L1L2_GPS_Antenna_Array_for_E_mailing.pdf, 2013.

[8] F. Leveau, S. Boucher, E. Goron, and H. Lattard, "Anti-Jam Protection by Antenna." http://www.gpsworld.com/anti-jam-protection-by-antenna/, 2013.

[9] M. Narandzic, C. Schneider, R. Thoma, T. Jamsa, P. Kyosti, and X. Zhao, "Comparison of SCM, SCME, and WINNER Channel Models," in *Vehicular Technology Conference, 2007. VTC2007-Spring. IEEE 65th*, pp. 413–417, April 2007.

[10] A. Rügamer, F. Förster, M. Stahl, and G. Rohmer, "A Flexible and Portable Multiband GNSS Front-end System," in *in Proceedings of the 25th International Technical Meeting of the Satellite Division of the Insitute of Navigation, ION GNSS 2012, September 17-21, 2012, Nashville, Tennessee, USA*, September 2012.

[11] R. Thomä, M. Landmann, and A. Richter, "RIMAX-a maximum likelihood framework channel parameter estimation in multidimensional channel sounding," in *Proc. Int. Symp. on Antennas and Propag.*, (Sendai, Japan), pp. 53–56, August 2004.

[12] A. Konovaltsev, F. Antreich, and A. Hornbostel, "Performance Assessment of Antenna Array Algorithms for Multipath and Interference Mitigation," in *2nd Workshop on GNSS Signals & Signal Processing - GNSS SIGNALS 2007*, 2007.