

# Antenna Array and Receiver Testing With a Multi-RF Output GNSS Simulator

This article discusses the GALANT adaptively steered antenna array and receiver, demonstrating the test scenarios generated with the GNSS simulator. Exemplary results of different static and dynamic test scenarios are presented, validating the attitude determination capabilities as well as the interference detection and mitigation capabilities.

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**T**he vulnerability of GNSS to radio frequency interference and spoofing has become more and more of a concern for navigation applications requiring a high level of accuracy and reliability, for example, safety of life applications in aviation, railway, and maritime environments. In addition to pure power jamming with continuous wave (CW), noise or chirp signals, cases of intentional or unintentional spoofing with wrong GNSS signals have also been reported.

Hardware simulations with GNSS constellation signal generators enable the investigation of the impact of radio interference and spoofing on GNSS receivers in a systematic, parameterized and repeatable way. The behavior of different receivers and receiver algorithms for detection and mitigation can be analyzed in dependence on interference power, distance of spoofers, and other parameters. This article gives examples of realistic and advanced simulation scenarios, set up for simulation of several user antennas simultaneously.

The professional-grade high-end satellite navigation

testing and R&D device used here is powerful, easy to use, and fully capable of multi-constellation / multi-frequency GNSS simulations for safety-of-life, spatial and professional applications. It provides all L-band frequencies for GPS, GLONASS, Galileo, BeiDou, QZSS, SBAS and beyond in one box simultaneously. It avoids the extra complexity and cost of using additional signal generators or intricate architectures involving several hardware boxes, and offers full control of scenario generation. A multi-RF capable version provides up to four independent RF outputs and a master RF output that combines the RF signal of each of the up to four individual RF outputs.

Each individual RF output is connected to one or more “Merlin” modules (the core signal generator module for one single carrier) allowing simulation of up to 12 satellites per module. Because of the flexible design of the Merlin module, each one can be configured to any of the supported L-band frequencies.

As one chassis supports up to nine individual Merlin

modules, different Multi-RF combinations are feasible:

- two RF outputs with up to four modules each
- three RF outputs with up to three modules each
- four RF outputs with up to two modules each.

With these configurations, the user can simulate different static or dynamic receivers or even one receiver with multiple antennas, covering such challenging scenarios as ground networks, formation flying or use of beam-forming antennas.

As the user is free to assign each individual module to a dedicated simulated antenna, the user could also employ up to nine modules to simulate nine different carrier signals for one single antenna using the master RF output, thus simulating the complete frequency spectrum for all current available GNSS systems in one single simulation.

All modules are calibrated to guarantee a carrier phase coherency of better than  $\pm 0.5^\circ$ . **FIGURE 1** shows the output at the RF master of two modules assigned to the same carrier but with a phase offset of  $180^\circ$ . Theoretically the resulting signal should be zero because of the destructive interference. In practice, a small residual signal remains because of component tolerance, small amplitude differences and other influences. Nevertheless the best cancellation can be seen at this point.

The phase accuracy can now simply be estimated from the measured power level of the residual signal:

$$s(t) = \sin(2\omega t) + \sin(2\omega t + \varphi) \tag{1}$$

$$= 2 \sin\left(\frac{2\omega t + \varphi}{2}\right) \cos\left(-\frac{\varphi}{2}\right) \tag{2}$$

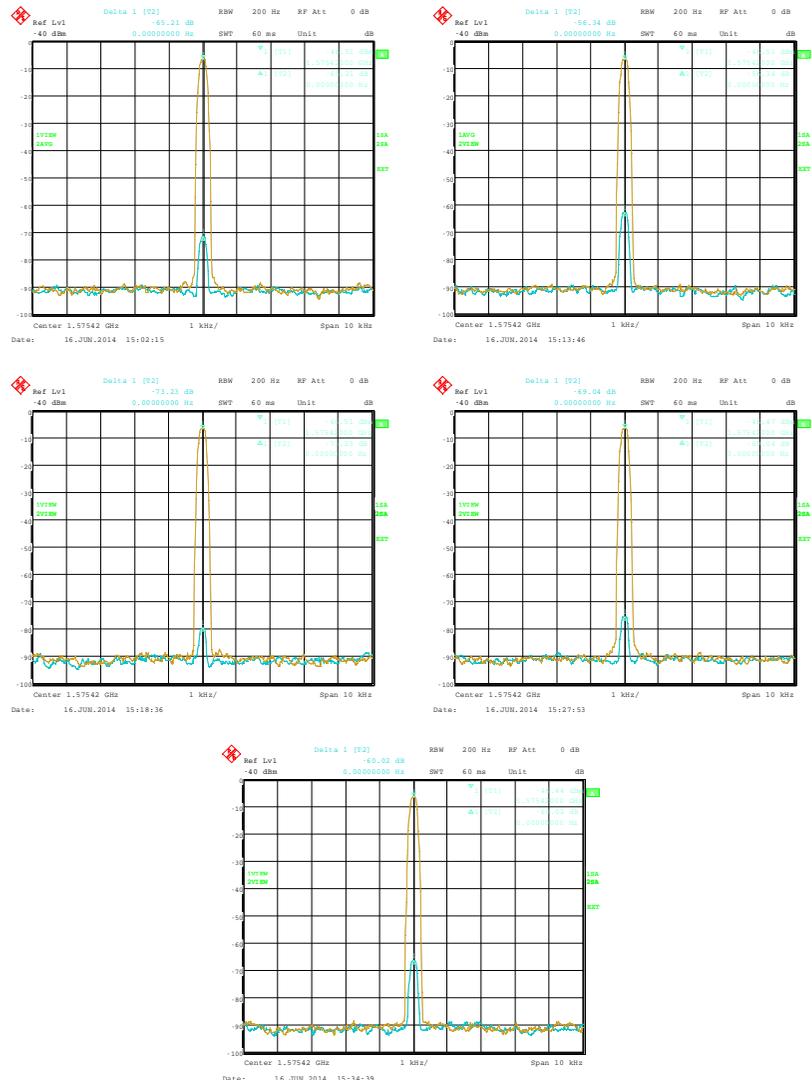
$$= 2 \sin\left(2\omega t + \frac{\varphi}{2}\right) \cos\left(\frac{\varphi}{2}\right)$$

$$= A \sin\left(2\omega t + \frac{\varphi}{2}\right)$$

with

$$A = 2 \cos\left(\frac{\varphi}{2}\right)$$

This means that the sum of two sine waves with the same



▲ **FIGURE 1** Carrier-phase alignment of the high-end simulator with six modules compared to the first module.

frequency gives another sine wave. It has again the same frequency, but a phase offset and its amplitude is changed by the factor A. The factor A does affect the power level. If  $\varphi$  is  $180^\circ$  then A is 0, which means complete cancellation.

So A shows the power of the resulting signal relative to the single sine wave. It can also be transformed to dB:

$$A_{dBc} = 20\log_{10}(A) \tag{3}$$

$$= 20\log_{10}\left(2\cos\left(\frac{\varphi}{2}\right)\right)$$

**FIGURE 2** shows the carrier suppression as a function of carrier phase offset with a pole at  $180^\circ$ .

The factory calibration aligns the modules to a maximum of  $0.5^\circ$  misalignment. The measured suppression therefore shall be better than 41.18 dBc. In practice, the residual signal is also caused by other influences, so that the actual phase alignment can be expected to be much better.

With four RF outputs, the received signal of a four element antenna can be configured very easily. FIGURE 3 shows the dialog to configure a four-element antenna with the geometry shown in FIGURE 4. Note that the antenna elements are configured in the body-fixed system with the  $x$ -axis to front and the  $y$ -axis to the right (inline with a north-east-down, NED, system when facing to north), while the geometry shown in Figure 4 follows an east-north-up (ENU) convention.

The following sections give an overview of multi-antenna systems and discuss results from a measurement campaign of the German Aerospace Center (DLR) utilizing the simulator and the DLR GALileo ANTenna array (GALANT) four-element multi-antenna receiver.

**Multi-Antenna Receivers**

Multi-antenna receivers utilize an antenna array with a number of antenna elements. The signals of each antenna element are mixed down and converted from analog to digital for baseband processing. In the baseband, the signals received by the different antenna elements are multiplied with complex weighting factors and summed. The weighting factors are chosen in such a way that the received signals from each antenna element cancel out into the direction of the interferers (nulling) and additionally, for advanced digital beamforming, such that the gain is increased into the direction of the satellites by forming of individual beams to each satellite. Because all these methods work with carrier phases, it is important that in the simulation setup, the signals contain the correct carrier phases at the RF-outputs of the simulator corresponding to the user satellite and user-interferer geometry, and the position and attitude of the simulated array antenna.

FIGURE 5 presents the geometry of a rectangular antenna array with 2x2 elements and a signal  $s(t)$  impinging from direction  $(\phi, \theta)$ .

The spacings of the elements  $dx$ ,  $dy$  are typically half a wavelength, but can also be less. The range difference for antenna element  $i$  relative to the reference element in the center of the coordinate system depends on the incident direction  $(\phi, \theta)$  and the position  $(m=0,1, n=0,1)$  of the element within the array:

$$\Delta r_i = m d_x \sin \theta \cos \varphi + n d_y \sin \theta \sin \varphi \tag{4}$$

The corresponding carrier phase shift is:

$$\Delta \Phi_i(\theta, \varphi) = -\frac{2\pi}{\lambda} \Delta r_i \tag{5}$$

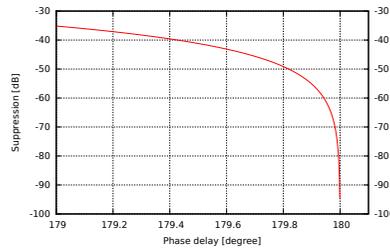
For CRPA and adaptive beam forming applications, the differential code delays may be neglected if they are small compared to the code chip length. However, it is essential that the carrier phase differences are precisely simulated, because they contain the information about the incident

direction of the signal and are the basis for the array processing in the receiver. For instance, the receiver can estimate the directions of arrival of the incident signals from these carrier phase differences.

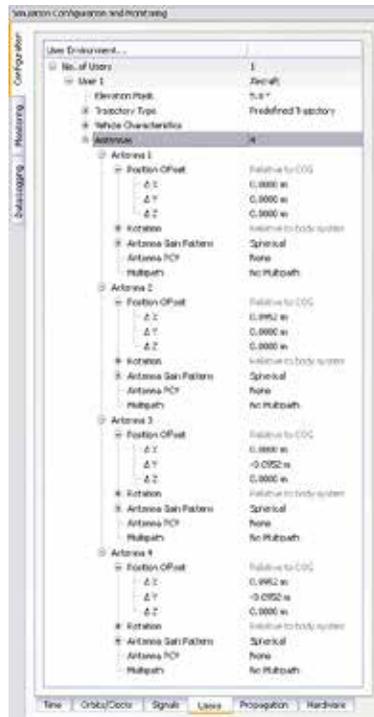
Now we consider a 2x2 array antenna. It can be simulated with the simulator with four RF outputs, where each output corresponds to one antenna element. In the simulator control software, a user with four antennas is set up, where the position of each antenna element is defined as an antenna position offset relative to the user position. In this approach, both differential code and carrier delays due to the simulated array geometry are taken into account, because the code and carrier pseudoranges are computed by the simulator for the position of each antenna element. However, the RF hardware channels of the receiver front-end may have differential delays against each other, which may even vary with time. If the direction of the satellites and interferers shall be estimated correctly by the receiver algorithms, a calibration signal is required to measure and compensate these differential hardware delays.

For the real antenna system, a binary phase-shift keying (BPSK) signal with zero delay for each antenna channel is generated by the array receiver and fed into the antenna calibration port. For the simulation, this calibration signal must also be generated by the constellation simulator.

In a simple way, a satellite in the zenith of the user antenna can be simulated, which has the same distance and delay to all antenna elements. Unfortunately, this simple solution includes some limitations to the simulated position and attitude of the user, because the user position must be at the Equator (if a “real” satellite is simulated in form of a



▲ FIGURE 2 Carrier suppression as a function of phase delay.



▲ FIGURE 3 Configuration of individual antennas per receiver.

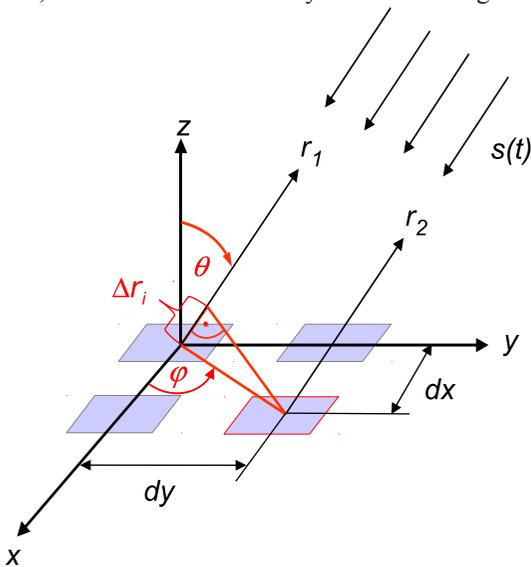
geostationary satellite) and the antenna must not be tilted.

With a small customization of the simulator software, these limitations could be overcome. FIGURE 6 shows how to set up the generation of a reference signal. This reference signal can either be simulated as a transmitter directly above the user position, which follows the user position and thus allows also simulations offside the Equator, or simulated as a zero-range signal on all RF outputs, neglecting any geometry, which is the preferred method. The latter one is more or less identical to the reference/calibration signal generated by the receiver itself.

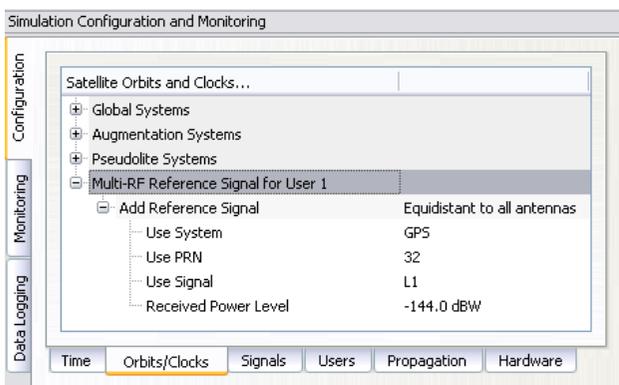
The power level of this signal is held constant and is not affected by any propagation delay or attenuation simulated by the control center.

### Attitude Determination

According to Figure 5, the phase difference measured between antenna elements is a function of the direction of arrival (DoA). Thus, the DoAs of the incident signals can be estimated from the phase differences. In the GALANT receiver, the DoAs are estimated by an EPSPRIT algorithm



▲ FIGURE 5 Parallel wavefront impinging on a rectangular array with 2x2 elements.

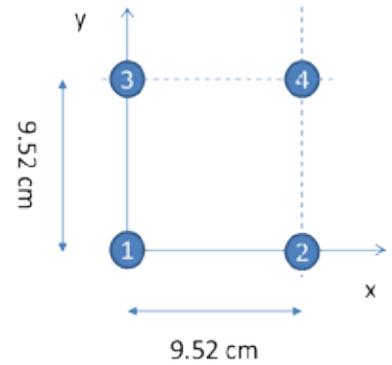


▲ FIGURE 6 Configuration of a modulated reference signal.

after correlation of the signals.

Compared with the (known) positions of the GNSS satellites, this allows the estimation of the antenna array attitude. FIGURE 7 shows the skyplot of simulated satellites as seen at receiver location (simulated on the right; reconstructed

by the receiver from the decoded almanac in the middle and the DoA on the left). By comparison of the estimated DoAs of all satellites and the skyplot from the almanac, the attitude of the antenna is estimated (left). In addition, the attitude angles simulated by the simulator is given (right).



▲ FIGURE 4 Geometry of the GALANT four-element phased-array antenna (view from top).

### Simulation of Interference

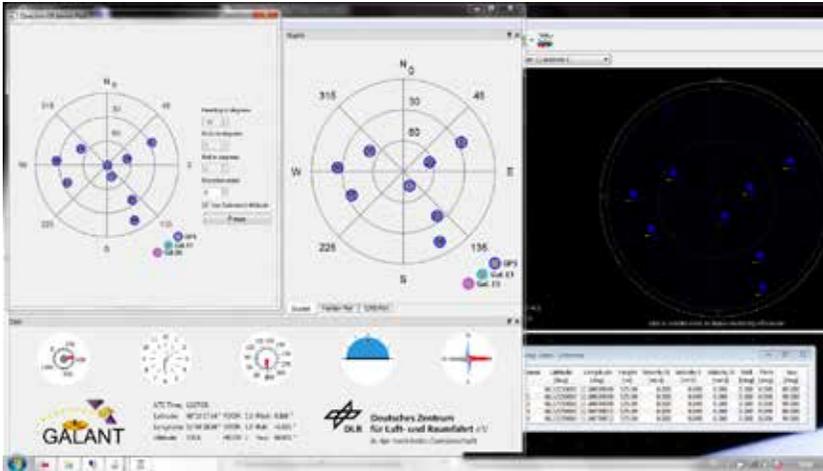
It is possible to simulate some simple types of interference. Possible interference scenarios are:

**Wideband Noise.** By increasing the power of a single satellite of the same or another GNSS constellation, a wideband pseudo-noise signal can be generated. Using a geostationary satellite also enables simulating an interference source at low elevations and constant position. Use of power-level files also allow generation of scenarios with intermittent interference (switching on and off the interference) with switching rates up to 5 Hz.

**CW or Multi-Carrier IF.** By disabling the spreading code and navigation message, a CW signal can be generated. The simulator also allows configuration of subcarrier modulations. Without spreading code (or to be precise with a spreading code of constant zero) the generated signal will consist of two carriers symmetrically around the original signal carrier (for example, configuring a BOC(1,1) signal will create two CW signals at  $1.57542 \text{ GHz} \pm 1.023 \text{ MHz}$ , thus producing “ideal” interferer for the Galileo E1 OS signal.)

Depending on the number of Merlin modules per RF output, interference to signal ratios up to 80 dB could be realized, limited by a dynamic range of 40 dB within one module and additional 40 dB range between two modules. However, the maximum power level of one individual signal is currently limited to -90 dBm. If only one channel per module is used, the maximum power level of this single signal can be increased by another 18 dB (for example, by using one module solely for interference generation and another module for GNSS simulation).

FIGURE 8 shows the simulated geometry for an interference scenario based on wideband noise generated by a



▲ FIGURE 7 Simulating and estimating attitude with a multi-element antenna.

geostationary satellite, producing  $-90$  dBm signal power at the receiver front end. The interference source is very near to the direction of PRN 22 with a jammer power of  $-90$  dBm, resulting in a jammer to signal ratio of  $J/S = 25$  dB.

FIGURE 9 shows the two-dimensional antenna pattern as a result of the beamforming before and after switching on the interferer. The mitigation algorithm tries to minimize gain into the direction of the interferer. As this also decreases gain into the direction of the intended satellite, the  $C/N_0$  drops by approximately 10 dB for PRN 22, because its main beam is shifted away from the interference direction. For satellites in other directions, the decrease in  $C/N_0$  is less: compare Figure 9 with FIGURE 10.

However, the receiver still keeps tracking the satellite. After switching of beamforming, the signal is lost.

### Simulation of Spoofing

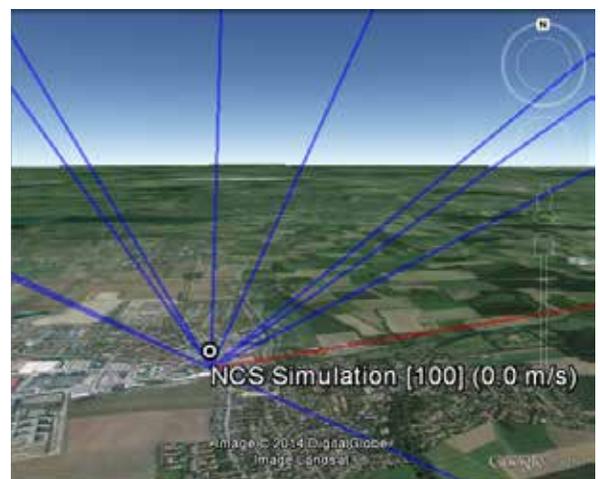
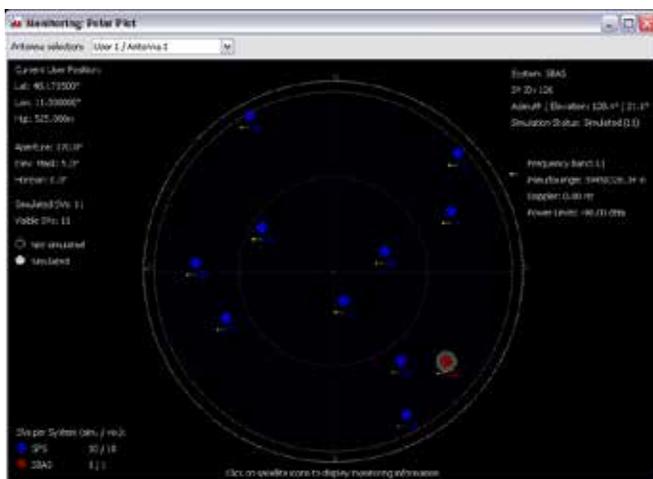
The simulation of a spoofing signal requires twice the resources as the real-world scenario, as every “real” LoS-signal must also be generated for the spoofing source. A simulation of an intentional spoofer who aims to spoof a dedicated position in this context is, however, very similar to the simulation of a repeater ([un-]intentional interferer) device:

The repeater (re-)transmits the RF signal received at its receiver position. A receiver tracking this signal will generate the position of the repeater location but will observe an additional

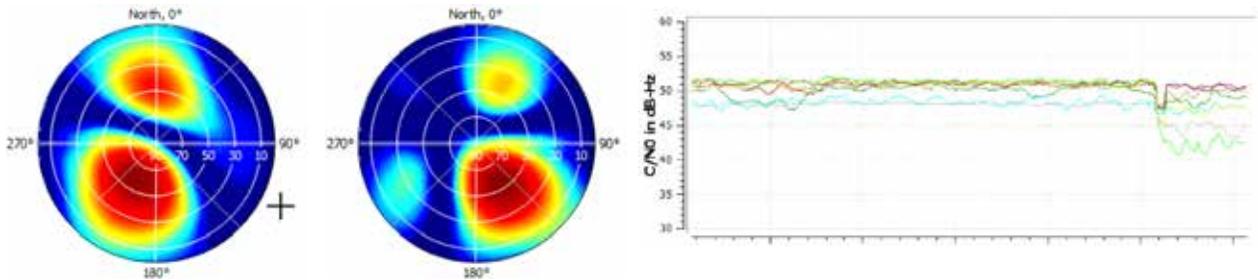
local clock error defined by the processing time within the repeater and the travel time between repeater and receiver position. A correct simulation for a multi-antenna receiver therefore has to superpose the code and carrier range as observed at the repeater location (considering geometric range between the transmit antenna of the repeater and the individual antenna elements) with the code and carrier ranges at the receiver location.

Instead of the location of the repeater P2, however, any intended location P<sub>x</sub> could be used to simulate an intelligent spoofer attack (FIGURE 11).

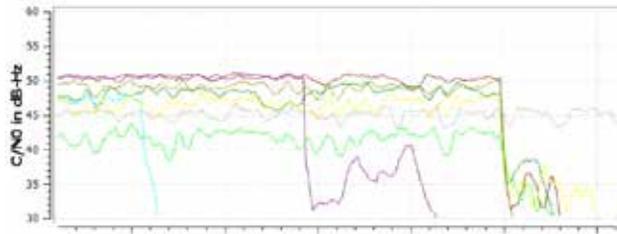
The simulator can generate such scenarios by configuring the position of the (re-)transmitting antenna and the intended position (for example, the position of the repeater). By calculating the difference between the real receiver position and the position of the transmitting antenna, the additional delay and free-space loss can be taken into account. The user may also configure the gain of the transmit antenna and the processing time within the repeater. Currently, this setup does only support one “user” antenna to be simulated. However, this feature combined with multi-antenna support will enable the simulator to simulate repeater or intelligent spoofer attacks in the future (FIGURE 12). To distinguish the “real” signal from the “repeated” signal, the “repeated” signal



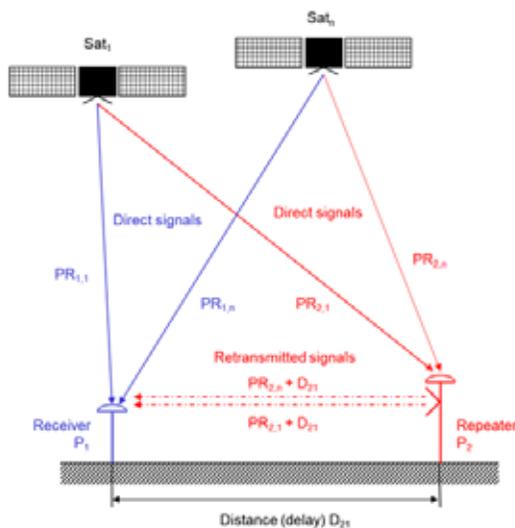
▲ FIGURE 8 Geometry for the wideband noise interference scenario.



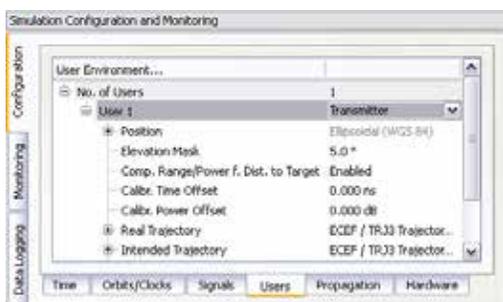
▲ FIGURE 9 Beamforming for PRN 22 (light green line in lower plot) to mitigate for interference.



▲ FIGURE 10 Tracking is lost after switching off beamforming for individual channels (light blue, purple) and all channels (at the end of the plot).



▲ FIGURE 11 Geometry of repeater/spoofers and GNSS receiver.



▲ FIGURE 12 Simulator's capability to simulate a repeater.

could be tagged as a multipath signal. This approach would allow simulation of the complete environment of “real” and “repeated” GNSS signals in one single simulator.

### Manufacturers

The simulator producing the results described here is the NavX-NCS from **IFEN GmbH** ([www.ifen.com](http://www.ifen.com)). The simulator is valuable laboratory equipment for testing not only standard or high-end single-antenna GNSS receivers, but also offers additional benefit for multi-antenna GNSS receivers like the DLR GALANT controlled reception pattern antenna system.

The GNSS constellation simulator offers up to four phase-coherent RF outputs, allowing the simulation of four antenna elements with two carrier frequencies, each utilizing one single chassis being 19 inch wide and 2 HU high.

Simulation of intentional and unintentional interference is a possible feature of the simulator and allows receiver designers and algorithm developers to test and enhance their applications in the presence of interference to identify, locate and mitigate for interference sources.

**THORSTEN LÜCK** studied electrical engineering at the universities in Stuttgart and Bochum. He received a Ph.D. (Dr.-Ing.) from the University of the Federal Armed Forces in Munich in 2007 on INS/GNSS integration for rail applications. Since 2003, he has worked for IFEN GmbH, where he started as head of R&D embedded systems in the receiver technology division. In 2012 he changed from receiver development to simulator technologies as product manager of IFEN's professional GNSS simulator series NavX-NCS and head of the navigation products department.

**GÜNTER HEINRICH** is the head of the Customer Applications Department and business development at IFEN GmbH, Poing, Germany. He received a Dipl.-Ing. degree in communications engineering in 1988, a Dipl.-Ing. degree in data processing engineering and a Dr.-Ing. degree in electrical engineering in 1991 and 1995, respectively. In 1996 he joined the satellite navigation department of MAN Technologie AG in Augsburg, Germany, where he was responsible for system architectures and design, digital signals, and data processing of satellite navigation receiver systems. From 1999 to April 2002 he served as head and R&D manager of MAN Technologie's satellite navigation department.

**ACHIM HORNPOSTEL** joined the German Aerospace Center (DLR) in 1989 after he received his engineer diploma in electrical engineering from the University of Hannover in the same year. Since 2000, he has been a staff member of the Institute of Communications and Navigation at DLR. He was involved in several projects for remote sensing, satellite communications and satellite navigation. In 1995 he received his Ph.D. in electrical engineering from the University of Hannover. His main activities are in receiver development, interference mitigation and signal propagation.