Test Solutions for Simulating Realistic GNSS Scenarios

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Biography

Markus Irsigler received his diploma in Geodesy and Geomatics from the University of Stuttgart, Germany, and a doctoral degree (Dr.-Ing.) in Aeronautics and Astronautics from the Bundeswehr University Munich. After working as a research associate in the field of GNSS at the Bundeswehr University Munich, he joined IFEN GmbH in 2007, where he worked as product manager and systems engineer. Since 2012, he has been working for Rohde & Schwarz GmbH & Co. KG as a product manager. He is involved in product management and marketing activities for R&S's signal generators and power meters with a special focus on GNSS test solutions.

Abstract

GNSS receiver tests can only be conclusive when they are performed under realistic conditions. A GNSS simulation must take into consideration the satellite constellation itself (in terms of a proper simulation of the satellite orbits), the signal propagation characteristics, the characteristics of the receive antenna and the receiver environment. Realistic modeling of user movement with consideration of vehicle attitude is also part of this simulation process. Generation of interfering and jamming signals may also be of interest to setup a simulation environment which is close to reality.

This paper starts with an overview of typical GNSS tests and a discussion of the advantages of using a signal generator over real world testing or using a record/replay system. After pointing out the most important requirements to ensure realistic GNSS simulations, Rohde & Schwarz's platform for GNSS testing, the R&S®SMBV100A is introduced and its essential simulation capabilities are presented. A special focus is placed on features like simulating vehicle motion including attitude, signal obscuration and multipath, and antenna pattern modeling. These features make it possible to set up realistic and complex yet reproducible GNSS scenarios. The final part of this paper describes some special aerospace applications which can be addressed with the R&S®SMBV100A, namely hardware in the loop (HIL), the simulation of rotating vehicles and the simulation of ground-based augmentation systems (GBAS).

The Need for GNSS Testing

In order to characterize the performance of GNSS receivers, their basic functions need to be tested under controlled and repeatable conditions. Moreover, it is often required to test the receiver's performance under special conditions or in dedicated environments such as interference or multipath environments. The following tests are typically carried out to verify and characterize some basic receiver functions:

- Time-To-First-Fix (TTFF) tests are performed to determine the time the receiver needs to get a valid positioning solution after switching on the device.
- Sensitivity tests are conducted to determine the minimum C/N_0 the receiver requires to acquire a signal (acquisition sensitivity) or – after having successfully acquired a signal - to maintain lock on that signal (tracking sensitivity).
- Reacquisition time is the period of time the receiver needs to re-acquire a signal after it has been interrupted due to temporary signal obstruction, e.g. when exiting a tunnel.

- Location accuracy tests are carried out to determine the spatial accuracy to which the receiver can determine its position relative to its true location. The difference between the receiver's true position and its computed position determines the absolute location accuracy. The relative location accuracy can be tested by comparing the deviations of successive positioning solutions obtained by the receiver. Location accuracy tests can also be carried out for moving receivers.

The following tests are conducted in order to characterize the receiver performance under special conditions:

- Interference testing. Such tests characterize the receiver performance (TTFF, sensitivity, location accuracy) when interfering signals are present. This includes both unintentional and intentional interference (jamming).
- Multipath testing. In many cases, the satellite signals do not reach the receive antenna directly but are reflected by buildings, trees or the ground. Compared to the direct signal, multipath signals of this kind arrive later at the antenna and exhibit loss, which can cause significant positioning errors. The magnitude of such positioning errors ultimately depends on the multipath characteristics and especially the signal processing in the receiver. To efficiently test a receiver's internal multipath mitigation techniques, highly realistic and reproducible simulation of multipath signals is mandatory.
- Testing under varying ionospheric and tropospheric conditions. This type of test characterizes the receiver performance (TTFF, sensitivity, location accuracy) under varying ionospheric and tropospheric conditions.

GNSS receivers may also be tested according to standardized test procedures to verify that they are able to operate according to certain wireless standards. In order to prove that they are able to process assisted data correctly, for example, GNSS receiver must be tested against the 3GPP and 3GPP2 specification for A-GNSS testing.

Simulation vs. Real World Testing

Using signal generators for GNSS simulations has some major advantages over using a live GNSS signal. One major drawback of using a live signal is that the system conditions are mostly unknown at a certain point in time and – most importantly – that they change over time. The locations of the satellites and thus the geometric conditions change over time as the satellites move along their orbits. Error influences like atmospheric effects are also time- and location-dependent. One of the most unpredictable error influences is multipath. The magnitude of multipath errors for a given GNSS receiver mainly depends on the characteristics of the user environment, e.g. the number of occurring echoes and the distance between the reflection point and the antenna or the strength of the reflected signal, which is determined by the material properties of the reflecting surface. Both the geometric conditions and the material properties of the reflectors change or may change over time – the geometric conditions due to the permanent motion of the satellites and the reflector properties due to meteorological influences like rain, dew or snow. As a result, when using live signals, we have to expect that the conditions change permanently and unpredictably, and will never be the same for two distinct points in time. As a result, it is very unlikely that two successive test runs can be performed under identical conditions. Repeatable testing which is one of the most important test requirements is impossible when using live GNSS signals.

In contrast, well-defined and controlled simulation conditions can be ensured when using a GNSS simulator. A simulator typically offers fully customizable and repeatable scenarios, i.e. that one and the same test scenario can be replayed as often as needed and produce the same signals with the same characteristics. Moreover, a simulator is often a cost-effective and efficient solution where using live signals would be time-consuming, complex, expensive or even impractical (e.g. test of airborne and spaceborne GNSS receivers). Finally, a GNSS simulator can ensure the availability of all required test parameters. As an example, a simulator can already provide complete satellite constellations for the European Galileo or the new Chinese BeiDou system. When using live signals, there are currently only a few Galileo and BeiDou satellites whose signals can be used for testing.

Simulation Requirements

GNSS receiver tests can only be conclusive when they are performed under realistic conditions. In order to ensure realistic simulations, a GNSS simulator must be able to model not only system-inherent characteristics but also the near environment of the simulated user. As a GNSS receiver under test is directly connected to the GNSS simulator in most cases (i.e. no antenna is connected to the receiver), it is also desirable to simulate the antenna reception characteristics. The following paragraphs summarize some important requirements a GNSS simulator has to meet to ensure realistic simulations.

Satellite orbit simulation. The space segment of a GNSS typically consists of ~30 space vehicles (SVs) orbiting the Earth in different orbit planes. This provides global system availability and ensures that a minimum amount of satellites are visible from any location around the world. A realistic GNSS simulation has to be capable to support the simulation of different classes of satellite orbits such as Low and Medium Earth orbits (LEO/MEO), geostationary orbits (GEO), or inclined geosynchronous orbits (IGSO).

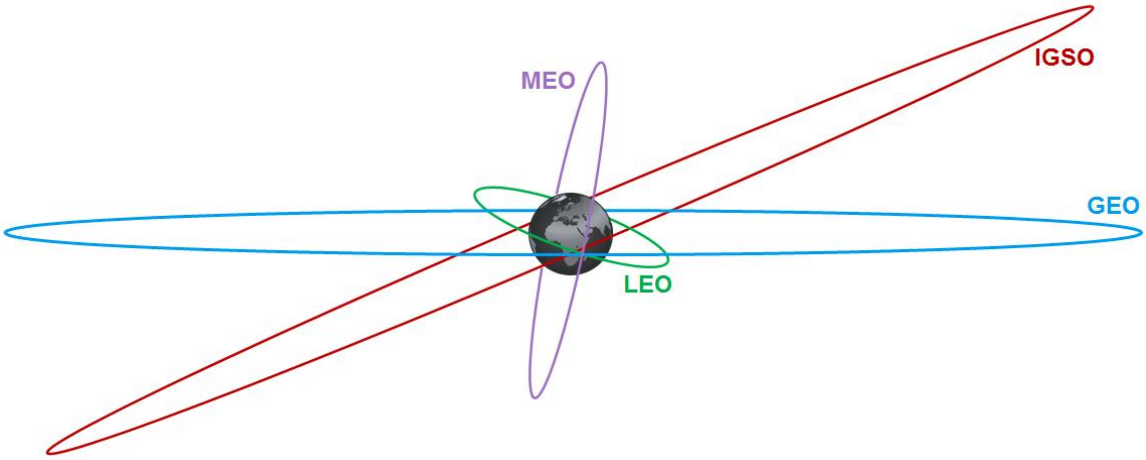

Figure 1: Examples for different orbit classes.

User location. A GNSS simulator must be capable of simulating at least a static user at any location on or near the Earth's surface.

Range simulation. The range between the satellite and the receive antenna is the basic measurement a GNSS receiver performs in order to compute its position. As the GNSS signal travels through different layers of the Earth's atmosphere, it is not sufficient to simulate only the geometric range between the satellite and the receive antenna. It is rather necessary to take into account ionospheric and tropospheric effects such as path delays for a realistic range simulation. In addition, the range observable obtained from a GNSS receiver contains other system-inherent errors, like satellite clock errors or unexpected range steps or ramps (referred to as "Feared Events" (FE) in Figure 2). Assuming that the simulation is based on a realistic SV motion, the resulting range simulation is also realistic in terms of the simulated Doppler shifts.

Multipath. When multipath is present, not only the direct signal component enters the receiver but rather a composite signal consisting of the LOS signal plus one or several multipath signals. The amount of multipath signals and its impact on the positioning performance of a receiver is strongly dependent on the environment (e.g. open, rural, suburban, urban canyon). Even in an open environment, multipath influences must be expected from time to time. With a GNSS simulator, multipath can typically be simulated in many different ways, from simple tapped-delay or ground multipath models to highly sophisticated statistical channel models or by computing all multipath signals deterministically based on a city model with configurable geometric and surface properties.

Obscuration. GNSS signals may also be obstructed by buildings or trees. Signal obstruction is an important effect, especially in an urban environment where signals are often blocked by buildings. Signal obstruction may also be important to consider in combination with multipath. The reason is that it is possible that the line of sight (LOS) signal is completely obstructed so that the receiver processes only the multipath components.

Vehicle movement. There a many applications and test tasks, which require the simulation of a moving receiver and for which the simulation of a static, non-moving receiver is insufficient. Therefore, it should be possible for the user to configure a user trajectory. The trajectory simulation should take into account different vehicle types and should also include the simulation of vehicle attitude (roll/pitch/yaw angles). In order to test moving receivers under high signal dynamics (as occurring in aerospace or space applications), the GNSS simulator has to be able to support scenarios where the simulated user is exposed to high velocities and accelerations.

Antenna pattern. As each receive antenna has its specific directional response pattern, the simulation of an omnidirectional user antenna is only an approximation. Instead, the user should be able to customize the receive antenna characteristics in terms antenna gain and phase response.

Jamming and interference. In order to emulate a real GNSS environment, it may sometimes be desirable to simulate external influences like jamming or interference signals. That way, the presence of additional signals like WLAN or Bluetooth can be simulated and its influence on the reception of the GNSS signals can be evaluated.

These simulation requirements are visualized and summarized in the following illustration:

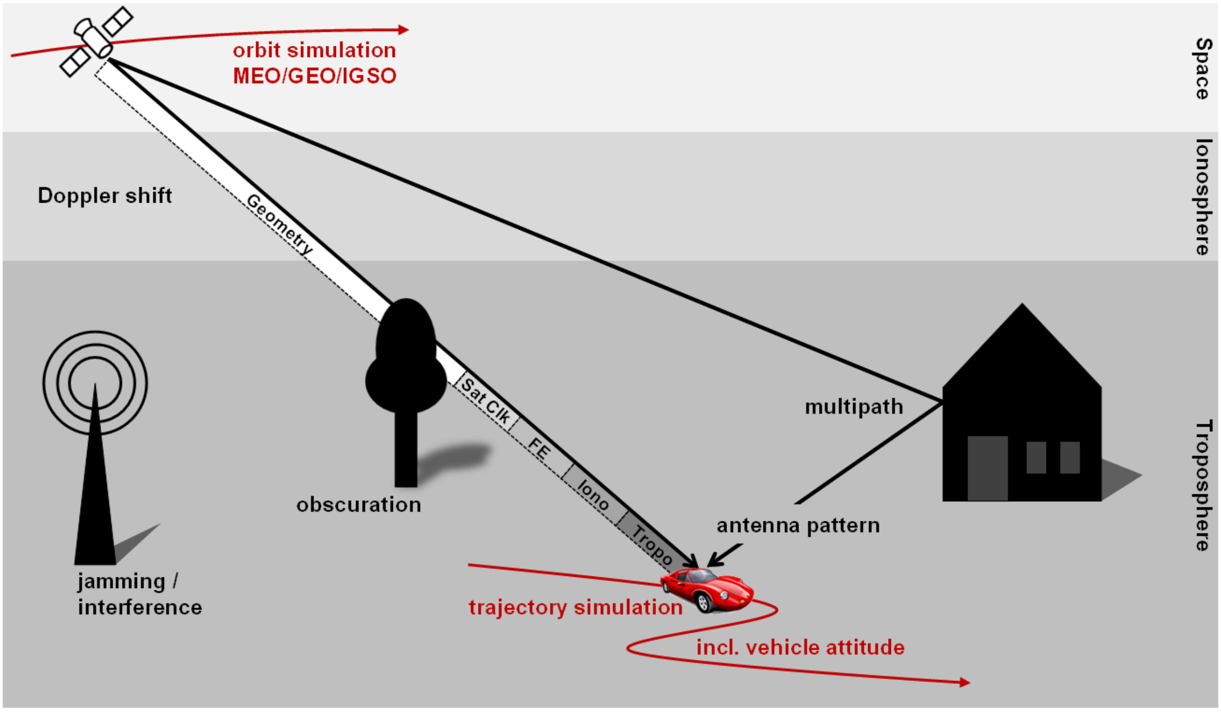

Figure 2: Summary of simulation requirements for realistic GNSS scenarios.

The R&S®SMBV100A is able to cover most of these simulation requirements. Its simulation capabilities are discussed in more detail in the following sections. A special focus is put on its capabilities to realistically model the near environment of the simulated user as this is vital to ensure a simulation which is close to reality.

Realistic GNSS Testing with the R&S SMBV100A

The R&S®SMBV100A is a general purpose vector signal generator. The signals are generated at baseband and then upconverted to the desired frequency band. The R&S®SMBV100A is not only a pure GNSS simulator. The instrument can also be used generate a variety of other signals from other digital standards such as WLAN, LTE or NFC, to name only a few. A GNSS scenario can be configured completely using the controls of the device. An external PC is not needed for this purpose.

Figure 3: The R&S®SMBV100A is a general purpose vector signal generator and can be used as a full-featured GNSS simulator.

Key GNSS features. The R&S®SMBV100A is able to generate signals for GPS, GLONASS, Galileo and BeiDou. With up to 24 available channels and the ability to simulate hybrid constellations (e.g. 8 GPS + 8 Glonass + 8 BeiDou SVs), it is possible to perform multi-standard simulations. The R&S®SMBV100A supports signal generation in the frequency bands L1 or L2, including signal generation for GPS P-Code signals. The following signals can be generated:

- GPS L1 C/A + NAV
- GPS L1 C/A + NAV + P-Code
- GPS L2 C/A + NAV
- GPS L2 C/A + NAV + P-Code
- Galileo E1 CBOC
- Glonass G1
- Glonass G2
- BeiDou B1

In addition to GPS, Glonass, Galileo and BeiDou, the platform is ready to support other satellite-based navigation or augmentation systems as well. The R&S®SMBV100A allows to simulate high dynamic user motion. With velocity, acceleration and jerk up to 10000m/s, 1600 m/s^2 and 400 m/s^3, respectively, a multitude of test applications can be covered, from low dynamic pedestrian to aerospace, defense or even space applications.

Vehicle movement and attitude simulation. There are two basic approaches to simulate moving vehicles with the R&S SMBV100A. The first method is to use motion files that can be loaded onto the instrument. A variety of different proprietary and common file formats are supported. Examples for common file formats that can be used in the R&S®SMBV100A are KML files or NMEA files. The latter allow replaying user trajectories that have been recorded by a GNSS receiver during a test using real GNSS signals. The second method is to feed trajectory data to the instrument in real time. To accomplish this task, a set of SCPI commands is available, which can be used for this purpose. Using the real time trajectory feed enables hardware in the loop (HIL) applications.

Waypoint files may contain attitude data defining roll, pitch and yaw angles during the motion of the vehicle. Even if the waypoint file does not contain attitude information, it is possible to add attitude data automatically. If necessary or desired, pitch and heading information can be derived from the vehicle motion vector resulting in a simplified attitude simulation.

Obscuration and multipath. The R&S®SMBV100A offers extensive configuration capabilities for simulating multipath signals. A number of models are available ranging from simple manual definition of multiple indirect paths per satellite signal to automatic generation of ground reflections and simulation of complex multipath environments, including signal obscuration. Simulation of urban canyon environments plays an especially important role, because signal availability and signal quality in these canyons are heavily affected by multipath propagation and obscuration.

The R&S®SMBV100A offers a selection of preconfigured environments, which can be modified with a built-in editor. All relevant multipath signals and obscuration effects due to buildings can be automatically calculated and simulated based on the building geometry, user movement and surface characteristics. In this way, trips through inner-city areas as well as influences of highway bridges or tunnels can be easily simulated.

Figure 4 shows an example for a customized urban scenery, which can be created and modified using the built-in obstacle editor. In addition, a vehicle trajectory can be placed into this scenery. Based on the motion of the satellites, the vehicle movement and the geometrical conditions, multipath and signal obscuration is simulated automatically. As an additional configuration option, multipath generation can be switched off, so that only signal obscuration is considered in the simulation.

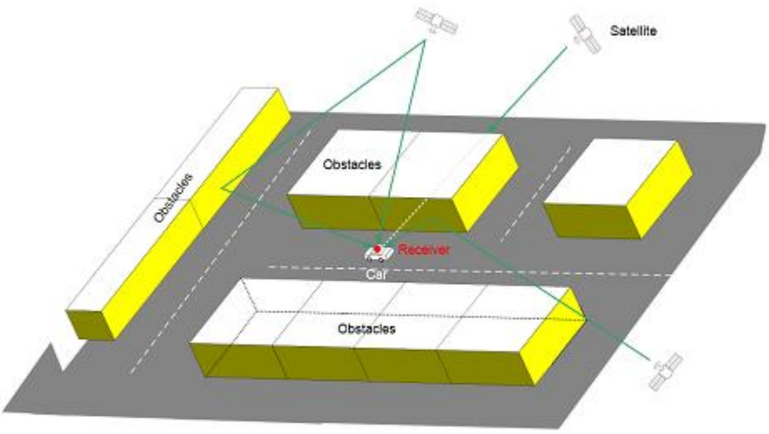

Figure 4: Customized urban user environment consisting of several buildings. Based on the geometrical conditions and surface properties, multipath and signal obscuration is simulated automatically.

In addition to using the obstacle editor, the user can select from many predefined sceneries representing various environment types. One example of such a predefined scenery is the simulation of ground multipath for an aircraft flying over a flat surface as illustrated in Figure 5:

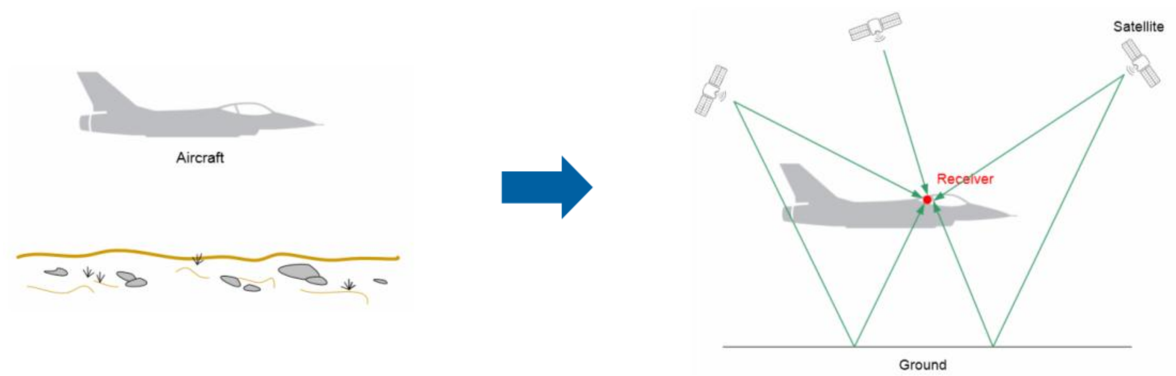

Figure 5: Simulation of ground multipath for an aircraft flying over a flat surface.

The surface is modeled as a reflective plane, for which either the surface properties (in terms of permittivity) or the power loss can be specified. Alternatively, the user can select from different surface types. It is also possible to model an aircraft flying through a canyon. In such a case, not only ground multipath is modelled but also signal obscuration caused by canyon walls to the left and/or to the right of the flight path.

Antenna pattern and body mask. In addition to multipath and signal obstruction, the signal reception conditions are also determined by the antenna characteristics. These conditions can be configured in terms of antenna gain and phase pattern. When configuring the antenna gain pattern, it is also possible to define regions of total signal blockage. That way, signal obstruction by vehicle body parts can be simulated. The basic concept is illustrated in Figure 6:

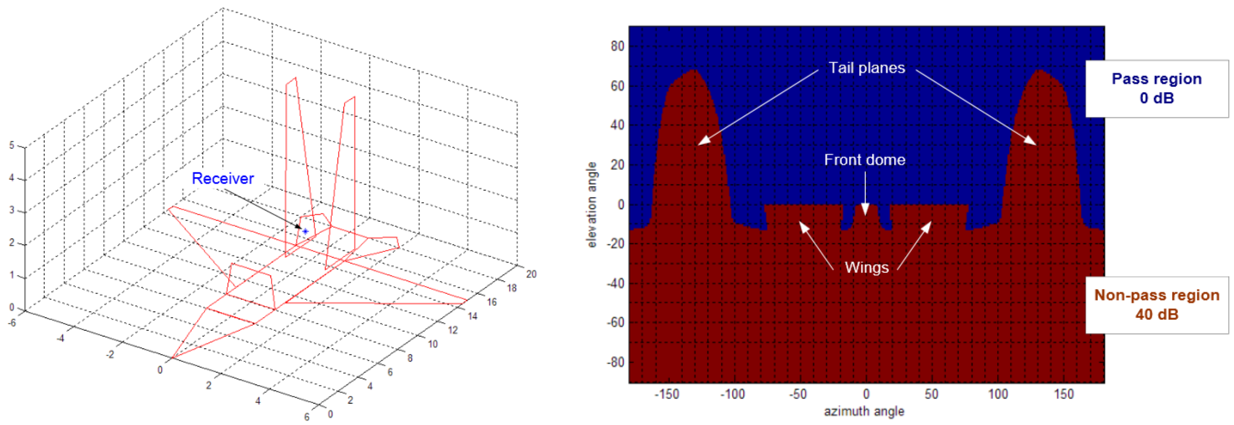

Figure 6: Simplified model of a military aircraft (left plot) and resulting body mask (dark red area in the right plot). The receiver is assumed to be located near the tail of the aircraft.

By combining all the simulation capabilities described in the previous paragraphs, it is possible to simulate signal reception conditions, which are close to reality. As an example, a realistic trajectory of a landing aircraft can be simulated by providing an appropriate motion file including attitude information. Flight maneuvers such as curved approaches or holding patterns can be simulated realistically including the consideration of signal obstruction due to wings or other aircraft body parts. During its final approach, ground multipath could also be added to the simulation. An example for such a flight maneuver is illustrated in Figure 7. The aircraft performs a turn with a high bank angle. This leads to signal obstruction caused by the wings or the aircraft body.

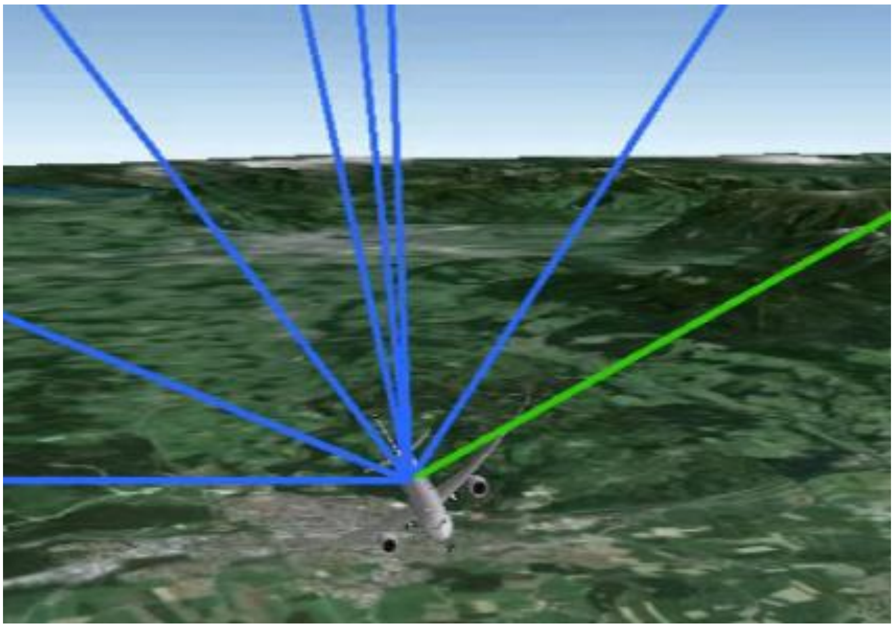

Figure 7: Simulation of a banking aircraft with consideration of a vehicle body mask. Due to the high banking angle, some signals are obstructed by the wings or by the aircraft body. Signals that can be received by the antenna are plotted as blue lines; obstructed signals are plotted as green lines.

Special Aerospace Applications

This section covers some special simulation capabilities for aerospace applications. This includes the generation of GNSS signals in a hardware in the loop (HIL) environment, the simulation of rotating vehicles (spinning) and the generation of signals for ground-based augmentation systems (GBAS).

Hardware in the loop. As already mentioned, motion data (position, velocity, acceleration and jerk plus attitude information) can be fed to the R&S®SMBV100A instrument in real time. This can be done via a set of specific SCPI commands.

A basic HIL setup is illustrated in Figure 8. The HIL simulator, which may be a car or a flight simulator controlled by an operator, for example, generates position data and also kinetic parameters such as velocity, acceleration and jerk plus optionally attitude information in the form of yaw, pitch and roll angles. This data is sent to the SMBV in form of specific SCPI remote control commands. The R&S®SMBV100A processes these HIL commands and adjusts the simulated GNSS signal accordingly in real-time. The updated GNSS signal is fed to a GNSS receiver which calculates a position. This position information is sent back to the HIL simulator where the updated position may be displayed on a map or processed and used otherwise.

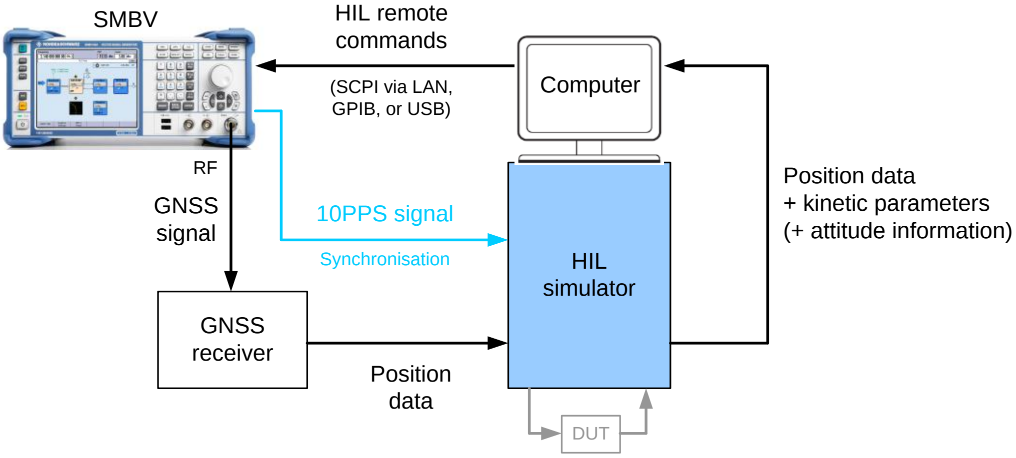

Figure 8: Using the real time trajectory feed capability of the R&S®SMBV100A to generate GNSS signals in a hardware in the loop environment.

Trajectory and attitude data can be fed to the instrument with an update rate of up to 100Hz. This results in a minimum system latency of 10ms. The hardware in the loop capability can be used to incorporate GNSS RF signals to a car or a flight simulator, for example, and to test GNSS receivers that may be part of such a simulator.

Spinning. With the R&S®SMBV100A, it is possible to simulate rotating vehicles such as missiles. To ensure a stable flight path, the rocket is put into rotation. Missiles and rockets are usually equipped with GNSS units, which have multiple antennas attached to the surface of the rocket. Usually, the antennas are evenly distributed so that a sufficient amount of satellites are visible at any given time. This ensures that the position can always be accurately determined. For a realistic simulation, the individual variations in reception strength for these antennas due to the rotation process must be simulated in the GNSS simulator.

This can be accomplished using a suitable trajectory file representing the missile motion, by configuring a constant roll rate for the simulated missile and by providing a suitable antenna pattern, including masking information to simulate signal obstruction by the missile body. R&S®SMBV100A supports spinning rates up to 400Hz.

Ground-based augmentation systems (GBAS). The main purpose of GBAS is to provide a special ground infrastructure, which helps to enhance the positioning performance of a GNSS receiver so that it can be used for applications where very accurate and reliable positioning information is required. GBAS has originally been designed as an aircraft landing system based on the concept using differential GNSS observations. It is supposed to be an alternative to the ILS infrastructure.

The basic GBAS concept is illustrated in Figure 9. The GPS signals are received by several GPS reference receivers which are located at known positions in the vicinity of the airport. As these locations are known exactly, the Central Processing Facility (CPF) is able to compute differential corrections, which are then sent to the landing aircrafts via a VHF radio link. The aircraft can then use these corrections to correct its own GPS observations and subsequently obtains a very accurate GPS position.

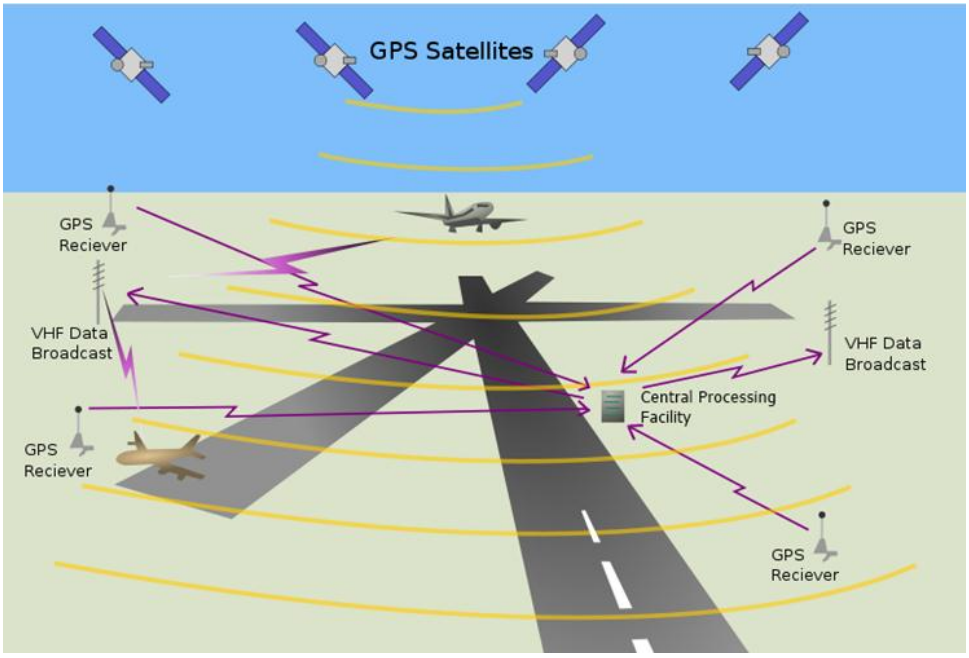

Figure 9: Basic GBAS infrastructure (image source: FAA).

The R&S®SMBV100A is able to generate GBAS VHF signals in the frequency band between 108 MHz and 118 MHz. The generated VHF signals contain differential GNSS corrections and other critical landing information (MsgTypes 1,2,4,11 are supported).

Summary

The R&S®SMBV100A is a reliable and sophisticated platform for GNSS testing. Its advanced simulation capabilities allow configuring realistic and complex yet repeatable GNSS scenarios, which can be run under controlled conditions. The R&S®SMBV100A aims at providing a feature set to perform GNSS simulations close to reality. This includes realistic modeling of GNSS orbits and constellations, realistic modeling of signal propagation effects and systems errors as well as a realistic modeling of the user environment.

Further Reading

[1] Tröster-Schmid, C. [2013]: *Simulating Automatic Obscuration and for Realistic GNSS Receiver Testing*, Application Note 1GP101, Rohde & Schwarz GmbH & Co. KG, Munich, 2013

[2] Tröster-Schmid, C. [2013]: *Hardware in the Loop (HIL) Testing with a GNSS Simulator,* Application Note 1GP102, Rohde & Schwarz GmbH & Co. KG, Munich, 2013