Digital GNSS Signal Recorder, Generator, and Simulator for Receiver Test, Qualification, and Certification

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BIOGRAPHY

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Juergen Seybold received his Dipl.-Ing. degree in 1980 from Stuttgart Technical Professional Academy. Among others, he was working in leading positions for companies like Alcatel / Airsys Navigation Systems, Thales ATM, and Alcatel SEL Defence & Aerospace Division for several years. Since 2006 he is Managing Partner and Chief Operating Officer (COO) of TeleConsult Austria GmbH.

ABSTRACT

The concept and the architectural design of a GNSS multi-system performance simulation environment are discussed. The proposed system allows simulating satellite constellations, generating digital signals, and replaying these signals for receiver performance analysis. For baseband receiver testing, verification, and comparison, the analog RF-output of common GNSS signal generators has to be down-converted and digitized first. The omnipresent white Gaussian noise within this process destroys the required controllability of the simulation environment since every time the process is restarted another set of Gaussian noise is added to the signal samples. With respect to the low power of the GNSS signals this is a considerable drawback in the simulation process. In contrast, the presented solution can be used as a deterministic digital GNSS generator with exactly reproducible digital samples. Moreover real-world data can be recorded and replayed in the same accurate way. This considerably improves the development, qualification, and certification process.

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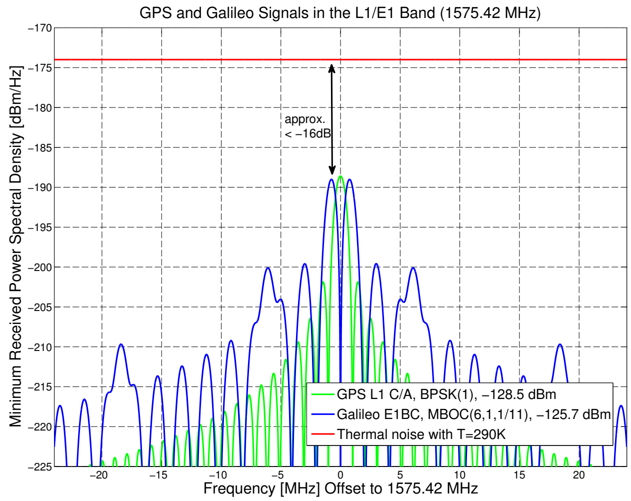

Figure 1. Negative signal-to-noise ratio of GPS and Galileo signals

INTRODUCTION

One common approach for saving costs during global navigation satellite system (GNSS) receiver development, qualification, and certification phases is to use a simulation environment rather than performing resource- and time-intensive field testing and validation. Moreover, as there is no fully operational Galileo constellation in space yet and due to repeatability of testing, manufacturers use commercial hardware GNSS signal generators to simulate the GPS/Galileo/SBAS constellations for receiver testing, verification, and validation. The third reason for using GNSS signal generators is the ability to simulate relevant error sources only needed for verification, tuning, or comparison of receiver hardware, software and algorithms.

Due to the inherent low power of GNSS signals, additive white Gaussian noise dominates the RF-output of GNSS simulators and is about hundred to a few thousand times stronger than the GNSS signal power itself. Figure 1 shows, by example, the power spectrum density of the minimum received power level as specified in the (Signal-In-Space) Interface Control Documents (ICD) [1],[2]. The integration over the frequency results into the power levels stated in the legend of the figure. Thus, the down-converted and digitized samples taken from the analog RF-output of typical GNSS simulators are different each time even if the scenario is meant to be exactly the same. This complicates baseband algorithm development since the controllability is not given anymore.

Looking at the performance analysis in a different way, there are many interference and degradation sources in the real world that cannot be captured in a complete and accurate way in a signal generator. Even the best synthetically generated simulation environment cannot reproduce reality better than recorded live samples. These issues complicate baseband algorithm development since the authenticity is not given and the simulation environment always remains an approximation of real-world conditions. Therefore the objective is to create a simulation environment which provides the possibility to use both: synthetically generated data and recorded real-world samples – both exactly reproducible. Such a tool would considerably improve the development, qualification, and certification process of baseband receiver hardware as well as positioning algorithms.

Unlike other simulators, the proposed GNSS constellation simulator and digital signal generator provides a deterministic digital intermediate frequency (IF) data output. This can be used for development, optimization, test, and verification of acquisition and tracking algorithms. Also a precise evaluation of baseband receiver hardware or position algorithms is possible due to highly reproducible digital data, which is helpful during the development as well as during the design of multipath and interference mitigation strategies and algorithms. In addition to simulated data, live scenarios can be recorded and replayed sample-wise using the digital signal generator, e.g., to compare the characteristics of different algorithms under exactly the same conditions. This enables a successful testing, verification, and certification of each receiver component and of the whole receiver.

At first the paper focuses on the concept and the architectural design of the proposed GNSS multisystem performance simulation environment with digital signal generation, recording and replaying. After this introduction, the paper details the possibilities of this simulator with respect to receiver testing and certifying. Each module is briefly introduced and their tasks within the overall procedure are highlighted. At the end, the testing of a multi-frequency L1/E1, L5/E5a and E5b GPS/Galileo baseband receiver is presented as a first application example.

SYSTEM ARCHITECTURE

An appealing simulation environment for signal generation and simulation must comprise four main flexible and modular components in software and also in hardware:

- Satellite constellation simulator
- Intermediate frequency signal simulator
- Digital signal generator and recorder
- Performance analyzer

For signal recording it shall be capable of being extended with:

- Multi-band GNSS antenna
- Multi-band RF front-end

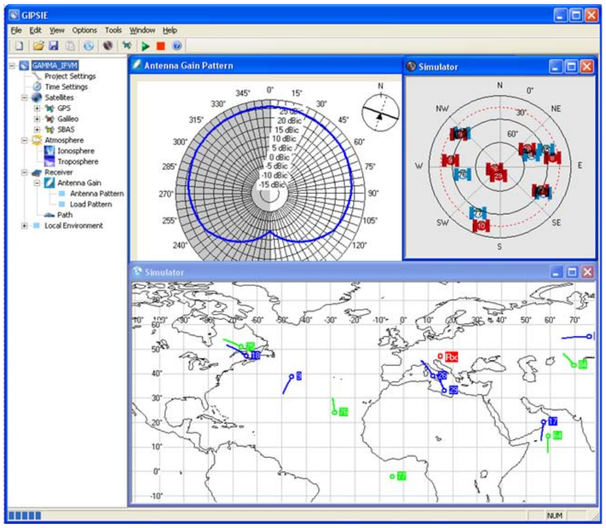

Figure 2. GIPSIE®-SCS graphical user interface

The device under test is the user's baseband GNSS receiver. A flexible GNSS baseband receiver prototyping hardware and software environment, furthermore allows customers without baseband hardware to port and evaluate their baseband algorithms.

The requirements onto the different elements of such a simulation system are discussed in more detail in the following subsections.

Satellite constellation simulator

The satellite constellation simulator enables arbitrary GNSS orbit simulations by a sophisticated orbit integrator. It shall be possible to simulate either static or dynamic user receivers, thereby considering pedestrian, vehicular, aeronautical, or maritime users. It shall provide the possibility of modeling environmental parameters and error sources like clock errors and propagation effects by using the user-friendly graphical interface. An example of such a GUI is shown in Figure 2. It shall implement different models to account for atmospheric influences as well as multipath or interference. The satellite transmit power and the antenna gain patterns shall be adjustable. The satellite constellation simulator shall compute raw measurements (pseudo ranges, Doppler data, etc.) and raw navigation data in a configurable data format. These data-sets shall either be usable in position computation algorithms (e.g., using RINEX format), or shall serve as an input to the other elements of the simulation environment. Different visualization and reporting possibilities, as e.g. described by [3], can complete the constellation simulator.

Intermediate frequency signal simulator

The intermediate frequency signal simulator software shall generate digital intermediate frequency data of GPS, Galileo, and other signals. It shall use the output of the satellite

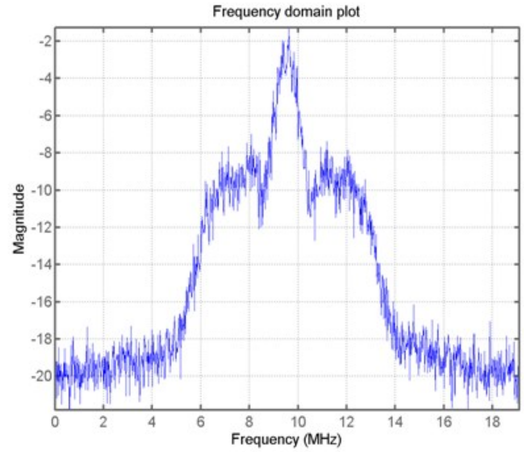

Figure 3. Spectrum of GIPSIE®-IFS output

Table 1. Currently available and planned systems and signals for the synthetic data generation

GNSS	Available Signals	Planned Signals
GPS	L1 C/A	L1C, L2C, L5 I/Q
Galileo	E1b, E1c	E6, E5a, E5b
SBAS	L1	L5

constellation simulator as an input and shall generate a digital intermediate frequency signal stream based on current ICDs, cf. [1], [2]. An RF front-end shall be simulated whereby the front-end design and behavior shall be parameterized and therefore user configurable. The intermediate frequency (IF) as well as different RF front-end parameters like analog-to-digital converter (ADC-)sampling rate and resolution, transfer function, and filter bandwidth shall be considered in particular. The digital IF output samples shall be stored in a file on hard disk. This allows efficient testing of the same signal with several channel and receiver configurations by uploading the binary stream of signal samples from the dedicated memory block. Table 1 lists the currently available and planned systems and signals of the GIPSIE® simulator environment which will be introduced later. The modular design, however, allows extending these to any signal.

Digital signal player and recorder

The digital IF samples stored in data files by the IF signal generator shall be streamed to the baseband GNSS-receiver under test using a digital signal player and recorder. The streaming-hardware shall support an input/output data rate of, e.g., up to 400 MBit/s in order to mask numerous frequencies and signal bandwidths. The hardware device shall consist of a high-speed digital input/output data card and a flexible hardware interface adapter card in order to interface to different baseband hardware.

This interface adapter, cf. Figure 4 for an exemplary block diagram, shall be configurable and adaptable to the cus-

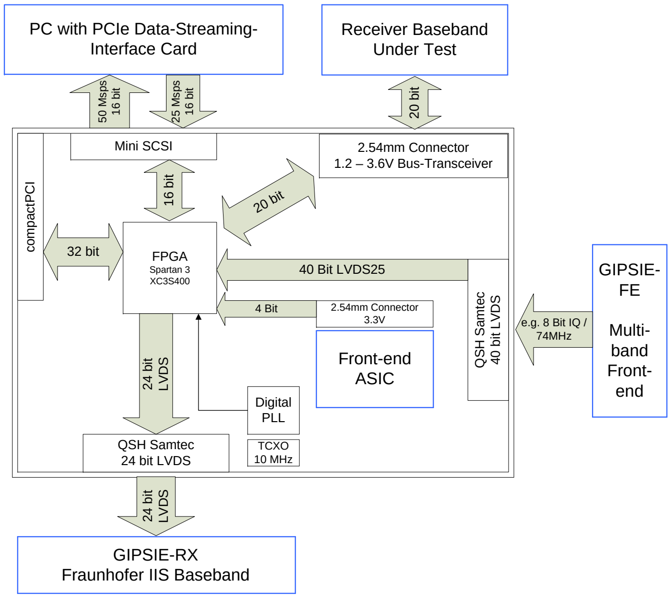

Figure 4. Digital signal generator and recorder interface adapter block diagram

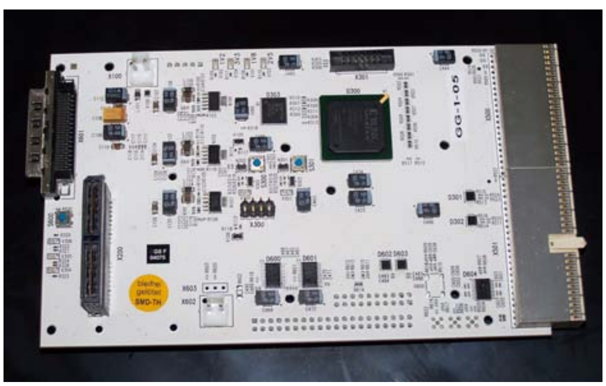

Figure 5. Digital signal generator and recorder interface adapter hardware

tomer's proprietary receiver under test interface. Therefore different input/output standards like LVCMOS or LVDS shall be provided, also supporting different voltage levels. A field-programmable gate array (FPGA) on the interface adapter card would enable real-time data conversion if needed. Thus, e.g., the intermediate frequency or the ADC data format could be adjusted on the fly.

The digital signal player card, optimally shall not only provide synthetically generated GNSS data as an input to the receiver under test but shall also be able to record real life-data by using a GNSS antenna and an appropriate GNSS RF front-end. The recorded data shall then be replayed to the receiver under test using the playback function of the streaming-hardware. This will guarantee real-world compatibility of testing. The recorded real-life samples could also be modified, e.g., overlaid with additional interference or multipath signals, before being replayed.

Figure 6. Active multi-band GNSS-antenna for all GNSS-bands

Performance analyzer

Using the performance analyzer, the receiver-under-test hardware/software-loop is closed. When using the synthetically generated data, the performance analyzer shall be able to compare the user defined input parameters with the results of the baseband or with the position output. This enables a GNSS receiver verification, evaluation, and certification process. The performance analyzer, furthermore, shall be able to analyze the output of the receiver when processing real-life samples, input by the digital signal player.

Multi-band GNSS antenna

Within the simulator environment, the multi-band GNSS antenna is optional. The antenna can either be used in conjunction with the digital signal recorder, but it can also be used together with the receiver under test for real-world processing. The characteristic of the multi-band antenna, and its performance have to be calibrated and known. This allows to trace system behavior either to the antenna or to the receiver. Furthermore, the calibration parameters can be used within the digital IF simulator.

Figure 6 shows an example of an active multi-band GNSS-antenna for all currently available and upcoming GNSS L-band signals. The antenna has been developed by Fraunhofer IIS [4]. It receives, filters and amplifies the frequency bands 1164-1300 MHz (GPS L5, L2; Galileo E5ab, E6) and 1559-1610 MHz (GPS L1; Galileo E1; Glonass) [5].

Multi-band RF front-end

Also the multi-band RF front-end is optional within the simulator environment. Several RF front-end boards are available in different configurations for receiving all L-band signals in different and partially selectable bandwidths, sampling rates, and ADC resolutions. With the help of the flexible interface adapter of the digital signal generator unit,

Figure 7. Portable RF front-end USB solution

Figure 8. GNSS rapid-prototyping baseband receiver

user RF front-ends can be applied. Important, however, is that the behavior and the performance of the front-end is known or calibrated. Only in this way certain positioning behavior can be traced back to the front-end performance or to the baseband receiver, which is under test.

Figure 7 shows Fraunhofer IIS' triband L125 USB front-end for recording GPS L1, L2, L5 and Galileo E1, E5a, respectively. The portable front-end solution does not require a digital signal recorder as specified before for recording, since data is directly transferred via USB port to e.g. the recording laptop's hard disk. However, these files can be streamed with a before mentioned digital signal player to the receiver under test.

Baseband GNSS receiver

It has been assumed that the device under test is the user's baseband GNSS receiver. Customers without their own baseband hardware can use an already certified baseband receiver. This one shall be a flexible GNSS baseband receiver prototyping hardware based on a FPGA and a flexible multi-processor software environment. This platform shall allow porting and evaluating of baseband algorithms on real hardware and shall be usable, e.g., for GNSS baseband ASIC design approaches. Figure 8 shows an example of such a platform based on a Xilinx Virtex 5 FPGA.

SIGNAL SIMULATOR CAPABILITIES

The specified GNSS signal recording, generation, and simulation environment shall allow precise evaluation of baseband receiver hardware or position algorithms based on the highly reproducible digital data. This shall not only be helpful for development, optimization, test, and verification of acquisition and tracking algorithms, it shall also be used for multipath and interference mitigation strategies and algorithms. In addition live scenarios shall be able to be recorded and replayed sample-wise in the laboratory, e.g. to compare the characteristics of different algorithms with real-world data under exactly the same conditions. Powerful trigger events could be defined in the performance analyzer, e.g. to trigger the exact sample, chip or bit when the receiver under test loses lock. The scenario could then be started right at the challenging position or some samples, chips, or bits before to be able to provide steady state conditions without replaying the whole scenario from the start again. Furthermore it shall allow a direct and fair comparison of algorithms and identification of optimal performance settings. The next subsections discuss different fields of application.

Digital-IF and deterministic GNSS signal generator

The user specifies a scenario and generates a digital IF data file applying the satellite constellation simulator and IF digital signal simulator software chain. The scenario encompasses various user settings and also the RF front-end characteristics. The output file is then streamed using the digital signal player over the adapter interface to the receiver hardware under test. The, e.g., RTCM-output of the baseband GNSS receiver can be analyzed in the performance analyzer and, e.g., compared to the satellite constellation simulator user input for receiver verification. The digital output data is always sample-, chip-, and bit-wise exactly reproducible. This allows new opportunities in development, optimization, test, and verification of GNSS baseband receivers. For example, the tracking algorithms can be tested on their performance during varying ionospheric effects without the variability introduced by noise.

Digital signal recorder and player

The propagation of the satellite signals is affected in reality due to the difficult reception conditions caused by shadowing, multipath, and permanently changing environmental conditions. Using calibrated antenna and RF front-end, such real-world data can be recorded using the digital signal recorder hardware. The recording length is only limited by the available hard disk space. The recorded data can then be replayed to the receiver under test in the same accurate way as with synthetically generated data. This enables the test, comparison, and tuning of receiver algorithms, acquisition and tracking under a certain real-world scenario in the laboratory. No cost- and time-intensive field testing and validation are necessary. This can also be useful if a special scenario, e.g., a challenging movement through an urban canyon, should be compared against different algorithms or baseband solutions.

Software-only signal simulator

The output of the satellite constellation simulator and IF digital signal simulator can also be directly used without any hardware components. For example, the RINEX data output stream of the constellation simulator can be used within positioning algorithms or the digital signal output can be used to develop, test, and certify software defined radio receivers.

GIPSIE® SIMULATION ENVIRONMENT

TeleConsult Austria GmbH in cooperation with Fraunhofer IIS developed the **G**NSS Mult**i**system **P**erformance **Si**mulation **E**nvironment - GIPSIE®, which provides the different elements shown in Figure 9 and 10. GIPSIE® consists of four main components for signal simulation and generation:

- GIPSIE®-SCS (Satellite Constellation Simulator)
- GIPSIE®-IFS (Intermediate Frequency Signal Simulator)
- GIPSIE®-DSG (Digital Signal Generator and Recorder)
- GIPSIE®-PA (Performance Analyzer)

For signal recording it can be extended by:

- GIPSIE®-ANT (Multi-band GNSS Antenna)
- GIPSIE®-FE (Multi-band RF Front-end)
- GIPSIE®-RX (GNSS Baseband Receiver)

All these elements meet the requirements identified before. GIPSIE® was designed to be used in a wide range of applications. Compared to common analog RF-output GNSS signal generators, this digital output GNSS signal generator has the significant advantage of a deterministic data output. Using the digital baseband samples directly without an RF-front-end enables the reproduction of exactly sample-, chip-, and bit-wise data. Additionally multi-band GNSS signals can be recorded under real-world conditions. The recorded data can then be replayed in the laboratory again in the same accurate way (sample-, chip-, and bit-wise) as with synthetically generated. This allows new opportunities in development, optimization, test, and verification of GNSS baseband receivers.

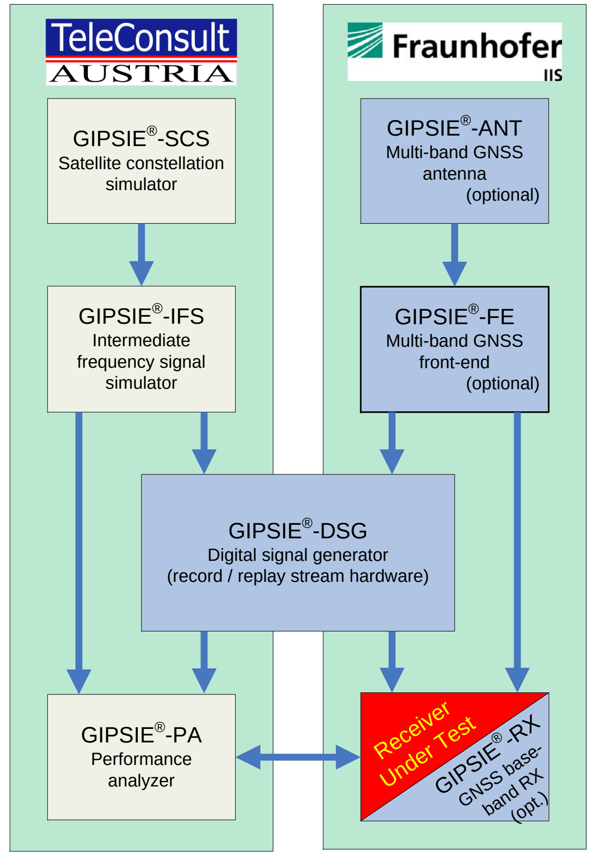

Figure 9. GIPSIE® system architecture

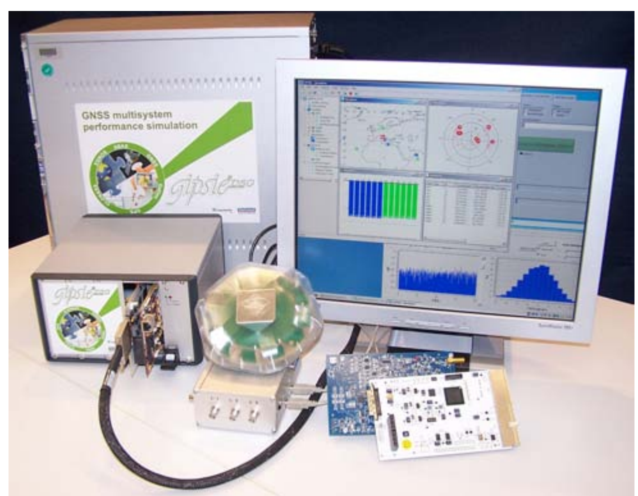

Figure 10. GIPSIE® hardware/software components

APPLICATION EXAMPLE

GIPSIE® has been used during the development phase of the 3-frequency automotive receiver development project GAMMA-A founded by the European Union's Seventh Framework Programme (FP7/2007-2013) under grant agreement nr. 228339 (GAMMA-A project) [6].

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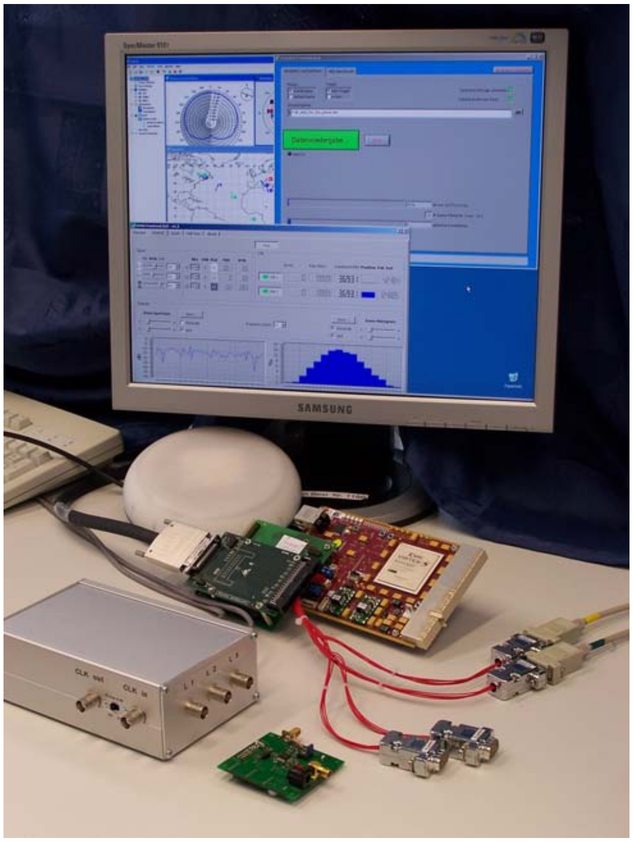

Figure 11. Using the GIPSIE®environment for baseband development

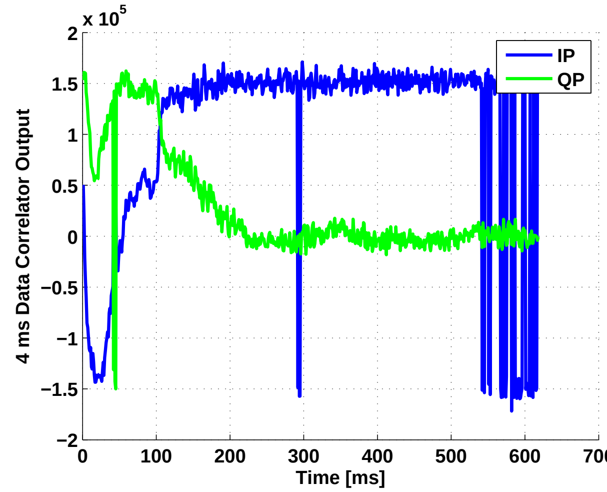

Figure 12. E1 data prompt correlator going into tracking with recorded data

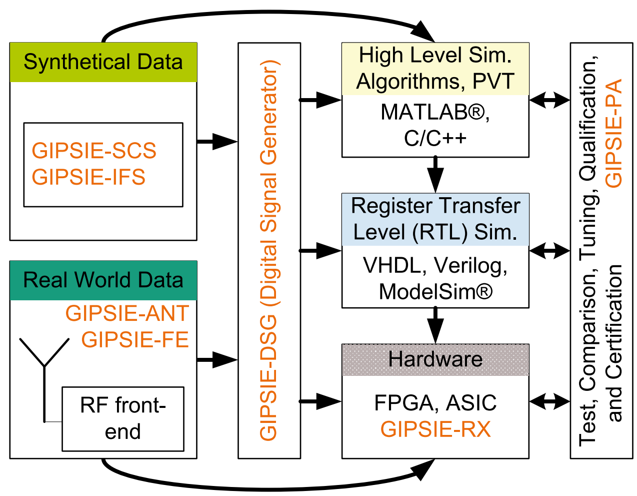

Figure 13. Using the GIPSIE®environment for GAMMA-A digital baseband development

Figure 11 shows the baseband development setup using the GIPSIE®environment. The receiver under test and development is a FPGA with a multi-processor environment used for a GPS/Galileo/SBAS L1/E1 and L5/E5a/E5b processing. The integrated RF front-ends provide an IF of 11.18 MHz for L1/E1 and ±15.345 MHz for L5/E5a/E5b, with an ADC sampling rate of 74.487 MHz and 4-bit resolution each.

GIPSIE®-IFS is used to simulate the mentioned RF front-ends parameters. Therefore the development and verification setup from the high level simulations down to the hardware level benefits from exactly reproducible, synthetically generated IF-sample data, facilitating the development phase considerably.

Since every RF front-end has some inherent degradations (spurs, phase-noise, non-linearity) which cannot be modeled exactly, some datasets were recorded using both the GIPSIE®-FE RF front-end and the GAMMA-A project RF front-end ASICs with the GIPSIE®-ANT and the recording option of the GIPSIE®-DSG.

While replaying now the degraded but actual real-world datasets, the accurate IF-sample reproduction can be guaranteed. This helps tuning the baseband algorithms to the not ideal but real RF front-end input data stream and gaining a deeper insight in the non-trivially simulated real life signal distortion and their impact on receiver operations. Figure 12 shows results of the high level simulation in MATLAB. The tracking loops pull the prompt correlator into tracking for the data signal [7]. The same digital IF-samples were then used for the development and verification of the register transfer level (RTL) design. Afterwards the samples are streamed to the FPGA prototyping hardware in order to be able to compare the behavior of the preliminary RTL simulation and the real hardware. The step from high level simulation to the final hardware implementation can be kept as small and faultless as possible by this approach. This flow is depicted in Figure 13.

CERTIFICATION OF DIGITAL SIGNAL GENERATORS

The certification of receiver technologies requires putting appropriate processes in place. This follows a three step procedure as mentioned by [8] and schematically shown in Figure 14: in the first step an appropriate test approach has to be chosen; in the second step, test cases have to be designed; and finally the implementation of the test cases within the test environment has to be certified. Therefore again certification routines have to be put in place, either by relying on long-term experiences or by agreeing on certain standards. Thereby it has to be ensured that test systems properly implement the agreed standard.

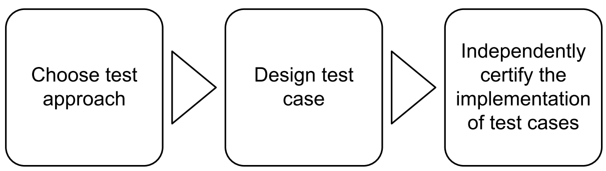

Figure 14. Test case implementation [8]

As soon as test cases have been designed, developers of test environments can adjust their systems to them. An independent, public or private, agency or institution, however, then has to certify the test environments for building confidence of the user market into certified products.

It is vital that the agreed test cases for certification account for the receiver or system under test rather than on the environment to be used for testing. In this way, it might be necessary to apply software-based signal simulators as well as hardware-based signal simulators in order to cover the full range of test cases. Different test levels resulting in different certificates might be agreed on to facilitate certification procedures. For the end-user it is therefore important tracking the certification procedure down to the related standard.

A modular and flexible design of the test environment, like the one of GIPSIE®, allows testing single receiver parts, like the baseband processing or the position, velocity, and time software (PVT), but also performing full end-to-end receiver tests. Thus, GIPSIE® provides the flexibility which is required for coping with different test cases and certification procedures and eases test planning and conducting the specified test.

CONCLUSION

TeleConsult Austria GmbH in cooperation with Fraunhofer IIS developed a digital GNSS signal recorder, generator, and simulator for receiver test, qualification, and certification. Compared to common analog RF-output GNSS signal generators, this digital output GNSS signal generator has the significant advantage of a deterministic data output. Using the digital baseband samples directly without an RF front-end enables exact reproduction of sample-, chip-, and bit-wise data. Additionally multi-band GNSS signals can be recorded under real-world conditions. The recorded data can then be replayed in the laboratory as accurately as with synthetically generated data. This provides new opportunities and efficient procedures in the development, optimization, test, and verification of GNSS baseband receivers. For certification, however, it might be necessary to apply software-based signal simulators as well as hardware-based signal simulators in order to cover the full range of test cases.

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