

# Everything You Always Wanted to Know About GNSS Simulators But Were Afraid to Ask

This second article on simulators and testing examines various simulator designs, and how these designs affect simulator specifications.

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In this article we describe the design and operation of a generic GNSS RF simulator. We also will look at the main types of GNSS RF simulators, their designs and specifics, their advantages and disadvantages.

Product designers, manufacturers, and systems integrators have used simulators for decades now for various purposes. We use them for testing, R&D, and education. In the previous article in this series (*Inside GNSS*, July/August 2010), we looked at the simulator as a tool needed at every stage of receiver development from R&D to a production, certification, and maintenance.

## A Growing Family

Simulator technology is now a mature one with sophisticated algorithms and

designs behind it. For a long time many users only needed to see simulators as “black boxes,” supplying them with GNSS signals “out of the box.” The time has come, however, for all users to be able look inside of a simulator and understand its design, specification, functions, and limitations, because all of these devices provide a different set of capabilities, often constrained by their design.

Recently, new devices with functionality similar to that of simulators have appeared, expanding the simulator’s family. These include digitized intermediate frequency (DIF) generators, constellation simulators, signal recorders, record and playback systems, and more. How can we best use all these devices?

As the simulator family expands (see **Figure 1**), users need to understand those devices more than ever in order to ensure quality of the solutions for which the equipment is employed.

As we might expect, particular simulator devices better fit a particular

task than others. In this article we look at various designs of some members of the simulator family and discuss how a simulator design may affect its specification and functionality.

Let’s start off with probably the most familiar category: GNSS signal simulators. Full-scale RF signal simulators have had their functionality shifted to a digital domain, which provides a more flexible and economic solution. This type is generally divided into two groups, single-channel and multi-channel simulators.

## Single-Channel Simulator

A single-channel simulator — sometimes also known as a *signal generator* — is usually capable of simulating a signal from one satellite with extended control over various parameters.

In particular, such a simulator can usually control a signal’s Doppler profile. This function is very handy when it comes to tuning up receiver tracking loops. Simulators of this type are

widely used for production and R&D tests.

A single-channel simulator can be designed in pretty much the same way as a satellite transmitter. We illustrate all designs in this article using GPS L1 simulation as an example.

An L1 signal carrier is modulated by code and navigation message. The difference in perception of a simulator and an actual satellite transmitter is the extra control over a Doppler shift made possible with the former. An example of single-channel simulator design and its generation of a Doppler profile is presented in **Figure 2**.

A navigation message is applied directly to code in order to avoid possible misalignment between code chips and navigation message bits. A Doppler shift should be coherently introduced both in the code and carrier.

In a simple simulator design the Doppler effect only shifts code chips. More sophisticated designs change the chips' size as well.

Figure 2 depicts an analog type of single-channel simulator. As we show later, proper results accurately representing a Doppler effect are much easier to achieve in a digital simulator than in the analog type.

General requirements for single-channel simulator include a capability to generate a signal with the following:

- the correct RF carrier frequency
- expected range of power levels (for example, from -60dBm to -155dBm)
- the expected range of the Doppler shift
- the correct modulation,
- a navigation message.

A user should be able to control all these features. Moreover, we should be able to introduce a Doppler shift as a profile, to edit the navigation message, and to change the signal power level during a simulator run.

The range of a Doppler shift depends on the application. The rules of thumb are as follows: A GPS satellite moves with a velocity of approximately four kilometers per second. The projection of this velocity to a line-of-sight (LOS)

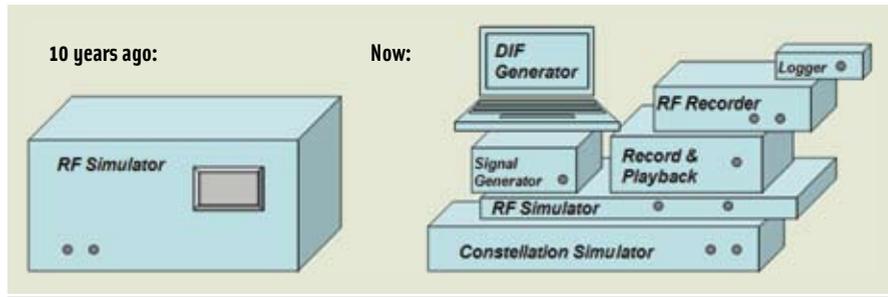


FIGURE 1 GNSS multi-channel signal simulator 10 years ago on its own (left) and with its ever-growing family (right)

between the satellite and a user is usually within 800 meters per second.

The shift in a frequency due to a Doppler effect is described as follows.

$$f_D = L_1 \frac{v_{LOS}}{c}$$

where  $L_1$  is transmitted signal frequency (in this case GPS  $L_1$ ),  $c$  is speed of light and  $v_{LOS}$  is relative transmitter-receiver velocity along line-

of-sight. This yields a Doppler shift of less than 4.5 kilohertz. The shift increases the frequency if a receiver and transmitter are converging.

A standard simulated vehicle has low dynamics. Therefore, the Doppler shift for most applications can be limited to 6 kilohertz. For a high-dynamic user, equation (1) describing a Doppler shift is generally not adequate because it fails to incorporate derivatives of higher order necessary for a correct solution.

### Pseudolite

A single-channel simulator can be used as a pseudolite. Such a simulator should implement RTCM pulsing and a frequency offset to confront a “near-far” problem and reduce potential effects on non-participant receivers. Pulsing is a pulse-wise interruption of the transmitted signal made to decrease the value of receiving signal power for non-participant receivers.

Pseudolites are sometimes implemented to provide in-the-field simu-

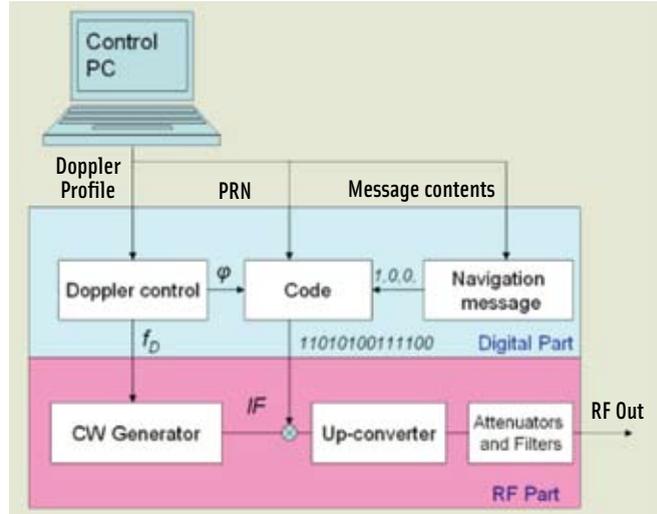


FIGURE 2 Single-channel simulator design flowchart for Doppler profiles

lation of future satellite systems. For example, an airborne pseudolite on board of a helicopter has been implemented to simulate QZSS satellite in real environment, described in the paper by T. Tsujii et alia (2007) listed in the Additional Resources section near the end of this article. Pseudolites also are being used to simulate Galileo satellites in real environment, such as in the Galileo Test and Development Environment (GATE) described in the article by Günter Heinrichs et alia (cited in Additional Resources), as well as in robotics (see the article by I. Petrovski et alia cited in Additional Resources).

However, some challenges still need to be taken into account when it comes to other than those limited implementations of the pseudolites. The pseudolite implementation in GNSS band is only acceptable for test and research purposes in limited and restricted areas. In case of more general applications, they must be — and in many cases have been — moved to other frequencies.

Keeping pseudolites in the GNSS band has a minor advantage at the R&D stage — the ability to reuse receiver RF components. But this advantage fades away in comparison with a danger of jamming non-participant receivers or increasing the RF noise floor, an effect that is very difficult to predict or to estimate.

Even when implemented only indoors, use of pseudolites is still not safe outside of specially licensed locations. After all, if a high-sensitivity receiver can acquire a low-powered GNSS satellite signal indoors from 20,000 kilometers away, the same receiver can almost certainly hear a pseudolite located next door.

**Multi-Channel Simulator**

A simulator from the second type within the RF type has multiple channels and is also sometimes called a *constellation simulator*. It provides one with coherent simulation of multiple satellite signals in a defined operating environment. This type of equipment is widely used

for R&D work and in almost all design, manufacturing, and post-sales tests.

Three key features define a multi-channel simulator: the capability of recreating GNSS RF signals so as to be indistinguishable from the real signals by a tested receiver; the capability of providing repeatability of the signal generation; and the ability of a user to control most of the simulation environment.

The user should be able to know exactly what parameters have been set for the simulation, which is known as the *true model*.

In general a multi-channel simulator design is quite different from that of a single-channel simulator. The mechanism behind a multi-channel simulator works as follows: A vehicle coordinates are introduced either as static or as a trajectory. If the vehicle is not static, then the coordinates are provided versus time. Satellite coordinates are also calculated for each epoch based on satellite ephemerides. The ephemeris can come from

a recorded broadcast navigation message, satellite almanac, or user input.

We can describe satellite ephemerides at several levels of increasing precision. The least precise formalization is given by six main Keplerian parameters that essentially describe an orbital ellipsoid, its shape, and its position in relation to the Earth. The current epoch specifies the satellite position on the ellipsoid. These parameters basically constitute a GPS almanac.

In a real environment, a GPS almanac gives just enough information to calculate an approximate satellite position with sufficient accuracy to enable a receiver to “guess” which satellite to look for and where, as well as to estimate the expected Doppler shift to assist in acquiring the signal.

In order to make an initial position fix, however, the receiver needs more precise orbits that are described by the main Keplerian parameters plus osculating parameters. These osculating param-

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eters describe a deviation of the satellite orbit from an ideal ellipsoid, similar to the one contained in the almanac. Such a complete set of the orbital parameters can come, for example, from a receiver in a RINEX (receiver independent exchange) format file.

A simulator, however, may use just almanac parameters and leave all osculating parameters set to zero. In a sense, that creates a special case, but the receiver undergoing test will calculate a position all the same, because those parameters are presented to the receiver in a simulated navigation message as a satellite ephemeris (orbital position). The accuracy of a tested receiver's positioning will not suffer, because only almanac parameters are used both in a true model and broadcast model.

### Ionospheric Error: Broadcast and True Models

The distances between a given receiver and the satellites it is tracking are calculated and serve as the basis for creating code and carrier observations for each instance of time. In the real world, however, GNSS signals are delayed and distorted during their propagation through the atmosphere and often obstructed and attenuated by foliage or buildings. There are also other error sources.

These errors are calculated based on various sophisticated models and added on top of the estimated distances between satellites and the user to create the *true model* signals.

The navigation message transmitted by a GNSS satellite carries ionospheric model parameters, satellite orbits, and clock parameters that represent our supposed knowledge about a true model — but with an element of inaccuracy. The true model parameters are used for signal creation and normally should be slightly different from the corresponding parameters embedded in the navigation message (see **Figure 3**).

The broadcast ionospheric-corrections model is implemented either in a shape of a Klobuchar model in case of GPS or in the form of NeQuick model for Galileo. If the simulator is simulating both systems at the same time,

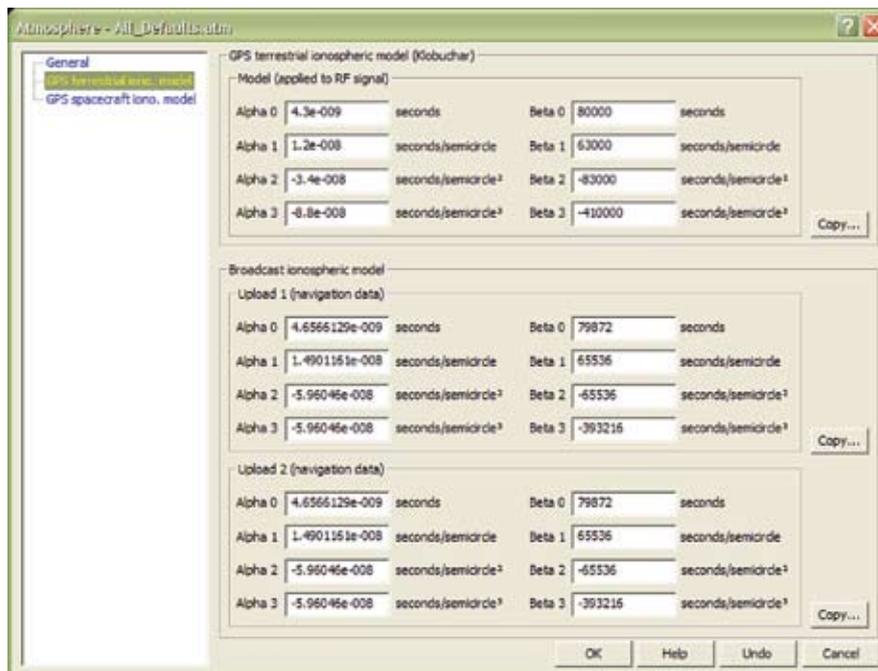


FIGURE 3 Atmospheric error parameters for broadcast and true model (RF Simulator software menu)

then it *must* use the same underlying true model for both broadcast models.

Because we do not have a standard way to transfer from one model to another, it would be desirable for a user to make sure that the models are correctly interconnected. That could be achieved if a simulator provides

a graphical representation of TEC distribution similar to one depicted in **Figure 4** for the Klobuchar model.

### Ionospheric Error: Code Delay and Phase Advance

GNSS ranging errors mainly come from signal propagation through the atmosphere. Ionospheric error is calculated as a delay in code observations and an advance in phase observations. All other errors contribute to code and phase observations with the same sign, only as delays. Most significant errors among these are tropospheric delays and satellite clock errors.

The line-of-sight (LOS) distance between a receiver and satellite as it

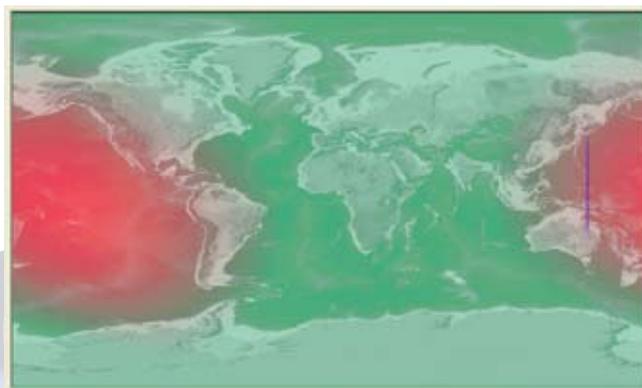


FIGURE 4 Worldwide TEC distribution map for Klobuchar model with a plasma bubble (DIF generator software menu option)

measured by a receiver can be calculated as follows.

$$\rho_{code} = d + d_{clock} + I + T$$

$$\rho_{carrier} = d + d_{clock} - I + T \quad (2)$$

where  $d$  is a LOS distance between a receiver and satellite,  $d_{clock}$  is the satellite clock error (i.e., the offset between each satellite clock and GPS time),  $I$  is an ionospheric error along the signal LOS path, and  $T$  is a tropospheric error along the signal LOS path.

These  $\rho_{code}$  and  $\rho_{carrier}$  distances unambiguously specify code and carrier phase values of the generated signal. Sometimes these distances are referred as pseudoranges, which is not exactly correct, because a pseudor-

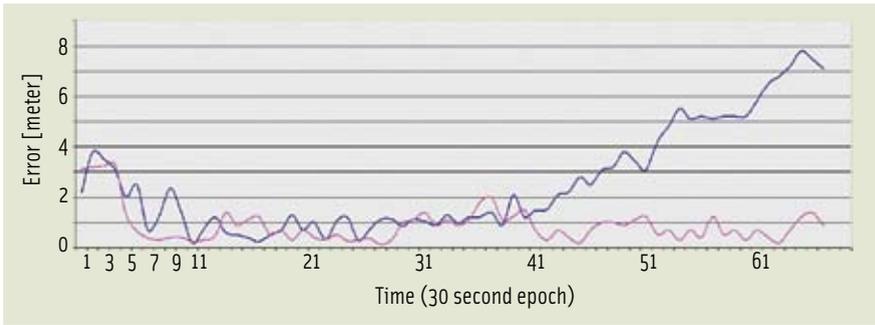


FIGURE 5 Carrier-smoothed code measurements from a software receiver. The measurements resulting from the incorrect signal with an erroneous ionospheric model, corrupted on purpose, are in red; the measurements resulting from a signal generated with correct ionospheric models are in blue.

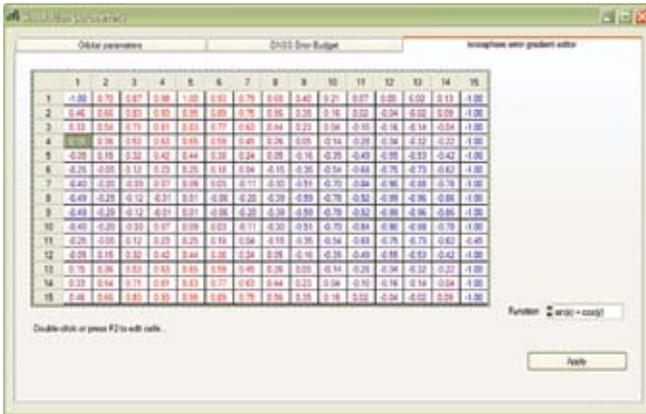


FIGURE 6 Spatial ionospheric-error editor panel in a DIF generator. It allows a user to edit TEC variation values, range colored for convenience. The size of the table is changeable and the resulting table then is patched over the nominal TEC distribution.

ange is an output of a receiver and, as such, includes receiver clock error. This receiver clock error is not simulated in the simulator, but naturally added by a receiver in test.

It is very important that a simulator accounts for ionospheric error correctly, i.e., as a delay in code and advance in carrier measurements. Even today this feature cannot be taken for granted.

In order to appreciate its importance, let's give an example of a single-frequency receiver undergoing a carrier-smoothing test. We will use our real-time software receiver for this test.

Two correct signals are generated by RF simulator and our DIF generator. We also are able to generate an intentionally incorrect signal in which the sign of the ionospheric error is the same in both the code and carrier equations. In this case, both code and carrier ionospheric errors are modeled as delays, because a possible mistake would be just to ignore that the carrier error is advancing and to model it as all other errors as a delay. We could

change a treatment of the ionospheric model for signal generation, because we have access to the DIF generator source code and can change it to generate an incorrect signal for our purposes.

We can see that having code and phase incorrectly simulated would directly affect the results of our approach to a

positioning algorithm design. We use a simple smoothing algorithm without a reset. The code-carrier divergence becomes evident after about 30-60 minutes of filtering depending on receiver the noise and multipath errors. The test results applying a smoothing algorithm are depicted in Figure 5.

A simulator should also be able to display raw data to the user in a way that shows distances in equation (2). In the simulator that we use in our tests, a raw data display shows these errors calculated per epoch.

In order to check the correctness of the model, the user should generate two scenarios:

1. A scenario without errors, in which case only the LOS distance between a receiver and satellite ( $d$ ) in equations (2) is simulated.
2. A scenario with only an error due to ionosphere ( $I$ ).

Tropospheric and clock errors should be set to zero in both scenarios and equations (2) become simplified as follows:

$$\rho_{code} = d + I$$

$$\rho_{carrier} = d - I$$

By comparing  $p_{code}$ ,  $p_{carrier}$ , and the error due to ionosphere ( $I$ ) we should see that these values are calculated correctly as in equations (2). In the case of the RF simulator that we are using in our tests, they were, of course, calculated correctly.

### Additional Ionospheric Error Models: Spatial Correlation

Some R&D tasks may require more specific models to be implemented, especially where it concerns a development of new algorithms.

One example is spatially correlated ionospheric errors. Algorithm development related to virtual reference station (VRS), network RTK, or ionospheric research may require an ability to generate a spatially correlated ionospheric model in which the signal is generated for more than one receiver and ionospheric errors are properly correlated.

The specific fluctuations of TEC distribution can be added on top of the nominal TEC distribution (see Figure 6). These nominal TEC distribution values come from true Klobuchar, NeQuick, or IGS models. We can also specify an anomalous ionospheric gradient with parameters in accordance with Wide Area Augmentation System (WAAS) Super Truth data analysis and simulate a moving slope for ionospheric gradients. For details of Threat Model of Anomalous Ionosphere Gradient see FAA Non-Fed Specification, FAA-E-AJW44-2937A, Category I Local Area Augmentation System Ground Facility.

Simulation of such errors allow us to verify correct implementations of local area augmentation system (LAAS) or similar algorithms (see Figure 7).

### Additional Ionospheric Error Models: Scintillation.

Both scintillation and multipath errors are implemented in simulation differently from other errors because they don't affect code and carrier measurements in the same way as propagation

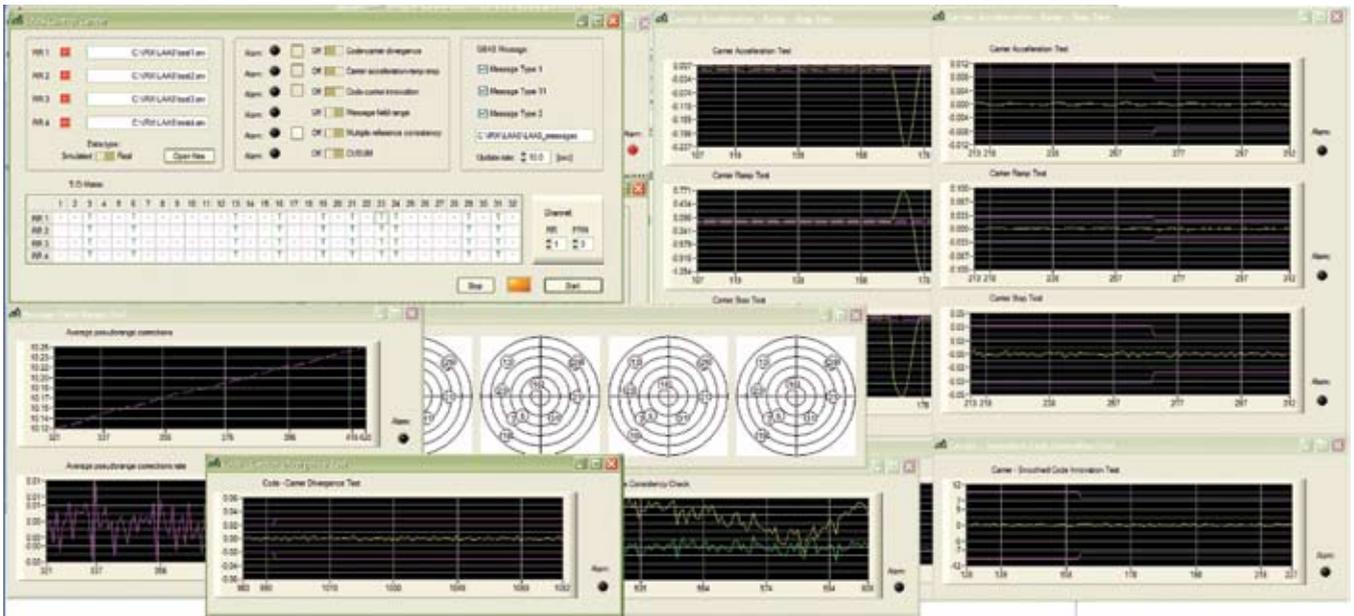


FIGURE 7 Display of an LGF (LAAS Ground Facility) test emulation software, which enables analysis of spatial correlations between ionospheric errors generated for four distantly located receivers.

delays. Multipath errors and scintillation errors are transformed to range errors only after they go through a receiver baseband processor.

The simulated L1 signal at each epoch is simulated as an L1 carrier wave modulated by code and navigation message.

$$A = A_0 \sin(\omega t + \varphi) \cdot B \quad (3)$$

where  $B$  is a result of code and navigation message summation and either 1 or 0.

The calculated distance  $\rho_{carrier}$  in equations (2) is used to determine the carrier phase  $\varphi$ , and calculated distance  $\rho_{code}$  is used to determine  $B$ , whether it is 1 or 0 at this epoch.

Scintillation causes fluctuations in amplitude and phase of the carrier. These fluctuations can be added to the simulated signal as shown in equation (4). For details on this technique, see the article by S. Pullen et alia in the Additional Resources section near the end of this article.

$$A = A_0 \cdot \delta A \cdot \sin(\omega t + \varphi + \delta\varphi) \cdot B \quad (4)$$

Scintillation is a rather complicated process to simulate. Stochastic processes describing amplitude ( $\delta A$ ) and phase scintillations ( $\delta\varphi$ ) are negatively correlated. The phase scintillation is described as a Gaussian process, whereas the amplitude scintillation is described by a Nakagami distribution, which is a

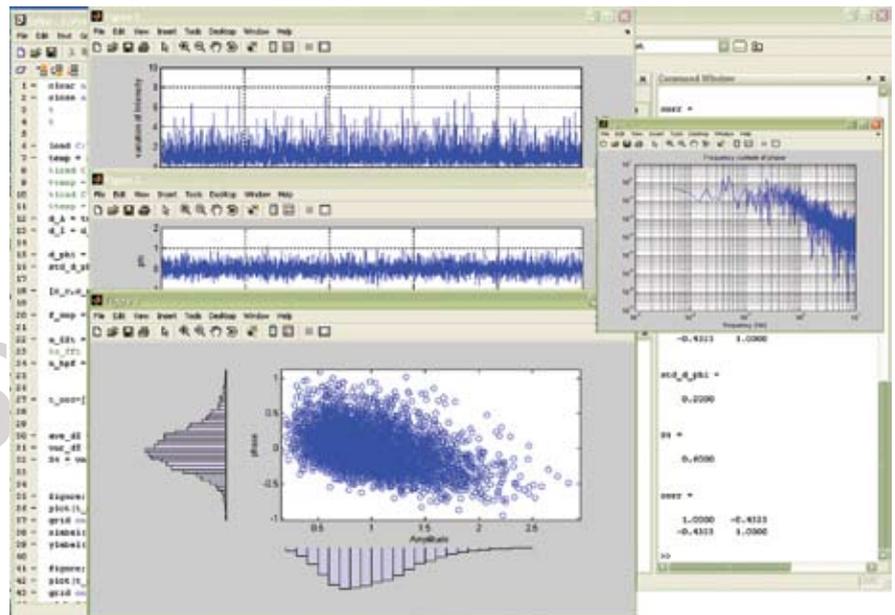


FIGURE 8 Analysis of scintillation errors generated by DIF generator (Courtesy of Dr. Toshiaki Tsujii, JAXA)

special case of Gamma distribution.

A signal simulated with scintillation (see Figure 8) can then be processed by a software receiver to allow closely investigate how tracking loops are affected by the scintillation. The editor depicted in Figure 6 can be also used to specify a size and location of a scintillation bubble.

### Multipath: an Error That Is Simulated Differently

The multipath error is created in a simu-

lator by duplicating a simulated satellite signal with a phase shift and attenuation in amplitude. The multipath error can be expressed in the following way:

$$A_M = k_M \cdot A_0 \cdot \sin(\omega t + \varphi + \varphi_M) \cdot B(\varphi_M) \quad (5)$$

The signal is attenuated by  $k_M$  and delayed by  $\varphi_M$ .

In the case of simulating scintillation equation (4) was describing a main signal. In the case of simulating multipath equation (5) is describing an extra sig-

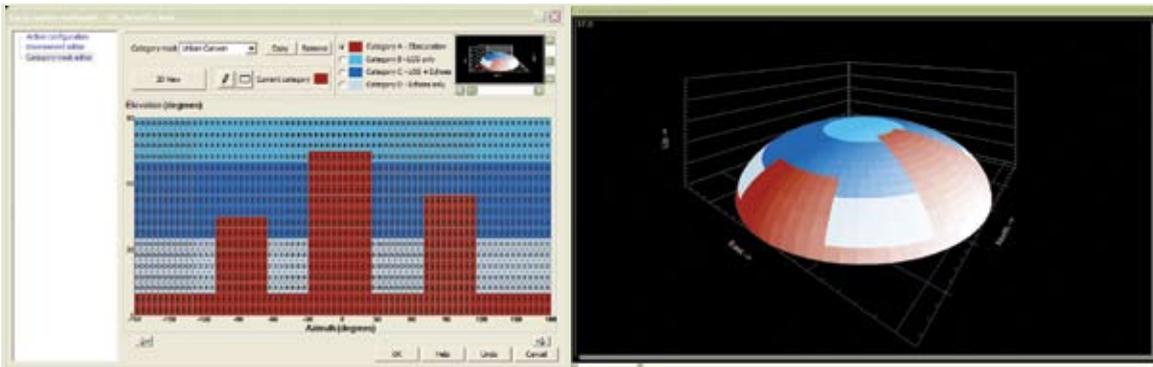


FIGURE 9 Multipath editor of an RF multi-channel simulator

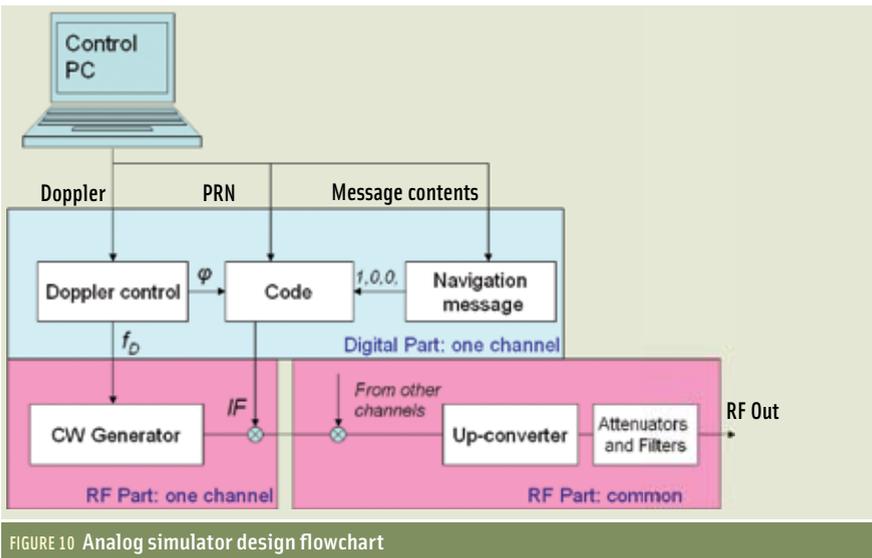


FIGURE 10 Analog simulator design flowchart

nal, which should be added to the main signal, as described by equation (3).

There are interesting special cases for multipath generation. For example, when a reflected signal is stronger than the direct signal and  $k_M > 1$ . In real life such situations can happen, for example, in urban canyons.

Figure 9 shows an advanced sophisticated editor, which allows a user to specify complex, statistical multipath effects in the RF multi-channel simulator. It enables control of the complete signal environment including signal attenuation and signal obstruction.

### Simulator of Type I: Analog Simulator

Now we look at the ways in which the signal calculated in equations (3), (4) and (5) is transferred to RF signal. How it works depends on the simulator type.

At first we consider an analog simulator, which was the first type of a simu-

lator to be developed. It was designed in a very similar manner to the way a satellite transmitter is working.

The simulator generates an IF carrier, adjusts it with Doppler values, and incorporates the code and navigation message. The baseband signal from the various channels is then mixed together and up-converted to L-band. A flowchart of this kind of simulator design is shown in Figure 10.

In general, an analog simulator costs much more than a digital one because of the larger RF part, the components of which comprise the equipment's most expensive items.

### Simulator of Type II: Digital Simulator

We continue our discussion about creating simulated signals using the other type of simulator family, namely the digital simulator. These have appeared quite recently, within the last decade.

We will concentrate on the digital category because we consider that its underlying technology is superior to the analog type. Moreover, even the satellite trans-

mitters for future and modernized current GNSSes may move to digital signal generation, because it makes the transmitters more flexible and easy to reprogram on-the-fly.

The digital versus analog issue with GNSS simulators is not the same as with cameras. One can argue that an analog camera would provide one with a better quality, although almost everyone uses a digital one nowadays — probably because a digital camera is easy, more flexible, and more modern technologically. Some people make the same argument regarding vinyl records and compact disks — that the analog technology produces a better, truer musical sound quality.

From such examples, one could easily get a wrong impression that analog design is by definition superior to digital. In fact, an analog simulator may provide way less signal quality than a digital one, for reasons both related and unrelated to its analog character.

For example, multi-channel and especially multi-frequency analog simulators have many more separated RF tracks, which can interfere with each other and with a digital component. For example, in a digital simulator we can and usually do combine all channels before the DAC and then use only one RF track for one frequency.

An analog simulator generally requires a separate frequency generator for each satellite even in the same L1/L2/L5 frequency, whereas a digital simulator may require only one RF channel for each frequency. Therefore, an analog simulator has inter-frequency and inter-channel biases, whereas a digital one has no inter-channel biases and, depending

on the design, may have no inter-frequency biases either.

Analog simulators may also suffer from higher phase noise in comparison with digital versions. Digital simulators have high quality, low aging, and high predictability. Among their other advantages is a high precision of frequency set and frequency resolution.

Let us look at the digital simulator design. **Figure 11** depicts the flowchart of a typical digital simulator design.

If we put a borderline between simulator hardware including the digital part (i.e., FPGA) and a PC part, then all the information coming from the PC constitutes a *scenario*. The carrier is generated by a numerically controlled oscillator (NCO), mixed with the code and navigation message, to create a DIF signal.

The simulated signal is then combined with DIF signals from other channels and goes through digital to analog converters (DACs) to become an intermediate frequency (IF) signal. The rest of the signal path is no different from that of an analog simulator.

We need to be aware of two main issues with digital simulators, however: potentially high spurious frequencies and a relatively small bandwidth. The spurious frequencies are caused by a ladder-shaped carrier wave generated by an NCO. Therefore, simulator designers may need to apply rather complicated techniques to reduce spurious signals so that the simulated signal meets GNSS specification requirements as described in the various interface control documents (ICDs).

A key metric applied to this issue is the *spurious free dynamic range* (SFDR), which is defined in GNSS ICDs as 40 decibels. (SFDR is the measure of the ratio in amplitude between the signal and the largest harmonically or non-harmonically related spur. Essentially, it indicates a usable dynamic range before debilitating RF noise interferes with the signal.)

The SFDR of a DAC is defined by its specification. The difference between the required GPS SFDR and DAC SFDR represents the available headroom for channel gain and power control resolution between channels (see **Figure 12**), i.e., dynamic range for the signal power level control. The lack in this headroom may force a trade-off between available signal power range for a separate channel and minimum power step.

Such parameters are especially important for AGPS systems, where channels may differ significantly in signal power level and require fine steps during the level increase. This challenge doesn't exist if the difference between signal powers on different channels is not substantial.

In general, for normal dynamics the calculations for equations (3), (4), and (5) should be done for each 10–100 milliseconds. The data are then interpolated inside this interval to the DAC frequency before going to DACs.

## Doppler Effect: Is It Really There?

We usually think of a Doppler effect as a physical change in a signal frequency caused by movement of a transmitter relative to receiver (or vice versa) at substantial velocity. In reality, if we just recreate a signal with code and carrier observations

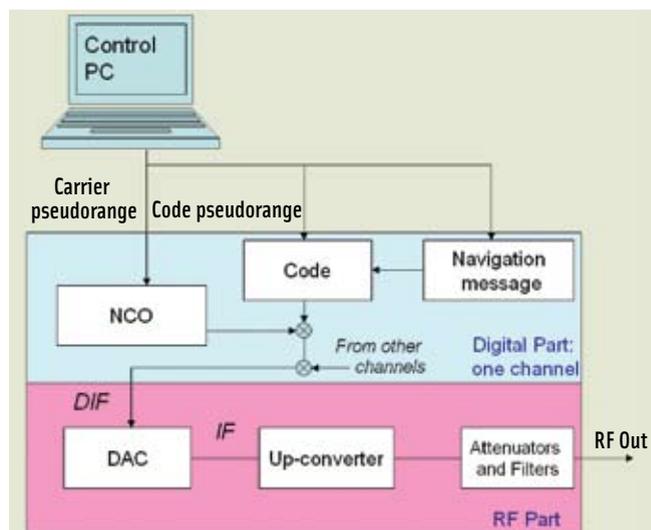


FIGURE 11 Digital simulator design flowchart

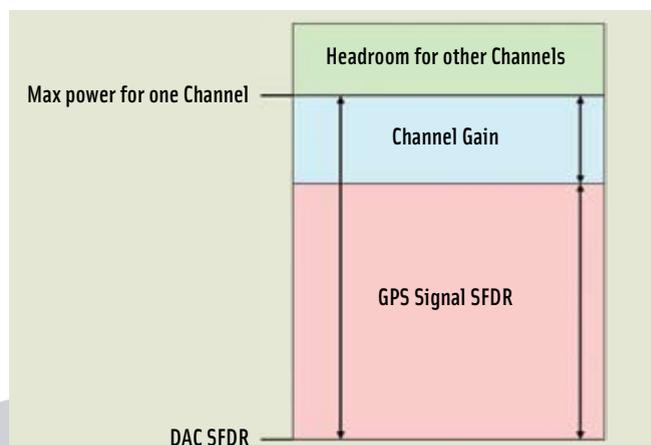


FIGURE 12 Signal purity versus power control resolution trade-off

for each epoch on the receiver side using equation (2), then we get the correct signal representation without any extra care for explicit changes caused by Doppler effect.

This means that the Doppler effect just comes purely from the receiver-transmitter geometry. It also means in particular that if a receiver or transmitter moves with some acceleration rather than a constant speed, then this Doppler frequency shift of the received signal will depend on the derivatives of higher order, which may be important for simulation of high dynamic vehicles.

The difference in perception of a Doppler effect actually plays a role when we consider the different types of simulators. In the case of an analog simulator (Figure 9), the Doppler shift should be calculated explicitly and applied to both carrier and code. However, in a digital simulator, one can just calculate a code-based range and carrier-based range between a satellite and a receiver and a Doppler effect will appear as it should from the receiver's point of view.

This difference between analog and digital simulators may greatly affect a simulator's ability to generate dynamic profiles. Doppler effects must be implemented in the code generator as

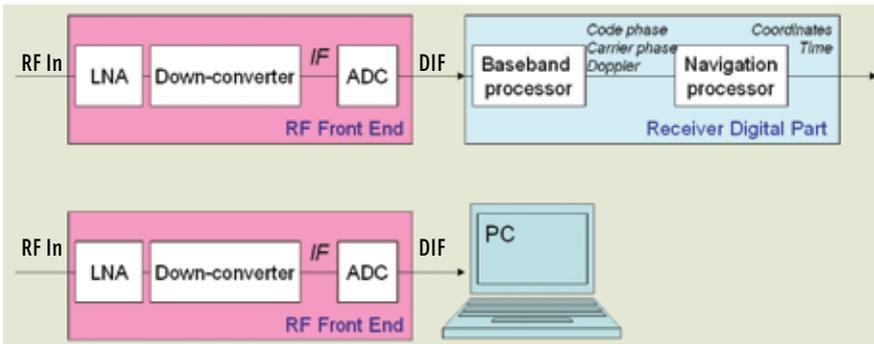


FIGURE 13 Receiver (upper flowchart) and recorder (bottom flowchart) designs

a proper transformation of code chips and not simply translation of the code chips. It comes at no extra price in a digital simulator but requires special care in an analog one.

### Simulator Type III: DIF Generator/Record & Playback

We could logically call the third type of simulator a *software simulator*. However, we prefer to avoid this term in order to escape confusion with other less sophisticated software bearing a similar name that simulates a GNSS receiver's operation as an output.

This latter type of software simulator produces either receiver coordinates or pseudorange data based on equation (2), which is basically part of the output of the receiver baseband processor (see the receiver digital part in the upper flowchart of Figure 13).

So, to distinguish a simulator, which creates a DIF signal indistinguishable from those recorded from live satellites, we prefer to call this kind of equipment a *DIF generator*.

In a generic receiver, a GNSS signal goes to a baseband processor through an

RF front end. A GNSS signal recorder uses exactly the same front end as a receiver (Figure 13). The signal just goes to storage media instead of the receiver baseband processor and can be processed by the receiver in exactly the same way later.

Moreover, the same test can be processed over and over with different settings, in the same way as with the simulator. A DIF signal thus is the signal taken after it passes through a receiver front end and can be stored in memory for future use. The recorded or generated DIF signal can then be played back as an RF signal by a playback device, which we will consider in detail later. A DIF generator simulates a signal similar to one that can be recorded from live satellites. It also can simulate all special cases similar to a simulator.

A DIF signal can be useful on its own. It can be recorded on media such as a CD or DVD, stored, and distributed, even through the Internet. We have put such a signal, artificially generated, on our website as an example; it can be found at <http://www.ip-solutions.jp/services/dif.htm>. One can use a soft-

ware receiver to process the signal.

A GNSS signal can be recorded in various forms with various sample rates or bit resolution and be represented either as I/Q data or a real signal.

The other important characteristic of a recorder, which affects the specification of a signal that is recorded and subsequently played back, is the accuracy of the front-end clock. We have recorded simultaneously the same RF signal divided through a splitter by a recorder with an oven-controlled crystal oscillator (OCXO) and one with a temperature-compensated crystal oscillator (TCXO). We used our software receiver in assisted mode to process both signals.

The left panel of Figure 14 depicts the results of the satellite signal acquisition using Doppler assistance by processing the signal recorded by equipment incorporating a TCXO. Only four out of seven satellites had been successfully acquired. The other satellites were not successfully acquired because front-end clock drift put the Doppler frequency of these satellites outside of the three-bin search area in the assisted mode.

The right-hand panel of Figure 13 depicts the results of Doppler-assisted signal acquisition processing the signal recorded using an OCXO. All seven out of seven satellites have been successfully acquired, including the three that were outside the search bins in the case of the TCXO.

When we changed the setting in the control panel to remove the Doppler assistance option, the whole area was searched and all signals were successfully acquired. However, the acquisition

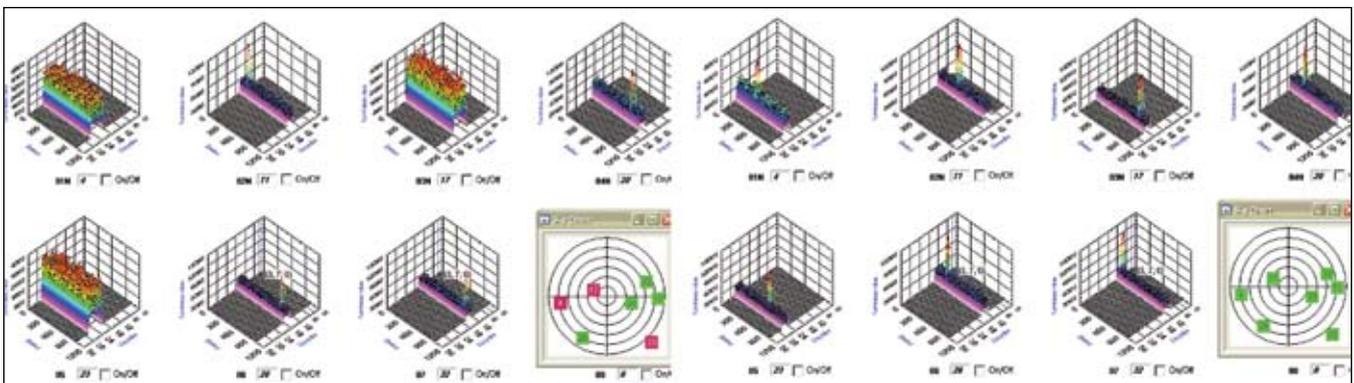


FIGURE 14 Results for satellite acquisition in signals recorded with TCXO (left) and OCXO (right)

process took 12 times longer. Of course, we can always process signals recorded with a TCXO by incorporating an initial estimate of the TCXO drift, which makes the acquisition process much quicker.

A more important advantage of OCXO is the oscillator's low carrier-phase noise. This can be important when using a recorder, for example, for monitoring ionospheric scintillations. It gives researchers a way to post-process data and try out various algorithms, as well as offering altogether much more flexibility. Consequently, such equipment provides much potential in comparison with just recording S4 (amplitude scintillation index) and sigma (phase scintillation) data from a specialized hardware receiver.

Of course, in this case the use of an OCXO-aided recorder is essential in order to eliminate phase noise. A dual-frequency recorder device can provide even more information enabling the correlation of scintillation effects with TEC measurements.

RF recorders also provide a convenient way to gather flight data. For example, such data can be collected and processed later by a software receiver in order to test various methods ultra-tight integration of GNSS receivers and an inertial navigation system (INS), as discussed in the paper by T. Tsujii et alia (2009) listed in Additional Resources.

It would be difficult to facilitate such research without recorders, because it would require hundreds of flights instead of just one. Of course, such recorders for dynamic applications and INS aiding research should use OCXOs.

Special types of RF recorders exist that allow users to record such signals in the real environment (Figure 15). The unit shown in this figure has three operational inputs: one for an antenna acquiring a direct signal and others for antennas acquiring a reflected signal.

Such tests also can be applied for assisted-GPS scenarios, in which case one signal is coming from an indoors environment and another from clear sky. The latter signal carries navigation bit information, which can be used to

increase sensitivity in the acquisition of the first signal.

Playback devices can help out when a DIF signal is insufficient for some applications, such as when one is working with a conventional hardware receiver, and it is inconvenient to by-pass a receiver front end, or when one is testing the whole receiver or, in particular, the receiver front end. We can playback a

recorded signal, reversing all operations that it underwent: through the DAC and becoming an analog IF signal, then being up-converted and turning back into an RF signal.

As in case of a simulator, the quality of a signal restored in this way depends on the quality of the front-end hardware. We will look at the quality and constraints of playback devices in detail in the final article of this series.

## Simulators: The Dark Side

As with any advanced technological achievement, from the invention of smoking to creation of the Internet, the possibility of misuse and even unlawful use must be faced at some stage.

We look here at two main issues. First of all, we should address a theoretical concern about potential use of simulators as jammers. Luckily, we are not in any danger of that — because it makes no sense from a cost/benefit perspective. Simulators are inherently far more flexible, complex, calibrated, and, consequently, expensive devices than any jammer would need to be. On the contrary, simulators provide a way to research and understand how we can deal with the problem of intentional and unintentional signal interference.

Another potential problem that probably will require regulating at some point is copyright infringement of simulator products — in particular, the sell-



FIGURE 15 Special RF recorder with two synchronized recording tracks for high-sensitivity and multipath research

ing or distributing of files recorded from simulators.

A recorder/playback device can record and playback a signal from a simulator. One way to confront such unlicensed copying is to embed a watermark into a signal, — the equivalent of a digital signature. Such a watermark, though recorded and retransmitted, cannot be detected by a conventional receiver, in effect, providing a copyright for the products of a simulator.

## What's Next?

In the final article in this series to be published in a forthcoming issue of *Inside GNSS*, we will look at the specifications of various types of simulators, their parameters, and the ranges, constraints, and importance of these factors for particular tests.

## Additional Resources

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**Manufacturers**

The tests described in this article used the multi-channel multi-GNSS GSS6700 simulator, single-channel GSS6300 simulator, and SimGen software suite from **Spirent Communications**, Paignton, United Kingdom. Real-time software iPRx receiver, RF Recorders, and ReGen DIF Generator came from **iP-Solutions**, Japan.

Figures 3 and 9 depict screenshots of SimGen software suite from Spirent Communications, figures 4 and 6 show screenshots of ReGen software from iP-Solutions. Figure 8 shows analysis of ReGen-generated scintillation data with MATLAB. Figure 14 shows a screenshot of the iPRx receiver acquisition panel. Figure 7 shows a screenshot of LGF tests emulation software from iP-Solutions, Japan.

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