Testing GNSS System Errors

Application Note DAN002 Issue 1-01

Table of contents

1. Audience

This Application Note is for designers, developers, integrators and testers of GNSS receivers or systems, who need to ensure their products will perform in the intended environment.
Spirent recommends you have a basic understanding of satellite navigation principles and awareness of RF simulation as a test method is desirable.

2. Introduction

There is a steady growth in the use of GNSS navigation systems in new and existing markets. The increasing use of GNSS brings an increasing reliance on the technology. Individuals, businesses and organisations are relying on the technology for personal pleasure and safety to commercial advantage. With this in mind, it is important for designers, manufacturers and consumers of these products to understand what to expect from GNSS systems, which requires an understanding of the limitations and problems of what can often be a fragile, prone to error, and easily disabled technology.

This Application Note discusses some of the sources of error inherent in GNSS systems. Complementary to this, it demonstrates how Spirent's range of GNSS Test Solutions enable you to create and run controlled and repeatable simulations and benchmark your receiver's performance when subjected to these errors. It demonstrates that a GNSS RF Simulator is able to generate the conditions required for performing suitable tests. The application determines the test criteria, and the importance of each criteria may vary significantly from one application to another.

3. RF simulation

An RF Constellation Simulator reproduces the environment of a GNSS receiver on a dynamic platform by modelling vehicle and satellite motion, signal characteristics, atmospheric and other effects, causing the receiver to actually navigate according to the parameters of the test scenario.

By its very nature, simulation is a representation of the real world. Simulation cannot reproduce the full richness of real world conditions. A common misconception is the need to exactly replicate real world conditions for a GNSS test to be valid. However, application of representative effects via simulation is proven (over some 25 years of testing) to exercise receivers and adequately identify their limitations allowing for design centering and optimisation. More importantly, it gives complete repeatability, control and exact knowledge – down to bit level – of the signal stimulating the receiver. This is not possible in the real world. We should look upon simulator testing as representing the real world, rather than replicating it. Spirent simulators include statistical models enabling simulation of richer multipath environments, but consideration of these is outside the scope of this document.

Figure 1 shows the concept of simulation (using a GSS6560 simulator).

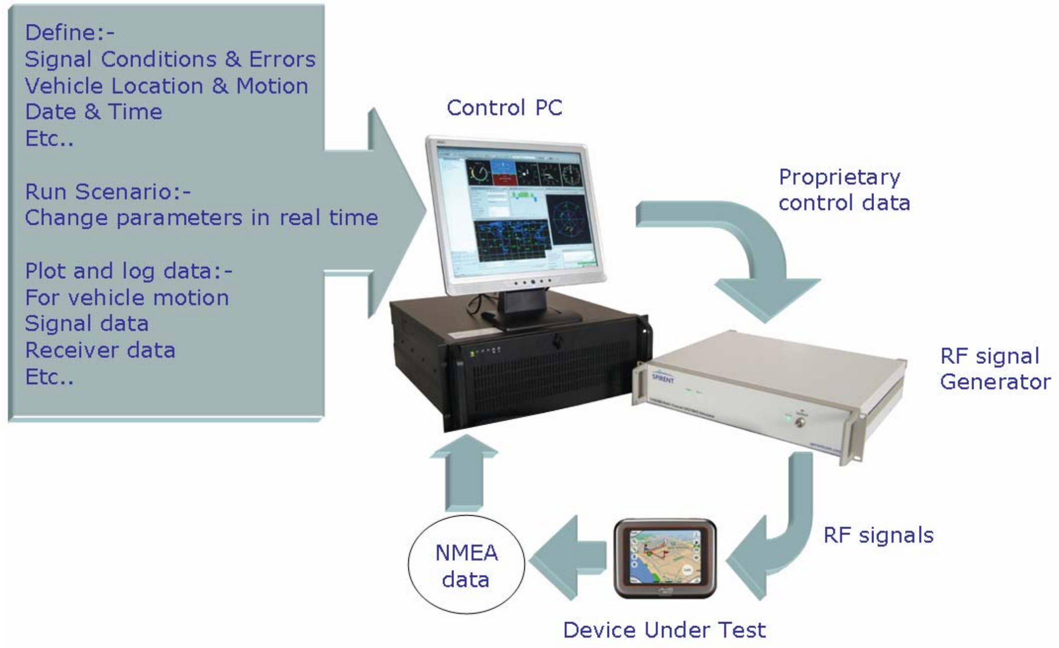

Figure 1 RF Simulation Flow

4. Typical GPS Simulators

All the tests discussed in this Application Note can be performed using any of Spirent's multi-channel simulators. For further information on Spirent's range of Simulators, please contact your local Spirent representative, or visit www.spirent.com/positioning, or www.spirent.com and click the Satellite Navigation link.

5. The GNSS environment

A GNSS receiver works well when it has a clear, un-interrupted view of the orbiting satellites transmitting the ranging and navigation signals. In many situations this is not the case, and ranging measurements to the satellites are affected. The degree that performance is affected depends on the application and the environment of the receiver. Common to all applications, are additional sources of error from the GNSS system infrastructure. These errors are produced by inaccuracies in the satellites and in control equipment, deficiencies in monitoring and prediction systems and data processing anomalies. Finally, the receiver generates its own errors.

6. A Typical GNSS System

Basically, a GNSS comprises three main parts: The **Space Segment**:- the constellation of orbiting satellites that transmit ranging and navigation data signals. The **Control Segment**:- the Master Control Station and associated monitoring and data uplink stations/facilities that measure and predict space segment performance and provide the corrections broadcast in the navigation data. The **User Segment:-** GNSS receivers and systems that autonomously navigate using the GNSS signals.

The most important performance characteristics for all GNSS systems are:

- Accuracy
- Availability
- Integrity
- Continuity

The quality of these depends on the particular GNSS system.

Each characteristic is defined (in reference 2 as follows:

Accuracy – for a given constellation, how close to the theoretical true position you can get in three dimensions. For several measurements taken in a static position, it is normally specified as the error magnitude sphere containing 95% of measurements. For GPS SPS, 95% vertical Position Accuracy is 22.7m (based on a 24-satellite constellation with VDOP of 1.6, and system UERE of 7.1)

Accuracy is a complex topic, and can be defined in a number of ways. Reference 2 discussed accuracy in detail.

Availability – the percentage of time the services of the system are useable.

Integrity – the ability of the GNSS to provide timely warnings and alerts to users that advise when they should not use the system.

Continuity – the probability the specified system performance will be maintained for the duration of a phase of operation.

Unless otherwise stated, details refer to the Global Positioning System.

7. Sources of Error

This section describes the main sources of error, and how a simulator can be used to reproduce each error. The contribution of errors from each segment is summarised in Table 1.

Segment	Error Source	GPS 1s Error (m)
SPACE	Satellite Clock Stability	3.0
	Satellite perturbations	1.5
CONTROL	Ephemeris prediction error	4.2
	Other (thruster performance etc)	0.9
USER	Ionospheric Delay	2.3
	Tropospheric Delay	2.0
	Receiver noise resolution	1.5
	Multipath	1.2
	Other (interchannel bias, etc)	0.5
TOTAL	**System UERE Total (RSS)**	**6.6**

Table 1 GNSS Error Sources

7.1. Space Segment Errors

7.1.1. Satellite clock errors

Fundamental to GNSS operation is the radio ranging that ultimately depends upon predictability of satellite clock stability. Although satellites have accurate atomic clocks, a 1 millisecond error equates to a 300km pseudorange error, so even small clock errors are significant. Errors 24 hours after an upload of navigation data can be in the order of 1 to 4 m (see Reference 2). Ephemeris error and clock error are progressive, getting steadily worse over time, until corrected for in the next control segment navigation data upload.

For a simulator test, you can define a scenario in which the clock correction terms transmitted in the navigation data diverge from the clock behaviour as represented by the simulated RF signal. On Spirent’s SimGEN software, for any satellites, you can enter zero - first - and second-order ‘Af’ terms for the clock corrections, which will be transmitted in the navigation data AND modelled in the simulated RF signal; plus ‘Delta-Af’ terms, describing a signal timing error, which are modelled only by the simulated RF signal and NOT declared in the navigation data. A receiver applying these Delta-Af corrections will see the effect of an incorrect pseudorange due to clock error.

7.1.1.1. Intentional Satellite Clock Noise (ISCN)

Selective Availability (S/A) is an intentional satellite clock noise error. It is the only *intentional* error associated with the GPS system. As at 2008, S/A has not been enabled since May 2000, but is a potential source of error to C/A code receivers.
S/A is the deliberate degradation of the SPS signals by a time varying bias. S/A is controlled by the US DoD to limit accuracy for non-U.S. military and government users. The accuracy of the C/A code is reduced to 100 metres (two standard deviations).
The S/A bias on each satellite signal is different, therefore the resulting position solution is a function of the combined S/A bias from each SV used in the navigation solution. Because S/A is a changing bias with low frequency terms in excess of a few hours, position solutions or individual SV pseudo-ranges cannot be effectively averaged over periods shorter than a few hours.

While the US government has stated they will not re-enable S/A and future satellites will not have the capability, denial on a regional basis is theoretically possible. Spirent recommends you test for this potential occurrence.

Spirent simulators controlled by SimGEN allow you to test your receiver in the presence of ISCN. You can apply a number of different models to all satellites or selected satellites that will generate S/A-like effects on the simulated RF signal that are not declared in the navigation data.

7.1.1.2. Receiver Autonomous Integrity Monitoring (RAIM)

RAIM is a technology developed to assess the integrity of GPS signals in a GPS receiver system. It is of special importance in safety-critical GPS applications, such as aviation or marine navigation. RAIM detects faults with redundant GPS pseudorange measurements. That is, when more satellites are available than needed to produce a position fix, the extra pseudoranges should all be consistent with the computed position. A pseudorange differing significantly from the expected value may indicate a fault with the associated satellite (such as a clock failure) or another signal integrity problem (such as ionospheric dispersion). Traditional RAIM uses Fault Detection only (FD); however newer GPS receivers incorporate Fault Detection and Exclusion (FDE) which enables them to continue to operate in the presence of a GPS failure.

Spirent simulators controlled by SimGEN have a Pseusorange Ramp feature, that allows you to change the simulated position of the satellite in a controlled, but abnormal way and is not declared in the navigation message. A receiver with a RAIM algorithm should detect this abnormality and either initiate an alert or exclude the offending satellite from its solution. The speed of the pseudrorange change can be adjusted (gradually reduced) until the receiver’s detection threshold is reached.

7.1.2. Orbital Perturbations

Orbital perturbations are caused by external influences that alter the satellite orbits. Such influences include;

- Non-central gravitational force due to the Earth being slightly elliptical (it is 20km larger in its equatorial radius than its polar radius): This causes orbital plane rotation and harmonic perturbations with a 6-hour period corresponding to the satellite’s transition over the equator, where its velocity increases.
- Gravitational fields of the Sun and Moon. The Moon dominates, as it is much closer to the earth. Visual examples of this are the tides. In a similar way, the Moon (and negligibly the Sun) pull on the satellite’s orbit. The effect is very small, but cumulative, and must be corrected for in the control segment’s orbital predictions. If left un-corrected, a 25 m error would result after just one hour (see reference 5).
- Solar radiation pressure: Photons from the sun’s radiation exert a minute force on it. The force depends on the mass of the satellite and how much of it is exposed to the sun.

For the GPS system, the navigation data contains six parameters relating to cyclic perturbation:

Cuc, Cus - Amplitude of the cosine and harmonic correction terms to the argument of latitude
Cic, Cis - Amplitude of the cosine and sine harmonic correction terms to the angle of inclination
Crc, Crs - Amplitude of the cosine and sine harmonic correction terms to the orbit radius
In SimGEN, apply perturbations using these six terms to one or more satellites. These are errors, as they are not declared in the navigation message.

7.1.3. Satellite Geometry

The relative positions of visible satellites, as observed by the receiver, determine a ‘quality parameter’ called Dilution Of Precision (DOP). If a receiver sees four satellites and all are arranged, for example, in the north-west, this leads to a “bad” geometry. In the theoretical worst case, no position determination is possible, because all distance determinations point to the same direction. Even if a position is determined, the error of the positions may be up to 100 – 150 m. If the four satellites are well distributed over the whole sky the position is much more accurate.

Depending on the factors used for calculation of DOP values, different variants of DOP are used:

- **GDOP** (Geometric Dilution Of Precision); Overall accuracy; 3-D coordinates and time
- **PDOP** (Positional Dilution Of Precision) ; Position accuracy; 3-D coordinates
- **HDOP** (Horizontal Dilution Of Precision); horizontal accuracy; 2-D coordinates
- **VDOP** (Vertical Dilution Of Precision); vertical accuracy; height
- **TDOP** (Time Dilution Of Precision); time accuracy; time

HDOP values below 4 are good, above 8 bad. HDOP values become worse if the received satellites are high in the sky. VDOP values become worse the closer the satellites are to the horizon and PDOP values are best if one satellite is positioned vertically above and three are evenly distributed close to the horizon. To determine accurate positions, the GDOP value should not be less than five. The satellite geometry does not cause inaccuracies in the determination of position, so DOP is unitless. DOP values amplify other inaccuracies and high DOP values amplify other errors more than low DOP values.

The error in position caused by the satellite geometry also depends on the latitude of the receiver.

For a simulator test you can subject a receiver to different combinations of satellites by deliberately excluding certain satellites from the simulated visible constellation. SimGEN will identify the four satellites in a given constellation that will give the best DOP performance, depending on the selection criteria, which will be one of the five DOP types. If, for example these satellites are deliberately excluded, this will force the DOP to be worsened. This feature is useful for identifying a receiver’s ability to use satellites that are not ideally positioned. For example, in an urban canyon environment a receiver will probably see only satellites that are directly above. This means the HDOP will be poor so the receiver or system developer must optimise the design to work in these conditions.

There are several different methods for restricting a receiver’s visibility of certain satellites, including manualy enabling and disabling satellites or using scripted commands to enable and disable satellites, using terrain obscuration and by using antenna patterns (See reference 4).

7.2. Control Segment and User Segment errors

7.2.1. Ephemeris prediction errors

These are errors in the declared position of a satellite (as transmitted in the navigation data message). In other words; the satellite wasn't where the system said it was when you made a measurement on its signal. Radial and cross-track errors contribute to ephemeris errors. Ephemeris corrections are calculated using a curve-fit of the control segment's best prediction of each satellite's position at the time of an upload and contain inherent errors. In addition, the errors tend to grow over time from the last control segment navigation data upload.

For a simulator test, you can define a scenario in which the ephemeris prediction data in the navigation message gradually diverges from being correct according to a specified 'graceful degradation of accuracy' curve as defined in Reference 1. When you enable the **Diverge Ephemeris** feature SimGEN applies errors to the data for each satellite, but does not alter the simulated signal. This is opposite to the real world, where the physical satellite position (and signal) changes; however, the effect is identical.

Another effect you can apply is a Track Error, where you specify the orbit trajectory of a given satellite to have an error in either or all of the three axes; Along (forward or backward on the trajectory), Across (left or right on the trajectory) and Down (up or down from the trajectory). Figure 2 illustrates this principle.

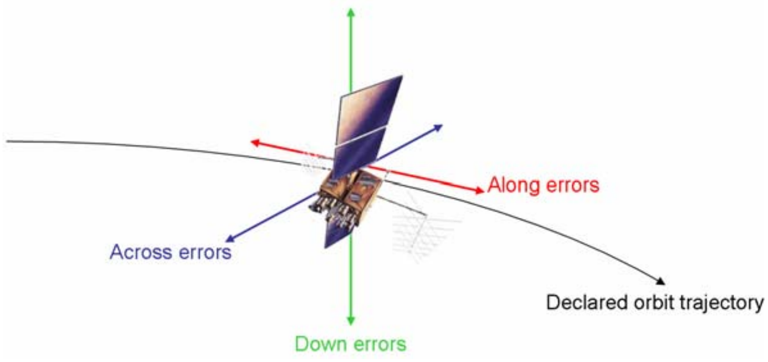

Figure 2 Satellite orbital track errors

7.2.2. Navigation data errors

Navigation data is a key part of any GNSS system. For GPS, each satellite broadcasts this as a 50 bps message formatted into 25 frames of 1500 bits. Each frame takes 30 seconds to transmit. The frames are sub-divided into five sub-frames, each containing ten, 30-bit words and taking six seconds to transmit. The last 6 bits of each word are parity bits employing a 32,26 Hamming code that allows the receiver equipment to detect bit errors during demodulation. It takes 12.5 minutes to transmit the complete navigation message. The data content is updated by the Control Segment approximately twice a day for each satellite.

The content of the message sub-frames is summarized as follows:

1:	satellite clock corrections, health indication, age of data.
2 and 3:	satellite ephemeris parameters.
4:	ionosphere model parameters, UTC data, almanac & health status data for satellites numbered 25 and higher.
5:	almanac & health status data for satellites numbered 1 to 24.

Reference 1 gives a detailed description of each bit of the navigation message.

Because the navigation message contains information vital to the operation of the receiver, any errors in the message not detected by the parity check may corrupt the receiver's calculation of PVT. you can replicate such errors using a simulator. SimGEN lets you simulate errors and apply various post-parity corruptions to selected words/sub-frames at certain times and on certain satellites. This tests a receiver's error detection & correction algorithms.

You can also modify any of the navigation message to maintain parity.

Another feature relevant to the navigation message is scheduling an upload. It is possible to simulate control segment uploads to each or all satellites and specify the subsequent upload times, apply various health status settings, L1/L2 delays and URA. Specifying an abnormally long time between uploads will make the age of the data increase and for example, clock corrections will be less and less accurate. This tests a receiver's satellite exclusion algorithm, where it reads the IODC value and determines that a particular satellite is bad due to the age of the clock correction data.

7.2.3. Ionospheric prediction error

Sub-frame 4, page 8 of the GPS navigation message contains the data describing the ionospheric model used by single frequency L1 receivers (L1 + L2 receivers can all but eliminate ionospheric delay)

This model was developed by Klobuchar in 1996 (see Reference 5). The GPS Master Control Station selects a set of coefficients from a database of 370 such sets associated with different seasons and levels of solar activity. The model is constrained by the number of parameters that can be used and the frequency of updates (one per day maximum) therefore it is not completely accurate and any receiver using it to correct for the ionospheric delay will benefit from a 50% reduction in error compared to a completely un-compensated delay.

For a simulator test you can simulate the inaccuracies inherent in the control segment's ionospheric predictions. SimGEN allows you to enter a model to be applied to the RF signal, and a different model to be broadcast in the navigation message. In addition, it is possible to enter different broadcast models depending on the control segment navigation data upload, simulating either an improvement of degradation due to the change in data. It is also possible to fix the ionospheric delay and even disable the ionosphere. A receiver can navigate far more accurately than it would in real life if its ionospheric model is disabled and the simulator's model is also disabled. Disabling the ionosphere can help to benchmark the receiver's true theoretical performance and quantify the relative performance of its atmospheric modelling capabilities when they are re-enabled.

7.2.4. Tropospheric delay

The lower part of the atmosphere is known as the Troposphere. This contains the 'weather region' in the lowest part and a 'dry region' in the uppermost part. Unlike the Ionosphere, the Troposphere is a non-dispersive medium where radio signals are refracted equally, regardless of frequency. Given this, it is not possible to use GPS measurements on L1 and L2 to estimate the delay and you have to rely on a model. The navigation message does not provide Tropospheric prediction as tropospheric effects are too regional.

A Simulator applies a Tropospheric model to the RF signal to simulate the effects of the Troposphere. In SimGEN, the STANAG, Bean-Dutton 2, RTCA96 and RTCA98 models are available, together with a surface refractivity index data entry. As with the Ionosphere model, the Troposphere model can also be disabled.

7.2.5. Multipath

Multipath, is a phenomenon where a signal that takes one line-of-sight path from the satellite to the receiver, in practice undergoes a reflection(s) and a receiver sees multiple versions of the direct signal, each with different time of arrival and signal level.

The receiver has no way of determining which signal is the 'real' non-delayed one, as it cannot distinguish them as discrete 'rays'. Usually, a receiver can readily resolve a multipath signal if the path travelled is greater than twice the spreading code symbol period for the BPSK modulation. This is because the direct (wanted) signal arrives much earlier than any multipath. The problem is when multipath reflections from nearby objects arrive very soon after the arrival of the wanted signal. Such signals (with delays as small as 10 to 100 ns) distort the correlation function between the received signal and the locally generated reference in the receiver. They also distort the composite phase of the received signal, introducing errors in pseudorange and carrier phase that vary between different satellites.

These errors contribute to an overall error in the receiver's PVT solution.

Figure 3 shows the concept of a simple single-reflection multipath.

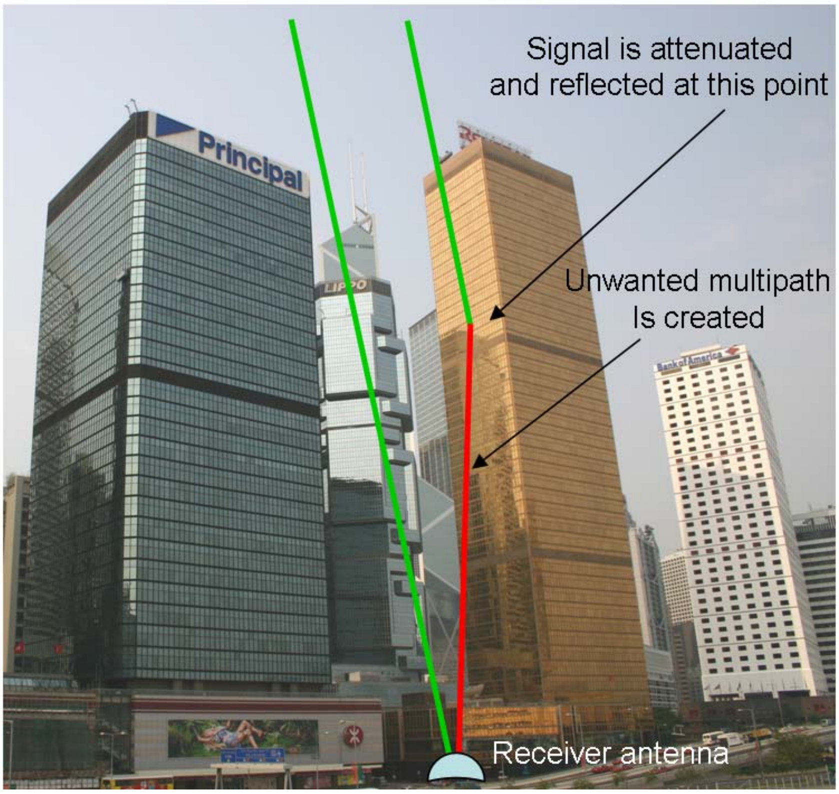

Figure 3 Multipath concept

There are many types of multipath, and a detailed discussion is beyond the scope of this document. Reference 6 gives an in-depth look at multipath, and how to test a receiver under multipath conditions.

7.2.6. Receiver errors

Another source of user segment errors are those due to the receiver.

Modern receivers have multiple digital receiver channels, and with silicon chip integration densities continually increasing, more parallel processing is possible, leading to, for example, shorter time to first fix performance.

However, with increased processing comes increased noise, and new designs are still susceptible to classical error sources such as LNA noise, PLL/FLL thermal noise, oscillator phase noise and ADC aliasing.

An average modern receiver should contribute less than 0.5 m rms error in bias and less than 0.2 m in noise, according to Reference 2. As the receiver under test is obviously part of the test set-up, it will contribute its own errors and there is no requirement for the simulator to replicate receiver errors.

8. Conclusions

This Application Note describes some of the many sources of error within the GNSS system. These errors are common to all applications and are in addition to application-specific errors due to the local environment. This Application Note identifies the principal sources of error and shows that a GNSS simulator allows you to introduce these errors in a test scenario, enabling the receiver under test to be fully exercised. SimGEN offers very high resolution control of signals and bit-level manipulation of data, reproducing the most complex error effects while its easy-to-use interface allows straightforward tests to be carried out with the same powerful modelling taking place in the background.

9. Referenced Documents

1. ICD-GPS-200 Navstar GPS Space Segment/Navigation User Interface Control Document, Revision IRN-200C-004, 12th April 2000
2. Understanding GPS – Principles & Applications, [E. Kaplan, C. Hegarty, 2nd Ed, 2006]
3. White House Press Release on the disabling of S/A [Office of the Press Secretary, 1st May 2000]
4. DAN001 Testing GNSS for automotive applications [Spirent Application Note]
5. Global Positioning System – Signals, Measurements & Performance [P. Misra, P. Eng, 2004]
6. DAN004-TM Simulating Multipath [Spirent Application Note]

7. Glossary of Terms

ADC – Analogue to Digital converter
BPSK – Binary Phase shift Keying modulation
DoD – United Stated Department of Defence
DOP – Dilution of Precision (GDOP = Geometric DOP, HDOP = Horizontal DOP, VDOP = Vertical DOP, PDOP = Position DOP, TDOP = Time DOP)
Ephemeris – precise satellite orbital information
Firmament – the heavens, the sky
FLL – Frequency Locked Loop
GNSS – Global Navigation Satellite System (GPS, Galileo, GLONASS etc.)
IODC – Issue Of Data Clock, The issue number for the clock correction data set that identifies its age
LNA – Low Noise Amplifier
Navigation Data – In the context of a GNSS, the data transmitted by the satellite to the user conveying system information necessary for navigation
Pseudorange – a radio-measure of satellite to user distance
PLL – Phase Locked Loop
PVT – Position Velocity & Time, the three navigational parameters calculated by a GNSS receiver
RSS – The square root or the sum of the squares of a range of values
SPS – Standard Positioning Service of GPS
SV – Satellite Vehicle
URA – User Range Accuracy
UERE – User Estimated Range Error

8. Further Information

Spirent's Test Services Team is dedicated to providing you with information and test solutions to help you with your testing needs, and to that end, we are actively producing Application Notes and Test

Methodologies on a wide variety of GNSS test subjects. Please visit www.spirent.com/positioning, or www.spirent.com and click the Satellite Navigation link regularly to find the latest articles, or ask your Spirent Sales representative for more information.

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