

Keysight Technologies

GNSS Technologies and Receiver Testing

Application Note

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GNSS Overview

Global Navigation Satellite Systems (GNSS) is the general term used for systems that allow users to determine their location based on information from satellites. In addition to the Global Positioning System (GPS) which is run by the United States, the GLONASS system from Russia is now in full operation. The Beidou system from China, also known as Compass, and the Galileo system from the European Union are also in the process of being deployed.

Of the 4 main systems in various stages of deployment today, GPS is the oldest, and has been in operation providing worldwide coverage since 1994. The system continues to be upgraded, with Block IIF satellites launched in 2012 and launches of Block III satellites planned in order to provide additional signals and services. The GLONASS system was first launched by the Soviet Union in 1982, but fell into disrepair after the collapse of the Soviet Union. Russia has restored and completed the system which became fully operational in October 2011 and provides worldwide coverage today. Russia is continuing to enhance the system with the launch of new GLONASS-K satellites which will provide new signals similar in nature to GPS and Galileo.

The other two systems, Galileo and Beidou, are still being deployed. Galileo has been under development by the European Community and European Space Agency for many years. Two experimental satellites were launched in 2005 and 2008. In 2011 and 2012, the first 4 in-orbit validation satellites that will be part of the operational system were launched. Initial limited service is planned to begin by 2015, with the completion of the full system planned for 2020.

With the launches that took place in September 2012, the Beidou system which began limited operation in December 2011 has been expanded to include 15 satellites, enabling regional service covering Asia Pacific. Completion of the full system is planned for 2020. Development of products supporting Beidou has been somewhat limited because the complete Interface Control Document (ICD) was not released by the Chinese government until December 2012. Now that the ICD is available, development of Beidou products is expected to increase rapidly.

In addition to these 4 satellite systems that allow receivers to determine their location, there are other related satellite systems. Satellite-based augmentation systems (SBAS) are geostationary satellites that provide data to improve the positioning accuracy of GNSS receivers in a region. These include the Wide Area Augmentation System (WAAS) for North America, European Geostationary Navigation Overlay Service (EGNOS) for Europe, the Japanese Multi-functional Satellite Augmentation System (MSAS), and the Indian GPS Aided Geo Augmented Navigation (GAGAN) system. Regional navigation satellite systems such as Japan's Quasi-Zenith Satellite System (QZSS) include satellites that orbit over a specific region, providing improved coverage over limited areas. The first QZSS satellite is in operation and there are devices that support QZSS today. The Indian Regional Navigation Satellite System (IRNSS) is also under development, with 3 geostationary and 4 geosynchronous satellites planned.

GNSS technology applications and growth drivers

Growth in the GNSS market is being driven by several factors, the primary one being the burgeoning demand for location-based services and applications in smart phones and tablets. Other factors include more vehicles being sold with in-car navigation systems and the addition of GPS in consumer devices such as digital cameras and sports watches. Tracking applications are also becoming more common. For example, companies are tracking the vehicles in their fleets to get real-time logistical information, and personal tracking applications monitor workers or the elderly for safety. Additionally, police use this technology to track criminals who are under house arrest or are on parole. Pet tracking devices and services are now available as well.

To support the growth of these applications, WLAN and cellular chipset companies are actively engaged in the development of GNSS chipsets and modules. Additionally, growing demand for devices that support multiple GNSS has prompted the development of multi-GNSS chipsets including GPS + GLONASS and GPS + Galileo or Beidou.

There are also applications for GNSS in the high-precision commercial market such as surveying and aviation, as well as aerospace/defense applications such as guidance systems for unmanned aerial vehicles or missiles. This application note will focus on consumer devices and applications.

GNSS system description

There are 3 major segments of a GNSS system.

- The space segment consists of the satellites or space vehicles (SV), which transmit a navigation message with information about the satellite's orbit and position and the time of the transmission.
- The control segment consists of monitoring and control stations on the ground that track the satellites in view, collect data from the transmissions, and provide navigation information updates, atmospheric and correction information, and satellite control.
- The user segment is the GNSS receiver.

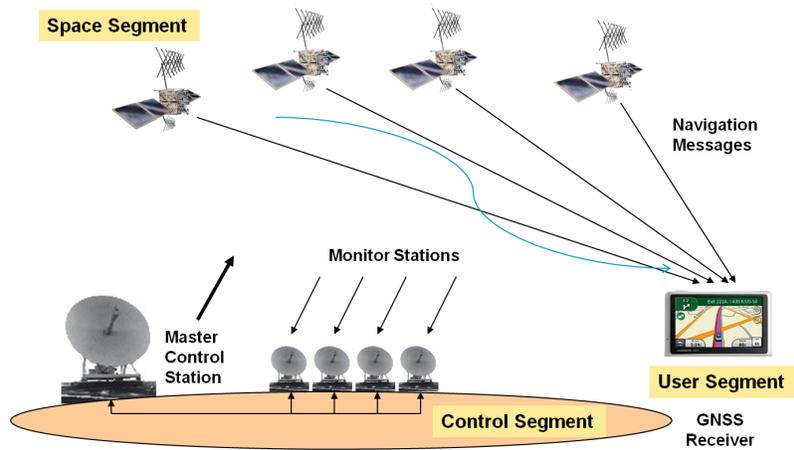


Figure 1. The three major segments of the GNSS system.

A GNSS receiver determines its location through a process called trilateration. It uses the transmitted time and position data in the navigation message in order to measure the time delay for the signal from the satellite and calculate its distance from that satellite, called the pseudorange. The distance from each satellite gives a sphere on which the receiver could be located. The intersection of 2 spheres is a circle, and the 3 spheres intersect at 2 points. A fourth data point is needed to identify the correct point as the receiver's location. For receivers that are assumed to be on the Earth's surface, the point that is on the Earth's surface would be the correct value. For a more general solution, the pseudorange for a fourth satellite is needed. Simultaneous measurements from at least 4 satellites are also necessary to allow the receiver to correct for clock errors and determine the correct time, in addition to determining its latitude, longitude, and altitude.

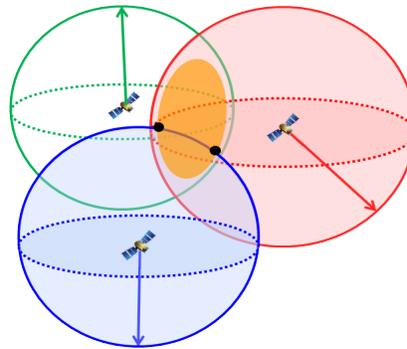


Figure 2. With trilateration, a GNSS receiver calculates the distance to at least 3 satellites. The intersections of the distance spheres around each satellite determine the location of the receiver.

GNSS satellites transmit with fairly low power. At the Earth's surface the power level is around -155 to -160 dBW (-125 to -130 dBm). Signal levels may be even lower where there are obstructions. GNSS receivers include amplification and signal processing to allow them to recover the GNSS signals.

GPS

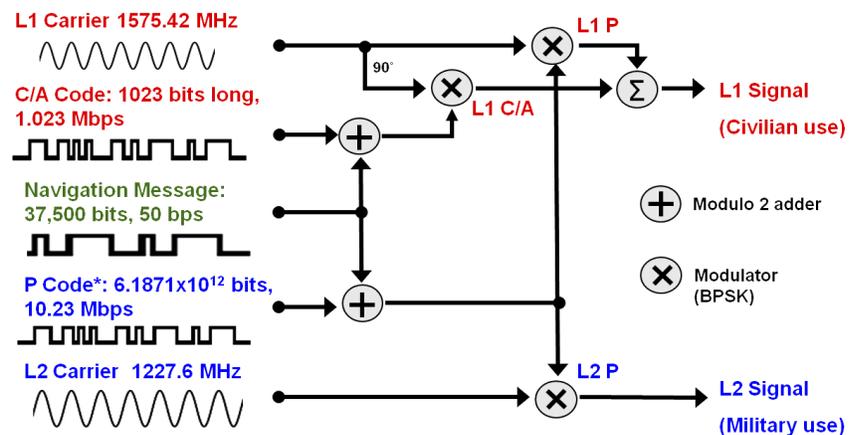
The GPS constellation was originally designed for 24 satellites orbiting in 6 planes, but it was modified in 2011 to include 27 satellites. Typically there are 31 or 32 satellites in operation, with some of the satellites functioning as spares. Each satellite orbits the Earth twice a day at an altitude of about 20,200 km. A minimum of 6 satellites are typically visible at any point on Earth, and up to 15 satellites may be visible.

The GPS transmitted signal

There are 3 main components of the signal transmitted by GPS satellites:

- Carrier wave
- Ranging (pseudorandom) codes
- Navigation message

Each satellite modulates its navigation message (described in more detail in the next section) with two pseudorandom spread spectrum codes: the **Coarse/Acquisition (C/A) code**, which is freely available for public use, and the **Precise (P) code**, which is used for high precision applications by government and military agencies. The C/A code is a 1,023 bit pseudo-random (PRN) code transmitted at a rate of 1.023 million bits per second, so it repeats every millisecond. Each satellite has its own unique C/A code so that its transmission can be identified and received separately from the other satellites that are transmitting on the same frequency, making GPS a code domain multiple access or CDMA system. The P-code is a PRN code that is 6.1871×10^{12} bits long and it is transmitted at 10.23 million bits/sec, so it repeats once a week.



* GPS satellites transmit an encrypted version called P(Y) code

Figure 3. The GPS transmitted signal is a combination of the navigation message and the C/A or P code, modulated onto the L1 and L2 carriers.

Since 1994, an encrypted version of the P-code, called the P(Y) code, has been transmitted to prevent “spoofing” or fake transmissions, and this code is restricted to military applications. The P-code is modulated with the W-code, an encryption sequence, to create the P(Y) code.

After being combined with the ranging code, the signal is modulated onto the RF carrier wave. Both the C/A and P(Y) code signals are modulated onto the L1 carrier with a frequency of 1575.42 MHz. The P(Y) code is also modulated onto the L2 carrier with a frequency of 1227.6 MHz.

The GPS navigation message

The navigation message contains 37,500 bits of data divided into 25 pages or frames. Due to the slow transmission rate of 50 bits/s, it takes 12.5 minutes to transmit the full message. Each frame contains 5 sub-frames that include time and clock correction information, satellite health status, and the ephemeris or precise orbit information for the transmitting satellite, as well as a portion of the almanac data that provides more general orbit information about all of the satellites in the constellation.

A receiver needs the ephemeris data for each satellite in order to determine the satellite’s position in space, and it also needs the time of transmission and clock correction data in order to use that information to calculate the receiver’s location. Since this data is contained in the first 3 sub-frames, it takes a minimum of 16 seconds (or 30 seconds in the worst case) in order for a receiver to obtain the necessary data.

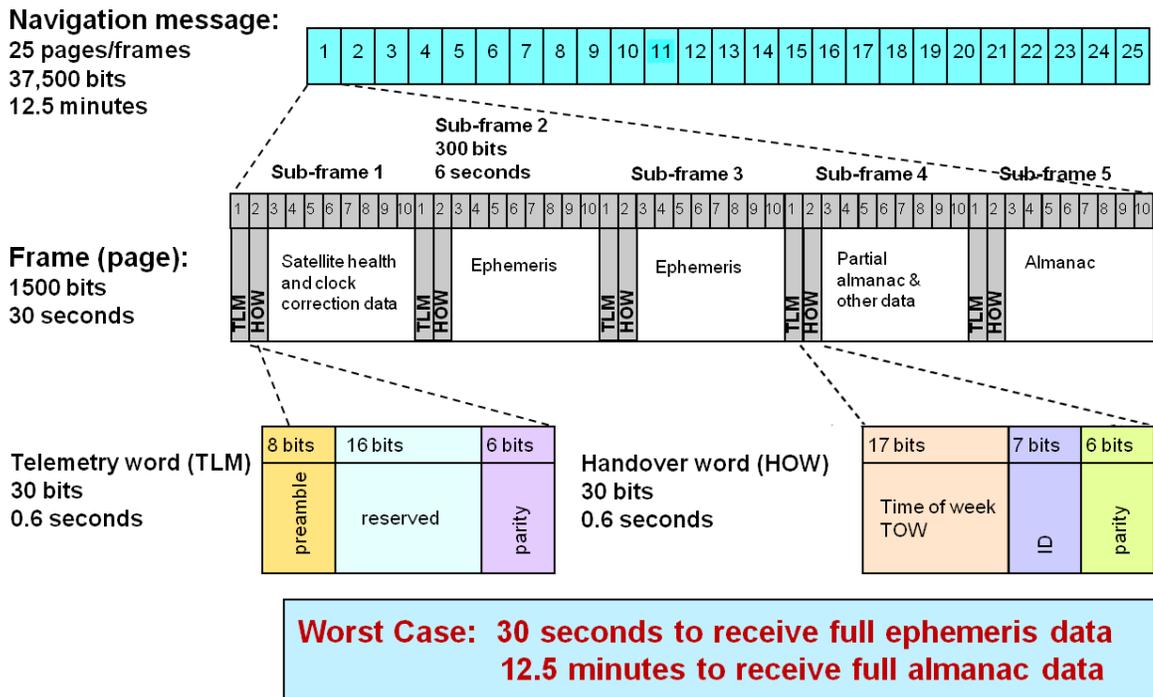


Figure 4. GPS navigation message.

Assisted GPS

Mobile phones use a technique called assisted GPS (A-GPS), which helps them determine their locations more quickly. This system was driven by programs like E911 in the U.S., and similar programs in other countries, that aim to provide fast and accurate location of mobile phones by emergency service agencies. It is especially important when mobile phones are indoors or in areas where there are not enough line-of-sight satellites available. With A-GPS, a GPS assistance server monitors the GPS satellites and obtains the navigation message information. This assistance data is sent to the cellular base station for transmission to mobile phones using the cellular network, allowing a phone to determine its rough location quickly, and to know which satellites are available at that location.

With other GNSS becoming available, standards are being developed by the 3GPP and 3GPP2 standards organizations to expand A-GPS functionality in order to provide assisted GNSS (A-GNSS) location determination capability.

GLONASS

The GLONASS constellation is designed for 24 satellites, like GPS, but orbits at a lower altitude of 19,100 km, with 3 planes of 8 satellites each. It provides better coverage at higher latitudes (close to the north or south pole) than GPS, which is an advantage for Russia and northern Europe. Although the full complement of 24 satellites is in operation, additional satellites are being added to the system. Most of the current satellites are the GLONASS-M series, which were deployed beginning in 2003. The newer GLONASS-K satellites began launching in 2011 and will provide additional types of signals.

Dual-mode GPS+GLONASS devices are now available and these devices can benefit from the availability of a greater number of visible satellites, especially in difficult environments like “urban canyons” where there are tall buildings blocking some satellites. This enables receivers to get a faster location fix with better accuracy.

The GLONASS transmitted signal

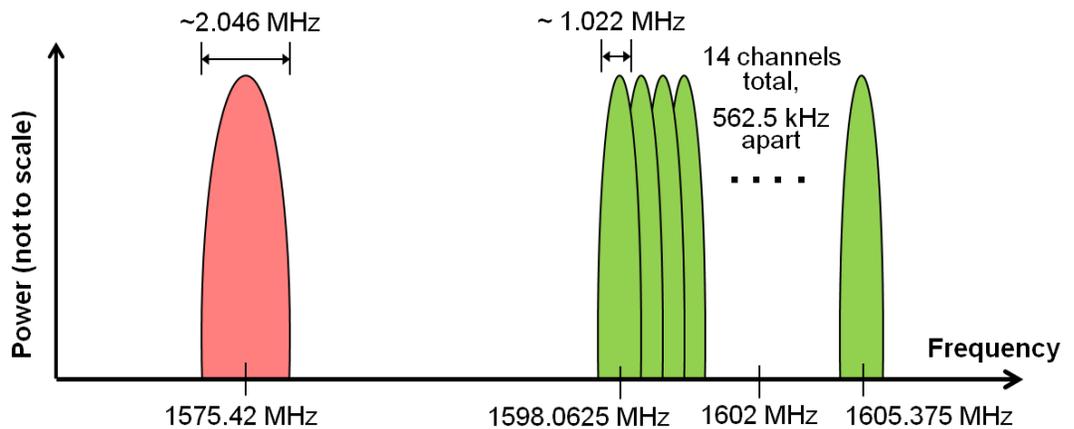
The GLONASS-M satellites transmit signals on one of 14 frequencies using the same PRN code, making GLONASS a frequency domain multiple access or FDMA system. The 14 frequencies are sufficient to support 24 satellites because frequency channels are reused for satellites on opposite sides of the Earth. Like GPS, GLONASS has both a standard precision signal for public use and a high precision signal that's restricted to authorized users for military and defense applications. Both types of signals are transmitted in the L1 and L2 bands.

L1 band:

- Signals transmitted around 1602 MHz, 562.5 kHz apart (~1597-1606 MHz)
- L1 frequency = 1602 MHz + (K * 562.5 kHz), where channel K = -7, -6, ..., 5, 6

L2 band:

- Signals transmitted around 1246 MHz, 437.5 kHz apart (~1238-1254 MHz)
- L2 frequency = 1246 MHz + (K * 437.5 kHz), where channel K = -7, -6, ..., 5, 6



GPS L1 C/A signal:

All satellites transmit at the same frequency using different PRN codes

GLONASS L1 C/A signal (FDMA):

Satellites transmit at different frequencies around 1602 MHz using the same PRN code

Note: Simplified diagrams of spectrum do not show signal side lobes.

Figure 5. Comparison of the L1 standard precision (C/A) signals for GPS and GLONASS.

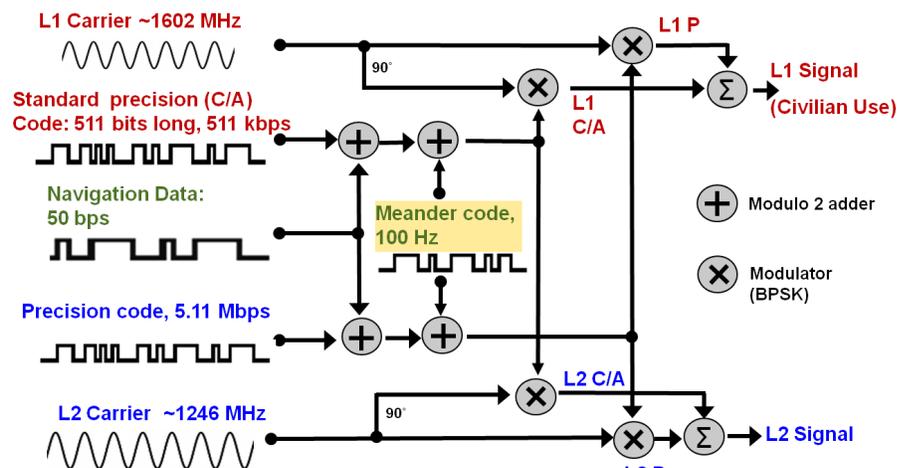
The new generation of GLONASS-K satellites will transmit both this FDMA signal and a newer CDMA signal. The CDMA signal is similar to GPS and Galileo and uses different PRN codes for satellites, with all satellites transmitting at the same frequency. It will be several years before there are enough GLONASS-K satellites in operation to support location services using the new CDMA signals. For now, all GLONASS receivers will continue to use the FDMA signals, and that is the signal that is described in this application note.

GLONASS signal components

The GLONASS signal has the following components:

- Carrier wave
- Ranging codes
- Navigation message
- Meander code

Most of these components are similar to those for GPS, but there are some important differences. For GLONASS, different L1 and L2 carrier wave frequencies are used by each satellite, depending on which channel is being used for its transmission, as described in the previous section. Next, we have the ranging codes and navigation data. As with GPS, there is both a C/A code for standard precision signals and a precise code for authorized users, but all GLONASS satellites use the same ranging codes. The GLONASS C/A code is shorter than it is for GPS, with a chip rate of 511 kbps, while the high precision code has a chip rate of 5.11 Mbps. The component that is unique to GLONASS is the meander code, a bit sequence that is combined by modulo 2 addition with the ranging code and navigation data. The signal creation process is shown in Figure 6, which is a somewhat simplified diagram that does not show the construction of the navigation message superframe prior to signal modulation.

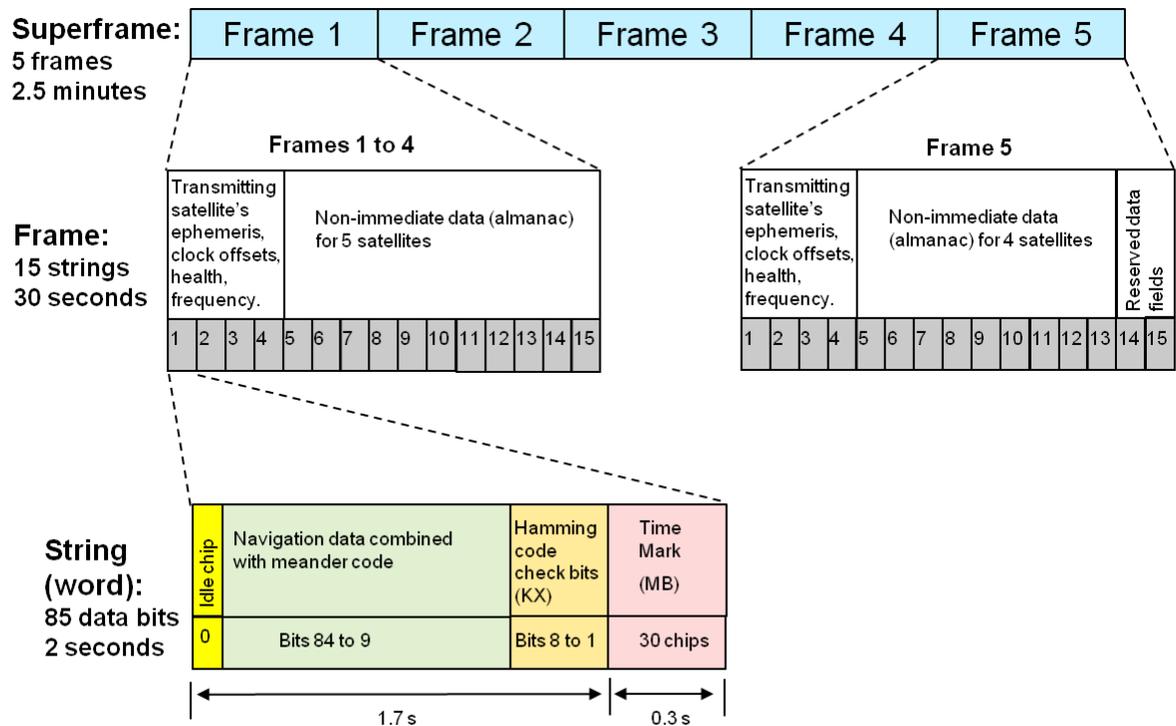


Note: Full details for precision code have not been published.

Figure 6. In the GLONASS system, both the standard and high precision signals are transmitted on both the L1 and L2 signals.

The GLONASS navigation message

The GLONASS navigation message for the standard precision signal is structured as a superframe, which consists of 5 frames, with a total duration of 2.5 minutes. Each frame contains 15 strings and takes 30 seconds to transmit. The first 4 strings of each frame contain the transmitting satellite's ephemeris data, clock offsets, health status, and frequency information. The remaining strings contain almanac data for all of the satellites in the constellation. Each string contains navigation data combined with the meander code, check bits, and a time mark. The time mark is a fixed 30-bit pseudorandom sequence transmitted at a rate of 100 bits per second.



Note: Navigation message for high precision signal has not been officially published.

Figure 7. GLONASS navigation message structure.

Galileo

When deployment is complete, the full Galileo constellation will consist of 27 satellites with 3 spares, orbiting the Earth at an altitude of 23,222 km in 3 orbital planes. Each Galileo satellite transmits signals at 4 different carrier frequencies:

- E1 at 1575.42 MHz
- E6 at 1278.75 MHz
- E5a at 1176.45 MHz
- E5b at 1207.14 MHz

These signals differ significantly in their construction and modulation. In keeping with this application note's focus on consumer applications and devices, the remaining description will be for the E1 open service (OS) signal only.

The Galileo E1 Open Service transmitted signal

The open service signal for Galileo consists of the E1b data and E1c pilot channels and uses composite binary offset carrier (CBOC) modulation. This signal is transmitted at the same frequency as the GPS L1 signal. GPS uses BPSK modulation, which results in a spectrum shaped like a sinc(x) function with a main lobe at the center frequency. BOC modulation spreads the energy to two side lobes, leaving a null at the center frequency, which minimizes the interference with GPS. BOC signals are commonly referred to as BOC(m,n) or BOC(f_s, f_c), where subcarrier frequency (f_s) = $m * 1.023$ MHz, and coding frequency (f_c) = $n * 1.023$ MHz. CBOC combines a narrowband BOC(1,1) signal with a wideband BOC(6,1) signal to provide improved multipath performance.

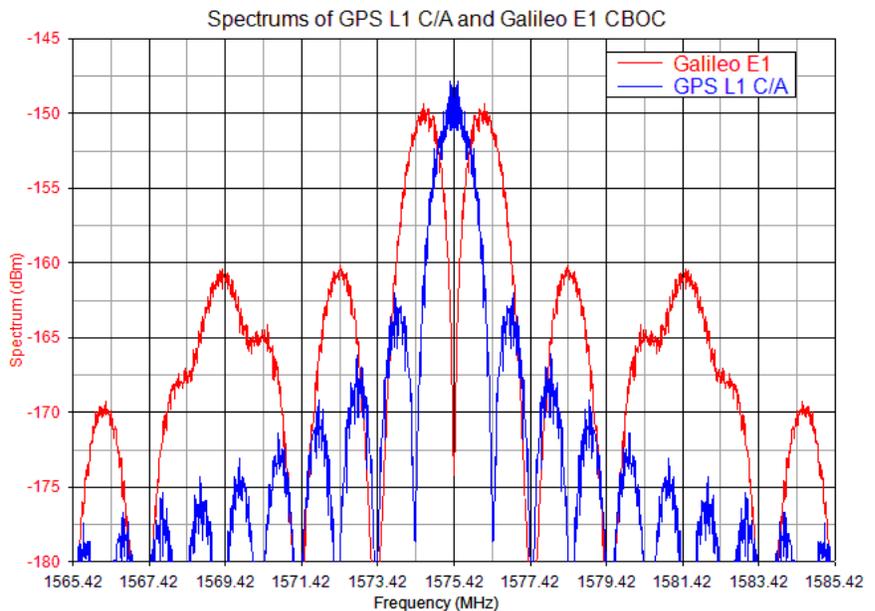


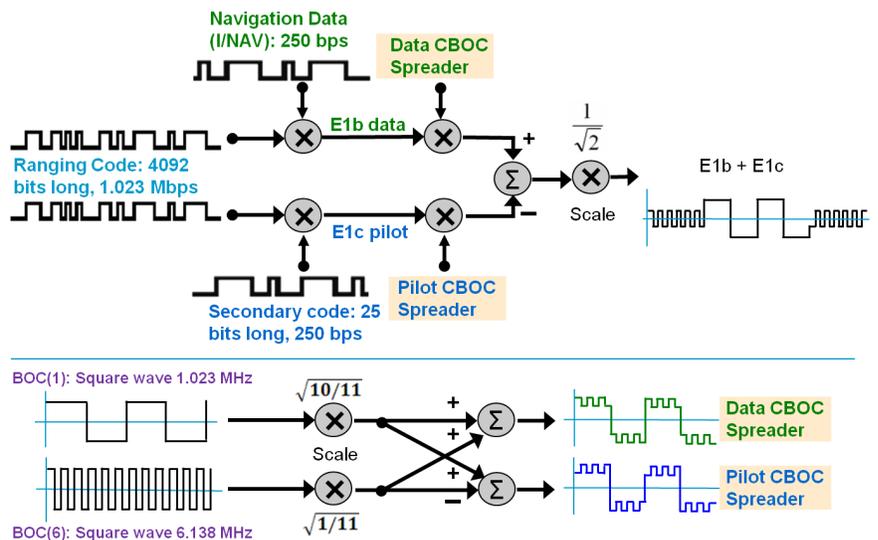
Figure 8. Spectrum of GPS L1 C/A signal compared to Galileo CBOC signal.

Galileo signal components

The Galileo E1 signal has the following components as shown in Figure 9:

- Ranging code
- Navigation data
- Secondary code
- Carrier, shown in the diagram as the Data CBOC Spreader and Pilot CBOC Spreader

For the E1b data channel, the navigation data is transmitted at a rate of 250 bps and combined with a ranging code that is 4092 bits long, transmitted at 1.023 Mbps to form the E1b data stream. Each satellite has a unique ranging code, similar to GPS. For the E1c pilot channel, instead of navigation data, a secondary code is combined with the ranging code. The secondary code is a fixed 25-bit sequence that is the same for all satellites, transmitted at a rate of 250 bps. Both the E1b and E1c bit streams are then modulated onto the carrier, but in this case the carrier is not a simple sine wave. Instead, it is a signal formed by combining the BOC(1) component, a square wave with a frequency of 1.023 MHz, with the BOC(6) component, a square wave with 6 times higher frequency at 6.138 MHz. These components are scaled so that 10/11 of the power is in the BOC(1) component while 1/11 of the power is in the BOC(6) component. The 2 components are summed to form the Data CBOC Spreader, while the Pilot CBOC Spreader consists of the BOC(1) component minus the BOC(6) component.



Note: Navigation message for high precision signal has not been officially published.

Figure 9. Construction of Galileo E1b and E1c signals.

The Galileo navigation message

The navigation message type for the E1 open service is referred to as I/NAV in the Galileo ICD, and the structure is shown in Figure 10. The message is structured as a frame that consists of 24 sub-frames and lasts 720 seconds. Each sub-frame is 30 seconds long and contains 15 pages. A page lasts 2 seconds and consists of sync bits followed by the even page part and odd page part. The diagram shows the data components contained in various portions of the navigation message.

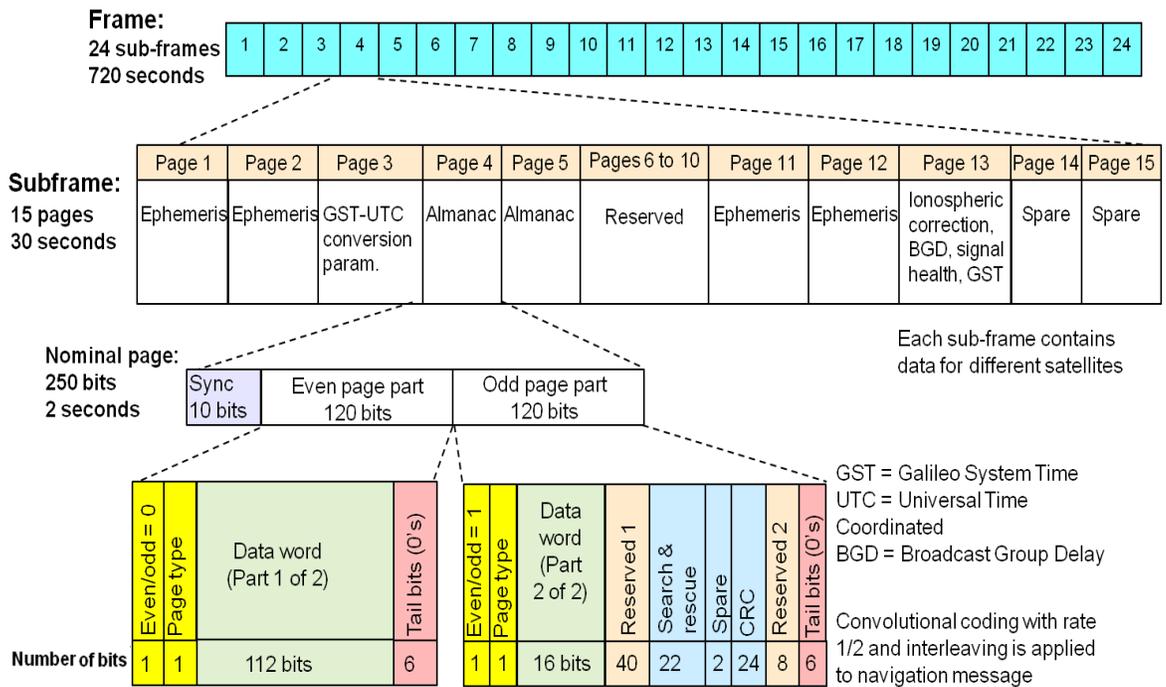


Figure 10. Galileo E1 open service navigation message structure.

Beidou

The official name of the Chinese GNSS is BeiDou Navigation Satellite System, also called the BeiDou System (BDS). Previously, the system was also known as Beidou-2, to distinguish it from the earlier experimental Beidou-1 system. The name Compass was also used, derived from the names of the satellites.

Unlike the other GNSS systems that only have medium earth orbit (MEO) satellites, Beidou will also include 5 geostationary Earth orbit (GEO) satellites and 3 satellites with inclined geosynchronous orbit (IGSO). There were 14 satellites in operation as of January 2013.

The ICD released in December 2012 covers the B1I open service signal, which is transmitted at 1561.098 MHz. Other frequencies allocated for Beidou include the B2 and B3 bands, which overlap with the E5b and E6 bands for Galileo. The definitions for those signals have not been publicly released, so this application note will only describe the B1I signal.

The Beidou transmitted signal

Like GPS and Galileo, Beidou is a CDMA system with a different ranging code for each satellite. The signals transmitted by the MEO and IGSO satellites are different from the signals transmitted by the GEO satellites.

Beidou signal components

The Beidou signal has the following components, as shown in Figure 11:

- Ranging code
- Secondary (Neumann-Hoffman) code
- Navigation data
- Carrier wave

For the MEO and IGSO satellites, the 2046-bit long ranging code is multiplied by a secondary code called the Neumann-Hoffman code, a fixed 20-bit sequence with a data rate of 1 kbps. This data is combined with the D1 navigation message, transmitted at 50 bps. The resulting stream is modulated onto the B1 carrier, a sine wave at 1561.098 MHz using QPSK modulation. However, since the ICD is defining only the I (real) component of the signal, the modulation appears to be BPSK.

For the GEO satellites, the secondary code is not used, and a different navigation message is transmitted. The ranging code is combined with the D2 navigation message data transmitted at 500 bps, and the combined data is modulated with QPSK onto the B1 carrier.

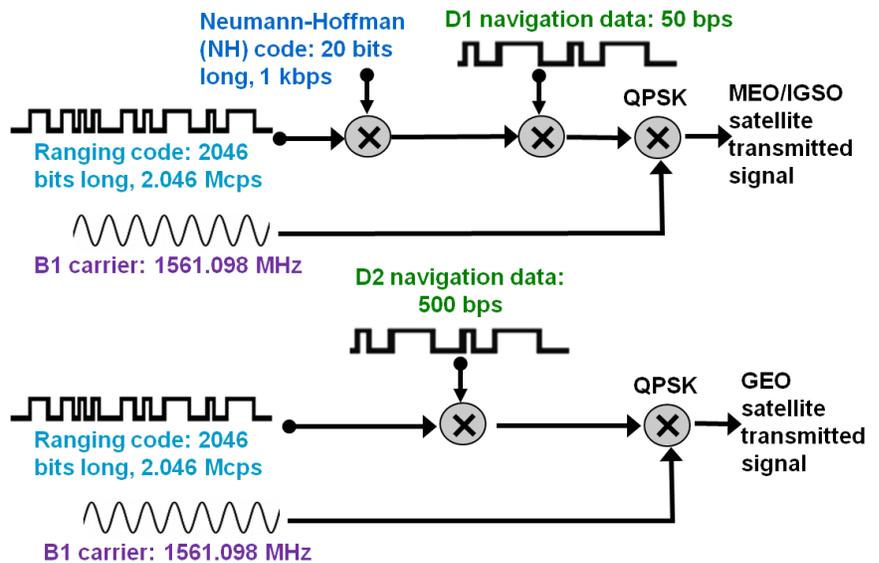


Figure 11. Construction of Beidou B1 transmitted signals.

The Beidou navigation messages

The structure of the Beidou navigation messages is similar to that of GPS. Figure 12 shows the D1 navigation message that is broadcast by the MEO and IGSO satellites. This message is structured as a superframe containing 36,000 bits of data in 24 pages or frames. Each frame consists of 5 subframes. The first 3 subframes contain the basic navigation information for the broadcasting satellite, including the time, clock correction data, health status, ephemeris, and ionosphere model parameters. Subframes 4 and 5 contain parts of the almanac for all of the satellites and information on the time offsets from other GNSS systems. Each subframe consists of 10 words. The first word in each subframe has the same format, containing a preamble, subframe ID, seconds of week time data, and parity bits. The remaining words contain 22 bits of data followed by 8 parity check bits.

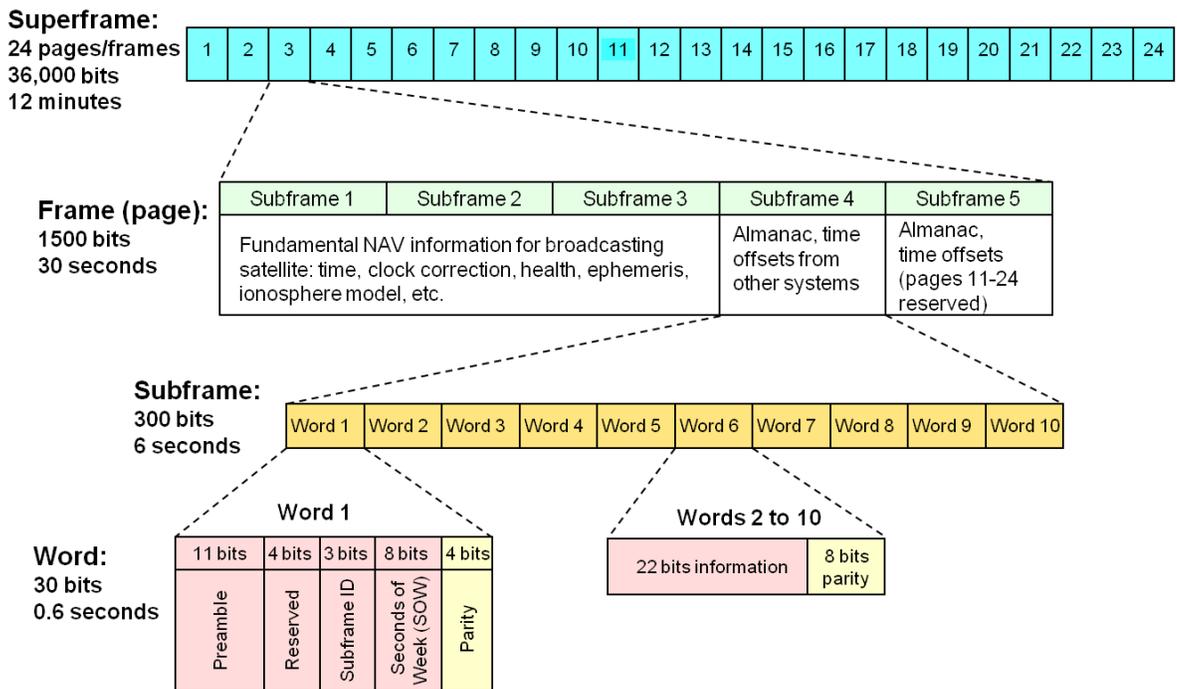


Figure 12. Structure of the D1 navigation message broadcast by MEO/IGSO satellites.

Figure 13 shows the D2 navigation message that is broadcast by the GEO satellites. The D2 navigation message contains much more data than the D1 message; one superframe consists of 180,000 bits of data (5 times more than D1) organized into 120 pages or frames. Since D2 is transmitted at a rate that is 10 times higher than D1, a D2 superframe only takes 6 minutes to transmit, compared to 12 minutes for D1.

The structure of the frames, subframes, and words are similar to those for D1. For D2, only subframe 1 is used to transmit the basic NAV information for the broadcasting satellite. Subframes 2, 3, and 4 are used to transmit system integrity and differential correction information. Subframe 5 is used to transmit the almanac, ionospheric model data, and time offsets from other systems.

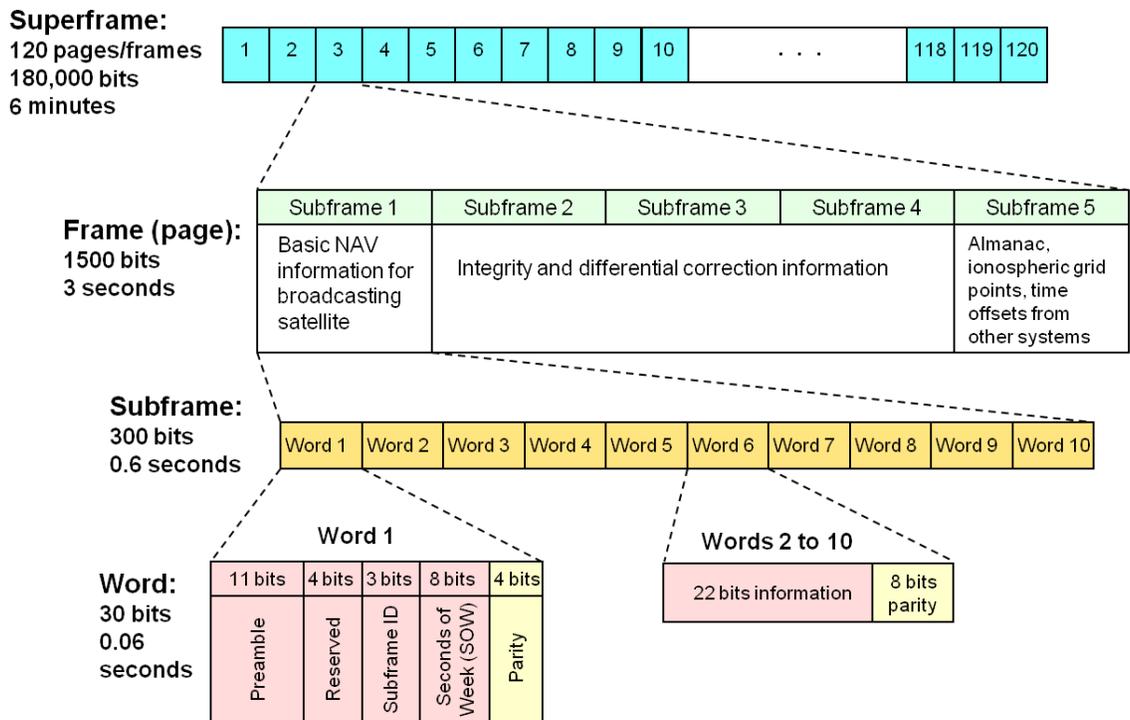


Figure 13. Structure of the D2 navigation message broadcast by GEO satellites.

GNSS Receiver Testing

For most wireless digital systems, receiver testing includes some form of bit error rate testing (BER, FER, PER, or BLER). For a GNSS receiver, since most navigation message data is transmitted at only 50 bits per second, checking for a typical BER of 1 in 10^6 would require a very long time, so BER is seldom tested. Instead, the focus is on verifying a receiver's ability to acquire and track a satellite signal, and checking the receiver's ability to calculate a location fix at various power levels and under varying conditions.

Typical GNSS receiver tests

Time to first fix or TTFF, receiver sensitivity, and location accuracy represent the most common GNSS receiver verification tests. TTFF is the time between "turn-on" of the GNSS receiver and the acquisition of a location fix. TTFF can be tested under cold, warm, and hot start conditions. In a cold start, the GNSS receiver has no data about the satellites in its memory, so it must search each possible PRN code and also search over a frequency range of around ± 5 kHz to account for Doppler shift in the satellite signals. With a cold start, the receiver needs to receive the ephemeris data for each satellite in order to determine the satellite's location. For GPS, this requires a minimum of 18 seconds of good data. TTFF with a cold start is commonly tested in a GNSS receiver, and typical receivers require 30-45 seconds to obtain a location fix. With a warm start, the receiver retains the approximate time, last location, and almanac data and tries to use these to acquire the satellites. With a hot start, the receiver also remembers the last satellites that were used and tries to acquire them again. This may work if the receiver has only been off for a short time and has not moved much. In most the cases the GNSS receiver can be put into these states using some form of receiver control software, often supplied by the chipset vendor.

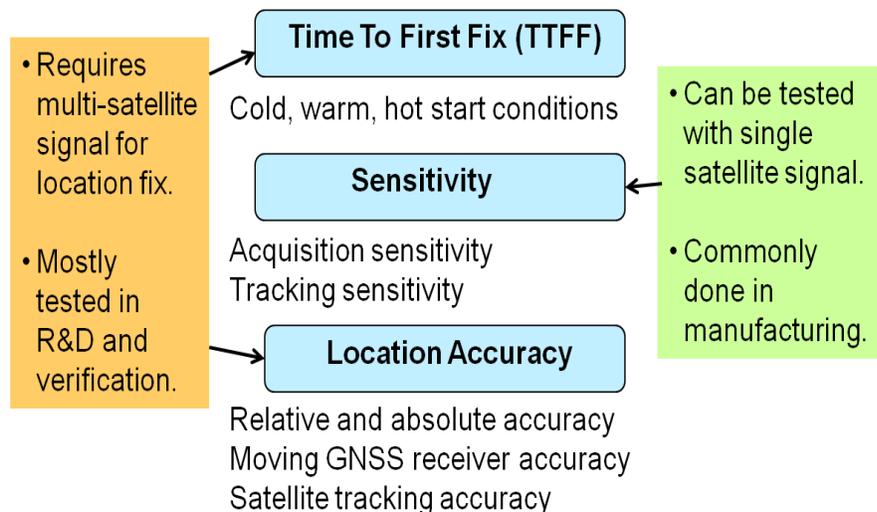


Figure 14. Typical GNSS receiver tests.

Sensitivity refers to the minimum level of signal that is needed in order for the receiver to either acquire a satellite signal or track a satellite that has already been acquired. This test can be performed much more quickly than TTFF, and the signal for this type of test can be much simpler since a single satellite can be used, and valid navigation data is usually not needed.

Location accuracy refers to the receiver's ability to calculate a location fix close to the actual or simulated position. Relative accuracy refers to comparisons between tests, and absolute accuracy refers to comparisons between the calculated location and the simulated location. Accuracy can also be measured for either stationary or moving GNSS receivers. Other tests such as re-acquisition time and interference testing are also performed, but they are less common.

TTFF and location accuracy require testing with a multi-satellite signal in order for the receiver to calculate a location fix. These tests are often performed in R&D and system verification, and less frequently in manufacturing, due to the test time required. Sensitivity tests can be done using a simple single satellite signal and they are commonly used in manufacturing.

Requirements for GNSS receiver testing

It is possible to test a GNSS receiver by using an antenna and trying to receive off-the-air signals. While this approach is realistic, it can only provide limited information because the signals presented to the receiver are highly variable and non-repeatable. There may not be adequate satellite signals available at a particular location and time. In addition, testing under specific conditions, such as in particular locations or at high velocities, can become expensive and impractical.

A record-and-playback system can also be used to provide simulated GNSS signals to test the receiver. While this system does provide a very repeatable test signal, it is not possible to modify the recorded signals, make adjustments to individual satellite signals, or add impairments in real-time while the signals are playing back.

To address these issues, a GNSS signal simulator may be used. A GNSS signal simulator produces an output signal that models the signal that would be received by the GNSS receiver: a mix of signals from many different satellites at different time delays, Doppler shifts, and power levels. A real-time GNSS simulator allows modifications to the signal while it is being generated. Another advantage is that a GNSS simulator can simulate satellites that are not yet present in the real world, allowing earlier testing of systems like Galileo and Beidou before the satellites are fully deployed.

GNSS test signals for R&D and design verification

Let's consider the key features that would be desired in a GNSS simulator in order to perform the tests that have been described. Table 1 describes some of those features, along with what test challenges they address.

Table 1. GNSS signal simulation requirements

Feature	Test challenges met
Multiple channels to simulate multiple satellites for each constellation	Minimum of 4 satellites for TTFF. Up to 12 or 13 satellites may be visible at one time.
Simulate multiple GNSS constellations	Test the receiver's ability to use each constellation separately or to combine satellites from multiple constellations to calculate its location
Stationary and moving GNSS receiver scenarios	Test the more realistic and complex case of a moving receiver, as well as the simple stationary case
Real-time satellite power adjustments, satellite visibility on/off	Test sensitivity and the ability to reacquire satellite signals
Custom scenario generation capability	Flexibility to create scenarios for any date, time, location, or trajectory for a moving receiver

For R&D and verification, a GNSS simulator should be able to simulate at least 4 satellites per constellation, and preferably up to 12 or more for maximum satellite visibility, allowing the user to reproduce all of the satellite signals that would be visible from any point on Earth. The simulator should also have the ability to simulate both stationary and moving receiver scenarios to test basic TTFF as well as a receiver's ability to track the satellites and maintain a location fix while in motion. Being able to control the visibility and power of the satellites in real-time allows for testing the receiver's sensitivity and its ability to reacquire the satellite signals. The ability to generate custom scenarios for any date, time, and location is also necessary for R&D.

Especially for R&D, the GNSS simulator must also have the ability to include signal impairments in order to test the performance limits of GNSS receivers under a wide variety of conditions. Impairments include multipath signals, which are typically caused by buildings, trees, and other obstructions that reflect the satellite signals. Multipath signals are indirect satellite signals that are received by the GNSS receiver at lower power levels, with delay and different Doppler shifts than the direct line-of-sight signals. Control of satellite visibility allows a user to simulate partial or complete loss of visibility due to tunnels and other LOS obstructions. The ability to add an elevation mask allows you to restrict the visible satellites to those above a certain elevation angle, which can be used to model obstruction from mountains or surrounding buildings in an "urban canyon" environment. Being able to model the atmospheric attenuation and delay from the ionosphere and troposphere provides a more realistic signal to the GNSS receiver. Finally, the ability to add calibrated AWGN (additive white Gaussian noise) to the GNSS signal allows you to control the C/N of the GNSS signal precisely.

Table 2. GNSS signal impairments

Feature	Test challenges met
Multipath signals (requires more channels)	Simulate real-world situation with reflected signals from obstructions
Reduced satellite visibility: partial or complete, elevation mask	Test loss of visibility due to tunnels, mountains, or other obstructions
Ionospheric and tropospheric modeling	Account for atmospheric effects on GNSS signals (refraction, delay)
Add calibrated AWGN	Add broadband noise to control C/N of GNSS signal
Model GNSS receiver antenna	Simulate effects of antenna for more realistic test of receiver

GNSS test signals for manufacturing

While TTFF is sometimes tested in manufacturing, often testing is performed with a simple static single satellite signal that can be used to verify the receiver's ability to acquire the satellite signal, report the received power, and track the satellite. These tests are faster than calculating a location for TTFF, which can take 30-45 seconds. A static satellite signal or waveform file can be used for this test, which generally does not require real navigation message data.

GNSS Receiver Testing Using N7609B Signal Studio for GNSS

One GNSS signal simulation solution that meets the requirements described in the previous section is the Keysight Technologies, Inc. N7609B Signal Studio for GNSS software, used with a signal generator that can generate baseband and RF signals for testing GNSS receivers.

Signal Studio for GNSS is a software application that enables real-time simulation of the L1 C/A code satellite signals from the GPS and GLONASS systems, the E1 open service signals from the Galileo system, and the B1 open service signals for Beidou. Up to 15 line-of-sight satellites can be simulated for each constellation, and a total of 40 channels are available for line-of-sight and multipath signals combined for GPS, GLONASS, and/or Beidou, with an additional 16 channels for Galileo. The software provides the ability to control the visibility and power of the satellites, add pseudorange error, or add multipath impairments in real-time. Custom scenarios can be created to simulate stationary or moving receivers for any location, date, and time.

GNSS receiver test setup

Figure 15 shows two possible test setups for using N7609B systems to test GNSS receivers. The top configuration uses one of Keysight's X-series signal generators to perform real-time signal generation. In this configuration, the N7609B software runs on an external PC. The software allows a user to configure the signal parameters and generates the scenario data. The data is downloaded to the X-series signal generator, where the FPGA is configured to create the GNSS signal in real-time. The EXG/MXG outputs the simulated RF GNSS signals to the GNSS receiver under test. The receiver is connected via USB to the PC, which also runs the GNSS receiver monitoring/control software to display results.

The second configuration uses the N5106A PXB baseband generator and channel emulator. In this case, the N7609B software runs inside the PXB as part of the instrument firmware, and it generates the scenario data and configures the PXB to create the real-time baseband GNSS signals. For RF output, a vector EXG, MXG, or ESG signal generator may be used to upconvert the baseband I/Q signals to RF. If an EXG or MXG is used as the RF upconverter, the instrument does not require the baseband generator option.

If you are performing simple RF front end verification of a receiver in manufacturing and don't need real-time signal generation, you can use the N7609B's basic single satellite waveform option to generate waveform files that simulate a single satellite for GPS, GLONASS, Galileo, Beidou, SBAS, or QZSS. These waveform files can be played back using the N5172B EXG, N5182A/B MXG, E4438C ESG, E8267D PSG, or M9381A PXIe vector signal generators, as well as the E6607 EXT or E6630A wireless test sets and the N5106A PXB.

The remainder of this section will focus on real-time multi-satellite GNSS signal simulation for more complex receiver testing cases. The first example was created using the top configuration in Figure 15, with a u-blox 6 evaluation kit from u-blox AG as the GNSS receiver under test.

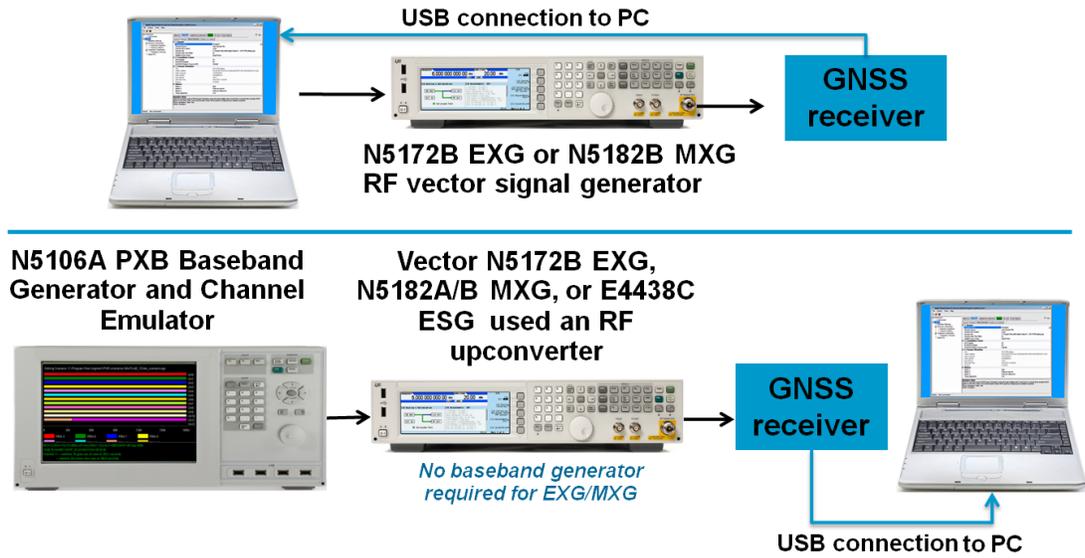


Figure 15. N7609B Signal Studio for GNSS solution configurations.

Generating real-time GNSS signals

The N7609B software includes a number of preconfigured scenario files that allow a user to start testing quickly. To generate signals using one of these scenarios, the user starts the N7609B software and goes to the main “GNSS” settings page as shown in Figure 16. The default **Simulation Mode** of “Navigation” provides multi-satellite signals with navigation messages which allow the receiver to calculate its location. The other available choice is “Static Test” mode where the navigation data and satellite characteristics do not change unless the user inputs a change. The **Scenario Source** parameter allows the user to choose either “User Scenario File,” which uses a saved scenario file for up to 24 hours of non-repeating signal generation, or “Scenario Generator Settings,” which creates short scenario files and downloads them to the instrument continuously to allow for longer scenario simulations. Using the “Scenario Generator Settings” mode requires the instrument to be connected to the PC, while it is possible to simulate signals using saved scenario files without being connected to a PC. Choose “User Scenario File” to use a previously saved scenario file, and click on **Scenario File** to select a file. Several scenario files are supplied with the N7609B software.

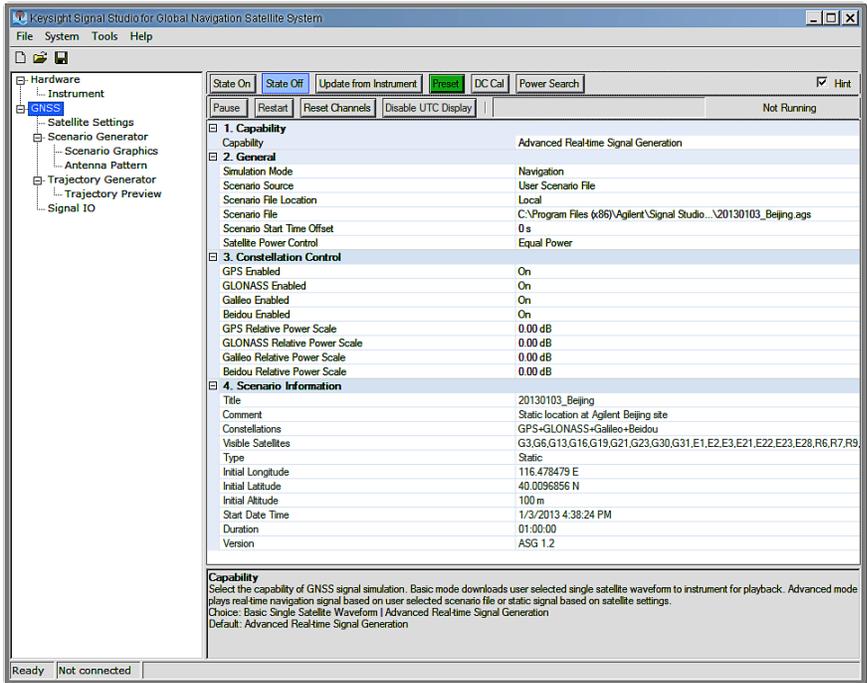


Figure 16. Main GNSS settings page in the N7609B software.

The **Constellation Control** section allows you to enable or disable all of the satellites in each GNSS constellation easily, or to apply a relative power offset for all satellites in the constellation. The **Scenario Information** section displays details about the selected scenario file. We can see that the default scenario file simulates a static location with the displayed latitude, longitude, and altitude, along with information about which satellites are visible at the start of the scenario.

You can click on **Instrument** in the left panel to set the output power level, and then click the **State On** button to start generating this signal.

As the signal is playing, the receiver monitoring software provides information from the receiver under test. As an example, Figure 17 shows the u-Center software from u-blox. Here we can see the satellites being tracked and used by the receiver (in green), the C/N reported for each satellite (bottom center window), the sky view of the satellites (middle right window), and the calculated position, time-to-first-fix, HDOP and VDOP (upper right window).

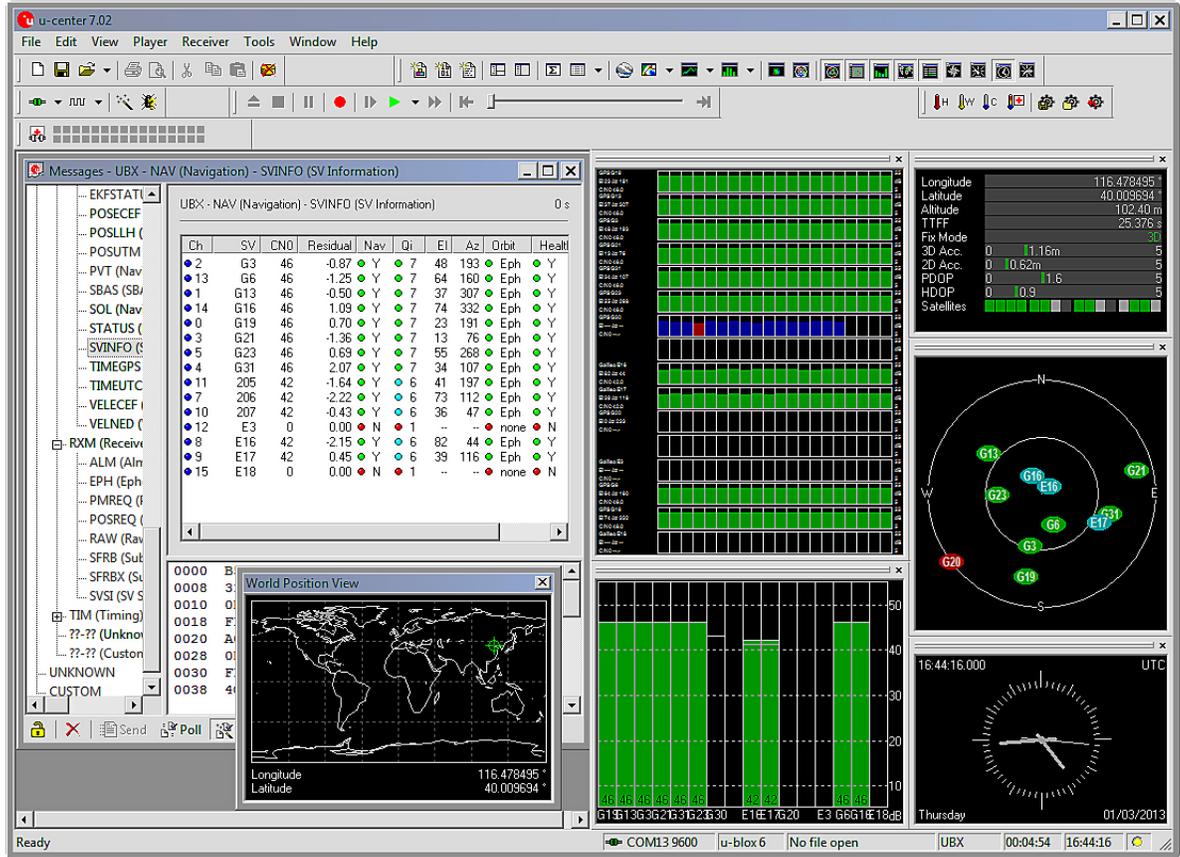


Figure 17. Receiver software shows information about satellites being used for navigation.

Real-time control of satellite signals

Figure 18 shows the “Satellite Settings” page, which can be used to control the power and visibility of individual or groups of satellites, or add impairments while the signals are playing.

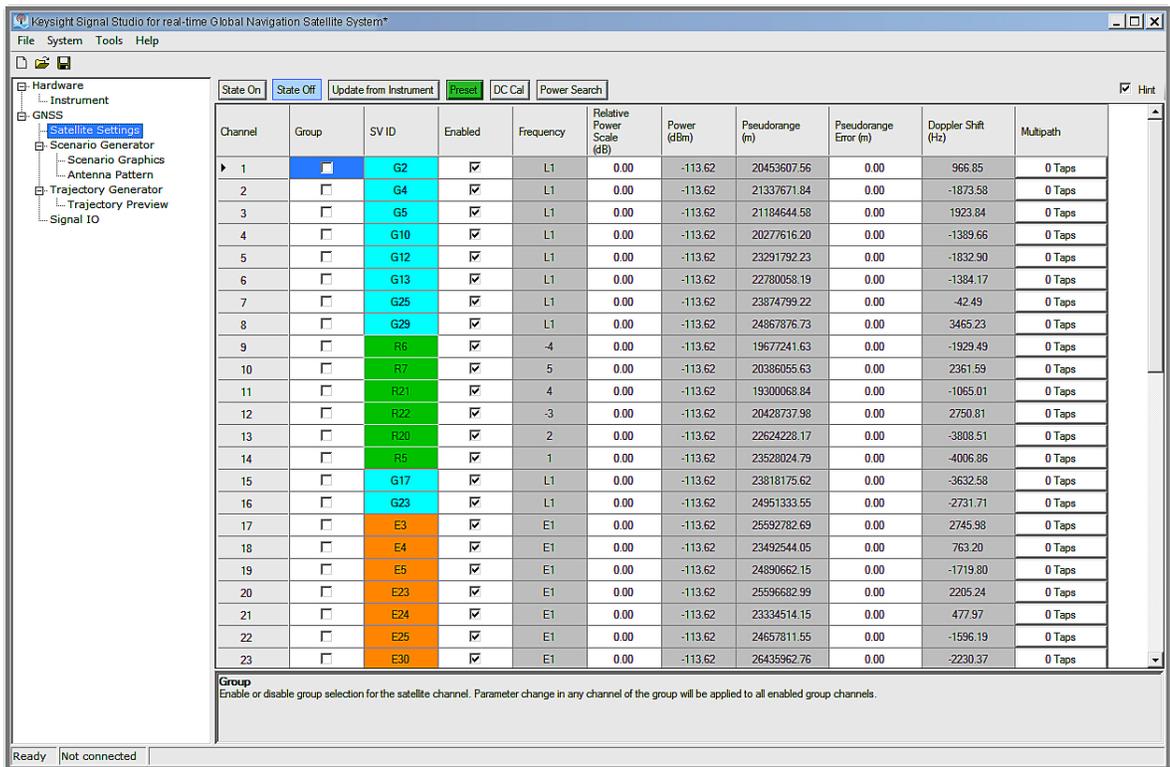


Figure 18. The Satellite Settings page provides real-time control of individual satellite signals.

All visible satellites are displayed, with GPS satellites beginning with “G”, Galileo satellites beginning with “E”, GLONASS satellites beginning with “R”, and Beidou satellites beginning with “B”. For each satellite, you can turn the satellite on/off by checking the “Enabled” column, enter a relative power offset, add a pseudorange error, or add multipath. Changes can also be applied to a group of satellites at the same time by checking the “Group” column for the desired satellites before changing a parameter. This real-time control allows you to model impairments such as loss of power or visibility due to obstructions or pseudorange error and quickly see the impact on the receiver.

Create custom scenarios for any time, date, and location

The ability to create custom scenarios is important for R&D engineers who want the flexibility to test GNSS receivers with scenarios for any date, time, and location. This can be done using the scenario generator function in the N7609B software. Figure 19 shows the settings page for creating a static scenario to simulate a stationary receiver.

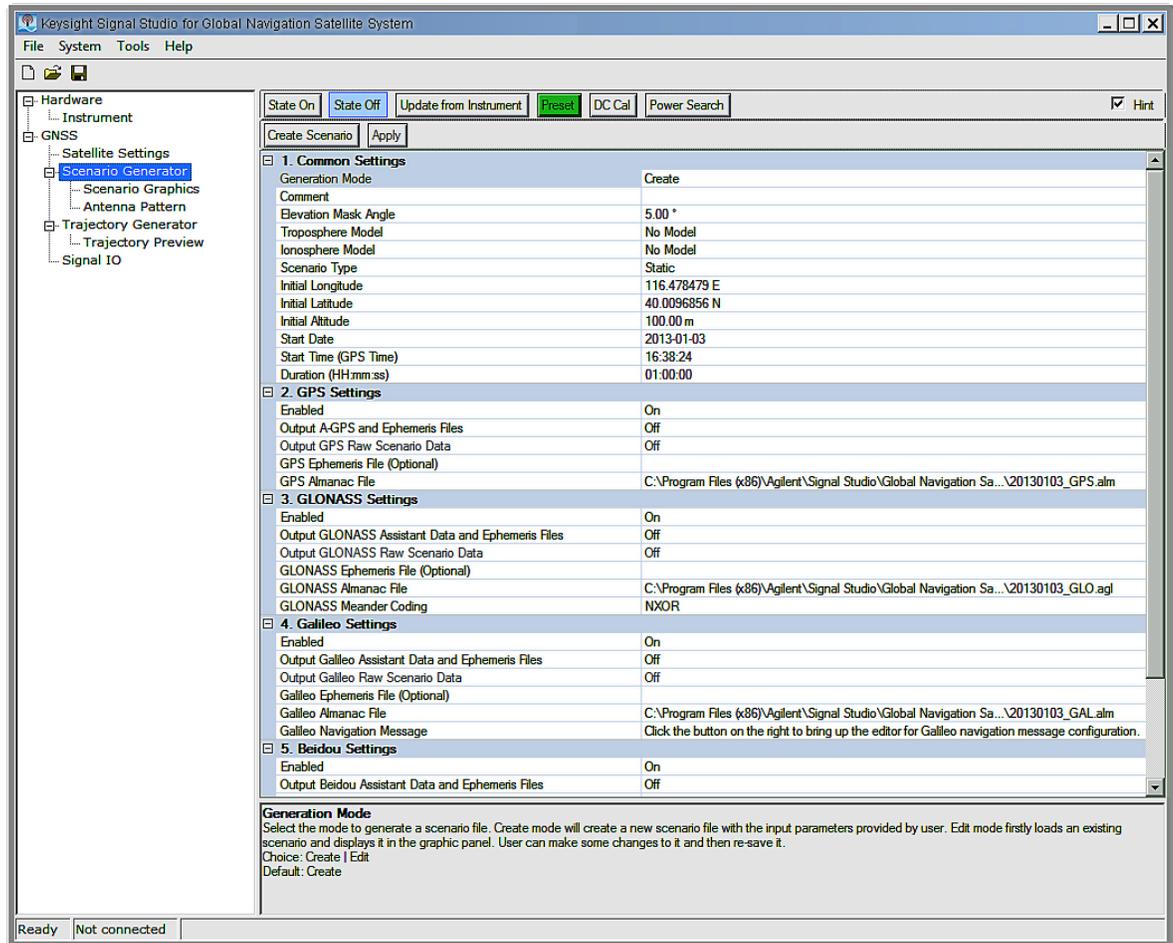


Figure 19. Scenario generator settings page for creating a static scenario.

To create a static scenario, the user specifies the desired location, start date and time, and duration (up to 24 hours). An elevation mask angle can be configured, and modeling can be enabled for the troposphere and ionosphere. When these models are enabled, the scenario generator will include the model parameters in the navigation message and apply the impairments to the GNSS signal.

The user can choose which constellations to include in the scenario. For each desired constellation, the user needs to select an almanac file to describe the satellite locations for the desired date and time for the scenario. YUMA format files for GPS are available from <http://navcen.uscg.gov/gps/almanacs.htm> and GLONASS almanac files are available at <ftp://ftp.glonass-iac.ru/MCC/ALMANAC>). Almanac files are not yet available on the Web for Galileo or Beidou. The N7609B uses modified versions of GPS almanac files for those constellations, and you can edit the ones included in the software to modify the date and time for your desired simulation.

For Assisted GNSS (A-GNSS) testing, the scenario generator accepts ephemeris data files, which are used in conformance tests, and also has the ability to output the ephemeris and A-GNSS assistance data for each scenario.

The scenario generator can also create a dynamic scenario to simulate a moving GNSS receiver. Figure 20 shows the settings, which are similar to those used for static scenarios, except that the location settings are replaced by selection of an NMEA message file (GGA or RMC format) to describe the trajectory of the receiver as a time-stamped sequence of locations. NMEA is the National Marine Electronics Association and they have defined a specification for data communications between various types of marine electronic equipment. GNSS receivers use the NMEA data formats for data output. Several example GGA files are included in the N7609B software, and a trajectory generator utility is provided for creating these files which will be described later. The GGA data can also be recorded from a GNSS receiver using the receiver control and interface software provided by the manufacturer.

The date and time will be read from the NMEA message file if available and displayed as default values. The user can override these with his own settings if desired.

For more details on other scenario generator settings, please refer to the N7609B online help. Once all settings have been entered, the user can click the "Create Scenario" button to create and save the scenario file. This file can then be selected on the main "GNSS" settings page for use in generating the real-time GNSS signals.

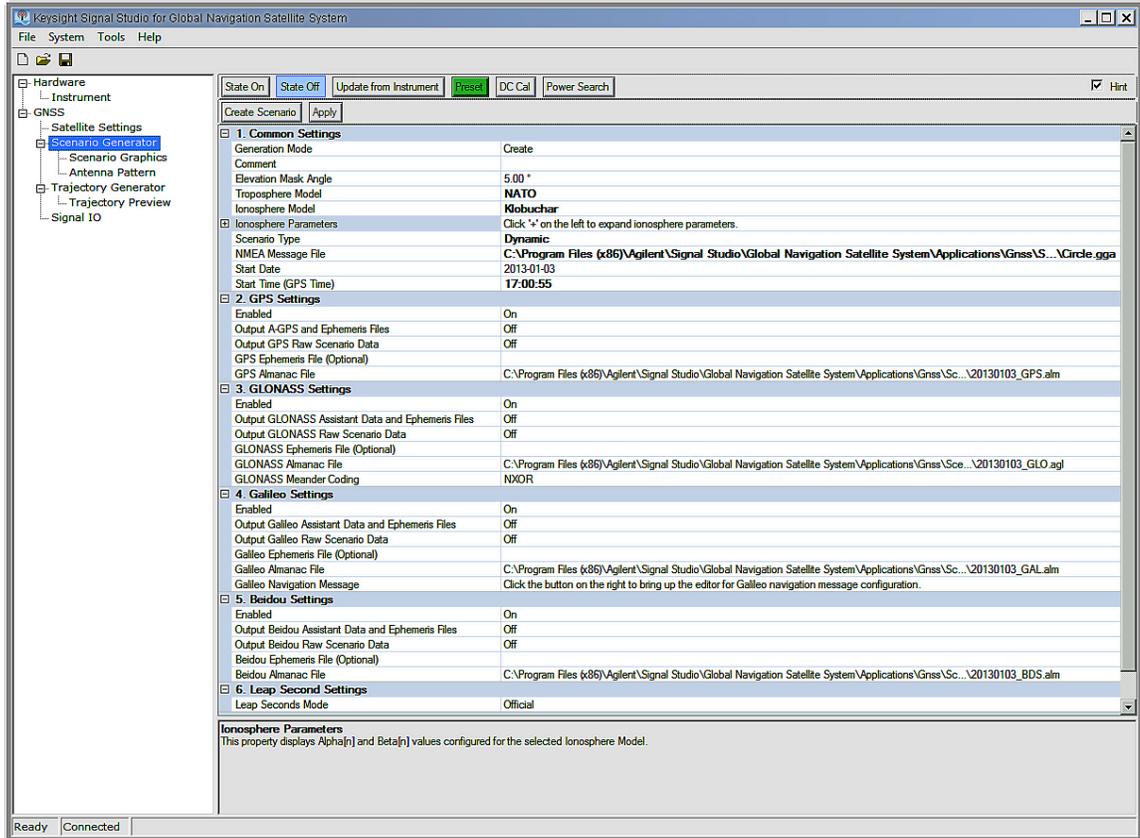


Figure 20. Scenario generator settings for creating a dynamic scenario.

As an example, we can create a dynamic scenario by going to the Scenario Generator settings page shown in Figure 20 and setting "Scenario Type" to "Dynamic." For the "NMEA Message File," select the "Circle.gga" trajectory file that is supplied with the N7609B software. The other settings may be left at their default values or modified if desired. Click the "Create Scenario" button to generate and save the scenario file. Next, click on "GNSS" on the left panel of the window and select this scenario file, then click "State On" to start generating the real-time signal.

Figure 21 shows the results from using this signal to test an NVS Technologies NV08C-CSM Evaluation Kit, which supports GPS, GLONASS, and Galileo. The screen shot is from the STOREGIS software that is supplied by NVS Technologies. At the bottom we can see the signal-to-noise ratio of the GPS satellites in the blue bars, the GLONASS satellites in the red bars, and the Galileo satellites in the orange bars. The graph on the upper right displays the trajectory of the receiver, which is traveling in a circle with a radius of 1 km around the center location of latitude 37.0 degrees north, longitude 122 degrees west. The "Position" section of the display also shows the speed at about 100 km/h.

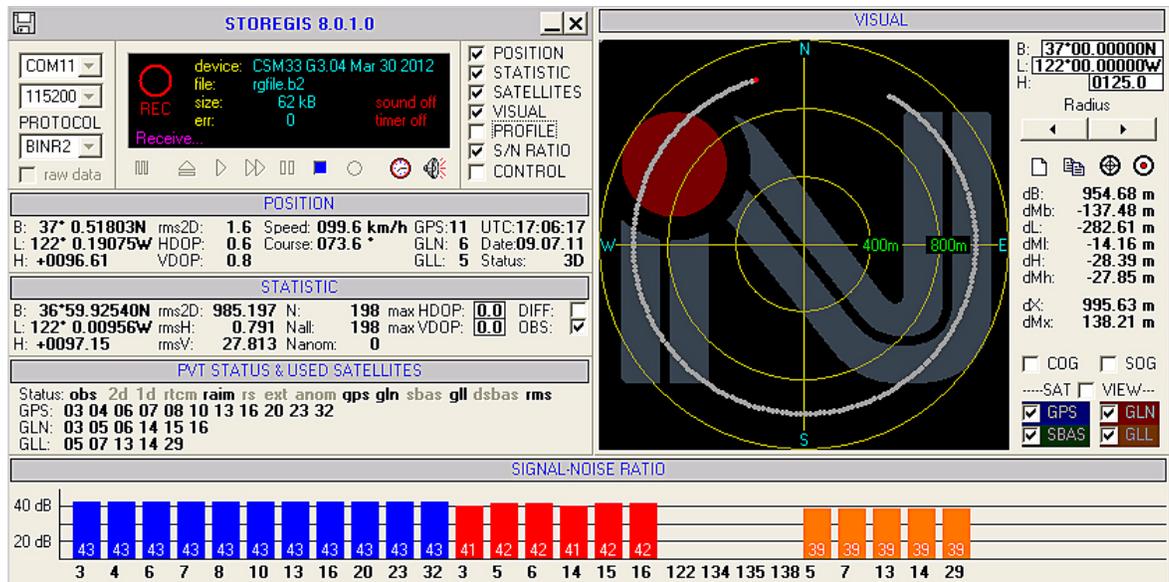


Figure 21. Results from NV08C-CSM receiver showing satellites used for navigation and the receiver's trajectory for the dynamic scenario test.

Editing scenario files to provide repeatable impairments

Scenario files can be modified using the scenario editing function ability to add impairments so that they can be applied in a repeatable way to run multiple tests under the same conditions. The scenario editor allows you to add a power offset to one or more satellites over some period of time, so you can simulate conditions like a drop in power from the satellites due to driving through a tunnel. You can also add multipath by selecting the line-of-sight satellite, assigning a multipath channel, and specifying the start/stop time, Doppler shift, delay, and power offset, as shown in Figure 22. The scenario editor also allows you to delete a channel from the scenario or to trim the scenario to shorten its length.

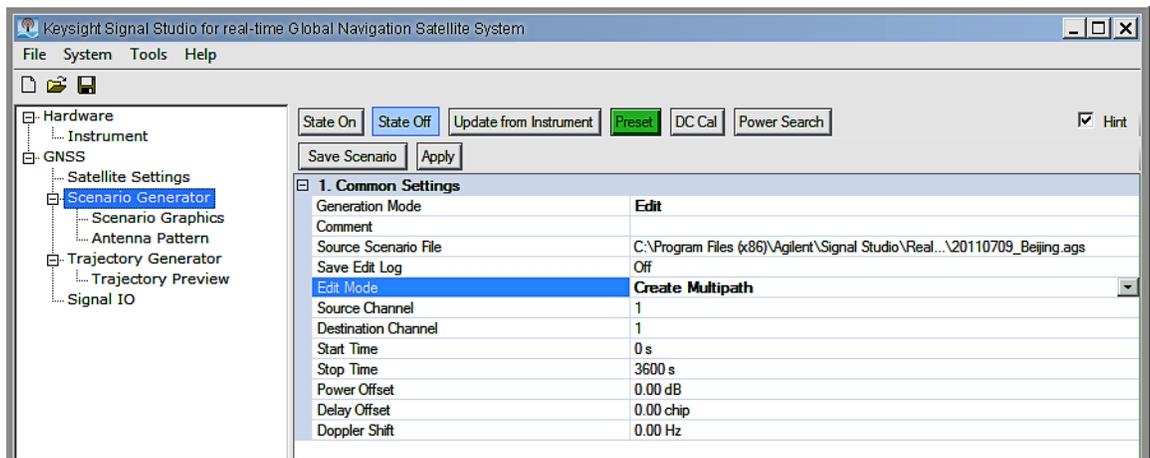


Figure 22. Settings for adding a multipath signal.

The N7609B software provides a Scenario Graphics display that enables you to see the satellites present on each channel over time, as shown in Figure 23. The satellites are identified by color-coding and satellite ID. The display also contains a record of the changes that have been made during the editing session at the bottom of the window.

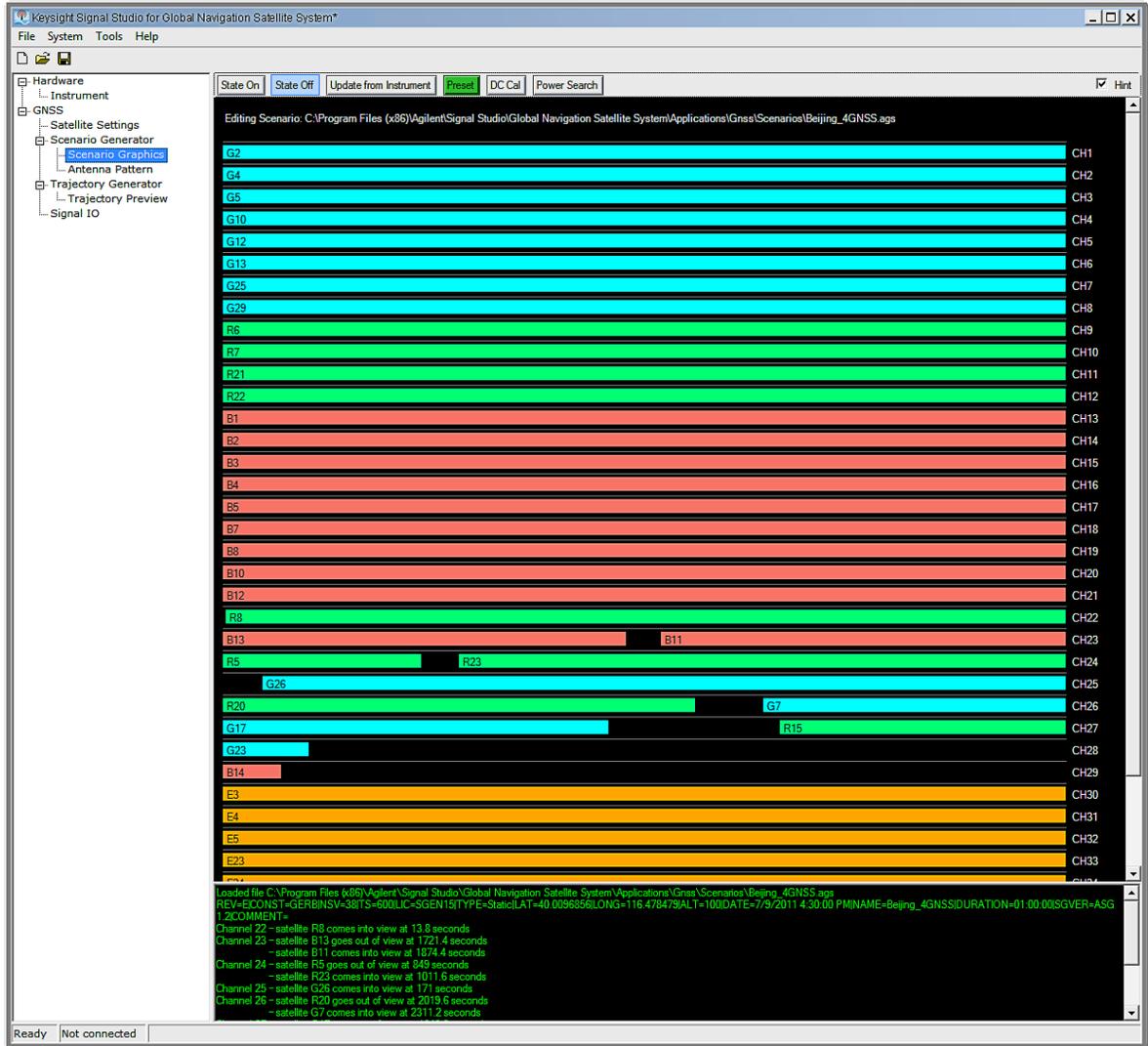


Figure 23. Scenario Graphics display shows the satellites present in each channel over time with a log of any editing changes.

Trajectory generator utility

The trajectory generator utility creates the NMEA GGA message files that describe the motion of a moving receiver, for use in generating dynamic scenarios to test the receiver's ability to track satellites and report accurate locations while it is moving at various speeds.

Users can create a list of segments such as straight lines, turns, and wait states with information about the velocity, acceleration, etc. to describe the receiver's path. They can also choose to create the trajectory in Google Earth or Google Maps, save the trajectory as a *.KML file, and then import the KML file to convert it to an NMEA message file.

With the trajectory generator utility, you can:

- Specify initial location, sampling rate
- Add or delete segments for wait, straight, or turn, or choose a preset shape
- Specify velocity and acceleration vs. time or distance
- Preview the receiver's path on the display
- Save trajectory data as an NMEA GGA format file, Google Map HTML file, or Google Earth KML file
- Create a path in Google Earth and convert the Google Earth KML file into an NMEA GGA file

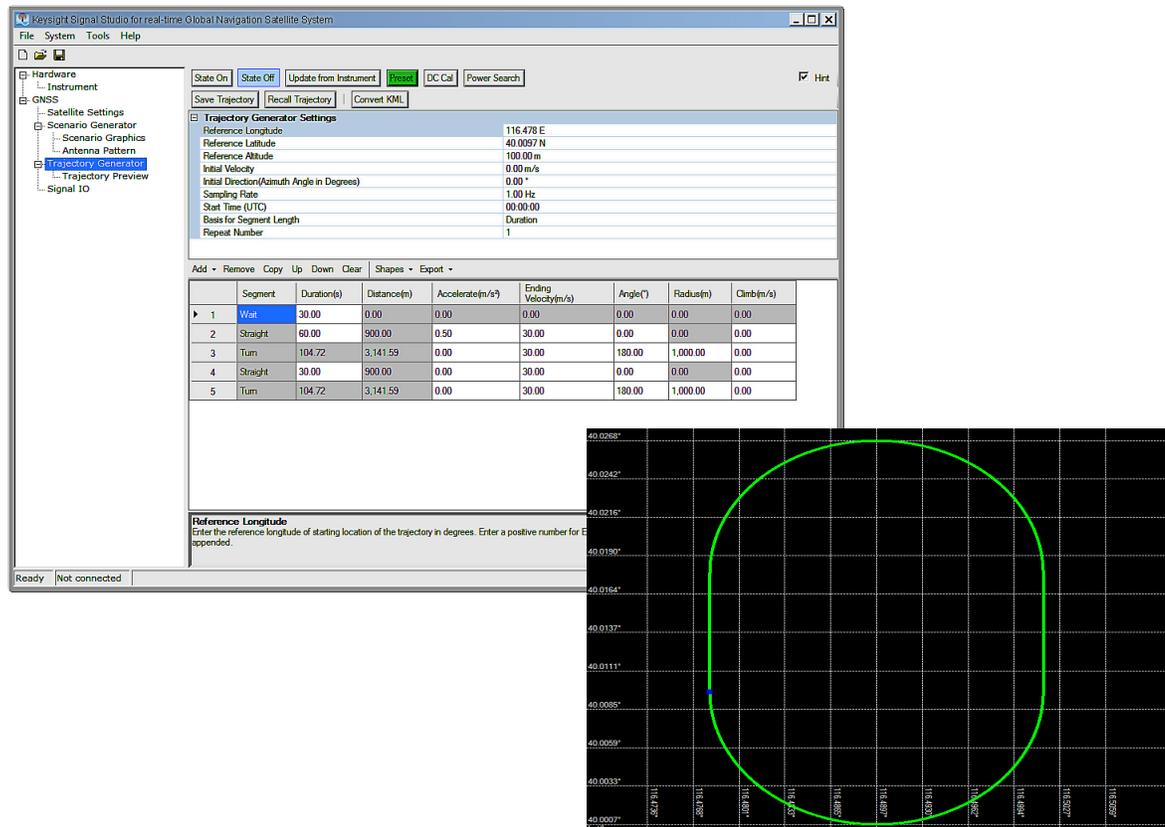


Figure 24. Trajectory preview shows the path described in the trajectory generator setup.

Apply an antenna model

GNSS receivers are often tested under conducted conditions using a cable connected directly to the receiver input, since this is easier to do than to perform a radiated test that includes the effects of the receiver's antenna. To better account for the antenna's effects with conducted testing, the N7609B provides a graphical user interface to allow a user to configure and apply an antenna pattern to model the power profile of a receiver's antenna. This can also be used to model obstructions or signal absorption around the receiver. The software's antenna modeling settings allow you to do the following:

- Define the resolution for azimuth and elevation
- Specify the power offset for particular azimuth and elevation
- Apply azimuth rotation
- Apply a pattern based on absolute azimuth/elevation for static scenarios, or relative to the GNSS receiver's orientation for dynamic scenarios

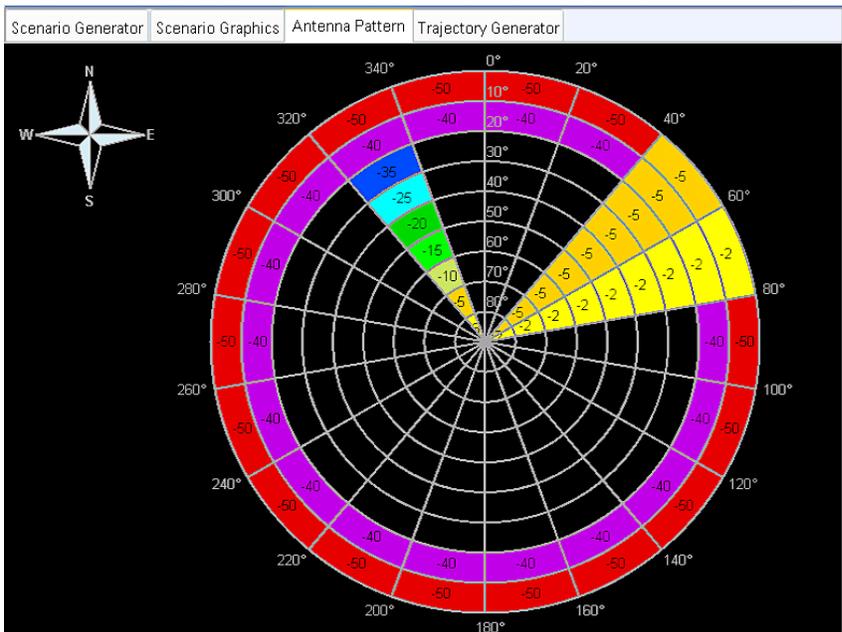


Figure 25. Antenna model with gain mask to be applied to satellite signals.

Conclusion

The rapid growth of location-based services and applications, increasing integration of navigation receivers into consumer devices, and the expansion of GNSS systems beyond GPS, with deployment of newer systems such as GLONASS, Beidou/Compass, and Galileo, present new challenges for testing GNSS receivers. For thorough testing of GNSS receivers, it is necessary to have the ability to simulate multiple GNSS constellations and to model different impairments in the satellite signals. The N7609B Signal Studio for GNSS software provides real-time GNSS signal simulation with the features needed to test today's multi-GNSS receivers.

Web Resources

Keysight GNSS solutions
www.keysight.com/find/gnss

Keysight A-GPS solutions
www.keysight.com/find/agps

Keysight N7609B Signal Studio for GNSS software
www.keysight.com/find/N7609B

Demo Video of N7609B with X-series signal generators:
www.youtube.com/watch?v=-I_NEdIbOYI&feature=channel&list=UL

Related Literature

Keysight N7609B Signal Studio for Global Navigation Satellite Systems (GNSS) Technical Overview, Literature number 5990-9363EN

GPS Receiver Testing, Application Note, Literature number 5990-4934EN

Functional A-GPS Receiver Testing Using 8960 and E4438C ESG, Application Note, Literature number 5989-9141EN

References

GNSS Tutorials and Links:

GNSS Tutorials:

GPS System Information: www.gps.gov/systems/gps

ESA Navipedia: http://www.navipedia.net/index.php/Main_Page

Palo Wireless GPS Resource Center: www.palowireless.com/gps/tutorial.asp
gnss.be/gnss_tutorial.php
www.u-blox.com/en/tutorials-links-gps.html
www.trimble.com/gps_tutorial

U.S. Coast Guard Navigation Center: GPS status, almanacs, link to ephemeris data, general GPS information: www.navcen.uscg.gov/gps/default.htm

Russian Space Agency: Information on GLONASS, almanac files:
www.glonass-ianc.rsa.ru

ESA Galileo Information:
www.esa.int/Our_Activities/Navigation/The_future_-_Galileo/What_is_Galileo

Beidou Information: en.beidou.gov.cn

Industry Magazines: InsideGNSS: insidegnss.com, GPS World : gpsworld.com

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