GNSS Inside Mobile Phones

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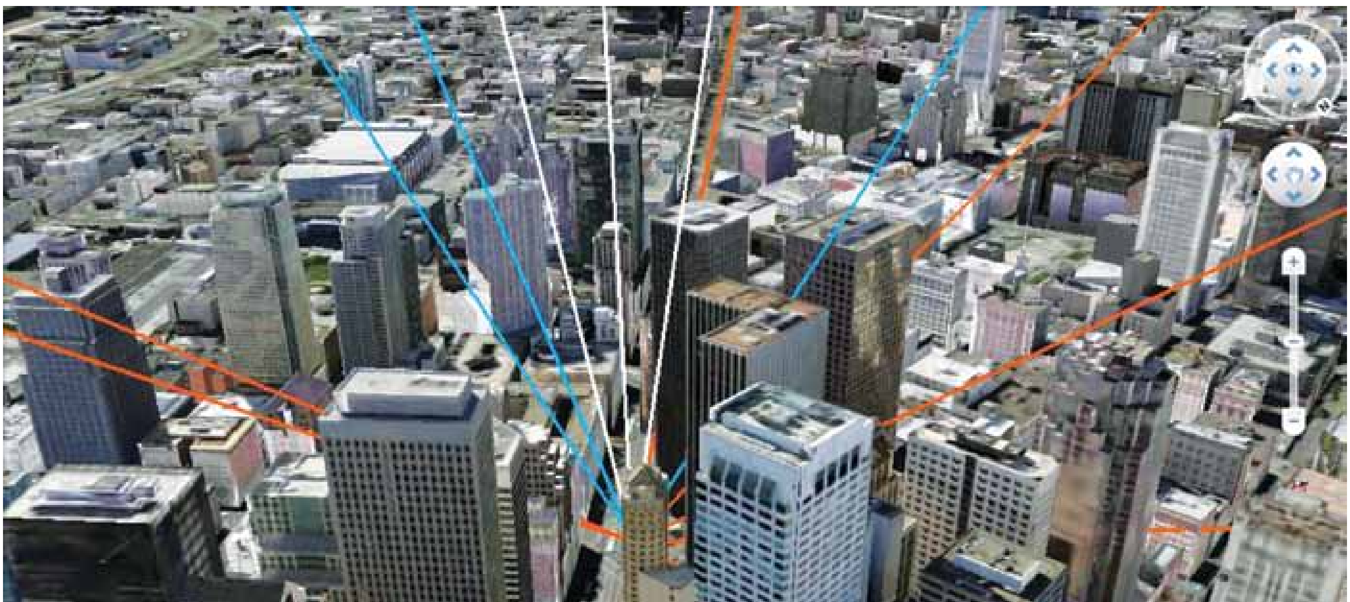
GPS, GLONASS, QZSS, and SBAS in a Single Chip



Development of multiple GNSS satellite constellations, including regional and augmentation systems, has raised new — and commercially strategic — questions for product designers and system integrators. Are additional satellite signals sufficiently beneficial to include in receiver designs? What are the product development issues associated with technical differences among GNSS systems? Can they be successfully addressed in single-die receiver chip designs?

Recent years have seen GPS receivers built in as a standard feature in many consumer products. A growing number of mobile phones, personal navigation devices, netbooks and tablets are equipped with GPS receiver chips and navigation software that enable consumers to navigate from A to B or find their nearest coffee shop. According to Berg Insight, annual shipments of GPS-equipped mobile phones are estimated to reach 960 million devices in 2014.

Integration of a GPS receiver in mobile phones faces important restrictions, such as reduced space, interference from neighboring radio transmitters (oftentimes located in the same chip), low-cost oscillators, and poor antennas. Such factors make it a challenging task to deliver the navigation performance that consumers demand.

Oblivious to all these limitations facing designers of GPS integrated circuits (ICs) and mobile phones, consumers expect their GPS receivers to work wherever their mobile phones do. We sometimes forget that the received outdoor GNSS signal in a mobile phone (around –135 dBm, and worse if the antenna is too small or badly located) is more than 10^{16} times weaker than typical transmitted cellular signals from the same phone (27 dBm).

For these reasons GPS receivers in mobile phones are often augmented by using other sensors such as accelerometers, gyrocompasses, and even WiFi positioning data to aid the navigation function when the satellite visibility conditions are poor.

We are also watching an explosion in the number of GNSS satellites available from multiple nations around the world. Besides the omnipresent GPS constellation, the Russian GLONASS system would have been complete if the recent Proton launch carrying three GLONASS-

M satellites had not failed on December 5, 2010. Still, with 22 operational satellites (one spare satellite has been made operational) now in its planned 24-satellite constellation, GLONASS provides almost global coverage.

Because of its slightly greater orbit inclination than GPS (60 degrees versus 55 degrees), GLONASS improves GNSS coverage in high latitudes. Of course, other GNSS systems, Europe's Galileo and China's Compass/BeiDou2, are under development. Moreover, local augmentation constellations are appearing, such as the Quasi-Zenith Satellite System (QZSS) in Japan, and several space-based augmentation systems (SBASes) have been completed or are being built in various regions: U.S. Wide Area Augmentation System (WAAS), European Geostationary Navigation Overlay Service (EGNOS), Japan's MTSAT Space-based Augmentation System (MSAS), and India's GPS-Aided GEO-Augmented Navigation (GAGAN) system.

In this article, we discuss the architecture of single-die GNSS receiver chips. We also show the performance advantage of using multiple constellations, especially in environments where the satellite visibility is impaired. Two different L1 GNSS receiver ICs are used to illustrate our points. Both receivers can track satellites from GPS, GLONASS, SBAS and QZSS constellations. One of the receivers is part of a combination IC that also adds Bluetooth (BT) and FM functionality in the same die.

In the architecture section, we show the main building blocks of a single die GNSS receiver as well as the necessary external components to implement a complete receiver inside a consumer product such as a mobile phone.

We will also address two well-known system-level issues related to GLONASS. The first involves the inter-channel biases that are present in GLONASS due to the frequency division multiple access (FDMA) nature of its signals. The second is caused by the fact that GPS/QZSS/SBAS system-time differs from GLONASS system-time. Therefore, care must be exercised when mixing measurements from these systems and GLONASS into a single navigation solution.

Finally, we will present results from test drives performed in deep urban canyon areas where initially only GPS satellite signals are used, and then we will show the improvements when the same receiver is augmented with GLONASS.

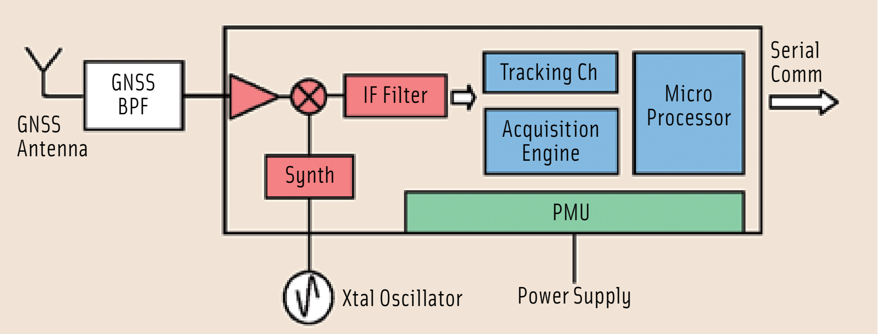


FIGURE 1 Schematic of a GNSS receiver inside a consumer product

System	Carrier Frequency (L1)	Multiple Access	Chipping Rate	PRN Length	Data Modulation
GPS/SBAS/QZSS	1575.42 MHz	CDMA	1.023 Mcs	1,023 chips	BPSK
GLONASS	1602+K*0.5625 MHz K=-7..+6	FDMA	0.511 Mcs	511 chips	BPSK + Meander seq.

TABLE 1. Signal-in-space differences between GPS/QZSS/SBAS and GLONASS that affect chip design

GNSS Receiver Architecture in a Single Die

Low-cost GNSS receivers are usually implemented using a single piece of a silicon wafer. This means all receiver circuits — for example, digital logic, memories, and microprocessors as well as analog blocks such as power supplies and radio circuits — are designed to use standard complementary metal oxide silicon (CMOS) processes that leverage economies of scale at IC fabrication plants. A single-die IC also benefits from modern wafer-level IC packaging techniques that bring the cost further down and speed up the testing process.

Figure 1 shows a block diagram of a complete GNSS receiver inside a consumer product, consisting of a GNSS antenna, a GNSS band pass filter (BPF), a crystal oscillator, and the GNSS IC that, in this case, is represented by the GNSS section of the combo GPS/GLONASS/Bluetooth/FM IC or the stand-alone GPS/GLONASS IC. Both are equivalent from a GNSS functionality point of view.

The complete GNSS solution is a highly integrated one and can be realized in a phone using about 25 square millimeters of board space — less than one-tenth the area of a U.S. dime. A few passive components are used in the design to improve matching and filter the different power supplies from noise sources. Let's take a look at each of these blocks separately and consider the implications of having to support additional constellations with an emphasis in GLONASS because of its particular FDMA signal characteristics. We will first describe the components around the GNSS IC and then delve into the inner blocks of the chip itself as shown in Figure 1.

Table 1 summarizes some of the signal-in-space differences between GPS/QZSS/SBAS and GLONASS that affect the design of combined GNSS chips.

Components One by One

A GNSS receiver — whether a stand-alone GPS-only or multi-GNSS device, or integrated into a multi-technology product such as a smart phone — consists of numerous components. We will briefly review the main ones, pointing some of the particular factors that must be considered in designing a single-die chip.

GNSS Antenna. GNSS antennas in consumer products are very inexpensive items. A typical antenna used in mobile phones is a PIFA (planar inverted-F

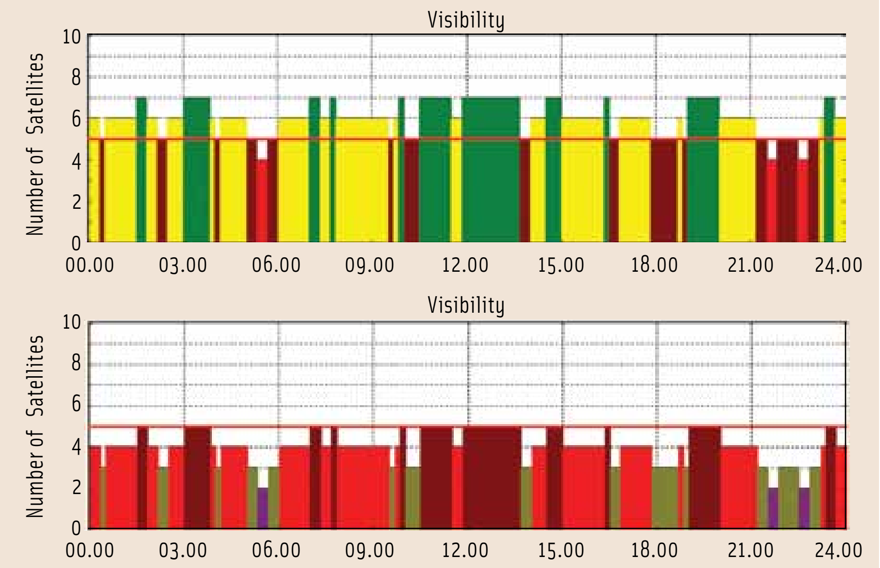


FIGURE 2 Simulated test results for San Francisco showing satellite visibility with a GPS-only receiver (bottom graph) and GPS plus SBAS (top graph)

antenna), which is essentially a microstrip antenna that is built using a piece of printed circuit board (PCB) trace so that the cost is negligible.

A single antenna can be tuned to receive GPS/QZSS/SBAS *and* GLONASS signals, despite the fact that their frequencies do not overlap — GLONASS L1 is slightly higher in the spectrum — and each GLONASS satellite transmits on a different frequency channel. PIFA antennas are not ideal because they are linearly polarized while GPS, QZSS, SBAS, and GLONASS signals are circularly polarized. This kind of antenna also has more directive radiation patterns, which can result in some GNSS satellite transmissions being heavily attenuated, depending on the direction that they are received by the antenna.

Another factor that plays an important part is an antenna's location within the phone. Real estate is at a premium in multi-RF mobile devices, and many radios are competing to have their antennas in the best possible locations. Mobile phone designers have sometimes little choice but to put GNSS antennas in less-than-ideal locations, such as the bottom part of the phone.

Sometimes designers end up having to place the GNSS antenna in a spot where the user's hand will cover part or all of the antenna, resulting in even weaker signals for the GNSS receiver. One way to mitigate this problem is the use of combined antennas, not only for GNSS but also for other radios such as BT or a wireless local access network (WLAN).

GNSS Band Pass Filter. The use of band pass filters is a must for all GNSS designs that place the receiver IC in the vicinity of other radios. As mentioned earlier, GNSS signals are many orders of magnitude weaker than other radios present in mobile phones or even in the same GNSS IC.

As is the case with the GNSS antenna, we can build a single band pass filter that is tuned to let GPS, QZSS, SBAS, and GLONASS signals pass through while sharply attenuating other potential interferers. Examples of interferer signals include cellular signals (GSM/EDGE/WCDMA), Bluetooth, WLAN, and FM radio. GNSS band pass filters are typically built using SAW (surface acoustic wave) technology.

Crystal Oscillator. An external oscillator is used just as in stand-alone GPS receiver designs. This oscillator is compensated for temperature variations (i.e., a temperature compensated crystal oscillator or TCXO) so that the receiver can maintain greater frequency stability.

Receiver Blocks

Let us turn now to the various blocks of a GNSS receiver IC. We will cluster these inside the GNSS IC in the same three groups as indicated by the different colors in Figure 1: RF blocks, baseband blocks, and power blocks. Again, where applicable, we will point out differences from existing GPS-only solutions.

RF Blocks. The RF section consists of the low noise amplifier (LNA), mixer, synthesizer, and intermediate frequency (IF) filter. The LNA amplifies the GNSS signal, adding as little noise as possible. That signal is then down-converted in the mixer to an intermediate frequency (IF).

The next stage involves the IF filtering of the GNSS signals to be processed later in the digital baseband section. All of the RF blocks have been redesigned from a typical GPS-only RF section. Careful design minimizes the size increase involved in supporting multiple different GNSS signals in a single RF section.

Baseband Blocks. The baseband section consists of an acquisition engine, tracking channels, and the microprocessor unit. The acquisition engine is able to search for a large number of delay/frequency hypotheses for both GPS and GLONASS signals. Once the signals are acquired, they are passed on to the tracking channels where the range, Doppler, and phase measurements are taken.

The microprocessor unit manages all the tasks that the hardware blocks perform as well as communicates with the mobile device's host processor to pass on the measurements that can be used by the position computation engine.

We have seen from Table 1 that GPS/QZSS/SBAS and GLONASS signals not only have different carrier frequencies but also have different pseudorandom noise (PRN) code lengths, different chipping rates, and different data modulation schemes that greatly affect the baseband design of a combined receiver when compared to a GPS-only receiver.

Power Management Unit Block. The PMU block provides power to the various sections of the IC so that a single power source from the host can be used, employing internal regulators for each power domain. The design of the PMU block is not really different in a GNSS receiver when compared with a GPS-only receiver.

Benefits of Multi-GNSS Receiver in Urban Canyons

The number of "line of sight" (LOS) satellites that a GPS/GNSS receiver uses in its position computation directly influences the accuracy of the resulting position. Modern receivers are very sensitive and can often receive many satellite signals in obstructed environments (even indoors).

More often than not, these signals are reflected from buildings and other objects and often hurt more than help a receiver's accuracy. Even though a GPS receiver would typically flag these satellites as having multipath, it has little choice but to use them because such environments simply do not admit enough LOS satellite signals to compute a navigation solution with these LOS signals alone.

A common figure of merit for the resulting position error is the so-called *horizontal dilution of precision* or HDOP. HDOP is defined as

$$HDOP = \sqrt{d_x^2 + d_y^2}$$

where d_x^2 and d_y^2 are the variances for the horizontal coordinates (latitude, longitude) in the covariance matrix that results from an unweighted least-squares solution. Loosely speaking, the resulting accuracy of the GPS position solution is the HDOP multiplied by the error in the measured range, assuming that the error is similar for all satellites.

In practice, GPS receivers use more complex navigation filters (e.g., Kalman filters) than a simple least squares solution, and not all satellites will have the same measurement errors. However, we believe that, for a figure of merit, using the HDOP that would result from using the LOS satellites is a very good approximation of the position accuracy that can be obtained.

HDOP in Action

In this section, we will compare the HDOP values from a GPS receiver that uses only GPS satellites with receivers that gain additional benefit from SBAS, QZSS and GLONASS. We will first show simulations of the satellites and HDOPs for receivers in *virtual sites* representing San Francisco, Tokyo, and Madrid. Later on in the section, we will show real data collected in San Francisco and San Jose, California, with equipment incorporating the GNSS/SBAS/QZSS/BT/FM IC.

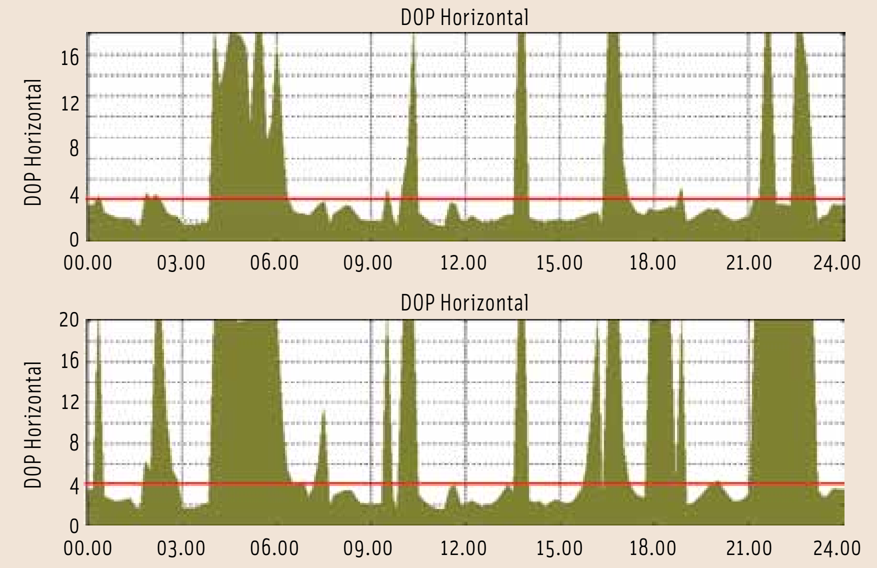


FIGURE 3 HDOP values in simulated San Francisco test with a GPS-only receiver (bottom graph) and GPS plus SBAS (top graph)

Our simulations are done taking advantage an off-the-shelf mission planning software using real satellite almanacs. The exception is QZSS. Here we modified a QZSS almanac so that we could simulate a three-satellite QZSS constellation. The planning software includes an "obstruction editor" tool that we used to recreate a north-south street that is 30 meters wide and has five-storey buildings on both sides.

Three scenarios of GNSS receivers compared with standard GPS-only receivers were contemplated in the simulations:

- San Francisco, USA — GNSS receiver using GPS+SBAS
- Tokyo, Japan — GNSS receiver using GPS+SBAS+QZSS
- Madrid, Spain — GNSS receiver using GPS+GLONASS

In this way we can show the incremental benefit of each additional GNSS constellation. Of course, in real life, the GPS/SBAS/QZSS/GLONASS ICs take advantage of all available constellations.

The almanacs used in the simulations assumed:

- 31 GPS satellites
- 4 SBAS satellites (MSAS and WAAS)
- 3 QZSS satellites
- 22 GLONASS satellites.

SBAS satellites over Europe (EGNOS) were not used in the Madrid simulations because the clocks in EGNOS satellites are *not* synchronized with GPS, which prevents the EGNOS satellites from being used for ranging. This limitation is not present in other SBAS satellites, such as MSAS or WAAS; so, we included SBAS satellites in the Tokyo and San Francisco simulations.

Each location has two sets of plots. The first one compares the number of LOS satellites available, and the second plot compares the HDOP values that would be obtained using only these LOS satellites. The plots cover a 24-hour period. Note that the scales are not always the same; so, the various figures plotting our test results include a red horizontal line that indicates where the number of satellites equals 5 and HDOP equals 4.

San Francisco. Figure 2 compares the two receivers in terms of the number of LOS satellites. The plot at the top represents results from the GNSS receiver using GPS+SBAS and the one at the bottom is the GPS-only receiver.

Figure 3 shows a similar plot for the HDOP. Again, the top plot corresponds to the case of the GNSS receiver (GPS+SBAS) while the bottom plot is GPS only. For GPS only, the HDOP is greater than 4 for 46 percent of the time

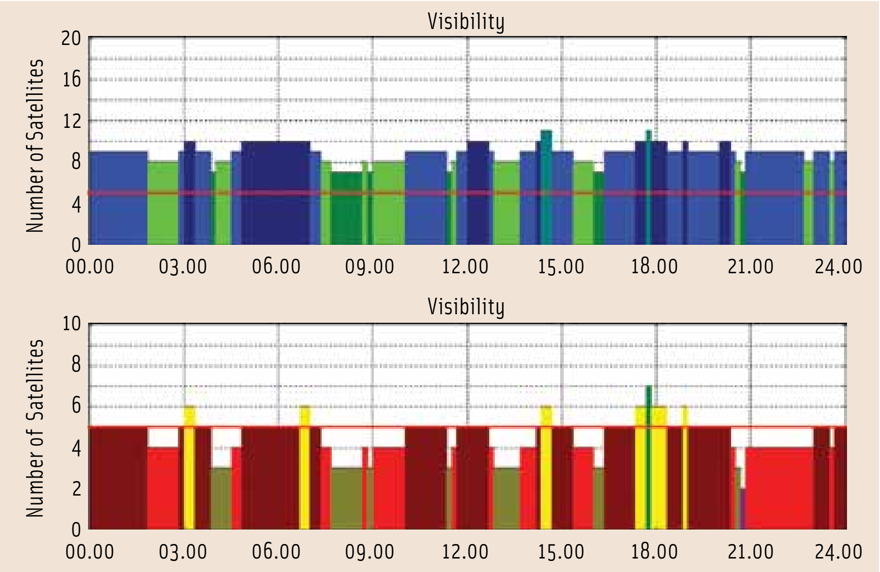


FIGURE 4 Satellite visibility in simulated Tokyo test with a GPS-only receiver (bottom graph) and GPS plus SBAS and QZSS (top graph)

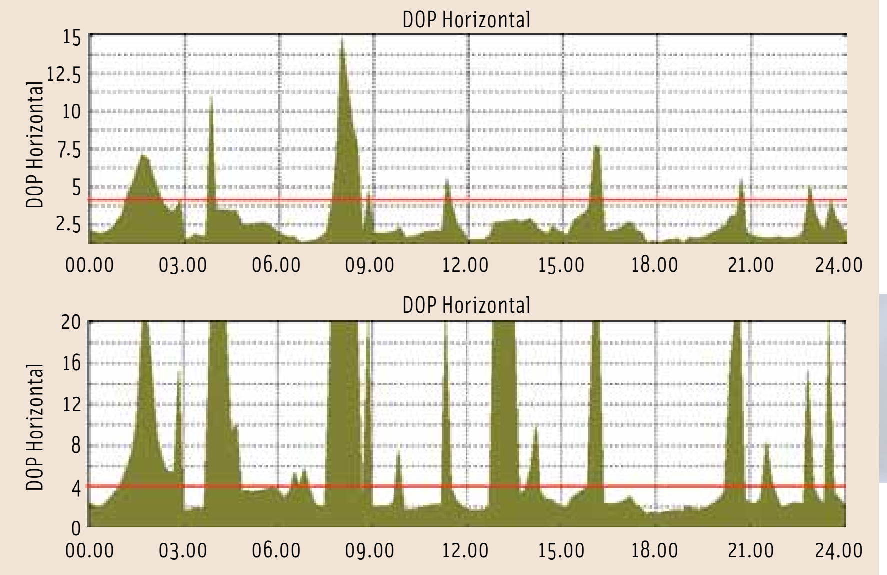


FIGURE 5 HDOP values in simulated Tokyo test with a GPS-only receiver (bottom graph) and GPS plus SBAS and QZSS (top graph)

Scenario	GPS HDOP >4	GNSS HDOP >4	GPS # SV <5	GNSS # SV <5
San Francisco (GPS+SBAS)	46%	26%	70%	3.8%
Tokyo (GPS+SBAS+QZSS)	40%	19%	41%	0%
Madrid (GPS+GLONASS)	30%	6.3%	45%	1.2%

TABLE 2. Comparison of results from three simulations

while this number goes down to 26 percent for GPS+SBAS. The difference is clearly significant, but we still see HDOP "chimneys" in the GNSS receiver that can cause position errors of hundreds of meters.

Tokyo. Figure 4 and Figure 5 show analogous data for Tokyo. In this case, the GPS-only receiver has an HDOP greater than 4 for 40 percent of the time that comes down to 19 percent when we add SBAS and QZSS.

Note as well how the "number of satellites" plot shows that, for the GPS-only receiver, there will be fewer that five LOS satellites almost 40 percent of the time. Adding SBAS and QZSS, we can see that at no time during the day will the number of satellites be fewer that five. This result is expected because the QZSS satellites are at high elevations in the Asian regions; so, they are visible almost all the time despite the receiver being in obstructed environments.

Madrid. Figure 6 and Figure 7 show the simulated plots for Madrid. Note how GLONASS makes a significant difference over GPS. The percentage of the time that we see fewer than five satellites is 45 percent with GPS-alone while the number goes down to 1.2 percent when we have GPS + GLONASS. Analogously for the HDOP values, the value is greater than 4 for 30 percent of the time for GPS-only. Adding GLONASS the number goes down to 6.3 percent.

Table 2 summarizes the results for all three simulations.

GNSS/SBAS Results in San Francisco. Real-life drive tests were conducted using the GNSS/SBAS/BT/FM receiver in downtown San Francisco. Using commercial Earth imaging service and a tool that our company developed, we can see which satellites are in line of sight and which ones are obstructed and therefore tracked through reflections.

Referring to the picture in Figure 8, the lines are color coded after analyzing the 3D buildings. The picture shows seven orange lines from satellites that were blocked by buildings but nonetheless were tracked by the high-sensitivity receiver, which acquires and tracks reflected signals from these blocked satellites. The figure also shows three blue lines from GPS satellites that were not obstructed (LOS GPS), and three white lines from GLONASS satellites that were not obstructed either (LOS GLONASS).

Calculating the HDOP value that would result using only GPS satellites, we obtain an HDOP of 50; using GLONASS only, the HDOP would be 45; and finally, using the combined total of six GPS+GLONASS satellites, we obtain an HDOP of 2.2.

This example should put to rest the false notion that additional high satellites will not improve HDOP. In this case the HDOP improves by more than 20 times, from 50 to 2.2. And it is easy to find many similar examples using GPS+QZSS, GPS+GLONASS or any other GNSS combination. At times, extra satellites do *not* help HDOP that much, but more often than not they improve the situation significantly.

Figure 9 shows a zoomed version of the area of interest, again with the lines that represent the satellite sources and directions using the same color code as in Figure 8. It provides a very graphical view of how challenging the environment is in terms of satellite visibility.

In Figure 9, the white dots represent the track of the GNSS receiver using GPS and GLONASS satellites and the yellow dots, the track using GPS satellites only. (Note that SBAS was being used in the field trial but was not tracked at this corner.) We can see that there is a position jump in the yellow (GPS-only) track just at this precise corner where the LOS HDOP increases while the white dots of the LOS GPS+GLONASS track show a much smoother trajectory turning the corner despite the difficulty of the environment.

Real life data seems to corroborate the results that were anticipated in the previous simulations. In a later section, we will focus on a more thorough accuracy comparison over an entire drive test to quantify the benefit of GLONASS more completely.

Before we delve into that, we would like to address two very well-known system-level topics that surface almost every time that GPS+GLONASS integration is discussed, and the solutions that have been implemented in our GNSS receivers. The first one is how to handle inter-channel biases in GLONASS receivers caused by the FDMA nature of GLONASS signals and resulting variations in propagation of the signals on different frequencies.

The second issue is how to deal with the differences in system times between GPS and GLONASS, and how a navigation solution that combines GPS and GLONASS satellites solves the problem.

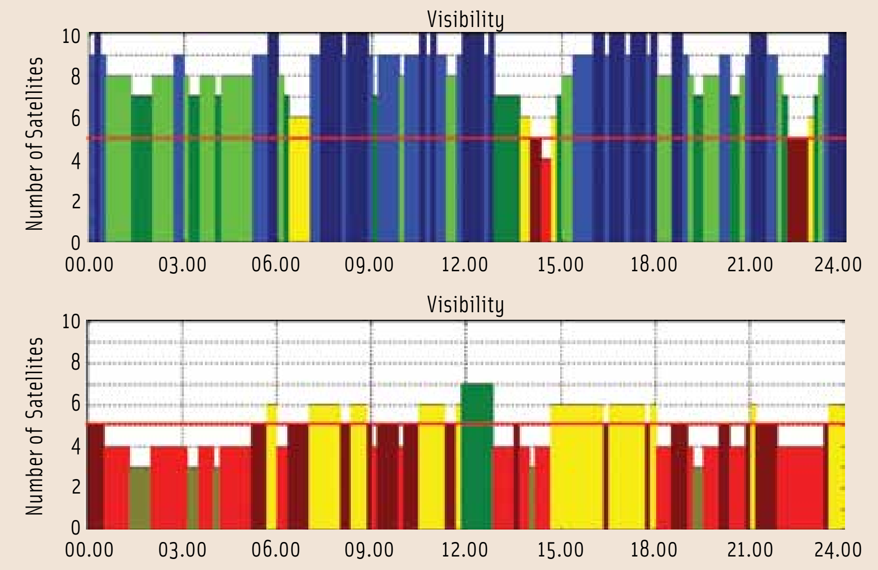


FIGURE 6 Simulated test results for Madrid showing satellite visibility with a GPS-only receiver (bottom graph) and GPS plus GLONASS (top graph)

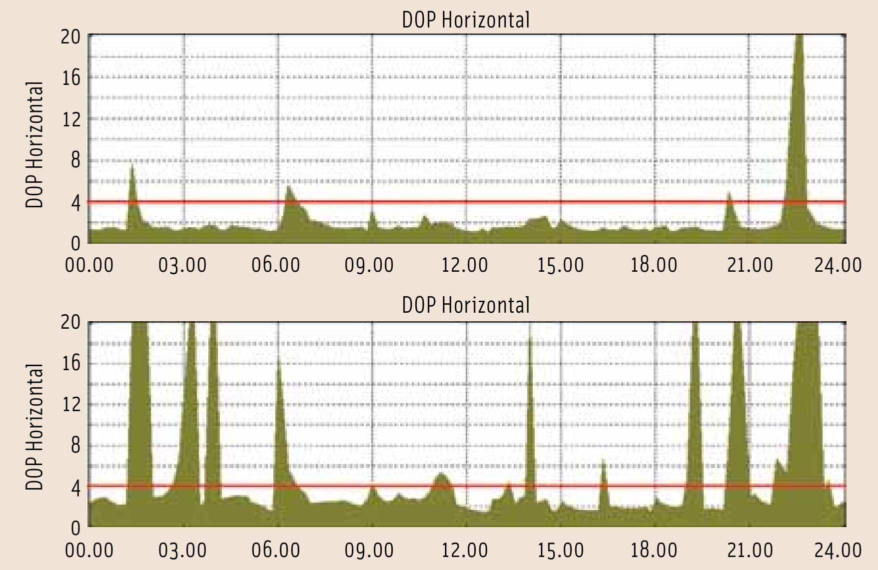


FIGURE 7 HDOP values in simulated Madrid test with a GPS-only receiver (bottom graph) and GPS+GLONASS plus SBAS (top graph)

Inter-Channel Biases in GLONASS Receivers

GLONASS signals undergo different propagation delays through the front-end hardware because GLONASS satellites transmit at different frequencies. This results in biased range measurements. These biases, known as inter-channel biases, are estimated based on knowledge of the hardware components used in the receiver. However, the biases cannot be completely calibrated in advance.

During normal operation, the factory calibration is refined as part of the navigation algorithm. In addition to measuring the inter-channel bias, the uncertainty in the bias is also estimated and is added to the overall expected measurement error.

This uncertainty is high initially before the receiver learns the residual biases and declines over time as the receiver continues operating.

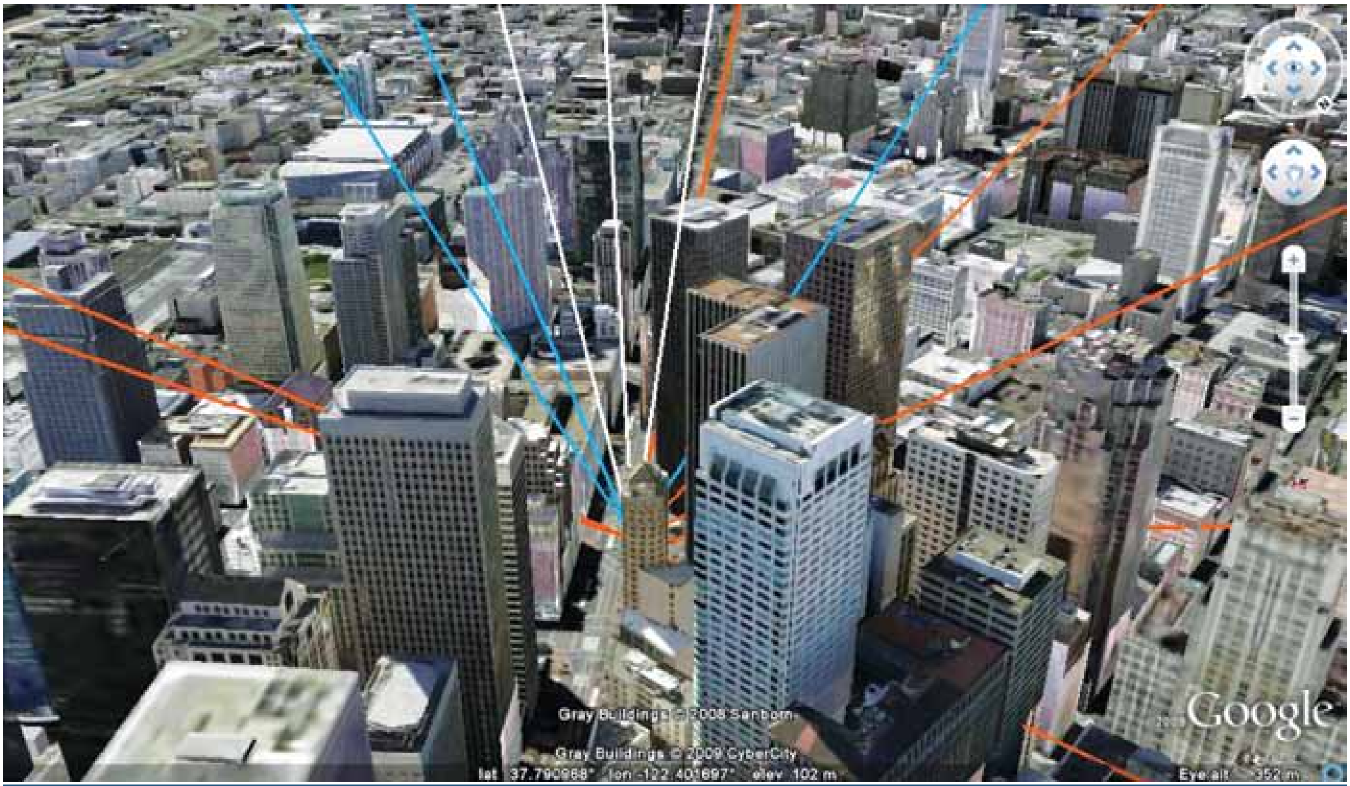


FIGURE 8 Satellite signals in San Francisco field trial: orange = blocked-but-reflected signals, white = LOS GLONASS, and blue = LOS GPS

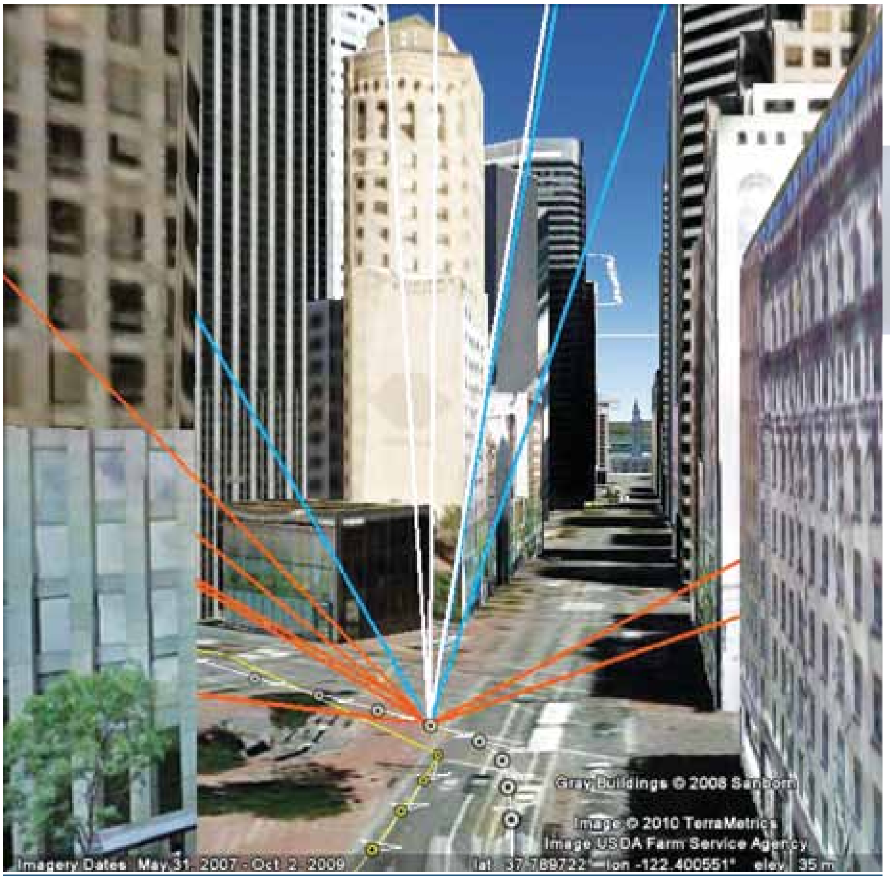


FIGURE 9 Satellite signals at street level in San Francisco field trial: orange = blocked-but-reflected signals, white = LOS GLONASS, and blue = LOS GPS

System Time Differences

GLONASS time differs from GPS in three major respects (from biggest to smallest):

1. The GLONASS version of Coordinated Universal Time (still using the former Soviet Union designation UTC SU) is maintained in the Moscow time zone, which is +3 hours from the UTC to which GPS is referenced.
2. GLONASS is bound to UTC SU time. Therefore, when leap seconds are introduced to UTC, GLONASS system time is simultaneously adjusted — unlike GPS time whose delta to UTC time continues to grow. This currently accounts for a 15-second offset between the two system times.
3. A sub-second system time difference, called Tau GPS (τGPS), also exists and is described in the latest GLONASS Interface Control Document 5.1. This is a small offset that changes relatively slowly and is presently around 370 nanoseconds.

When computing a single-system solution, these time differences do not apply. Only when a GNSS receiver computes a GPS (or QZSS or SBAS) +

FIGURE 10 Test drive in San Francisco financial district. Colored lines show vehicle tracks as recorded by the following: yellow, truth data collected by the GNSS/IMU system; blue, results from GNSS/SBAS/BT/FM receiver with GLONASS disabled; red, receiver results with GPS+GLONASS.

GLONASS solution must these differences be accounted for.

The first difference — the time zone offset — is simply known. The receiver can become aware of the second difference from one of the following sources:

- GPS UTC model from non-volatile memory or external assistance
- Compute the time of day from a GLONASS string and the time of week in a GPS subframe. This can take about 30 seconds and requires strong enough signals for bit decoding.
- Receive the GPS UTC model from the GPS broadcast (which can take up to 12.5 minutes)
- In an assisted-GPS system, receive this information from a network server.

The final sub-second system difference, Tau GPS, is broadcast in the GLONASS NAV message every 30 seconds. This value can also be stored in non-volatile memory.

Drive Tests Using GPS+GLONASS

We later performed another round of drive tests with an early release of the GNSS/SBAS/BT/FM product to quantify the benefit of GPS+GLONASS in a challenging urban canyon signal environment. A course was created through narrow streets of San Francisco, an area known for high multipath.

A truth system was used to simultaneously provide a best estimate of the actual path traveled by the test vehicle. The truth system consisted of commercial equipment that combines a dual-frequency GPS/GLONASS receiver with a tactical-grade inertial measurement unit (IMU).

The ground plots in **Figure 10** show three traces overlaid. Yellow is the truth data collected by the GNSS/IMU system. Blue is the drive test result of the GNSS/SBAS/BT/FM receiver with GLONASS disabled, and red shows the drive test results with GPS+ GLONASS. A quick examination of the plots is enough to show that the GPS+GLONASS system has fewer outliers and is generally much closer to the true path.

To help quantify the benefit, we collected statistics on the horizontal

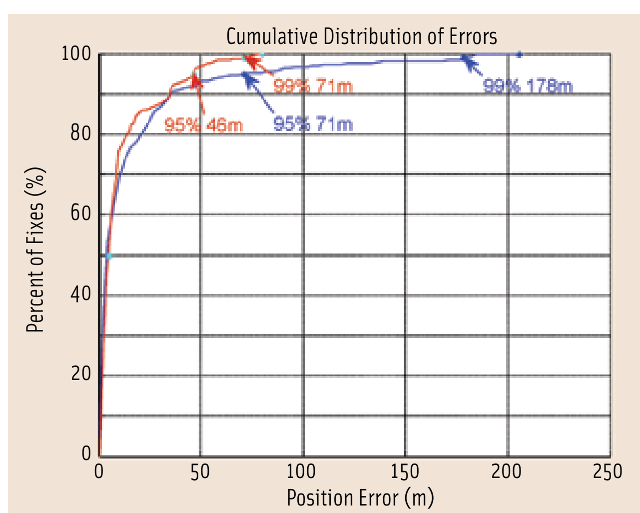


FIGURE 11 Comparison of GPS-only (blue line) and GPS+GLONASS (red line) cumulative distribution of errors in San Francisco driving test

position error of the GPS and GPS+GLONASS system. These results are best illustrated by a plot of the cumulative distribution of the errors as shown in **Figure 11**. In the plot, the same color scheme applies: blue shows GPS-only performance and red shows GPS+GLONASS performance.

Note the interesting convergence of the curves, which are almost identical at the 50-percentile level. This is easily explained by re-examining the ground plots. For both receivers, one sees in Figure 10 a high degree of accuracy for much of the time, especially in the long straight sections of roads in the less challenging portions of the drive test.

However, as we examine the 95-percentile statistics a clear difference emerges, with the accuracy of the GPS+GLONASS hybrid solution beating GPS-only by a margin of almost 2:1. In fact, the 99-percentile performance of the hybrid solution (with 71-meter accuracy) equals the performance of the GPS-only solution at the 95th percentile.

One way of looking at this is that the GPS-only solution will be wrong by a certain amount more than five times as often as the GPS+ GLONASS solution. In a navigation product, this might equate to five times more erroneous re-routes.

The most dramatic comparison occurs in the worst-case errors — in Figure 11, the furthest right point on each cumulative distribution function (CDF) line, red and blue. In this particular run, the worst-case GPS-only solution was 2.5 times worse than the hybrid case.

Worst-case results will change each test, but this one illustrates how dramatic the difference can be. We should also remember that the cumulative distribution function results are for a particular test drive and, of course, will vary substantially as the test route is changed to incorporate a different mix of tougher or more benign conditions.

An example of results from a more typical urban environment is presented in **Figures 12–14**, where we show the result of multi-constellation GNSS in a more moderate urban environment, San Jose, the capital of Silicon Valley. This environment is much more typical of most U.S. cities (from the point of view of satellite blockage), while San Francisco represents a dramatic worst case (matched only by Chicago and Manhattan).

As can be seen in Figures 12 -14 the performance of the GPS+SBAS+GLONASS receiver is almost perfect in this environment, even in the narrowest streets, such as the notorious Lightston Alley shown in detail in Figure 13. This untypically narrow American street is less than five meters wide and closely fronted by tall buildings.

Conclusion

The availability of multiple constellation GNSS receivers for consumer markets has long been anticipated. The years of waiting are now over with the introduction of the industry's first single-die multi-constellation GNSS IC. The component has already been integrated into a popular smart phone and will quickly find its way into an array of other phones, personal navigation devices, cameras, and GPS watches.

The theoretical advantages of multiple constellations are clear: a simple

FIGURE 12 GPS+SBAS+GLONASS performance in San Jose, California

FIGURE 13 Detail from Figure 12, Lighston Alley, less than five meters wide. As can clearly be seen, multi-GNSS accuracy is good to a few meters, even in this environment.

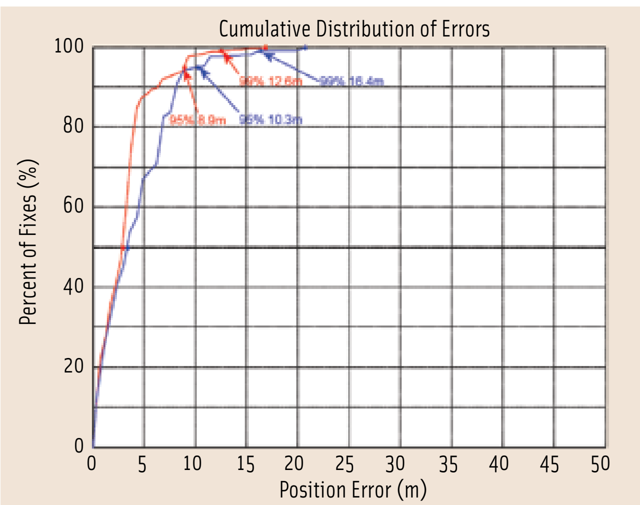


FIGURE 14 Comparison of GPS+SBAS (blue line) and GPS+SBAS+GLONASS (red line) CDF of errors in San Jose Urban environment

HDOP analysis shows that position accuracy improves with multiple constellations. It is pleasing to see that this theoretical advantage occurs in practice in the urban environments where GPS is most challenged.

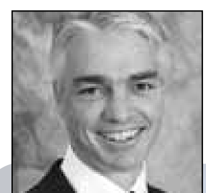
In an urban canyon with blockages everywhere, satellite visibility is a game of chance, and nearly doubling the number of available satellites greatly improves the odds of tracking enough satellites to keep a navigation filter running smoothly. In this article we have seen real-world examples of improved performance from multi-GNSS receivers in both modest and tough urban environments.

Broadcom Corporation receivers: left, BCM2076; right, BCM47511

Manufacturers

The GPS/GLONASS/SBAS/QZSS receivers used in the tests are the BCM2076 and BCM47511 from **Broadcom Corporation**, Irvine, California, USA. The combination IC that incorporates Bluetooth (BT) and FM functionality with a GPS/GLONASS/SBAS/QZSS receiver is the BCM2076 from Broadcom Corporation. The mission planning software used in the test simulations was NavPlan from **Trimble**, Sunnyvale, California, USA. The Earth imaging service was **Google Earth**, Mountain View, California, USA. The truth system used in the driving tests was the SPAN GNSS/INS system from **NovAtel, Inc.**, Calgary, Alberta, Canada.

Authors



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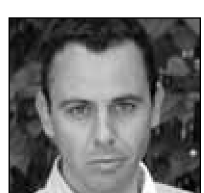

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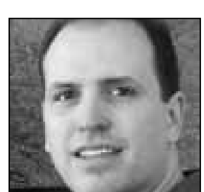

Randy Silva has been a principal software engineer and system architect in the GPS industry for 20 years. He presently works for Broadcom Corporation developing GNSS navigation software. He holds a computer science degree from the University of Colorado, in Boulder, Colorado, USA. IG