GNSS Solutions:

Carrier Phase Ambiguity Resolution, GNSS Use In Cellular Telephone Systems, and New Antennas?

"GNSS Solutions" is a regular column featuring questions and answers about technical aspects of GNSS. Readers are invited to send their questions to the columnists, **Professor Gérard Lachapelle** and **Dr. Mark Petovello**, Department of Geomatics Engineering, University of Calgary, who will find experts to answer them. Their e-mail addresses can be found with their biographies at the conclusion of the column.

Will I need a new antenna for the new GPS and Galileo signals? Will one antenna work for both systems?

To answer these questions, information will be presented on the GPS and Galileo signal formats, some antenna basic fundamentals with various user applications in mind, followed by some predicted performance assessment.

The well known "Basic GPS" signals are centered at L1 (1575.42 MHz) and L2 (1227.60 MHz), with the GPS Coarse/Acquisition (C/A) code, at a chipping rate of 1.023 Mcps (million chips per second) on L1. The Precise (P) code is transmitted with a chipping rate of 10.23 Mcps on L1 and L2; if encrypted, it is then called the P(Y) or Y-code when broadcast at the 10.23 Mcps rate. See Figure 1a for the GPS signal power spectral densities.

For these binary phase shift key (BPSK) modulated signals we often use the null-to-null bandwidth (twice the chipping rate) to characterize the signal bandwidth, which is 2.046 MHz and 20.046 MHz for the C/A and P(Y) codes that are transmitted in phase quadrature, respectively. Note that for many high performance applications we often require additional signal bandwidth to include the power in the sidebands of the signal spectrum. This is a very important factor in considering antenna bandwidth for a particular application.

In **Figure 1a**, the normalized GPS signal power spectral density (psd) functions are each plotted over a 40 MHz bandwidth, and the BPSK argument indicates the spreading code multiplication factor with respect to a nominal 1.023 Mcps rate. Each space vehicle (SV) typically transmits in a 30 MHz bandwidth about the L1 and L2 frequencies, and the radio navigation satellite service (RNSS) bandwidths are 24 MHz centered at the L1 and L2 frequencies.

With the launch of the first GPS Block IIR-M ("R" for replenishment and "M" for modernized) SV on September 21, 2005, a new L2C ("C" for civil) signal format is available. The L2C signal, composed of two codes, employs BPSK modulation and has a net chipping rate of 1.023 Mcps. Additionally, a modernized military (M-code) signal is available, which uses binary offset carrier (BOC) modulation to produce a split spectrum signal about the carrier. Here a BOC(10,5) is used where the first argument indicates the sub-carrier frequency factor, and the second argument indicates the spreading code rate factor, with respect to a nominal chipping rate of 1.023 MHz. The M-code is centered at the L1 and L2 frequencies.

The GPS Block IIF ("F" for follow-on) SV, scheduled for its first launch in 2007, will add a new civil signal format (L5) at a center frequency of 1176.45 MHz, BPSK-modulated with a signal chipping rate of 10.23 Mcps. Provisional plans call for Block IIIA SVs to add a new L1C signal, still in refinement, which is projected for its first launch in 2013. The GPS Joint Program Office plans to launch new GPS SVs to sustain the GPS constellation. Thus, several years will pass after the first SV of a given type before the GPS constellation will be populated with these new capabilities. Approximately three new SVs are planned for launch each year.

Although information on the new Galileo signals has yet to be published in a complete, formal interface specification, a wide variety of services, signals,

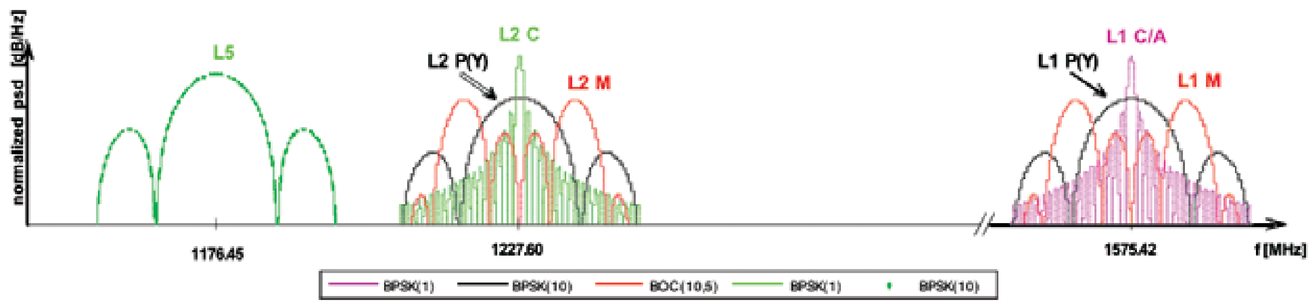


FIGURE 1A. Normalized GPS Power Spectral Densities

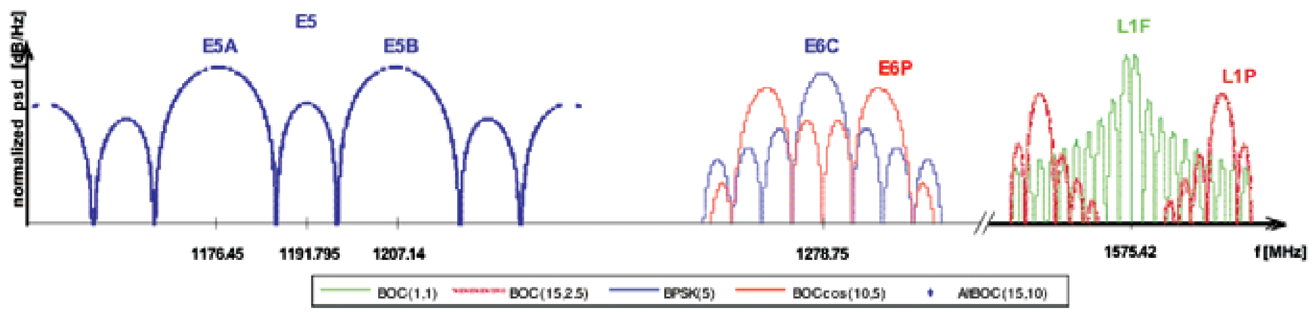


FIGURE 1B. Normalized Galileo Power Spectral Densities

and formats are planned. **Figure 1b** illustrates the normalized Galileo signal psd functions. In the L1 frequency band, the L1F signal with a familiar chipping rate of 1.023 Mcps using a BOC(1,1) modulation, and an L1P, Public Regulated Service (PRS) signal with a BOCcos(15,2.5) modulation are planned. While the stated band of operation of these two signals is 40x1.023 MHz, the L1P PRS signal format and the BOC(15,2.5) modulation dominate.

Within the Galileo E5 band (centered at 1191.795 MHz) is the E5a signal (centered at the GPS L5 frequency of 1176.45 MHz) and the E5b signal (centered at 1207.14 MHz), which is a combined AltBOC(15,10) modulated signal, that will occupy a planned 90x1.023 MHz bandwidth. (The E5a and E5b signals each appear as BPSK modulated signals.) Additionally, the E6 band will be centered at 1278.75 MHz and have an E6C BPSK modulated signal along with an E6P BOCcos(10,5) modulated signal, both with chipping rates of 5.115 Mcps. These two signals will occupy a stated 40x1.023 MHz bandwidth. (The Galileo L1 and E6 spectrums are plotted over a 40 MHz bandwidth in Figure 1b, where the E5 signals are plotted over a 90 MHz band.)

When we say an antenna "works," we really mean that it provides a level of performance for the particular applications at hand. An antenna that works for one application may not be well suited for another application. The performance of an antenna can be characterised in terms of antenna performance or system performance.

If we look closely at antenna performance, the antenna's radiation pattern (magnitude and phase) serves as a good indicator. Antenna radiation patterns are typically characterized at a center frequency, for a particular polarization, and in the far-field of the antenna. Additionally, radiation patterns off the system center frequency, bandwidth, coverage (i.e., beamwidth), polarization (i.e., axial ratio), group delays, phase center offsets, voltage standing wave ratio (VSWR), input impedances, size, and cost parameters also provide some useful metrics, but are not complete indications of antenna performance for a particular application.

In terms of system performance, some manufacturers may not perform a thorough test and evaluation on the antenna alone, but simply design, build, and test the performance of the antenna in conjunction with a particular receiver in its planned operational environment. This type of system level performance evaluation may produce very satisfactory results for particular applications. Other more thorough system level antenna performance evaluations can be performed by, for example, examining the receiver carrier-to-noise ratio (C/N), code minus carrier, or the code and carrier phase residuals after removing all other error sources.

When we say an antenna "works," we really mean that it provides a level of performance for the particular applications at hand.

Additional factors to consider are that most antennas used in GNSS applications typically have many components including the radiating element itself, low-noise amplifier, bandpass filters, power combiners, bias-T, and supporting components. The complex frequency response of each of these items, in combination with each other and the receiver system, can produce varying levels of performance over frequency and bandwidths to support signals of interest.

Without specifying the exact antenna, application, and GNSS signals planned for use, it is hard to say definitively whether an existing GPS antenna can be used with the new GPS and Galileo signals, but guidance is in order. Generally, if one of the new GNSS signals is commensurate with the existing signal center frequency and bandwidth, the existing antenna should have no problem supporting the new signal, provided the applications (i.e., performance requirements) are similar.

If, however, the bandwidth of the new signal is greater than the existing signal, the performance of the antenna could possibly deteriorate in some fashion. This reduction in performance will likely increase as the center frequency offset and bandwidth increase and could be in terms of the radiation pattern, gain, axial ratio, and so forth. Consider the following examples.

1. For an existing civil L1-only GPS antenna, this antenna will probably work, with possibly some small performance degradations, for the Galileo L1F signal, even though the Galileo L1F signal is a little bit wider. This will most often be the case for low-cost civil L1–only antennas, even those that implement a narrowband bandpass filter, as they usually have a very slow rolloff in frequency rejection. Remember, we probably would not want to use a low-cost civil GPS L1–only antenna for high-performance Galileo L1F applications because it may not have the necessary bandwidth to support high-performance applications. (An analogous argument could be made for a similarly formatted L1C signal, which is still in refinement.)

2 For an existing civil dual-frequency GPS L1 and L2 antenna, the L2C signals should be received without problems, since the bandwidth of the antenna at L2 would have to be sufficient to effectively perform semi-codeless tracking of the existing L2 P signal.

3. As for the L5/E5 frequency, depending upon the type of radiating element and components within the antenna, an L1 only, or an L1/L2 antenna, will probably not work effectively for these signals, due to center frequency and bandwidth considerations. Additionally, largely because of the center frequency, it is again very unlikely that an existing GPS antenna will work effectively for the E6 signals.

If you have an existing antenna, and want to investigate its performance for the new signal formats, use caution in this assessment. Do not be fooled, for example, by only taking a VSWR measurement on a network analyzer, as an antenna may have a very good VSWR, but have poor gain and pattern performance. Remember, a 50-ohm load has a great VSWR but is not a good antenna. Additionally, good C/Ns may produce non-negligible group and phase delays.

A quick test performed at the Ohio University Antenna Anechoic Chamber on several popular dual-frequency (L1 and L2) GPS survey and aviation style patch antennas indicated the following: relatively good VSWR performance at L1, L2, and L5; good pattern and gain characteristics at L1 and L2; but poor L5 pattern and gain characteristics. Short of making measurements yourself, watch for manufacturers to begin including signal formats supported for the antennas they sell.

This brings us to the part of the posed question, "Can it all be done in one antenna?" The answer will be driven by the performance requirements on the antenna such as size, coverage, bandwidth, cost, and so on. The more stringent the performance requirement, generally the larger and/or more expensive the antenna will be. There will be a strong need to keep all of the GNSS signals being received via a common antenna in a blended GNSS solution to minimize corrections (i.e., group and phase).

Most manufacturers will likely modify their existing antenna designs to optimally support the new signal formats for particular applications. High-performance, combined GPS and Galileo antennas that cover the full L1, L2, L5, E5, and E6 bands will be challenging due to their multi-band nature and the need to optimize the performance with respect to the parameters listed earlier. For example, to design an antenna to cover the 1.1 to 1.6 GHz band is relatively easy, but doing this with the added requirements that we have for high-performance GNSS applications will be the challenging part. So, the good news is that we will have new GNSS signal formats to support a wide variety of applications; however, procurement of new receivers and antennas to support these signals will probably be appropriate for most users, keeping in mind the particular application at hand.

CHRIS BARTONE, P.E.

Dr. Chris Bartone, P.E., is an associate professor at Ohio University. His research and development concentrates on all aspects of navigation. bartone@ohio.edu

Editor's Note

For more information on the various signals discussed in this contribution, please refer to the following documents.

GPS Signals

Navstar GPS Program Office, Interface Specification, IS-GPS-200D

Galileo Signals

Hollreiser, M., Galileo Status, Civil Global Positioning System Service Interface Committee (CGSIC), Long Beach, CA,13 September 2005.

BOC Signals

Betz, J., "Binary Offset Carrier Modulation for Radionavigation," *Navigation: Journal of The Institute of Navigation*, Vol. 48, No. 4, Winter 2001–2002

Rebeyrol, E., "BOC Power Spectrum Densities," ION National Technical Meeting 2005, January 24-26, 2005

How will the new frequencies in GPS and Galileo affect carrier phase ambiguity resolution?

In the years to come, GNSS users will benefit from the availability of more satellites and signals with the coming of Galileo and the modernization of GPS. Galileo will consist of a brand new constellation of 30 satellites transmitting their signals on four frequencies. Four different navigation services will be offered, meaning that some of the signals and information is available for free to every user, but other services are either to be paid for or are only available to certain authorities.

The first milestone for GPS modernization is the availability of the L2C code for civil users. In the next phase, the L5 signal will also be available. An overview of the future frequencies and services is given in **Table 1**.

GNSS positioning will thus be possible with improved precision, reliability, availability and integrity. Still, for rapid and high precision positioning, carrier phase ambiguity resolution remains indispensable. Only with the ambiguities fixed to their correct integer values do the carrier phase observations start to act as very precise pseudorange observations. This implies that the probability of correct integer estimation, generally referred to as the *success rate*, should be very close to unity.

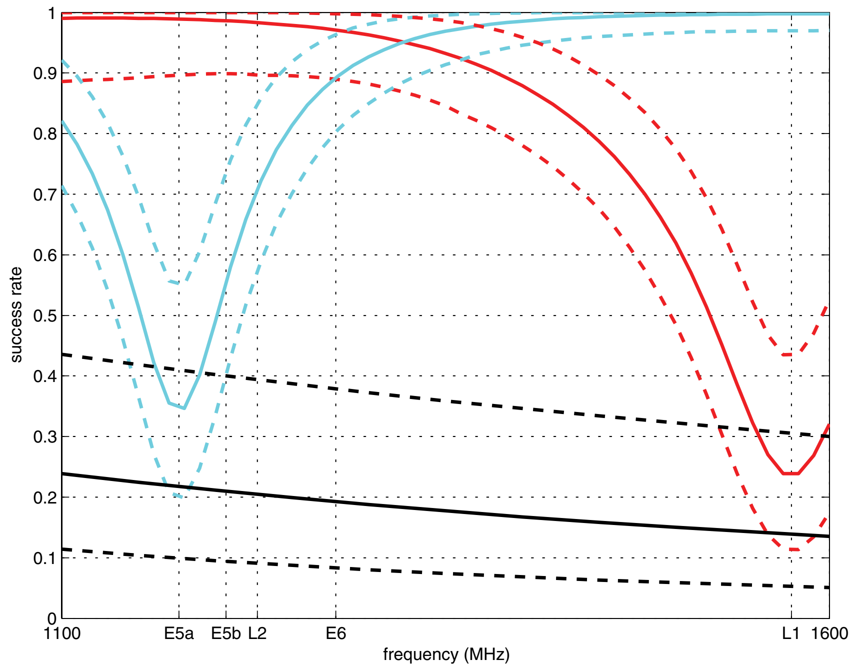


FIGURE 1. Mean, minimum, and maximum success rates during the day with Galileo. Black represents single-frequency; red, dual-frequency with one frequency fixed to L1; Blue: dual-frequency with one frequency fixed to E5a.

In order to answer the question how ambiguity resolution will be affected by the new frequencies, two possible effects have to be considered. Firstly, there is the effect on the ambiguity resolution algorithms. In the past, many integer ambiguity resolution algorithms have been proposed. Most of the algorithms currently in use are based on the optimal integer least-squares estimator. In principle these algorithms, such as the LAMBDA method, need not be changed with the advent of Galileo. Some, however, use linear combinations of the carrier phase observations in order to set the size of the ambiguity search space and/or to get an initial estimate of the integer ambiguities.

However, looking at the effect of the new frequencies on the reliability of ambiguity resolution is more interesting. The effect depends, of course, on the number of frequencies used, as well as on the specific choice of frequencies.

A small study has been made by the author in which computations of the success rates for instantaneous ambiguity resolution for a whole day were made based on the GPS Yuma almanac of GPS week 328 with 28 healthy satellites together with the full nominal Galileo constellation of 30 satellites. The study looks at three GPS signal bands (L1, L2, and L5) and thee Galileo frequencies (L1, E5a, and E6) and assumes that the code and carrier noise on all frequencies will be the same.

Three different locations are considered: one at the equator, one at 52°N, and one at 70°N. It is assumed that

Frequency		GPS	Galileo			
Band	[MHz]		Open	Commercial	Public Regulated	Safety of Life
L1	1575.42					
L2	1227.60					
L5 / E5a	1176.45					
E5b	1207.14					
E6	1278.75					

TABLE 1. Overview of future GPS and Galileo frequencies and services.

tropospheric delays are accounted for; however, in order to handle propagation effects in the ionosphere, an ionosphere-weighted model is used. The baseline length was set to approximately 30 kilometers.

Figure 1 shows the effect of the frequency choice on the success rates obtained with Galileo at the most northern location. The mean, minimum, and maximum success rates during the day are shown for the single-frequency case in black, the dual-frequency case with one frequency fixed to L1 in red, and a dual-frequency case with one frequency fixed to E5a in blue.

With only one frequency the best approach is obviously to choose a low frequency so as to maximize the wavelength since this yields the highest success rate. However, the effect of the longer wavelength also implies a larger ionospheric effect. So, for longer baselines a higher frequency may prove better, whereas for shorter baselines use a low frequency will be even more beneficial. With two frequencies it is important to choose the frequencies far apart if possible. Note the difference in the results when one of the frequencies is either fixed to L1 or to E5a.

Of course, users will not be entirely free in choosing the frequencies. Figure 1 is meant to show the effect of the frequency choice. **Figure 2** shows the results for GPS and Galileo with realistic frequency choices. The bars show the range of values that the success rates take during the day; the dots show the mean values.

If we compare the results of the three GPS frequency combinations, it follows that the L1+L5 combination is somewhat better than the L1+L2 combination, because the mean and maximum values are somewhat higher. On the other hand, the minimum values can be much lower. Using three-frequency GPS gives better results, as expected, although the improvement is marginal if we take into account that we want the success rate to be very close to 1.

Comparing GPS L1+L5 with Galileo L1+E5a shows the effect of the different configurations (number of orbital planes and inclination angles) of the two constellations on the success rate. For all locations Galileo provides higher success rates, but the difference is especially large at the equator. Using Galileo L1+E6 instead of L1+E5a gives somewhat lower success rates, and using all three Galileo frequencies gives only marginal improvements.

Combined GPS-Galileo has also been considered, but the results are not shown because success rates above 0.999 are obtained all the time, which is a tremendous improvement when compared to the individual systems.

In conclusion, we can say that the availability of new signals/frequencies will improve the reliability of ambiguity resolution, although the improvements may be marginal if only one of the GNSSes is used. In that case, a larger improvement can be expected from the availability of more satellites, improved troposphere and ionosphere models, less observation noise, and improved multipath characteristics and mitigation.

SANDRA VERHAGEN

Sandra Verhagen is a postdoctoral researcher at the Delft University of Technology, where she obtained her M.Sc. and Ph.D. in geodesy. Her research interests are GNSS ambiguity resolution and quality control.

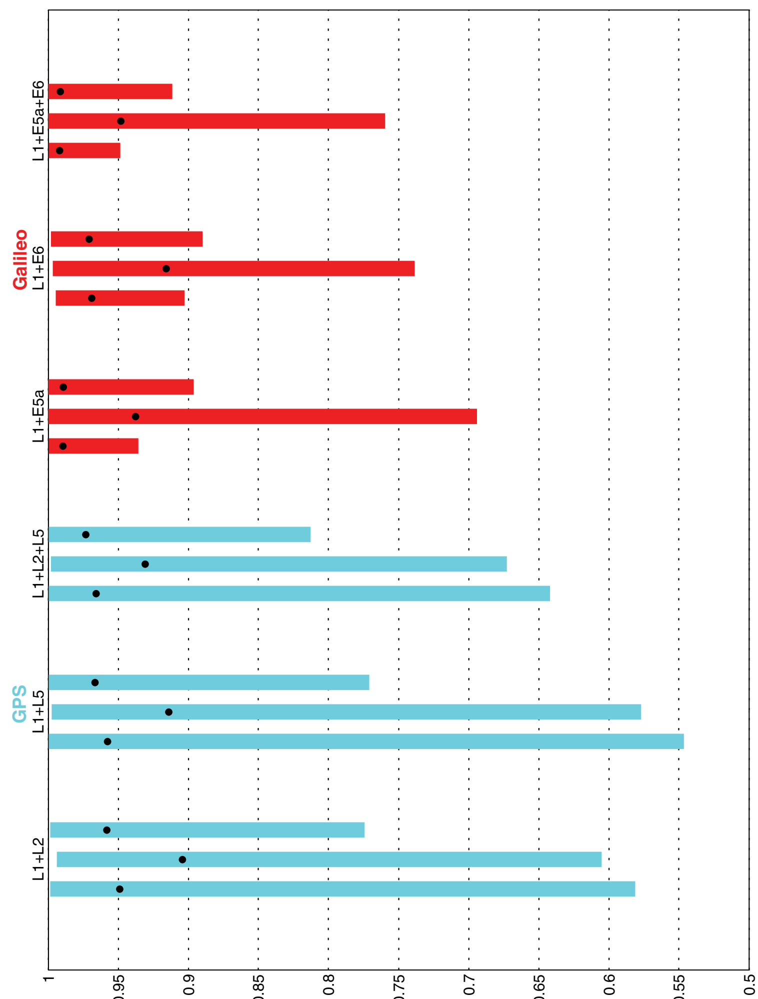


FIGURE 2. Mean (dots), minimum (bottom of bars) and maximum (top of bars) success rates during the day with GPS and Galileo at three locations: at the equator (left), 52°N (middle), at 70 °N (right).

"Aside from E-911 and E-112, how is GNSS used in cellular telephone systems?"

While mobile positioning for E-911 and E-112 emergency services are becoming more pervasive, other important applications of GNSS exist that are less obvious. These fall into two main categories: namely, those associated with direct mobile user applications based on the mobile's location and those associated with enhancing the performance of the overall cellular network.

A plethora of user applications based on mobile location are rapidly emerging including street map and direction finding, fleet position data logging and targeted advertising. No dominant "killer application" has emerged at this stage, but the steady accumulation of these minor location-sensitive services is rapidly making GNSS an indispensable component of cellular functionality and markets.

The other main application category of GNSS in cellular telephony is associated with the enhancement of the overall performance of the wireless network infrastructure from the perspective of network capacity and quality of service. First-generation cellular wireless systems were based on time division or frequency division multiplexing.

Time synchronization of each cellular base station (BS) was provided by clocking signals available via the backhaul link connecting the BS to the overall network. This was sufficient as mobile handoff coordination between neighborhood BSs was crude and simple. Also, as the BSs used different carrier frequencies that inherently resulted in independent channels, time synchronization between BSs was not necessary.

In the mid-1990s a second-generation cellular technology appeared in North America based on code division multiple access (CDMA) technology, which was standardized as IS95. The superior performance and robustness of IS95 came at the cost of having to tightly synchronize the timing and the common downlink carrier frequency used by the networked BSs. As the timing accuracy and frequency stability requirements exceeded the capability of the backhaul link, the only viable solution was to provide synchronization signals at each BS by means of collocated dedicated GPS receivers.

IS95 BSs broadcast a continuous pilot that provides the necessary signal for the mobile receiver for timing and carrier frequency synchronization. This pilot signal is a quadrature phase skip keying signal that is modulated by two orthogonal direct-sequence (DS) signals with a chip rate of 1.2288×10^6 chips per second and a period of 26.67 milliseconds. The start of every 75th pilot period is exactly aligned with the even-second signal provided by a GPS receiver collocated with the BS that in turn is accurately aligned with GPS time.

Typically, after calibration of the base station, the timing accuracy of the broadcast pilot signal emanating from the transmitter antenna phase center is better than 50 nanoseconds. Furthermore, there are severe specifications for timing errors of the pilot signal drift should the even-second GPS referenced signal become unavailable: usually a 12- or 24-hour holdover time during which the pilot signal code-phase error must be limited to within several microseconds. Finally, the frequency error of the BS carrier frequency is tightly specified to within 50 ppb, which is readily achieved by phase locking to the GPS even second signal. Hence, in summary, the only relevant requirement of the BS GPS receiver is an accurate even-second signal.

The tight synchronization allows different BSs and different sectors within the same BS to use the same pilot signal but with different code offsets. In IS95, the minimum code offsets used is 64 chips. Therefore, the mobile phone can search and track various pilot signals and identify the different base stations based on code offset of a common pilot signal, which greatly simplifies the required receiver processing.

Over the past decade, GNSS systems have matured, demonstrated impeccable reliability and are, notwithstanding possible global conflicts, significantly influenced by the civilian community.

Accurate synchronization also facilitates the handoff process in IS95. Notwithstanding small differences in propagation delay, the signals obtained at the mobile from multiple BSs are synchronously combined, enabling efficient handoff. As well, since the same signal is received simultaneously from the set of BSs involved in the handoff, an associated diversity gain can provide significant performance enhancement. This handoff coordination is possible but more difficult with non-synchronized BSs. As other researchers have pointed out, significant parameter exchanges are required between the BSs for each handoff. Also, pilot acquisition by the mobile requires significantly more processing in a nonsynchronized network.

Third- and fourth-generation cellular wireless have built on the successes and refinements of IS95 from which IS2000 and UMTS standards emerged and are currently being implemented. IS2000 and variants have the same synchronous architecture and pilot structure as IS95, relying on GNSS receivers available at each base station for accurate code phase timing.

The Universal Mobile Telecommunications System or UMTS, which originated in Europe, was originally designed to be an unsynchronized network. This stemmed primarily from a reluctance of wireless service providers to rely on American or Russian GNSSes for synchronization and because the timing accuracy of existing backhaul links were inadequate. Pilots based on orthogonal maximum length code sequences were used for BS and sector identification instead of unique code phases of a common DS signal as in IS95.

However, over the past decade, GNSS systems have matured, demonstrated impeccable reliability and are, notwithstanding possible global conflicts, significantly influenced by the civilian community. As a result, the opposition towards reliance of GNSS in UMTS networks has subsided and current implementations of UMTS networks are now synchronous.

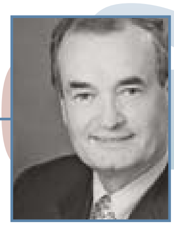
An interesting question currently being researched is whether knowing the location of all the active mobiles in a cellular network can be used to further optimize handover and BS radio resource management. As an example, knowing that a mobile is moving towards a cell boundary, an optimized smooth handover strategy can be devised based on a current set of operating conditions and cellular traffic that minimizes the overall radio resource requirements. This could be coupled with the use of smart antennas and dynamic pilot power control that adjusts the network coverage based on current traffic conditions. GNSS clearly plays an essential role in such refinements.

In summary, the initial impetus for applying GNSS in cellular telephony systems was network synchronization. As the BSs were synchronized, network based mobile location became a natural extension which led to the E-911 mandate and a multitude of location-based services as well as the European E-112. The accumulation of these requirements has fully entrenched GNSS as an essential component of mobile wireless. IG

JOHN NIELSEN

Dr. John Nielsen is an associate professor with the Department of Electrical and Computer Engineering of the University of Calgary conducting research into ultrawideband communications and radio location. Prior to this he was with Nortel and Research In Motion designing CDMA infrastructure and handsets for 12 years.

Mark Petovello is a Senior Research Engineer in the Department of Geomatics Engineering at the University of Calgary. He has been actively involved in many aspects of positioning and navigation since 1997 including GNSS algorithm development, inertial navigation, sensor integration, and software development.
Email: mpetovello@geomatics.ucalgary.ca



Professor Gérard Lachapelle holds a CRC/iCORE Chair in Wireless Location in the Department of Geomatics Engineering at the University of Calgary. He has been involved with GNSS since 1980 and has received numerous awards for his contributions in the area of differential kinematic GPS and indoor location.
Email: lachapel@geomatics.ucalgary.ca