Galileo open service and weak signal acquisition

# GNSS Solutions:

## Galileo Open Service and weak signal acquisition

"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.

## How will the Open Service Galileo signal in space change the acquisition process in GNSS receivers?

The Galileo signal in space (SiS) for the Open Service (OS) essentially differs from the GPS C/A-code by its use of the binary offset carrier (BOC) modulation and the adoption of longer spreading codes. Moreover, two different channels have been allocated for the OS: the data and the pilot channels. The former carries the navigation message whereas the latter is data-free.

The pilot channel is characterized by a secondary code that modulates the primary spreading sequence, producing a tiered code with a period of 100 milliseconds. The bit-rate of the data channel is 250 sps (symbols per second) against the 50 sps of the GPS C/A-code. A GNSS receiver can perform acquisition of the pilot and data channels separately, and the results of the two processes can be non-coherently combined in order to exploit the fact that the two signals experience the same code delay and Doppler frequency.

The first stage of a GNSS receiver consists of an acquisition block, which provides a rough estimation of the code delay and of the Doppler frequency of the received GNSS signals. These two quantities are obtained by correlating the received signal with several locally generated signal replicas, characterized by a specific code delay and Doppler frequency. Due to the spreading codes' properties, the correlation between the received and the locally generated signals assumes a significant value only if the delay and the Doppler frequency of the local replica match those of the received signal.

The acquisition process searches for all possible delays and Doppler frequencies until the correlation passes a threshold. When that happens, the GNSS signal is considered to have been acquired, and the delay and Doppler frequency of the local replica are the estimates of the corresponding parameters of the received GNSS signal.

Acquisition performances are essentially measured by the searching time and the acquisition sensitivity. The former is the mean time needed to detect the GNSS signal and to estimate its parameters; the latter is directly related to the $C/N_0$ (carrier-to-noise density ratio) of the weakest signal the receiver can acquire.

Various factors can impair signal acquisition. These may be related either to the GNSS signal structure, such as the presence of bit transitions in the navigation message, or to external causes such as interference, signal fading, and shadowing.

The use of the BOC modulation shapes the correlation of the Galileo OS signals slightly differently than that for GPS. **Figure 1** compares the main peak of the BOC(1,1) correlation with that of the BPSK(1) (binary phase shift keyed) modulation employed by the GPS C/A-code. The BOC(1,1) produces a narrower peak than the BPSK(1) and has two side lobes. A narrow peak requires a smaller step for the acquisition search grid along the delay dimension.

In the GPS case, a delay step of half a chip guarantees a maximum misalignment between the received signal and the local code replica of a quarter of chip, producing a maximum loss of about 2.5 dB with respect to correlation maximum. In the BOC(1,1) case, similar performances in terms of peak loss are assured by a misalignment of a quarter of chip. Thus, a smaller step along the delay dimension is required, increasing the computational load of the acquisition process.

One period of the Galileo OS code is 4,092 chips, corresponding to 4 milliseconds. This implies that, by using a code search step of a quarter of chip, 4,092 × 4 = 16,368 delays must be tested. Furthermore the frequency step for the Doppler search generally has to be set such that the following rule of thumb is respected

$$\Delta f \leq \frac{2}{3T_c}$$

where $T_c$ is the accumulation interval (or predetection integration interval) that corresponds to the duration of the signal portion employed by the "Accumulate and Dump" (A&D) blocks for the evaluation of the signal correlation.

Since the minimum $T_c$ corresponds to one code period — that is, 4 milliseconds — the maximum Doppler step is equal to 166.7 Hz, against the 666.7 Hz of the GPS C/A-code. Thus, for fast and low-complexity applications, the GNSS receiver designers have to adopt special acquisition techniques — for example, one based on *partial correlation* that exploit only a portion of the spreading code for acquiring the Galileo signal.

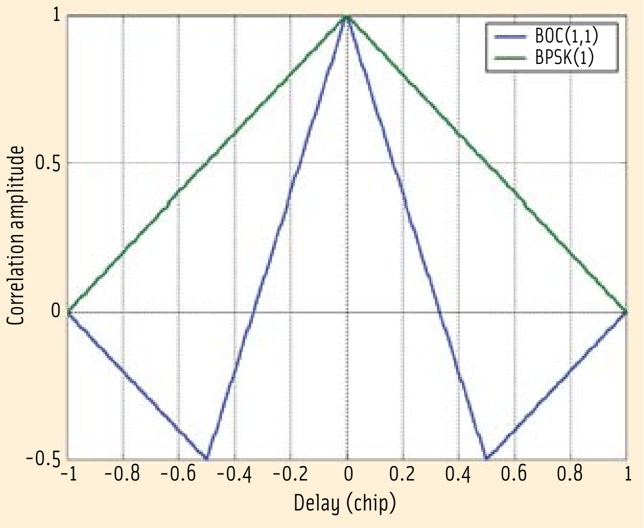



FIGURE 1 Correlation peak of the BOC(1,1) and of the BPSK(1) modulations.

The presence of the secondary code on the pilot channel and the higher bit-rate of the data channel with respect to the GPS case means a bit transition could potentially happen every 4 mil-

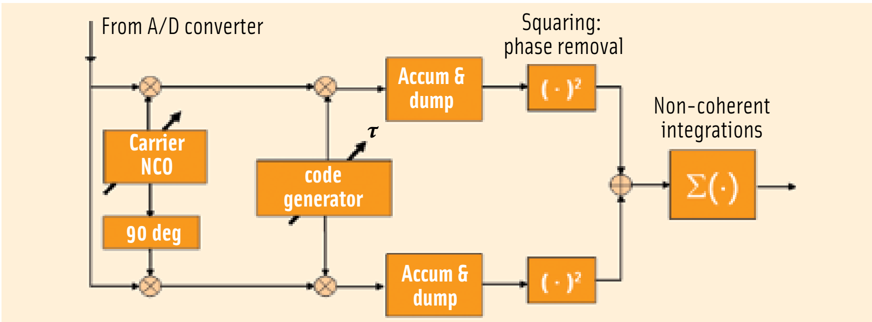



FIGURE 2 Serial-search receiver architecture with non-coherent integrations

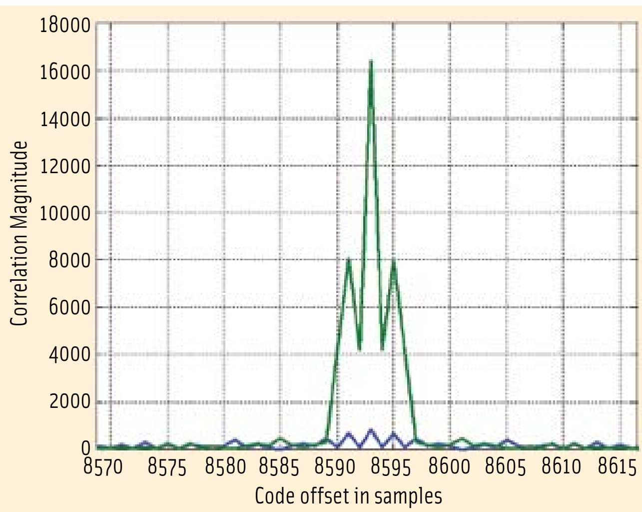



FIGURE 3 Linear (green) vs. circular (blue) correlation in presence of bit transition

liseconds; in the GPS case a bit transition could occur each 20 milliseconds. Bit transitions limit the predetection integration interval $T_c$ because a bit transition during the predetection accumulation process changes the sign of the received samples, leading to a power cancellation.

Thus, for precise or weak signal applications, the GNSS receiver (without exploiting the secondary code or somehow removing the navigation data bits) has to employ other accumulation techniques such as *non-coherent* integrations. Non-coherent integrations are immune to sign reversal, but the gain in sensitivity is lower than the one achieved by increasing the predetection interval.

**Figure 2** illustrates a serial-search receiver architecture employing non-coherent integrations: after the A&D blocks the in-phase (I) and quadrature (Q) components are squared and further accumulated.

We should note that the presence of bit transitions potentially occurring each code period requires the use of an input data set lasting twice the code period. Doing so guarantees that at least one code period, multiplied by the same bit, is present in the recovered data set.

For each code delay search a different set of samples of the received signal, selected by a delayed moving window, is correlated with the local code. Thus, when the received and local signals are aligned, the bit transition is at the boundary of the received data set with no effect on the correlation main peak.

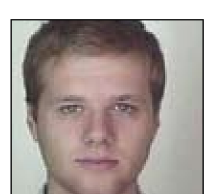
If we employ the parallel code search acquisition architecture, discussed in the “GNSS Solutions” column in the March/April 2007 issue of *Inside GNSS*, some precautions have to be taken as well. In fact, the correlation between the received and local signals evaluated by using the FFT/IFFT based techniques is a circular convolution. This means that each correlation sample is the correlation between a circularly shifted version of the input signal and of the code replica. Thus, if a bit transition occurs, it affects all the correlation samples, causing a power cancellation for each delay tested during the searching process.

To solve the problem, the correlation is evaluated between a two-code period long portion of the received signal (i.e., 8 milliseconds for Galileo OS) and a local signal obtained by concatenating the local code replica with a one code period–long sequence of zeros. **Figure 3** highlights the effect of the bit transition on the parallel code search architecture. In the figure, the circular correlation of a one period–long data set and the linear correlation of the same input signal have been evaluated: the bit transition reduces the useful signal correlation peak when the circular correlation is employed.

Another issue in the acquisition of the Galileo OS signal is represented by the presence of secondary lobes in the BOC(1,1) correlation function. These side lobes can cause false alarm events, that is, the receiver incorrectly assumes the secondary lobe is the main correlation peak. This introduces a bias in the delay estimation and appropriate countermeasures have to be adopted, for example, use of verification strategies that check if the correlation sample under test is really the correlation maximum.

The new Galileo OS signals present new challenges and require increased computational power with respect to the GPS counterpart. However, the use of the BOC guarantees higher immunity against multipath fading, and the presence of long tiered codes makes the Galileo OS signals suitable for indoor and precise positioning applications.

**DANIELE BORIO AND LETIZIA LO PRESTI**



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# What are the main factors affecting the acquisition of weak GNSS signals? What can be done to alleviate them?

The acquisition of weak GNSS signals is not a trivial task. Many effects that can be safely ignored when acquiring strong signals become significant as receiver sensitivity increases.

In brief, acquisition is a two-dimensional search process. The receiver knows that, if a given satellite signal is being received, then the code phase and Doppler frequency of that signal must be within certain known ranges.

These two ranges of values define a two-dimensional uncertainty region, as illustrated in **Figure 1**. This uncertainty region is divided into a finite number of search cells, each of which represents a single code phase and Doppler frequency estimate pair.

During acquisition the receiver observes the received signal for a certain period of time in each cell, say $T_{Obs}$, subsequently making a decision as to whether or not a signal from a particular satellite is present in a given cell. The sensitivity of the receiver is critically dependent on $T_{Obs}$ as a longer observation time permits the detection of weaker signals.

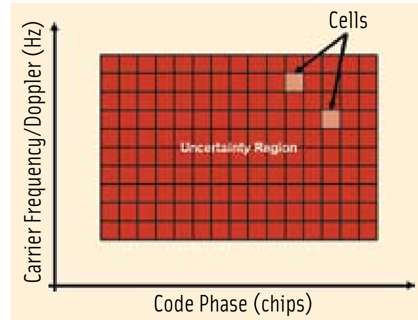


FIGURE 1 Two dimensional uncertainty region divided into search cells for acquisition

This requirement to observe the signal for longer periods is the cause of most of the difficulty with weak signal acquisition, as we will discuss in the next section.

**A longer observation time means an increased computational cost and a longer time to acquire.** Traditional serial search acquisition considers each cell in the

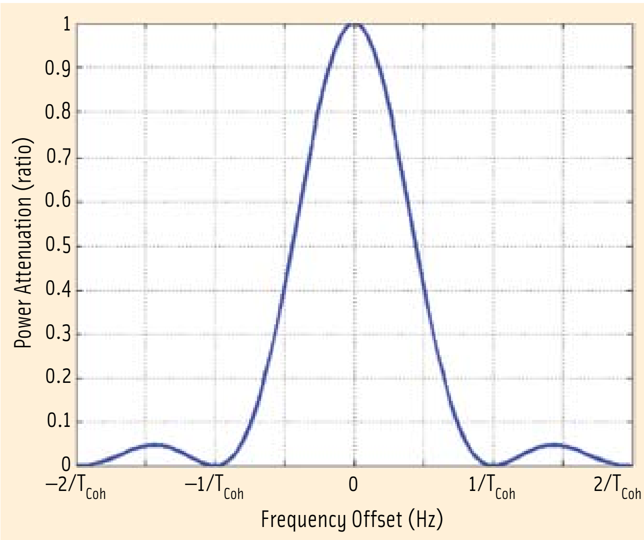


FIGURE 2 **Power attenuation versus frequency offset normalized by the coherent integration time**

search space consecutively. A longer dwell in a given cell requires more computations and also increases the overall time to acquire the signal.

To overcome this factor, receiver designs can employ parallel acquisition techniques. This entails calculating the decision statistics for multiple cells all at once. Although this does not alleviate the computational burden, it does help to reduce the mean time to first fix.

The computational cost can be reduced somewhat by taking advantage of the inherent redundancy in the computation of many regularly spaced samples in the code phase and carrier Doppler domains.

One highly efficient technique is to use the Discrete Fourier Transform (DFT) to implement correlation in the frequency domain. A number of techniques exist for implementing frequency domain correlation, the most common of which is circular correlation, which has recently been discussed in this column (Michael Braasch – March/April 2007).

An alternate approach, linear correlation by DFT, has also been receiving attention lately particularly in the form of the Double Block Zero Padding (DBZP) technique. Linear correlation is particularly applicable for longer spreading codes such as the GPS L2C codes where the number of samples per code period is too large to implement circular correlation over one full code epoch. It has also been applied to the GPS C/A code to reduce sensitivity to data modulation, which is discussed below.

An alternative approach to alleviate this computational load is to provide the receiver with some form of aiding through a communications back-channel. This aiding can take the form of almanac or ephemeris information, or accurate time and frequency reference information.

All of these approaches result in the reduction of the size of the search space, thereby saving computations. Currently the major mobile telephony standards (GSM, UMTS, CDMA200, etc.) all provide protocols for the provision of such information through the mobile network.

**A long coherent integration time increases sensitivity to frequency offset effects.** The “shape” of the de-spread GNSS signal in the frequency domain is very closely approximated by the sinc, or sin cardinal, function. The bulk of the signal energy is concentrated in the main lobe, the width of which is dependent on the duration of the coherent observation time $T_{coh}$. In fact, the main lobe double-sided width is given by $2/T_{coh}$ Hz, as illustrated in Figure 2. So, increasing the coherent observation time, which is the most efficient way to increase receiver sensitivity, effectively increases the number of frequency bins in the uncertainty region for a given tolerable power attenuation.

Consider the simple case of an initial frequency uncertainty of 10 kHz and a frequency bin width chosen to be $1/T_{coh}$ Hz. For strong signal acquisition, $T_{coh}$=1 ms, yields a search space of 10 frequency bins. Assuming parallel search in the code domain using DFT techniques, then a total of 10 ms is required to cover the entire uncertainty region.

Consider in constrast the acquisition of weak signals with, say, $T_{coh}$=10 ms. The search space now consists of 100 bins, such that a total of 1000 milliseconds is required, or a factor of 100 times the strong signal case.

To overcome this difficulty, we need to find a way to increase the overall observation time (to increase sensitivity) without increasing the coherent observation time significantly (to avoid increasing the number of frequency bins).

The most common technique to achieve this is called *non-coherent combining*. Here the square magnitudes of, say $K$, successive coherent correlator outputs are summed to produce a final decision statistic. The total observation interval is then $T_{Obs} = KT_{coh}$, but the frequency sensitivity is identical to that of the coherent observation time.

The drawback of non-coherent combining is that the increase in sensitivity for a given observation time is less than that of pure coherent correlation. In terms of mean acquisition time, however, the use of non-coherent combining is often a much better choice. It can be shown that the square sum combining form is the optimal form of non-coherent integration for low signal to noise ratios (SNRs).

An alternative combining technique, called *differentially coherent combining*, has also been proposed recently in a number of papers. This can be shown to be superior to non-coherent combining when signals are weak and $T_{coh}$ is relatively short. (Longer coherent observation times increase the sensitivity to modulation effects dramatically).

**Data bit transitions reduce signal power in the correlator outputs thereby reducing receiver sensitivity.** The GPS C/A code is modulated by a 50 bps binary phase shift keyed (BPSK) data message. This leads to bit boundaries every 20 ms, with a probability of a bit transition of approximately 0.5 at each boundary. A bit transition implies a 180° phase shift, which is effectively a change in sign. If a bit transition occurs mid-way through a coherent observation interval then the signal can be completely eliminated from the correlator output. Note that may of the modernized GNSS signals also have a secondary BPSK modulation, either due to navigation data or to a secondary code sequence.

There are a number of approaches to limiting the effect of data modulation:

- *Use of non-coherent combining,* discussed earlier
- *Aligning the correlator with the local code epoch.* This approach eliminates the possibility of a bit transition occurring in the middle of a code epoch.

**In contrast to auto-correlation, cross-correlation in effect results in a respreading of the interfering signal.**

However, if the coherent observation time is greater than one epoch then it may still be possible to have a bit transition in the middle of the coherent correlation. For example, consider acquisition of the C/A code with 2 millisecond coherent correlation, which is aligned to the local code epoch. Then a bit transition at the start of the second millisecond could completely eliminate the signal from the correlator output.

This can be avoided by running 20 correlators in parallel, offset from each other by 1 ms; one of these correlators is guaranteed to be unaffected by modulation effects (referred to as the "Full Bits Method"). This does have a significant impact on computational complexity however. This is also essentially the technique applied in the DBZP algorithm, which uses a 20 ms coherent integration time.

- *External assistance information.* Typically employed in so-called assisted-GNSS techniques, this method can also be used to estimate the location and sign of


the data bits within the signal. This requires the existence of a communications back-channel that can provide accurate timing information with low latency.

**Cross-correlation effects due to strong signals lead to false acquisition.** All current and future GNSS signals, with the exception of the GLONASS L1 signal, are code division multiple access (CDMA) signals. This implies that all satellites transmit in the same frequency band at the same time; the receiver distinguishes one satellite signal from another using the unique spreading code assigned to each satellite.

The spreading codes are designed to provide good cross-correlation protection. That is, the signal power resulting from cross-correlating the spreading code from one satellite with that from another is significantly less than the power resulting from the auto-correlation of a satellite signal with the replicated signal in a receiver.

The GPS C/A code provides approximately 20 dB of cross-correlation protection. Therefore, if one satellite signal is received with 20 dB more power than another, the receiver may not be able to distinguish the weaker signal from the stronger. Without some form of multi-access interference mitigation this represents an absolute limit on the acquisition sensitivity of a GNSS receiver.

We should note here that, whereas auto-correlation results in a localization (or de-spreading) of the signal in the delay and frequency domains, cross-correlation in effect results in a respreading of the interfering signal. This means that the power of the interfering signal is spread throughout the frequency range of interest, so that a frequency offset between the local replica and the interfering signal does not provide any cross-correlation protection.

Fortunately, mechanisms exist for the mitigation of multi-access interference, such as *parallel interference cancellation* (PIC) and *successive interference cancellation* (SIC). These techniques require the acquisition of stronger signals first. Once these signals are being tracked, they are effectively "subtracted" from the incoming signal and the result is passed on for acquisition of the weaker signals. This represents a significant computational burden on the receiver, but is essential to enable acquisition and tracking of weak signals in the presence of strong interferers.

**Higher order Doppler effects due to dynamics and receiver oscillator instabilities lead to decreased sensitivity.** The coherent integration portion of signal acquisition is, in essence, a matched filter, which can be shown to be the optimal signal detector. For true optimality the matched filter involves correlating the received signal with a local replica, which is perfectly matched to it.

For short observation times, it is usually sufficient to model the signal as consisting of an initial code-phase and constant Doppler frequency offset. As the observation time increases, however, this model becomes increasingly less accurate and the power attenuation shown in Figure 1 again becomes important.

Over intervals of many hundreds of milliseconds the frequency offset between the received signal and the locally generated replica can drift quite significantly, due to the combined effects of satellite-receiver dynamics (including user motion) and instabilities in the local oscillator.

So, even if the initial frequency uncertainty is very small and data modulation effects can be removed, the maximum length of the coherent integration time is typically limited by the quality of the oscillator. Again, non-coherent combining techniques can be employed to reduce sensitivity to frequency offsets.

In summary, the acquisition of weaker signals requires increased observation times to increase receiver sensitivity. The theoretically optimal way to increase the observation time is to increase the coherent integration time. However, increasing the coherent integration time increases the receiver sensitivity to frequency error (including user dynamics), data modulation, multi-access interference effects and received signal/local replica mismatch. There are four main tools that can be used to mitigate these effects: aiding, efficient parallel correlation by FFT, non-coherent combining, and multi-access interference suppression.

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