GNSS Solutions:

Differences between Signal Acquistion and Tracking

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

"Why is acquisition of GNSS signals generally more difficult than tracking and what are the limiting factors?"

A fairly good analogy of the difference between GNSS signal acquisition and tracking can be found in the rescue of victims of a sunken ship whose location is not accurately known. The first stage of the rescue attempt typically involves an aircraft flying a search pattern, which hopefully encompasses the location where the ship went down.

For two main reasons, spotters aboard the plane may have great difficulty finding a person afloat in a vast expanse of ocean. First, because the human eye is most sensitive in its relatively small area of central vision, the spotter must scan over a wide area to locate what appears to be a tiny spot on the ocean's surface. Second, detecting a human figure can be very difficult among numerous whitecaps whipped up by the wind in a rough sea, which appears as "noise."

The process of searching for a person at sea is analogous to the search required for acquisition of a GNSS signal.

However, once the victim is located (acquired), the spotters must keep the person in sight (tracked) for some period of time during rescue operations. The tracking process is generally much easier than acquisition, as the spotter now knows quite accurately where the person is located.

In this phase, the sophisticated tracking capability of the eye's central vision area comes into play. Even momentary disappearance of the victim is not a problem, because reliable reacquisition is possible by performing a search over a very small area, and the clutter (noise) outside this area can be disregarded. This type of operation is analogous to tracking a GNSS signal.

For concreteness, we will compare the acquisition and tracking processes for a legacy L1 C/A-coded GPS signal from a single satellite, with simplifications that facilitate understanding. In this case *acquisition sensitivity* is defined as the minimum signal power required for a specified reliability of correct acquisition, with a similar definition for *tracking sensitivity*.

Although with enough processing there is no theoretical limit for either, the sensitivity for tracking in GPS receivers is generally better (typically about two to five decibels lower in signal power) than for acquisition.

Why does this happen?

When a typical GPS receiver is turned on, the following sequence of operations must occur before the receiver can access the information in a GPS signal and use it to provide a navigation solution:

1. Determine which satellites are visible to the antenna.
2. Determine the approximate Doppler of each visible satellite.
3. Search for the signal in both C/A-code delay and frequency (i.e., Doppler shift).
4. Detect a signal and determine its code delay and carrier frequency.
5. Track the C/A-code delay and carrier frequency as they change.

Signal Acquisition

The acquisition process consists of Steps 1–4 in the foregoing list. In Steps 1 and 2 the visible satellites and approximate Doppler shifts are usually found using approximate time, approximate receiver position, and almanac data (for satellite position and velocity) — all of which have been previously stored in the receiver. This permits the receiver to establish a frequency search region for each visible satellite, and is similar to establishing the region of ocean to search in the above analogy.

Step 3 requires by far the most computation. The C/A-code search is necessary because GPS signals are spread-spectrum signals in which the C/A code spreads the total signal power over a wide bandwidth, dropping its power density well below that of a receiver's thermal noise. A signal is therefore virtually undetectable unless it is de-spread to a much narrower bandwidth by correlation with a replica code in the receiver that is precisely time-aligned with the received code.

Because the signal cannot be detected until alignment has been achieved, a search over all possible alignment positions is required. For each trial code alignment position, the signal must be averaged over a sufficiently long time period to build up the signal-to-noise ratio (SNR) to a usable level.

Such averaging requires that the receiver be accurately tuned to the received carrier frequency; otherwise the averaging can be severely degraded. However, at L-band the frequency uncertainty of a typical receiver's reference oscillators and the Doppler uncertainty due to uncertainty in receiver location and velocity can make the tuning uncertainty as large as several kilohertz (satellite motion alone account for approximately ±5 kilohertz at L1). Thus, in addition to the code search, a receiver also needs to search in frequency.

The basic method for performing the code and frequency search is illustrated in **Figure 1**, in which the received signal is multiplied by various receiver-generated delayed replicas of the C/A code, translated by various frequencies to a complex baseband signal, and averaged for each combination of code delay and frequency.

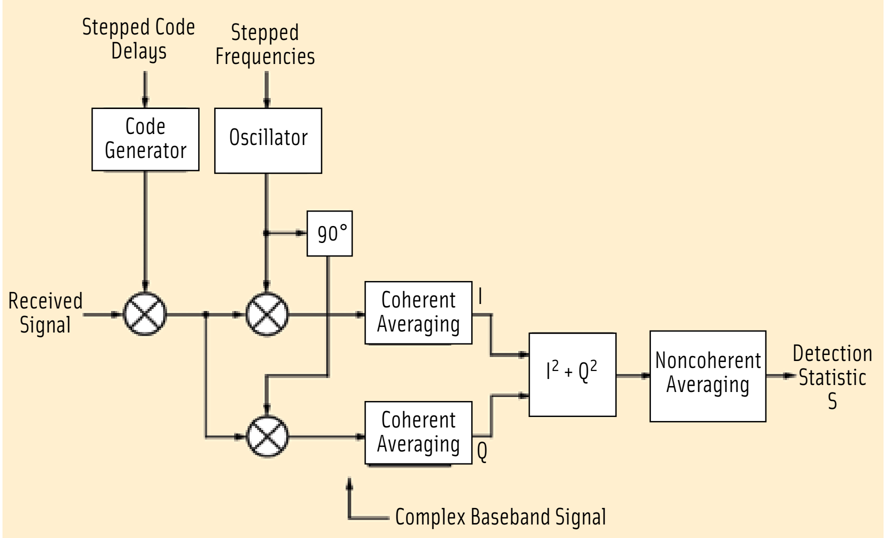

FIGURE 1 Basic signal search method

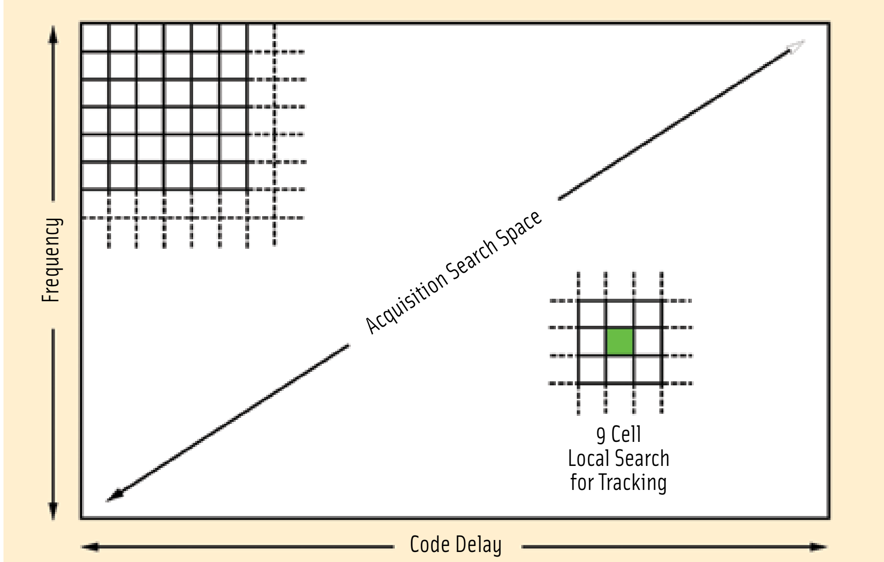

FIGURE 2 Acquisition search space and local tracking search

A combination of coherent and noncoherent averaging is generally used. The coherent averaging, which is over multiple periods of the C/A code, provides a real part in phase (I) and imaginary part in quadrature (Q). The noncoherent averaging accumulates the power $I^2 + Q^2$ over a number of coherent averages to form a detection statistic, S. The value of S will tend to be largest when both the selected code delay and frequency closely match those of the received signal, but S can be corrupted by noise.

Although coherent averaging gives better processing gain than noncoherent averaging, the coherent averaging time must be limited to a fraction of 20 milliseconds in order to prevent excessive coherence loss by 50 bit-per-second navigation data bit polarity changes occurring at unknown times during acquisition.

The two-dimensional array of cells shown in **Figure 2** is a representation of the *acquisition search space*, consisting of all combinations of code delay and frequency used in the acquisition search.

The *maximum likelihood* (ML) method of signal detection assumed here selects the delay/frequency cell

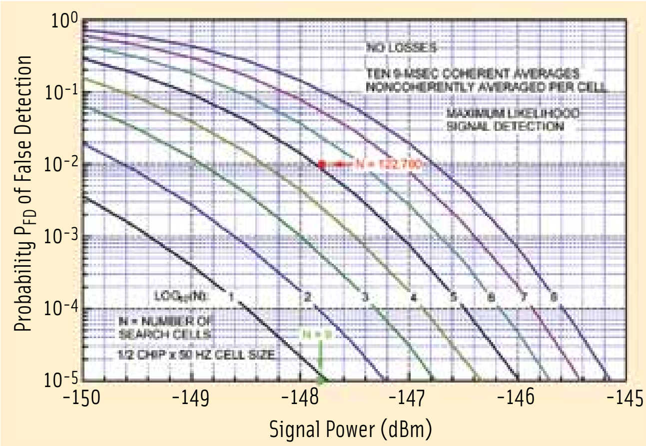

FIGURE 3 Dependence of P_{FD} on signal power and number of search cells

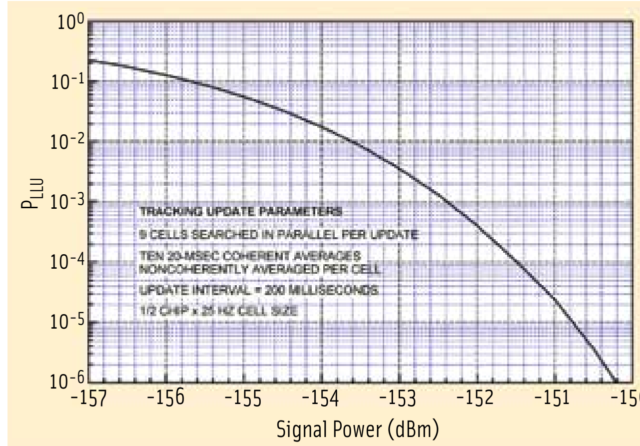

FIGURE 4 Probability P_{LLU} of losing lock per tracking update

giving the maximum value of *S*, and declares that a signal is present in that cell. However, there is a nonzero *probability of false detection* (P_{FD}), in which noise alone in some other cell will cause its value of *S* to be larger than that of the signal's cell.

Assuming a fixed average noise level, P_{FD} decreases with increasing signal power. On the other hand, P_{FD} increases as the number *N* of cells in the search space becomes larger, because more opportunities arise for noise to make the largest *S* occur in a non–signal-bearing cell.

Figure 3 shows how P_{FD} varies as a function of signal power and *N* for a lossless receiver when 10 nine-millisecond coherent averages are noncoherently averaged to compute the detection statistic *S* for each cell in the search space. In this case frequency search increments of 50 hertz will avoid excessive coherence loss from residual frequency error during the search.

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Assuming a ±1,500 hertz frequency uncertainty, 60 search frequency bins would be required.

The search in code delay over the 1,023 chips of the C/A code is typically conducted in half-chip increments to avoid excessive correlation loss, resulting in 2,046 code delays to be searched. Using these parameters, the search space would contain $N = 60 \times 2{,}046 = 122{,}760$ cells. Using this value of *N* and $P_{FD} = 10^{-2}$ in Figure 3 (red dot), the receiver's acquisition sensitivity would be about –147.8 dBm.

Note that in this example, 1,227,600 coherent averages and 122,760 noncoherent averages are needed to cover the search space. This large amount of computation is one reason acquisition is more difficult than tracking. Massively parallel computation can speed up the process, but at greater hardware cost and power consumption.

Signal Tracking

Once the cell containing the signal has been detected in Step 4, typical receivers use code and carrier tracking loops in Step 5 to generate error signals that keep the replica and received codes aligned and also keep the receiver tuned to the correct frequency as changes in Doppler occur. However, a discrete approximation to these methods of tracking is to repeatedly compare the values of *S* in the current signal cell (shown in green in Figure 2) with the values in the eight cells surrounding it.

Although the approximation is somewhat crude, it makes analysis of tracking sensitivity much easier and does not really falsify our understanding. If the maximum value of S in the surrounding cells exceeds that of the central cell, the cell with that maximum value is declared as the new signal cell. In this way, both the code delay and carrier frequency of the received signal can be tracked by repeatedly performing a local search over only $N = 9$ cells, each local search resulting in a tracking update.

As can be seen from reexamining Figure 3, at –147.8 dBm, the small value $N = 9$ results in a probability of about 10^{-5} (green dot) of missing the correct signal cell per tracking update, which is much smaller than the probability 10^{-2} of missing that cell during acquisition with its much larger number of searched cells, as previously discussed.

Additionally, after acquisition the timing of the navigation bit boundaries can be determined, which permits coherent averaging over the full data bit length of 20 milliseconds. This provides additional sensitivity during tracking as compared to acquisition.

As an example for tracking, *S* might be calculated by noncoherently averaging ten 20-millisecond coherent averages for each of the nine cells used in a tracking update. For that case, **Figure 4** shows the probability P_{LLU} of losing lock (missing the correct signal cell) per tracking update. Computation of *S* for the nine cells in each tracking

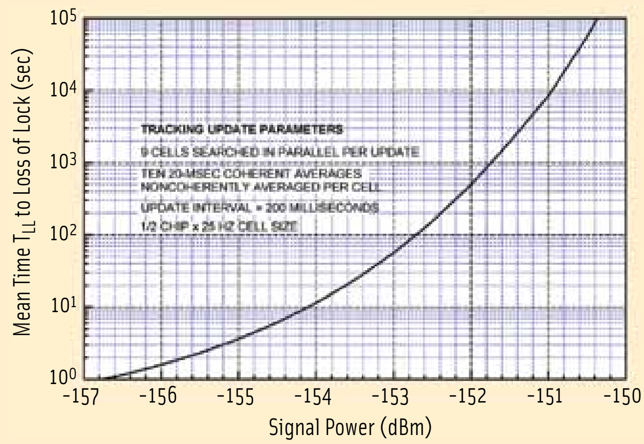


FIGURE 5 Mean Time T_{LL} to loss of lock

update is easily done in parallel.

Tracking performance is typically measured by the *mean time to loss of lock* T_{LL}. For our simplified tracking method, we compute this using the formula

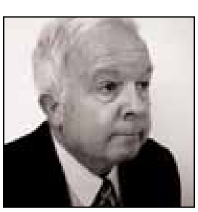
$$T_{LL} = \frac{T_U}{P_{LLU}}$$

where T_U is the tracking update interval, in this case 200 milliseconds for parallel processing of the nine cells.

Figure 5 is a plot of T_{LL} versus signal power, and it shows that $T_{LL} = 10^4$ seconds (2.8 hours) can be achieved with a signal power of –151 dBm. This is 3.2 dB better than the acquisition sensitivity previously computed.

To summarize, with enough processing, no theoretical limit exists for either acquisition or tracking sensitivity. However, because tracking requires examination of only a local code delay and carrier frequency region (and coherent averaging can be used as well over the full length of data bits in legacy L1 GPS signals), tracking can be made more sensitive than acquisition before cost limits (either in hardware or processing time) are reached.

Similar conclusions can be reached for other GNSS signals, even taking into account differences in their characteristics.



Lawrence R. Weill is one of the three technical founders of Magellan Systems Corporation, which in 1989 produced the world's first low-cost handheld GPS receiver for the consumer market. He received B.S. and M.S. degrees in electrical engineering from the California Institute of Technology. He earned an M.S. degree in mathematics at San Diego State University and a Ph.D. in mathematics at the University of Idaho. He is professor of mathematics emeritus at California State University, Fullerton, and has operated his own consulting firm for 28 years.

As an active researcher, Weill has published numerous papers on signal processing for GNSS, radar, sonar, optical sensor, and satellite communication systems, including substantial contributions to the theoretical foundations and practical aspects of GNSS signal compression and multipath mitigation. IG