GPS Signal Acquisition and Sensitivity Analysis Using Different Algorithms on a Software Receiver

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Abstract — In this paper three different acquisition algorithms are implemented in a GPS software receiver and compared by the correlation strategy employed. Their theoretical models are first analyzed and then implemented in Matlab. Both simulated GPS data and realistic signals from a Sat-Surf receiver are used to verify the performance of the acquisition schemes. The software acquisition approach provides flexibility and low cost for algorithm redesign and improved intermediate frequency selection capability. The performances of serial search in time domain, parallel search in time and frequency domain acquisition algorithms are compared and evaluated using different incoming signals Carrier-to-Noise density ratios. The serial search acquisition algorithm in time domain has the advantage of working both on block of data or sample. The main disadvantage is the bigger acquisition time it requires. The acquisition in time domain employing FFT is a very fast acquisition algorithm.

Keywords — GPS; frequency-domain acquisition; software receiver; time-domain acquisition.

I. INTRODUCTION

Global Positioning System (GPS) satellites broadcast ranging signals and navigation data allowing users to estimate their position and velocity. Recently, with the development of digital signal processing technologies, the receiving and processing of GPS satellite signals more and more tends to use the software methods. Compared to the conventional hardware GPS receiver, the software receiver has the advantage of upgradability and compatibility with new positioning methods. In addition, it is very flexible to process various frequency signals collected by hardware and can exploit and validate algorithms without changing hardware [1].

In a conventional GPS receiver, the acquisition and tracking of the signals are all processed by the hardware. However, in a software GPS receiver, the signal is digitized using an analog-to-digital converter (ADC). Acquisition and tracking of GPS satellites are the key processes involved in a GPS receiver. Software GPS receivers capture the RF modulated signals at L1 frequency, downconvert them to an intermediate frequency (IF), digitize them, and perform signal processing to extract the position information from the navigation message. The digitized input signal is then processed using the software receiver. The acquisition process searches for the presence of a signal from a particular satellite, and the tracking program finds the phase transition of the navigation data from that satellite. Ephemeris data and pseudorange can be recovered from the navigation data bits. Finally the user position can be calculated from the ephemeris obtained. The data input to the software receiver does not have to be processed in real time. Therefore the receiver does not have to be constantly tracking the signals, which is useful in cases where data cannot be collected continuously [2]. In order to determine the difference between the transmission time from the satellite and the signal reception time, a GPS receiver has to synchronize a locally generated reference code with the received signal. Thus, in any spread spectrum system, such as GPS or Galileo, in order to despread and demodulate the sent data, it is necessary to estimate the timing and frequency shift of the received signal [3].

The common serial search acquisition strategy might be the most time consuming operation in a real receiver. In order to speed up the search process, modern receivers use fast acquisition techniques, based on the use of Fast Fourier Transform (FFT). These techniques are particularly effective both in hardware and software implementations [4].

The focus of this paper is to implement three acquisition algorithms both in time and frequency domain. Simulated and real GPS signals are used to compare and evaluate their performance. The structure of the paper is as follows: Section II describes the acquisition of GPS signals and theoretical models of acquisition algorithms in time and frequency domain. Section III presents the required experimental setup for gathering real GPS signals, followed by the graphical results and comparative analysis of the different acquisition techniques. Finally, Section IV draws the conclusion.

II. GPS SIGNAL ACQUISITION ALGORITHMS

The first step in digital GPS processing is the signal acquisition: the receiver has to detect the satellites in view and give a rough estimation of the Doppler shift and the code phase. Then the signal tracking refines the code synchronization and allows for demodulating the low rate navigation data and estimates the pseudorange (i.e.: distance between the satellite and user, fundamental in the computation of the user’s position). The conventional approach to signal acquisition is to search for the satellites
in the time domain through hardware. The search for the satellites can be performed in series as well as in parallel depending on the hardware design. In a software receiver, the acquisition is generally performed on a block of data using parallel search algorithm [5].

The beginning of the Coarse/Acquisiton (C/A) code and the carrier intermediate frequency (IF) of a GPS signal from a satellite can be found by correlating the incoming signal with the receiver generated signal. There are several different algorithms to perform acquisition. Three algorithms analyzed in this paper are the serial search in time domain, parallel search in time domain and parallel search using fast Fourier transform (FFT) in frequency domain. Though serial search is the slowest search method, it is usually implemented in hardware based receivers due to its simplicity. The parallel search (FFT method) in frequency domain usually implemented by software receiver since serial search method is computation intensive in the software approach [2].

A. Serial Search Acquisition Algorithm in Time Domain

Serial search is the simplest and most frequently used acquisition method especially in hardware GPS receivers. In a serial search, each possible frequency and code offset is evaluated serially until the correct values are found. This approach follows these steps:

Step 1: the digital IF signal, \( x[n] \) is multiplied by the locally generated C/A code, \( CA[n + m] \) where \( n \) is the \( n \)-th sample and \( m \) is the number of phase shifted samples of the replicated C/A code. \( L \) is the sample length of one C/A code period. \( n \) and \( m \) are numbers from \( 0 \) to \( L - 1 \). \( K \) is the noncoherent integration time.

Step 2: after the code removal, the in-phase (I) and quadrature-phase (Q) components are generated.

Step 3: the I and Q components are accumulated for one or more code periods, \( N \).

Step 4: the accumulated sum of I and Q components is squared.

Step 5: next, \( K \) correlations are accumulated to produce an averaged correlation point.

Step 6: if the correlation peak is larger than a certain threshold, it is assumed that the satellite is acquired.

The flowchart of serial search acquisition algorithm in time domain is shown in Fig. 1. The correlation in discrete time domain is expressed as (1).

\[
R^2[m] = \sum_{j=0}^{K-1} \left( \sum_{n=NjL}^{NjL-1} x[n] \cdot CA[n + m] \cdot \cos[\omega n] \right)^2 \\
+ \sum_{j=0}^{K-1} \left( \sum_{n=NjL}^{NjL-1} x[n] \cdot CA[n + m] \cdot \sin[\omega n] \right)^2 \tag{1}
\]

where \( \omega \) is the radian frequency. Setting \( N \) and \( K \) to smaller values allows faster acquisition. However, choosing larger values for \( N \) and \( K \) will improve the acquisition of weaker signals and reduce the probability of false acquisition [6].

B. Parallel Search Acquisition Algorithm using FFT

In parallel search techniques based on parallel matched-filter (MF) implementation, more than one correlating element is used to explore simultaneously different regions and in an extreme case, there is one correlating element for every searching position (fully parallel search). A bank of matched filters is used, each matched to a different waveform pattern of PRN code, for all possible code phases and Doppler uncertainties [7]. The decision statistic is based on all outputs from all filters. Obviously, this approach will reduce largely the acquisition time, but it will increase the implementation complexity. Parallel code acquisition using simple schemes was studied in [8]. The parallel search algorithm can also be implemented using circular correlation. The samples of the received data are correlated with the replica code by circularly shifting the replica code. The circular correlation is a multiplication in the frequency domain that can be expressed as (2).

\[
R[m] = \sum_{n=0}^{L-1} x[n] \otimes CA[(n + m)_L] \tag{2}
\]

The FFT approach performs circular convolution in the frequency domain. The discrete Fourier transform (DFT) and its inverse is used to calculate \( R[m] \) given by (3).

\[
R[m] = \sum_{n=0}^{L-1} x[n] \cdot CA[(m + n)] \\
= F^{-1} \left\{ F(x[n]) \cdot F(CA[n]) \right\} \tag{3}
\]

where the fast Fourier transform (FFT) and its inverse (IFFT) is used to calculate \( R \) [6]. Since the fast Fourier transform is used to implement the DFT and IDFT, the acquisition is also called the FFT search. In the case of the software GPS receiver the following steps are performed:

Step 1: the incoming signal is mixed to baseband and the in-phase and quadrature components are used as the real and imaginary inputs when calculating the FFT.

Step 2: the result is multiplied by the complex conjugate of the FFT of the C/A code.

Step 3: the circular correlation is obtained by taking the magnitude of the inverse FFT of the result as it is shown in Fig. 2.
In [14] is presented a FFT-based fast algorithm which reduces the computation in order to achieve rapid long code acquisition.

III. EXPERIMENTAL SETUP AND RESULTS

Both simulated and real GPS data are used to verify the performance of the acquisition algorithms. N-Fuels is the GPS signal simulator used to generate C/A GPS signals for post-processing while real data were collected by SAT-SURF [9] receiver manufactured by SAET s.r.l. The acquisition algorithms were implemented using MATLAB® 7.0. Fig. 3 illustrates the simplified structure of the GPS receiver used for collecting data for further processing.

A. Receiver Unit

In this section is given a brief description of the receiver used to collect the real GPS data and of the software used to process them. SAT-SURF is a hardware black-box integrating GPS and GSM/GPRS functionalities. The SAT-SURF hardware allows getting out from the GPS receiver several data and also each available raw measurement (depending on the receiver capabilities). Each GPS parameter is logged with a related GPS time stamp, so that it can be aligned to the evolution of all the others. SAT-SURFER is the software suite running on a standard PC that uses data coming from SAT-SURF. It is a software suite able to talk in real-time with state-of-the-art GPS receiver modules as well as external professional GPS units. SAT-SURFER gets raw data, displays such data on the screen and log them in different files allowing any post-processing activity.

B. Simulated and Real Scenario

Using N-Fuels [10] signal simulator are generated 7 ms of GPS L1 signal for satellite number 21 with a code delay of 200 chips and a Doppler frequency of 1.5 kHz, with and without front-end filter. The sampling frequency is 16.3676 MHz and the IF is 4.152 MHz. For the same satellite a 1 ms local code with no delay was generated. In different trials we repeat the generation of the signal sequence at different levels of C/N₀, limited to test and compare the performance of acquisition algorithms. Noise computation is an important part of the acquisition process. A detection threshold is used to decide whether a signal is present or not. The detection threshold is the minimum noise level which the correlation peak should exceed to be detected as a signal. The acquisition algorithm after evaluating the Cross Ambiguity Function (CAF), looks for a correlation peak in results from all cells. A signal is acquired when the correlation peak exceeds the detection threshold and estimates of the code phase and Doppler of the cell under search are passed to the tracking process. If a signal is not detected, the acquisition manager searches the next cell. Once all the cells are exhausted the next GPS satellite is searched and the process is repeated [11].

An experiment was conducted using GPS C/A data collected outside our laboratory in the Polytechnic University of Tirana Campus. Totally 2300 epochs of data were analyzed for the experiment and post-processed in Matlab® environment. A Doppler frequency range, reasonably comprised between -5 kHz and 5 kHz, which is scanned with a 500 Hz step is used. The integration period is equal to one code period. The RF down converter gets the input GPS satellite signal from an antenna-cable assembly. It uses mixers, local oscillators and band pass filters to down convert the carrier to a low IF. The IF is then sampled by a programmable sampling frequency to generate digitized IF signal of the satellites.

C. Results and Discussion

From Fig. 4 and Table 1 it can be observed that due to the low value of C/N₀, the strong presence of the noise hides the signal power and avoids a correct estimate of the time delay and Doppler shift by the serial search acquisition algorithm. Looking at the result in Fig. 5, notice that there is a peak when the code delay and the Doppler shift of local signal are both matched to the received signal. With the use of the front-end filter, a group delay is added to the received signal, so the acquired code delay is different from the result in the case without front-end filter. The residual estimated code delay error increased with a value of 0.233 chips. However, the difference is small and it did not affect the signal acquisition.

In Fig. 6 and 8 are shown the results of the acquisition for frequency parallel search and time parallel search acquisition algorithms for the lowest value of C/N₀. In this case one can observe the incorrect estimated values of Doppler shift and code delay (Table 2 and 3). The use of different acquisition algorithms give different results, but in general the parallel in time approach (Table 2) has better results in less time. The problem concerning this scheme is the fact of the data transition, which can be reduced using a non-coherent average [13].

Figure 2. Parallel search FFT-based acquisition algorithm.

Figure 3. Simplified structure of a GPS receiver.
The time spent on a single cell for CAF evaluation in time domain depends on the value of integration time, while the overall acquisition time depends on the total amount of cells of the search space. CAF evaluation approach in time domain using FFT requires a \( L \times L \) step of the incoming code to spam all the frequency bins. The cells of a single row are computed in one shot which makes the frequency bin a free parameter and the delay bin not a free one. In this case the delay bin is strictly related to the number of points over which the FFT is computed. The delay bin is a free parameter for CAF evaluation in frequency domain as in the case of the serial search scheme. The frequency bin depends on the time windows FFT is performed and more precisely it is inverse proportional to the integration time.

Figure 4. Serial search acquisition results for satellite No. 21 with \( \text{C/N}_0=33\text{dBHz} \).

![Figure 4. Serial search acquisition results for satellite No. 21 with \( \text{C/N}_0=33\text{dBHz} \).](image)

**TABLE I.** COMPARISON OF THE CORRELATION RESULTS OF DIFFERENT C/\( \text{N}_0 \) (SERIAL SEARCH)

<table>
<thead>
<tr>
<th>( \text{C/N}_0 ) (dBHz)</th>
<th>Doppler frequency shift (kHz)</th>
<th>Code delay (Chips)</th>
<th>Maximum value of CAF</th>
</tr>
</thead>
<tbody>
<tr>
<td>33</td>
<td>-2.3737</td>
<td>738.4826</td>
<td>0.9121 (-10^8)</td>
</tr>
<tr>
<td>38</td>
<td>3.8889</td>
<td>842.5515</td>
<td>0.9713 (-10^8)</td>
</tr>
<tr>
<td>44</td>
<td>1.4646</td>
<td>199.6372</td>
<td>1.4169 (-10^8)</td>
</tr>
<tr>
<td>50</td>
<td>1.5657</td>
<td>199.6997</td>
<td>2.7007 (-10^8)</td>
</tr>
</tbody>
</table>

Figure 5. Serial search acquisition results for satellite No. 21 with \( \text{C/N}_0=50\text{dBHz} \).

![Figure 5. Serial search acquisition results for satellite No. 21 with \( \text{C/N}_0=50\text{dBHz} \).](image)

**TABLE II.** COMPARISON OF THE CORRELATION RESULTS OF DIFFERENT C/\( \text{N}_0 \) (FREQUENCY PARALLEL SEARCH)

<table>
<thead>
<tr>
<th>( \text{C/N}_0 ) (dBHz)</th>
<th>Doppler frequency shift (kHz)</th>
<th>Code delay (Chips)</th>
<th>Maximum value of CAF</th>
</tr>
</thead>
<tbody>
<tr>
<td>33</td>
<td>-1.3135</td>
<td>681.8542</td>
<td>9.9852 (-10^{15})</td>
</tr>
<tr>
<td>38</td>
<td>-1.0564</td>
<td>78.4423</td>
<td>8.1493 (-10^{15})</td>
</tr>
<tr>
<td>44</td>
<td>1.5470</td>
<td>199.7622</td>
<td>9.8447 (-10^{15})</td>
</tr>
<tr>
<td>50</td>
<td>1.5468</td>
<td>199.7622</td>
<td>3.9941 (-10^{12})</td>
</tr>
</tbody>
</table>

Figure 6. Frequency parallel search acquisition results for satellite No. 21 with \( \text{C/N}_0=33\text{dBHz} \).

![Figure 6. Frequency parallel search acquisition results for satellite No. 21 with \( \text{C/N}_0=33\text{dBHz} \).](image)

Figure 7. Frequency parallel search acquisition results for satellite No. 21 with \( \text{C/N}_0=50\text{dBHz} \).

![Figure 7. Frequency parallel search acquisition results for satellite No. 21 with \( \text{C/N}_0=50\text{dBHz} \).](image)
The results of the real scenario are summarized in Table 4. After implementing the Parallel search FFT-based acquisition algorithm we were able to acquire 6 GPS satellites in view. As previously mentioned a detection threshold is used to decide whether a signal is present or not. It is important to say that the decision criterion used in the Matlab code consists in look for the first maximum in a search space (inside the integration time), save its value, clean around it and then look for the second maximum. If the first maximum is 1.5 times larger than the second one, this peak is declared as a present satellite, otherwise it is discarded [12].

### Table III. Comparison of the Correlation Results of Different C/No (Time Parallel Search)

<table>
<thead>
<tr>
<th>C/No (dBHz)</th>
<th>Doppler Frequency (kHz)</th>
<th>Code Delay (Chips)</th>
<th>Maximum Value of CAF</th>
</tr>
</thead>
<tbody>
<tr>
<td>33</td>
<td>-2.2727</td>
<td>158.3847</td>
<td>1.5074 \times 10^{16}</td>
</tr>
<tr>
<td>38</td>
<td>-1.5657</td>
<td>674.7287</td>
<td>1.7186 \times 10^{16}</td>
</tr>
<tr>
<td>44</td>
<td>1.6667</td>
<td>199.8247</td>
<td>3.2335 \times 10^{16}</td>
</tr>
<tr>
<td>50</td>
<td>1.6667</td>
<td>199.7622</td>
<td>1.2142 \times 10^{15}</td>
</tr>
</tbody>
</table>

### Table IV. GPS Satellites in View for the Real Scenario

<table>
<thead>
<tr>
<th>PRN</th>
<th>Doppler Frequency (kHz)</th>
<th>Code Delay (Chips)</th>
<th>CAF Ratio (First peak/Second peak)</th>
</tr>
</thead>
<tbody>
<tr>
<td>9</td>
<td>-641.1</td>
<td>966.81</td>
<td>4.5817</td>
</tr>
<tr>
<td>12</td>
<td>1153.8</td>
<td>859.75</td>
<td>5.5848</td>
</tr>
<tr>
<td>15</td>
<td>-3717.9</td>
<td>793.06</td>
<td>3.8309</td>
</tr>
<tr>
<td>17</td>
<td>-2948.7</td>
<td>949.63</td>
<td>3.4785</td>
</tr>
<tr>
<td>25</td>
<td>2692.3</td>
<td>251.56</td>
<td>2.0459</td>
</tr>
<tr>
<td>27</td>
<td>-1410.3</td>
<td>716.81</td>
<td>3.8414</td>
</tr>
</tbody>
</table>

### IV. Conclusion

In this paper we have investigated GPS signal acquisition algorithms for software GPS receiver. In a GPS software receiver this flexibility is very useful when different algorithms should be tested. Three theoretical models of acquisition algorithms in time and frequency domain were first analyzed and then implemented in Matlab. Through simulations and real GPS signals, a performance comparison between these algorithms was done in terms of sensitivity. A simple detection strategy was implemented for real GPS signal acquisition. When the received signal was not sufficiently strong the acquisition algorithms estimated wrong Doppler shift and code delay. The serial search acquisition algorithm in time domain has the advantage of working both on block of data or sample and the two parameters of search space; delay and frequency bin are both free. The main disadvantage is the bigger acquisition time it requires. The acquisition in time domain employing FFT is a very fast acquisition algorithm, but has the disadvantage of working only on block of data which makes this approach more sensible to the data transition problem. The parallel search FFT-based acquisition algorithm in frequency domain can work both on block of data or sample, but has the disadvantage of frequency bin not being a free parameter. The analysis in this paper could be useful in design of new acquisition algorithms.
REFERENCES


