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GPS Signal Acquisition and Tracking
An Approach towards Development of Software-based GPS Receiver

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Abstract Software-based GPS (SGR) Receiver helps us processing the GPS signal at the lowest level of GPS raw signal data from the antenna. A software-based GPS receiver consists of a front-end device that converts the radio frequency signal from the antenna to an intermediate frequency in digital format. The signal thus converted is processed by high level programming language to compute position and velocity. In SGR, it is possible to do acquisition and tracking using different parameters and threshold values, which give a user total flexibility of operation. This helps in processing weaker signal, multipath mitigation and simulate "what-if" scenarios. In this paper, we will discuss about GPS signal acquisition and tracking that will form a base for the development of SGR.

Keyword Software GPS, Acquisition, Tracking, DLL, PLL

1. Introduction

Global Positioning System (GPS) is a satellite-based navigation system. It is based on the computation of range from the receiver to multiple satellites by multiplying the time delay that a GPS signal needs to travel from the satellites to the receiver by velocity of light. GPS has already been used widely both in civilian and military community for positioning, navigation, timing and other position related applications. The system has already proved it's reliability, availability and good accuracy for many applications. Due to this nature, in future, other countries like Europe are going to launch new satellite-based navigation system called Galileo. There is also a proposal to launch Quasi Zenith Satellite System for navigation in Japan.

It is necessary to simulate and analyse the new signal structures for the development of new satellite-based navigation systems. In the research community, many researchers come out with new ideas and algorithms for the better accuracy of GPS by mitigating or minimizing various types of errors and effects like multipath. However, it is quite difficult to implement the user developed algorithms in the current hardware-based GPS receivers. The hardware-based GPS receivers contain ASICs that provide the least user flexibility. Thus, it is necessary to have Software-based GPS receivers, at least in the research community for easy and quick implementation, simulation and analysis of algorithms, parameters and threshold values. Since, the CPU processing power is increasing with reduced cost, it is now possible to build real-time software-based GPS receivers at least for static or low dynamic environments. As predicted by Moor's Law, the CPU power is increasing and we hope that this trend will continue in future as well and hence, it will be possible to develop real-time all environment software-based GPS receivers.

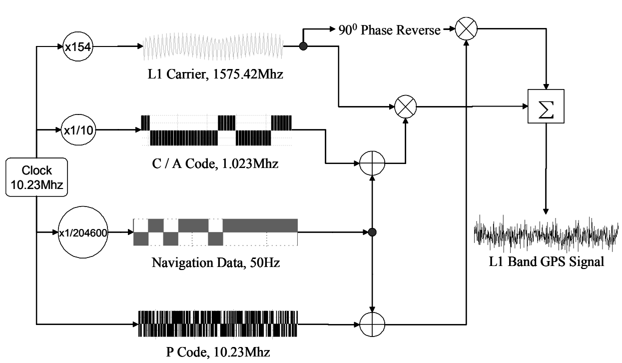
In this paper, we limit our discussion within the L1 band and C/A code only since L2 band and P code are used primarily for military purpose and the encryption codes are not available to the civilian community. We will explain briefly GPS signal structure and software-based GPS receiver architecture. The main focus of the paper is on how GPS signal can be processed by using acquisition and tracking algorithms to extract the navigation data bits from the raw data. The navigation data bits provide all the necessary information to compute the pseudorange between the receiver and the visible satellites.

2. GPS Signal Structure

GPS has two bands, L1 and L2. L1 band has C/A code, P-code and navigation data. L2 band has only P-code. The P-code is encrypted using encryption code and is called Y-code. C/A code is a sequence of zeros and ones and is unique for every satellite. The code is based on Gold Codes. Two sets of gold codes with different phase tappings are used to generate unique C/A code for every satellite. The C/A code is also called PRN code. PRN code or number is assigned to each satellite based on which PRN code is assigned to a particular satellite. If PRN (C/A) code 1 is assigned to a satellite, then this satellite is named as PRN-1. The properties of C/A codes are that they have the best cross-correlation characteristic. The cross-correlation between any two codes is much lower than auto-correlation of each of the codes. The frequency of the C/A code is 1.023 MHz. P-code is also a sequence of zeros and ones and is generated using a set of Gold Codes. P-code has a frequency of 10.23Mhz.

The GPS L1 band frequency is 1575.42Mhz and L2 band frequency is 1227.60Mhz. Navigation data are also a sequence of zeros and ones based at a rate of 50 bits per second. The navigation data structure is defined in the interface control document (ICD) of GPS. The navigation data and C/A code are modulated with the carrier wave using BPSK (Binary Phase Shift Keying) and DSSS (Direct Sequence Spread Spectrum) techniques. DSSS is a type of CDMA hence all the satellites use the same carrier frequency but different code.

Fig.1 shows a general schematic to generate a L1 band signal as represented by the equation shown in the figure for C/A code. Navigation Data Format is given in detail in Interface Control Document.



$$r_i(t) = \sqrt{2P_i(t)} \cdot CA(t - \tau_i(t)) \cdot D(t - \tau_i(t)) \cdot \cos\left(2\pi\left(f_L + \delta f_{L,i}(t)\right)t + \phi_i(t)\right) + n_i(t)$$

Fig. 1: Schematic showing the generation of L1 band GPS signal. The equation is the mathematical representation of C/A code in L1 band

3. Software-based GPS Receiver Architecture

The architecture of software-based GPS receiver is as shown in Fig. 2. It consists of an antenna and a RF front-end devices, which are the only hardware devices of the system. The RF front-end device is necessary to downconvert the GPS signal to an intermediate frequency (IF), sample the IF signal and digitize it. The present CPU capacity is still unable to process the GPS signal directly from the antenna in completely software-based approach. Thus a RF front-end device is still necessary. In conventional hardware-based GPS receiver, the lower three blocks in Fig. 2 are implemented in an IC chip and hence the user does not have a free access to the algorithms built inside the chips. In software-based receiver, these blocks are fully implemented using high level programming languages and hence the user has complete control over the algorithms. This is the main difference between the software-based GPS receiver and a conventional hardware receiver. The front-end IF is 4.1304Mhz, sampling frequency is 16.368Mhz and four bits per sample.

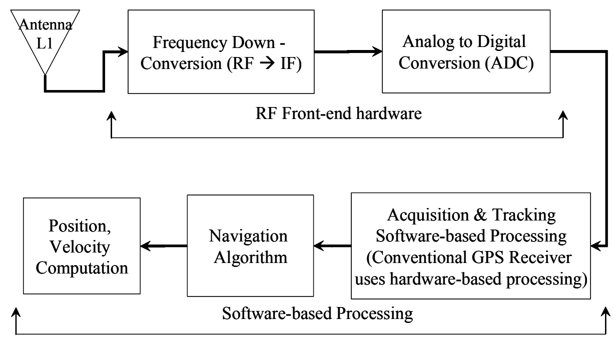


Fig. 2: Architecture of Software-based GPS Receiver

4. Signal Acquisition

The GPS signal is combination of carrier wave, C/A code and navigation message. In order to extract the navigation message from the GPS signal, it is necessary to remove the carrier wave (demodulate) and the C/A code (de-spread). After, demodulation and de-spreading, we get only the navigation message and noise. These navigation messages are then interpreted based on the definitions or coding scheme provided in the interface control document (ICD) of GPS. Fig. 3 shows raw GPS signal.

The main purpose of acquisition is to identify the visible satellites in the data and then find the beginning point of the C/A code and the Doppler frequency by correlating the incoming signal with receiver generated signal. There are different methods to perform acquisition, for example, serial search in time domain or parallel search (FFT method) in frequency domain. Serial search is implemented in hardware based receivers due to it’s simplicity in implementation though it is the slowest method. Fig. 4 shows algorithm description for serial search. We will discuss in detail only the parallel search (FFT method) in frequency domain since serial search method is extremely slow for software-based implementation.

4.1. Data Length for Acquisition

It is necessary to know how much data is necessary to perform acquisition. The longer the data the longer is the processing time. Longer data improves S/No ratio. However, since, fast acquisition is critical for real-time implementation of software-based GPS receiver, the optimum length of data should be used for successful acquisition. There are two factors that limit the selection of longer data period. One of them is the length of the navigation data, which is 20ms and the other one is the change in Doppler frequency. Since, the navigation data length is 20ms, the possible longest data length is 10ms. It is based on the fact that, if the first 10ms of the data has phase transition due to the navigation data bit, there will be no phase transition in the next 10ms of data. Since, the C/A code is 1ms long, it is enough to perform acquisition on 1ms of data. Even if there is a navigation data transition in 1ms of data, there will be no such transition for the next 19ms of data. Hence, at least a few milliseconds of data shall be used for successful acquisition. However, this is again the balance between the processing time and data length. A rule of thumb is to use one or two millisecond of data for strong signals and use around five to ten milliseconds of data for weaker signals. But, the problem, again is how to find out whether a signal from a particular satellite is strong or weak before acquisition. Thus, it is recommended to perform acquisition at least on two consecutive data sets. In any case, the data length can not exceed 10ms unless we have a technique to handle the navigation data transition effect during the acquisition process.

The effect of change in Doppler frequency imposes restriction on data length. If a perfect correlation is one, the correlation peak decreases by half when a C/A code is off by half a chip [6]. This corresponds to six dB decrease in amplitude. Let's assume that C/A code frequency is 1.023Mhz and the maximum Doppler frequency possible on C/A code is 6.4Hz [6], it takes 78ms for two frequencies to differ by 6.4Hz to change by half a chip. Since, 78ms is much longer than 10ms limitation due to navigation data transition, 10ms shall be considered as the maximum possible data length for acquisition.

4.2. Doppler Frequency Search Step

Doppler frequency search step is another key factor for successful and fast acquisition. The maximum Doppler frequency that needs to be searched is +/-10Khz [6]. It is necessary to determine the frequency step to cover this 20Khz of frequency range. The frequency step is related to the length of data used in acquisition. When the two signals are off by one chip, there is no correlation. If they are off by half a chip, there will be partial correlation. Let's assume that the maximum chip offset allowed is half a chip. In this case the correlation amplitude decreases by 6dB. If the data length is 1ms, 1Khz signal will change one cycle in 1ms. In order to keep the maximum frequency separation within 0.5 cycle in 1ms, the frequency step should be 1Khz. Hence, the furthest frequency separation between the input signal and receiver generated signal is 500Hz or 0.5Hz/ms. If the data length is 10ms, a search frequency step of 100Hz will fulfill this requirement. Thus, we can conclude that if the data length is 1ms, frequency step is 1Khz, and of the data step is 10ms, the frequency step is 100Hz.

4.3. FFT based Method

The purpose of acquisition is to identify the visible satellites in the GPS raw data. This can be achieved by correlating the incoming signal by the receiver generated signal. If the two signal matches, we find a very high correlation peak (this is the characteristics of C/A codes). However, since the carrier wave is affected by the Doppler shift, we have to account for the Doppler frequency in the receiver generated signal. Since, we do not know the exact Doppler shift, we need to search within a possible range of the Doppler frequency values. Also, in the beginning, we do not have any idea of visible satellites and hence we need to search for all the possible satellites. This means generating the receiver signal at different carrier frequency offset by Doppler frequency increment with different C/A codes. If we already have some prediction of visible satellites, then we can limit our search within those satellites and hence searching for a few satellites only that are supposed to be visible. Computation time for acquisition is critical for real time implementation of software-based GPS receiver. The outputs of acquisition are used for tracking the signal so that both carrier and code can be stripped off from the incoming signal.

Since the sampling frequency of the signal is 16.368Mhz, there are 16368 points (chips) in one C/A code period of duration 1ms. In order to perform acquisition, we generate C/A code of 1ms period and resample it to 16.368Mhz so that we will have 16368 points. The carrier wave is generated for a frequency range of 10Khz above and below the centre frequency with a frequency step of 1000Hz or 500Hz. If we use 1000Hz search frequency step, we will have a total of 21 Doppler frequency steps to cover a search space of 10Khz above and below the center frequency. FFT on 16000 points with 21 frequency components will generate altogether 16000x21 pint outputs. The C/A code search resolution is 62ns which is about 18.33mtr. The acquisition algorithm using FFT based method is shown in Fig. 5. Fig. 4 shows the acquisition algorithm for serial search method.

Fig. 3 shows a raw GPS signal output from the RF front-end device. This signal is correlated with receiver generated C/A code and carrier frequency with Doppler frequency range of +/-10Khz at a step of 1Khz. Fig. 6 shows the result of acquisition for satellite 10. The figure shows both the C/A code beginning point and the Doppler frequency component. Fig. 7 shows the acquisition result of the same data set but using 3ms of data length. We can see a clear improvement of S/No ratio in case of longer data period but it needs longer computation time. The outputs from acquisition are used in tracking algorithm as the initial C/A code beginning point and Doppler frequency estimate.

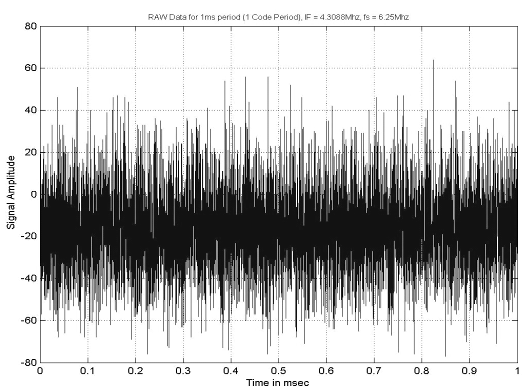


Fig. 3: Raw GPS Signal, Front-end output

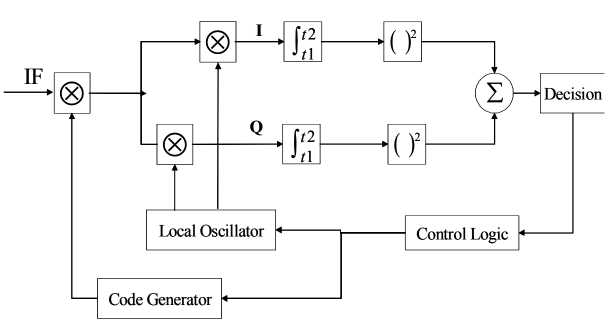


Fig. 4: Algorithm for Serial Search Acquisition

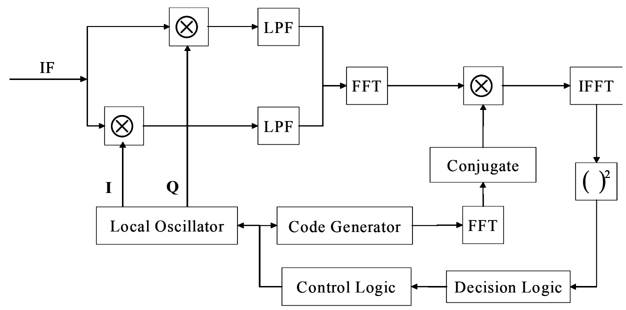


Fig. 5: Algorithm for Parallel Search FFT-based Method Acquisition

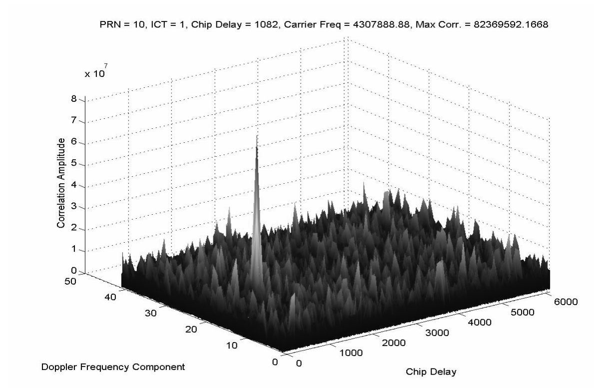


Fig. 6: Acquisiton of GPS signal with 1ms data

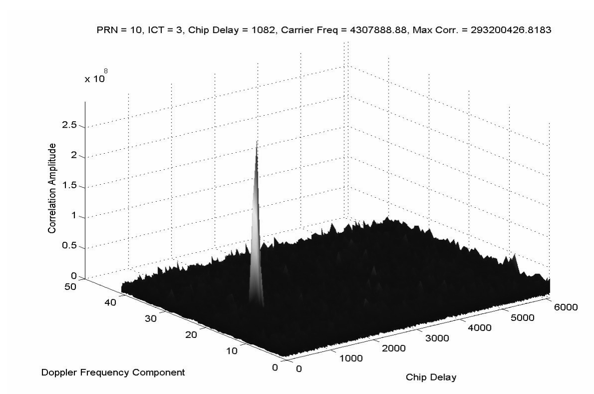


Fig. 7: Acquisition of GPS signal with 3ms data

5. Signal Tracking

The tracking loop follows the incoming signal and adjusts itself to de-spread and de-modulate the incoming signal. If the receiver is stationary, the rate of change of Doppler frequency is small and hence the update rate of tracking loop is also small. In order to track the incoming GPS signal, we need to use two tracking loops. Delay Lock Loop (DLL) is used to track the C/A code (de-spread) and Phase Lock Loop (PLL) is used to track the frequency of the incoming signal that is related with Doppler frequency. Fig. 8 shows the algorithm details of tracking loop. DLL consists of early, prompt and late code generators, filters and discriminators. The early and late codes are prompt code that is time shifted by half a chip or less. The early an late codes correlate with incoming C/A codes to produce two outputs. These outputs are filtered, squared and compared using a discriminator. Based on discriminator output, a control signal can be generated to adjust the rate of the locally generated C/A code to match the C/A code of the incoming signal. Different discriminators can be used, for example, E-L envelope (which is used in the present algorithm), E-L power or E-L normalized. The locally generated prompt signal is used to de-spread the incoming signal.

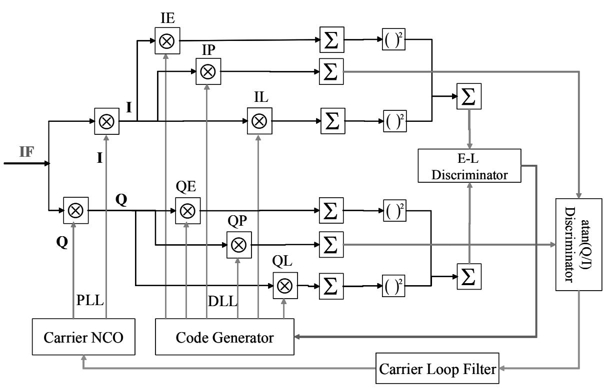


Fig. 8: Algorithm details for signal tracking loop. The loop contains DLL and PLL

The Phase Lock Loop (PLL) consists of NCO (Numerically Controlled Oscillator), carrier loop filter and a discriminator. PLL receives signal that is only modulated by navigation message. The NCO generates a carrier frequency based on the Doppler frequency computed during the acquisition process. The signal generated is divided into in-phase (I) and quadrature (Q) components. The input signal is correlated with I and Q channel signals. The outputs of the correlators are filtered and the phase is analysed suing a discriminator. The discriminator used in this algorithm is arc tangent discriminator that is insensitive to the phase transition. A PLL that uses arc tangent discriminator is similar to Costas Loop. The output of the discriminator is used to generate a control signal to tune the frequency of the oscillator (NCO) so that the loop can continuously de-modulate the incoming signal. We can use second or third order of PLL. Higher order PLL is recommended for high dynamics of the GPS receiver. The second order PLL is given by (1). Refer [6] for details on PLL.

The parameter values of damping factor, natural frequency and loop gain are chosen by hit and trial or by applying thumb rule. The damping factor value of 0.707 considered to be optimum, but this is not only the solution. This value seems to be behaving well when tested with different types of data sets. However, the change in natural frequency (which depends on the noise bandwidth) and loop gain has effects on success or failure of the tracking. These parameters are related with the incoming signal strength. Normally a noise bandwidth of 20Hz and loop gain of 400*π shall successfully track the incoming signal.

$$H(z)=\frac{k_0k_1(C_1+C_2)z^{-1}-k_0k_1C_1z^{-2}}{1+[k_0k_1(C_1+C_2)-2]z^{-1}+(1-k_0k_1C_1)z^{-2}} \qquad (1)$$

where,

$$C_1=\frac{1}{k_0k_1}\frac{8\xi\omega_n t_s}{4+4\xi\omega_n t_s+(\omega_n t_s)^2} \qquad (2)$$

$$C_2=\frac{1}{k_0k_1}\frac{4(\omega_n t_s)^2}{4+4\xi\omega_n t_s+(\omega_n t_s)^2} \qquad (3)$$

Fig. 9 shows the output of the tracking loop. In this case, a non-coherent integration of 10ms is done. I-channel consists of representation of navigation data bits and Q-channel consists of noise only. As seen in Fig. 9, it takes some time for the loop to track the incoming signal with correct phase.

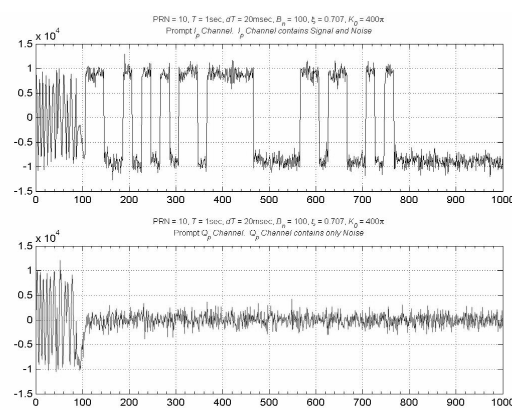


Fig. 9: I (top) and Q (bottom) channel output from tracking loop. I-channel represents navigation data and Q-channel contains only noise

As long as the loop can keep the track with the incoming signal, the navigation data are extracted and we call it lock on the incoming signal. This continuous lock depends on the sensitivity of the loop with respect to the incoming signal. If the receiver is moving with high dynamics (higher velocity or change in velocity), the loop update rate must be able to be keep in track of the incoming signal. Thus, a stationary receiver is easier to maintain continuous track. Fig. 10 shows the extraction of navigation data bits from the output of I-channel. There is one navigation data bit for every 20ms of data.

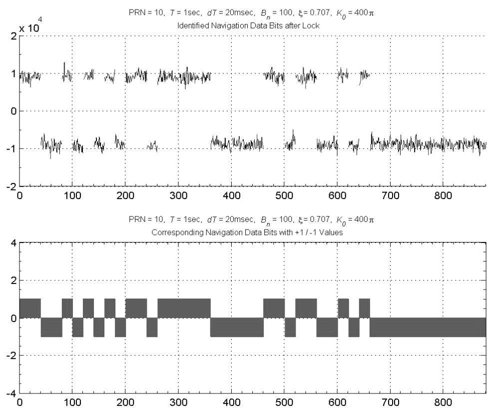


Fig. 10: Coding of navigation data from I-channel

6. Conclusions

We have completed the algorithms for acquisition and tracking. The algorithms have been tested on various data sets in different environment using different type of antenna including left hand and right hand polarized antenna. We have found that, it is necessary to tune the parameters of the tracking algorithm and threshold values of acquisition either dynamically or based on some rule for successful acquisition and tracking of GPS signal in standard environment. In some cases, we have found that tracking could not be done for satellites though acquisition is perfect. In this case, a change of parameter values of the PLL loop manually makes the tracking successful. This type of manual setting shall be automated in the future. The future work consists of extracting the navigation message from the tracking output and to compute the position of the receiver. It is also necessary to make the processing as fast as possible.

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