Acquisition to Tracking and Coasting for Software GPS Receiver

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Abstract

The goal the software GPS receiver is to do acquisition and real-time tracking of GPS C/A codes in software using a receiver front-end, an Analog-to-Digital converter (ADC) and a PC to do the processing. To start tracking two parameters need to be obtained from the acquisition process: the Doppler frequency of the signal, and the sample on which the C/A code sequence for the satellite begins. Software based acquisition normally uses 1 msec of data (5 msec for fine frequency resolution), but the process can take 1 sec or more for weak signals. The C/A code position shifts over time, and for stationary receivers there is a linear relationship between the rate of this shift and the Doppler frequency of the signal. One way to deal with this shift in the C/A code is to store all samples collected during the acquisition process so as to start tracking at a point immediately after acquisition, but this would be prohibitive in both processing time and storage requirements. A better way is to develop a method to estimate on which sample the C/A code sequence begins after a period of time. The linear relationship between the Doppler frequency and the C/A code shift can be used to predict the code position, and this method is affective for a period of up to 30 seconds after acquisition. This linear relationship can also be used to allow C/A code tracking to coast and immediately resume after a drop out due to interference or jamming. Since A/D converters clocks often have small variances from their specified sampling frequencies and this variance leads to a bias in the amount of C/A code shifting relative to the Doppler frequency. Because of this, one must test each A/D converter to find this bias.

I. Introduction

One problem with the software approach to a GPS receiver is the flood of data that is constantly being input to the PC. The ADC we used to collect C/A code data operates at 5 Msamples/s and software based acquisition takes from approximately 1second for strong signals to 10 seconds or more for weak ones. The C/A code position relative to the 1 msec integration interval shifts over time due to the Doppler frequency and errors in the ADC clock and local oscillator. Because of this, it is not possible to simply take the code position result obtained from the acquisition process and use it to start tracking the signal with data coming in when the PC finishes acquisition. One way to deal with this shift in the C/A code is to store all samples collected during the acquisition process so as to start tracking at a point immediately after acquisition, but this would be prohibitive in both processing time and storage requirements. A better way is to develop a method to estimate on which sample the C/A code sequence begins after a period of time. The linear relationship between the Doppler frequency and the C/A code shift can be used to predict the code position, and as we shall see, this method is effective for a period of up to 30 seconds after acquisition.

II. The Software GPS Receiver

Although it is covered in the paper *Block Adjustment of Synchronizing Signal (BASS) for Global Positioning System (GPS) Receiver Signal Processing* [(1)], a short description of this receiver is in order here. The basic difference between the software GPS receiver and a conventional GPS receiver is that in the software receiver everything after the ADC is done strictly in software. In a conventional receiver the satellite acquisition and the early-prompt-late tracking code correlators are done in hardware. Figure 1 shows a block diagram of the software GPS receiver.

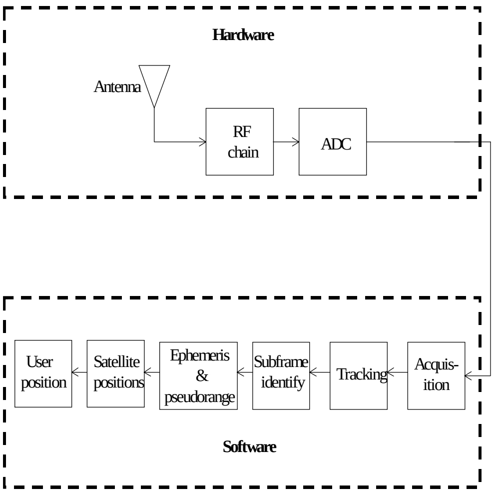

Figure 1 - Software GPS Receiver

The hardware portion of the receiver consists of antenna with an integrated 25 dB amplifier. The RF chain provides an additional 90 dB of and filtering to reduce the bandwidth to 2 MHz. A local oscillator operating at a nominal frequency of 1554.17 MHz downconverts the L1 carrier to 21.25 MHz. The ADC operates at 5 Msamples/s yielding an unambiguous bandwidth of 2.5 MHz. The ADC folds the downconverted signal to the center of its band, with a center frequency of 1.25 MHz. With this sampling rate 5000 samples equals 1 msec which is the period of one complete C/A code.

Acquisition is a two dimensional process that determines the Doppler shifted frequency of the carrier and on which sample the C/A code sequence of the satellite begins. A detailed description of how the GPS software receiver performs acquisition is given in the above mentioned paper, so it will only be briefly discussed here. The first step is to do a circular convolution in the frequency domain between the input signal and 21 distinct locally generated signals. Each local signal is generated by the product of a digitized C/A code and a complex sinusoid at one of 21 possible carrier frequencies spaced 1 kHz apart to cover 20 kHz centered at 1.25 MHz. The peak value of these convolutions yields the sample on which the C/A code begins and coarse determination of the carrier frequency (+/- 500 Hz). Further calculations are then performed to give a finer estimate of the carrier frequency, which is usually well within 10 Hz of the true incoming signal frequency plus any offset due to errors in the local oscillator and the ADC clock frequencies. Since it is difficult to separate these two errors, in the future we will combine them and simply call it the clock error. Since these errors are also present in tracking data so they need to be included in the Doppler frequency passed to the tracking routines. Figure 2 shows a typical result of the acquisition process.

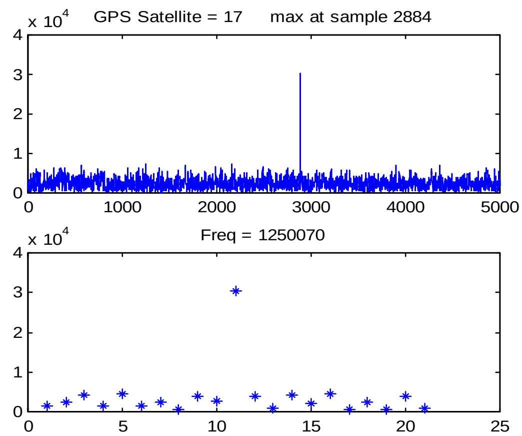

Figure 2 – Typical Acquisition Result

III. Acquisition to Tracking

The problem with the above process when used in a real-time processing situation is that acquisition for most satellites takes approximately 1 second when using compiled C++ code on a Pentium II 400 MHz PC. For weaker signals this process can take as much as 10 seconds due to longer integration periods or the use of non-coherent integration methods. Signal tracking in the GPS software receiver is done by taking 1msec segments of input data aligned with the C/A code sequence and correlating them with a local code. If the received signal had a Doppler frequency offset of zero and the ADC clock and local oscillator were exactly at the specified frequency i.e. precisely 5 MHz and 1554.17 MHz respectively, then however long into the future you wanted to start tracking you could use the code position result of the acquisition process. For example, if the sampling rate is 5 Msamples/s and acquisition said that the C/A code sequence begins on sample 1500, then one second later a C/A code will begin on sample 1500 + 5,000,000 = 5,000,1500. But in the real world satellites are rarely overhead and ADC clocks are not so precise. One consolation is that during short time frames the Doppler shift on the carrier for a stationary receiver will not change enough (< 30 Hz per second) to cause a problem.

As stated in the introduction there are two ways to solve this problem; store the incoming data collected while the acquisition processing is being done, or predict the C/A code position after some interval. The first solution is for the moment not practicable in a real-world situation because of the storage and computational requirements. For example, if acquisition required 10 seconds and you are using a 5 Msamples/s 8-bit ADC, then 50 MB of data would have to be stored. Just as bad would be the requirement of tracking 4 or more satellites at greater than real-time speed while data from the ADC continued to pour in. Because of this predicting the position of the C/A position is much preferred and is also quite simple to implement.

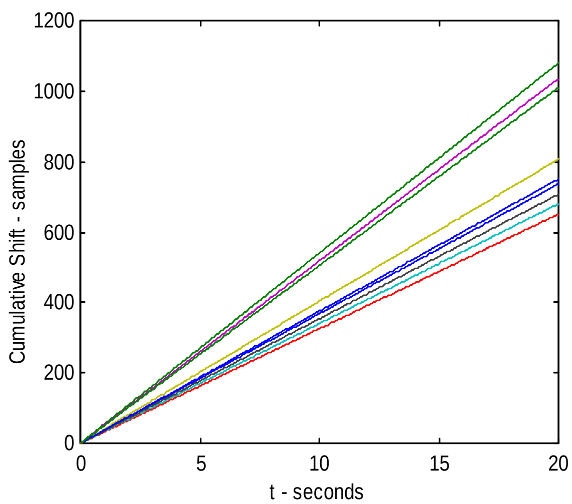

Figure 3 – Cumulative C/A code Shifts

IV. Predicting C/A Code Position

As can be seen in figure 3, the relationship between the Doppler frequency of the carrier and the rate of C/A code shift is a linear one. This graph takes some explanation, but is a good way to visualize the relationship between the Doppler frequency and code shifting. The graph represents the cumulative shifting in the C/A code start position for 9 satellites over 20 seconds. If you divide the sampled data into nominal 1 msec segments of $n = F_S / 1000$ samples, then in the first segment the C/A code sequence will begin on some sample *pt* of *n* samples. If 10 msec later there is a shift of one sample to the right, then the C/A code begins on sample *pt + 1* of *n* samples. The cumulative shift at this point would be one. For example, GPS data is being sampled at 5 Msamples/s, so *n* = 5000. If satellite 17's C/A code begins on sample 1500 of 5000 and after 10 seconds it begins on sample 1900 of 5000, then the cumulative shift after 10 seconds is 400 samples.

The two critical factors that that are used to estimate the code position are the Doppler frequency of the carrier and the clock error.

The formula for this prediction is:

$$pt = pt_0 + \left(-\frac{F_S}{F_C} \times T_{C/A} \times F_D + err \right) \times t \qquad (1)$$

Where:

pt	Predicted C/A code start sample
pt_0	Initial C/A code start sample
F_S	Nominal sampling frequency (Hz)
F_C	Nominal carrier frequency w/o Doppler (Hz)
F_D	Measured carrier frequency - F_C (Hz)
$T_{C/A}$	Length of C/A code sequence (1 msec)
err	Clock error (samples/second)
t	Coasting time (seconds)

For example, if acquisition for satellite 17 in the above example gives a Doppler frequency F_D of 1200 Hz as measured by the acquisition process, an initial C/A code position of 1500, and their is a clock error of 45 Hz, then the code position after 10 seconds would be:

$$pt = 1500 + \left(-\frac{5\times10^6}{1.25\times10^6} \times 10^{-3} \times 1200 + 45 \right) \times 10$$

$$pt = 1902 \qquad (2)$$

If the above equation is used to make the jump from acquisition to tracking it is necessary to have an accurate estimate of the clock error. In the above example, there was a positive shift of 225 samples due to the clock error while there was negative shift of only 24 samples due to the measured Doppler frequency. Note that the Doppler frequency measured by the acquisition process is inaccurate and contains errors. Since these errors included in the Doppler frequency are multiplied by 10^{-3}, they are much less of a factor. All this means that the ADC clock error is the dominant factor in the calculation as can be seen in figure 3. Since satellites used in this graph had both positive and negative measured Doppler frequencies, the clock error gave all the results a sharp positive slope. Deviations of 45 Hz or more from the nominal frequency as seen in the above example are not unusual for crystal oscillators. An estimate of this clock error can be obtained in many ways, but one method is to reverse the above equation and compare the cumulative shifts in C/A code tracking to the Doppler frequency of the signal.

Figure 4 is another view of the relationship between Doppler frequency and C/A code shift. This figure shows a graph of Doppler frequency measured by the acquisition process vs. the slope of the cumulative shift lines seen in figure 3. The points on this graph approximate a straight line and clearly show the linear relationship between Doppler frequency and C/A code shifting. Note that one of the satellites has a Doppler frequency near zero (70 Hz) and still there is a shift of approximately 40 samples/second. Modifying equation 1 and using the slope of the cumulative shifts gives the following equation for predicting the clock error:

$$err = slope + \left(\frac{F_S}{F_C} \times T_{C/A} \times F_D \right) \qquad (3)$$

Best results with this equation are obtained when averaged over all the satellites being tracked. Using the data found in Figure 4 and averaging for all the satellites; we obtained a result of 40.315 samples/second in clock error.

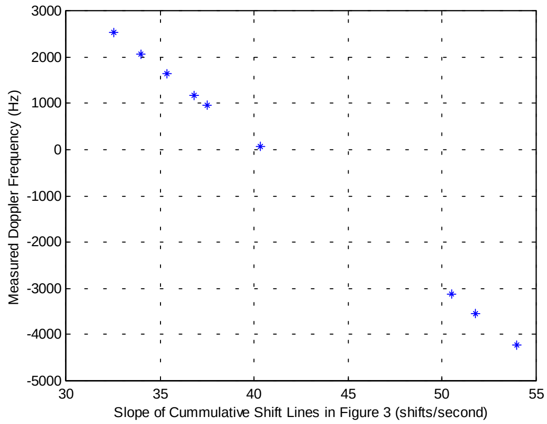

Figure 4 – Doppler Frequency vs. C/A Code shifts/second

The linear relationship between Doppler frequency and C/A code shifting can also be used to coast during tracking, and is in fact even easier to implement since there is no need for an accurate estimate of ADC clock error. Coasting can be easily done by keeping track of the cumulative shifts in the C/A code on the fly, then linearly extrapolating these shifts into the future. This ability to coast can be used to resume tracking after a momentary loss of signal without having to redo acquisition. It can also be used to intentionally stop tracking and skip ahead in time and then seamlessly resume tracking the signal. For example, each satellite can be tracked for only 100 msec out every second to obtain a psuedorange for position calculations. This would cut the calculation load for tracking by a factor of 10 and since tracking is the most computationally intense part of the GPS software receiver, this would result in great increase in speed.

It should be noted that predicting the C/A code start sample does not work for an indefinite time period. Errors in the measured Doppler frequency, the estimate of the ADC clock and local oscillator error and even changes in the Doppler frequency over time limit the period over which this method can be applied. Once these errors exceed one half a chip, the tracking routine will not lock onto the satellite's signal. In our experiments, this method generally worked out to about 30 seconds but quickly ceased to function after this. Working with other hardware will of course give lesser or greater intervals depending on it's quality.

V. Conclusions

As we have shown, it is possible to predict where the C/A code sequence begins after a time of up 30 seconds without actually tracking the signal. This method can be applied to making a seamless jump from acquisition to tracking in the software GPS receiver. It can also be used to resume tracking after a momentary loss of signal without having to reacquire the signal. For stationary or slow moving vehicles the simple method we outlined should be sufficient to resume tracking. For highly maneuverable vehicles it may be necessary to couple the above equation with the velocity and acceleration outputs of a Kalman filter position estimator.

References

1. Tsui, J.B.Y., Akos, D.M. and Stockmaster, M.H., "Block Adjustment of Synchronizing Signal (BASS) for Global Positioning System (GPS) Receiver Signal Processing ", Proc. ION, September 1997.
2. Kaplan, Elliot D., et al., *Understanding GPS Principles and Applications,* Boston, MA: Artech House, Inc., 1996, pp. 48-54