COMPARISON OF DIRECT AND DOWNCONVERTED DIGITIZATION IN GPS RECEIVER FRONT END DESIGNS

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ABSTRACT

This paper compares two front end designs of a global positioning system (GPS) receiver. The first approach is the direct digitization of the input signal and the second approach is to downconvert the input signal to an intermediate frequency (IF) then digitize it. Theoretically, these two methods should produce similar results and our experimental data support this argument.

I. INTRODUCTION

The signal of interest in this study is the GPS L1 band signal modulated with the coarse/acquisition (C/A) code and navigation data. A majority of the GPS receivers digitized the input signal and use digital signal processing to perform the necessary functions.

The conventional approach used in the frond end of a GPS receiver is to amplify the input signal, then downconvert it to an IF. The IF signal is further amplified and digitized(1). In this approach, the radio frequency (RF) chain in front of the analog-to-digital converter (ADC) contains amplifiers, filters, a mixer and a local oscillator. The advantages of this approach are: 1) The requirements of the ADC are less stringent, because the input frequency is only required to accommodate the reduced IF. 2) The filter after the IF requires a lower Q value to cover the same bandwidth. The disadvantage is that a local oscillator and a mixer are required, or even additional components if multiple stages are used, to downconvert the input frequency before digitization.

Theoretically, the input signal can be digitized directly and similar results should be obtained. In this approach, the mixer and local oscillator are no longer needed. The disadvantages are: 1) The ADC must accommodate the input L1 frequency of 1.57542 GHz, although the sampling frequency is much lower at 5 MHz. 2) The filter centered at the L1 frequency with a desired bandwidth of approximately 2 MHz requires a very high Q.

In this paper both direct digitization and downconverted approaches are discussed with experimental results presented. A direct digitization approach has been published by Brown(2). In that work the ADC operates at 800 MHz but only with one bit sampling. In this experiment, the ADC operates at 5 MHz with 8 bit sampling. Off line processing was used to detect the signals.

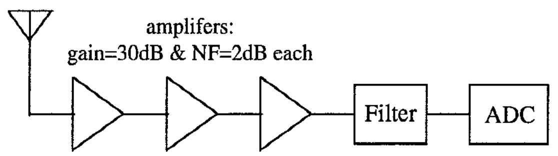
In the next section, the experimental set-up will be presented. In Section III, a continuous wave (CW) is used to determined the signal-to-noise ratio and the results are compared with the theoretically predicted ones. In Section IV, results obtained using true GPS signals will be discussed briefly. The paper concludes with a summary of the results.

II. EXPERIMENTAL SET-UP

The guaranteed minimum power level of the L1 band C/A code GPS signal is at -130 dBm. A Tektronix TDS 684A digital scope was used as the ADC which has a minimum sensitivity of 1 mv (about -50 dBm). Therefore, the input signal must be amplified at least by 80 dB. In both the direct and downconverted digitization experiments over 90 dB gain was used. The input bandwidth of the scope is specified as 1 GHz and 8 bit amplitude resolution, but it can digitize the L1 frequency without problems. One of the disadvantages of using the scope as the digitizer is that the sampling frequency can only be set at certain fixed values. Under this condition, the input frequency may not be aliased to a desired frequency. This problem will be further discussed later in this section.

In the direct digitization, the experimental set-up is shown in Figure 1. The input signal was

Figure 1: Experimental Set-up for Direct Digitization



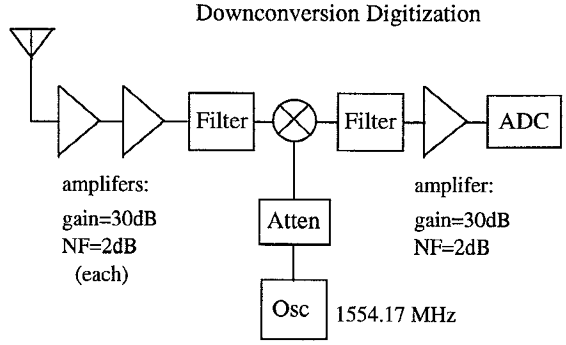
amplified using 3 amplifiers with a nominal gain of 30 dB and noise figure of 2 dB. A total of 92 dB of gain was measured from three amplifiers combined. The filter following the amplifier chain has an insertion loss of 3.2 dB and 3 dB and 30 dB bandwidths of 3.4 MHz and 10.3 MHz, respectively. It is difficult to build a filter with a narrower bandwidth, because of the relatively high center frequency. The filter dimension is 3x6x14 cm^3.

The null-to-null bandwidth of the C/A signal is about 2 MHz. Theoretically a minimum sampling frequency of 4 MHz will accommodate the signal, although the center frequency is close to 1.6 GHz. In this experiment, a 5 MHz sampling frequency was used which should accommodate the 2 MHz bandwidth without spectrum overlap. This sampling frequency will alias the 1575.42 MHz into 420 kHz. It is desirable to alias the input frequency close to 1.25 MHz, the center of the band, because the sideband will have less interference. Since the input data is real, in contrast to complex, one single frequency will produce two outputs through the FFT. If the frequency is close to an alias zone boundary, the sideband of the two outputs may interference with each other. If the sampling frequency can be changed to 4.99737 MHz, the input frequency will be alias close to 1.25 MHz. However, the sampling frequency cannot be changed arbitrarily and 5 MHz was used to sample the input signal.

In this arrangement, one can consider that there are four disadvantages: 1) The filter has a bandwidth of 3.2 MHz which is wider than the minimum required of 2.0 MHz. As a result, additional noise will be aliased into the digitized data and the sensitivity of the receiver will suffer. 2) The physical dimensions of the filter are rather bulky. 3) The input frequency range of the ADC must be high enough to accommodate the input signal. 4) The input signal is aliased close to a zone boundary, but this problem is not an essential one in the general case as it can be corrected if the proper sampling frequency is used.

The downconverted arrangement is shown in Figure 2. In this figure about 60 dB of gain is

Figure 2: Experimental Set-up for Downconversion Digitization



placed in front of the first filter which has a center frequency of 1575.42 MHz and an insertion loss of 2.2 dB with 3 dB and 30 dB bandwidth of 86 MHz and 280 MHz respectively. The physical dimension of the filter is 1x2.5x3.5 cm^3. The mixer has an insertion loss of 6 dB. The local oscillator generates a 1554.17 MHz frequency which is applied to the mixer through a 3 dB attenuator. The downconverted frequency is at 21.25 MHz. The second filter has a center frequency of 21.4 MHz which is slightly off from the desired frequency. It has an insertion loss of 2 dB with 3 dB and 30 dB bandwidth of 2.25 and 5.16 MHz respectively. The filter dimension is 1x1.3x4.5 cm^3. These two filters are much smaller than the one used in the direct digitization. The 21.25 MHz signal sampled at 5 MHz will alias to 1.25 MHz, the center of the alias zone. The input frequency of the ADC required to digitize this IF signal is only in the 20 MHz range instead in the GHz range.

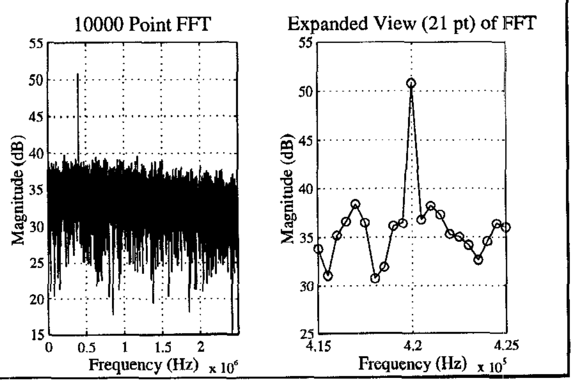
The disadvantage of this approach is the amount of hardware. A mixer and a local oscillator are needed. However, the filters are small in size and the IF filter has better selectivity.

III. CW TEST RESULTS

Two types of signals were applied to the input of the receiver front end. A GPS antenna was used to collect actual GPS signals. However, using GPS with its code division multiple access (CDMA) spread spectrum transmission it is difficult to obtain quantitative results to compare the performance of the two front end designs. Rather, a CW signal is used to determine the signal-to-noise ratio of both front end designs. This approach can provide a comparative level of performance. In this section the results of the CW test will be reported.

The digital scope used as the ADC can perform near real time FFT operation. The FFT output was used to determine the signal-to-noise ratio. For the direct digitization approach, a CW signal with frequency close to 1575.42 MHz and amplitude of -110 dBm was used as the input signal. The scope performed a 10,000 point FFT. Since the sampling frequency is 5 MHz, a 10,000 point FFT will span 2 ms which corresponds to a frequency resolution of 500 Hz. The input frequency was adjusted slightly so that the energy of the CW signal was contained within a single frequency bin. Figure 3 shows the results of the 10000 point FFT (positive frequencies only) and an enlarged view of only 21 points centered about the frequency bin of the CW signal. It appears that the signal only occupies one frequency bin.

Figure 3: 10000 Point FFT of CW Signal (Direct Digitization)



The signal power is calculated from the square of the signal amplitude and the noise power is calculated from averaging the square of the remaining data points. The signal-to-noise ratio measured is 32.0 dB.

For the downconverted case a similar approach was performed. The input frequency was adjusted to correspond with one output frequency bin. The only difference is output from the mixer is close to 21.25 MHz. The signal-to-noise ratio measured under this condition is 32.6 dB.

The expected signal-to-noise ratio can be found from the following procedure. The noise floor of a 500 Hz bandwidth system with 3 dB noise (including 1 dB insertion loss of the input cable) is:

$$NoiseFloor = -174 + 10\log(500) + 3 = -174 + 27 + 3 = -144 \; dBm$$

The corresponding signal-to-noise ratio (S/N) is:

$$S / N = InputSignal - NoiseFloor = -110 + 144 = 34 \; dB$$

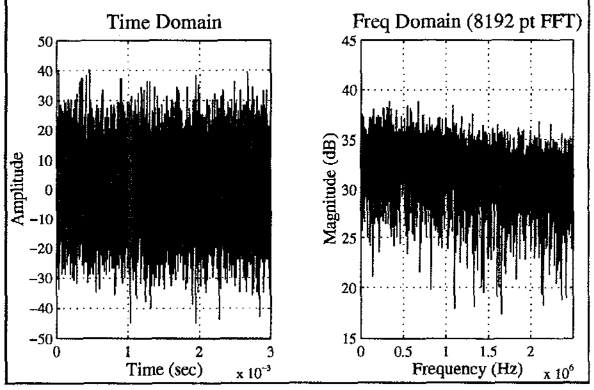
This result is about 1.4 dB lower than the predicted one. This error might be a result of the measurement equipment, e.g., there is no known equipment in our laboratory to measure the input power directly at -110 dBm. The other possibility is that filter bandwidth (2.25 MHz) is very close to the Nyquist sampling frequency (2.5 MHz), thus additional noise is folded into the desired band. However, the relative measurement, i.e. the results obtained from the downconversion method and direct digitization, should be accurate.

The signal-to-noise ratio of the down converted approach is 0.6 dB (32.6-32.0) better than the direct digitization. This difference can be ascribed as that the RF filter bandwidth (3.4 MHz) is wider than the Nyquist sampling frequency of 2.5 MHz and more noise will fold in the desired band. If a filter with narrower bandwidth can be built, the signal-to-noise ratio of both approaches should be equal.

IV. RESULTS WITH TRUE GPS SIGNALS

In this experiment, an antennas was placed at the input of the receiver front end to collect data from the GPS satellites. A GEC Plessey GPS receiver was used to determine which satellites were visible. The two antennas of the two systems were placed next to each other. The direct digitization configuration, depicted in Figure 1, has been modified slightly by the inclusion of an additional filter after the first amplifier to suppress out-of-band signals. A total of 15,000 data points were collected and Figure 4 shows the collected data from direct digitization in the time and frequency domains. Data obtained

Figure 4: Time/Freq Plots for a Direct Digitized Data Set



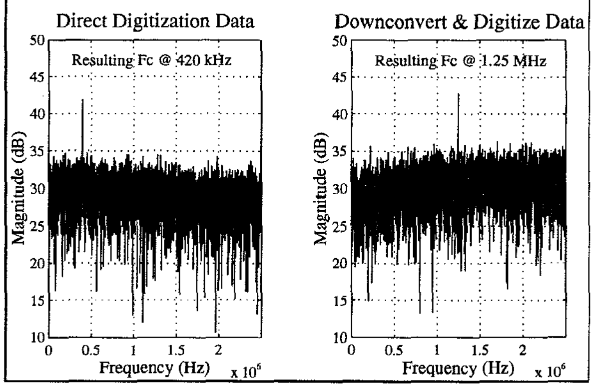
from the downconverted case, similar in appearance, is not shown

As is typically the case with CDMA transmissions, there is no discernible signal in the data set, as the signal power level is often below that of the noise floor of the receiver. It is important to note that at the same time the data was being collected for Figure 4, the GEC Plessey receiver was tracking five satellites. Thus these satellite's transmissions should be contained within the collected data set.

The first step in processing the GPS, or any CDMA signal is acquisition. That is the search to obtain the three parameters necessary for demodulation: spreading code, code phase, and carrier frequency. Once these have been identified, an FFT of the result of the correlation of the collected data and synchronized spreading code reveal the underlying GPS signal.

An acquisition algorithm was developed and applied to collected data from both front end designs[3]. The acquisition algorithm was coded to identify the acquisition parameters for one of the satellites being tracking. Figure 5 shows the post correlation FFT for both front end designs. In each case, the underlying signal is clearly evident. Thus this initial work shows either implementation can be successfully used as a GPS receiver front end.

Figure 5: Post Acquisition (Correlation) 8192 Point FFT



V. SUMMARY

This paper compares the results of two GPS front end designs: a direct digitization against downconversion. Theoretically, there is no difference in performance, and the measured results support this claim. The selection of the designs should base on the availability of hardware and cost. In the direct digitization, the requirements of the filter and ADC are more stringent. In the downconversion case, a mixer and local oscillator are needed.

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