Design and Implementation of a Direct Digitization GPS Receiver Front End

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***Abstract*— A direct digitization approach greatly reduces the hardware requirements in traditional front end design. Further, the hardware that has been eliminated is typically the source of a number of potential difficulties including age-based, temperature-based, and/or nonlinear performance. This paper presents a case study on the design and implementation of direct digitization Global Positioning System (GPS) receiver front end. First, sensitivity and dynamic range issues for a generic front end are discussed with particular attention given to the unique requirements in the direct digitization approach. Second, two GPS front end implementations are compared. The first is the direct digitization of the input signal at radio frequency (RF) as is the case in the true digital receiver or software radio. The second uses a more standard approach of downconverting the input signal to an intermediate frequency (IF) for further processing or digitization. Experimental data is presented which characterizes the relative signal-to-noise ratio for both implementations as well as the results of initial acquisition processing of true GPS data.**

I. Introduction

IN AN analog receiver, the components from the output of the antenna to the input of the crystal detector are considered the RF front end. The front end of a digital receiver typically uses a similar chain of RF components with the output of the final stage connected to an analog-to-digital converter (ADC) so that the resulting samples can be processed further using discrete signal processing. This chain of RF components, common to both implementations and depicted in Fig. 1, typically includes amplifiers, filters, local oscillators (LO), and mixers. As a result of the analog nature of these components, there are a number of negative consequences which can result from their use including age-based and temperature-based performance variations from the oscillators, as well as the nonlinear operation of the mixers. These performance issues are difficult to eliminate and can be even more difficult to model precisely.

High frequency sampling, or moving the ADC closer to the antenna, is typically advantageous as this reduces the number of components associated with frequency downconversion in the front end. However, there are two problems associated with high frequency sampling. First, it is difficult to fabricate high speed ADC's, especially with a significant number of bits. Second, even if a high frequency ADC can be built, it is formidable to process the output of such a device. Thus if a lower sampling frequency is adequate, it is desirable to build a narrower band system because of the less stringent processing requirements and associated potential lower cost.

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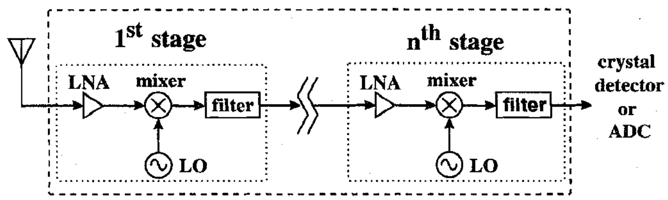

Fig. 1. Traditional receiver front end design (n stages).

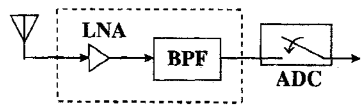

Fig. 2. Direct digitization receiver front end design.

A direct digitization front end eliminates the need for the various stages of frequency downconversion through bandpass sampling. Bandpass sampling, which will be examined in further detail in subsequent sections, is a technique where intentional aliasing is used to provide frequency translation [2], [3]. A direct digitization front end is depicted in Fig. 2. All of the components related to frequency downconversion have been eliminated. All that remains is the amplifier needed to obtain the necessary gain for processing and a filter for noise reduction. It is important to note that the direct digitization approach implies a digital receiver after bandpass sampling as analog signal processing is no longer applicable.

Although this paper focuses on the design and implementation of a Global Positioning System (GPS) receiver front end, the material presented can be generalized to the generic case. In the Section I, basic front end design equations are reviewed and a practical GPS front end implementation is considered. Section II discusses the sampling requirement for digital GPS receivers and reviews the possible techniques including bandpass sampling. Section III illustrates an additional consideration that must be taken into account in designing a direct digitization front end in order to achieve the expected performance. Last, a comparison is done between two GPS front end designs: one that uses the direct digitization technique and one that uses the more traditional downconvert and digitize approach. Theoretically, these two methods should produce similar results and our data support this argument. Experimental results are obtained for a test CW signal as well as true GPS signals.

II. Basic Front End Design

In general, sensitivity and dynamic range are the most important factors in a front end design. There are well-known equations to calculate both the sensitivity and the dynamic range of a receiver, if the RF front end design is selected [4]. These equations, with slight modification, can be used to calculate the performance of a digital receiver as well [5]. However, for digital receivers using bandpass sampling, additional conditions must be considered, otherwise the predicted results can not be realized.

An RF front end consists of amplifiers, filters, attenuators, and mixers. Each component has three fundamental parameters: gain, noise figure, and third-order intercept point. These three parameters and the way the components are arranged determine the gain, sensitivity, and dynamic range of the receiver. Three equations are used to determine the overall gain, noise figure, and the resulting third-order intermodulation point. The noise figure and third-order intermodulation point in turn determine the sensitivity and dynamic range. These equations are

$$G_T = G_1 G_2 \cdots G_N \tag{1}$$

where G_T is the overall gain of the front end and G_i is the gain of each component. The overall noise figure F_T can be written as

$$F_T = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1 G_2} + \cdots + \frac{F_N - 1}{G_1 G_2 \cdots G_{N-1}} \tag{2}$$

where F_i is the noise figure of each component. The overall third-order intermodulation product Q_{3T} is

$$Q_{3T} = \frac{G_T}{\dfrac{G_1}{Q_{31}} + \dfrac{G_1 G_2}{Q_{32}} + \cdots + \dfrac{G_1 G_2 \cdots G_{N-1}}{Q_{3N}}} \tag{3}$$

where Q_{3i} is the third-order intermodulation product of each individual component.

The three important criteria used to determine the gain, noise figure, and third-order intermodulation product are: 1) the gain must be matched, by adding attenuators, to a desired value, 2) the noise figure can be as low as possible, and 3) the third-order intermodulation can be as high as possible. However, the noise figure and the third-order intermodulation product are opposing parameters. The lower the noise figure is, the lower the third-order intermodulation product. In general, a compromise must be achieved between the noise figure and the third-order intermodulation and this arrangement determines the desired gain value.

As an example, consider the implementation of a front end to received the L1-band GPS Coarse Acquisition (C/A) code signal [6]. This example assumes that all necessary amplification and noise reduction filtering occurs directly at the RF carrier frequency of 1575.42 MHz, as would occur in a direct digitization front end. In a traditional front end design, this is not the case as these operations typically occur at the various stages of downconversion as to reduce the individual requirements on each of the components.

The guaranteed minimum power level of the GPS C/A code signal is −130 dBm. In order to detect the signal by a crystal detector or digitized it using an ADC, the power level should be at least of −40 dBm. A total of 90 dB gain is chosen to amplify the signal to the desired power level. Since a single 90 dB gain amplifier is impractical, the necessary gain can be obtained by cascading three identical commercially available amplifiers, each with the following specifications; frequency range: 1–2 GHz, gain: 30 dB, noise figure: 2 dB, third-order intermodulation point: 23 dBm. A bandpass filter centered at 1575.42 MHz with a 3 dB and 30 dB bandwidths of 3.4 MHz and 10.3 MHz, respectively, and insertion loss of 3.2 dB was available to limit the out of band noise. Ideally this filter should have a 3 dB bandwidth of 2 MHz, approximately the null-to-null bandwidth of the GPS C/A code signal. However, this would require a high Q value. These same components will be used in the actual implementation of the direct digitization front end of a digital receiver.

The above four components can be cascaded in different ways to obtain different designs. The general rule can be stated as follows. The closer the filter is placed to the antenna, the higher the noise figure and dynamic range are. If the filter is placed far away from the antenna, the opposite is true. All the input GPS signals are close in amplitude, thus the dynamic range requirement on the receiver is low, neglecting interference. All have the same carrier frequency, with any deviation caused by the Doppler effect. Since each amplifier has 30 dB gain and a 2 dB noise figure, the filter can be placed at any position after the first amplifier, with a negligible effect on the overall noise figure.

However, in a practical implementation it is judicious to place the filter after the first amplifier in order to limit other signals from generating spurious responses. This arrangement will limit out-of-band signals from getting into the second and third amplifiers. It is also possible to place the filter before the first amplifier to limit undesired signals. This arrangement will degrade the sensitivity by 3.2 dB, the insertion loss of the filter.

In the practical implementation of a direct digitization front end, there is another factor that must be considered. If the final component prior to ADC is an amplifier rather than a filter, additional noise will be folded, or aliased, into the resulting information band. The amount of noise folded into this band will be proportional to the amount of amplification, in terms of both gain and bandwidth, between the last filter and the ADC. This will be described and illustrated in further detail in the next two sections.

III. Sampling Frequency Requirement of Digital GPS Receivers

The center frequency of the L1-band GPS signal is at 1575.42 MHz and the C/A code has a null-to-null bandwidth of 2 MHz. There are two ways to consider the required sampling rate of the ADC. One way is determined from the center frequency and the other is from the bandwidth. In this section both sampling methodologies will be discussed.

If one desires the entire band unambiguously, the sampling rule requires a sampling rate of two times the center frequency. Therefore, the ADC must sample higher than 3 GHz which requires a state-of-the-art device. Even if one can find an ADC

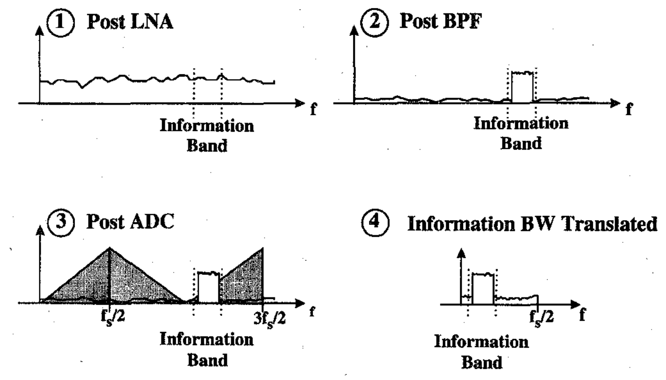

Fig. 3. Resulting frequency domain representation of the output of the various stages in the direct digitization front end (depicted in Fig. 2).

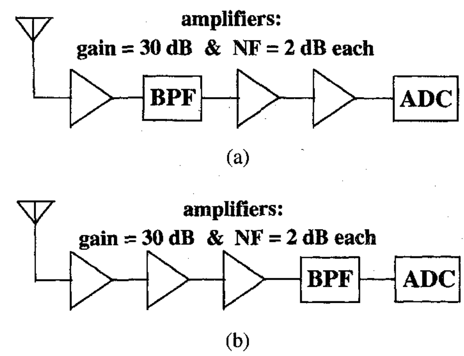

Fig. 4. Two different direct digitization front end configurations.

operating at this frequency, it is difficult, if not impossible, to process the output data at this rate. One advantage of this approach is that all the information from DC to 1575.42 MHz is unambiguous identified. For example, the information in the C/A code bandwidth will be uniquely determined. No signals or noise from other bands will fold into the desired bandwidth. This design is similar to an analog receiver implementation in which the information is uniquely identified. Limited by present technology, this approach may not be practical.

The Nyquist sampling theorem requires that the minimum sampling frequency must be two times the information bandwidth. This indicates a minimum sampling rate of 4 MHz will provide sufficient bandwidth to process the signal. In order to take a nonideal filter shape into consideration, 2.5 times the bandwidth is usually required. Thus a 5 MHz sampling frequency should be adequate. This is a much more reasonable rate to digitize the input signal particularly since the resulting discrete signal processing can occur at 5 MHz.

It is important to recognized that this implies given an appropriate filter and ADC, it is possible to sample an RF signal based only on its information bandwidth. The various stages of LO's, mixers, and image reject filters are no longer necessary. Frequency translation is accomplished by intentionally aliasing the signal of interest. Based on the direct digitization front end implementation in Fig. 2, the resulting output of each stage, depicted in the frequency domain, is shown in Fig. 3.

The choice of sampling frequency is dependent on the original carrier frequency, information bandwidth, and desired carrier frequency, or IF, after aliasing. Once these parameters have been established, (4)–(6) provide the necessary mathematical relationships to determine an appropriate sampling frequency [7]

$$\text{if fix}\left(\frac{\frac{F_C}{F_S}}{2}\right) \text{ is } \begin{cases} \text{even,} & F_{\text{IF}} = \text{rem}\,(F_C, F_S) \\ \text{odd,} & F_{\text{IF}} = F_S - \text{rem}\,(F_C, F_S) \end{cases} \tag{4}$$

$$\text{where fix}\,(a) \text{ is } \begin{cases} \text{the truncated integer} \\ \text{portion of argument } a \end{cases} \tag{5}$$

$$\text{where rem}\,(a, b) \text{ is } \begin{cases} \text{the remainder after} \\ \text{division of } a \text{ by } b \end{cases} \tag{6}$$

In the experiments that follow, a Tektronix TDS 684A digital oscilloscope was used as the ADC. This oscilloscope has a minimum sensitivity of 1 mV (about −50 dBm). The input bandwidth is specified as 1 GHz and 8 bit amplitude resolution, but experimental results show it can digitize the L1 frequency band. One of the disadvantages of using the oscilloscope as the ADC 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.

For example, with a null-to-null bandwidth of approximately 2 MHz, a 5 MHz sampling frequency should accommodate the information bandwidth without spectrum overlap. However, this sampling frequency will alias the 1575.42 MHz carrier to an IF at 420 kHz. It is desirable to alias the input frequency close to a 1.25 MHz IF, the center of the band, because there will be less interference introduced into the sidebands. Since the input data is real, in contrast to complex, one single frequency will produce two outputs through the Fast Fourier Transform (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 4.997 37 MHz, the input frequency will be aliased close to an IF of 1.25 MHz by folding the desired information band 630 times. However, using the available equipment the sampling frequency cannot be changed arbitrarily and 5 MHz was used to sample the input signal.

IV. Two Variations on a Direct Digitization Implementation

In this section, two direct digitization front end design examples will be presented. The signal-to-noise ratio (SNR) was measured using a CW signal as input. In the first example, the arrangement is the equivalent to that used in analog receiver design. The filter is placed after the first amplifier as shown in Fig. 4(a). Since the amplifier has a gain of 30 dB, the noise figure of the system is approximately 2 dB, the noise figure of the first amplifier. In this case, the filter only limits the noise generated from the first amplifier, but the noise generated from the second and third amplifiers is not limited by the filter.

The second example places the filter after the last amplifier as shown in Fig. 4(b). The noise figure is still about 2 dB, but the third-order intermodulation will be lower than the first arrangement. Since typical GPS receivers do not have a stringent dynamic range requirement, this arrangement will not

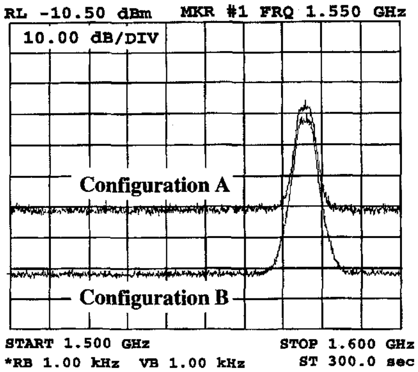

Fig. 5. Spectrum analyzer measurement results for front end configurations A and B.

create an adverse effect on the receiver performance barring RF interference. In this configuration, the filter limits the noise from all the three amplifiers.

The frequency responses, measured via a spectrum analyzer, from these two arrangements are shown in Fig. 5. The displayed frequency range is from 1.5 to 1.6 GHz. Curve A and curve B show the results of the first and second arrangements respectively. Since only noise from the first amplifier is limited in configuration A, the noise floor is higher. The noise floor of curve A should be approximately 60 dB higher than curve B, due the limitation of the spectrum analyzer, only 20 dB difference is illustrated.

In the passband of the filter, the two curves should have the same amplitude. However, the measured results show that curve B has a higher output than curve A. The reason is that in this arrangement, Fig. 4(b), the last amplifier is operating in saturation since the input noise is not band limited. The measured power output from the third amplifier before the filter is 16.4 dBm which is higher than the 1 dB compression point of 13 dBm. Thus the amplifier has less gain because it is driven into saturation. The power measured from the output of the third amplifier of the arrangement, depicted in Fig. 4(a), is -9.3 dBm which is still in the linear region of the amplifier, thus, the gain does not degrade.

In order to evaluate both arrangements for a direct digitization implementation, a CW signal was used. Although both configurations were designed to perform as an L1-band GPS C/A code receiver front end, it is difficult to obtain quantitative results with actual GPS signals due to their code division multiple access (CDMA) spread spectrum modulation. Therefore, a CW signal generator was used as input with a center frequency of 1575.42 MHz and output power setting of -110 dBm, slightly stronger than the guaranteed minimum power level of the GPS C/A code signal to ensure an adequate measurement. Yet the input CW signal used in the experiment exhibits similar characteristics of the true signal.

The expected SNR can be found from the following procedure. The noise floor of a 500 Hz bandwidth system (2 ms of data) with 3 dB noise (including 1 dB insertion loss of the input cable) is

$$-174 + 10\log(500) + 3 = -144\,\text{dBm}. \tag{7}$$

The corresponding SNR is

$$\text{SNR} = -110 - (-144) = 34\,\text{dB}. \tag{8}$$

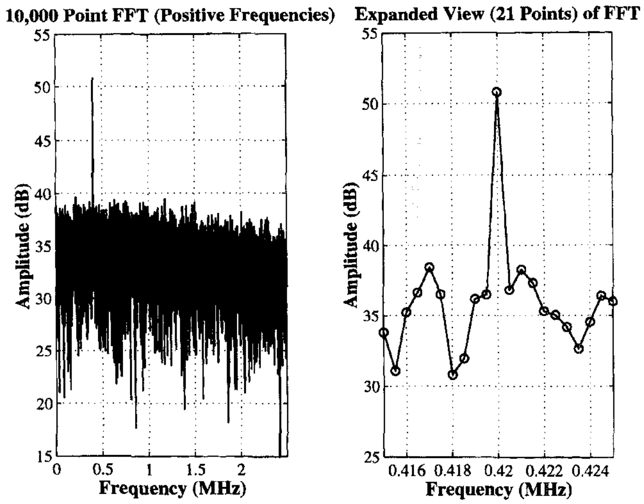

Fig. 6. 10 000 point FFT of CW signal (direct digitization).

The CW signal is applied to the input of the first amplifier in both configurations in order to measure the SNR. This ratio is calculated by using the fast Fourier transform (FFT) of the digitized signal. The Tektronix TDS 684A digital oscilloscope is used as the ADC with a sampling rate of 5 MHz, thus the CW signal will be aliased to a 420 kHz center frequency. A 10 000 point FFT, which spans 2 ms and corresponds to a frequency resolution of 500 Hz, is performed on the sampled data. The input frequency was perturbed slightly from the 1575.42 MHz setting so that the energy of the CW signal was contained within a single frequency bin. Fig. 6 shows the results of the 10 000 point FFT and an enlarged view of only 21 points about the center frequency bin of the CW signal. It appears that the signal only occupies one frequency bin.

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 measured SNR is 31.8 dB for the second arrangement [Fig. 4(b)]. This result is about 2.2 dB lower than the predicted one. This error might be a result of the measurement equipment, as there is no known equipment in our laboratory to measure the input power directly at -110 dBm. The other possibility is that the filter 3 dB bandwidth of 3.4 MHz is greater than the Nyquist sampling frequency (2.5 MHz), thus additional noise is folded into the desired band.

The SNR of the first arrangement [Fig. 4(a)] is 24.8 dB which is 6.8 dB less than the second arrangement. Although the absolute SNR measured could contain some error, the relative values between the two measurements should be accurate.

From this result one may conclude that the filter should be placed at the end of the amplifier chain to obtain the best SNR. This novel sampling technique precludes the use of an anti-aliasing filter with the ADC as the intent is to purposely alias the information band. In order to do so effectively, a bandpass filter, centered about the carrier frequency with passband equal to the desired signal bandwidth, should directly precede the ADC. Also, it is important that this filter has an ultimate reject stopband as low as possible from DC to input bandwidth of

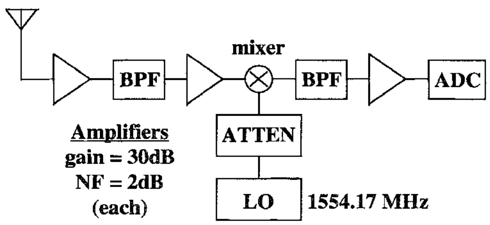

Fig. 7. Downconvert and digitize front end configuration.

the ADC. Any noise within this region will be cumulatively aliased, or folded, into the resulting sampled bandwidth as a result of the direct digitization and degrade the final SNR.

V. Direct Digitization and Conventional Front End Design Comparison

Again, the signal of interest is the L1-band GPS signal modulated with the CDMA spreading code, i.e., C/A code and navigation data. The conventional approach used in the front end of a GPS receiver is to amplify the input signal, then downconvert it to an IF. The IF signal is further amplified and typically digitized for further processing. In this section both direct digitization and downconverted approaches are implemented and compared

A direct digitization approach has been published by Brown [8]. 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.

In direct digitization, the experimental set-up has been depicted previously in Fig. 4(a). The configuration uses the same hardware as the previous experiment. Once again, the filter utilized has a bandwidth of 3.2 MHz, that is again wider than the minimum requirement of 2.0 MHz. As a result, additional noise will be aliased into the digitized data and the sensitivity of the receiver will suffer.

The downconverted arrangement is shown in Fig. 7. In this figure about 30 dB of gain is placed in front of the first filter. This filter has parameters more typical of a first stage filter: a center frequency of 1575.42 MHz, an insertion loss of 2.2 dB, and 3 dB and 30 dB bandwidths of 86 MHz and 280 MHz, respectively. The mixer has an insertion loss of 6 dB. The local oscillator generates a 1554.17 MHz frequency signal that 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 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 21.25 MHz signal sampled at 5 MHz will alias to 1.25 MHz, the center of the alias zone. Bandpass sampling is also used in this case, however the input bandwidth of the ADC required to digitize this IF signal is only in the 20 MHz range rather than the GHz range. A factor that was discussed earlier, but has been ignored here is the need for a filter directly prior to the ADC. Although this filter would still be beneficial should it be incorporated into the design, its exclusion will have only a minor effect on the system. The reason for this is that this last amplifier, which will raise the noise folded into the resulting information band, has a much smaller bandwidth than the 1 GHz bandwidth of the first stage amplifiers and is directly preceded by a filter. This approach uses additional hardware, however the filters are small in size and the IF filter has better selectivity.

Two types of signals were applied to the input of the receiver front end. A GPS antenna was used to collect actual GPS signals and a CW signal was also used, as in the previous experiment. The CW input provides a quantitative comparison between the two front end implementations. The results of CW experiment are described first, then the performance of both front end implementations is investigated when true GPS signals are used as an input.

The same digital oscilloscope was used as the ADC and the FFT magnitude output was utilized to determine the SNR. For the direct digitization approach, the results of the previous experiment using the CW signal can be utilized. This configuration resulted in a measurement of 31.8 dB for the SNR.

For the downconverted case a similar approach was performed. The only difference is the input analog IF and resulting output digital IF, which are 21.25 MHz and 1.25 MHz, respectively. The SNR measured under this condition is 32.6 dB.

As previously calculated the expected SNR is 34 dB. The measured values are slightly less than that expected, but again the relative values provide the desired insight. The SNR of the downconverted approach is 0.8 dB (32.6–31.8) better than the direct digitization. This difference can be ascribed as the RF filter bandwidth (3.4 MHz) is wider than the resulting sampled bandwidth of 2.5 MHz and more noise will fold in the desired band. If a filter with narrower bandwidth can be utilized, the SNR of both approaches should be equal.

VI. Front End Evaluation Using True GPS Signals

In this experiment, an antennas was used as input to the front ends to collect true data from the GPS satellites. A GEC Plessey GPS receiver was used to determine which satellites were visible. The two antennas of the systems were placed next to each other. The direct digitization configuration, depicted in Fig. 4(b), has been modified slightly by the inclusion of an additional wideband filter after the first amplifier to suppress out-of-band signals. The inclusion of this filter was deemed necessary as a result of the spurious response obtained when the depicted design was connected to the antenna. This was not necessary in prior CW experiments as the input was limited to the output of the signal generator. A total of 15 000 data points were collected, and Fig. 8 shows the collected data from direct digitization in the time and frequency domains. Data obtained 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 Fig. 8, 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

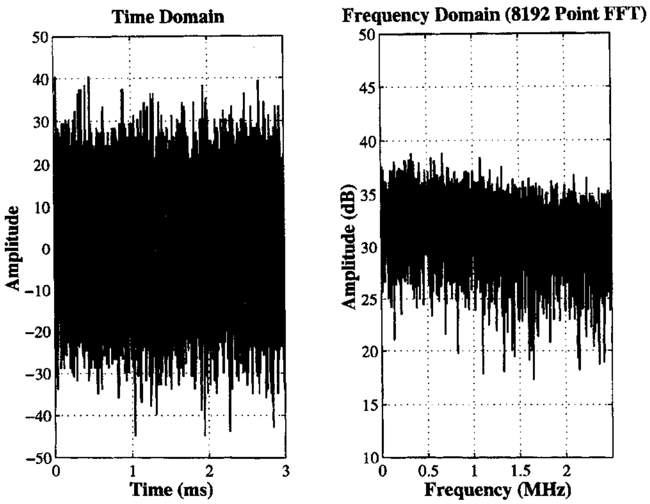

Fig. 8. Time/frequency plots for a direct digitization data set.

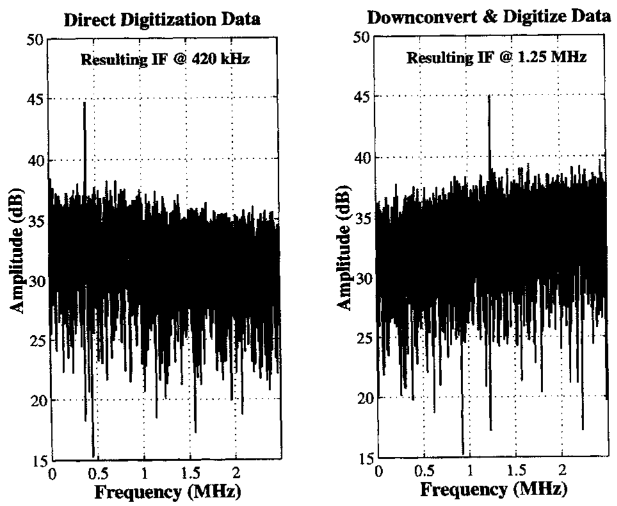

Fig. 9. Post acquisition (correlation) 8192 point FFT.

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 [9]. The acquisition algorithm was coded to identify the acquisition parameters for the satellites being tracking. Fig. 9 shows the result of the post correlation FFT for a single satellite for both front end designs. In each case, the underlying signal is clearly evident. The acquisition algorithm was then used to successfully identify all satellites that were being tracking concurrent to data collection. In both front end designs, all satellites were identified with results similar to those depicted in Fig. 9. Thus this initial work shows either implementation can be used as a GPS receiver front end.

VII. Summary

This paper discusses the implementation of a direct digitization GPS receiver front end. This technique should offer significant advantages over the conventional design through the removal of analog-based hardware. Both theoretical and practical implementation guidelines are presented which apply to the development of a generic direct digitization front end. Experimental data is presented which compares the results of two GPS front end designs: 1) direct digitization and 2) downconvert and digitize. 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, cost, and system requirements. In the direct digitization, the requirements of the filter and ADC are more stringent, while in the downconversion case, a mixer and local oscillator are needed for each stage of frequency downconversion.

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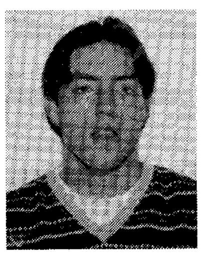

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