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Filtering IF Samples to Reduce the Computational Load of Frequency Domain Acquisition in GNSS Receivers

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BIOGRAPHY

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Prof. Chris Rizos is currently the Head of the School of Surveying & Spatial Information Systems at UNSW. Chris has been researching the technology and applications of GPS since 1985, and established over a decade ago the Satellite Navigation and Positioning group at UNSW, today the largest and best known academic GPS and wireless location technology R&D laboratory in Australia. Chris is the Vice President of the International Association of Geodesy (IAG), and a member of the Governing Board of the International GNSS Service. Chris is a Fellow of the IAG and of the Australian Institute of Navigation.

ABSTRACT

Frequency domain search is a preferred method for rapid acquisition of GNSS signals. In a frequency domain acquisition, the spectra of both local and incoming signals are processed and the result is then returned to the time domain. In this process, most of the computational resources are consumed in inter-domain translation of signals. An FFT algorithm is generally used for these translations. Hence most of the computational resources, in a frequency domain search, are consumed by the FFT algorithm. The computational load of the FFT algorithm depends on the number of samples to be processed. Reducing the number of samples required by the FFT algorithm can thus reduce the computational load of frequency domain acquisition.

The minimum number of samples required by the FFT algorithm in a signal search depends on the length of the PRN code and its chipping rate. For a half-chip spacing correlator, at least $2f_cT$ samples are required by the FFT algorithm, where f_c and T are the code chipping rate and code period (in seconds), respectively.

The authors propose an approach to reduce the required number of samples below $2f_cT$. In this approach, the IF signal is passed through an anti-aliasing filter and then down sampled to a frequency that is twice the filter cutoff. Selection of the filter cutoff is a trade off between desired improvement in the computational load and the correlation loss (caused by the filter). A lower cutoff is desired to minimize the computational load while keeping the correlation loss within acceptable limits.

Acquisition of the new civilian GPS L2C signal and the L1 C/A signal is performed with the proposed method on both software and hardware platforms. A comparison of the performance of the proposed method is made with the conventional approach for frequency domain acquisition.

It is shown that the proposed method achieves a significant reduction in the computational load at the cost of minor correlation loss.

I. INTRODUCTION

A frequency domain search is often preferred (over the time domain) for efficient acquisition of GNSS signals. This is because the time domain search can take a serial approach while the frequency domain employs a parallel search strategy. A frequency domain search, however, is resource intensive and therefore remains an expensive choice. This becomes even more critical in new GNSS signals with longer PRN codes.

An FFT algorithm is generally used to accomplish the frequency domain search [1]. Resources required in a frequency domain search are therefore determined by the FFT algorithm. To exploit the circular convolution, an FFT algorithm must process at least one code period of the input signal. Consequently, for a half-chip spacing correlator, at least $2f_cT$ samples must be processed by the FFT algorithm, where f_c and T are the code chipping rate and code period (in seconds), respectively. The computational load of frequency domain acquisition can therefore be reduced by reducing the number of IF samples to be processed by the FFT algorithm.

A number of research attempts have been made to reduce the computational load of signal acquisition. For example, in [2], the authors propose to drop the sampling frequency of IF samples to $2f_c$. The technique was proposed to minimize the power consumption and simplify the correlator architecture in a Direct Sequence Spread Spectrum receiver. It uses a low pass anti-aliasing filter in combination with an interpolation filter. The timing of the interpolation filter is controlled by the contents of an NCO register, which adjusts the data frequency to match the local code sampling frequency of exactly two samples per chip. This ends up with 2046 samples per C/A code period and additional processing resource requirements. In [3], the authors present a sub-sampling technique for reducing the processing load in GPS C/A code parallel acquisition. Here, 5000 samples in the C/A code period are sub-sampled to 4096 samples. The FFT algorithm is then performed on 10 consecutive input data blocks of 4096 samples each. The first half (2048 samples) of each FFT output is multiplied by the corresponding local code FFT outputs. Hence the processing in multiplication and inverse FFT operations is reduced by half. However for final code phase extraction using this technique, the correlation scaling has implementation issues. Also the technique is not very effective for higher sampling rates such as 16.3676 MHz, used in commercial receivers. In [4], the authors exploited the spectrum envelope to reduce the FFT size for GPS L2C signal acquisition.

We propose to reduce the minimum number of samples required for acquisition to below $2f_cT$. This employs an anti-aliasing filter before the down-sampling of signal. The bandwidth of anti-aliasing filter determines the down-sampling factor and eventually the correlation loss. Further processing for signal acquisition is performed in the down-sampled domain. This allows use of smaller FFT blocks for signal acquisition, reducing the computational load. We investigate the correlation loss due to the proposed IF filtering and down-sampling. Acquisition of the new modernized L2C civil signal and the L1 signal is performed with the proposed method. An analysis of the trade off between the signal acquisition sensitivity and the desired reduction in the computational load is presented. It is concluded that the proposed approach makes frequency domain searches more feasible to implement.

The proposed acquisition approach is described in section II. Correlation loss due to filtering and down sampling is then analyzed. Section III presents the performance comparison of the conventional and proposed methods, for test signals. Hardware implementation is described in section IV. Finally, some concluding remarks are given in section V.

II. PROPOSED ACQUISITION APPROACH

In the proposed approach, both IF signal (after carrier removal) and local reference code are passed through a low pass anti-aliasing filter and then down sampled. FFT operations are then performed on the down sampled signals. This method is illustrated in Figure 1.

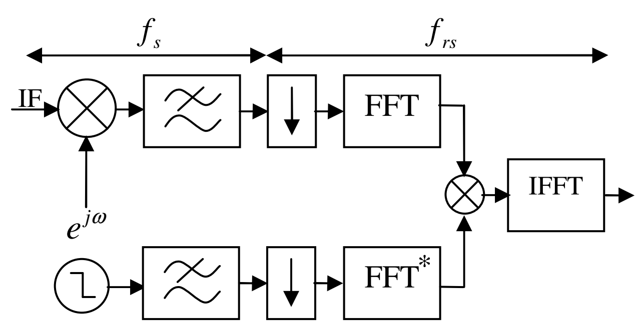


Figure 1. Proposed acquisition approach

Where f_s and f_{rs} are the original and down sampled frequencies, respectively while * denotes the complex conjugate operation.

i. The Anti Aliasing Filter

The main lobe of the IF signal's spectrum is typically selected by the last stage filter in the RF front-end. The proposed anti-aliasing filter is a simple low pass filter that is used to remove the tail of main spectral lobe. The narrow band lobe is then used for further processing. This pre-correlation filtering causes the signal to lose some of its power. The signal power in a single-sided bandwidth of '*B*' Hertz is expressed as [5]:

$$P = \frac{1}{\pi} \int_{0}^{2\pi B} S(\omega) d\omega \qquad (1)$$

Where $S(\omega)$ denotes the power spectral density. For the L1 C/A signal, the power spectral density is given in [5] as:

$$S(\omega) = \frac{A^2 T_c}{2} \frac{\sin^2(\omega T_c / 2)}{(\omega T_c / 2)} \qquad (2)$$

Here '*A*' is the signal amplitude and 'T_c' is the C/A code chip period.

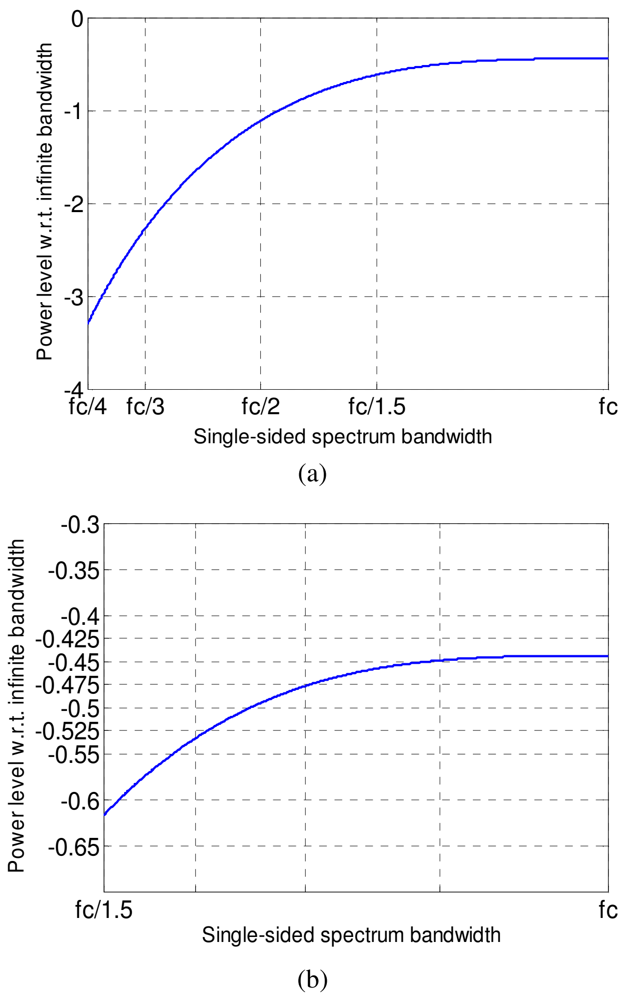


Figure 2. GPS L1 C/A signal power as a function of spectrum bandwidth. Power levels shown are in dB, with reference to the infinite bandwidth. Note the approximately 0.15 dB loss in the plateau at the right due to restricting the single-sided signal bandwidth to f_c (1.023 MHz), zoomed in (b)

Evaluating equation (2) as a function of single-sided spectrum bandwidth '*B*' from '$f_c/4$' to 'f_c', and recording the resulting power levels with reference to infinite bandwidth, i.e. $B = \infty$, gives the results given in Figure 2.

This power loss due to filtering results in a drop in the level of the acquisition peak, also known as correlation loss. The fact that the signal power loss is minimal near the edges of the main spectral lobe and that the proposed filtering removes some of the noise from the signal, is exploited in this quest to reduce the computational load of frequency domain acquisition.

ii. Side Lobe Energies

With the IF filtering, spreading codes lose their original correlation characteristics and consequently their side lobe energies (or subpeak, i.e. second highest peak in the correlation result) are increased. This in turn can affect the probability of false alarm. The authors plot the peak-to-subpeak ratio of L1 C/A correlation result as a function of spectrum bandwidth, with reference to the peak-to-subpeak ratio at infinite bandwidth, in Figure 3. Note the similarity in the loss characteristic of Figure 1. Table 1 summarizes the data set used for generating Figure 3.

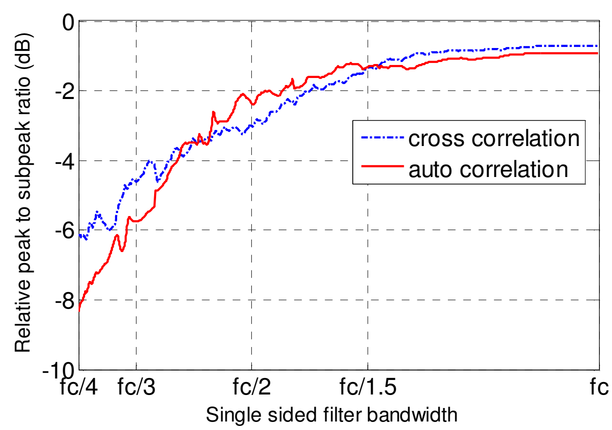


Figure 3. Peak-to-subpeak ratio of L1 C/A auto-correlation and cross-correlation results, as a function of filter bandwidth. The peak-to-subpeak ratio at infinite bandwidth is set as reference

Auto-correlation PRN	Cross-correlation PRN	f_s	B
21	21 & 2	5.115 MHz	$f_c/4 - f_c$

Table 1. Data set used for generating Figure 3

Again, it can be observed from Figure 3 that when single sided filter bandwidth approaches f_c, the peak to subpeak ratio relatively remains constant, offering a safe filtering margin in that region. It is this region we are interested in. The rise of side lobe energies is however more critical in weak signal environments where a strong satellite signal can prevent the acquisition of a desired weak signal.

iii. The Down-Sampling Process

In the proposed approach, the downsampling factor Ψ is decided by the bandwidth of anti aliasing filter and is given as:

$$\psi = B \quad (3)$$

Where B, as already mentioned, is the single sided filter bandwidth. The down sampled frequency is therefore given as:

$$f_{rs} = f_s / \psi \quad (4)$$

And the new sampling interval is:

$$T_{rs} = 1/f_{rs} = B/f_s \quad (5)$$

The down sampling is carried out by the following algorithm. An index vector is generated as:

$$x[n] = \left\lfloor \frac{f_s}{f_{rs}} \cdot (n-1) \right\rfloor + 1 \quad (6)$$

Where n is an integer, given by:

$$n = 1,2,3 \cdots f_{rs}T \quad (7)$$

Here T is the period of spreading code (in seconds) and the function $\lfloor\ \rfloor$ represents the integer part of its real number arguments. Input IF samples on the indices given by x (equation 6), are then selected. This reduces the number of samples per code period so that they can fit into smaller FFT blocks.

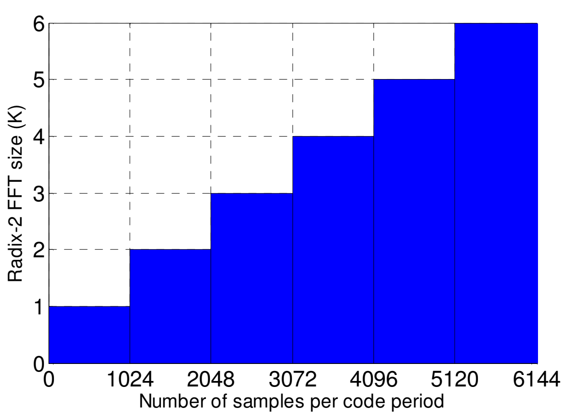


Figure 4. Radix-2 FFT size required for acquisition versus number of samples per code period. The two axes are restricted for illustration purposes

Figure 4 illustrates the relationship of Radix-2 FFT size with number of samples per code period. The Radix-2 FFT is used here for its simplicity and availability. However, the analysis remains valid for any non 2^N FFTs which can be realized using Prime-factor and Mixed-radix algorithms for GNSS signal acquisition, proposed in [11]. The down-sampling of a signal, however, can cause additional correlation loss. For a code search resolution of T_s, where T_s is the sampling interval, the worst correlation loss due to phase mismatch between the incoming and local code sequences is well known as:

$$\gamma_s = \frac{T_s}{2T_c} \quad (8)$$

Where T_c is the chip period. With down-sampling, the search resolution drops to T_{rs} and consequently the worst correlation loss in this case can be given as:

$$\gamma_{rs} = \frac{T_s + T_{rs}}{2T_c} \quad (9)$$

In [6], the authors discuss the details on correlation loss due to various phase offsets and the filter cutoff frequency for undersampled signals acquisition.

III. EXPERIMENTS ON REAL DATA

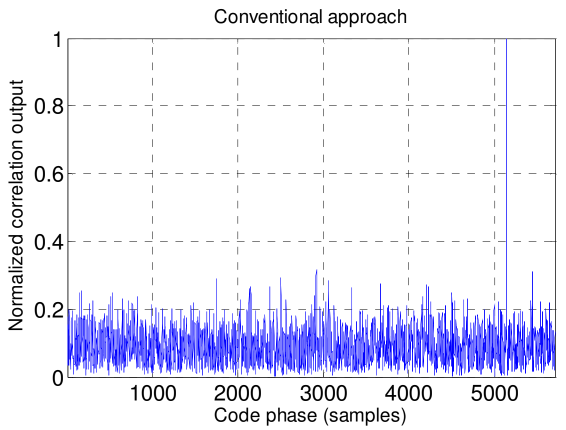
Acquisition of live GPS L1 C/A and L2C signals is performed with the proposed algorithm using both software and FPGA platforms. The IF samples for L1 and L2C signals were collected by two different receivers; the UNSW's 'Namuru' receiver that uses a Zarlink GP2015 RF front-end at 5.714 MHz sampling [7] and the 'NordNav Rxx-2' that uses a sampling frequency of 16.367 MHz.

i. L1 C/A Signal Acquisition

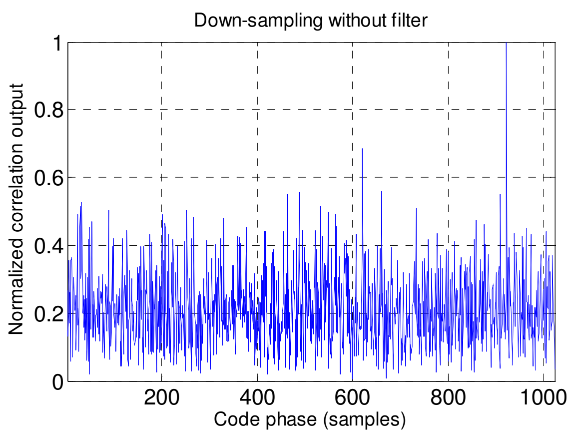
For the L1 C/A signal, IF signal (after removing the carrier) and the local code were both passed through a low-pass (anti-aliasing) filter with a cutoff frequency of 512 KHz. The IF signal was then down-sampled from its original sampling frequency of 5.714 MHz to 2×512 = 1.024 MHz. This produces 1024 samples in one millisecond of C/A signal that exactly fit into a 1K FFT block. The filter outputs are thus processed by 1K FFTs instead of 8K FFTs required for 5.714 MHz sampling. Similarly, 16K FFTs required for 16.367 MHz sampling are replaced by 1K FFT blocks. For all experiments in this research, the following performance metric is used to measure the correlation output:

$$\eta = 10\log\left(\frac{A_p}{A_{2p}}\right)^2 \quad (10)$$

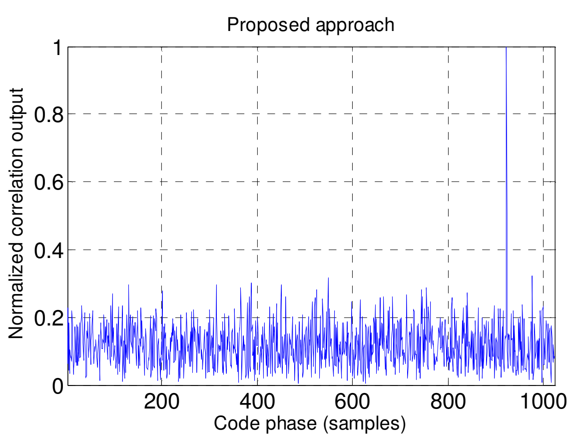
Where A_p is the highest correlation peak and A_{2p} is the second highest peak in the search space.



(a)



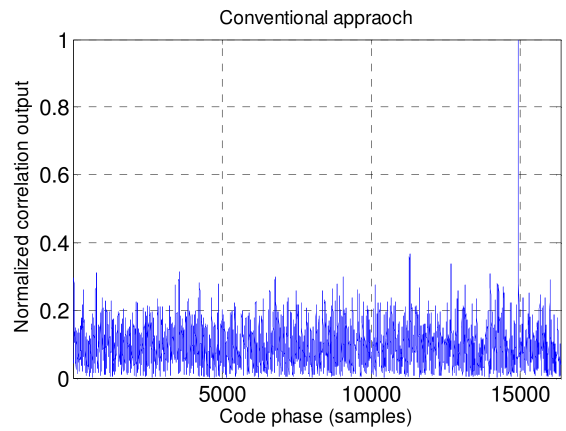
(b)



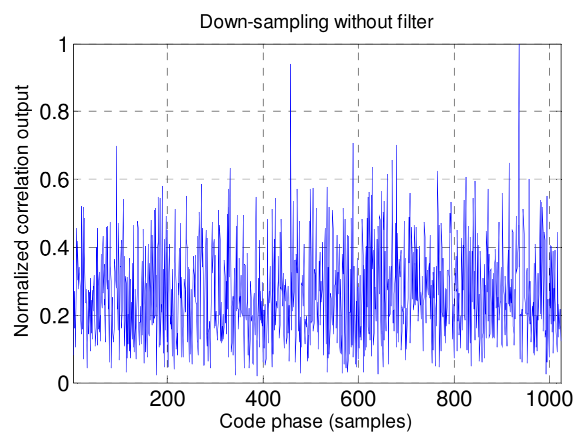
(c)

Figure 5. L1 C/A (PRN-18) acquisition result with "Namuru" (f_s = 5.714 MHz) data records. (a) Conventional approach, η = 9.9378 dB, (b) Down-sampling without filter, η = 3.2865 dB, (c) Proposed approach, η = 9.8348 dB

The results for conventional and proposed methods are shown in Figures 5 and 6. It can be observed from the results that use of filter makes a significant difference by preventing the aliasing as well as removing some of the thermal noise. Details on the optimal filter bandwidth that maximize the SNR at the correlator output are discussed in [6].



(a)



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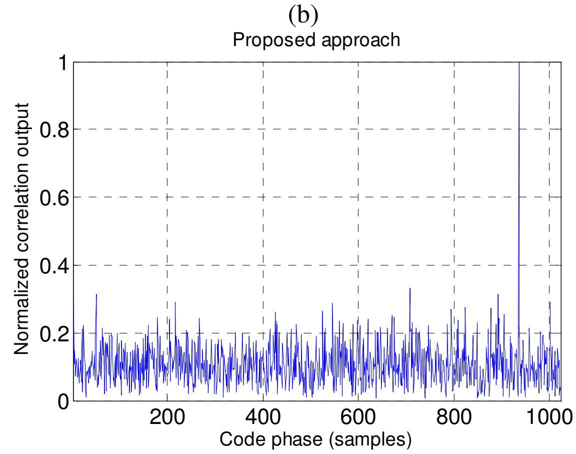

(c)

Figure 6. L1 C/A (PRN-12) acquisition result with "NordNav" (f_s = 16.367 MHz) data records. (a) Conventional approach, η = 8.7233 dB, (b) Down-sampling without filter, η = 0.5519 dB, (c) Proposed approach, η = 9.6165 dB

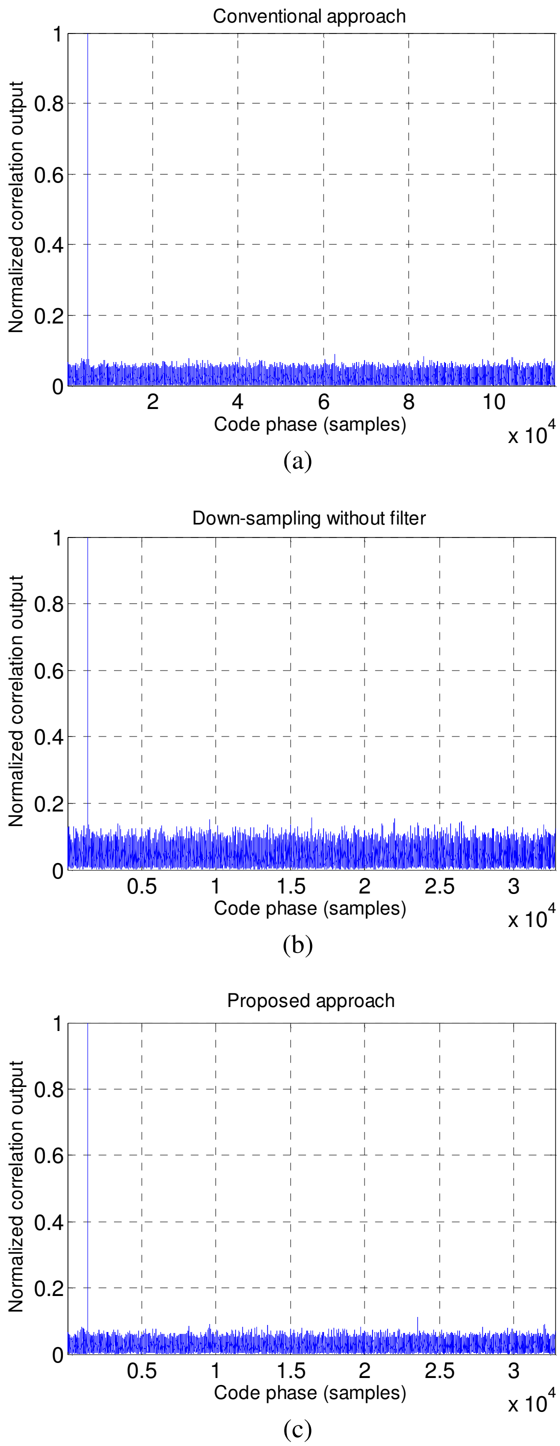

Figure 7. L2C (PRN-17) acquisition result with "Namuru" (f_s = 5.714 MHz) data records. (a) Conventional approach, η = 20.9238 dB, (b) Down-sampling without filter, η = 16.0931 dB, (c) Proposed approach, η = 19.0311 dB

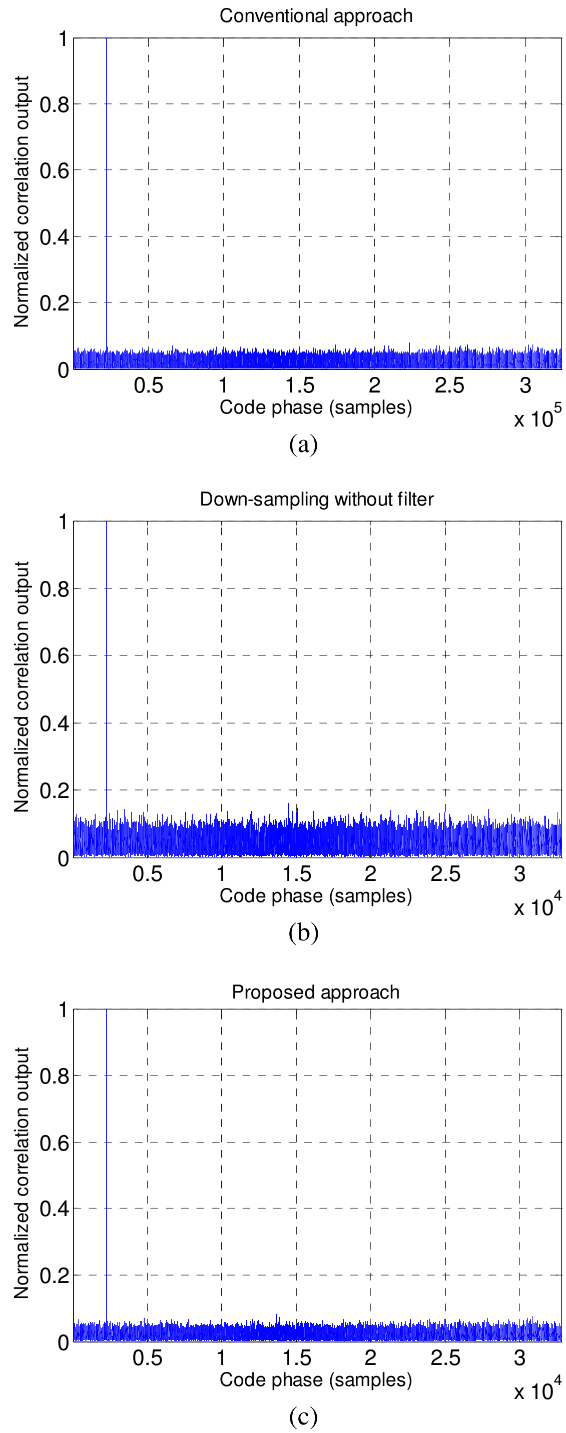

Figure 8. L2C (PRN-17) acquisition result with "NordNav" (f_s = 16.367 MHz) data records. (a) Conventional approach, η = 22.0750 dB, (b) Down-sampling without filter, η = 15.8959 dB, (c) Proposed approach, η = 21.6132 dB

ii. L2C Signal Acquisition

L2C is the second GPS civil signal, now available on all of the six operational Block IIR-M satellites. The L2C signal is composed of two codes, L2 CM and L2 CL. The L2 CM-code is 20 milliseconds long and has 10230 chips while the L2 CL-code is 1.5 seconds long and has 767250 chips. The CM-code is modulo-2 added to data (i.e. it modulates the data) and the resultant sequence of chips is time-multiplexed with the CL-code on a chip-by-chip basis. This multiplexed sequence modulates the L2 (1227.6 M Hz.) carrier [8]. A return-to-zero CM code was used as the local code for observing the L2C signal as it allows searches across 20 milliseconds and that it removes half of the cross-correlation between CM and CL chips [9][10]. For this case, both the IF signal, after carrier removal, and the local PRN code were passed through the low-pass filter with a (single-sided) cutoff frequency of 819.2 KHz. The two signals were then down-sampled to 2×819.2 =1.6384 MHz. With this sampling frequency, 20 milliseconds of L2C data exactly fit into a 32K FFT block. The output of low-pass filter is hence processed by 32K FFTs instead of 128K FFTs required for 5.714 MHz sampling and 512K FFTs required for 16.367 MHz sampling frequency. This reduction of FFT size significantly reduces the computational load. The L2C acquisition results are shown in Figures 7 and 8.

iii. FFT Size Comparison

With the well known "$N\log_2 N$" growth in FFT processing effort, where N is the number of data samples to be processed, higher sampling frequencies and longer data blocks require huge FFTs for acquisition [10]. This becomes more problematic with new GNSS signals like L2C, characterized by long code periods. Table 2 summarizes the acquisition results in terms of computational gain. Each "$n\log_2 n$" computation given here considers two (one direct and one inverse) Radix2 FFT operations, required for signal acquisition.

Approach	Signal	f_s (MHz)	Samples per code period	FFT size	$N\log_2 N$ ($\times 10^5$)
Conventional	L1 C/A	5.714	5714	8K	2.2937
		16.367	16367	16K	4.9152
	L2C	5.714	114280	128K	47.185
		16.367	327340	512	209.71
Proposed	L1 C/A	1.024	1024	1K	0.2252
	L2C	1.6384	32768	32K	10.485

Table 2. Comparison of computational load between the conventional and proposed acquisition approaches

IV. HARDWARE IMPLEMENTATION

The proposed acquisition approach was tested on the Altera Stratix EP1S25 DSP Development Board equipped with an Altera Stratix FPGA device [12], shown in Figure 9. A standard Radix2 scheme is considered for the FFT implementation. The binary stream of the design was generated using DSP Builder for the Altera Stratix EP1S25 DSP Development Board. The design is then downloaded to the FPGA chip. The output from FPGA chip is read by Altera Signal Tap II Logic Analyzer and then saved and plotted.

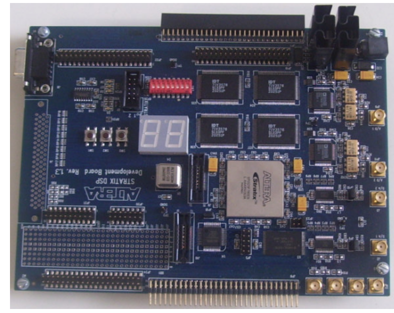

Figure 9. Altera Stratix FPGA test board used for hardware implementation

Acquisition of the L1 C/A and L2C signals, using the proposed approach are shown in Figures 10 and 11 respectively. These results are based on the same data records used for software acquisition.

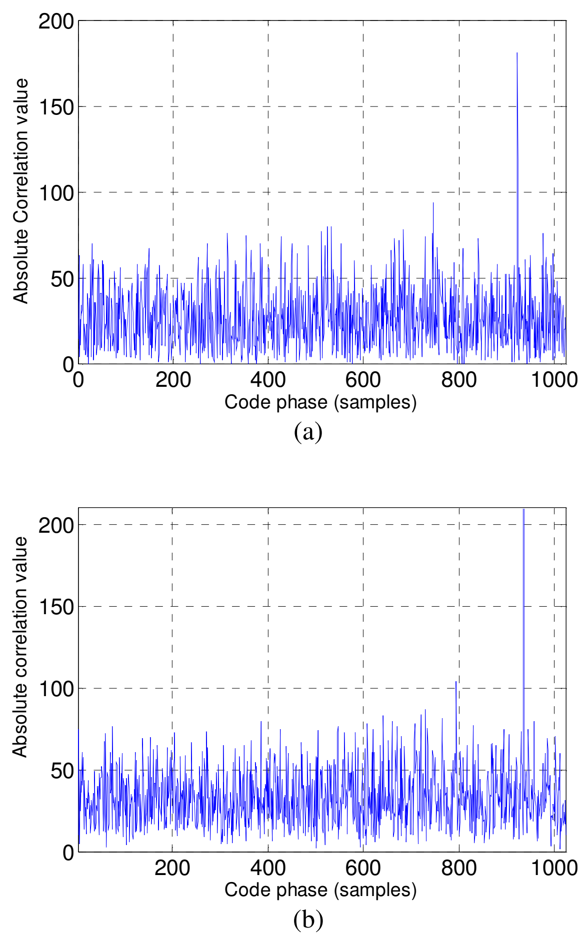

Figure 10. L1 C/A acquisition result using the Altera Stratix FPGA device. (a) PRN-12, f_s = 5.714 MHz, η = 5.6910 dB, (b) PRN-18, f_s = 16.367 MHz, η = 6.192 dB

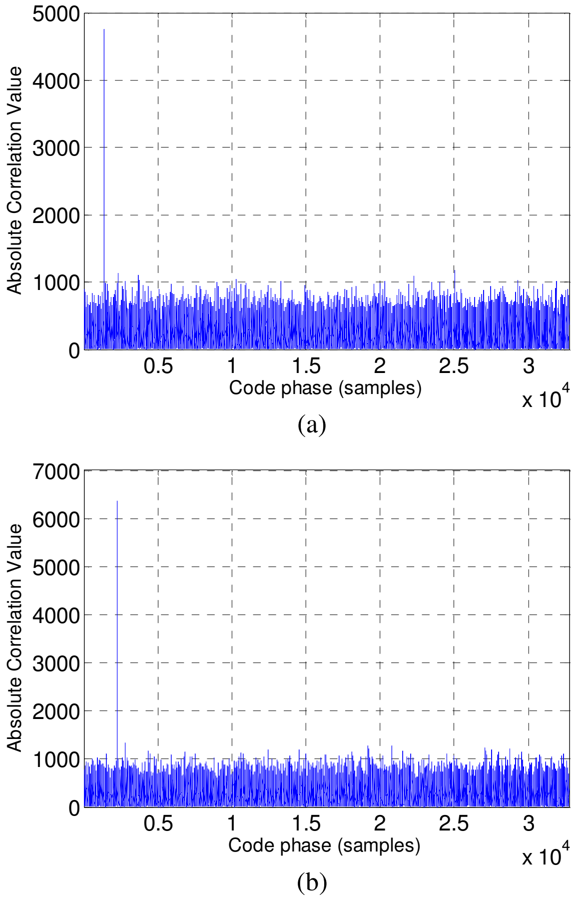

Figure 10. L2C acquisition results using the Altera Stratix FPGA device. (a) PRN=17, f_s = 5.714 MHz, η = 12.0613 (b) PRN=17, f_s = 16.367 MHz, η = 13.5684

V. CONCLUSIONS

Pre correlation filtering of IF samples is investigated in order to reduce the computational load of frequency domain acquisition in GNSS receivers. Acquisition of the modernized L2C civil signal and the L1 C/A signal is performed with the proposed approach on software and hardware platforms. It is concluded that the proposed approach significantly reduces the FFT size making frequency domain search more efficient and feasible to implement.

ACKNOWLEDGMENTS

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