Delayed Parallel Interference Cancellation for GPS C/A Code Receivers

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Abstract

A number of different techniques are available to mitigate the problem of cross correlations caused by the limited dynamic range of the 10-bit Gold codes in the GPS C/A code. These techniques include successive-interference cancellation (SIC) and parallel-interference cancellation (PIC), where the strong signals are subtracted at IF prior to attempting to detect the weak signals. In this paper, a variation of these techniques is proposed whereby the subtraction process is delayed until after the correlation process, although still employing a pure reconstructed C/A code signal to permit prediction of the cross correlation process. The paper provides details on the method as well as showing the results obtained when the method was implemented using a software GPS receiver. The benefits of this approach are also described, as is the application of the method to the cancellation of CW interference.

Keywords: Cross correlation mitigation, near-far problem, interference cancellation, SIC, PIC, de-correlating detector, C/A Gold codes

1. Introduction

The use of 10-bit Gold codes as the spreading codes in the Global Positioning System limits the dynamic range of the signals that may be easily tracked to no more than 21 dB weaker than the strongest GPS signal present [1]. This inherent design limitation of the system causes difficulties in a number of applications. One such application includes the Enhanced-911 requirement for mobile cellular phones in which the presence of a single strong GPS signal may interfere with acquisition of other weak signals. Another application involves the use of GPS pseudolites as an augmentation to GPS where the presence of the pseudolite signal interferes with the acquisition of the standard GPS signals.

A number of different techniques are available to mitigate the cross correlation problem [2, 3]. One of the more well known techniques is successive interference cancellation (SIC) [4-6], with this method being notable due to having been applied to the GPS pseudolite problem [7]. Parallel interference cancellation (PIC) is similar except that multiple strong signals are subtracted in parallel rather than being subtracted serially [8]. The new method described here is similar to [9], although it does not suffer its problems which are described later. There is also has some similarity to [10], although the new method offers a simpler implementation.

This paper provides a short review of the successive interference cancellation (SIC) cross correlation mitigation (CCM) technique followed by details on the delayed parallel interference cancellation (DPIC) method. The method is also related to the well known multi-user 'Decorrelating Detector' [11]. Some results showing the performance of the method using a software GPS receiver are also provided.

2. Successive Interference Cancellation

A block diagram showing successive interference cancellation (SIC) is given in Figure 1. The SIC process is to serially subtract strong signals from strongest to weakest thereby reducing the cross correlation noise for all of the subsequent stages. Removing the strongest signal first has two advantages. The first is that the signal causing the worst case cross correlations is removed first thereby ensuring that the maximum benefit is obtained for all subsequent stages. Secondly, the strongest signal is the signal for which it is easiest to estimate the required signal input parameters of carrier frequency, carrier phase, amplitude, and code-phase since the input signal to noise ratio is high. This is important because any errors in the reconstruction of the strong signal will result in residual cross correlations. It is not necessary to subject all the input signals to SIC since conventional processing can be performed at the final stage for all remaining signals.

One purpose of the "regenerate delay" element is to allow for the value of the data-bit modulation to be established prior to signal reconstruction since for BPSK signals, any error in the data-bits could result in signal addition rather than signal subtraction. In some cases where signal post-processing takes place it is possible to omit this stage since the strong signal data-bit values can be determined a-priori. Alternatively, it is possible to simply use the previous data-bit value during the next bit interval and to simply assume that no change has taken place, an approach which for GPS will work for 19 of the 20 code epochs. It is also possible to employ a small delay to permit changes in strong signal data-bit values to be detected and to only change

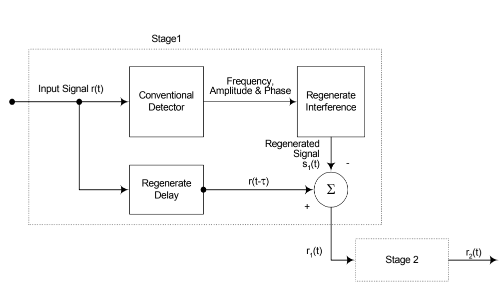

Figure 1: Successive Interference Cancellation (SIC)

the value if partially accumulated bit-value indicates that a bit-transition has occurred.

Another purpose of the delay element may be to include filtering to match the filtering of the input signal. For example, in the case of C/A code GPS the input signal is usually subject to filtering that limits the bandwidth of the input signal to ±1 MHz despite the fact that the total bandwidth of the signal is ±10 MHz. This has the effect of rounding the top of the triangular correlation curve compared to the ideal correlation shape and thereby reducing the amplitude of the prompt signal. This could be corrected through the use of digital filtering of the wideband signal generated by the system.

The SIC method has a number of disadvantages, the first of which is the need to continuously monitor which signal is strongest so as to ensure that this signal is removed first. This can cause a problem because when the strongest signal changes the subtraction order needs to be changed as well. The second problem is that due to the serial nature of the process, the amount of delay introduced into the signal processing increases as the number of signals to be detected increases. Thirdly, in the case of GPS the raw input signals are often one or two bit signals and since the GPS spread spectrum signals are buried well below the noise, the question arises as to how the subtraction of the strong signal may be carried out. One method would be to simply expand the one or two bit input signals to say eight bits thereby permitting subtraction to be performed at eight bit resolution. This has the disadvantage of increasing the complexity of the subsequent mixing and despreading operations. Alternatively it may be possible to re-quantize the one or two bit inputs to a larger number of bits, perform the subtraction and then re-quantize back to one-or two bits whilst employing dithering to ensure that the subtraction process is not negated in the re-quantization process. The proposed method was determined as a means of overcoming this subtraction problem.

3. Delayed Parallel Interference Cancellation

To see where the Delayed Parallel Interference Cancellation (DPIC) technique comes from, consider the detailed SIC block diagram stage shown in Figure 2, where this implementation omits the delay stage shown in Figure 1.

It will be observed that following subtraction of the reconstructed pure strong signal IF from the input IF signal,

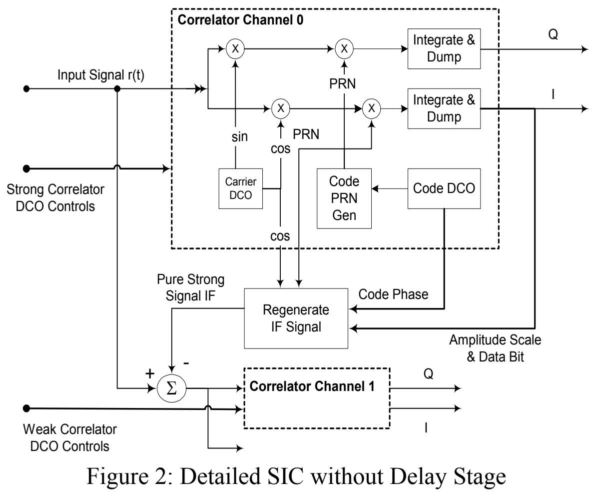

Figure 2: Detailed SIC without Delay Stage

the differenced signal is then input into a correlator channel block containing downconverters, despreading and integrate and dump filters. This process is shown in Figure 3.

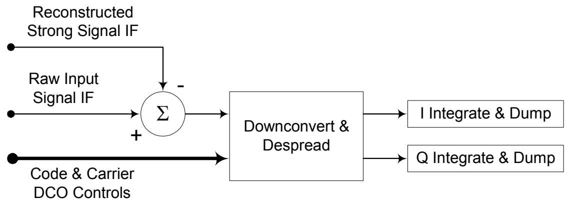

Figure. 3: Standard Processing of Differenced IF

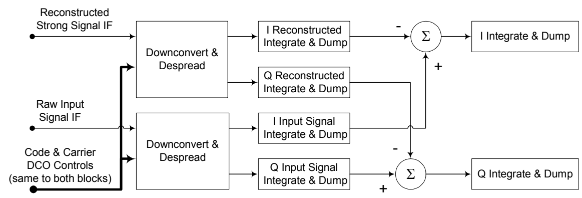

Figure 4: Alternate Processing of Differenced IF

It is possible to rearrange this signal flow by exploiting the linearity of the 'Downconvert and Despread' and 'Integrate and Dump' blocks thereby producing the alternative implementation shown in Figure 4.

This alternative implementation shows that once the strong signal IF has been reconstructed, it is possible to process it using a standard GPS correlator that is controlled using the same control signals used to search for the weak signal. Hence in this mathematically equivalent implementation, two standard correlators are employed rather than a single correlator, where one of the correlators processes the raw input signal from the GPS antenna and the second correlator processes the 'pure reconstructed' signal obtained as a result of tracking the strong GPS signal that requires cancellation. The control signals that are used to drive the two correlators are identical and hence the 'reconstructed-IF' correlator is slaved to the 'weak-signal' correlator.

Since this process may be carried out on any or all of the strong signals, the process becomes a parallel interference cancellation (PIC) technique. The final subtraction process may also be performed in software and as such, the correct scaling of the reconstructed signal may also be performed in software and is therefore delayed rather than being performed immediately. This means the one or two bit subtraction process required for the standard SIC technique is eliminated.

In this scheme the additional 'pure-IF' correlator is essentially being used to generate in hardware the ideal cross correlations between the strong signal and the weak signal being searched for at a particular code phase of the weak signal. For this to work it is essential that the reconstructed IF correlator have exactly the same code and correlator digital-controlled-oscillator (DCO) controls as the weak signal channel, which is why the same set of controls are applied to both downconvert and despread blocks. This means that the reconstructed correlator is slaved to the weak signal correlator and follows the weak signal correlator exactly. It is also necessary that the strong signal correlator is phase-locked to the strong signal since the strong signal reconstruction process performed in the 'Regenerate IF Signal' block only uses the carrier DCO signal from in 'in-phase' correlator channel.

A detailed DPIC block diagram with cancellation for a single strong signal is shown in Figure 5, where the scaling and final subtraction process is performed in software and all other processes are performed in hardware.

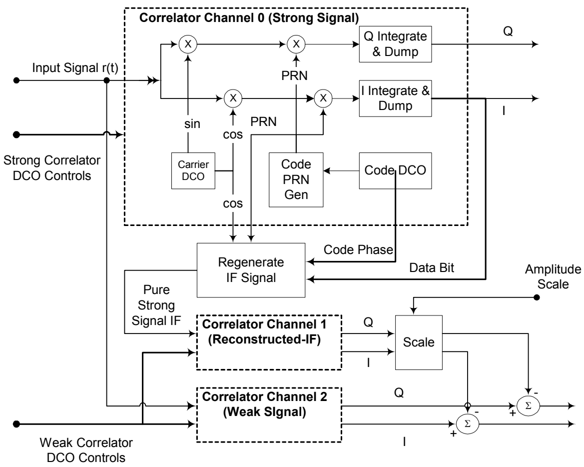

Figure 5: Detailed DPIC with one strong signal cancellation

A disadvantage of the scheme occurs if there are a large number of strong and weak signals that need to be detected since the total number of hardware correlators that are required can grow quickly. If there are N_s strong signals and N_w weak signals, then the total number of correlator channels N_c required to detect all of the signals are

$N_c = N_s + N_w + N_s \times N_w$

$N_v = N_s + N_w$

where N_v is the total number of visible signals, which in the case of GPS is usually constrained to be less than 12. Hence in the case of GPS, a total of 48 correlator channels are required if a maximum of 12 channels need to be processed. This is not an unreasonably large number with current technology.

The total cost of this technique need not be as bad as the worst case analysis suggests because the slave channels are able to employ the code and carrier DCO's of the weak signal master correlators. As such, it would be possible to construct a set of reduced complexity slave channel correlators without code and carrier DCO's since these are taken from the master channels that are already present.

Further savings are also possible if a decision is made to leave unmitigated any strong signals for which the relative Doppler frequency does not occur near an integer multiple of 1 kHz [12]. Although cross correlations will still occur in this case, in general the effect of these cross correlations will average to zero when integrated over several code epochs and hence signal detection can take place despite the presence of multiple access noise.

As already stated, DPIC is similar to the method described in [9], although unlike that method DPIC creates exact estimates of the cross correlations for each integrate and dump operation. Contrast this with [9] where the cross correlations at a relative Doppler carrier frequency offset of Δf Hz are (incorrectly) approximated as the product of the DC cross correlation and $sinc(\Delta f)$ scale-factor when the correct estimation technique should use the exact formulation described in [13]. As such, the cross correlations in [9] will often be incorrectly estimated thereby degrading the process. This is due to incorrect handling of the effect of relative Doppler carrier phase which modulates the strong signal code sequence to produce a weighted code sequence that is no longer a Gold code.

4. Relationship to the Decorrelating Detector

The Decorrelating Detector (DD) is a well studied multi-user detector that is also capable of eliminating multiple access interference (MAI) from DS/CDMA communications systems [11]. Like DPIC, the DD performs post-correlation removal of the MAI through the use of a linear combination of the standard correlator matched filter outputs. To understand the operation of the DD, consider the output from each correlator tracking satellite i:

$$y_i(n) = \sum_{k=1}^{N} \int_{nT}^{(n+M)T} A_k d_k(t-\tau_k^d)\, c_k(t-\tau_k)\, d_k(t-\tau_i) c_i(t-\tau_i)\, e^{j(2\pi f t+\phi)}\, dt + n_i$$

A_k, d_k, and c_k are the amplitude, data-bit, spreading code for satellite k, f_{dki} and φ_{ki} are relative Doppler carrier frequency and phases between satellite k and i respectively and n_i is the noise. This can be written in a matrix/vector format whereby the data-bits d_i are considered to be elements of input vector $\boldsymbol{d}$ and the amplitudes A_k are the diagonal elements in a diagonal matrix A. The integral term comprised of the product of the spreading codes and relative Doppler are elements ρ_{ki} in the matrix **R**, where:

$$\rho_{ki} = \int_{nT}^{(n+M)T} d_k(t-\tau_k^d)\, c_k(t-\tau_k)\, c_i(t-\tau_i)\, e^{j(2\pi f t+\phi)}\, dt$$

R is therefore a matrix is a matrix of 'normalised' cross correlations, where the diagonal elements will be autocorrelations with values of 1 and the off-diagonal elements are generally small in magnitude, assuming the codes are scaled appropriately. The entire system to be written as:

$$\mathbf{y} = R\,A\,\mathbf{d} + \mathbf{n}$$

Multiplying both sides by R^{-1} then permits the original input A **d** to be recovered, with this process completely eliminating the MAI.

$$R^{-1}\mathbf{y} = A\,\mathbf{d} + R^{-1}\mathbf{n}$$

Expressing R as the sum of the identity matrix and a matrix of small zero-diagonal cross correlation terms C, it is possible to approximate R^{-1} as:

$$R^{-1} = (I + C)^{-1} \approx I - C$$

$$A\,\mathbf{d} \approx (I - C)\,\mathbf{y} = \mathbf{y} - C\,\mathbf{y}$$

Hence it is clear that DPIC calculates the elements R via the slaved correlator channels and then performs a very simple approximation when applying R^{-1}.

5. Software Correlator Implementation

In order to test these concepts, a software correlator based on the techniques of [14] was employed, where the correlation was for a Zarlink GP2015 front end and duplicates in software the correlators contained within the Zarlink GP2021/GP4020 baseband devices. This GPS software correlation method performs all of the required correlations in the time domain by processing small (16 or 32 bit) batches of sign and magnitude bits that match the processing capabilities of the processor being used to perform the correlation. Some minor changes were made with regard to the lookup tables used to obtain the values for the carrier DCO values and the despreading codes. In particular, rather than using a single large lookup tables of up to 960 kB, smaller tables specific to a single carrier or code DCO frequency are employed. These tables are generated dynamically at very little processing cost whenever the channel is started or the selected frequency becomes sufficiently different from the required value. Each table covers a range of initial phase angles for each batch of 16 (or 32) input samples, with the carrier or code phase DCO value used as an index into each table. 64 and 128 initial phases were found to give reasonable results for the carrier and code PRN lookup tables resulting in table sizes of 0.5 kB and 8 kB for each channel respectively. This reduces the size of the required tables substantially thereby making the technique more applicable for use in an embedded processor where memory may be constrained.

6. DPIC Software Correlator Modifications

Two additions need to be applied to the standard software correlator to implement DPIC. One is the channel slaving feature, where this implementation permits a particular correlator channel to be slaved to another master channel. Processing of the slave channel then employs the correlator and code DCO's of the master channel.

The other addition is a processing block to regenerate the pure-IF of the strong signal. This involves mixing the strong signal carrier DCO, code PRN sequence and the current strong signal data-bit values to create a scaled version of the actual strong signal. Table 1 provides a truth-table showing the required logic to perform this mixing given the data-modulated strong signal PRN and the strong signal carrier signal. In this case, the data-modulated strong signal PRN is calculated as the one-bit product (exclusive-or) between the current data bit estimate and the PRN code sequence.

Using this truth table, the following logic equations can be derived, where D_s is the sign of the current data-bit, P_s is the sign of the current PRN chip, C_s is the sign of the in-phase carrier signal and C_m is the magnitude of the in-phase carrier signal.

$$\begin{aligned} DPs &= Ds\ XOR\ Ps \\ RSs &= DPs\ XOR\ Cs \\ RSm &= Cm \end{aligned} \tag{1}$$

One difference between the reconstructed pure-IF signal produced using this method and an ideal reconstructed pure-IF signal lies in the scaling of the output, which in this case has values of {±2, ±1} but should have values of {±3, ±1}. As such, when the reconstructed signal is fed into the slave correlator channels the magnitude bit will be interpreted as having a weighting of 3 even though when it was being generated the value had a weighting of 2. In practice this turns out not to be a problem because it effectively represents a fixed scale-factor error which is calibrated out during the scaling of the pure cross-correlation prior to the subtraction process.

Table 1: Strong Signal Reconstruction Truth Table

Data Bit Modulated Strong PRN Chip Sample		Strong In-Phase Carrier DCO Sample			Reconstructed Strong Signal Sample		
DP	DPs	C	Cs	Cm	RS	RSs	RSm
1	0	-2	1	1	-2	1	1
1	0	-1	1	0	-1	1	0
1	0	1	0	0	1	0	0
1	0	2	0	1	2	0	1
-1	1	-2	1	1	2	0	1
-1	1	-1	1	0	1	0	0
-1	1	1	0	0	-1	1	0
-1	1	2	0	1	-2	1	1

Since the re-generation process employs the carrier and code PRN's as they are generated by the master channels, there is no delay process in order to permit the current value of the data-bit to be determined. The approach used to deal with this problem is to determine the current bit-value based on the current partial C/A code integrate-and-dump process when the current code-phase exceeds a given code-phase threshold, such as 256 chips and to use the previous integrate-and-dump sample value when the code-phase is less than this threshold. This fairly crude technique has the disadvantage of estimating new values for the data-bit every C/A code epoch regardless of the fact that data-bits only change every 20 epochs. An improvement could be easily made provided that a hardware C/A code epoch counter was included as well as a means of indicating that the counter had been properly initialized. In this case, the same process could be applied but would use a partial bit accumulation starting from the start of the bit up to the very end of the bit. Only during the very first portion of a bit would the previous value be employed. Use of a variable threshold would also permit selection of the threshold to be varied with the strong signal signal-to-noise ratio.

The noise-cancelled output samples are then constructed in the following way:

$$iq = iq_w - \sum_{k=0}^{N-1} iqs_k \cdot \frac{|i_k|}{20000}$$

where iq is the complex noise cancelled correlator output, iq_w is the complex weak signal correlator output, iqs_k are the complex correlator outputs for slave channels k, i_k is the in-phase output for strong signal k, N is the number of slave channels and *20000* is the scale factor for a Zarlink GP2015 front end.

7. Software Correlator Test Results

Experimental verification of DPIC was performed using both simulated data generated using Matlab and data acquired from a Welnavigate GS700 GPS simulator, a SigNav Pty Ltd MG5001 GPS receiver modified to permit capture of the sign, magnitude and sample clock signals, a custom interface board used to group the sign and magnitude bits into 16-bit batches and a National Instruments NI6530 digital I/O card to log the data to a PC.

Table 2: Test Case Dataset Parameters

Test / Dataset	SV	SNR (dB-Hz)	Doppler (Hz)	Code (Chips)	Data Modulation
1, WelNav wncc117	31	~50	-2500	-	Y
	1	~27	-1500	-	N
2, WelNav wncc127	31	~50	-2500	-	Y
	30	~50	-2500	-	Y
	1	~27	-1500	-	N
3, WelNav wncc137	31	~50	-2500	-	Y
	30	~50	-2500	-	Y
	29	~50	-500	-	Y
	1	~27	-1500	-	N
4, WelNav wncc147	31	~50	-2500	-	Y
	30	~50	-2500	-	Y
	29	~50	-500	-	Y
	28	~50	-3500	-	Y
	1	~27	-1500	-	N
5, WelNav wncwicc108	31	~50	-2600	-	N
	CW	~55	~600	-	n/a
	1	~27	-1600	-	N

However, due to space limitations the Matlab results have been omitted here. Use of the simulator permitted greater control of the types of signals being processed thereby ensuring that the weak signals were significantly affected by cross correlations and that the scenarios of concern were actually captured. The use of a hardware simulator for signal generation and hardware data capture also provides convincing evidence for the effectiveness of the technique compared to a set of software simulation results only.

Table 2 describes the data-sets that were used to verify the algorithm and for which results are presented. The first four test results employ simulator generated input data for one to four strong signals at 50 dBHz and a single weak signal at 27 dB Hz. In all cases the relative Doppler carrier frequency between the weak signal and strong signal is close to an integer multiple of 1000 Hz as this represents the worst possible case for cross correlation. Data modulation is also present on all of the strong and weak signals thereby making proper handling of the data-bits essential for proper operation.

The results of trying to detect the weak SV 1 using both DPIC search and using a standard processing are shown in Figures 6 to 9. In each case a 5 ms coherent integration and 80 non-coherent rounds (giving 400 ms total integration) have been employed, where the Doppler frequencies have been tuned to match the actual Doppler frequency of the signal. In all cases, the use of DPIC results in the otherwise undetectable signal being easily detected. This can be quantified by calculating a detectability factor *DF* for the process, which is similar to a power signal to noise ratio.

$$DF = \frac{(P - Mean(N))^2}{Var(N)} \qquad (2)$$

P is the amplitude of the 'true' signal (generally the peak when DPIC has been used), *Mean(N)* is the mean noise floor and *Var(N)* is the noise floor variance. The WelNav simulated data with the 23 dB of dynamic range gave *DF* values of approximately 203 or 23 dB.

The final set of results show the ability of DPIC to also cancel continuous wave interference (CWI), where the datasets were created using a "feature" of the WelNavigate GS700 simulator to generate CW signals when the satellite PRN number is set to zero. Although the initial datasets were created inadvertently, it was quickly realized that the DPIC process is inherently able to mitigate such interference provided that the tracking loops are modified to track CWI and the standard mitigation process applied. To this end, the software was modified so that SV numbers greater than or equal to 255 were considered to be CW, in which case the code-DLL was bypassed and no code-despreading performed within the software correlator. This permitted CWI signals to be tracked. The DPIC process was then applied to one of the specific datasets created to illustrate the CWI mitigation capability of DPIC.

Figure 10 shows the difference between a standard correlation process (bottom), DPIC cancellation of the strong SV31 at 50 dHB only (middle) and DPIC cancellation of both the strong SV31 and the strong CWI at ~55 dBHz (top). As before, the signal is undetectable without DPIC but full DPIC results in a final DF value of 378 or 25.7 dB. The effect of the CWI is to raise the noise floor to a value greater than it would otherwise be, as is evident by a comparison between the noise-floors in Figure 6 (bottom) and Figure 10

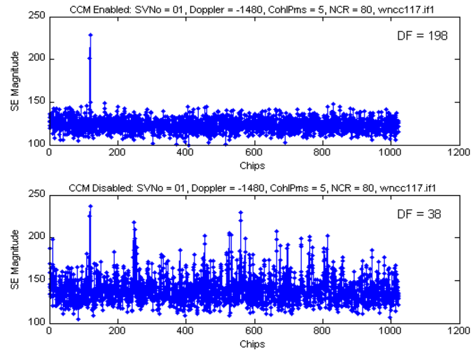

Figure 6: Detection of a weak signal in the presence of 1 strong signal with and without DPIC (wncc117).

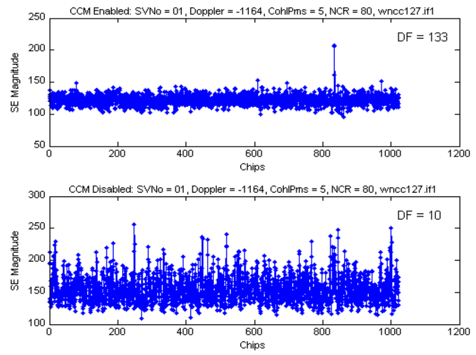

Figure 7: Detection of a weak signal in the presence of 2 strong signals with and without DPIC (wncc127).

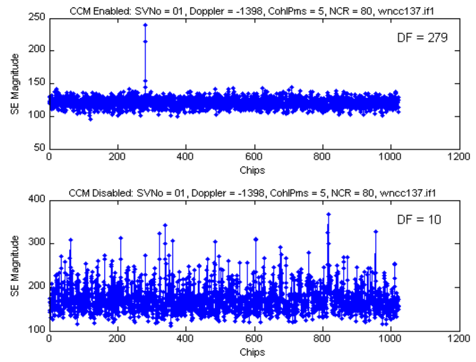

Figure 8: Detection of a weak signal in the presence of 3 strong signals with and without DPIC (wncc137).

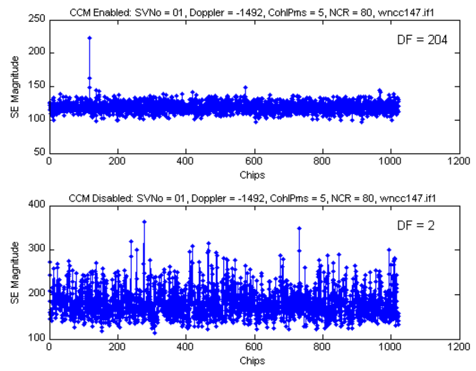

Figure 9: Detection of a weak signal in the present of 4 strong signals with and without DPIC (wncc147)

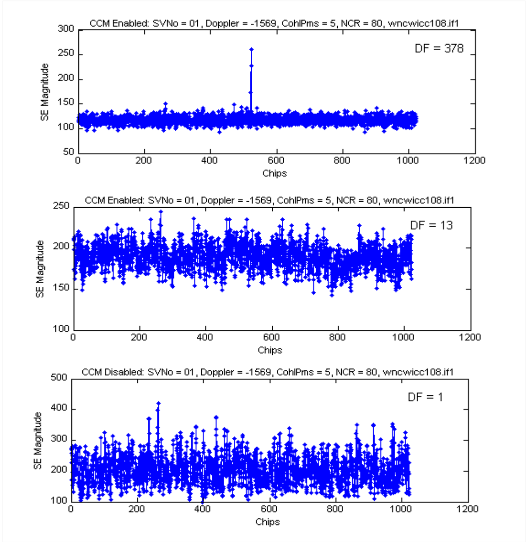

Figure 10: DPIC cancellation of strong signal and CWI (top), strong signal only (middle) and no cancellation (bottom) (wncwicc108).

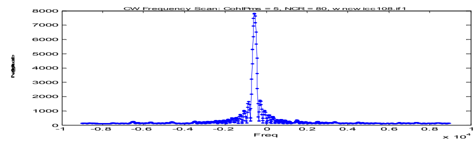

Figure 11: Frequency scan of the signal 'wncwicc108' from -10kH to +10 kHz showing the CWI at –600 Hz.

(bottom). If DPIC is only applied to the strong signal SV31, but the CWI is ignored then the weak signal is unable to be detected, as shown in Figure 10 (middle). Figure 11 contains a frequency scan showing the single tone at -600 Hz for the test signal.

The DPIC ability to cancel CWI further serves to differentiate the method from [9], which would simply subtract a constant from all output.

8. Conclusions

In this paper, it has been shown that C/A code cross correlation mitigation may be performed post-correlation provided that the post-correlation cross correlations are independently estimated from each strong signal. A hardware or software implementation that permits this estimation to be performed through the use of hardware IF signal regeneration and additional slave correlator channels has been proposed. The method has a number of advantages, including elimination of the need to perform subtraction on highly quantized (1 or 2 bit) signals and offers a low complexity solution for any hardware or software design.

The method was prototyped and verified using a software GPS correlator written in C and tested with datasets generated in Matlab and captured using a hardware GPS simulator and receiver. In both cases, the technique was able to remove the multiple access noise from the weak signal correlations making the otherwise undetectable signal easily observable. These datasets included up to four strong signals that were each 23 dB stronger than the weak signal to be detected, and all at relative Doppler carrier frequencies near an integer 1 kHz boundary, this being the worst possible case. It was also shown that the method is capable of assisting in cases where CWI interference is present provided the CWI interference is being tracked by one of the channels.

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