(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
31 December 2008 (31.12.2008)

PCT

(10) International Publication Number
WO 2009/002936 A1

(51) International Patent Classification:
G01S 1/00 (2006.01)

(21) International Application Number: PCT/US2008/067912

(22) International Filing Date: 23 June 2008 (23.06.2008)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
60/945,747 22 June 2007 (22.06.2007) US

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(81) Designated States *(unless otherwise indicated, for every kind of national protection available)*: AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BR, BW, BY, BZ, CA, CH, CN, CO, CR, CU, CZ, DE, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IS, JP, KE, KG, KM, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LT, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PG, PH, PL, PT, RO, RS, RU, SC, SD, SE, SG, SK, SL, SM, SV, SY, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) Designated States *(unless otherwise indicated, for every kind of regional protection available)*: ARIPO (BW, GH, GM, KE, LS, MW, MZ, NA, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European (AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MT, NL, NO, PL, PT, RO, SE, SI, SK, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

Published:
— *with international search report*

(54) Title: DELAYED PARALLEL INTERFERENCE CANCELLATION FOR GPS C/A CODE RECEIVERS

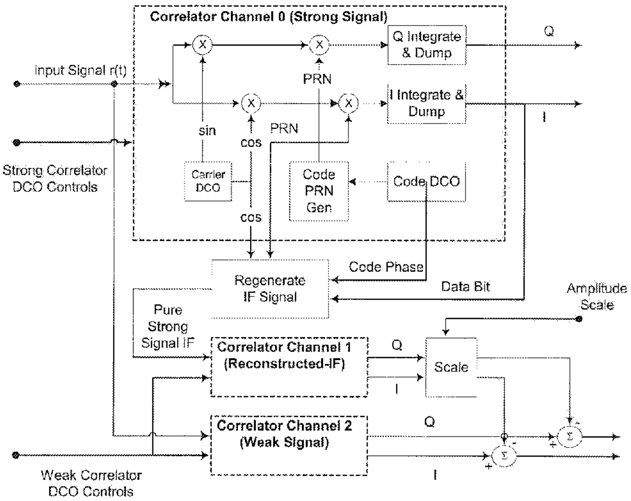


Fig. 5

(57) Abstract: A modified method and implementation is disclosed 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. In this method and implementation, successive-interference cancellation (SIC) and parallel-interference cancellation (PIC) techniques, where strong signals are subtracted at IF prior to attempting to detect weak signals, are modified so that 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 method and implementation is particularly useful for the cancellation of CW interference.

WO 2009/002936 A1

Delayed Parallel Interference Cancellation for GPS C/A Code Receivers

Inventors: Éamonn P. Glennon, Roderick C. Bryant and Andrew G. Dempster

Field of Invention:

This invention relates to GPS signal reception. In particular it relates to methods and hardware for the mitigation of cross correlations between weak and strong GPS signals.

I. BACKGROUND OF THE INVENTION

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. 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. One of the more well known techniques is successive interference cancellation (SIC), with this method being notable due to having been applied to the GPS pseudolite problem. Parallel interference cancellation (PIC) is similar except that multiple strong signals are subtracted in parallel rather than being subtracted serially.

Successive Interference Cancellation

A block diagram showing the successive interference cancellation process (SIC) is given in Figure 1. The SIC process is generally described in J. M. Holtzman, "DS/CDMA successive interference cancellation," presented at Spread Spectrum Techniques and Applications, 1994. IEEE ISSSTA '94., IEEE Third International Symposium on, 1994; P. Patel and J. Holtzman, "Analysis of a simple successive interference cancellation scheme in a DS/CDMA system," Selected Areas in Communications, IEEE Journal on, vol. 12, pp. 796-807, 1994; and K. I. Pedersen, T. E. Kolding, I. Seskar, and J. M. Holtzman, "Practical implementation of successive interference cancellation in DS/CDMA systems," presented at Universal Personal Communications, 1996. Record., 1996 5th IEEE International Conference on, 1996.

The SIC process serially subtracts 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 advantage 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 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 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 punctual 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 present invention overcomes this subtraction problem.

The problem of interference cancellation is also addressed in United States Patent 6,707,843, entitled "Strong Signal Cancellation to Enhance Processing of Weak Spread Spectrum Signal".

Parallel Interference Cancellation

Parallel interface cancellation is generally described in P. Patel and J. Holtzman, "Performance comparison of a DS/CDMA system using a successive interference cancellation (IC) scheme and a parallel IC scheme under fading," presented at Communications, 1994. ICC 94, SUPERCOMM/ICC '94, Conference Record, Serving Humanity Through Communications. IEEE International Conference on, 1994.

Decorrelating Detectors

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. It is generally described in S. Moshavi, "Multi-user detection for DS-CDMA communications," Communications Magazine, IEEE, vol. 34, pp. 124-136, 1996.

BRIEF DESCRIPTION OF THE PRESENT INVENTION

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, 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.

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. As such, 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.

Delayed Parallel Interference Cancellation (DPIC)

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.

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 a n integer multiple of 1 kHz. 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.

Unlike the method described in US patent 6,707,843, (herein the '843 patent), DPIC creates exact estimates of the cross correlations for each integrate dump operation. Contrast this with the '843 patent, 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. The correct estimation technique should use the exact formulation described in A. J. Van Dierendonck, R. Erlandson, and G. McGraw, "Determination of C/A Code Self Interference Using Cross-Correlation Simulations and Receiver Bench Tests," presented at Proceedings of the

15th International Technical Meeting of the Satellite Division of the U.S. Inst. Of Navigation, Portland, OR, 2002. As such, the cross correlations in the '843 patent's technique 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.

Relationship of the invention to a decorrelating detector

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_l 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 'normalized' 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}.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 depicts a Successive Interference Cancellation technique.

Figure 2 depicts a Successive Interference Cancellation technique without a delay stage.

Figure 3 depicts a standard processing of differenced IF.

Figure 4 depicts an alternate processing of differenced IF.

Figure 5 depicts a detailed DPIC with one strong signal cancellation.

Figure 6 depicts the detection of a weak signal in the presence of 1 strong signal with (top) and without (bottom) DPIC (1J_2).

Figure 7 depicts detection of a weak signal in the presence of 2 strong signals with (top) and without (below) DPIC (2J_2).

Figure 8 depicts detection of a weak signal in the presence of 3 strong signals with (top) and without (below) DPIC (3J_2).

Figure 9 depicts detection of a weak signal in the present of 4 strong signals with (top) and without (bottom) DPIC (4J_2)

Figure 10 depicts detection of a weak signal in the presence of 1 strong signal with and without DPIC (wncc117).

Figure 11 depicts detection of a weak signal in the presence of 2 strong signals with and without DPIC (wncc127).

Figure 12 depicts detection of a weak signal in the presence of 3 strong signals with and without DPIC (wncc137).

Figure 13 depicts detection of a weak signal in the present of 4 strong signals with and without DPIC (wncc147)

Figure 14 depicts detection of a weak signal in the presence of 1 strong signal and CWI with (top) and without (below) DPIC (wncwicc108).

Figure 15 depicts attempted detection of a weak signal in the presence of 1 strong signal and CWI with (top) and without (below) DPIC, but where DPIC is only applied to the strong signal (wncwiccl08).

Figure 16 depicts frequency scan of the signal 'wncwiccl08' from -10kH to +10 kHz showing the CWI at –600 Hz.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS OF THE INVENTION

Software Correlator Implementation

In order to test these concepts, a software correlator was employed based on the techniques of B. M. Ledvina, M. L. Psiaki, S. P. Powell, and P. M. Kintner, "Bit-wise parallel algorithms for efficient software correlation applied to a GPS software receiver," Wireless Communications, IEEE Transactions on, vol. 3, pp. 1469-1473, 2004, (herein "LPPK") 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.

To perform the required correlations it is necessary to take two bit sign and magnitude intermediate frequency (IF) input and to mix it with two bit carrier DCO output and one bit spreading code output. The IF input data takes on the values of ±1 and ±3, the carrier DCO output has the values of ±1 and ±2 while the spreading code has values of ±1. Five bits are used to represent the final product term since by assigning a single bit for the values 1, 2, 3 and 6, the final stage accumulation process may be more easily performed.

A truth table showing the values for the input IF, carrier DCO output and calculated product bits is given in Table 1, but does not include any despreading terms.

Raw IFin			Carrier DCO OP				±	6	3	2	1
IFin	S	M	C	Cs	Cm	OP	P4	P3	P2	P1	P0
-3	1	1	-2	1	1	6	0	1	0	0	0
-3	1	1	-1	1	0	3	0	0	1	0	0
-3	1	1	1	0	0	-3	1	0	1	0	0
-3	1	1	2	0	1	-6	1	1	0	0	0
-1	1	0	-2	1	1	2	0	0	0	1	0
-1	1	0	-1	1	0	1	0	0	0	0	1
-1	1	0	1	0	1	-1	1	0	0	0	1
-1	1	0	2	0	1	-2	1	0	0	1	0
1	0	0	-2	1	1	-2	1	0	0	1	0
1	0	0	-1	1	0	-1	1	0	0	0	1
1	0	0	1	0	1	1	0	0	0	0	1
1	0	0	2	0	1	2	0	0	0	1	0
3	0	1	-2	1	1	-6	1	1	0	0	0
3	0	1	-1	1	0	-3	1	0	1	0	0
3	0	1	1	0	1	3	0	0	1	0	0
3	0	1	2	0	1	6	0	1	0	0	0

TABLE 1: SOFTWARE CORRELATION TRUTH TABLE

The output bits of P4, P3, P2, P1 and P0 are easily calculated using the following simple logic equations.

$$\begin{aligned} &P4 = S\ XOR\ Cs \\ &P3 = M\ AND\ Cm \\ &P2 = M\ AND\ NOT(Cm) \qquad (1) \\ &P1 = NOT(M)\ AND\ Cm \\ &P0 = NOT(M)\ AND\ NOT(Cm) \end{aligned}$$

If each of the above quantities is assigned a single word in the software receiver, then 16 or 32 bits may be processed in parallel. These equations apply to the down-conversion and do not include the despreading process which only affects the P4 sign bit term. As such, different correlator channel fingers each with a slightly different despreading code may be used to update the P4 quantity only. The "integrate and dump" process is also easily performed by counting the number of bits for the different weightings (6, 3, 2 and 1) and then accumulating those bits while taking into account the value of the sign quantity P4 after despreading. The despreading process is performed by an exclusive-or between P4 and the despreading code.

Although the above process is exactly as given in LPPK, some changes have been 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.

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 2 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.

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	1	-1	1	0
-1	1	2	0	1	-2	1	1

TABLE 2: STRONG SIGNAL RECONSTRUCTION TRUTH TABLE

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.

$$\begin{aligned} DPs &= Ds\ XOR\ Ps \\ RSs &= DPs\ XOR\ Cs \\ RSm &= Cm \end{aligned} \tag{2}$$

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.

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.

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. 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 3 describes the data-sets that were used to verify the algorithm and for which results are presented. The first four test results employ Matlab generated input data for one to four strong signals at 50 dBHz and a single weak signal at 30 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 next four sets of results are equivalent datasets with similar characteristics, although the weak signals are 3 dB weaker and the datasets were obtained using real hardware.

Test / Dataset	SV	SNR (dB-Hz)	Doppler (Hz)	Code (Chips)	Data Modulation
1, Matlab 1J_2	31	50	1000	0	Y
	1	30	-10	100	Y
2, Matlab 2J_2	31	50	1000	0	Y
	30	50	-1000	0	Y
	1	30	-10	100	Y
3, Matlab 3J_2	31	50	1000	0	Y
	30	50	-1000	0	Y
	29	50	1000	0	Y
	1	30	-10	100	Y
4, Matlab 4J_2	31	50	1000	0	Y
	30	50	-1000	0	Y
	29	50	1000	0	Y
	28	50	0	0	Y
	1	30	0	100	Y
5, WelNav wncc117	31	~50	-2500	-	Y
	1	~27	-1500	-	N
6, WelNav wncc127	31	~50	-2500	-	Y
	30	~50	-2500	-	Y
	1	~27	-1500	-	N
7, WelNav wncc137	31	~50	-2500	-	Y
	30	~50	-2500	-	Y
	29	~50	-500	-	Y
	1	~27	-1500	-	N
8, WelNav wncc147	31	~50	-2500	-	Y
	30	~50	-2500	-	Y
	29	~50	-500	-	Y
	28	~50	-3500	-	Y
	1	~27	-1500	-	N
9, WelNav wncwicc108	31	~50	-2600	-	N
	CW	~55	~600	-	n/a
	1	~27	-1600	-	N

TABLE 3: TEST CASE DATASET PARAMETERS

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 13. 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.

$$DF = \frac{(P - Mean(N))^2}{Var(N)} \qquad (3)$$

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 Matlab simulated data with the 20 dB of dynamic range gave *DF* values of approximately 472 or 26 dB, while the WelNav data with its 23 dB dynamic range had an average *DF* of 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 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.

Fig. 14 shows the difference between a standard correlation process and DPIC cancellation of the single strong signal SV31 at ~50 dBHz and the CWI at ~55 dBHz. As before, the signal is undetectable without DPIC but 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 Fig 10 (bottom) and Fig 14 (bottom). Fig. 15 shows that if DPIC is only applied to the strong signal SV31, but the CWI is ignored then the weak signal is unable to be detected. Fig 16 contains a frequency scan showing the single tone at -600 Hz for the test signal.

It should be emphasized that the DPIC ability to cancel CWI further serves to differentiate the method from [9], which would simply subtract a constant from all output correlations (i.e. Fig. 15 top plot).

DPIC Featured Search Engine

Many high sensitivity GPS receivers feature massively parallel correlator banks that are capable of searching a significant portion of the code space at several frequency bins. Given that the purpose of such hardware is rapid detection of weak signals that may be subject to cross correlation (multiple access) noise, it is sensible to consider the feasibility of including DPIC within such a design. This in turn depends on how the search engine itself has been implemented.

In the synthesized search engine (SE) outputs presented in this paper, the SE functionality has been constructed on top of a basic correlator channel in which each correlator out of 32 channels contains 32 fingers of code phase. The correlator channel allocated to the SE function is then used repeatedly on the same set of IF input signal, but searching for different code phases each time at a selected Doppler frequency. For the DPIC enabled SE, the standard correlator employed in the SE was replaced with a DPIC enabled correlator instead, where the DPIC enabled correlator contained additional controls to permit the strong signal channels to be identified, performed the pure IF signal reconstruction and allocated an appropriate number of slave channels that obtained their input from the pure-IF signal. In addition, the output of the coherent in-phase (I) and quadrature (Q) samples from the weak channel were modified so that the scaled subtraction of each pure strong signal I & Q correlation outputs was performed to produce the clean I & Q correlation outputs. These clean I & Q outputs were then non-coherently accumulated to produce the final output, although in these results normalization for the number of accumulations also took place.

Given a hardware implementation that mirrors the above software implementation, it is clear that construction of a DPIC enabled SE is feasible despite the fact that each strong signal requires its own slave correlator channel (with matching number of fingers) to reconstruct the cross correlation at each code phase. Most likely the design would be limited to a fixed number of slave channels per SE, with one or two being recommended depending on the number of strong signals requiring mitigation. The main factor to bear in mind is that much of the cost involved in the construction of a SE is actually due to the large amount of memory required for the coherent and non-coherent rounds, so provided that the computational portion can be reduced through hardware re-use, there shouldn't be a problem. However, a naïve implementation that did not go through this process would probably be too expensive

We have 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.

APPENDIX A: RECONSTRUCTED PURE IF CORRELATION

The DPIC process involves estimation of the real weak signal cross correlation by correlating a pure (reconstructed) strong signal by a correlator that is slaved to the weak signal correlator. This creates a pure cross correlation signal that is related to the real cross correlation by means of a scale-factor that is dependent on the magnitude of the strong signal. To calculate the magnitude of the scale-factor, it is necessary to relate the magnitude of the strong signal correlation to the magnitude that would have been obtained were the strong signal pure IF processed using the same strong signal correlation.

To determine this relationship, consider the pure strong signal IF being correlated by the strong signal correlator. This process involves taking the product of the strong signal carrier DCO and spreading PRN code and mixing this with exactly the same strong signal carrier DCO and PRN code, except that the meaning associated with the magnitude bit changes during the correlation process. Since the spreading code is the same and the product of the two spreading codes is always one, this can be ignored. The magnitude of the pure strong signal correlation thereby simplifies to determining the expected value of the carrier DCO product after a C/A code period of integration., where one term of the product takes on values of ±1 and ±2 with a probability of ½, while the other term in the product takes on values of ±1 and ±3 also with a probability of ½. Since the two values are related, the product takes on values of 1 and 6 that each occur with a probability of ½. This permits the expected value of the integrate-and-dump process to be calculated as:

$$S = 5714.28\ E(1\times\tfrac{1}{2}+6\times\tfrac{1}{2}) = 20{,}000$$

where 5714.28 is the number of samples per integration period. Measuring the value in an operational system yields exactly the same value. As such, the scale factor used to scale back the pure cross correlation to the real cross correlation is:

$$Sf = Acc \times As/20000$$

where Acc is the amplitude of the pure cross correlation and As is the measured amplitude of the strong signal.

Although the invention has been described in terms of specific implementations, other implantations and variations will be apparent to persons of skill in the art based upon this disclosure. The following claims are intended to encompass those other implementations and variations.

What is claimed is:

1. A method for mitigating cross correlations in GPS signals comprising modifying successive interference cancellation techniques in which strong signals are subtracted at IF prior to attempting to detect weak signals, by delaying the subtraction process until after a correlation process.

2. The method for mitigating cross correlations in GPS signals of claim 1, wherein a pure reconstructed C/A signal is employed.

3. The method for mitigating cross correlations in GPS signals of claim 1, wherein the method is applied to the cancellation of CW interference.

4. A method for mitigating cross correlations in GPS signals comprising modifying parallel interference cancellation techniques in which strong signals are subtracted at IF prior to attempting to detect weak signals, by delaying the subtraction process until after a correlation process.

5. The method for mitigating cross correlations in GPS signals of claim 4, wherein a pure reconstructed C/A signal is employed.

6. The method for mitigating cross correlations in GPS signals of claim 4, wherein the method is applied to the cancellation of CW interference.

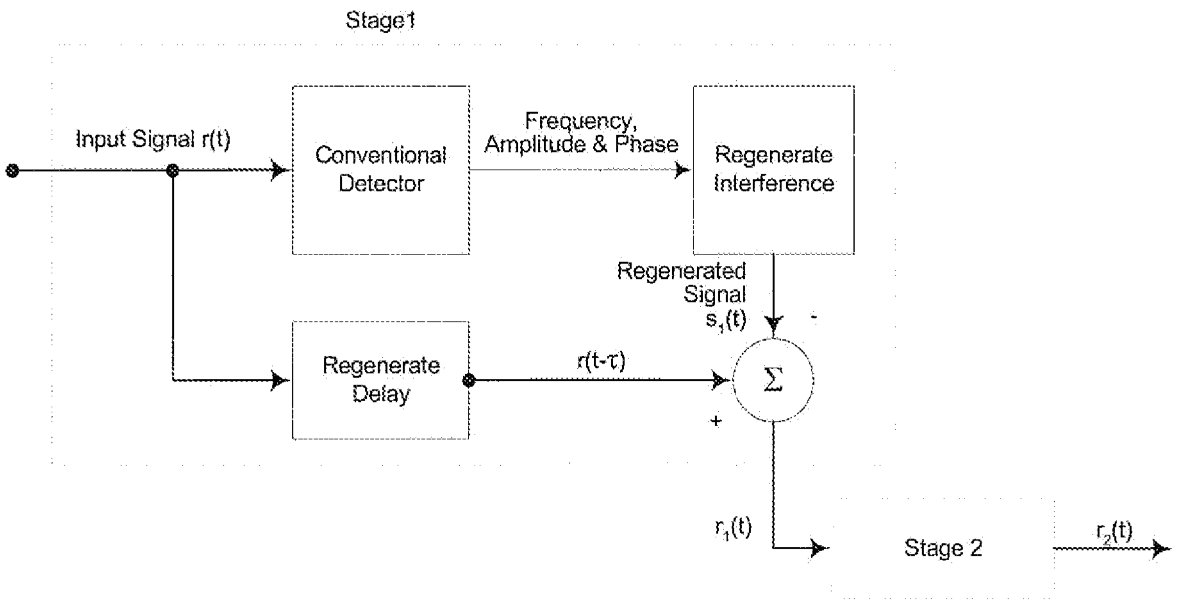

Stage1
Input Signal r(t)
Conventional Detector
Frequency, Amplitude & Phase
Regenerate Interference
Regenerated Signal $s_1(t)$
-
Regenerate Delay
r(t-τ)
Σ
+
$r_1(t)$
Stage 2
$r_2(t)$

Fig. 1

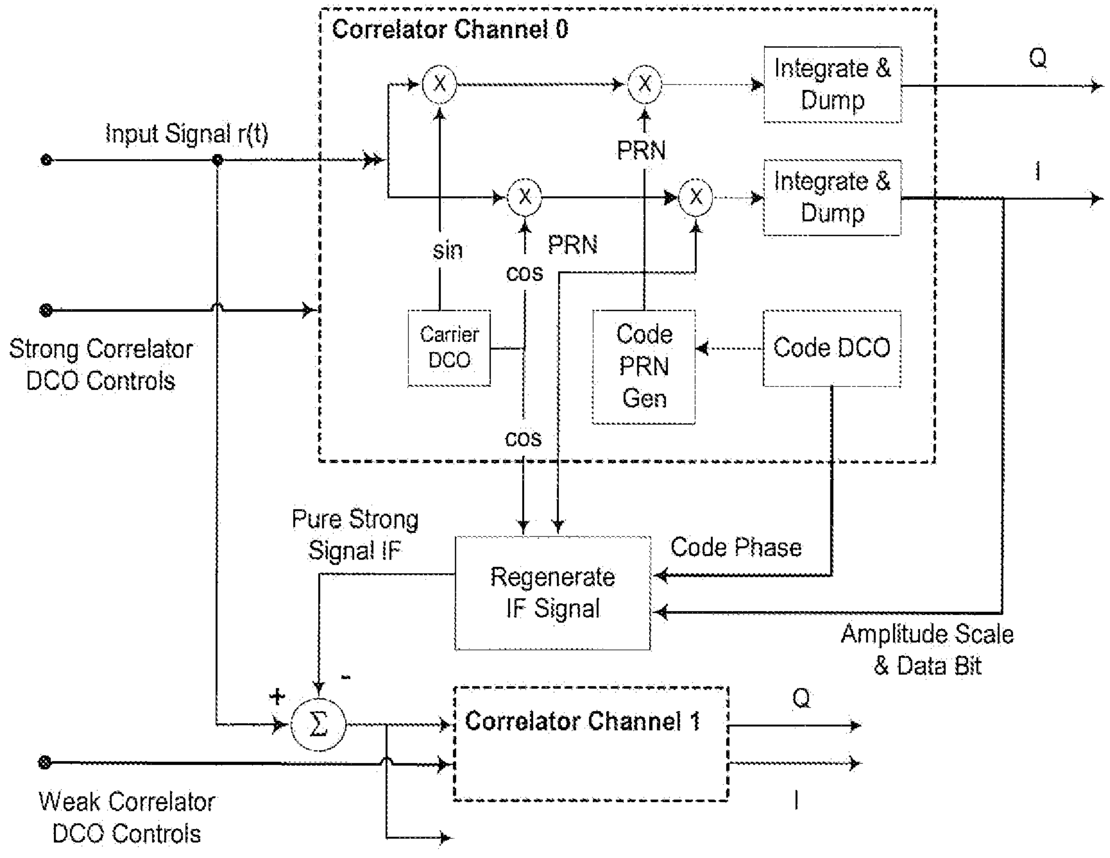

Correlator Channel 0
X
X
Integrate & Dump
Q
Input Signal r(t)
PRN
X
X
Integrate & Dump
I
sin
PRN
cos
Strong Correlator DCO Controls
Carrier DCO
Code PRN Gen
Code DCO
cos
Pure Strong Signal IF
Regenerate IF Signal
Code Phase
Amplitude Scale & Data Bit
+
-
Σ
Correlator Channel 1
Q
I
Weak Correlator DCO Controls

Fig. 2

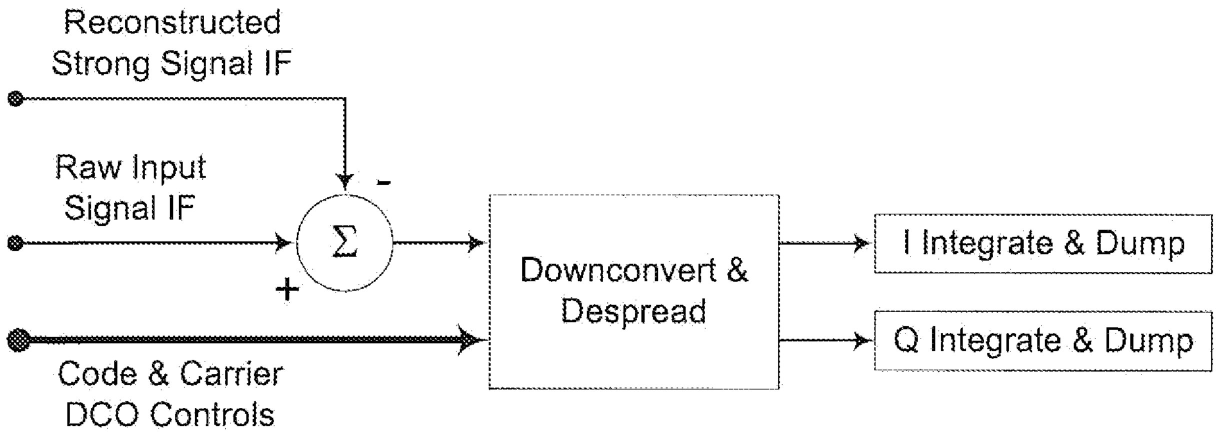

Reconstructed
Strong Signal IF
Raw Input
Signal IF
-
Σ
+
Downconvert &
Despread
I Integrate & Dump
Q Integrate & Dump
Code & Carrier
DCO Controls

Fig. 3

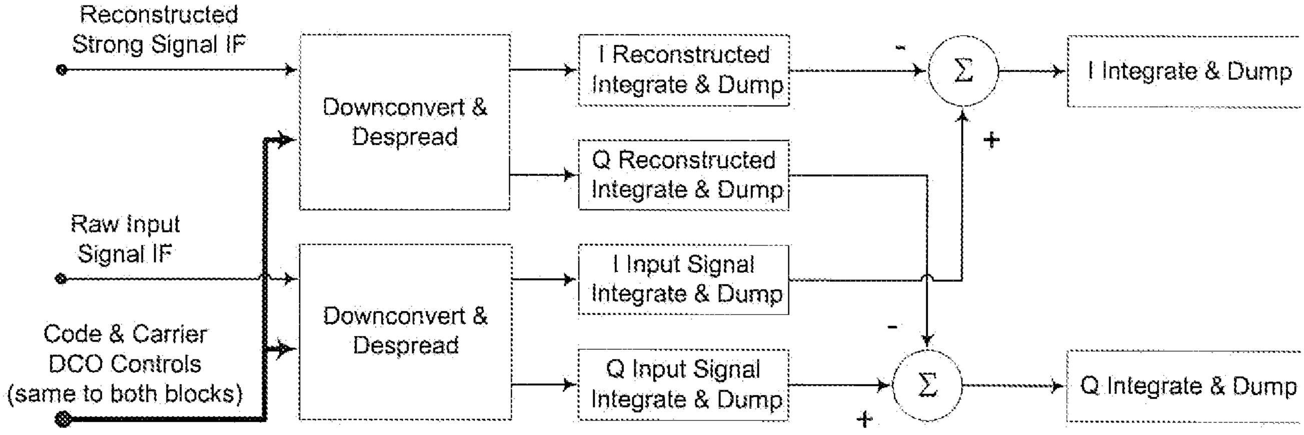

Reconstructed
Strong Signal IF
Downconvert &
Despread
I Reconstructed
Integrate & Dump
Q Reconstructed
Integrate & Dump
-
Σ
+
I Integrate & Dump
Raw Input
Signal IF
Downconvert &
Despread
I Input Signal
Integrate & Dump
Code & Carrier
DCO Controls
(same to both blocks)
Q Input Signal
Integrate & Dump
-
Σ
+
Q Integrate & Dump

Fig. 4

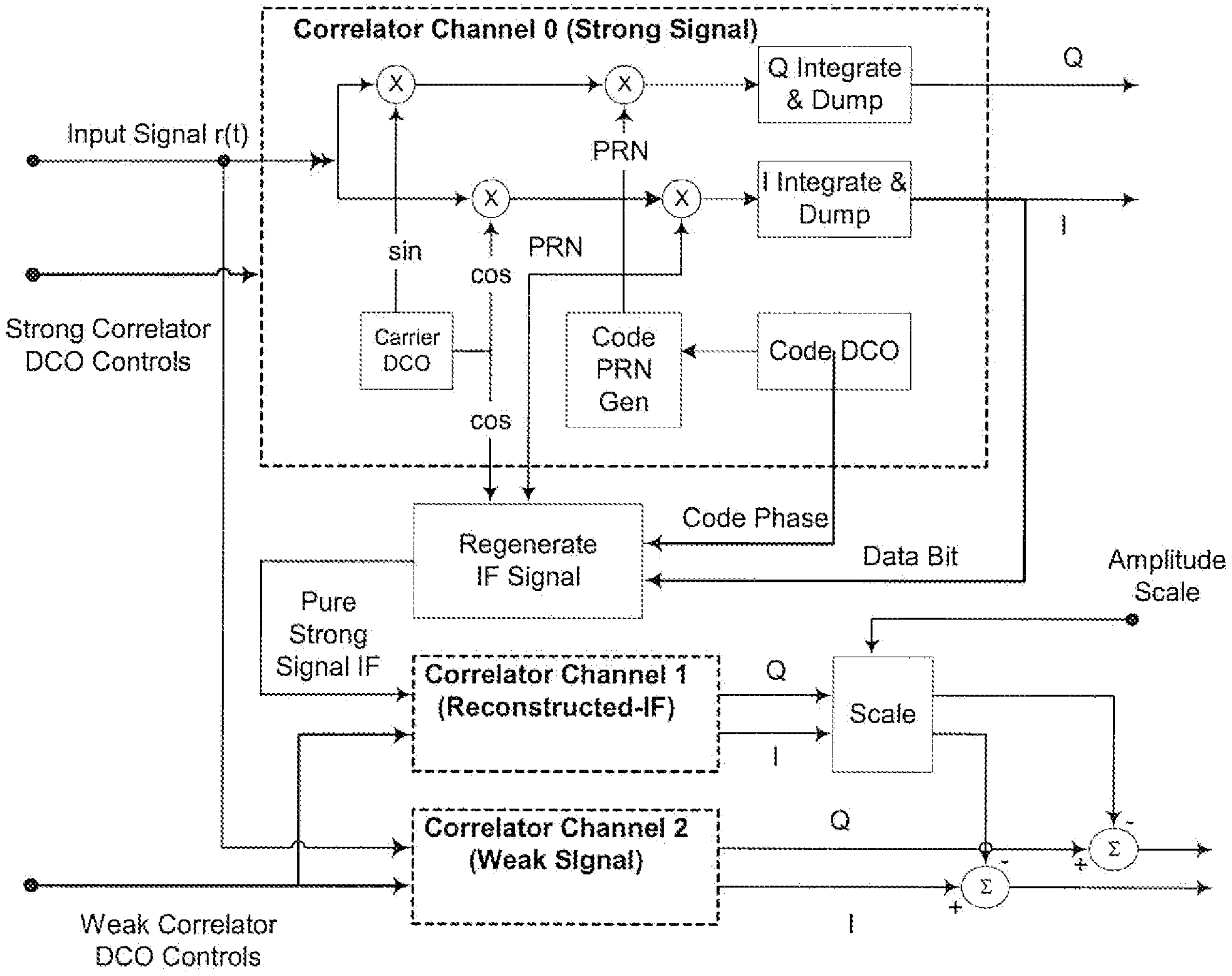
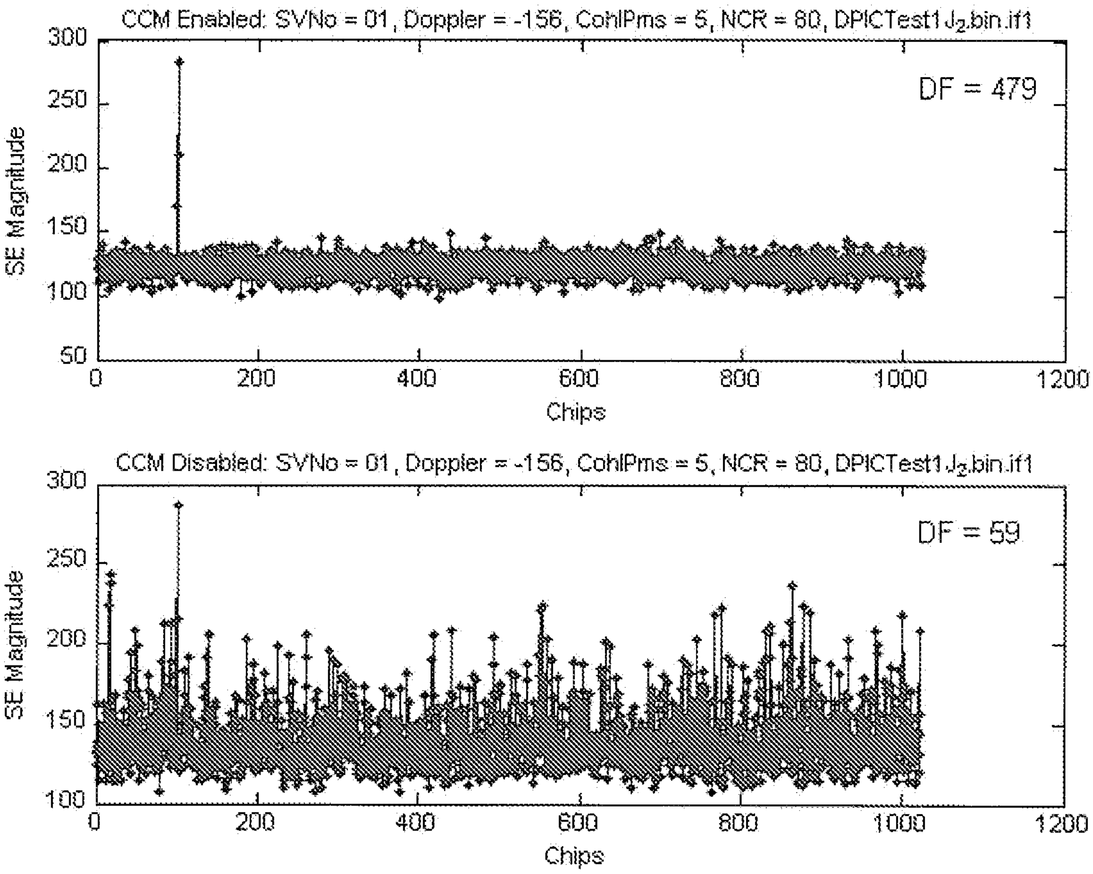

Correlator Channel 0 (Strong Signal)
Input Signal r(t)
Strong Correlator DCO Controls
X
X
X
X
sin
cos
cos
PRN
PRN
Carrier DCO
Code PRN Gen
Code DCO
Q Integrate & Dump
I Integrate & Dump
Q
I
Regenerate IF Signal
Code Phase
Data Bit
Pure Strong Signal IF
Amplitude Scale
Correlator Channel 1 (Reconstructed-IF)
Q
I
Scale
Correlator Channel 2 (Weak Signal)
Q
I
Σ
Σ
-
+
-
+
Weak Correlator DCO Controls

Fig. 5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SE Magnitude
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200
150
100
50
0
200
400
600
800
1000
1200
Chips
CCM Disabled: SVNo = 01, Doppler = -156, CohIPms = 5, NCR = 80, DPICTest1J_2.bin.if1
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SE Magnitude
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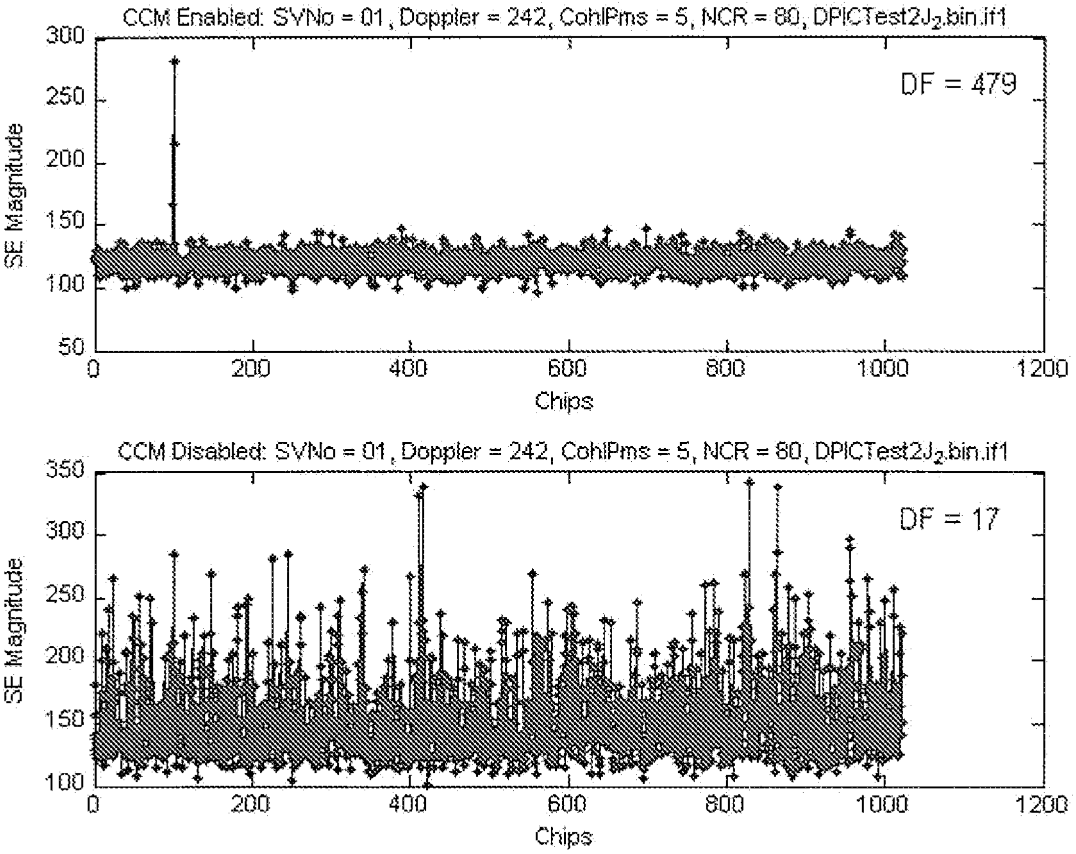
250
200
150
100
0
200
400
600
800
1000
1200
Chips

Fig. 6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DF = 479
SE Magnitude
300
250
200
150
100
50
0
200
400
600
800
1000
1200
Chips
CCM Disabled: SVNo = 01, Doppler = 242, CohIPms = 5, NCR = 80, DPICTest2J$_2$.bin.if1
DF = 17
SE Magnitude
350
300
250
200
150
100
0
200
400
600
800
1000
1200
Chips

Fig. 7

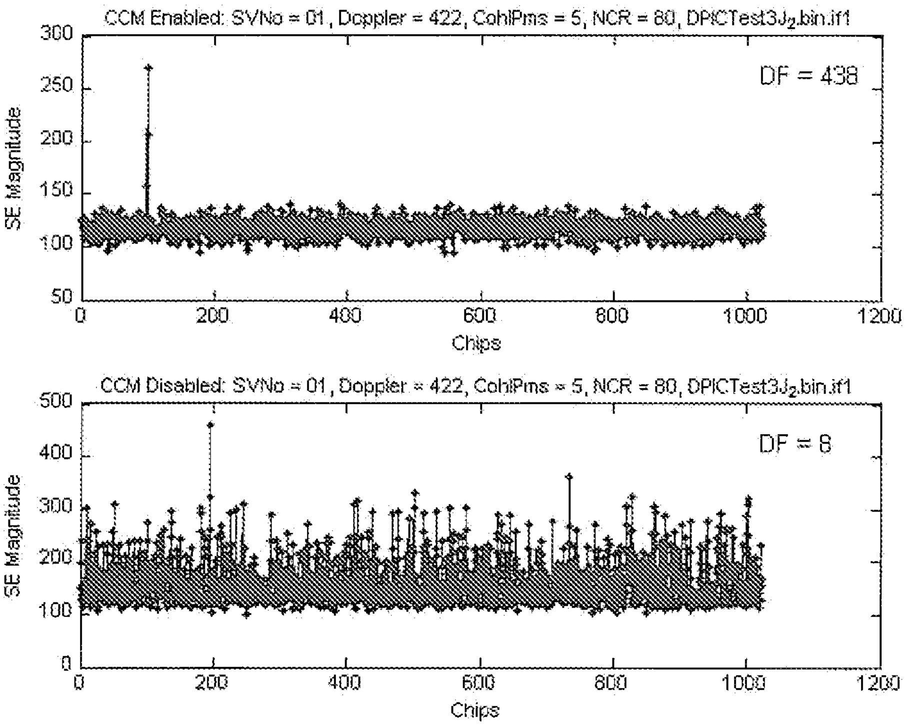

CCM Enabled: SVNo = 01, Doppler = 422, CohIPms = 5, NCR = 80, DPICTest3J$_2$.bin.if1
DF = 438
SE Magnitude
300
250
200
150
100
50
0
200
400
600
800
1000
1200
Chips
CCM Disabled: SVNo = 01, Doppler = 422, CohIPms = 5, NCR = 80, DPICTest3J$_2$.bin.if1
DF = 8
SE Magnitude
500
400
300
200
100
0
0
200
400
600
800
1000
1200
Chips

Fig. 8

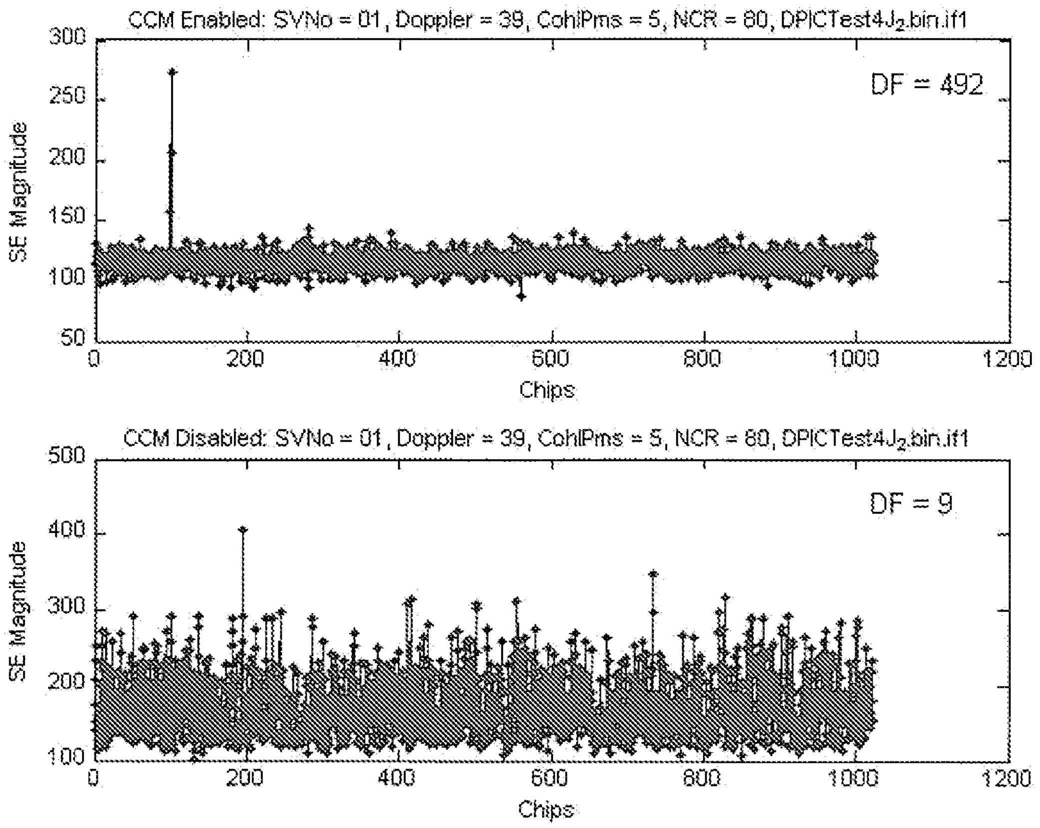

CCM Enabled: SVNo = 01, Doppler = 39, CohIPms = 5, NCR = 80, DPICTest4J_2.bin.if1
DF = 492
SE Magnitude
300
250
200
150
100
50
0
200
400
600
800
1000
1200
Chips
CCM Disabled: SVNo = 01, Doppler = 39, CohIPms = 5, NCR = 80, DPICTest4J_2.bin.if1
DF = 9
SE Magnitude
500
400
300
200
100
0
200
400
600
800
1000
1200
Chips

Fig. 9

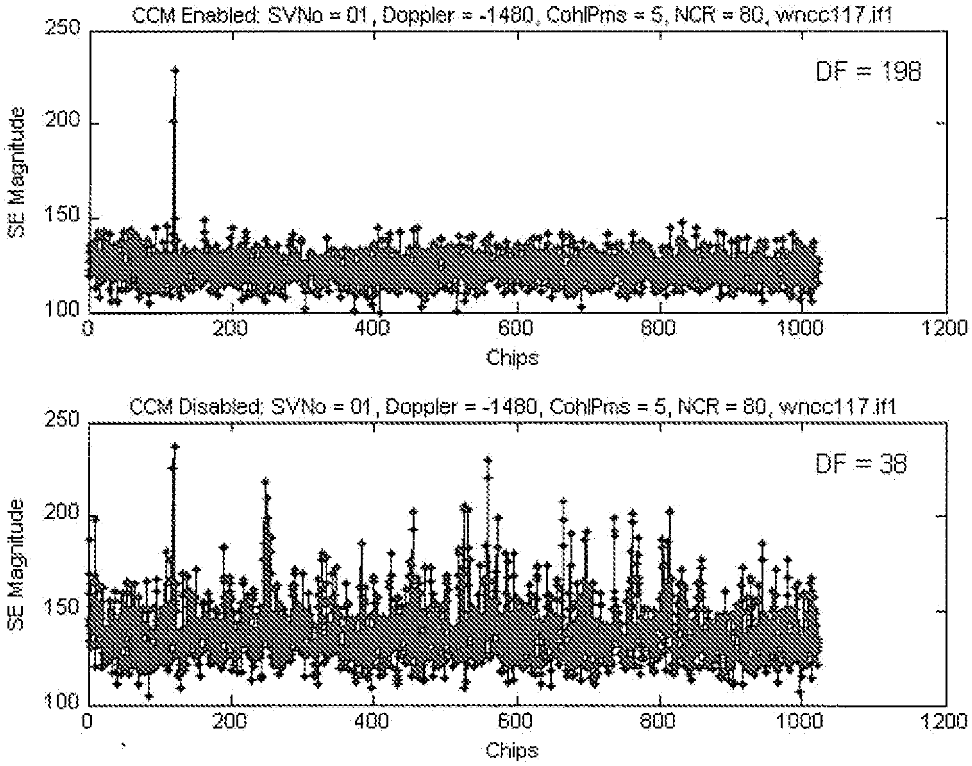
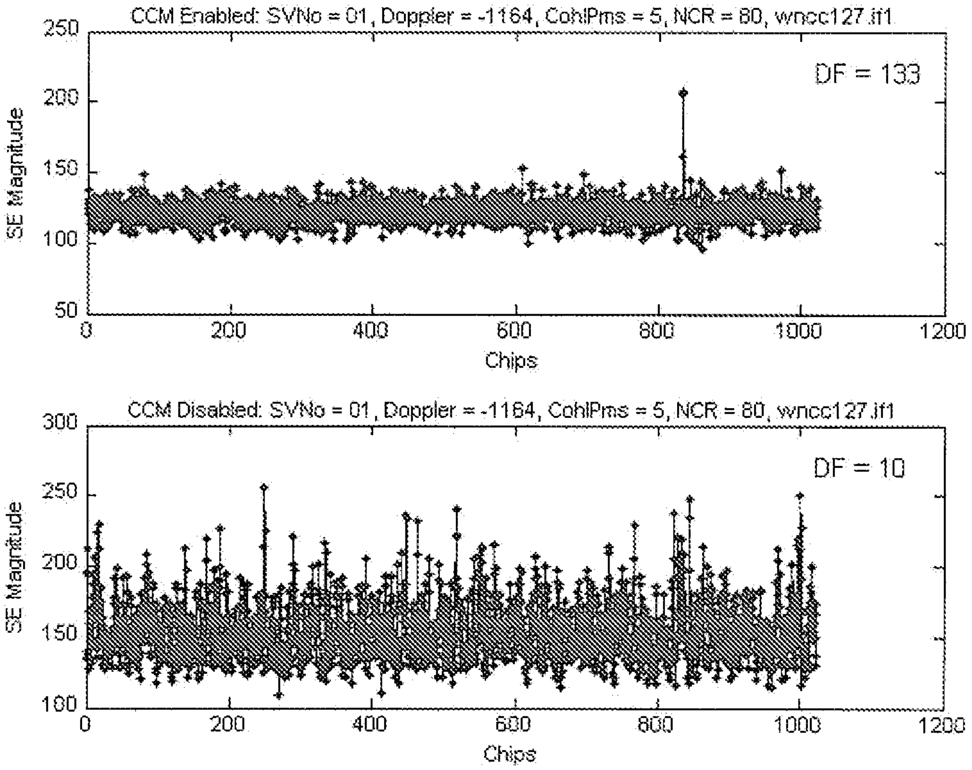

CCM Enabled: SVNo = 01, Doppler = -1480, CohIPms = 5, NCR = 80, wncc117.if1
DF = 198
SE Magnitude
250
200
150
100
0
200
400
600
800
1000
1200
Chips
CCM Disabled: SVNo = 01, Doppler = -1480, CohIPms = 5, NCR = 80, wncc117.if1
DF = 38
SE Magnitude
250
200
150
100
0
200
400
600
800
1000
1200
Chips

Fig 10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SE Magnitude
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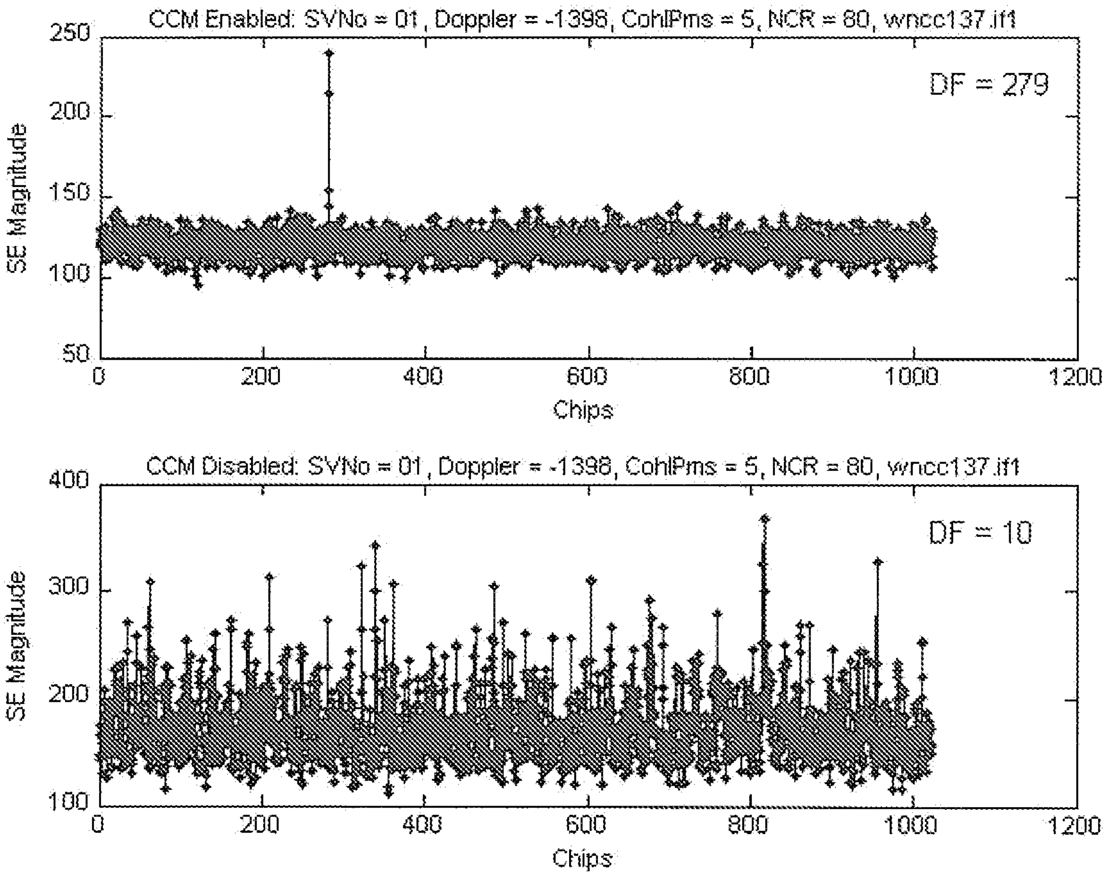
200
150
100
50
0
200
400
600
800
1000
1200
Chips
CCM Disabled: SVNo = 01, Doppler = -1164, CohIPms = 5, NCR = 80, wncc127.if1
DF = 10
SE Magnitude
300
250
200
150
100
0
200
400
600
800
1000
1200
Chips

Fig 11


CCM Enabled: SVNo = 01, Doppler = -1398, CohIPms = 5, NCR = 80, wncc137.if1
DF = 279
SE Magnitude
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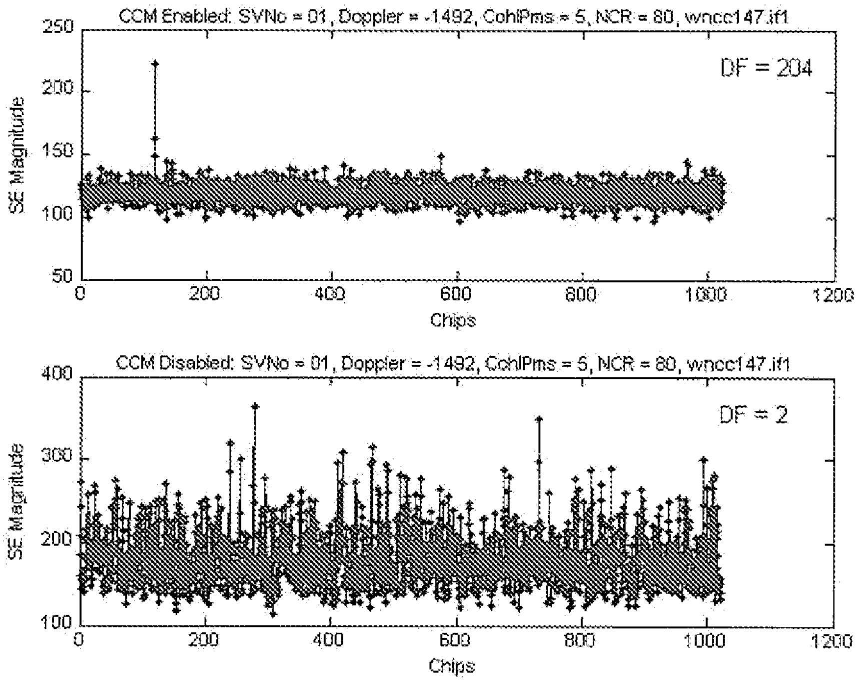
200
150
100
50
0
200
400
600
800
1000
1200
Chips
CCM Disabled: SVNo = 01, Doppler = -1398, CohIPms = 5, NCR = 80, wncc137.if1
DF = 10
SE Magnitude
400
300
200
100
0
200
400
600
800
1000
1200
Chips

Fig. 12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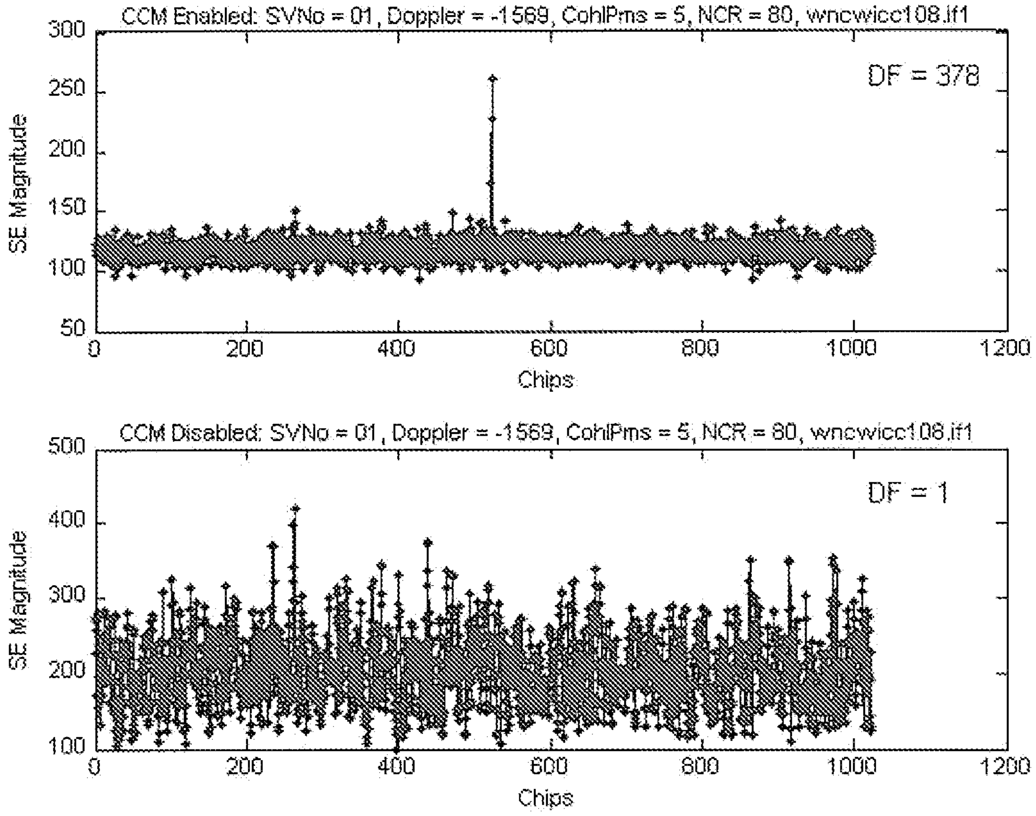
SE Magnitude
250
200
150
100
50
0
200
400
600
800
1000
1200
Chips
CCM Disabled: SVNo = 01, Doppler = -1492, CohIPms = 5, NCR = 80, wncc147.if1
DF = 2
SE Magnitude
400
300
200
100
0
200
400
600
800
1000
1200
Chips

Fig. 13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DF = 378
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150
100
50
0
200
400
600
800
1000
1200
Chips
CCM Disabled: SVNo = 01, Doppler = -1569, CohlPms = 5, NCR = 80, wncwicc108.if1
DF = 1
SE Magnitude
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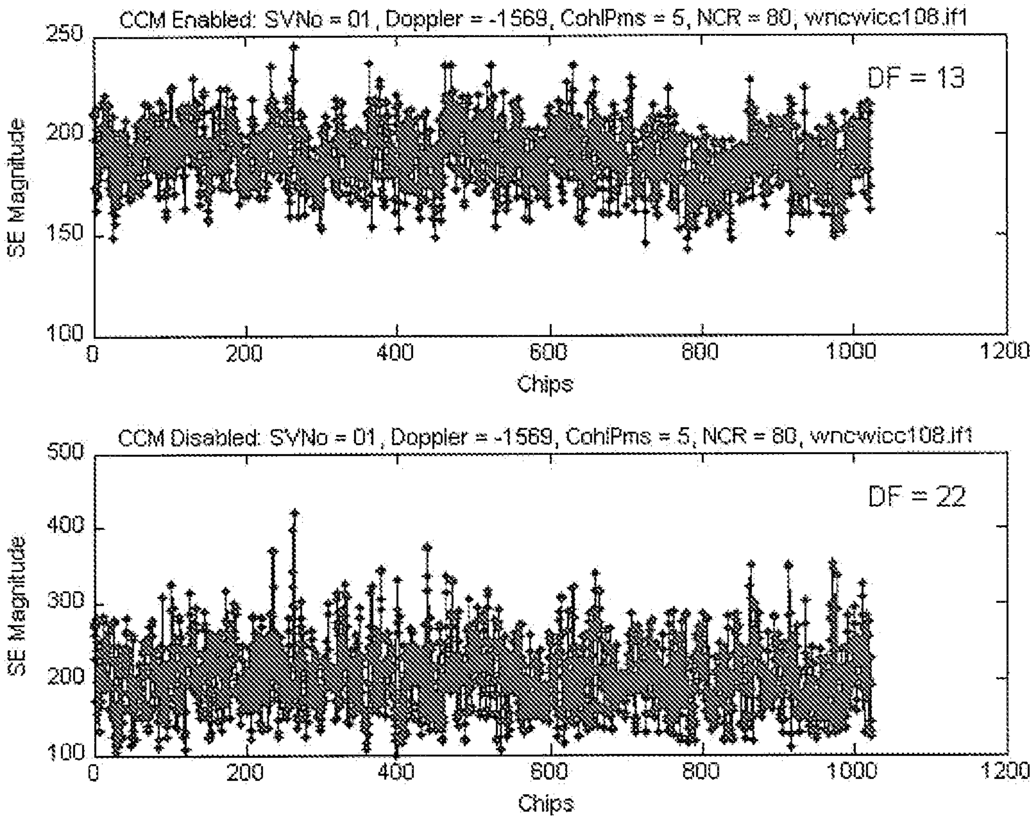
1200
Chips

Fig. 14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SE Magnitude
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200
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0
200
400
600
800
1000
1200
Chips
CCM Disabled: SVNo = 01, Doppler = -1569, CohIPms = 5, NCR = 80, wncwicc108.if1
DF = 22
SE Magnitude
500
400
300
200
100
0
200
400
600
800
1000
1200
Chips

Fig. 15

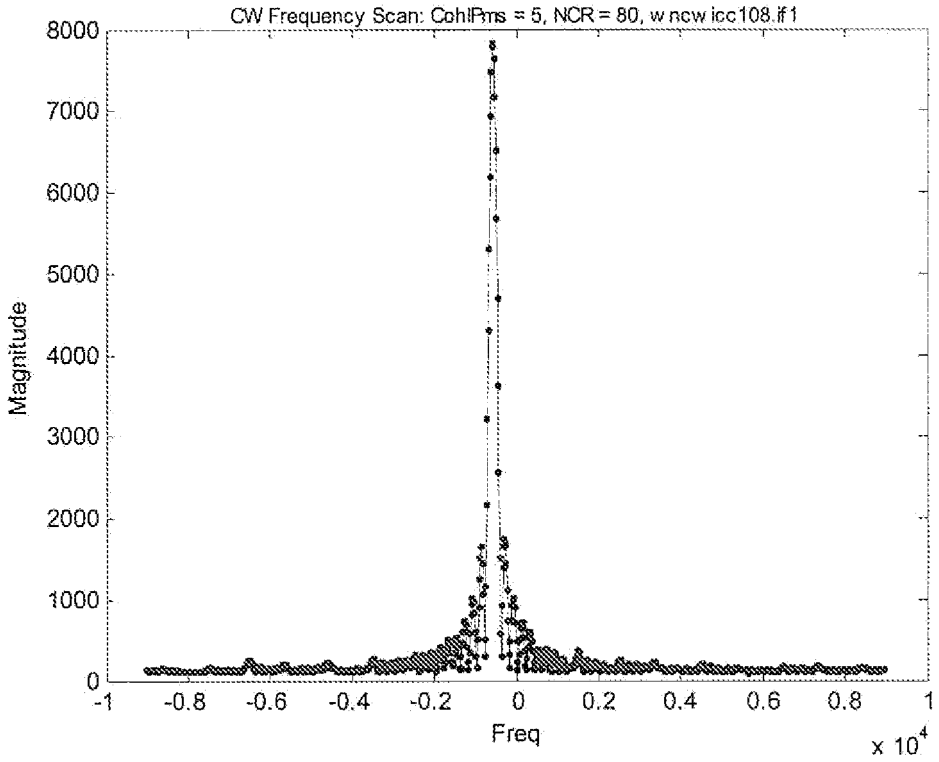
CW Frequency Scan: CohIPms = 5, NCR = 80, w ncw icc108.if1
Magnitude
8000
7000
6000
5000
4000
3000
2000
1000
0
-1
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1
Freq
x 10^4

Fig. 16

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US 08/67912

A. CLASSIFICATION OF SUBJECT MATTER
IPC(8) - G01S 1/00 (2008.04)
USPC - 342/357.12
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
USPC: 342/357.12

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
USPC: 342/357.01, 357.06, 358

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
PubWEST(USPT,PGPB,EPAB,JPAB); DialogPRO(Engineering); Google Scholar
Search Terms: GPS, successive/serial interference cancellation, parallel interference cancellation, intermediate frequency/IF, cross correlation, strong signal, weak signal, C/A, coarse acquisition, CWI, Continuous wave interference

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X ----- Y	US 7,116,704 B2 (Norman et al.) 03 October 2006 (03.10.2006) entire document especially abstract, Fig. 1, col.1, ln.14-29, col.1, ln.59-col.2, ln.16, col.2, ln.48-col.3, ln.9, col.4, ln.57-col.5, ln.6, col.6, ln.3-col.8, ln.39.	1, 2 ---------- 3-6
Y	US 2007/0024499 A1 (Bochkovskiy et al.) 01 February 2007 (01.02.2007) entire document especially abstract, Fig. 9, para [0045]-[0050].	3, 6
Y	US 2005/0031023 A1 (Narayan et al.) 10 February 2005 (10.02.2005) Figs. 1 and 2, para [0008] -[0010], [0049], [0062], [0080].	4-6

☐ Further documents are listed in the continuation of Box C. ☐

* Special categories of cited documents:
"A" document defining the general state of the art which is not considered to be of particular relevance
"E" earlier application or patent but published on or after the international filing date
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
"O" document referring to an oral disclosure, use, exhibition or other means
"P" document published prior to the international filing date but later than the priority date claimed
"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"&" document member of the same patent family

Date of the actual completion of the international search 31 July 2008 (31.07.2008)	Date of mailing of the international search report 0 8 AUG 2008
Name and mailing address of the ISA/US Mail Stop PCT, Attn: ISA/US, Commissioner for Patents P.O. Box 1450, Alexandria, Virginia 22313-1450 Facsimile No. 571-273-3201	Authorized officer: Lee W. Young PCT Helpdesk: 571-272-4300 PCT OSP: 571-272-7774