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Highly Sensitive Weak Signal Acquisition Method for GPS/Compass

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***Abstract*—For high sensitivity and operation efficiency in weak signal acquisition of Global Positioning System (GPS) software receiver, a differential coherent accumulated acquisition algorithm based on Fast Fourier Transform (FFT) is proposed. Limitation of coherent combining time is overcome by block accumulation of demodulated GPS intermediate frequency data. Based on FFT frequency shift characteristics, a Doppler circular frequency search is used to achieve low computation instead of frequency compensation search. Loss in frequency is resolved by different down conversions. Compared to the original non-coherent combining, SNR is improved by differential-coherent combining of coherent results. Weak signal in a -39dB poor SNR environment is successfully acquired in experiments. High sensitivity and operation efficiency of the proposed algorithm are confirmed by experiment results.**

Keywords—GPS; Compass; Weak signal; Acquisition; Satellite receiver

I. INTRODUCTION

The applications of Global Navigation Satellite System (GNSS) are almost popular in our lives. But in some environments, such as indoor, in tunnels or dense vegetation, GNSS signals are significantly weakened, which cause the general GNSS receivers not to work under these conditions. Weak signal is generally 20 dB lower than normal signal [1]. In order to make receiver to be suitable for these special cases, the processing algorithms of low SNR (signal-to-noise ratio) signal should be developed. There are two traditional satellite search algorithms. One is serial search in the time domain and the other is parallel code phase search in frequency domain. The first search algorithm is simple, but it will cost a lot of time. The second one improves the speed of acquisition by using FFT, but it need extend the length of the data for weak signal acquisition, so that the amount of FFT is larger. Although correlation can improve the SNR, signal losses might occur due to data bit transitions. The improved non-coherent combining has the problem of square-loss, and the length of data is limited. In addition, the effectiveness and resolution of weak signal acquisition are important, so a highly sensitive weak signal acquisition algorithm for GPS/Compass is proposed.

There are several methods adopted in the algorithm, such as alternate half-bits method, Doppler circular frequency search, the discrimination method of signal strength, precise frequency acquisition, differential-coherent combining of coherent combining and so on. Simulation and analysis show that the characteristics of the algorithm for GPS/Compass satellite receivers are high sensitive and efficient.

II. GENERAL WEAK SIGNAL ACQUISITION ALGORITHM

The usual acquisition algorithm is parallel phase search based on frequency domain. It can obtain all the relevant results of chip phases and save much operation time. When the signal is weak, it can't obtain the current result by using 1 millisecond (ms) signal data to acquire. Extending the length of signal data is adopted to improve SNR for weak signal acquisition, but the length might be limited by the data bit transitions. In order to overcome these problems, there are two common methods of nonlinear integral proposed. They are non-coherent combining and differential-coherent combining. The noise distributed in the signal is independent, so the amplification effect of noise is less than non-coherent combining while differential-coherent combining is used. The diagram of acquisition algorithm combined coherent combining with differential-coherent is shown as the following. Intermediate Frequency (IF) signal received from satellite receiver can be formulated as following.

$$y_n = \sqrt{2P_s}D(t_n - t_s)C(t_n - t_s)cos[w_{IF}t_n - (w_D + \phi_0)] + v_n \quad (1)$$

Where y_n is the output of sampling time tn. Ps is signal power, D(t) is navigation data, C(t) is pseudo code, t_s is the beginning phase of pseudo code, w_{IF} is IF frequency, its value is decided by RF circuit and Doppler frequency w_D, is the initial phase of carrier wave and v_n denotes noise.

Coherent combining time is L (ms) and N is the sampling points of 1 ms data, in-phase and orthogonal components of coherent combining after removing carrier wave can be denoted the following.

$$Y_I(t_s^{'}, w_D^{'}) = \sum_{n=0}^{LN-1} y_n C(t_n - t_s^{'}) \cos[(w_{IF} - w_D^{'})t_n] + v_{n,I} \quad (2)$$

$$Y_Q(t_s^{'}, w_D^{'}) = \sum_{n=0}^{LN-1} y_n C(t_n - t_s^{'}) \sin[(w_{IF} - w_D^{'})t_n] + v_{n,Q} \quad (3)$$

To combine them together,

$$S_L(t_s^{'}, w_D^{'}) = Y_I(t_s^{'}, w_D^{'}) + jY_Q(t_s^{'}, w_D^{'}) \quad (4)$$

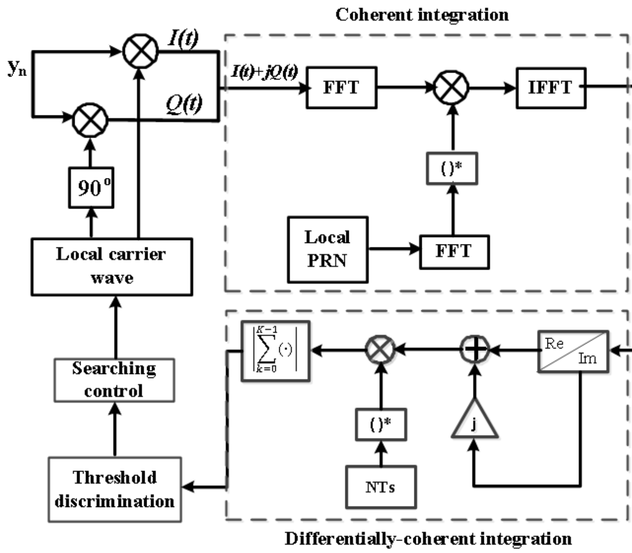


Fig. 1 Diagram of general signal acquisition algorithm combined coherent combining with differential-coherent

In (4), t_s' is the initial acquisition time, it can be converted to phase, w_D' is the carrier frequency. According to the circular nature related [2], the operation of coherent combining can be converted to the following.

$$S_L(t_s', w_D') = IFFT\left\{\sum_{n=0}^{LN-1} FFT(y_n \exp[-j(w_{IF} - w_D')t_n].* FFT(C(t_n - t_s'))^*\right\} \quad (5)$$

G_c=10lg(L) is the processing gain of coherent combining [2]. If K is the differential-coherent combining, the discrimination function can be denoted as (6).

$$S_{L,K}(t_s', w_D') = \sum_{k=0}^{K-1}\left|(Y_{I,k}(t_s', w_D') + jY_{Q,k}(t_s', w_D')) * (Y_{I,k-1}(t_s', w_D') + jY_{Q,k-1}(t_s', w_D'))\right| \quad (6)$$

General acquisition algorithm takes some measures to acquire signal, such as extend coherent combining or differential-coherent time, use circular correlation based on FFT after removing carrier wave. Coherent combining can get the gain and accumulate results of coherent combining can get further gain. At last, if the peak value is bigger than discrimination threshold, it means the acquisition is successful. Otherwise, change Doppler frequency shift to acquire again.

III. An Improved High-Sensitivity Weak Signal Acquisition Algorithm for GPS/Compass

A. Half-bit and full-bit searching method

In order to overcome the influence of the data bit transitions during using coherent combining, some measures are proposed to eliminate the effect of symbols reverse.

Half-bit search method is an effective way to eliminate the symbol flips [3]. At the beginning of the method, the data is cut into several blocks (2K, K is odd times of PRN period), and every block is done coherent combining, number the combining results, so that there are two sets of results: odd numbers and even numbers. The symbol flips would appear in one set, so using alternate half-bit method can ensure one of the integration results without the loss causing data bit transition. The method is simple and easy to operate.

B. Circular searching of Doppler frequency shift

Using parallel code phases searched based on FFT, it must search every point of Doppler frequency. The search interval can be set at 500Hz in the search range from -10KHz to 10KHz. There will be 41 groups of local carriers with different frequency shifts to multiply IF data, and performed FFT. In order to search all the frequency range, the number of FFT and IFFT will be increased and delay the acquisition.

The Doppler frequency shift is optimized in the proposed algorithm. The characteristic of FFT is frequency shift, in other word, the data in time domain multiply complex exponential sequence is the same of circular frequency shift by using FFT [4]. It can be denoted as the following.

$$Z_m = IFFT\left\{Y(k-l)C^*(k)\right\} = \sum_{n=0}^{N-1} c(n)y(n)e^{-j\frac{2\pi n}{N}l} \quad (7)$$

In (7), Y(k-1) cyclic shift in frequency domain and y(n) performed FFT in time domain with frequency compensation is equivalent. By the feature, FFT is only performed one time and then the Doppler frequency shift and parallel search of the coding phase can be completed. It greatly reduces the amount of acquisition operations.

The neighboring Fourier coefficients shifted 1 unit is equivalent to the circumference 1 KHz compensation in the time domain. So IF signal of the initial carrier frequency (fc_0) need perform only an FFT, and then get circular shift in frequency domain. It can complete the Doppler frequency shifts {fc_0, fc_0+1KHz, fc_0+2KHz,…, fc_0+10KHz } and reduce amount of operations.

The minimum change of Doppler frequency is equal to the frequency interval of neighboring Fourier Transform coefficients by using circular shift in frequency domain to replace compensate in time domain. So the step of frequency search can't be adjusted. When the actual Doppler frequency is in the interval of two searching frequency points, the SNR would be loss. There are two different initial IF frequency (f_{c0} & f_{c1}+500) using to improve the frequency resolution and reduce the loss in the proposed.

C. Discrimination of signal intensity

In order to acquire weak signal, it would need much more data to process and take more time to acquire weak signal than the strong using the same acquisition algorithm.

In the proposed algorithm, the SNR is decreased after the parallel phases search based on FFT. If the SNR extends the threshold, it means the signal is strong and the acquisition is successful. Otherwise, differential-coherent combining would be used to acquire.

Only one calculation can get the correlation of one frequency point after input signal multiplying local signals of all code phase-delay. If the search frequency is closed to the real Doppler frequency shift, the biggest correlation will be appeared. The biggest correlation and four adjacent points are treated as useful signal and others are noise. The power of signal and noise can be denoted as following.

$$P_{ds} = \sum_{i=-4}^{4} \left(S_i - \mathrm{b}\right)^2 \tag{8}$$

$$P_{dn} = \frac{\sum_{i=0}^{N-9} \left(n_i - b\right)^2}{N-9} \tag{9}$$

In the above, b is the average of noise. S_i denotes the biggest correlation value and four adjacent points of it. P_{ds} is the power of signal. N is the sampling points. n_i is the noise correlation value of the i frequency point. P_{dn} is the power of noise. The formula of detecting SNR is denoted as following.

$$SNR_P = 10lg\left(\frac{P_{ds}}{P_{dn}}\right) \tag{10}$$

Fixed SNR threshold is set by the false alarm based on Gaussian-distribution, but the environment of acquisition data can't be controlled and the fixed threshold is not suitable. In [2], when SNR_P is 17.5dB (or more than), detection probability and false alarm probability will be a good combination.

The acquisition will be efficient by using the discrimination of signal intensity.

D. Fine frequency estimation

The frequency resolution is 500 Hz by using circular search for Doppler shift, but the resolution is too coarse to track the signal. In the proposed algorithm, fine frequency estimation based FFT is used to improve Doppler frequency resolution during acquisition.

Firstly, the method is to split code and make the signal into continuous wave. And then to generate the local carrier wave by using the coarse frequency, and multiply the continuous wave to demodulate. Two signals with low frequency and high frequency components are obtained. If the length of input signal is 200ms, accumulate each 1ms data to a data point, the process is like a low-pass filter (LPF), it can filter high frequency component (more than 1 KHz). To avoid the influence of data bit-transition, 200 data points are taken square and performed FFT. The frequency precision can be reached to 5 Hz. The noise would be amplified during above processes, so a zero-padding increasing the points of FFT is used to improve the accuracy of frequency estimation.

E. Algorithm diagram

The above process of improved weak signal algorithm for GPS/Compass is shown in figure 2 flowchart.

The following algorithm is described as the following.

1) Take 200ms intermediate frequency data, multiply with two kinds of in-phase and orthogonal branch of the local carrier wave at fc0 and fc0+500Hz.

2) Take the first 10 ms Intermediate Frequency data to do FFT, and then do circular search for Doppler shift.

3) Perform FFT of the storage local codes and then do conjugation, and then multiply the output signal of 2). There are 41 sets of output signal of two different local initial frequency using 500Hz frequency search step, and perform IFFT of output signal, do coherent integrant of those outputs.

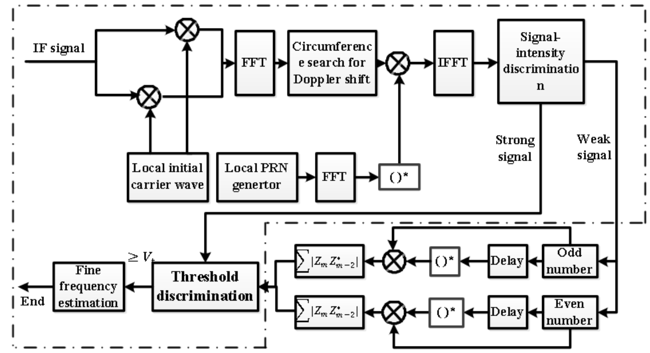


Fig. 2 Diagram of the proposed acquisition algorithm

4) According to the coherent combining of the output matrix from 3), calculate detection signal to noise ratio (SNR), when SNR is higher than 17.5dB, discriminated as a strong signal, otherwise weak signal.

5) Perform acquisition threshold discrimination when the signal is determined strong. If it exceeds the set threshold, the capture is successful and output the crude carrier frequency and the code phase. Or take weak signal process.

6) For weak signal, alternate half-bit coherent combining is performed. First the signal is divided into two groups: odd number and even number. Do coherent combining of difference each group separately. Output the bigger peak value of two groups, if the value exceeds the set threshold, the capture is successful. Otherwise the acquisition is failed.

7) Estimate fine frequency after rough acquisition capture, and the precise frequency resolution will be 5Hz.

IV. Simulation and Analysis

In order to test the performance of the proposed algorithm, the acquisition for GPS/Compass is designed. Simulating tools are set to generate digital IF signal source in Matlab. Different signal sources are shown as followings.

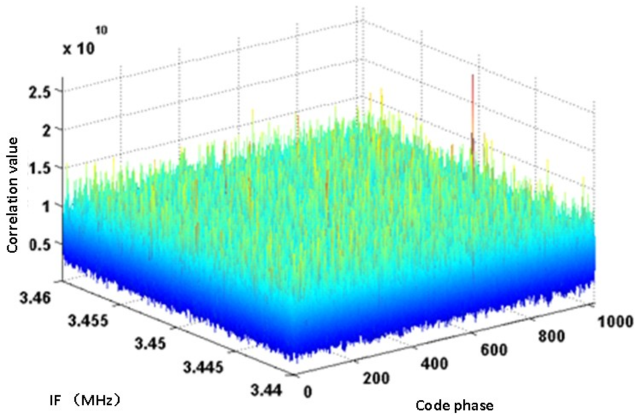
TABLE I. The parameter of GPS weak signal

PRN	SNR (dB)	Code phase	Doppler frequency shift
14	-29	159	4337
1	-36	245	-1789
26	-39	1000	3754
19	-40	897	-2543

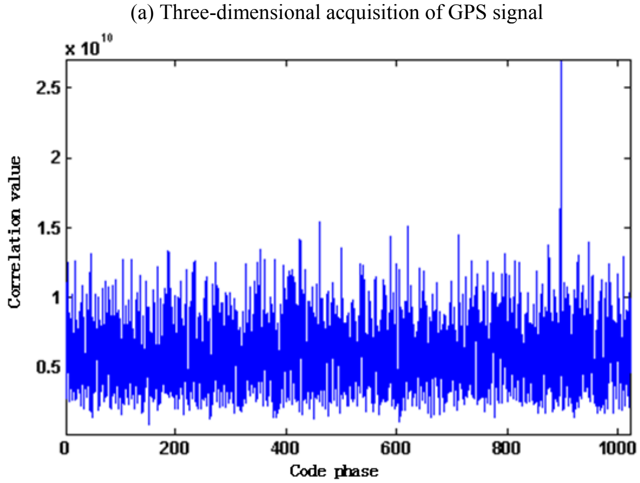
TABLE II. The parameter of COMPASS weak signal

PRN	SNR (dB)	Code phase	Doppler frequency shift
3	-29	159	4337
5	-36	245	-1789
14	-39	1000	3754
19	-40	897	-2543

In table Ⅰ and table Ⅱ, the SNR is lower than normal receiving signal standard of GNSS receiver [6]. The acquisition would search the Doppler frequency shift range from -10 KHz to 10KHz, and the code phase is 1023 chips about 32GPS satellites. The coherent combining time of weak signal is 10ms, and the strong is 1ms. The number of differential-coherent is 10 and alternate half-bit is used for GPS weak signal acquisition. For Compass satellite signal, Doppler frequency shift ranged from -10 KHz to 10 KHz and the searching code phase chips are 2046, and 37 satellites should be searched. In the experiment, the coherent combining time is set 1ms to acquire No.3 and No.5 satellite, the number of differential-coherent is 200. For No.14 satellite, the coherent combining time is set 10ms, the number of differential-coherent combining is 20 and alternate half-bit method is used. The SNR of No.19 is too low, the coherent combining time is set 10ms and the amount of differential-coherent is 40.



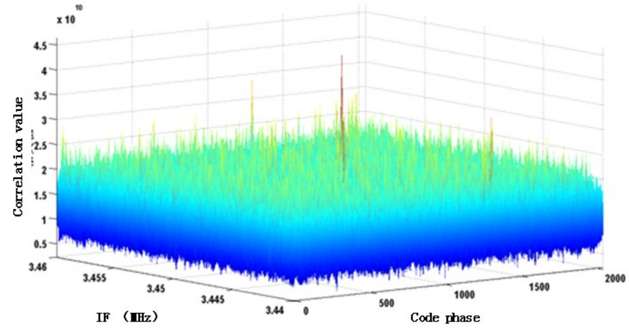
(a) Three-dimensional acquisition of GPS signal



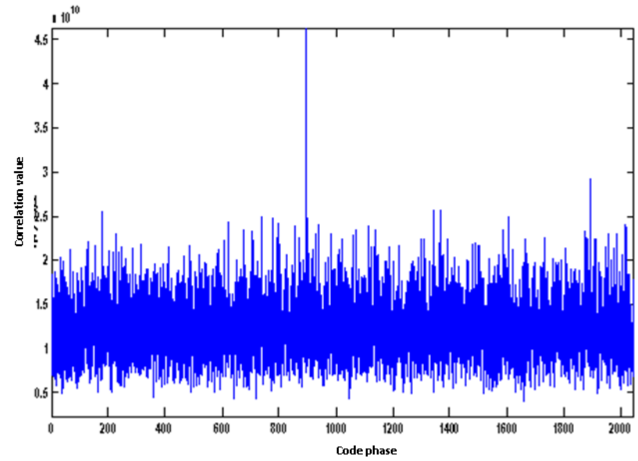
(b) Code phase acquisition of GPS signal

Fig. 3 Results of No.19 GPS-satellite acquisition

The results of No.19 GPS-satellite acquisition are shown in figure 3 and the results of No.19 Compass-satellite acquisition are shown in figure 4. From the figures, the weak signals of GPS/Compass (SNR=-40dB) are acquired successfully.



(a) Three-dimensional acquisition of Compass signal



(b) Code phase acquisition of Compass signal

Fig. 4 Results of No.19 Compass-satellite acquisition

TableⅢ and Ⅳ are the results of acquisition for GPS and Compass. All of these show that the proposed algorithm is more sensitive and accurate.

TABLE III. THE RESULTS OF ACQUISITON GPS

PRN	Detected SNR	Code phase	Error of code phase	Doppler frequency shift	Error of frequency shift
14	36.035	159	0	4325	-12
1	34.8643	245	0	-1800	-11
26	25.1484	1001	0	3765	11
19	20.4212	897	0	-2535	8

TABLE IV. THE RESULTS OF ACQUISITON COMPASS

PRN	Detected SNR	Code phase	Error of code phase	Doppler frequency shift	Error of frequency shift
14	36.035	159	0	4325	-12
1	34.8643	245	0	-1800	-11
26	25.1484	1001	0	3765	11
19	20.4212	897	0	-2535	8

In order to observe the performance of signal intensity discrimination, there are four groups of strong satellite signals to test and the results is shown in tableⅤ.

Coherent combining is used directly to acquire the strong signal, the average of cost time is about 1.21seconds. In the proposed algorithm, the acquisition would use differential-coherent combining and alternate half-bit method to improve the SNR, so the average time is 11.30 seconds. The percentage of the weak signal and the strong signal acquisition time is 10.71%. The results of the experience show that the speed of improved acquisition for GPS/Compass is 10 times faster than the algorithm without signal intensity discrimination.

TABLE V. ACQUSITION TIME STATISTICS OF SIGNAL INTENSITY DISCRIMINATION

No.	Time（T1）of strong signal acquisition (second)	Time （T2）of weak signal acquisition (second)	T1/T2
1	1.12	11.35	9.87%
2	1.21	11.25	10.76%
3	1.28	11.32	10.31%
4	1.22	11.27	10.83%
Average	1.21	11.3	10.71%

V. CONCLUSION

An improved weak signal acquisition algorithm for GPS/Compass is proposed in the paper. The algorithm is including alternate half-bit method, circular Doppler frequency search method, signal intensity discriminating method, accurate frequency acquisition and improved coherent combining method and so on. The simulation results show that the weak signal of GPS/Compass coherent combining method and so on. The simulation results show that the weak signal of GPS/Compass (SNR=-40dB) can be acquired. The acquisition speed by using signal intensity discrimination method is 10 times faster than the general algorithm without discrimination. The algorithm meets the requirements of acquisition weak signal of GPS/Compass with high sensitivity and operation efficiency.

ACKNOWLEDGMENT

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REFERENCES

[1] Gleason, Scott, and Demoz Gebre-Egziabher, eds. GNSS applications and methods. Artech House, 2009.

[2] James B-Y TSUI. Fundamentals of Global Positioning System Receivers A Software Approach. 2nd ed. New York: Wiley, 2004.

[3] D. M. Akos, P. Normark. J. Lee, et al. Low Power Global Navigation Satellite System (GNSS) Signal Detection and Processing. Proceedings of ION GPS 2000. Salt Lake City, UT. The Institute of Navigation, 2000: 784-791.

[4] CHEN Xue, XU Jian-hua, et al. FFT-Based Acquisition for Weak GPS Signals. Microelectronics & Computer, 2010.

[5] .NING Chun-lin, SHI Hu-li, et al. Study on frequency resolution of signal acquisition in GPS software receiver. Computer Engineering and Applications, 2008, 44(6): 14- 16.

[6] Yu W, Zheng B, Watson R, et al. Differential combining for acquiring weak GPS signals. Signal processing, 2007, 87(5): 824-840. 1.

[7] Zhaoshui He, Shengli Xie, Rafal Zdunek, Guoxu Zhou,and Andrzej Cichocki, Symmetric Nonnegative Matrix Factorization: Algorithms and Applications to Probabilistic Clustering, IEEE Trans Neural Networks, vol.22, no. 12, pp.2117-2131, December 2011. 2.

[8] Z.S. He, A. Cichocki , S.L. Xie and K. Choi. Detecting the Number of Clusters in n-Way Probabilistic Clustering. IEEE Transactions on Pattern Analysis and Machine Intelligence, vol. 32, no. 11, pp. 2006-2021, November, 2010. 3.

[9] Guoxu Zhou; Cichocki, A.; Shengli Xie, Fast Nonnegative Matrix/Tensor Factorization Based on Low-Rank Approximation, IEEE Transactions on Signal Processing, 60(6):2928 - 2940, 2012.4.

[10] S.L. Xie, Z.S He, Y.L. Fu, A Note on Stone’s Conjecture of Blind Signal Separation. Neural computation, 17(2):321-330, Feb.2005.