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New Method for GPS Direct Position Estimation Based on Collective Detection Approach

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***Abstract*— Collective detection is a direct position estimation method, which is shown to perform effectively in weak signal navigation applications. Different from the traditional GPS signal individual acquisition and tracking, this technique combines the received power from all GPS satellites in view and directly leads to a position solution, thus resulting in a very high sensitivity. However, the huge computation and computational complexity may limit its practical application. We then present a new method for position estimation based on collective detection scheme. We take full account of the structure of the problem to make our algorithm efficient and easy to realize. Real data test results suggest that our algorithm is effective and also good in terms of accuracy.**

***Keywords*— GPS; collective detection; weak signal navigation; vector-based tracking; acquisition**

I. INTRODUCTION

In recent two decades, GPS-based position and location requirements have become more and more ubiquitous for many different vehicles in terrestrial, sea, air and space. However, growing interest in indoor positioning is motivating research on techniques for weak GPS signal acquisition and tracking. Also, poor signal reception in other than open-sky environments is still a problem. Hence, a lot of effort is being directed to enhance signal sensitivity such as extending signal integration times [1] and using assisted-GPS techniques [2]. For these traditional methods, the signal of each satellite is acquired and processed individually, thus neglecting the association of different satellite signals on the same location.

More recently, it has been proposed that combining information from multiple satellites is also a feasible solution, represented by the collective detection technique. By combining the received power from all GPS satellites in view and directly leads to a position solution, this technique is suitable for any application that requires a navigation solution in a signal environment that challenges traditional acquisition techniques [3]. In essence, it is a vector-based acquisition approach. Even if all signals are too weak to be acquired and tracked by the traditional framework, a quick and coarse position solution can be directly estimated by combining the received signal power from each satellite. In addition, this approach could be used to aid deeply-coupled GPS/INS navigation and assist with terrain/feature-landmark recognition in an urban environment.

Although there is no required hardware change, it is shown that the computational complexity is huge for the traditional collective detection. The present new method aims to reduce the complexity of the algorithm and attempts to mitigate the shortcomings in practical application. Different from the simulated results in current literature, the experiments with actual data have also been performed.

The rest of this contribution is organized as follows. Section II provides a brief review on the traditional approach to signal acquisition and tracking. Section III describes the collective detection algorithm and its assumptions. Section IV proposes a new method for GPS direct position estimation based on collective detection approach. Section V elaborates on the actual experiments based on GPS observations, which have been performed to verify the correctness of new method and the accuracy of coarse position solution. Section VI concludes the overall contributions of this work and possible improvements are also discussed.

II. THE TRADITIONAL ACQUISITION THEORY

A. Motivation and Principle

The purpose of acquisition is to determine visible satellites and coarse values of carrier frequency and code phase of the satellite signals. GPS satellites are differentiated by the different PRN sequences. Only when a local PRN code that is perfectly aligned with the incoming code, a high correlation peak occurs and then the incoming code can be removed from the signal. It is also important to know the received frequency of the signal to be able to generate a local carrier signal, which is used to remove the incoming carrier from the signal. Based on both motivations, the acquisition algorithm assesses the signal's correlation power in discrete bins on a grid of code delay and Doppler frequency.

In detail, the correlation power calculations are based on multiplication of locally generated PRN code sequences and locally generated carrier signals with the sampled signal from the receiver's RF front end. Multiplication with the locally generated carrier signal generates the in-phase signal I, and multiplication with a 90◦ phase-shifted version of the locally generated carrier signal generates the quadrature signal Q. The correlation power is the sum of the I and Q components, $I^2 + Q^2$. By mixing the sampled signal with a family of receiver-generated replica signals that span the grid, we can plot the power as a function of code delay and frequency shift, thus producing a correlogram. If the highest correlation peak exceeds a predefined threshold, we assume that the frequency shit and code phase parameters are correct and both parameters can be passed on to the tracking algorithms, which produce more precise measurements of delay — dubbed 'pseudoranges' — from which the receiver's navigation solution is calculated.

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B.Strong Signal Case

The acquisition algorithm expects that a distinct peak appears in the correlogram bin that corresponds to the true GPS signal's code delay and Doppler frequency, as is shown in Figure 1. Normally, if a received signal is sufficiently powerful, a distinct peak appears in the correlogram bin.

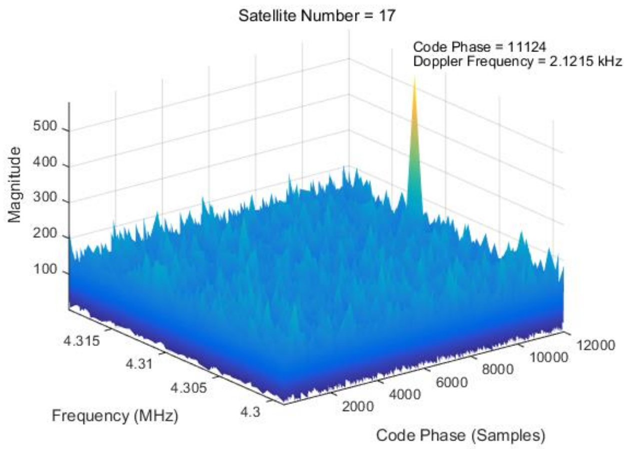

Fig.1 The correlograms for a strong GPS signal acqusitiuon (IF Frequency:4.309MHz;Sampling Frequency:12MHz)

C.Weak Signal Case

However, based on the given integration times, the fact that peak power exceeds a predefined threshold is not a certain event. In particular, when the weak signal is present, the correlation peak cannot be distinguished, resulting in the failure of the conventional acquisition approach, see Figure 2. The typical weak signal environments like indoors, foliage, forest, tunnel and deep urban canyons. The signal strength in these scenarios is normally 10-25 dB weaker than the lower bound of that in open-sky conditions [4].The theoretical probability of detection for traditional acquisition algorithm is discussed in [5].

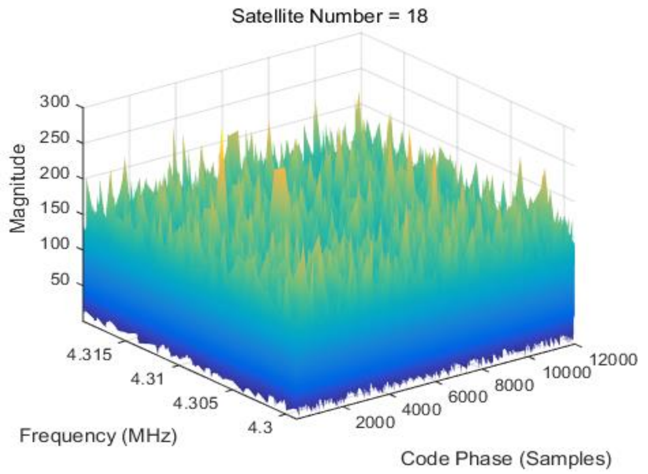

Fig.2 The correlograms for a weak GPS signal acqusitiuon (IF Frequency:4.309MHz;Sampling Frequency:12MHz)

D.Solution for Enhancing Signal Sensitivity

Increasing the coherent integration time is an effective solution for giving GPS some degree of capability to operate indoors and in other restricted environments [6]. It uses the fact that the zero-mean Gaussian noise accumulates slower than the signal of interest by a longer integrated period. However, the data-bit transitions in the signal's navigation message should be carefully wiped-off [1]. Any other adverse factors such as receiver clock instability and dynamics should also be sufficiently considered.

III. COLLECTIVE DETECTION THEORY

In the traditional acquisition, the signal's correlation power is evaluated in discrete bins on a grid of code delay and Doppler frequency. Different from that, in the collective detection algorithm, the combined correlation power is evaluated on the position and clock offset grid. Thus, it leads directly to the navigation solution. In other words, collective detection is a direct position estimation method. All the individual GPS signal correlations map into the navigation domain, in which the combined correlation power is evaluated. However, the mapping requires the receiver to have a priori knowledge.

A.Priori Informaiton

As a priori knowledge, the approximate position of the receiver, the GPS ephemerides and the current GPS time are often required for the collective detection technique. The approximate position can be provided by the extrapolation of the past positions or other positioning method like GSM and Wi-Fi. The GPS ephemerides can be obtained from the Internet, the wireless communication or the previous satellite data. The current GPS time is an important assumption, which can be attained after the first successful estimation of navigation solution. Then, the receiver clock can be corrected to GPS time and the clock-bias is assumed insignificant in a short period of time.

B.The Search Space

With the priori knowledge above, the collect detection algorithm defines the position and clock offset search grid centered on the assumed receiver state. The mapping then relates each one of the position and clock offset grid points to a specific code delay and Doppler frequency for each GPS satellite. Different from the grid of code delay and Doppler frequency which is used in traditional acquisition scheme, the search space of collective detection scheme is set up with all the possible position and clock bias of the receiver. In other words, the search space has four dimensions: three search dimensions for positions and a fourth dimension for the clock-bias. Next, for each candidate North-East-Down-Clock value in the search space, projections are performed from the code-phase/Doppler domain to position/clock-bias domain.

C.The Basic Principle

Collective detection is a direct position estimation method, which combines the received power from all GPS satellites in view and directly leads to a navigation solution. Based on the search space described above, the correlation power is summed over all the GPS satellites at each position /clock-offset grid point to create a navigation domain correlogram. The grid point that has the highest combined correlation power denotes the optimal position and clock-offset estimation. Since the correlogram is built based on the scheme of non-coherent combination of multiple satellites, the correlation power detection is assumed as "collective". It

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indicates that the signals which are too weak to be acquired and tracked can also be incorporated into the estimation of navigation solution.

D.The Computation Process

For each grid point of the search space, we should compute the correlation power for each satellite. The correlator values are taken as the multiplication of the sampled IF signal and the locally generated signal. We can use the computed pseudorange to compute the received code-phase by the following equation:

$$\hat{\tau} = \mathrm{mod}\left(\rho'/c, T_c\right) \quad (1)$$

where $\hat{\tau}$ is the computed code-phase and T_c is the period of the ranging code and ρ' is the computed pseudorange of each point in the search grid. We can compute each satellite's position using the ephemeris data and then compute the pseudorange with it. Assuming that ρ is the pseudorange at the center of the search space, ρ' is given by

$$\rho' = \rho - \Delta N \cos\alpha \cos\theta - \Delta E \sin\alpha \cos\theta + \Delta D \sin\theta + \Delta b \quad (2)$$

where α is the azimuth of the satellite and θ is the elevation of the satellite and $(\Delta N, \Delta E, \Delta D, \Delta b)$ is the difference between the candidate grid and the center grid. The details of the collective detection approach are presented in [7, 8]. Figure 3 demonstrates the basic principle and computation process of collective detection approach.

E.The Computational Complexity

Although the sensitivity can be improved significantly with collective detection, the main issue of the algorithm is the computational complexity.

Since the search space has four dimensions dubbed North-East-Down-Clock, the number of points to be evaluated is huge and requires large computational time. The computational complexity can be reduced to a certain extent by decreasing the step size of the grid, but the accuracy of navigation solution will be reduced significantly. In fact, the largest step size is limited by the length of one ranging code. Hence, the existing collective detection scheme has limited practical applications.

IV. NEW METHOD AND ITS IMPLEMENTATION

This section presents a new method for position estimation based on collective detection scheme. The proposed algorithm is efficient and easy to realize. Real data test is also performed to verify the correctness of the new method.

A.The Reduction of Search Space

In order to accelerate the traditional collective detection, a practical strategy is to cut down the dimension of the search space. Since the clock-bias dimension is much larger than the other three dimensions, it is assumed to be the major factor that increases the complexity of the collective detection algorithm. Thus, a very fine-time assistance will alleviate the computational load. More specifically, the reduction in clock-bias search domain can be achieved in the following two scenarios.

The first scenario is that a successful positioning has been done. Then, the receiver clock can be corrected to GPS time and the clock-bias is assumed insignificant in a short period of time. The second scenario is that the estimation of receiver clock bias is too coarse but as least one satellite is strong enough to be acquired individually by the acquisition block. In this case, the reference [9] proposed one method to estimate the clock-bias. The basic principle is that the clock bias can be computed by the difference between the measured code-phase and the geometric code-phase. The former can be extracted by the strong satellite's correlogram and the latter is calculated by the computed geometric range.

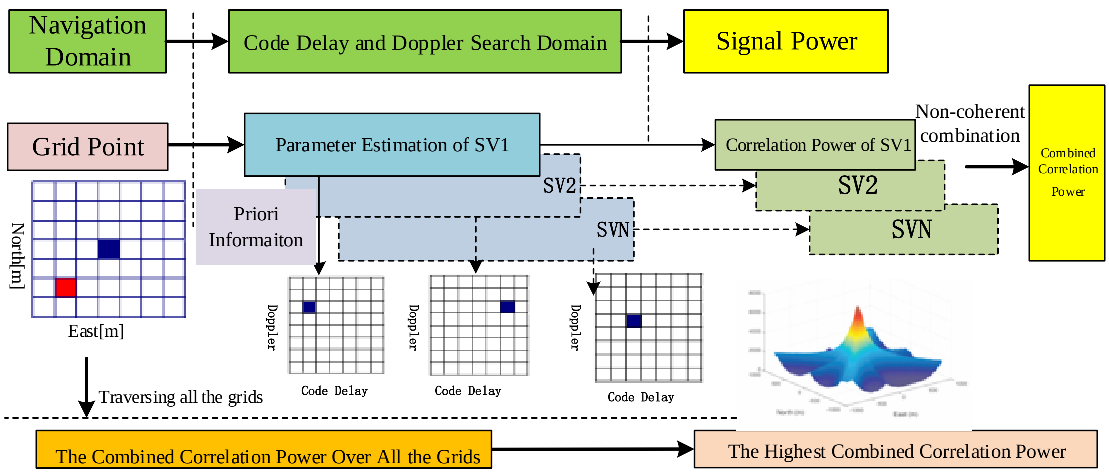

Fig.3 The basic principle and computation process of collective detection approach

B.The Calculation of Code Phase and Doppler

We assume that the receiver clock is synchronous with GPS time and the tiny clock-bias could be ignored. For each grid, the corresponding code phase and the Doppler frequency of each satellite are thus calculated as follows. Here the position coordinate of the candidate grid is denoted as $\vec{u}$, thus we have the following equation:

$$\left\|\vec{u}-\vec{s}^{i}(t_{rx}^{GPS}-\tau_{u}^{i})\right\|+T^{i}\left(\vec{u}\right)+I^{i}\left(\vec{u}\right)=c\tau_{u}^{i} \quad (3)$$

where t_{rx}^{GPS} is the GPS time for the received signal; τ_{u}^{i} is the signal transmission time from the satellite i to the candidate grid $\vec{u}$; $\vec{s}^{i}(t_{rx}^{GPS}-\tau_{u}^{i})$ is the satellite position when the electric signal is sent from the satellite, which can be computed with the known GPS ephemerides; $I^{i}\left(\vec{u}\right)$ is ionosphere error and $T^{i}\left(\vec{u}\right)$ is the troposphere error; c denotes the velocity of light.

Equation (3) can be solved by the dichotomy algorithm, which is described in the following section. Assuming that the transmission delay τ_{u}^{i} is resolved, the signal sending time of satellite clock is given by

$$t_{tx}^{i}=t_{rx}^{GPS}-\tau_{u}^{i}+dt^{i}(t_{rx}^{GPS}-\tau_{u}^{i}) \quad (4)$$

where $dt^{i}(t_{rx}^{GPS}-\tau_{u}^{i})$ is the satellite clock bias at the GPS time $(t_{rx}^{GPS}-\tau_{u}^{i})$. Thus, the received code-phase at GPS time t_{rx}^{GPS} can be computed by the following equation:

$$\hat{D}^{i}\left(t_{rx}^{GPS}\right)=\mathrm{mod}\left(t_{tx}^{i},T_{c}\right) \quad (5)$$

where $\hat{D}^{i}\left(t_{rx}^{GPS}\right)$ is the computed code-phase and T_{c} is the period of the ranging code (1ms for GPS L1 C/A). The Doppler frequency of satellite i is

$$\hat{f}^{i}\left(t_{rx}^{GPS}\right)=-\frac{d\left(\left\|\vec{u}-\vec{s}^{i}(t_{rx}^{GPS}-\tau_{u}^{i})\right\|\right)}{dt} \quad (6)$$

With the estimated code-phase $\hat{D}^{i}\left(t_{rx}^{GPS}\right)$ and the Doppler frequency $\hat{f}^{i}\left(t_{rx}^{GPS}\right)$, a local signal is generated. Next, the correlation power is calculated by the multiplication of the locally generated signal and the sampled signal from the receiver's RF front end. By combining information from multiple satellites, the total correlation power is given by

$$E\left(m,n,k\right)=\sum_{i=1}^{K}E^{i}\left(m,n,k\right) \quad (7)$$

where K is the number of visible satellites and $E^{i}\left(m,n,k\right)$ is the correlation power corresponding to satellite i for the grid $\left(m,n,k\right)$. By traversing all grids, the grid point that has the highest combined correlation power is assumed as the best position. Without loss of generality, we assume that a distinct peak appears in the correlogram bin $\left(m_{t},n_{t},k_{t}\right)$, thus giving by

$$\left(m_{t},n_{t},k_{t}\right)=\arg\max_{m,n,t}\left[\sum_{i=1}^{K}E^{i}\left(m,n,t\right)\right] \quad (8)$$

C.The Fast Estimation of Signal Transmission Time

Note that there is no analytic solution for (3) due to its nonlinearity. However, the signal transmission time can be resolved by the dichotomy algorithm. The specific steps are as follows:

(a) Supposing that the transmission time at epoch k for satellite i is τ_{k}^{i} and the maximum of fluctuation range of the transmission time at the next epoch is σ, the interval of τ_{k+1}^{i} can be given by

$$\begin{cases}\tau_{k+1}^{i}\in\left[\tau_{k}^{i},\tau_{k}^{i}+\sigma\right], if\ \hat{f}_{k}^{i}\left(t_{rx}^{GPS}\right)>0\\ \tau_{k+1}^{i}\in\left[\tau_{k}^{i}\text{-}\sigma,\tau_{k}^{i}\right], if\ \hat{f}_{k}^{i}\left(t_{rx}^{GPS}\right)<0\end{cases} \quad (9)$$

where $\hat{f}_{k}^{i}\left(t_{rx}^{GPS}\right)$ is the Doppler frequency of satellite i at epoch k.

(b) Compute the middle time in the interval given by (a):

$$\tau_{m}=\left(L+H\right)/2 \quad (10)$$

where L is the lower boundary of the interval and H is the upper boundary of the interval.

(c) Let τ_{k+1}^{i} be τ_{m}, if we have

$$\left\|\vec{u}-\vec{s}^{i}(t_{rx}^{GPS}-\tau_{k+1}^{i})\right\|+T^{i}\left(\vec{u}\right)+I^{i}\left(\vec{u}\right)<c\tau_{k+1}^{i} \quad (11)$$

then the interval will be updated with $\left[L,\tau_{m}\right]$.Otherwise, if

$$\left\|\vec{u}-\vec{s}^{i}(t_{rx}^{GPS}-\tau_{k+1}^{i})\right\|+T^{i}\left(\vec{u}\right)+I^{i}\left(\vec{u}\right)>c\tau_{k+1}^{i} \quad (12)$$

then the interval will be updated with $\left[\tau_{m},H\right]$.

(d) Repeat step (b) and step (c), until the following condition is required:

$$\left|\left\|\vec{u}-\vec{s}^{i}(t_{rx}^{GPS}-\tau_{k+1}^{i})\right\|+T^{i}\left(\vec{u}\right)+I^{i}\left(\vec{u}\right)-c\tau_{k+1}^{i}\right|<10^{-4} \quad (13)$$

Here τ_{k+1}^{i} can be treated as the solution of (3) at epoch k+1.

V. RESULTS AND DISCUSSION

In order to verify the correctness of proposed collective detection method, actual static pointing experiment has been carried out. The coordinates of the location of the data acquisition are (39.97995 º N,116.33410 º E,28.9m). For comparison purposes, a power divider is used to split the GPS signal from the antenna into two branches equally. For one branch, the GPS L1 data were logging by JAVAD Alpha-2 receiver with advanced multipath reduction. This branch is denotes as the normal branch. For the other branch, the GPS signal was first attenuated about 8dB by an attenuator and then data were collected by a RF front end and processed by Software-Defined Receiver. The important parameters for the signal processing are

- Sampling frequency: 12MHz
- Intermediate frequency: 4.309 MHz, and
- One-bit sample.

Figure 4 shows the constellation of GPS satellites, with seven satellites visible. The carrier-to-noise ratio of each satellite is given in Table 1 for both branches.

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TABLE I. SIGNAL POWER FOR BOTH BRANCHES

GPS Satellite's PRN	18	21	24	15	9	22	14
Normal Branch C/N0(dB-Hz)	49	46	46	43	42	41	40
Attenuated Branch C/N0(dB-Hz)	41	38	38	35	34	33	32

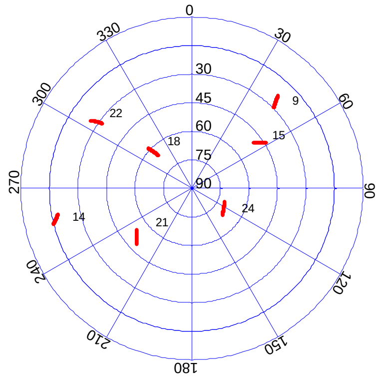

Fig.4 The constellation of GPS satellites

Note that the traditional positioning will not be achieved for the attenuated branch, because the satellites with strength 35 dB-Hz or lower are not acquired and are almost as noisy as the satellites not visible to the receiver. As is shown in Table 1, PRN 18, 21 and 24 have strong signals and they can be acquired using the standard method. However, the number of satellites with strong signal is less than four satellites, thus making the standard positioning impossible.

Different from the standard positioning method, the proposed collective detection approach combines the received power from all GPS satellites in view and directly leads to a position solution, as is shown in Figure 5. The priori knowledge about the approximate position of the receiver is provided by a cell-phone tower, and the receiver clock bias is estimated using the averaging clock-bias estimations across all strong satellites, based on the approach proposed in [9]. Both the position accuracy and computational load are determined by the step sizes or the density of grid partition.

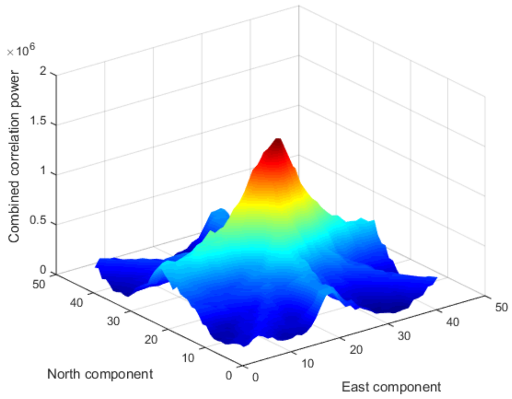

Fig.5 Direct position estimation using the proposed collective detection approach (The step sizes of both the north component and east component are 50m, using the priori height)

The elapsed times for the proposed method are measured at every epoch using Visual Studio 2008 development platform at a PC with Intel® Pentium(R) 4 CPU 2.40GHz and 2048MB RAM.

TABLE II. COMPUTING TIME FOR DIFFERENT STEP SIZE

Step Size	Position Estimation	
	Averaging computing time(second)	Standard deviation(meter)
25m	2.668	12.3
50m	0.958	30.2
100m	0.389	59.8
200m	0.245	119.5

Since the accuracy of position decreases as the computing time decreases, a balance should be achieved for the step size between the computing time and accuracy.

VI. CONCLUSIONS

This contribution provides a detailed implementation method of collective detection, and the example results from actual GPS signals show how the non-coherent combination of multiple satellite signals improves the GPS position error in cases where some of the signals are too weak to be acquired and tracked by traditional methods. This capability is particularly useful to a user who benefits from a rapid, but coarse, position solution in a weak signal environment such as indoors and urban Canyon. Although the accuracy of collective detection is in general lower than that of the traditional GPS positioning algorithm, the proposed method has obvious advantage for the quick position solution under the weak signal scenario. Thus, this technique could provide a new way to aid deeply-coupled GPS/inertial navigation.

ACKNOWLEDGMENTS

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