International Research Journal of Engineering and Technology (IRJET) e-ISSN: 2395-0056
Volume: 05 Issue: 07 | July 2018 www.irjet.net p-ISSN: 2395-0072

Signal Acquisition Algorithms in GNSS Software-Defined Receiver

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Abstract - *GNSS software receivers have achieved a level of considerable technological maturity and use, particularly in signal analysis and receiver engineering. These appear poised for much adopttion in commercial equipment and applications. The telecommunications infrastructure uses the GNSS signal as an integral and basic part of the system. The milestone of satellite navigation is the real time positioning and time synchronization. Increased timing accuracy provides overall improvements in system performance in terms of quality and efficiency. The software technology is more flexible because to implement new algorithms or track new GNSS signals, the hardware equipment does not need to be changed. Furthermore, the GNSS software receiver is not a black box as the hardware ones and it is possible to have access to data or functions in the core of the signal processing.This paper focuses on signal acquisition process. Acquisition provides rough estimate of code delay and Doppler frequency values of the received signal which plays very important role to synchronize local code with the received one. Acquisition technique used in mass-market GPS/Galileo L1 receivers signals tends to first acquire the GPS L1 C/A signals. Acquisition algorithms are implemented on 4MHz signal data of one millisecond period, sampled at 16.3676MHz. In all the acquisition algorithms, the Doppler frequency search range and code phase observed are ±10KHz in steps of 500Hz. The received signal is obtained from N-FUELS (Full Educational Library of Signals for Navigation) as signal generator which generates digitized intermediate frequency (IF) signal.*

Key Words: **GNSS Software Receiver, GPS, Acquisition, Code delay, Doppler Frequency**

1. INTRODUCTION

The basic blocks of a typical Global Navigation Satellite Systems (GNSS) include an antenna, RF front end, and digital baseband processor as shown in Fig- 1. The first one deals with the reception of the signal by the antenna and the Radio Frequency (RF) front-end processing (selection and amplification of the useful signal, down-conversion to an intermediate frequency, sampling and quantization). The second block concerns the actual digital signal processing. It consists in firstly estimating in a coarse way the incoming signal parameters, like timing and frequency information in the acquisition stage and later in refining these estimates by tracking the code delay and the carrier phase in the tracking circuit. Finally, in the last block, the navigation message is demodulated in order to have access to key information and to be able to compute the pseudo-range and the Position, Velocity, Time (PVT) solution. The main function of the signal processor in the receiver is the reconstruction of the carriers and extraction of codes and navigation messages. Due to the motion of satellite, the received signal is Doppler shifted. Global Navigation System (GNSS) Positioning has been widely applied in several areas of navigation technology [1].

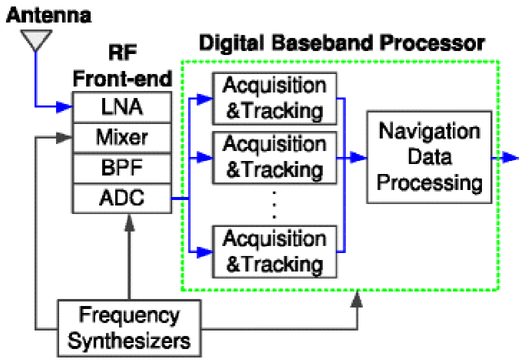


Fig -1: Block of Global Navigation Satellite System

GNSS software receivers can be grouped into three main categories as shown in Fig- 2. The ability to change the signal processing algorithms and their parameters makes the software receiver a flexible tool to work with GNSS systems.

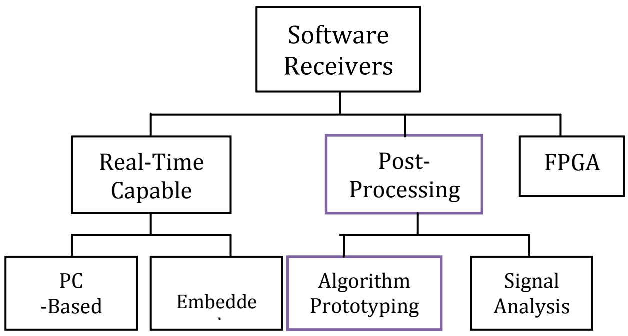


Fig -2: Different Categories of Software Receiver

Digital signal processing in software lets you deliver high-quality observational data. With access to the structure of the signal at a low level it is possible to optimize the process of its processing, use of advanced algorithms for signal amplification, filtering and tracking, to minimize the effect of multipath. Software receiver can simultaneously serve several functions that are implemented by shared or dedicated modules. By comparing results of different solutions, e.g. in real time, it is easier to analyze the quality, efficiency and influence of the algorithms. Many users may adopt different functions to suit their needs, using always the same hardware, but different parts of the software. Software receiver construction is open. It is limited only by user's creativity and the available computing power [2]. As another important solution contributing to the signal acquisition challenge, massive correlation-related approaches also have been widely investigated.

The rest of the paper is organized as follows: Section 2 reviews pseudo random sequence and coarse acquisition code. Signal acquisition basic concepts are described in section 3. Section 4 represents the conventional acquisition algorithms. Tests and Results are presented in Section 5. Section 6 concludes the paper.

2. PRN AND C/A CODE

The generation of pseudo random sequence (PRN) in the code is based on the use of an electronic hardware device called tapped feedback shift register (FBSR). This device can generate a large variety of pseudo random codes, but in this way the generated code repeat itself after some very long time. The receiver could distinguish the signals coming from different satellites because the receiving C/A code (coarse/acquisition) known as the Gold code, has low cross-correlation and is unique for each satellite. The C/A code is a bi-phased modulated signal with a chip rate of 1.023Mchip/s. Doppler shift in carrier frequency of GPS signal is due to the relative velocity of satellite with receiver and C/A code delay is due to the transit time of satellite signal from GPS satellite to the receiver. These parameters are very important to synchronies the locally generated signal with received signal and extract the navigational data.

After identifying the available satellites and acquiring the parameters, parallel channels are used to track the each satellite. In each channel, tracking loops are used and extract the navigational data. In tracking loops C/A code and carrier are removed by refining the code phase and Doppler frequency. So receiver performance depends on the accuracy of acquisition process. The modulation of the GNSS signal usually refers to the modulation of the PRN code. In the case of GPS L1 C/A, the modulation of the signal is referred to as Binary Phase Shift Keying (BPSK) since the PRN code chip are represented as rectangles with a length equal to the PRN code chip. In this case, the transmitted signal is represented in Fig-3 [3].

Acquisition process identifies the satellites that are visible to the receiver and provides the measurement of Doppler shift in carrier frequency and delay in the C/A code of the incoming GPS signal.

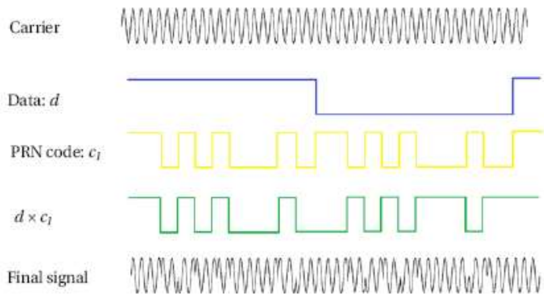


Fig -3: GPS L1 C/A code signal

3. GNSS SIGNAL ACQUISITON BASIC CONCEPTS

Acquisition is carried by synchronizing the locally generated C/A code and carrier with the received signals. The acquisition is usually performed on a block of data received from the satellite signal. In general the block size of data is period of C/A code i.e. one millisecond. The size of the data block used for acquisition depends on the Carrier to Noise Ratio (C/No) of the received signal. If the C/No is low, then the receiver must process the signal for more than a single C/A code period.

GNSS system, each satellite continuously transmits a periodic code signal, which is modulated by information symbols. The code signal is a spreading sequence made up of chips and the sequence length (or repetition period). Each satellite is characterized by an unique PRN code sequence. The cross correlation properties of such codes allow the GNSS receiver to efficiently separate received satellite signals which are superposed in the time domain. It is well known that the first task performed by any GNSS receiver is to detect the presence of a generic satellite and to perform a global search for approximate values of the code phase delay τ and Doppler shift f_d of the SIS (Signal in Space) of each detected satellite. This stage, known as signal acquisition, provides an estimation τ' and f_d' of the SIS parameters τ and f_d to the following signal tracking stage.

The first parameter, code delay τ is the time alignment of the PRN code in the current block of data, which contains the basic range and time information required to compute user position and clock offset. It is necessary to know the code phase delay in order to generate a local PRN code replica that is perfectly aligned with the incoming code. Only when this is the case, the incoming code can be removed from the received signal. PRN codes have high auto correlation only for zero lag. That is, the two signals must be perfectly aligned to remove the incoming code. The carrier frequency, which in case of down conversion corresponds to IF.

The IF should be known for example from the GPS L1 carrier frequency of 1575.42MHz and from the mixers in the down converter. However, the frequency can deviate from the expected value. The line-of-sight (LOS) velocity of the satellite (with respect to the receiver) causes a Doppler effect f_d resulting in a higher or lower frequency. In the worst case, the frequency can deviate up to ±10 kHz. This unknown Doppler shift f_d is the second parameter needed to be estimated in the signal acquisition stage. It is important to know the frequency of the signal to be able to generate a local carrier signal, which is used to remove the incoming carrier from the signal.

The purpose of the signal acquisition stage is not confined to accessing the presence or absence of a given satellite. The important task of the acquisition system is to provide the subsequent tracking system with rough estimates of the received signal parameters.

3.1 The Cross Ambiguity Function

All the acquisition systems for GNSS applications are based on the evaluation and processing of the cross ambiguity function (CAF) that, in the discrete time domain, can be defined as follows as:

$$R_{y,r}(\acute{\tau},\acute{f}_d)=\sum_{n=0}^{L-1} y_{IF}[n]C_i(nT_s-\acute{\tau})S_b(nT_s-\acute{\tau})exp(j2\pi(f_{IF}+\acute{f}_d)nT_s)$$

Equation (1)

Where , the CAF $R_{y,r}(\tau', f_d')$ is two-dimensional function in a delay τ' and Doppler f_d' domains.

Ideally the CAF should present a sharp peak that corresponds to the values of τ' and f_d' matching the code delay and the Doppler shift of the SIS as shown in Fig-4. However the phase of the incoming signal, the noise and other impairments can degrade the readability of the CAF and further processing is needed.

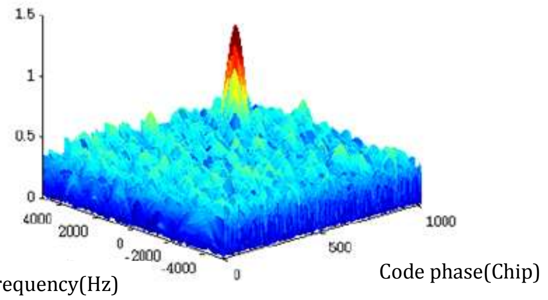


Fig -4: CAF evaluated over a GPS realistic signal

When the envelope of the averaged CAF is evaluated, the system can make a decision on the presence of the satellite. Different detection strategies can be employed. Some strategies are only based on the partial knowledge of the CAF and interactions among the different acquisition steps may be required. The detection can be further enhanced by using multi-trial techniques that require the use of CAFs evaluated on subsequent portions of the incoming signal.

Estimation is usually performed on the square envelop of the CAF in Equation (2), in order to be insensitive to the phase of the incoming signal and also to the sign of bits in case a data channel is acquired.

$$S_{y,r}^2(\acute{\tau},\acute{f}_d)=\left|R_{y,r}(\acute{\tau},\acute{f}_d)\right|^2$$ Equation (2)

3.2 Acquisition Search Space

The set of values over which Equation (2) is evaluated, represent the Search Space for the acquisition. The search space for acquisition operations must cover the full range of uncertainty in the code and Doppler offset.

A grid will be defined in the plane, by digitizing the two variables, and each couple of digitized variables in the grid will be referred as bin, as shown in Fig-5. Where, Δf_d is the frequency bin width in Hz and T_{int} is the predetection integration time in seconds. The combination of one Doppler bin and one bin represent a cell.

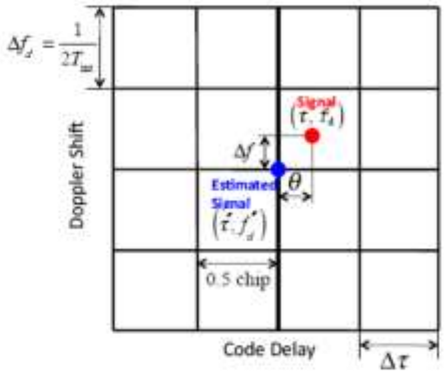


Fig -5: Acquisition Search Space

All possible code offset values will be typically examined because the GPS C/A codes are fairly short. The resolution of the code search is a half chip interval.

With longer codes, the complete exploration of the search space become computationally unaffordable or too lengthy The Doppler range depends on the vehicle and satellite dynamics and on the stability of the receiver oscillator.

For a terrestrial system, it typically ranges from 5 to 10kHz [4]. Having chosen a discretization step for the delay and the Doppler domain evaluation of the CAF becomes over the entire search space in Fig-4.

$$R_{y,r}(i\Delta\tau,k\Delta f)=\sum_{n=0}^{L-1} y_{IF}[n].C_i(nT_s-\Delta\tau)S_b(nT_s-i\Delta\tau).exp(j2\pi(f_{IF}+k\Delta f)nT_s)$$

Equation (3)

4. CONVENTIONAL ACQUISITION ALGORITMS

In this section, three acquisition strategies are discussed. These algorithms are Serial Search Algorithm, Parallel Frequency Space Search Algorithm and Parallel Code Phase Search Algorithm.

4.1 Serial Search Algorithm

Serial search acquisition is an often-used method for acquisition in code-division multiple access systems (CDMA). GPS is a CDMA system. Fig -6 is a block diagram of the serial search algorithm. This algorithm is based on multiplication of locally generated PRN code sequences and locally generated carrier signals. The PRN generator generates a PRN sequence corresponding to a specific satellite. The generated sequence has a certain code phase, from 0 to 1022 chips.

The incoming signal is initially multiplied by this locally generated PRN sequence. After multiplication with the PRN sequence, the signal is multiplied by a locally generated carrier signal. Multiplication with the locally generated carrier signal generates the inphase signal I, and multiplication with a 90° phase-shifted version of the locally generated carrier signal generates the quadrature signal Q.

The I and Q signals are integrated over 1 ms, corresponding to the length of one C/A code, and finally squared and added. Ideally, the signal power should be located in the I part of the signal, as the C/A code is only modulated onto that. However, in this case the I signal generated at the satellite does not necessarily correspond to the demodulated I.

This is because the phase of the received signal is unknown. So to be certain that the signal is detected, it is necessary to investigate both the I and the Q signal. The output is a value of correlation between the incoming signal and the locally generated signal. If a predefined threshold is exceeded, the frequency and code phase parameters are correct, and the parameters can be passed on to the tracking algorithms.

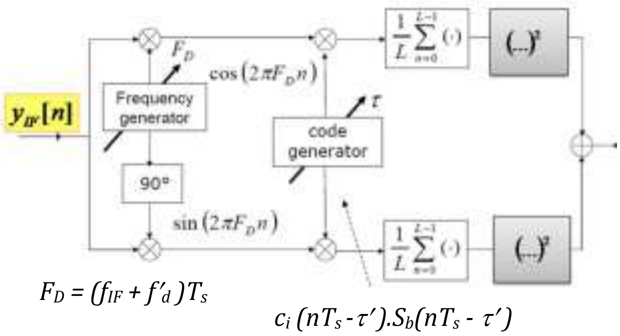


Fig -6: Block Diagram of Serial Search Algorithm

The serial search algorithm performs two different sweeps: a frequency sweep over all possible carrier frequencies of IF ±10 kHz in steps of 500 Hz and a code phase sweep over all 1023 different code phases. All in all, this sums up to a total of 41943 combinations. This is a very large number of combinations that tends to be the main weakness of the serial search acquisition.

The implementation of the serial search acquisition method is very straightforward. It is usually used in hardware receiver.

4.2 Parallel frequency Search Algorithm

This method utilizes the Fourier transform to perform a transformation from the time domain into the frequency domain. Fig-7 is a block diagram of the parallel frequency space search algorithm.

The incoming signal is multiplied by a locally generated PRN sequence, with a code corresponding to a specific satellite and a code phase between 0 and 1022 chips. The resulting signal is transformed into the frequency domain by a Fourier transform (DFT or FFT). The FFT is the faster of the two; but it requires an input sequence with a radix-2 length, that is, 2^n, where n takes positive integer value.

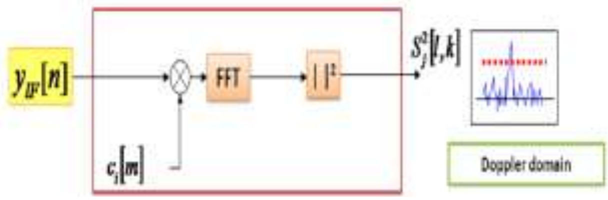


Fig -7: Block Diagram of Parallel Frequency Search Algorithm

If the incoming signal contains signal components from other satellites, these components will be minimized as a result of the cross-correlation properties of the PRN sequences. With a perfectly aligned PRN code, the output of the Fourier transform will show a distinct peak in magnitude. peak will be located at the frequency index corresponding to the frequency of the continuous-wave signal and thereby the frequency of the carrier wave signal.

The accuracy of the determined frequency depends on the length of the DFT. The accuracy of the determined frequency depends on the length of the DFT. The length corresponds to the number of samples in the analyzed data. If 1 ms of data is analyzed, the number of samples can be found as 1/1000 of the sampling frequency. That is, if the sampling frequency is f_s = 10 MHz, the number of samples is N = 10,000. With a DFT length of 10,000, the first N/2 output samples represent the frequencies from 0 to $f_s/2$ Hz.

$$\Delta f = \frac{f_s/2}{N/2} = \frac{f_s}{N} = \frac{10\,\text{MHz}}{10{,}000} = 1\,\text{kHz} \quad \text{Equation (4)}$$

In this case, the accuracy of the estimated carrier frequency is 1 kHz compared to the accuracy of 500 Hz in serial search acquisition. Depending on the implementation of the frequency domain transformation, it should be possible to make a faster implementation of this method compared to the serial search acquisition method.

4.3 Parallel Code Phase Search Algorithm

The amount of search steps in the code phase dimension is significantly larger than that of the frequency dimension (1023 compared to 41).

The goal of the acquisition is to perform a correlation with the incoming signal and a PRN code. Instead of multiplying the input signal with a PRN code with 1023 different code phases as done in the serial search acquisition method, it is more convenient to make a circular cross correlation between the input and the PRN code without shifted code phase.

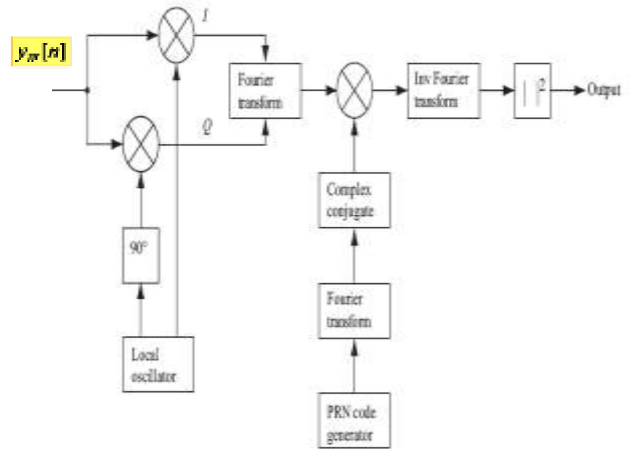


Fig -8: Block Diagram of Parallel Code Phase Algorithm

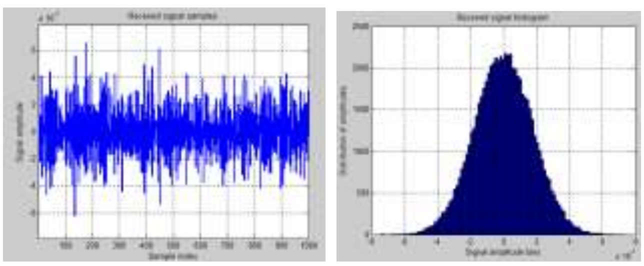
Fig-8 is a block diagram of the parallel code phase search algorithm. The incoming signal is multiplied by a locally generated carrier signal. Multiplication with the signal generates the I signal, and multiplication with a 90 ° phase-shifted version of the signal generates the Q signal. The I and Q signals are combined to form a complex input signal x(n) = I (n) + j Q(n) to the DFT function. The generated PRN code is transformed into the frequency domain and the result is complex conjugated.

The Fourier transform of the input is multiplied with the Fourier transform of the PRN code. The result of themultiplication is transformed into the time domain by an inverse Fourier transform. The absolute value of the output of the inverse Fourier transform represents the correlation between the input and the PRN code.

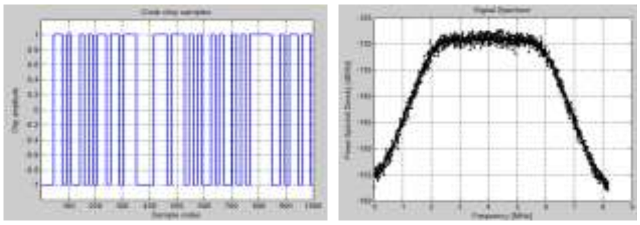
If a peak is present in the correlation, the index of this peak marks the PRN code phase of the incoming signal. the parallel code phase search acquisition method has cut down the search space to the 41 different carrier frequencies. The accuracy of the parameters estimated by this acquisition method regards the frequency similar to the serial search method [5].

5. TESTS AND RESULTS

In this paper, Simulation results are performed by MATLAB2015a. Test and Results are described in the following figures and table.



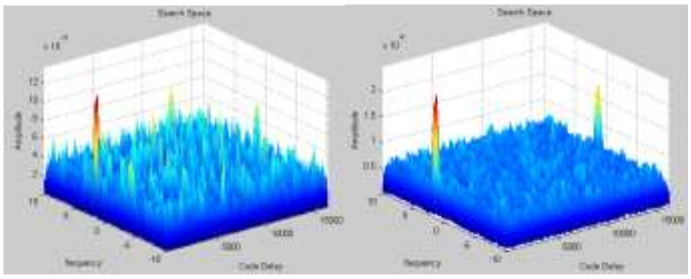
(a) (b)



(c) (d)

Fig -9: (a) Raw Data (b) Histogram (c) C/A code (d) Signal Spectrum with C/No-45dB-Hz

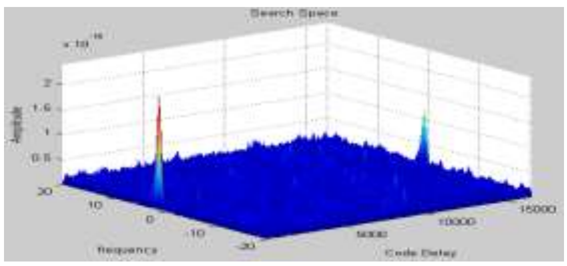
Regarding Fig-9, incoming signal from space with PRN 9 is recorded from N-Fuel as signal generator. Signal length is 4ms for Signal in Space. This type of histogram can easily detect the incoming signal including noise environment.



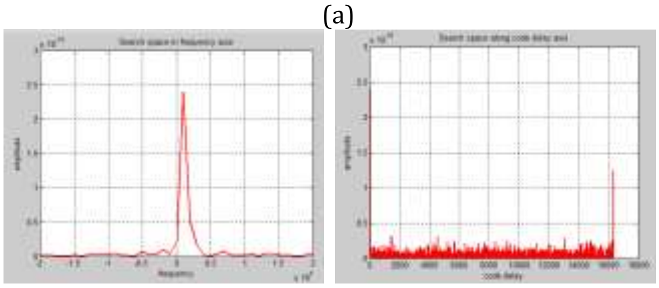
(a) (b)

Fig -10: Serial Search with C/No (a) 40dB–Hz and (b) 45dB-Hz

Fig-10(a) and (b) show the output from the serial search acquisition method. The output peak is clearly visible for C/No with 50dB-Hz.

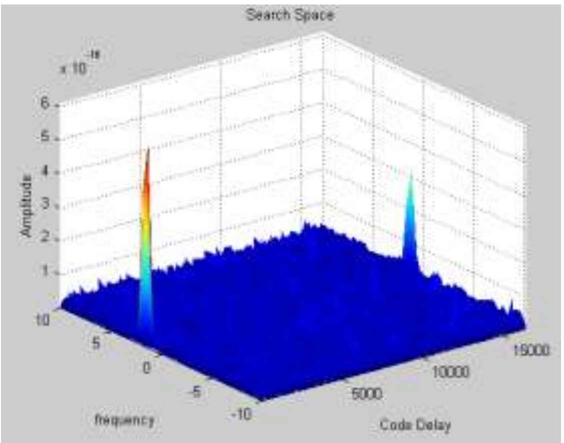


(a)

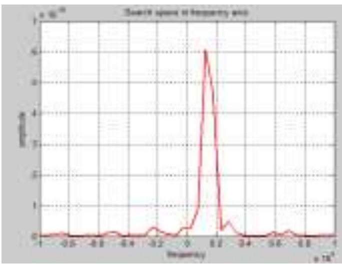


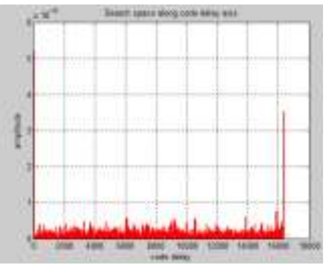
(b) (c)

Fig -11: (a) Search Space (b) In Frequency axis (c) Code delay axis of Parallel Frequency Search with C/No (45dB –Hz)



(a)





(b) (c)

Fig -12: (a) Search Space (b) In Frequency axis (c) Code delay axis of Parallel Code Phase Search with C/No (50dB –Hz)

Fig-11 describes the output from Parallel frequency search with 3D search space, search space in frequency axis and code delay axis.
The output performing the acquisition on a satellite PRN -9 that is tested with Parallel Code Phase method is described in Fig-12. Execution time and repetition for each of three acquisition algorithms are presented in Table-1.

Table -1: Execution Time and Repetition for each of three acquisition algorithms for Satellite PRN- 9

Algorithm	Execution Time (s)	Repetition
Serial Search	135.84	41,943
Parallel Frequency	100.30	1023
Parallel Code Phase	0.9431	41

6. CONCLUSIONS

Acquisition algorithms are implemented on 4MHz signal data of one millisecond period, sampled at 16.3676MHz for PRN-9. The Doppler frequency search range and code phase observed are ±10KHz in steps of 500Hz. The received signal is obtained from N-FUELS. Signal in Space is recorded by 4ms signal length.

PRN 9 is visible so a significant peak is present in the spectrum with C/No (50dB-Hz). The simulation result shows that the output is not clearly searched below 45dB-Hz. The peak is situated at code phase 249 chips and Doppler frequency 2.2kHz.

Comparing searching for three algorithms from simulation results, Parallel Code Phase method is the best. This method is the fastest execution. But the complexity of implementation Parallel Code Phase is high.

A compromise that will be used involves a data length of 1 ms for the acquisition algorithms. One ms corresponds exactly to the length of one complete C/A code, so it also simplifies the algorithm, making it unnecessary to duplicate the code.

The data length can hardly be shorter, because this would involve correlation with an incomplete code. It could be longer, but as mentioned this would decrease the computational performance of the algorithm. To ensure good probability of successful acquisition, the data length cannot be too short.

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