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Study on Carrier Phase Tracking Receivers in Difficult GPS Environments

– Issues on Signal to Noise Ratio and Signal Acquisition

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ABSTRACT

Current applications of GPS typically require the antenna of the user's receiver to have a clear view of sky in order to acquire and track the line-of-sight signals. However, there is an increasing interest in using GPS indoors or in environments where there may be signal blockage. These include general applications where the GPS signals are likely to be severely attenuated, such as emergency 'E911' calls from mobile phones or in support of Location-Based Services or 'telematic' applications, yet where robust operation of GPS is required in urban canyons, under trees, in multi-storey car-parks and even inside buildings. They also include machine control and surveying applications under trees and in other conditions of signal attenuation.

Carrier phase-based GPS techniques are now extensively used for high precision positioning applications. Such techniques may also be of benefit in severe multipath environments. However, due to the satellite signals being easily shaded in many GPS environments, there is difficulty in acquiring attenuated GPS signals and loss of signal lock can happen easily during extended periods of tracking, creating cycle slips or data gaps that require re-initialisation of carrier phase ambiguities. To maintain continuous signal tracking, and hence ensure the validity of the resolved (or estimated) integer ambiguities, a 'high sensitivity' carrier phase tracking GPS receiver is required.

This paper reports on investigations into the effect of difficult environments on signal-to-noise ratio and GPS signal acquisition. Though results presented are preliminary, they are very important for the determination of the optimal threshold of a high sensitivity receiver and related tracking strategies for a particular signal environment (indoors, under foliage, etc.).

KEYWORDS: Signal to noise ratio, Acquisition, GPS, Weak Signals.

1. INTRODUCTION

Ideal scenario for applications of GPS is a clear view of sky so that line-of-sight signals can reach the GPS antenna without intention. However, due to the widespread interest in of GPS technology, many applications that require fast and precise positioning results require the GPS receiver to be used in difficult environments such as under trees, in urban canyon, in multi-story car-parks and even in the forest [Hasegawa 2003]. The applications also include machine control and surveying under trees and in other conditions of signal attenuation. For those applications that require precise results, carrier phase based GPS technologies are adopted.

However, due to satellite signals being easily shaded in difficult environments, there is difficulty in acquiring attenuated GPS signals. In order to acquire attenuated signals, a longer dwell time is required [Kaplan 1996]. On the other hand, for foliated signals, loss of signal lock can happen easily during extended periods of tracking which can cause cycle slips or data gaps that require re-initialisation of carrier phase ambiguities. Signal foliage attenuation, signal blockage and multipath are the main characteristics of the environments that cause difficulties for GPS receivers. These interferences can be classified as RF interference causing a reduction of the Carrier-to-Noise Ratio (C/No) of the GPS signals [Kaplan 1996].

One of the solutions to the problems is to develop a high sensitivity carrier phase tracking GPS receiver which can, to the maximum extent, maintain continuous signal tracking (hence ensuring the validity of the resolved integer ambiguities).

The literature has reported investigations into the use of low power GPS signals (Akos *et al.* 2000, Bryant *et al.* 2002, van Diggelen and Abraham 2001, Sudhir *et al.* 2001, Peterson *et. al.* 1997). These investigations focused on using aiding information and special algorithms to provide measurements and positions, difficult or almost impossible using conventional GPS receivers. However, quantitative study of Signal-to-Noise Ratio attenuation and signal acquisition status in difficult user environments is necessary for further studies on carrier phase tracking performance for the determination of the sensitivity threshold.

This paper is organised as follows, in section two, the background knowledge of Signal-to-Noise Ratio attenuation and its impact on signal acquisition, and the sensitivity characteristics of GPS receiver, is presented. Section three presents quantitative studies on Signal-to-Noise Ratio attenuation and the possible frequency of re-initialisation of carrier phase ambiguity for carrier phase tracking receivers. Section four presents the simulation results of study on GPS signal acquisition under difficult environments.

2. BACKGROUND

2.1 Signal Strength and Receiver Sensitivity

Tracking and decoding the information in the GPS signal is the primary function of a GPS receiver before generating required coordinates. GPS signal acquisition is a search process to detect the presence of the signal. Once the signal is detected, the necessary information (parameters) are obtained and passed to a signal tracking process. Information such as navigation data is obtained from tracking process. In the acquisition process, the Pseudorandom Noise (PRN) code offset and the carrier Doppler are coarsely estimated for the tracking initialization. The PRN code and carrier Doppler form the searching space of the acquisition and the cell formed by the code and the Doppler can contain either signal and noise or noise only. The successful detection of the presence of signal will depend on whether the cell envelop is at or above the threshold chosen according to the probability of false alarm P_{fa} .

According to the definition of P_{fa} in Barton and Leonov (1997), the P_{fa} value can be calculated using equation (2-1) when the noise has a Rayleigh distribution:

$$P_{fa} = \exp\left(\frac{-V_T^2}{2\psi_0}\right) \quad (2-1)$$

where ψ_0 is the mean square value of the noise voltage, given by:

$$V_T = \sqrt{-2\psi_0 Ln P_{fa}} \quad (2-2)$$

Both (2-1) and (2-2) imply the Carrier to Noise ratio (C/N_0) of GPS signal power or simply the signal strength (Signal to Noise Ratio--SNR¹) will have impact on the signal acquisition process. The calculation of other statistic for signal detection process, P_d in (2-3), given in Kaplan (1996) indicates the impact of SNR and C/N_0 on the signal acquisition process.

$$P_d = \int_{V_T}^{\infty} P_s dz \quad (2-3)$$

where $P_s(z)$ is probability density function (PDF) of the envelop in the presence of the signal. This function can also be written as a function of SNR, C/N_0 and search dwelling time T .

If the SNR is high, it is easy to set a threshold for both low P_{fa} and low risk of missing signal detection. Low SNR will increase the number of false alarms. If increasing V_T is chosen, longer search dwelling time will have to be used to compensate. Also a higher threshold can reduce the probability of weak signals detection and hence reduce the sensitivity of the receiver.

The above discussion suggests a high sensitivity carrier phase tracking receiver is required for difficult user environment where GPS signals are weakened or attenuated. Due to low SNR signal, which have impact on the probability of false alarm and hence on the signal detection threshold, novel receiver algorithms and signal processing are needed. Assuming the development of a high sensitivity carrier phase tracking receiver as our long term goal, the first step is to look at the impact of difficult user environment on the SNR of GPS signals.

¹ Both C/N_0 and SNR have been used to describe the GPS signal strength though they are not identical. The received signal power is expressed either in "signal strength" dBm or as a "carrier to noise ratio, C/N_0 (dBHz)". These are equivalent scale.

3. QUANTITATIVE STUDY ON SIGNAL TO NOISE RATIO ATTENUATION

3.2 Experiments

According to Kaplan (1996), signal blockage, foliage attenuation, ionospheric scintillation, and multipath have the same effect on the code correlation and loop filtering functions of a GPS receiver. They are forms of RF interference in that they all reduce the effective C/No of the GPS signals. To obtain quantitative values of the signal attenuation, experiments were carried out with various kind GPS receivers. The difficult user environments are selected in the area where GPS signals are blocked by tree leaves and branches as indicated in Figure 1.



Figure 1. Difficult GPS user environments

The data has been collected from field receivers at position 1 (CMC Allstar 1, clear sky), position 2 (CMC Allstar 2, clear sky) and position 3 (CMC Allstar 3, under trees) and the reference station (Lica 500) at the EE building of the university of New South Wales (UNSW). The ambiguities of UNSW to position 1(CMC1) and position 2 (CMC2) (clear sky) have been fixed while the UNSW, CMC1 and CMC2 to the point under trees (CMC_tree) were not fixed.

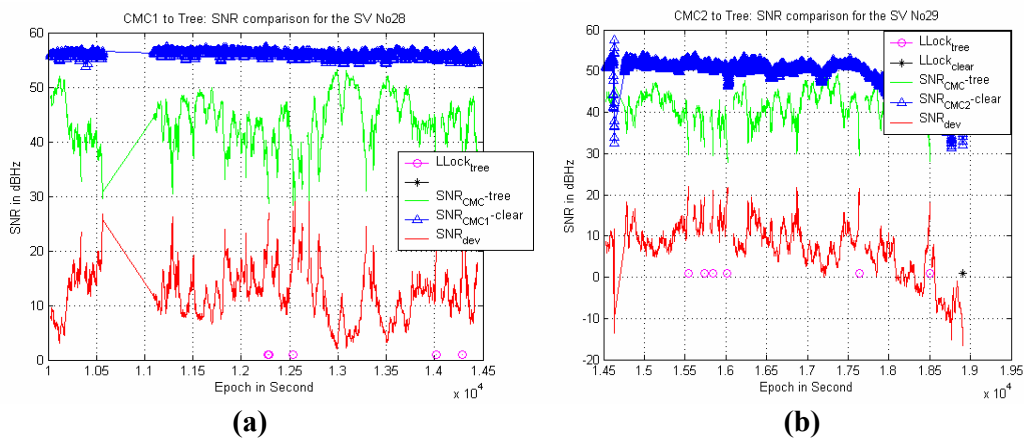


Figure 2. The SNR comparisons

Figure 2 shows the typical SNR comparisons between GPS receivers with line of sight signals and the receiver under trees. Figure 2 (a) is the SNR comparison between CMC 1 and CMC under trees while figure 2. (b) is CMC 2 and CMC under trees. The median of SNR deviation between CMC1 and CMC (under trees) for satellite PRN 28 is 11.75. The median of SNR

deviation between CMC2 and CMC (under trees) for PRN 29 is 7.5. Due to the loss of locks (cycle slips), it is not possible to obtain data statistics such as the standard deviation.

SV number	CMC1 to CMC under trees	CMC2 to CMC under trees	Median of SNR deviation
1	9.73	7.98	8.855
4	10.34	8.45	9.395
7	6.04	7.32	6.68
8	5.97	7.12	6.545
13	10.65	9.73	10.19
28	11.75	10.25	11
29	8.5	7.5	8
			8.666429

Table 1. The SNR comparisons summary

From the data processing, an average of 8.7dBHz SNR attenuation for the GPS signal under trees is observed. This result is close to the 11dB attenuation at L-Band signal transmitted from a 45° elevation angle helicopter by Goldhirsh and Vogel (1998). With this SNR attenuation and P_{fa} of 0.1, for the Tong-search detector (Kaplan, 1996), 1ms search dwelling time will fail to detect line-of-sight GPS signals with the SNR of less than -20dB. To acquire signal with SNR of 20dB, the search dwelling time will have to be increased up to 3ms or 5 ms. However, this will mean 3 times computational burden compare to the scenario of the open sky.

3.2 Study on The Frequency of Re-initialization of Carrier Phase Ambiguity

Due to the GPS signals being easily attenuated by trees, it is necessary to look at how frequently the loss of signal lock can happen for standard commercial carrier phase tracking GPS receivers. This can be done by studying the data gaps in the data collected.

The experiments were carried out for this purpose with Leica 500 and Topcon GPS receivers. Both receivers have been set up over the same ground-mark for about same time period (10:30 am to 1:30 pm). The collected data has been post processed with the same reference station data from UNSW. In the case of both the Leica and Topcon no ambiguity fixed solution could be obtained without careful selection of the data. After carefully selecting the data from particular time periods when the most satellites signals (L1 and L2) were available, both Leica and Topcon can generate fixed solutions. However, the coordinates obtained are not identical.

Figures 3 and 4 clearly show that both Topcon and Leica have not tracked more than 4 satellites continuously for over 15 minutes. The data length is about 10 minutes for Topcon and less than 5 minutes for Leica.

From Figures 5 and 6, more than 20 centimetre satellite L1 phase residual is observed. This indicates the existence of possible cycle slips.

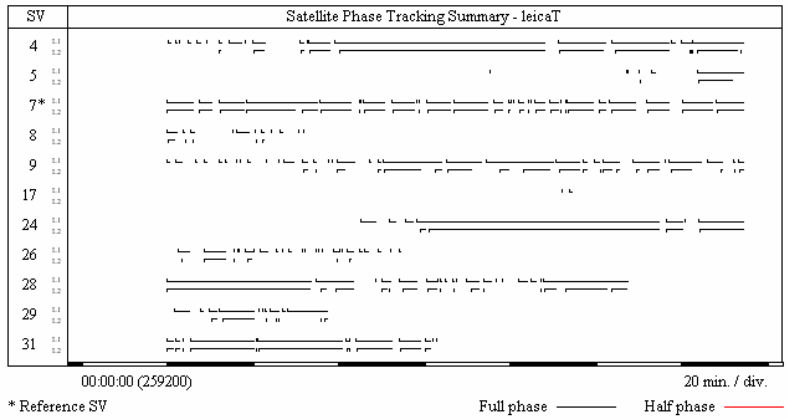


Figure 3. Satellite phase tracking summary for Leica receiver under trees

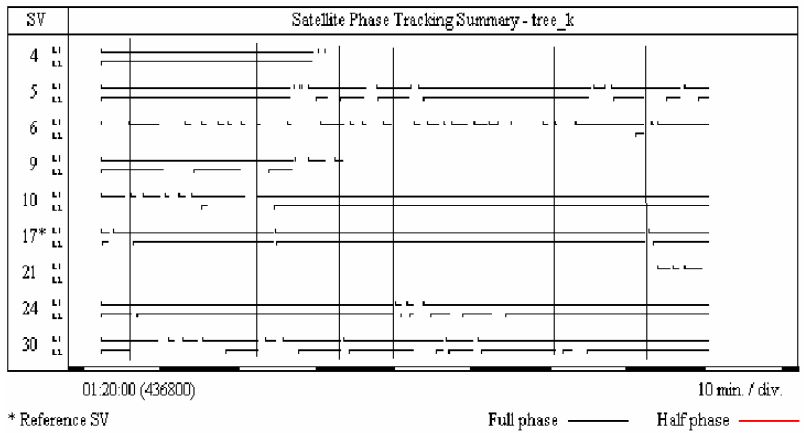


Figure 4. Satellite phase tracking summary for Topcon receiver under trees

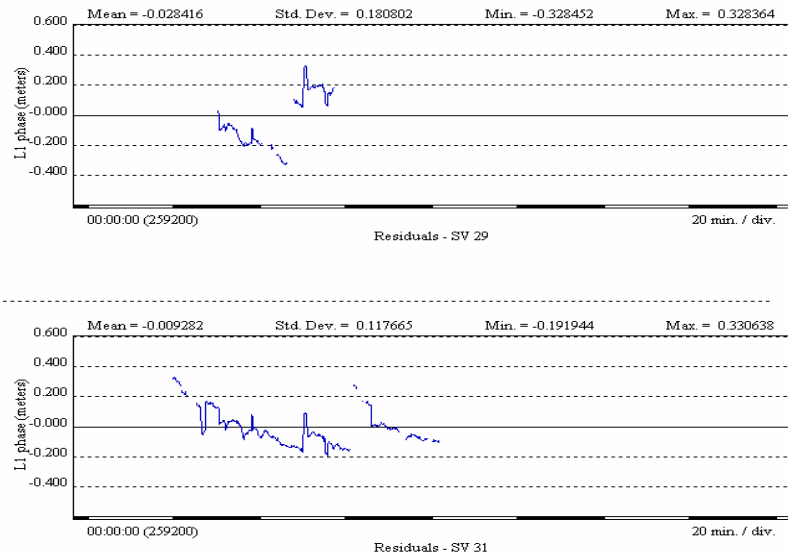


Figure 5. L1 phase residuals obtained from Leica receiver (PRN 29 and 31)

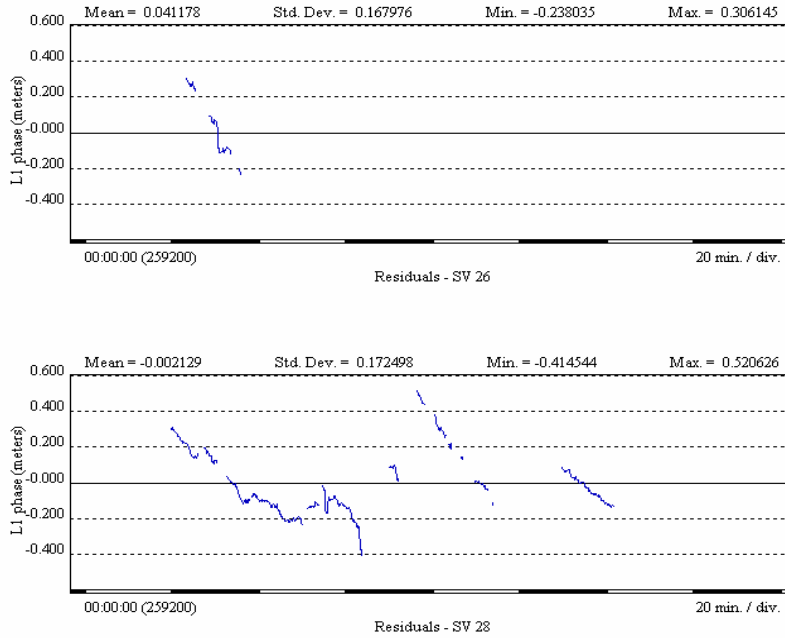


Figure 6. L1 phase residuals obtained from Topcon receiver (PRN 26 and 28)

This experiment illustrated that loss of signal lock actually happened to carrier phase tracking receivers quite often due to the difficult signal environment. Signal attenuation will severely affect the signal tracking process as well.

4. GPS SIGNAL ACQUISITION UNDER DIFFICULT ENVIRONMENTS

The main factors that affect GPS signal acquisition include signal strength, sampling frequency (if false alarm probability is based on the false alarm time defined in Tsui 2001) and the presence of jamming signals (Bryant *et al.* 2002). The first factor is discussed in sections 2 and 3 related to the detect threshold and the impact of C/N_0 on P_{fa} . The second factors also because of the impact of sampling frequency on the P_{fa} in the sense that P_{fa} can be expressed as a function of the sampling frequency f_s :

$$P_{fa} = \frac{1}{T_f f_s} \quad or \quad P_{fa} = \frac{N}{T_f f_T} \quad (4-1)$$

where T_f is the false alarm time and f_T is sampling frequency, N is the number of samples. The third factor is the most complicated and difficult problem to account for. Although Bryant *et al.* (2002) have been working on this issue, there hardly any effective methods reported in literature.

Simulations on GPS signal acquisition have been carried out and the aforementioned three factors can provide explanation to the results obtained. From our computer simulation, the third factor is the major cause for failing of signal detection if raw data is collected under a difficult signal environment.

4.1 Raw Data Collection And Conversion

The equipment used in data collection is particular designed for only collecting RF front end data. In other words, only data from Zalink GP2015 chipset RF front end (MAG and SIGN) is collected. The data is then converted to values according to the two bit Analog-to-Digital

(A/D) converter, as described in Amoroso (1983). The validity of the collected data collected has been verified with two different softwares. The receiver locations are also selected to be the same ground-marks as previous experiments and the antenna of the reference station at UNSW is the ideal line-of-sight signal environment.

4.2 Signal Acquisition Simulation

Two computer simulation programs have been used in this study. The program is designed for normal signal acquisition only. This simulation is mainly intended for situations when signal fails in detection, and assessing what would be the impact of a difficult user environment on the signal acquisition process - such as the phase shift of the frequency, cross-correlation between weak signal and the local code. In signal acquisition, two important parameters must be measured. One is the beginning of the Coarse/Acquisition (C/A) code and the other is the carrier frequency of the input signal.

Figure 7 presents the normal situation where a line-of-sight signal is being detected by the signal acquisition program for the purpose of comparison. When incoming signal is strong, the cross correlation between incoming signal and local code is negligible and the high value of the magnitude of envelop $\sqrt{I^2 + Q^2}$ can be obtained. If the magnitude is at or above the threshold, the signal is detected. Figure 7 clearly shows the beginning of the C/A code and the carrier frequency of SV6. However, small side lobes are also observable from frequency bins.

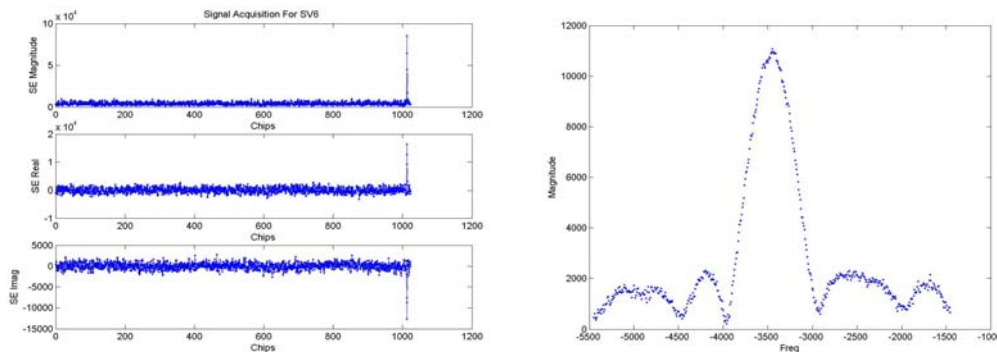


Figure 7. Simulation of signal acquisition with raw data under an open sky

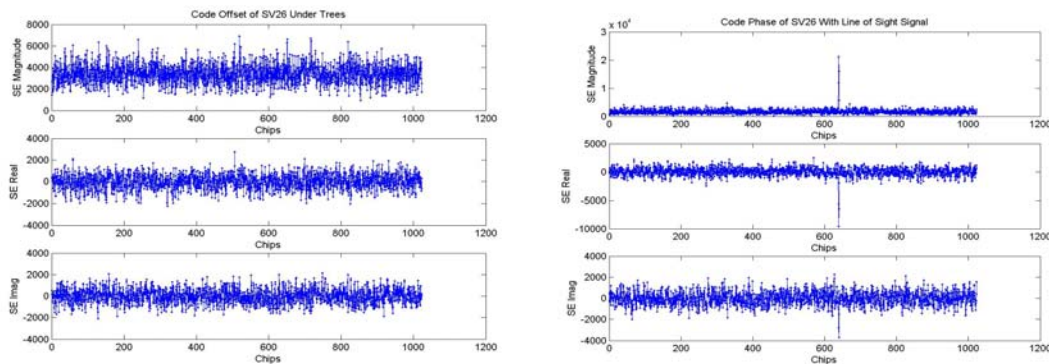


Figure 8. Code offset of PRN 26 under trees and an open sky

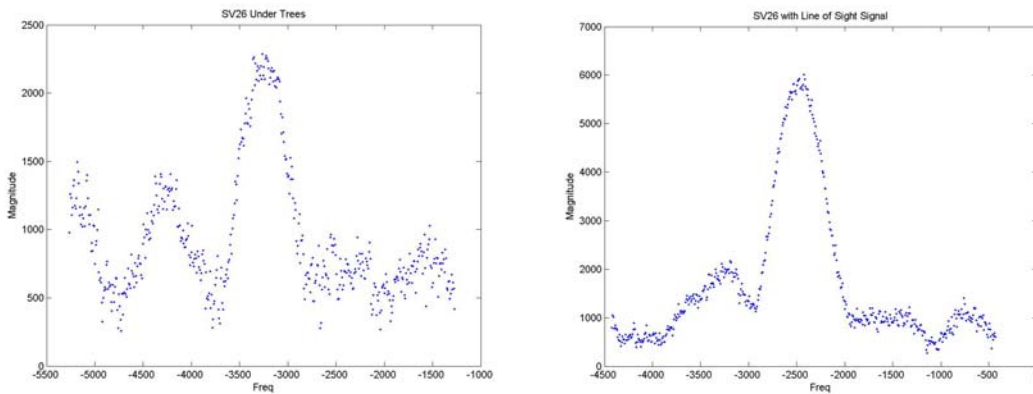


Figure 9. Frequency component of PRN 26 under trees and an open sky

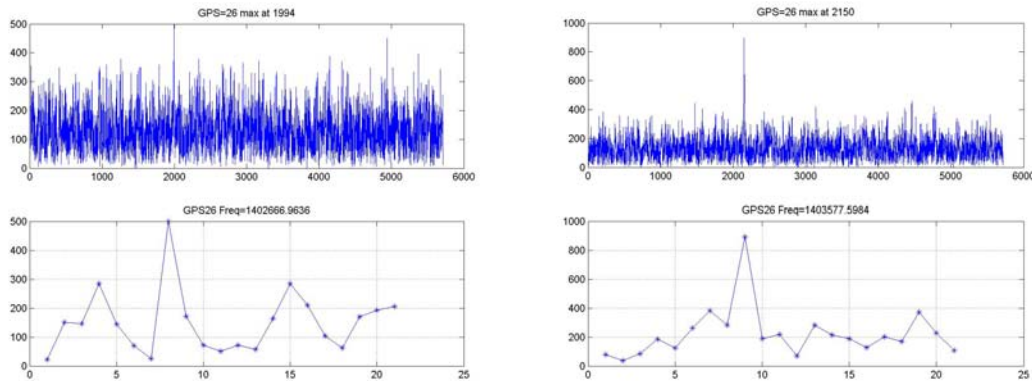


Figure 10. Code offset (upper) and frequency component (bottom) of PRN 26 under trees and an open sky

Figures 8 and 9 depict the scenarios for data collected under trees and open sky. The results of data collected under an open sky show little difference from Figure 7, while the results from the under trees scenario indicate significant discrepancies. There are two points that need to be emphasised. One is that the distinct peak of indicating the beginning of C/A code is not found in the left figure of Figure 8. This situation can not be improved upon by increasing the search dwelling time to 10ms. The other thing is that the Doppler peak has shifted about 1KHz compared to the results from the open sky scenario, and large side lobes are now evident. If the Doppler search bin is forced to the value in the right hand figure, large side lobes are observable and the beginning of C/A code still not obtainable.

Figure 10 shows almost identical results for the same set of data with different signal detection program. Severe signal attenuation and the effect of cross-correlation could be the reasons. As suggested in Bryant *et al.* (2002), identifying the strong “jamming” signals and separating them from weak signals would be critical for effectively improving the sensitivity and the dynamics of GPS receiver. This will pave the way to a carrier phase tracking receiver that works well under difficult signal environment. In addition, new signal acquisition and tracking algorithms are also required.

CONCLUDING REMARKS

An average of 8.7 dB of the SNR attenuation is observed while GPS receiver is set up under trees. This will impact on the probability of false alarm, as well as the signal detection threshold. Clearly this will cause the failure of signal detection.

The SNR attenuation can cause cycle slips and data gaps for carrier phase tracking GPS receiver due to loss of signal lock. For those applications that require precise measurements, high sensitivity carrier phase tracking GPS receivers with ability to identifying and separate strong “jamming” signals will be required. This paper also suggests that the high amplitude caused by cross-correlation should be mitigated and signal lock should be maintained continuously to prevent ambiguity re-initialisation. These issues will need to be addressed with new strategies and novel algorithms in signal acquisition and tracking. The authors of this paper will attempt to address these issues in future work.

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