OVERVIEW OF GNSS SIGNAL DEGRADATION PHENOMENA

Glenn MacGougan, Gerard Lachapelle, Rakesh Nayak
Department of Geomatics Engineering
University of Calgary
Alexander Wang
Norwegian University of Science and Technology, Trondheim

BIOGRAPHIES

Mr. Glenn MacGougan is a MSc. student in the Department of Geomatics Engineering at the University of Calgary. In 2000 he completed a BSc. in Geomatics Engineering at the University of Calgary. He will complete his second degree in September 2002.

Dr. Gerard Lachapelle is a Professor and Head of the Department of Geomatics Engineering where he is responsible for teaching and research related to positioning, navigation, and hydrography. He has been involved with GPS developments and applications since 1980.

Mr. Rakesh A. Nayak completed an M.Sc in Geomatics Engineering at the University of Calgary in 2000. He also holds a B.E. in Electronics Engineering from Mangalore University, India. He has been involved in GPS research since 1994 in the area of receiver hardware and software development and low cost sensor integration. He is currently working at Accord Software and Systems, India, designing GPS receivers.

Alexander Wang holds the Norwegian equivalent to a M.Sc. in electronic engineering, with focus on radio navigation system, from the Norwegian University of Science and Technology. He completed his thesis "Impact of RFI on GPS Aeronautical Applications" in May 2001, and now works with radio navigation systems and radio communication systems onboard ships, in the Norwegian classification society "Det Norske Veritas" in Oslo.

ABSTRACT

In an era of ever increasing wireless RF congestion, GNSS systems are becoming more at risk of signal degradation due to interference. GPS uses signals typically 20 dB below the ambient noise floor and it has only limited interference mitigation. Thus, there is a need to characterize GPS signal degradation and quantify the effects of interference sources. GPS signal deterioration typically occurs by signal masking caused by natural (e.g. foliage) and man-made (e.g. buildings) obstructions, ionospheric scintillation, Doppler shift, multipath, jamming, spurious satellite transmissions, and antenna effects. The impact of anyone of the above can result in partial to total loss of tracking and possible tracking errors, depending on the severity of the effect and the receiver tracking characteristics. Tracking errors, especially if undetected by the receiver firmware, can result in large position errors. Partial loss of tracking results in geometry degradation, which in turn affects position accuracy. This paper provides an overview of degradation phenomena affecting GPS satellite navigation signals.

INTRODUCTION

The Global Positioning System (GPS) is a radionavigation system developed by the United States Air Force comprising of 24 satellites orbiting the earth at an altitude of roughly 20,000km. It is a pseudorange (ranging with a time/range bias) based positioning system that uses radio frequency (RF) signals to determine range estimates, based on the time difference between transmission and reception, to each of the satellites. This is sometimes referred to as a time-of-arrival (TOA) ranging method. GPS utilizes two RF frequencies on the L-band (1-2 GHz), L1 = 1575.42 MHz and L2 = 1227.60 MHz. GPS uses these RF signals with received power levels typically 20dB below the ambient noise floor. Signals such as these are highly susceptible to interference and with the introduction of more and more wireless technologies the RF spectrum is becoming crowded.

In the case of GPS, signal deterioration occurs by signal masking caused by natural (e.g. foliage) and man-made (e.g. buildings) obstructions, ionospheric scintillation, Doppler shift, multipath, jamming, evil waveforms, and antenna effects. The impact of anyone of the above can result in partial to total loss of signal tracking and/or tracking errors, depending on the severity of the effect and the receiver tracking characteristics. Tracking errors, especially if undetected by the receiver firmware, can result in large position errors. Partial loss of tracking results in geometry degradation, which in turn affects position accuracy.

There is a strong need to characterize GPS signal deterioration, quantify the effects, and develop test procedures to determine the performance of military receivers under various types and degrees of deterioration. The aim of this document is to provide that classification and characterization of GPS signal deterioration.

The classification and characterization of GPS signal degradation in this document begins at the satellite, proceeds to discuss the signal propagation through space and the atmosphere, and finishes with reception at the user's receiver. The following figure illustrates an overview of the signal deterioration from satellite to receiver as discussed in this paper.

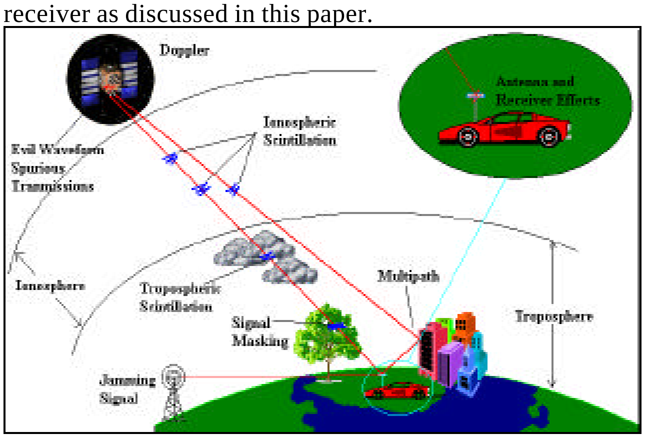

Figure 1: Signal Deterioration Overview.

SATELLITE SIGNAL EFFECTS

GPS satellites generate and transmit two carrier frequencies referred to as L1 and L2 at frequencies of 1575.24 MHz and 1227.60 MHz respectively. The carriers are modulated using spread spectrum codes and each satellite is identified with a technique called code division multiple access (CDMA) using pseudorandom noise (PRN) codes. The codes are referred to as the course/acquisition (C/A) code designed for civilians using the Standard Positioning Service (SPS) and the precise (P) code designed for military users using the Precise Positioning Service. The precision code is generally denied to the SPS segment via a technique called anti-spoofing, which modulates an encryption on the P code. The encrypted P code is referred to as the Y code. In addition to spread spectrum code modulation a navigation message is also modulated on the carrier signals.

GPS satellite and signal integrity is maintained to protect users against failures and anomalies through monitoring by the GPS Master Control Station and by satellite self-checks. In the event of a problem, the satellite health portion of the navigation message can be altered to indicate the problem to users. In some cases, spurious transmissions can be generated which are not detectable by standard means and integrity is compromised. The following excerpt concisely describes this issue.

"Several types of failures can occur in the GPS space segment designed to deliver the ranging signals to the users. Among the potential failures, a specific type of failure in the signal generation process aboard the satellite may result in an anomalous waveform being transmitted, called an 'evil waveform'. Such a failure was already observed in 1993 on an operating satellite, and an analysis of the causes of failures have led to the derivation of a mathematical model of these waveforms [Enge et al., 1999].

Evil waveforms are GPS signals that have a distorted PRN code modulation waveform. The deformation is modeled by a lead or a lag of the rising or falling edges of the modulation code, and/or by a second-order filtering of this waveform." (Macabiau, 2000)

The waveforms Macabiau mentions are illustrated in Figure 2.

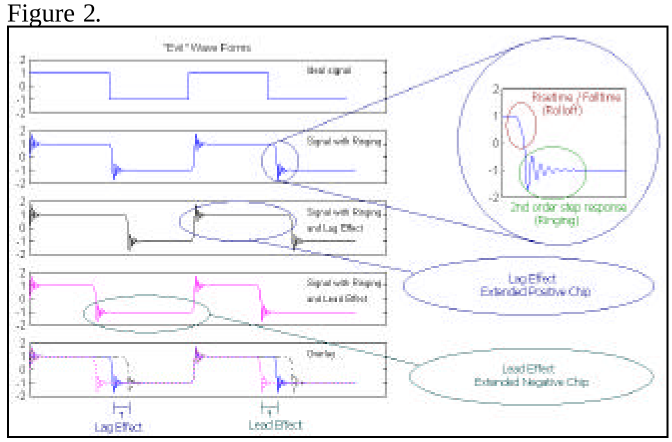

Figure 2 - Spurious GPS Signal Effects

The concerns about spurious satellite transmissions arise from an incident in March of 1993 on satellite vehicle (SV) 19. PRN 19 had served without known problems until it was discovered that its use had a negative impact on differential GPS. When including this satellite in solution an error of 3-8m resulted compared to an error of 0.5m when the satellite was omitted. The problem has since been fixed by switching to some redundant hardware on the satellite (Edgar, C. et al, 1999). No further incidents of spurious signals have been reported.

The impact of such satellite signals in terms of tracking error depends on the nature of the spurious transmission and the characteristics of the GPS receiver signal processing. Undetected, these signals degrade the signal code measurement but not the carrier information. Thus, code-only differential GPS and standalone GPS are directly effected by such error.

GPS SIGNAL BUDGET

The satellites radiate signal at a power level of 13.4 dB-W. The antennas on the satellites are directive antennas with the beam pointed to Earth. The one-sided beam angle is 14.3° as shown in the following figure.

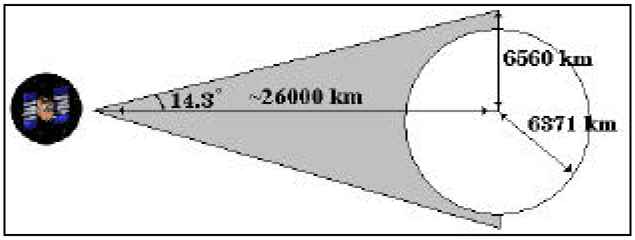

Figure 3: Satellite Radiation Pattern

Therefore, the effective directive gain of the antenna is 13.4 dB. The received power at the antenna on the ground is given by the equation

$$P_r = P_t A_r / 4pR^2 \quad (1)$$

Where,

P_r is the received power

P_t is the transmitted power

A_r is the antenna aperture

There fore the free space loss is given by (Lachapelle, 1998)

$$L_0 = P_r / P_t = l^2 / 4pR^2 \quad (2)$$

Where,

λ is the wavelength (19 cm for L1)

R is the radial distance between the transmitting and the receiving antenna (25092 km)

The signal budget for C/A – L1 is given in the table below.

Table 1: L1 GPS Signal Budget (Lachapelle, 1998)

SV antenna power	13.4 dB-W
SV antenna gain	13.4 dB-W
User antenna gain (hemispherical)	3.0
Free space loss (L1)	-184.4 dB
Atmospheric attenuation loss	-2.0 dB
Depolarization loss	-3.4 dB
User receiver power	-160.0 dB-W

The received minimum signal strengths for L1 and L2 codes are described in the GPS-ICD-200C document and are given in the table below.

Table 2: Received Minimum RF Signal Strength (ICD-GPS-200C, 1993)

Table 3-III. Received Minimum RF Signal Strength		
Channel	Signal	
	P(Y)	C/A
L1	-163.0 dB-W	-160.0 dB-W
L2	-166.0 dB-W	

Fortunately for GPS users, the minimum power is not generally used to transmit the signals. Most GPS satellites emit signals at 3 to 7 dB higher than the specified minimum with an average power level typically 5.4 dB above the minimum (Parkinson, B. et al, 1996).

IONOSPHERIC SCINTILLATION

The ionosphere is one of the largest sources of range error for high accuracy GPS users. This region of the atmosphere contains electrons freed by ionizing radiation from the sun. The free electrons disturb the propagation of RF signals including GPS. The ionospheric induced range error can vary from only a few metres at the zenith to many tens of metres at the horizon. The ionosphere is a dispersive medium; that is, the refractive index of the ionosphere is a function of the frequency. Therefore, dual frequency GPS users can make use of this property to measure and correct for the first order range and range rate error effects. The ionosphere can have the following effects on GPS signals: 1) group delay of the modulated signal, 2) carrier phase advance, 3) scintillation and 4) Faraday rotation to name a few (Klobuchar, 1996).

The ionosphere is made up of ionized plasma and can be generally classified into four regions, D, E, F1 and F2 illustrated in the figure below. The D region typically extends from 50-90 km and has a negligible effect on GPS frequencies. The E region typically extends from 90-140 km and is produced by solar soft x rays and also has a negligible effect on GPS frequencies. The region F1 typically extends from 140-210 km and has a significant impact on GPS frequencies. The heights of these regions are not fixed and fluctuate a great deal. Region F1 is estimated to account for 10% of the daytime ionospheric error. The regions D, E, F1 are associated with the daytime UV (ultra violet) ionization and hence is not present at night. The F2 region typically extends from 210-1000 km. It is also the most active region and its influence on GPS frequencies is maximum. The F2 region is present at nighttime unlike the D, E, and F1 regions. Most of the day-to-day (diurnal) effects can be modeled to a large extent, however the ionosphere exhibits non-deterministic levels of activity depending on the scintillation effects.

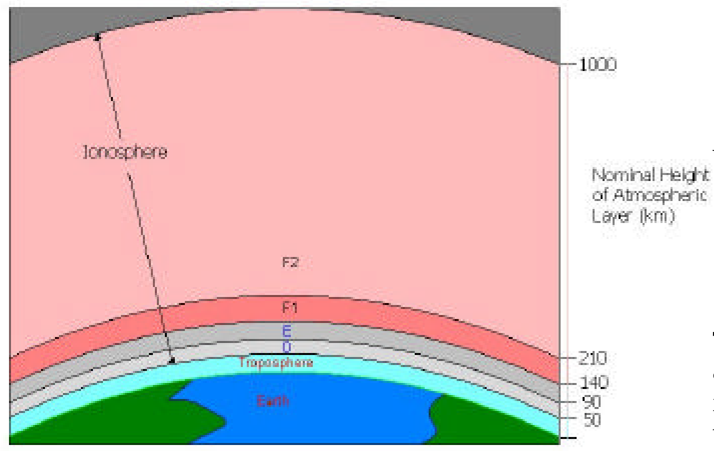

Figure 4: The Ionosphere

The ionosphere also induces a Faraday rotation on electromagnetic signals, which causes a linearly polarized signal to undergo additional rotation along the plane of its polarization. Since GPS signals are circularly polarized, Faraday rotation has no effect on GPS signals (Klobuchar, 1996).

Ionospheric induced error can be of the order of 2 – 50 m in single point mode but it can be reduced by DGPS. The improvement depends on the base line distance between the reference station and the remote receiver, as the ionosphere decorrelates spatially. The improvement is on the order of 2 ppm with differential corrections (Lachapelle, 1998), but can surpass 17 ppm under high ionospheric conditions (Fortes, 2000). Some of the various effects due to ionosphere are discussed in the following sections.

GROUP DELAY

The group delay or the absolute range error for a single frequency user can be expressed as

$$\Delta t = \frac{40.3}{cf^2} \int N dl, \quad seconds \tag{3}$$

Where,

f	is the frequency of the signal
c	is the speed of light
Δt	is the ionospheric time delay
N	is the electron (el) count
dl	is a unit length (m)

The above integral is also referred as the TEC (Total Electron Content), in el/m2, which is evaluated along the line of site from the user to each of the satellites. The group delay for a dual frequency GPS user can be written as (Klobuchar, 1996):

$$d(\Delta t) = (40.3/c) * TEC * \left[\left(1/f_2^2\right) - \left(1/f_1^2\right)\right] = \Delta t_1 \left[\left(f_1^2 - f_2^2\right)/f_2^2\right] \tag{4}$$

Where,

f_1	is the frequency of the L1 signal (1575.42 MHz)
f_2	is the frequency of the L2 signal (1227.6 MHz)
Δt_1	is the ionospheric time delay at L1

Therefore can be measured directly by subtracting the L1 and L2 measurements and an estimate of the absolute ionospheric delay on L1 or L2 can then be computed from the equation (4).

CARRIER PHASE ADVANCE

As radio signals travel through the ionosphere, the phase of the carrier of the radio signal gets advanced from its velocity in free space. The amount of this phase advance can not be readily measured on a single frequency unless both the transmitter and receiver has exceptional oscillator stability and orbital characteristics of the satellites are very well known (Klobuchar, 1996). The carrier phase advance is a function of frequency and if two coherently derived frequencies are used then the differential carrier phase shift between the two frequencies can be measured and is related to TEC.

The relationship between the group and phase delay is given by

$$\Delta\Phi = -f\Delta t \tag{5}$$

Where f is the frequency.

For GPS, one cycle of carrier phase advance is equivalent to 0.635 ns of group delay. The negative sign indicates that the differential code group delay and differential carrier phase advance move in opposite directions. Figure 5 shows the group and phase velocity on a carrier signal (Lachapelle, 1998).

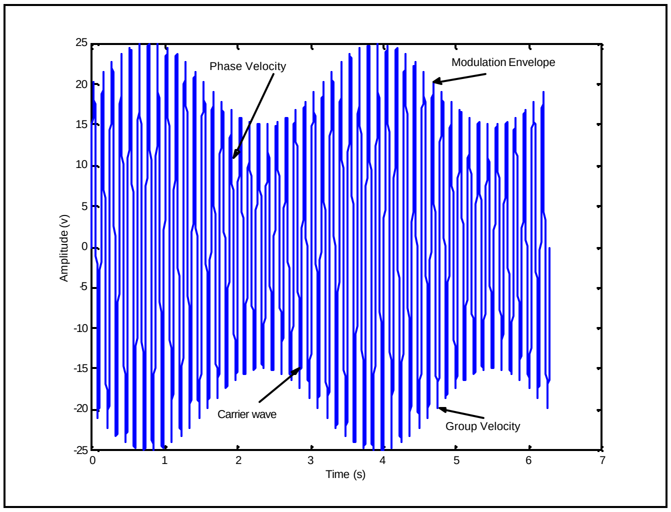

Figure 5: Group and Phase Velocity

SCINTILLATION

Ionospheric scintillation is caused by the electron density irregularities in the ionosphere. Scintillation is a rapid variation in the amplitude and/or phase of an RF signal. These variations occur along with high levels of solar and geomagnetic activities. The presence of the irregularities can cause GPS signals to experience phase and amplitude scintillation effects. Amplitude scintillation results in the fluctuations in the power of the received signal and can cause the received signal power to drop below the receiver tracking threshold. Phase scintillation is characterized by the rapid random variation in the phase rate. The receiver carrier tracking bandwidth is usually not designed to accommodate this variation and results in loss of lock.

Scintillation effects are significant in equatorial regions (±30° geomagnetic latitude) with largest effects in the region of ±10°. Equatorial scintillation is usually present during 1900-2400 hours local time (Klobuchar, 1996). Amplitude fading can be larger than 20 dB in this region during high solar activities (Basu et al., 1988).

Scintillation effects are also observed in the auroral zone and polar cap region (65° - 90° geomagnetic latitude), particularly during magnetic storms. This phenomenon is different from the equatorial scintillation effects and the two are not correlated. The high latitude scintillations are not restricted to any particular local time period and can last for many hours, even days (Skone, 1998). The auroral zone scintillation effects are less severe than the equatorial scintillation effects and can have maximum amplitudes fading of 10 dB (Cannon et al., 1997).

Scintillation also has a seasonal dependence. Scintillation is less common at the American, African and Indian latitudes during the months of April to August, while scintillation has maximum frequency in the Pacific region. These effects are reversed during the rest of the year (Klobuchar, 1996).

Basu et al, (1998) have determined a strong correlation between ionospheric scintillation and sunspot number. Scintillation effects are therefore expected to be larger and more frequent during solar maximum.

TROPOSPHERIC EFFECTS

For GPS purposes, the troposphere can be defined as the region of the atmosphere extending from the Earth's surface to approximately 50km in altitude. The troposphere is non-dispersive at GPS frequencies. The troposphere contributes to GPS signal degradation in terms of attenuation, signal delay, and to a small extent scintillation.

The attenuation of the GPS signal varies with the elevation angle of the satellite. Attenuation ranges from 0.38 dB at the horizon to typically 0.035 dB at the zenith. The attenuation effect is due to oxygen (O2) attenuation and effects due to water vapor, rainfall, and nitrogen are negligible (Spilker, 1994).

As the GPS signal is refracted as it travels through the atmosphere, the received signal is delayed. The troposphere can be divided into two components as far as delay is concerned. These are the dry and wet components. The dry component accounts for the majority (about 80-90%) of the delay effect and can be easily modeled. The dry effect corresponds to a delay of typically 2.3m at the zenith and varies by less than 1% over a few hours. On the other hand, the wet component varies by 10-20% over a few hours. Although, the magnitude of delay is much smaller, 1-80 cm at the zenith, than the dry effect. Lower elevation satellite signals have a much larger delay as the tropospheric path length increases. The delay terms for wet and dry can increase by up to a factor of ten as the elevation angle decreases. In general, for any satellite signal the tropospheric delay ranges from 2-25 m. Fortunately, tropospheric models can typically correct for about 90% of the delay. There are several models that estimate the tropospheric error. Saastamoinen (1972) proposed a constant lapse rate model for troposphere that estimates delay as a function of elevation. Hopfield (1963) developed separate zenith models for the dry and wet components of the troposphere. This is further extended by Black and Eisner (1984) to include an elevation angle mapping function.

Tropospheric scintillation is a 'smaller' effect that does not receive much attention. It is caused by irregularities in the refractive index along the signal path through the troposphere. This effect varies with time and is dependant upon elevation angle, and weather conditions. The perceived effect is a variation of the received signal power of up to 1 dB at very low elevation angles. In general though, this effect is very small (Spilker, 1994).

The tropospheric delay should be corrected about 80-90% by modeling in any single point GPS receiver. While in differential GPS, the spatial correlation of the delay between stations is very high and allows the majority of the effect of the delay to be corrected by differencing. GPS receivers also generally use an elevation mask to eliminate signals that are severely affected by atmospheric effects.

DOPPLER SHIFT

Doppler is a phenomenon where a change in frequency is perceived due to the motion of the source relative to the receiver. Therefore, GPS being a satellite based radio-navigation system will experience Doppler effects due to the satellite motion relative to the receiver on the ground and to a lesser extent due to receiver motion. For a static receiver Doppler frequencies can be as large as +/-5 kHz and can be much higher for air-borne receivers. The impact of high dynamics and the related Doppler shift includes possible velocity error, an increase in noise on the carrier phase measurement, and possibly even the loss of tracking of the GPS signal.

Very high Doppler due to high velocity or acceleration can induce severe stress on the carrier tracking loops in a receiver. It should be noted that GPS signal tracking usually includes code and carrier tracking loops. Both are needed and work together to maintain lock on the signal. In most cases the carrier tracking loop is the weak link. The ability of the receiver to track signals with high Doppler depends on the bandwidth of the tracking loop and the order of the tracking loop used. A second order tracking loop is sensitive to jerk, where as a third order loop is sensitive to rate of change of jerk.

Much research has been conducted on GPS derived velocities using a simulator for signal generation (Cannon et al., 1997; Hebert, 1997; Hebert et al., 1997) These studies have shown that velocity accuracies of 2 mm/s or better are achievable during periods of constant velocity. During dynamics, however, the accuracy of the velocity estimates were always dependent on the dynamic conditions. Depending on the receiver tested and the method used to generate the Doppler observable, the velocity accuracy exhibited a direct correlation with either the magnitude of acceleration or jerk (Ryan et al., 1997). In general, during medium to high dynamics the receivers under test exhibited velocity errors ranging from 200 mm/s to several meters per second.

The Doppler shifted frequency is different from the nominal L1 or L2 frequency. The Doppler shift caused by satellite and user motion is the projection of the relative velocities onto the line of sight scaled by the transmitted frequency. The equation below describes how the user's velocity can be derived.

$$D_i = -f_1\left(\frac{v_i - v_u}{c} \cdot l_i\right) \tag{6}$$

Dynamic stress affects the tracking performance of the receiver's carrier tracking. This corresponds to the Phase Lock Loop, PLL, of the receiver. From the equation expressed below, it can be seen that dynamic stress error is a major part of PLL phase jitter. It has an effect on PLL tracking as well as GPS signal C/N0, depending on PLL bandwidth and PLL predetection integration time that cause the PLL thermal noise.

$$s_{PLL} = \sqrt{s_t^2 + q_A^2 + s_v^2} + \frac{q_e}{3} \tag{7}$$

s_{PLL} 1-sigma value of PLL error, its rule-of-thumb tracking threshold is 15°

s_t 1-sigma thermal noise in degrees

s_v 1-sigma vibration induced oscillator jitter in degrees

q_A Allan variance-induced oscillator jitter in degrees

q_e dynamic stress error in the PLL tracking loop

When the dynamic stress error, along with other phase jitter error sources, exceeds the PLL noise threshold, a loss of PLL tracking occurs.

Thus methods to deal with the effect of dynamic stress and Doppler shift are very important to GPS receivers, both on the tracking performance and on the RTK velocity estimation.

SIGNAL MASKING

GPS Signals are microwave signals in the radio frequency spectrum and suffer from signal masking due to obstructions, such as buildings and dense foliage. Signal masking induces fading of the direct signal, multipath, and in some cases complete signal blockage.

Foliage attenuation is often characterized as attenuation in dB/m of foliage penetration. The attenuation depends on the nature of the tree and the height of the tree. When a mobile receiver is moving rapidly past intermittent trees, the mean attenuation should be considered instead of attenuation from a single tree. Parkinson and Spilker (1998) provide comprehensive analysis on foliage attenuation of GPS signals on moving and stationary GPS receivers.

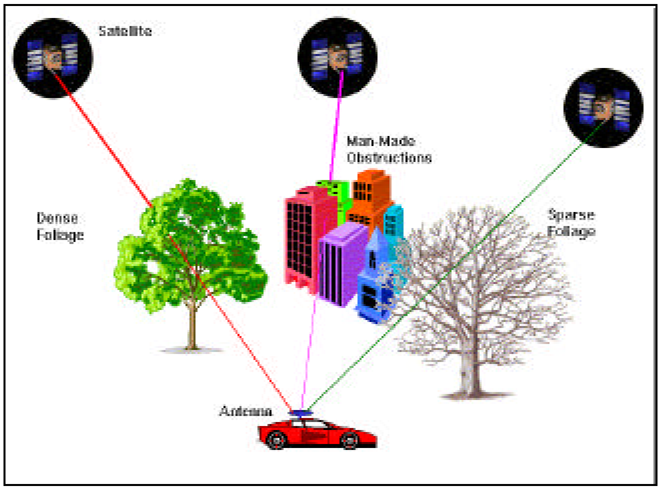

Figure 6: Signal Masking

The intermittent blockage imposes severe stress on the carrier and code tracking loops, which can result in frequent loss of signal lock. Also, the poor signal power (C/No) reaching the antenna will severely affect the quality of the measurements and the position estimates. The seasonal effect of foliage on GPS signal availability and the resulting accuracy implications was studied in detail by Lachapelle et al., (1994).

The overall consequences on satellite availability, signal quality and ultimately position accuracy is a function of following parameters (Lachapelle et al., 1994)

- thickness of leaves and branches
- density of foliage
- humidity
- season in the case of deciduous trees
- number of GPS receiver channels
- tracking loop robustness
- code accuracy
- re-acquisition time

A series of vehicular tests were conducted in Calgary on June 30 and September 9, 1999. Four NovAtel 501 active antennas were mounted on the roof of a vehicle. The antennas were connected to four NovAtel MiLLennium™ receivers. The purpose of the test was to study the tracking performance and the effects of multipath in Urban and foliage environments. The detailed description of the test setup and the environmental conditions is described in Nayak, et al., (2000). Figure 7 and Figure 8 shows the percentage visibility of satellites in each section of the test as computed by the post processing software. Figure 7 shows that seven satellites are visible by antenna A (shown in blue color) 15% of the time. The average number of satellites tracked and the corresponding GDOP in each of this section is given in Table 3 and Table 4 respectively.

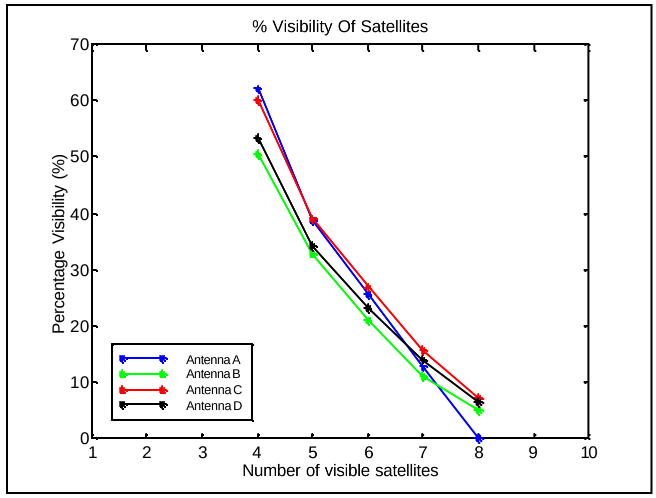

Figure 7: Percentage Visibility of Satellites – Urban Environment

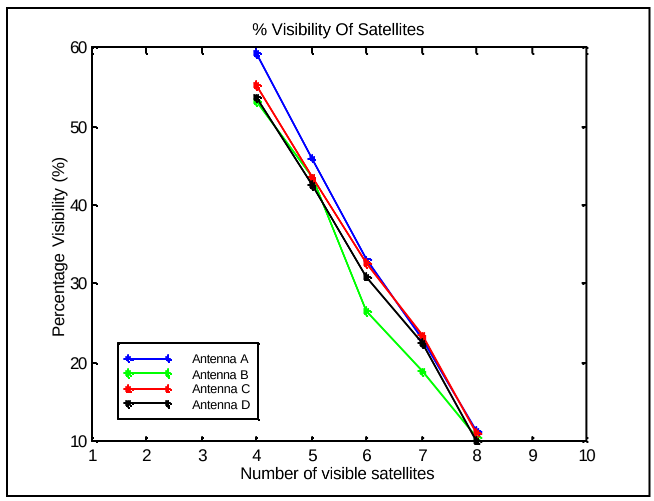

Figure 8: Percentage visibility of satellites – Foliage environment

Table 3: Average satellite visibility and GDOP – Urban environment

	Antenna A	Antenna B	Antenna C	Antenna D
Average GDOP	5.6	6.1	5.5	5.9
Average number of SVs	3.2	2.6	3.3	1.2

Table 4: Average satellite visibility and GDOP – Foliage environment

	Antenna A	Antenna B	Antenna C	Antenna D
Average GDOP	4.9	5.9	5.1	5.3
Average number of SVs	3.5	3.1	3.3	2.3

The numbers in the table represents the average satellites tracked for the entire section, and although all antennas tracked less than four satellites on an average, sufficient satellites were available to compute a position fix most of the time.

Receiver manufactures over the years have been working on various innovative approaches to improve the signal acquisition and tracking performance under sever signal masking. SnapTrack™ has developed a server aided GPS technology, where a remote server updates each of the receivers with information to aid in signal acquisition making use of the cellular network. This technique is effective under sever masking such as urban canyon's and inside buildings. The initial results show that this technique is capable of acquiring signals with attenuation as low as 25dB where as most of the conventional GPS receivers fail to acquire signals below 5 – 10 dB attenuation (Moeglein and Krasner, 2000).

The function of the receiver is greatly reduced as the receiver does not spend time in computing position fixes but uses all the resources to acquire and track weak signals. The receiver computes the pseudorange measurements and transfers it to the server where the navigation solution computes the position of the receiver. The receiver improves the acquisition and tracking sensitivity by coherent integration of the signal over long periods of time. Peterson et al., (1997) demonstrated the benefits of such an approach. This concept has been known for a long time and has been termed as 'data wipe off' approach. However, this approach is not very well suited in GPS receivers as external aiding is required. In this method, the data bits are wiped off and the receiver now does not have to limit the integration time to the data bit boundary (20 ms) but can integrate for any length of time. Longer integration results in better noise cancellation, which means weaker signal can now be detected. Peterson et al., (1997) demonstrated that with 80 to 160 ms of coherent integration a signal 60 dB weaker than normal could be acquired with this technique.

MULTIPATH

Multipath is one of the larger error sources in both single point and differential GPS. Multipath is the error caused by reflected signals entering the RF front end and mixing with the direct signal. These effects tend to be more pronounced in static receivers close to large reflectors. As shown in Figure 9, the reflectors of electromagnetic signals could be buildings, metal surfaces, water bodies, the ground, etc. Multipath error is specific to a receiver antenna and depends on the surrounding environment. Hence care has to be taken while installing GPS receivers for static applications, such as reference stations.

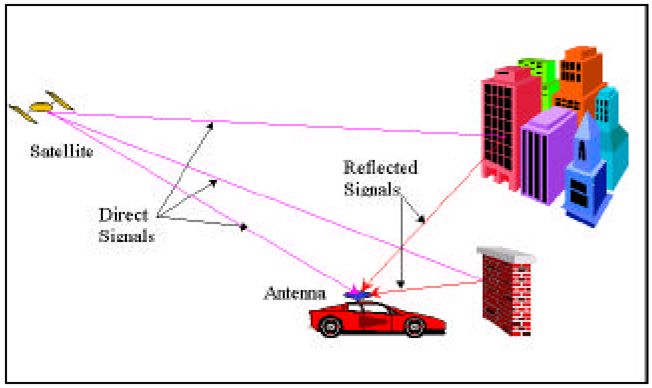

Figure 9: Multipath Environment

Code multipath errors depend on the code tracked by the GPS receiver. C/A code has a maximum delay of 1.5 code chips or 450m while this delay is reduced by a factor of ten when tracking the P-code. This factor-of-ten rule of thumb holds true for P-code multipath when compared to C/A code multipath. In fact, the instantaneous and average multipath error curves for P-code and C/A code are identical in shape but reduced by a factor of 10 in the case of P code.

Code multipath errors can be of tens of metres and are highly localized and hence cannot removed through differential techniques. Most of the multipath mitigation technologies are based on the design of suitable architectures in receivers that can minimize multipath, and there are also special antenna designs such as choke rings and other multipath-limiting antennas, which prevent multipath signals from entering the RF section of the receiver.

Code multipath is similar to carrier phase multipath, only its magnitude is several orders of magnitude higher. For code measurements, the multipath signals are always delayed compared to the line-of-sight signals because of the longer travel paths caused by the reflection. The direct and reflected signals will superimpose to produce the composite received signal and in turn affects the correlation property of the C/A code. This is illustrated in Figure 10.

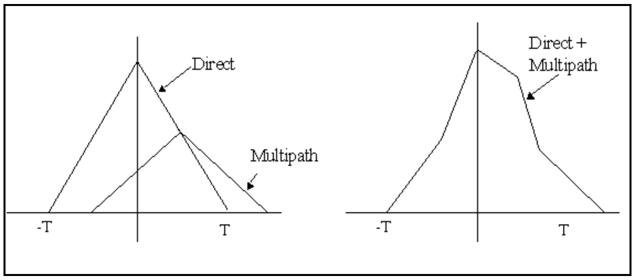

Figure 10: Multipath effect on the correlation triangle, (Lachapelle, 1998)

The composite multipath signal can be expressed as (Braasch, 1994),

$$s(t) = -Ap(t)\sin(w_o t) - aAp(t+d)\sin(w_o t + q_m) \qquad (8)$$

Where,

$s(t)$	is the composite signal
A	is the amplitude of the direct signal
$p(t)$	is the PRN sequence of the C/A code (± 1)
w_o	is the frequency of the direct signal (L1)
a	is the relative power of the multipath signal
d	is the delay of the multipath signal with respect to the direct signal
q	is the phase of the multipath signal relative to the direct signal

The superposition of direct and the reflected signal can either add or cancel the effective multipath. Hence, on a moving platform usually the multipath tends to average out over time, but can be significant in magnitude and decorrelates rapidly over spatial distances. The magnitude of the multipath error depends on the reflector distance and its strength, the correlator spacing and the receiver bandwidth. The code multipath can be on the order of tens of metres whereas the carrier phase multipath does not exceed 4.75 cm (Ray, 2000).

Multipath can be classified into diffused reflection, specular reflection and refraction. Diffused multipath results when the GPS signal gets reflected from rough surfaces and specular multipath results when the GPS signal gets reflected from smooth surfaces like water bodies and metal surfaces while refraction occurs due to the bending of the signal. Multipath affects the code and carrier of the GPS signal in different ways, for details see Ray (2000). The multipath signal travels a greater distance compared to the direct signal to arrive at the GPS antenna. The C/A code, which is a composite signal of the direct and the reflected signal, is distorted by the relative amount of phase shift of the reflected signal. If the direct signal is in-phase with the reflected signal then the signal power increases, and if they arrive out of phase at the antenna then the signal power at the antenna decreases. This has direct impact on the correlation peak and thus affects the pseudorange (and carrier phase, if applicable) measurements.

The magnitude of code multipath error in a receiver depends on the distance between the reflecting source and the receiving antenna. It also depends on the correlator spacing and the precorrelation bandwidth (Braasch, 1995). Figure 11 illustrates relative multipath induced tracking errors encountered among various correlators. The standard correlator has a spacing of 1.0 chip between the early and the late correlators and a precorrelation bandwidth of 2 MHz. In contrast, the Narrow Correlator™ has a precorrelation bandwidth of 8 MHz and a correlator spacing of 0.1 chip between the early and the late correlators (van Dierendonck et al., 1992). From Figure 11 it can be seen that the standard correlators are susceptible to substantial multipath errors for C/A code chip delays of up to 1.5 chips, with the most significant C/A code multipath errors occurring at about 0.25 and 0.75 chips (approaching 80 m error). On the other hand, in case of the Narrow Correlator™, multipath susceptibility peaks at about 0.2 chip (about 10 m error) and remains relatively constant out to 0.95 chip, where it rapidly declines to negligible errors after 1.1 chip. The code multipath error envelope for two more techniques MET™ (Multipath Elimination Technique, Townsend and Fenton, 1994) and MEDLL™ (Multipath Estimation Delay Lock Loop, Van Nee, 1995) are also shown below.

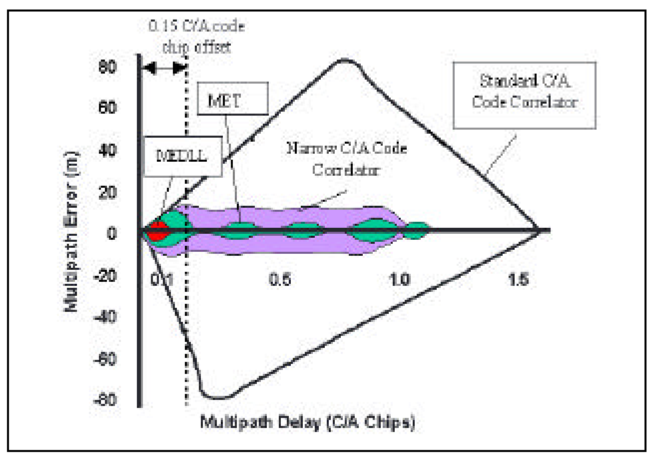

Figure 11: Multipath error envelope (Ford, 1998)

MET™ is an improvement of Narrow CorrelatorTM with respect to multipath mitigation (Townsend and Fenton, 1994). It estimates the slope of the two sides of the autocorrelation peak as well as the amplitude, thus estimating for two lines that intersect at the peak, irrespective of the slope. MET™ has a multipath error envelope, which is oscillatory in nature, but is less susceptible compared to the Narrow Correlator™. However, MEDLL™ performs the best under multipath environment. For details on MEDLL™ see Van Nee (1995). MEDLL uses multiple narrow-spaced correlators to estimate multipath and remove it from the correlation function to provide a more pure signal correlation function (Van Nee, 1995). As MEDLL uses multiple correlators the receiver is bulky and expensive and is usually used in reference stations. All correlator based mitigation techniques are effective for long delay multipath errors but are ineffective to short delay multipath. Ray (2000) developed a method to mitigate short delay multipath error for static receivers. All the techniques listed above can remove 50% to 60% of multipath error (Ray, 2000) and the residual multipath error can still be significant on the order of few metres.

The maximum multipath delay (delay between the direct signal and the reflected signal) that can introduce an error in the measurement also depends on the correlator spacing and is given by equation (9).

$$M_{delay} = T_C + T_D \qquad (9)$$

Where,

T_C is the C/A code chip width, and

T_D is the spacing between the prompt and early or prompt and the late correlator spacing

Hence, for a standard correlator with a spacing of 0.5 chip between early and prompt correlators, the maximum multipath delay can be 1.5 chips, which translates to 450m. However, for Narrow Correlator™ with a spacing of 0.1 chips, the maximum delay that can cause multipath error is 1.1 chips, which translates to 330m. Therefore a reflector placed more than 330m from the receiving antenna will not introduce any code multipath.

Some of the characteristics of code multipath can be summarized as:

- Maximum code multipath error can be up to +/-150 m for receivers with wide correlator spacing (Ray, 2000).
- Affected by multipath signal delayed up to 450 metres (signal delay – not error).
- Non zero mean (van Nee, 1995).
- Magnitude of multipath error depends on the precorrelation bandwidth.
- Error is high frequency in nature under dynamic conditions.
- Decorrelates rapidly over distance.
- Code multipath has day-to-day repeatability in static receivers, (sidereal time) see, (Lachapelle 1998).

For detailed description on the effect of multipath error on the various correlators, discriminator functions refer to Ray (2000).

JAMMING INTERFERENCE

A jammer is an intentional or unintentional signal that directly interferes within the L1 or L2 frequency bands. The various sources of jamming signals are summarized in the following table.

Table 5: Sources of Jamming Interference (Ward, 1996 a)

Types of Interference	Typical Sources
Wideband-Gaussian	Intentional noise jammers
Wideband phase/frequency modulation	Television transmitter's harmonics or near band microwave link transmitters overcoming front-end filter of the GPS receiver
Wideband-spread spectrum	Intentional spread spectrum jammers or near-field of pseudolites
Wideband-pulse	Radar transmissions
Narrowband phase/frequency modulation	AM stations transmitter's harmonics or CB transmitter's harmonics
Narrowband-swept continuous wave	Intentional CW jammers or FM stations transmitter's harmonics
Narrowband-continuous wave	Intentional CW jammers or near-band unmodulated transmitter's carriers

CONTINUOUS WAVE INTERFERENCE AND SOURCES

Continuous wave (CW) interference generally consists of signals with very narrow bandwidths, occupying less than 100 kHz (Rash, 1997). CW interference often only consists of one tone, i.e. one frequency. CW also implies that the signal is without any kind of modulation. Unmodulated narrow band interfering signals are hence referred to as CW signals.

The GPS C/A-codes are Gold-codes created by a specific combination of registers; it is hence not an optimal code (a 'maximum length'-code). This results in a line spectrum in the frequency domain, as shown in the figure below, which is susceptible to interference. The plot to the left depicts the GPS C/A-code spectrum. CW interference may be particularly detrimental, as its peak in the frequency domain may coincide with these local peaks in the GPS L1 spectrum. When this happens, the signal 'leaks through' in the correlation process and causes code measurement error. The figure below illustrates this effect. The plot depicts the GPS C/A-code line spectrum and an interfering CW signal. As the interfering signal coincides with a local peak, it will be mistaken with the GPS peak, and cause a false position to be calculated. This phenomenon only occurs with C/A code measurements and does not affect the P(Y) code measurements.

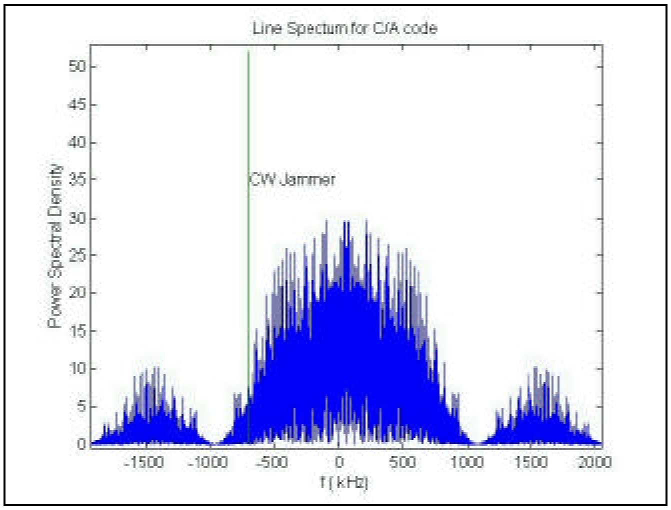

Figure 12: The C/A Code Spectrum and a CW Jammer

CW is hence considered one of the most harmful kinds of interference to GPS. It can be centered around L1, and effectively avoid the filtering techniques due to the fact that all the interfering power is located within its narrow bandwidth.

CW interference is also known to trick the PLL tracking loop into locking in on the interfering signal instead of the GPS ranging signals, even after spreading by the correlation process. Intricate jamming techniques utilize two CW-signals, separated by the known intermediate frequency of the target receiver. The unavoidable non-linearities of the receiving front-end filter will generate a CW component at base-band, which can be conceived by the tracking loop as a correlation peak.

Typical sources of CW interference in the GPS spectrum, apart from intentional jammers, are FM stations transmitter's harmonics or near-band unmodulated transmitter's carriers.

NARROWBAND INTERFERENCE AND SOURCES

Narrowband interference usually refers to any unwanted signal occupying more than 100 kHz of bandwidth, but less than the entire C/A-code spectrum of 10.23 MHz. Of course, what is a narrowband signal will also depend on the bandwidth of the wanted signal. Hence can the same signal be described as both wide and narrow, depending on the GPS receiver: A 5 MHz interfering signal can be regarded as wide if the receiver utilize a wide correlator design with a 4 MHz pre-correlation filter, and narrow with narrow correlator designs, which have bandwidths of up to 20 MHz.

Generally, narrowband interference is usually centered around one of the GPS frequencies to effectively jam the receiver, but not necessarily so. The center frequency is usually what decides how destructive an interfering CW or narrow band interference signal is.

Unintentional narrowband interference most often arises from spurious signals generated in all sorts of electrical equipment, which is inadequately shielded. Some narrow band radio links adjacent to GPS frequencies are also known to cause local interference problems.

WIDEBAND INTERFERENCE AND SOURCES

Wideband interference is interfering signals occupying the entire GPS C/A-code spectrum, covering bandwidths of 10.23 MHz or more (Rash, 1997). As with narrowband interference, what is regarded as wideband depend on the bandwidth of the original signal. The lower limit of what is considered wideband hence depends on the receiver pre-correlation filters.

Wideband jammers effectively lower the GPS signal C/N0 ratio by increasing noise level. The effect of such jamming varies from increased noise on code and carrier measurements to loss of signal tracking and the inability of the receiver to acquire the GPS signals.

Typical sources of wideband interference in the GPS spectrum, apart from intentional jammers, are television transmitter's harmonics or near band microwave link transmitters overcoming the front-end filter of the GPS receiver. Wideband noise from various electrical devices can lower the C/N0 below a receiver's tracking threshold.

Ultra Wide Band (UWB) refers to signals utilizing different spread spectrum techniques, which effectively use tens of GHz of bandwidth in the RF spectrum. It uses very short pulses of radio energy, and it is used in different radar applications, as well as in mobile communication links to cellular phones and other mobile Internet applications. As UWB has excellent characteristics which allows it to distinguish multipath, operate indoors and in cities and other obstructed areas, and low probability to be picked up by undesired receivers, there is expected a significant increase in the use of UWB technology in the future. Tests have shown that UWB transmitters very well may cause interference to GPS (Lou, 2000). Although good design of the UWB signals can avoid interference within the GPS signal spectrums.

Unintentional in-band (RF signals generated within the GPS frequency band) sources of interference include pseudolites signals, that can sometimes overpower other signal channels, and, to a small extent, the different C/A codes interfere with each other. Intentional in-band interference is associated with the military jamming systems. The L1 signal is within a protected signal bandwidth governed by the International Telecommunications Union (ITU). However, the L2 signal is not protected and there are some systems that broadcast interference within its frequency band.

The ITU, a sub committee of the United Nations (UN), is an organization that works to avoid interference problems amongst others, on an international level. The World Radio Conferences (WRC), hosted by ITU, decides on frequency assignments, spectrum allocations and interference resolutions. The ITU has over 180 member states, which all are obliged to follow the treaties agreed upon at the WRF. This should assure international interoperability of different systems, and ensure that no system interferes or is exposed to interference by other systems: “All electric or electronic systems shall be designed to be mutually compatible with other electric or electronic equipment within their expected operational environment” (DeSalvo, 1998).

Out-of-band interference is typically generated by harmonic frequencies of transmitters outside the GPS frequency band. For example, channel 66 broadcasts at close to 785 MHz and produces second harmonics centered very close to the L1 frequency, 1575.42 GHz.

The most effective form of wideband interference is called a spoofer. A spoofer is an intentional transmission of a false but strong version of a GPS signal so that it captures the receiver tracking loops and provides devious navigation information. Pseudolites can be considered spoofing signals in some circumstances. Military jamming systems using spoofing are not as much of a threat as jamming because of the high cost of a spoofer versus a jammer.

PULSED INTERFERENCE

Different radar systems, with inadequate out-of-band attenuation/filtering, are prevalent forms of interference. Certain navigation systems, such as Distance Measuring Equipment (DME) and Tactical Air Navigation (TACAN), but also some mobile communication equipment, utilize pulsed transmissions, which may also cause interference problems to GPS.

The effect of short, but strong pulses, is a linear degradation of the carrier-to-noise density ratio, with increasing duty cycles. The GPS receiver will, however, just ignore the part of the signal that is distorted, if the duty cycle is relatively modest. Pulsed interference will only affect some of the 1023 chips transmitted as illustrated in figure below. Short pulses and low duty cycles will not significantly degrade GPS navigation performance. It is however possible that pulsed interference can affect the receiver through the amplifying stages. Pulses may cause compression and distortion, due to a sudden rise in the power density at the GPS frequency, that force tracking loops to lose lock.

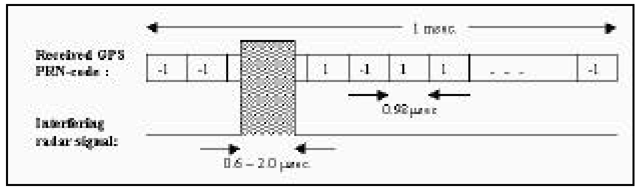

Figure 13: Pulsed Interference Diagram

Pulsed interference with duty cycles below 50 percent has been found to have little effect on the navigational performance (Owen, 1993). This is confirmed by recent studies (Winer, 1996), concluding that typical GPS receivers do not lose lock in the presence of pulsed CW interference, regardless of the power level, as long as the duty cycle stays below 30%. When the duty cycle is further increased, loss of the signal occurs at decreasingly lower interference levels. At duty cycles of 80% or more, the performance was equal to that of continuous interference from the same source, as can be seen in Figure 14.

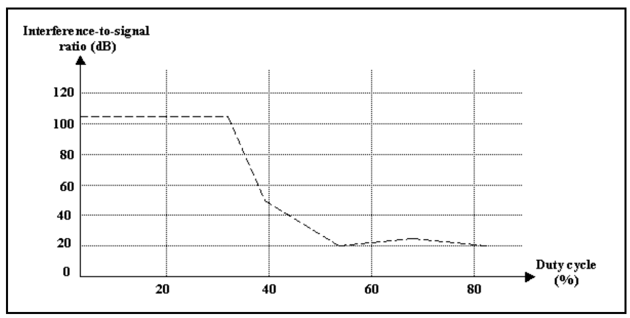

Figure 14: The Effect of Duty Cycle

The implications of these test results are favorable to aviation users, as most of the pulsed systems commonly used in aviation, such as DMEs, Secondary Surveillance Radars (SSRs) as well as primary radars have duty cycles of less than 10%. They are hence not expected to cause interference problems with GPS.

REFERENCES

Basu, S., E. Mackenzie and S. Basu (1988), Ionospheric Constraints on VHF/UHF Communication Links During Solar Maximum and Minimum Periods, Radio Science, Vol. 23, No. 3, pp 363 – 378.

Black, H.D. and A. Eisner (1984), Correcting Satellite Doppler Data for Tropospheric Effects, Journal of Geophysical Research, 89.

Braasch, M.S. (1994), Multipath Effects, Global Positioning Systems: Theory and Applications, Vol. I, ed.

B.W. Parkinson and J.J. Spilker Jr., American Institute of Aeronautics and Astronautics, Washington DC, pp. 547-568.

Braasch, M.S. (1995), Isolation of GPS Multipath and Receiver tracking Errors, NAVIGATION: Journal of The Institute of Navigation,Vol 41, No 4, pp 415 – 434.

Cannon, M.E., G. Lachapelle, M. Szarmes, J. Hebert, J.Keith and S. Jokerst, (1997), DGPS Kinematic Carrier Phase Signal Simulation Analysis for Precise Velocity and Position Determination, Proceedings of the ION NTM, Santa Monica, CA, January.

Cannon, M.E., S. Skone and C. Varner (1997), LINCSS Mission Data Segment System Definition Studies, Report submitted to Loral Integrated Navigation and Communication Satellite Services (LINCSS), Department of Geomatics Engineering, The University of Calgary.

Clyde, Edgar, et al. (1999), Cooperative Anomaly Resolution on PRN-19, Proceedings of ION GPS 1999, Nashville, Tennessee, September 14-27.

DeSalvo (1998), "SBIRS Low Industry Day Briefing", (slide presentation) U.S. Joint Spectrum Center, April 1998.

Ford, T. (1998), Lead Discussion on NovAtel's Narrow Corrleators, ENGO 625 Course seminar, Department of Geomatics Engineering, The University of Calgary.

Hebert, J. (1997), High Accuracy GPS Velocity Using the Carrier Phase Observable. Proceedings of KIS97, Department of Geomatics Engineering, The University of Calgary, Banff, June 3 – 6, pp. 265 – 269.

Hebert, J., J. Keith, S. Ryan, M. Szarmes, G. Lachapelle and M.E. Cannon (1997), DGPS Kinematic Carrier Phase Signal Simulation Analysis for Precise Aircraft Velocity Determination, Proceedings of the ION Annual Meeting, Albuquerque, NM, (July).

Hopfield, H.S. (1963), The Effect of Tropospheric Refraction on the Doppler Shift of Satellite Data, Journal of Geophysical Research, 68, 18, pp. 5157-5168.

Klobuchar, J. A. (1996), Ionospheric Effects on GPS, Global Positioning Systems: Theory and Applications, Vol I, ed. B.W. Parkinson and J.J. Spilker Jr., American Institute of Aeronautics and Astronautics, Washington DC, pp. 485-516.

Lachapelle, G. (1998), GPS Theory and Applications, ENGO 625 Course Lecture notes, Department of Geomatics Engineering, University of Calgary, Canada.

Lou, Ming et al. (2000), Interference to GPS from UWB transmitters, Proceedings of ION GPS 2000, Salt Lake, Utah, September 19 – 22, pp. 981 – 993.

Macabiau, Cristophe, Signal Quality Monitoring for Protection of GBAS Users Against Evil Waveforms, Proceedings of ION GPS 2000, Salt Lake City, Utah, September 19 – 22, In Press.

Moeglein, M. and N. Krasner (1998), An Introduction to SnapTrack Server-Aided GPS Technology, Proceedings of ION GPS 98, Nashville, Tennessee, September 15 – 18, pp. 333 – 342.

Owen J.I.R. (1993), A review of the Interference Resistance of SPS GPS receivers for aviation, Defense Research Agency, Farnborough, U.K., 1993.

Parkinson, B. and J. Spilker (1996), Editors, Global Positioning System,Vol. 1, American Institute of Aeronautics and Astronautics, Inc., Washington, DC, Chapter 3.

Peterson, B., D. Bruckner and S. Heye (1997), Measuring GPS Signals Indoors, Proceedings of ION GPS 97, Kansas City, Missouri, September 16 –19,pp. 615 – 624.

Rash, Gregory D., GPS jamming in a laboratory environment, Proceedings of the 53rd Annual Meeting, Institute of Navigation, June 30 – July 2, 1997

Ray, J. (2000), Mitigation of GPS Code and Carrier Phase Multipath Effects Using a Multi-antenna System, Ph.D. Thesis, UCGE Report 20136, Department of Geomatics Engineering, The University of Calgary, Alberta, Canada

Ryan, S., G. Lachapelle, and M.E. Cannon (1997) DGPS Kinematic Carrier Phase Simulation Analysis in the Measurement and Position Domain. Proceedings of ION GPS 97, Kansas City, Missouri, September 16-19, pp. 1035-1045.

Saastamoinen, J. (1972), Atmospheric Correction for the Troposphere and Stratosphere in Radio Ranging of Satellites, Geophysical Monograph 15, American Geophysical Union, Washington, DC.

Spilker, J. (1994), Global Positioning System,Vol. 1, ed. B. Parkinson and J. Spilker, American Institute of Aeronautics and Astronautics, Inc., Washington, DC, Chapter 13.

Townsend, B. and P. Fenton (1994), A Practical Approach to the Reduction of Pseudorange Multipath Errors in a L1 GPS Receiver, Proceedings of ION GPS-94, Salt Lake City, September 20-23, pp. 143-148.

van Dierendonck, A. J., P. Fenton, T. Ford (1992), Theory and Performance of Narrow Correlator Spacing in a GPS receiver, NAVIGATION: Journal of the Institute of Navigation, Vol 39. No 3, pp.265-283.

van Nee, R.D.J. (1995), Multipath and Multi-Transmitter Interference in Spread-Spectrum Communication and Navigation Systems, Delft University Press, Delft, The Netherlands, 208 pp.

Ward, P. W. (1996 a), Understanding GPS Principles and Applications, ed. Elliott D. Kaplan, Artech House Publishers, pp. 209-236.

Ward, P.W. (1996 b), GPS Receiver RF Interference Monitoring, Mitigation, and analysis Techniques, NAVIGATION, Journal of the Institute of Navigation, Vol. 41, No. 4, winter, 1994-95, pp. 367-391.

Winer B. et al (1996), "GPS receiver laboratory RFI tests", Proceedings of the National Technical Meeting, Institute of Navigation, January 22-24.