Review for Multipath Facts in the Realm of Weak GNSS Signal

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Abstract: One of the most significant problem pending to be mitigated for satellite navigation at indoor environments is the multipath errors. At indoor environments, weak GNSS signals should be acquired and tracked by the GPS receivers, this paper will give a review of the facts in multipath and its main influence in the GNSS navigation systems. Investigation in this field are not new, understanding and mitigating multipath effects on GPS receivers will lead to an important level where the system can be used within a desired tolerance reducing its errors due to more accurate positioning solution.

Keywords: multipath; multipath mitigation; indoor GNSS receivers; indoor environment

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1 Introduction

In wireless telecommunication multipath is the propagation phenomenon that results in radio signals reaching the receiving antenna by two or more paths, this effect can be triggered by causes such as atmospheric ducting, ionospheric reflection and refraction, refraction from terrestrial structures and/or objects. GNSS systems such as: GPS, GLONNAS, Compass and Galileo; allows everybody equipped with a receivers to determine their position (longitude, latitude and altitude), the GNSS system consist in the measuring of the propagation duration of the known coded signal from the emitter source (satellites) to the receiver, this delay measurement allows the calculation of the distance between the user and the satellite, when at least four signal's time of travel are calculated the positioning solution is obtained. Usually for GPS system, this signal travel around 20.200 km so when it arrive to earth these signals can be as weak as -150 dBw ~ -160 dBw in open sky, now when in different scenario such as urban areas or inside a building, buildings will attenuate more these signals, besides, in these scenarios one also need to deal with the presence of multipath.

That's why GNSS system can provided position solution in many but not all indoor locations due signal attenuation and signal reflection and/or fading as multipath. At indoors environments, the user may struggle to find a clear line of sight to just one satellite. Traditionally GNSS receivers were required to function in an open area with a clear view of the sky, but in new applications it is required to work in degraded signal environments[1], GPS signals in these difficult situations can contain serious multipath signals, which can degrade positioning accuracy significantly.

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In the case of multipath several investigation have been done in other to analyze, simulated and mitigated multipath components present in the received signal\cite{2-5}. The studies of multipath effects over navigation systems have been studied and the impacts of multipath error have been observed since the early 1970’s\cite{6}. For stationary users and base stations, antenna techniques are effective to stop most multipath signals before they enter the GPS receiver’s antenna.

It shows that in metropolitan areas, urban areas, multipath is highly present\cite{7-8} and moving users most have navigation solution in those environments as well. Therefore several investigations are aimed to mitigate multipath and provide high accuracy levels for indoor navigation solution.

Nowadays latest development has aim to the implementation of statistical process to overcome both problems, acquisition and tracking process for weak signals and mitigate the multipath component\cite{9-11} which is the big error source remaining for more accurate navigation solution.

2 Multipath

Multipath is defined as a reflected GPS satellite signal that arrives at a receiver by more than one path. Investigation of multipath effects on carrier phase GPS positioning are not new.

Fig. 1 shown the geometric relationship in multipath at a typical GPS station per Jonson (1995)

![Fig. 1 Geometric relationship in multipath at a typical GPS station](image)

Multipath radio signal travel more than one path via either reflection, diffraction, or scattering.

- Reflection occurs when an electromagnetic wave hits an object (such as the surface of the earth, a building, a car, etc.) whose dimensions are larger than the incoming signal’s wavelength.
- Diffraction occurs when the incoming signal bends upon interaction with an obstacle in its path.
- Scattering occurs when the incoming signal travels through a medium filled with objects which are small (such as leaves on a tree) compared with the signal wavelength.

Multipath can be classified into two different categories: diffuse and specular.

- Diffuse multipath is generated by diffuse scatterers and diffraction sources, thus the incoming signal is sent in many different directions’ is generally uncorrelated with time and noise-like in behavior [Braasch, 1996].
- Specular multipath is generated by reflection from smooth (relative to the signal wavelength) surfaces and results in discrete, coherent reflections; specular multipath is coherent and creates systematic errors in GPS observables.

Fig. 2 shows these two categories for multipath.

![Specular vs. diffuse reflection](image)

3 Multipath Characteristics

- Magnitude: the magnitude of multipath error is greater on pseudorange measurement than on carrier phase measurement. Pseudorange multipath is in the order of several tens meter, whereas carrier phase multipath is in the order of one to three centimeters. Lachapelle et al[1989] restates a maximum
error of 293 m for C/A code pseudorange and approximately 5 cm for the L1 carrier phase.

- Signal Strength: due to multipath reflected signal off the surface, the signal to noise ratio is generally lower than that of the line of sight. This characteristic is usually exploited in receivers to detect multipath rays.
- Repeatability: most important characteristic when considering a GNSS base station, multipath is highly repeatable its influences are the same when the satellite is in the same position during each orbital pass. This repeatability can be observed on consecutive days, this characteristic can be used to generate multipath corrections at GNSS base station sites.
- Satellite Elevation: multipath is caused by reflection off physical features, the effects can be related with satellite elevation because most obstruction exist at low elevation

### 4 Pseudorange Multipath

Multipath signals create a problem at the signal tracking level by changing the phase of the carrier and distorting the shape of the code correlation function, introducing error to phase and pseudorange measurements, respectively. Under severe conditions, multipath can cause receiver tracking loops to lose lock. The receiver must shift the local generated signal until it fully correlates the incoming signal; this operation is executed by the receiver delay lock loop (DLL). The DLL reach its maximum correlation during the tracking phase by using and early-late discriminator. However signal received from indirect path, with unknown time delays will compromise the DLL discriminator function, producing tracking errors.

The tracking loop response is a function of different fundamental parameters of the reflected signal(s):
- Amplitude (relative to the direct signal)
- Phase difference (again, relative to the direct signal)
- Phase rate (how quickly the relative phase changes with time)
- Delay (the additional path length traveled, relative to the direct signal)

Fig. 3 shows a correlation function with a perfect triangle with peak correlation achieved and also the opposite correlation with smaller peaks leading to a composite correlation function.

![Correlation functions with and without multipath](image)

The magnitude of the pseudorange error due to multipath is a combination of the path delay (offset between direct and multipath correlation functions) and multipath amplitude (height of the multipath correlation function relative to the direct). Fig. 4 shows the bounds of pseudorange multipath error, with the dashed and solid lines indicating error envelopes for two different multipath amplitudes. The upper trace is for constructive interference and the bottom trace is for destructive interference. As the relative phase between direct and indirect signals changes, the multipath error will oscillate between these bounds.

Fig. 4 assumes an \( \alpha = 0.5 \) (where \( \alpha = \frac{\text{Multipath amplitude}}{\text{Direct amplitude}} \)) and correlators spacing of 1.0, 0.5 and 0.1 chips and describes only short-delay multipath, where the indirect signal is delayed by less than 1.5 chips (for the C/A code, 1.5 microseconds or approximately 450 meters). Long-delay multipath (delay greater than 1.5 chips) will create enough separation between direct and multipath correlation functions so that the code
tracking loop rejects the multipath signal and therefore will not cause pseudorange errors [Misra and Enge, 2001]. Overall susceptibility to multipath can be reduced by using narrower correlator spacings [van Dierendonk et al., 1992] or tracking a signal with a higher chipping rate (for example, using the P-code over the C/A-code).

Fig. 4 Multipath error envelope for noncoherent early/late detector for C/A code

5 Carrier Phase Multipath

As with pseudorange multipath, carrier phase multipath occurs because the receiver tracks a composite signal which is the sum of the direct and one or more reflected signals. The carrier tracking loop is easily represented in terms of a phasor diagram. Fig. 5 shows the phase relationship between the in-phase and quadrature channels; the simple example presented here ignores the effects of code bit transitions [Betallie et al. 2003]. When no multipath is present, the carrier tracking loop measures the incoming signal’s phase based upon the position of the direct phasor. When multipath is introduced, the carrier tracking loop erroneously tracks the composite signal which is the vector sum of all phasors (direct plus reflected) and therefore reports an incorrect phase measurement.

The magnitude of the multipath phase error evolves over time as the relative phase between direct and reflected signals changes. In terms of the phasor diagram, changes in the relative phase cause the reflected phasor to spin around the end of the direct phasor. The phase errors then oscillate between an absolute maximum when the relative phase equals \(\text{asin}(\alpha)\) and a minimum when the direct and reflected signals are perfectly in-phase. From geometric relationships in this diagram, the theoretical maximum phase error would occur when the reflected signal amplitude is almost equal to the direct amplitude, yielding a phase error of approximately 1/4 of a cycle, about 4.8 cm for L1 phase.

Fig. 5 Phasor diagram for carrier tracking loop operation

6 GPS signal degradation

GPS signals in indoor environment can contain
serious multipath signals, which can degrade positioning accuracy significantly. Given multipath as the most severe error source, it is important to model and analyze it correctly. In order to deal with this situation a GPS signal channel must be analyzed as well as the signals classification.

First of all influence of Multipath on the receiver is characterized by the sum of delayed echoes of the emitted signal, hence the received signal could be written as follows

\[ S_r(t) = \sum_{m=0}^{N} a_m(t) p(t - \tau_m(t)) \sin \left( 2\pi f_p t + \varphi_m(t) \right) \]

where \( N \) is the number of reflected path, \( a_m \) the amplitude of path \( m \), \( \tau_m \) delay of path \( m \) and \( \varphi_m = 2\pi f_{dm} t - 2\pi f_p \tau_m \cdot f_{dm} \) is the Doppler shift of path \( m \).

The influence of multipath depends on their signal strength and delay compared to that of the line of sight signal, the delay loop makes a tracking error on direct path delay estimation called code offset.

For example Fig. 7 shows the different signal power according the level where the GPS signals arrive within a multilevel car parking lot.

![Fig. 7 Multilevel car park GPS signal degradation](image)

Degraded signals common operation problems

- GPS receiver sampling at the correlator output typically occurs at a sampling interval of 1 ms. In weak signals the SNR of these samples is too low to support LOCK-IN of Phase Locked Loop (PLL) or Frequency Locked Loop (FLL).

- SNR is too low to support the extraction of the 50 Hz BPS navigation message from the signal.

(Aiding data is therefore required from a external source)

- Because the data cannot be extracted, it is not possible for the receiver to synchronize with the incoming bits, words or subframes. (It is therefore not possible to construct pseudoranges without prior information).

In Ref. [1] to understand the effect of multipath on the code tracking, it is important to consider two situations

- The fading bandwidth \( B_F \) is larger than the tracking loop bandwidth \( B_L \): Fast Fading.
- The fading bandwidth \( B_F \) is smaller than the tracking loop bandwidth \( B_L \): Slow Fading.

6.1 Fast Fading

If \( B_F \) is large compared with the \( B_L \), all cross products are filtered out because of their high frequencies values.

\[ S_{nc}(\hat{\tau}_0) = \sum_{m=0}^{M} \left( a_m R(\hat{\tau}_0 - \tau_m + d/2) \right)^2 - \left( a_m R(\hat{\tau}_0 - \tau_m - d/2) \right)^2 \]

6.2 Slow Fading

If \( B_F \) is small compared with \( B_L \), then the averaging over \( T_0 \) seconds has no influence on the resulting multipath tracking errors.

\[ S_{nc}(\hat{\tau}) = \sum_{m=0}^{M} a_m R(\hat{\tau}_0 - \tau_m + d/2) e^{i\phi_m} - \sum_{m=0}^{M} a_m R(\hat{\tau}_0 - \tau_m - d/2) e^{i\phi_m} \]

This equation shows that the DLL tracking error induced by a given echo depends on three parameters:

- Relative amplitude: \( a_m / a_0 \)
- Relative delay: \( \tau_m - \tau_0 \)
- Relative phase: \( \phi_m - \phi_0 \)

7 Signal Classifications

Now with respect fading effects, GNSS signal can be divided in three categories:

- Clear Line of Sight (LOS): fading is only
due free space loss and atmosphere absorption.

- The fading distribution can be expressed by Ricean's probability density function
  \[ f_{\text{Ricean}}(v) = 2K_v \exp \left[ -\frac{K}{v^2 + 1} \right] I_0(2K_v) \]
- Shadowed Signal: propagation take place over the First Fresnel Zone (tree canopies).
  - For this signal classification Loo's probability density function can express the fading distribution
  \[ f_{\text{Loo}}(v) = \frac{2K_v}{\pi \sigma^2} \int_0^\infty \exp \left( \frac{(20\log(z) - m)^2}{2\sigma^2} - K(v^2 + z^2) \right) dz \]
- Blocked Signal: propagation path within the First Fresnel Zone is completely obstructed so signal reception is accomplished through diffraction and reflection (multipath).
  - For this signal classification Rayleigh's probability density function can carry the fading distribution
  \[ f_{\text{Rayleigh}}(v) = 2K_v \exp \left[ -Kv^2 \right] \]

The fading distribution can be expressed by Ricean probability density function

Now in order to deal with the presence of multipath in an indoor environment, where usually these three types of signal can be present, a useful statistic model is described\(^1\), this statistic distribution used to describe this type of fading is known as the Urban Three-State Fade Model, the composite amplitude probability density function is the combination of the above three pdfs:

\[ f(v, \alpha, \nu) = C(\alpha) f_{\text{Ricean}}(v) + S(\alpha) f_{\text{Loo}}(v) + B(\alpha) f_{\text{Rayleigh}}(v) \]

\[ C(\alpha) + S(\alpha) + B(\alpha) = 1 \]

where \( \alpha \) is the elevation and \( C(\alpha) \), \( S(\alpha) \) and \( B(\alpha) \) are weight coefficients.

Urban and indoor environment are compounded by multipath. Giving undesired effects such as:

- The reflected ray may destructively interfere with the direct ray and fade the composite signal power.
- The reflected ray may have approximately the same power as the direct ray and distort the correlation peak used by the receiver to make the GPS measurements.
- The reflected ray may be much stronger than the direct ray and cause the receiver to assume that the reflected ray is the direct ray. This last effect introduces the largest measurement errors.

There are several approaches to improve the system performance:

- Space based augmentations: completing the Galileo constellation by the GPS constellation.
- Add additional sensors at the user level: altimeter, dead reckoning.
- Use of differential correlations.
- Use of pseudolites.

That's why algorithm are the key, they must intelligent process GPS signals, integrate assisted data from various sources like Garnet, Cellular Networks and Altitude Data Bases.

### 8 Multipath Mitigation

Different mitigation techniques have been developed in order to mitigate the multipath; most of them were aim to work in open sky environments, where signal power is in decent levels for acquisition and tracking.

Site Selection: the simplest technique that can be taken to minimize the effect of multipath involves careful site location. In the establishment of GPS base stations, antenna site are generally selected on buildings which are clear of obstructions above 5 to 10 degrees elevation mask. Usually antennas should be raised as high as possible above the roof surface. In Ref. \([12]\) antennas at less than one meter above the roof surface the amount of multipath that can be observe is between 5 to 10 times bigger than in those antennas five meters above the roof surface.

Antenna Ground Plane: is a large metal disk
which is effective reducing multipath effects, provided for most manufactures with survey grade receivers been used in all application where feasible. Choke ring antenna ground planes are also available showing improvement over regular ground plane.

Narrow Correlator Spacing: receivers architecture using narrow correlator spacing successful reduce multipath effects in the GPS signals [Fenton et al., 1991], reducing also the pseudorange measurement noise, as a result, most receivers manufactures employ narrow correlator in modern receivers.

Multipath Estimating Delay Lock Loop (MEDLL): recently developments in GPS receiver technology involve the detection of a multipath effect signal within the receiver itself. Supported on the characteristic that reflected signals have weaker strengths and longer paths is used to isolate direct path measurements from reflected path measurements. Manufactures such a Novatel have introduced MEDLL in their receivers [ven Nee et at, 1994].

In order to deal with the new challenge of indoor, urban positioning solution, different approaches for mitigations techniques were adopted, there are more tendencies to reduce the error in short multipath, and strong multipath, where some times the reflected signal is stronger than the obstructed-blocked LOS, in Ref. [13] evaluate the performance in this scenario, showing that tracking error increase as the multipath time delay to direct path increase. However when the multipath time delay to direct path is bigger or equal to 1.3 chips, the error component no longer affect the regular discrimination function.

In Ref. [10] some mitigation techniques that relay in Maximum Likelihood such as: MEDLL, MMT(Multipath Mitigation Technique), VC (Vision Correlator) are describe in order to introduce FIMLA(Fast Iterative Maximum-Likelihood Algorithm) like the latest ML multipath mitigation approach.

Other methods of mitigation deal with the integration and frequency analysis, which are able to distinguish multipath at high resolution under low SNR, in Ref. [14] estimation of close-in multipath parameters of code carrier in low SNR environments were achieve, also in Ref.[15] same methodology is introduced where multipath error can be mitigated through frequency domain processing.

9 Conclusions

Multipath by far it has been especially challenging due its nature, remaining as the most significant obstacle to high-accuracy positioning applications, unfortunately there is not easy answer to solve GNSS multipath error due to the complexity and variation of indoor environments. Therefore additional researches are required to more thoroughly understand the effects of indoor propagation for GNSS signal.

It is difficult to completely remove multipath effects from range measurements, thus high precision and accuracy applications of GNSS may be severely degraded by reflected signals.

It should be noted that multipath is a dynamic and site-specific phenomenon. Multipath errors cannot be simply differenced away. Although not explicitly discussed in this paper, the geometric relationship between the receiving antenna, a reflecting object, and the satellite position will determine if any particular multipath ray is intercepted by the GNSS antenna and subsequently processed by the receiver. These factors, along with multipath amplitude and phase that change as the GNSS satellite moves, create systematic errors in GPS observables.

However with the increase of computer power new complex algorithms with computational intense requirements can be designs, in order to deal with the multipath effects on GNSS signals. It is show that reducing or eliminating the multipath effect will increase the accuracy and reliability of the system. The modern World doesn't work without GNSS. And
this is only the beginning. Nonetheless there is not yet a sufficient understanding of indoor multipath propagation to develop techniques suitable for the unique conditions encountered indoors.

References