Parameter Estimation for Multipath Error in GPS Dual Frequency Carrier Phase Measurements Using Unscented Kalman Filters

Eunsung Lee, Sebum Chun, Young Jae Lee*, Teasam Kang, Gyu-In Jee, and Jeongrae Kim

Abstract: This paper describes a multipath estimation method for Global Positioning System (GPS) dual frequency carrier phase measurements. Multipath is a major error source in high precision GPS applications, i.e., carrier phase measurements for precise positioning and attitude determinations. In order to estimate and remove multipath at carrier phase measurements, an array GPS antenna system has been used. The known geometry between the antennas is used to estimate multipath parameters. Dual frequency carrier phase measurements increase the redundancy of measurements, so it can reduce the number of antennas. The unscented Kalman filter (UKF) is recently applied to many areas to overcome some of the limitations of the extended Kalman filter (EKF) such as weakness to severe nonlinearity. This paper uses the UKF for estimating multipath parameters. A series of simulations were performed with GPS antenna arrays located on a straight line with one reflector. The geometry information of the antenna array reduces the number of estimated multipath parameters from four to three. Both the EKF and the UKF are used as estimation algorithms and the results of the EKF and the UKF are compared. When the initial parameters are far from true parameters, the UKF shows better performance than the EKF.

Keywords: Array antenna, carrier phase measurement, GPS, multipath error, unscented Kalman filter.

1. INTRODUCTION

Multipath means that one or more reflected signals reach the antenna in addition to the direct signal. Under particular circumstances only the reflected signal may reach the antenna. Multipath is the major error source in high precision Global Positioning System (GPS) static and kinematic positioning. This paper describes the development of a multipath mitigation method for GPS carrier phase measurements.

Most mitigation methods are very effective for the multipath of code measurements but, it is difficult for the carrier phase measurements. Various methods are supposed to mitigate the multipath of carrier phase measurements, but there are no distinguished methods. The multipath mitigation methods for GPS measurements are to be divided into three types. (1) Improving antenna gains, (2) New GPS receiver technology and (3) Post data processing.

(1) In order to improve antenna gain pattern, several methods exists. There is the usage of special antennas, spatial processing with multi-antenna arrays, proper antenna location strategies and long-term signal observation.
(2) A series of new GPS receiver technology help to mitigate the multipath effect. Narrow Correlator ™ has a 0.1 chip spacing and a larger bandwidth at the IF (Intermediate Frequency) and provides good long delay multipath mitigation [1]. MET™ (Multipath Elimination Technique) is an improvement of Narrow Correlator™ [2]. MEDLL™ (Multipath Estimation Delay Lock Loop) utilizes multiple narrow-spaced correlators to estimate the multipath and remove it from the correlation function to provide a more pure signal correlation function [3]. All the technologies can not be put together because the GPS receiver technologies

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belong to an independent GPS receiver's company and the hardware and software of GPS receivers cannot be changed by users.

(3) The post data processing includes the smoothing algorithm that combines GPS code measurements with carrier phase measurements to mitigate the multipath error in the code measurements [4]. Another method is using Signal-to-Noise Ratio (SNR) to correct the multipath error in differential phase measurements. This method involves the antenna gain pattern. Modeling reflector parameters of the multipath [5] with SNR is also used. Multiple references are used to estimate the multipath error of the code and carrier phase measurements [6].

With the known baseline length, the multipath effect can be estimated and can be divided into three types. The first one is to use the baseline-length constraint to reduce the search volume of GPS carrier phase integer ambiguities [6]. The second one is to simplify relative equations with the baseline geometry [7]. The last one is to reduce the number of the possible ambiguity solution candidates with the relationship of each ambiguity [8]. The first and second methods are usually used for attitude determination, while the third one is used for positioning. If the known baseline lengths are used, the minimum number of satellites should be three when conventional GPS receivers are used for attitude determination [3].

In order to estimate and remove the multipath in carrier phase measurements, a special array GPS antenna system has been proposed in this paper. The known geometry between the antennas is used to estimate multipath parameters. The array antenna system consists of 3 antennas and receivers which can receive dual frequency carrier phase measurements. All receivers are derived by common external clock. Dual frequency carrier phase measurements increase the redundancy of measurements so it can reduce the number of antennas. The extended Kalman filter (EKF) and the unscented Kalman filter (UKF) are used to estimate multipath parameters, and the results from two filters are compared. Recently developed the UKF overcomes some weak points of the EKF and improves the performance of estimating multipath parameters.

In the section "Carrier Phase Multipath Modeling," a brief review of carrier phase multipath modeling and the mathematical model of GPS are discussed. In the section "Array Antenna System," the method of reducing the multipath parameters is explained. In the section "Unscented Kalman Filter," the drawback of the EKF and the advantage of the UKF are represented. In the section "Simulation Results," the results of a simulation are explained. The final conclusions are summarized.

2. CARRIER PHASE MULTIPATH MODELING

Multipath is a phenomenon which affects most of the radio navigation systems and GPS is not an exception. Due to the reflection of nearby objects such as buildings, vehicles, the ground and water surfaces, the signal that is received by the a GPS antenna is composed of the line of sight signal directly from the satellite and signals reflected by nearby objects, called reflectors.

The magnitude and the phase of reflected signals depend on the surface property of the reflectors and on the geometry between the GPS satellite, receiver antenna and reflectors. Thus the multipath affects the carrier phase observation as well as environment conditions. After the GPS code signal has been removed in the phase-lock loop of GPS receivers, the GPS L1 signal can be reconstructed as follows:

$$S(t) = A_p \cos(\omega t + \Theta), \tag{1}$$

where A_p is the amplitude of a direct signal, ω is $2\pi f_1$, f_1 is the frequency of L1 carrier phase measurements, and Θ is the phase delay of a direct signal [9].

When the reflected signals are received by a GPS antenna together with the direct signal, the composite signal can be written as

$$S(t) = A_p \cos(\omega t + \Theta) + A_p \sum_{k=1}^{m} \alpha_k \cos(\omega t + \Theta + \gamma_k), \tag{2}$$

where α_k is the reflection ratio over the direct signal amplitude at k th reflected signal, k is a reflector index, γ_k is the phase delay of a reflect signal, and m is the total number of reflectors.

Equation (2) can be simplified as

$$S(t) = \beta A_p \cos(\omega t + \Theta + \Psi), \tag{3}$$

where β is the factor signal amplitude change, Ψ is the phase error due to multipath. β and Ψ can be written as

$$\beta = \sqrt{\left(1 + \sum_{k=1}^{m} \alpha_k \cos\gamma_k\right)^2 + \left(\sum_{k=1}^{m} \alpha_k \sin\gamma_k\right)^2},$$

$$\Psi = \arctan\left(\frac{\sum_{k=1}^{m} \alpha_k \sin\gamma_k}{1 + \sum_{k=1}^{m} \alpha_k \cos\gamma_k}\right).$$

The equation of GPS carrier phase measurements is described as follows:

$$\Phi^i_A = R^i_A + d_{ion} + d_{trop} + \lambda N^i_A + \delta^i + \delta_A + \frac{\lambda}{2\pi}\Psi^i_A + w^i_A, \tag{4}$$

where Φ^i_A is the carrier phase measurement, i is a satellite number (superscript), A is a receiver number (subscript), R^i_A is the true range from satellite i to receiver A, d_{ion} is a ionospheric error, d_{trop} is a tropospheric error, λ is a carrier phase wave length, N^i_A is a integer ambiguity, δ^i is a satellite clock error, δ_A is a receiver clock error, Ψ^i_A is phase error due to multipath, w^i_A is a measurements noise [10].

The phase error in (4) can be written for a single reflector case as

$$\Psi^i_A = \arctan\left(\frac{\alpha \sin\gamma^i_A}{1+\alpha\cos\gamma^i_A}\right), \tag{5}$$

where γ^i_A is the phase delay of a reflected signal also it can be written as $\gamma^i_A = \frac{2\pi a^i_A}{\lambda}$ and a^i_A is the distance delay of a reflected signal [11].

3. ARRAY ANTENNA SYSTEM

In order to estimate the multipath error parameters in carrier phase measurements, an array GPS antenna system is used. The known geometry between the antennas is the useful information to estimate the multipath error parameters. If the dual frequency receivers are used, the array antenna system, using 3 antennas with the same clock, helps estimate the multipath error parameters effectively. If the distance between antennas is a half wavelength and the antennas are located on a straight line, it is easy to fix the ambiguity integer, and the multipath error parameters of GPS carrier measurements can be estimated directly.

Let us assume two GPS antennas are fixed as Fig. 1. The distance between the antenna A and B is half of the GPS carrier phase signal wavelength. The differenced measurements equation between the antenna A and B is described as

$$\Phi^i_{AB} = \Phi^i_B - \Phi^i_A = \begin{pmatrix} R^i_B + d_{ion} + d_{trop} + \lambda N^i_B \\ +\delta^i + \delta_B + \frac{\lambda}{2\pi}\Psi^i_B + w^i_B \end{pmatrix} - \begin{pmatrix} R^i_A + d_{ion} + d_{trop} + \lambda N^i_A \\ +\delta^i + \delta_A + \frac{\lambda}{2\pi}\Psi^i_A + w^i_A \end{pmatrix}. \tag{6}$$

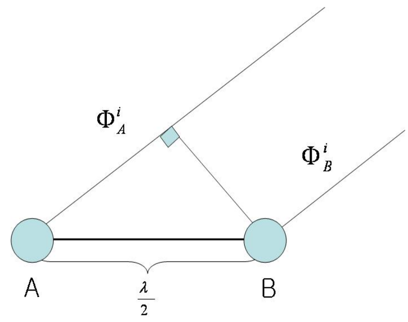

Fig. 1. Configuration of two antennas.

Since the distance between the two antennas is short, the common errors, i.e., ionospheric, tropospheric, satellite ephemeris and satellite clock, from the same satellite i can be cancelled out. Equation (6) can be rearranged as follows:

$$\Phi^i_{AB} = R^i_{AB} + \lambda N^i_{AB} + \delta_{AB} + \frac{\lambda}{2\pi}\Psi^i_{AB} + w^i_{AB}, \tag{7}$$

where R^i_{AB} is the difference of ranges, N^i_{AB} is the difference of integer ambiguities, δ_{AB} is the difference of receiver clock errors, Ψ^i_{AB} is the difference of phase errors, w^i_{AB} is the difference of measurements noises.

When the two GPS receivers are driven by a common external clock the term δ_{AB} can be zero. Equation (7) becomes

$$\Phi^i_{AB} = R^i_{AB} + \lambda N^i_{AB} + \frac{\lambda}{2\pi}\Psi^i_{AB} + w^i_{AB}, \tag{8}$$

where Ψ^i_{AB} is described as

$$\Psi^i_{AB} = \Psi^i_B - \Psi^i_A = \arctan\left(\frac{\alpha\sin\gamma^i_B - \alpha\sin\gamma^i_A + \alpha^2\sin\left(\gamma^i_B - \gamma^i_A\right)}{1+\alpha\cos\gamma^i_B - \alpha\cos\gamma^i_A + \alpha^2\cos\left(\gamma^i_B - \gamma^i_A\right)}\right). \tag{9}$$

Since the relative distance between the two antennas is constant, it is possible to calculate λN^i_{AB}. Equation (8) can be arranged as follows:

$$\left(\Phi^i_{AB}\right)_{MP} = \frac{\lambda}{2\pi}\Psi^i_{AB} + w^i_{AB}, \tag{10}$$

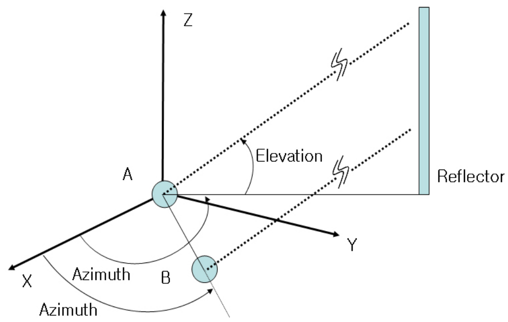

Fig. 2. Relationship of the phase delay at antennas A and B.

where $\left(\Phi_{AB}^i\right)_{MP}$ is $\Phi_{AB}^i - R_{AB}^i - \lambda N_{AB}^i$.

The left hand side of (10) is a known quantity while the right hand side is an unknown quantity or a quantity to be estimated. The subscript $(*)_{MP}$ means "Multipath".

The phase delay of the reflected signal at antenna A has a correction with the phase delay of the reflected signal at antenna B. Fig. 2 shows the relationship and it is described as

$$\gamma_B = \gamma_A + \frac{2\pi}{\lambda} d_{AB} \cos\left(\varphi_A - \phi_{AB}\right)\cos\theta_A, \qquad (11)$$

where γ_A is the phase delay of the reflected signal observed at antenna A, γ_B is the phase delay of the reflected signal observed at antenna B, d_{AB} is the distance between A and B, φ_A is the reflected signal azimuth, ϕ_{AB} is the azimuth of the vector AB, θ_A is the reflected signal elevation [9].

If an array antenna system is built with three antennas in a straight line as in Fig. 3, the phase delay relationship becomes

$$\gamma_B = \gamma_A + \frac{2\pi}{\lambda} d_{AB} \cos\left(\varphi_A - \phi_{AB}\right)\cos\theta_A, \qquad (12)$$

$$\gamma_C = \gamma_A + \frac{2\pi}{\lambda} d_{AC} \cos\left(\varphi_A - \phi_{AC}\right)\cos\theta_A. \qquad (13)$$

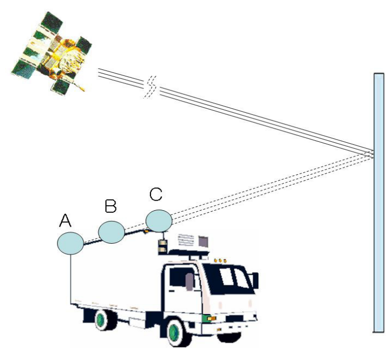

Fig. 3. Configuration of an array antenna system.

If three GPS antennas are fixed on the surface of the vehicle, then they have a relationship with a reflector as Fig. 3. Since the distances between each antennas are $\lambda/2$. Because of this constraint, $\phi_{AB} = \phi_{AC}$ is obtained. Equations (12) and (13) can be rewritten as follows:

$$\gamma_B = \gamma_A + \frac{2\pi}{\lambda} d_{AB} K, \qquad (14)$$

$$\gamma_C = \gamma_A + \frac{2\pi}{\lambda} d_{AC} K, \qquad (15)$$

where K is $\cos\left(\varphi_A - \phi_{AB}\right)\cos\theta_A$.

Like (10), the differenced equation between antenna B and antenna C is described as

$$\left(\Phi_{BC}^i\right)_{MP} = \frac{\lambda}{2\pi}\Psi_{BC}^i + w_{BC}^i, \qquad (16)$$

where

$$\Psi_{BC}^i = \Psi_C^i - \Psi_B^i = \arctan\left(\frac{\alpha\sin\gamma_C^i - \alpha\sin\gamma_B^i + \alpha^2\sin\left(\gamma_C^i - \gamma_B^i\right)}{1 + \alpha\cos\gamma_C^i - \alpha\cos\gamma_B^i + \alpha^2\cos\left(\gamma_C^i - \gamma_B^i\right)}\right).$$

Since all three antennas are separated with equal distance and since they are on a straight line, the phase delay equations become

$$\gamma_B^i = \gamma_A^i + S^i, \qquad (17)$$

$$\gamma_C^i = \gamma_A^i + S^i \times 2, \qquad (18)$$

where $S^i = \gamma_B^i - \gamma_A^i = \frac{2\pi}{\lambda}\left\{a_B^i - a_A^i\right\} = \frac{2\pi}{\lambda} d_{AB} K$.

The multipath parameters are $\alpha, \gamma_A, \theta_A$, and φ_A [9], but only three parameters α, γ_A, and S are required to estimate multipath. The multipath parameters θ_A and φ_A are replaced by S in this paper. The geometric information of the antenna array reduces the number of estimated multipath parameters reduced. If there is no geometric information, the four parameters have to be estimated. However in this paper the three parameters have to be estimated by using the geometric information.

When the single frequency carrier phase measurements are used, at least four antennas are needed to estimate the multipath error parameters [11]. When the dual frequency carrier phase measurements are used the number of antennas can be reduced. L1 frequency carrier phase measurements and L2 frequency carrier phase measurements have a

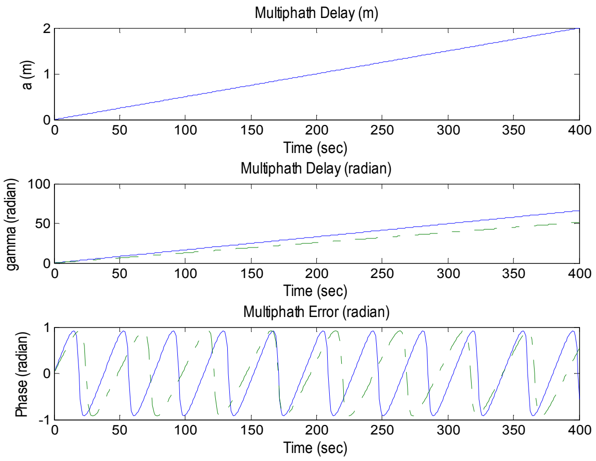

Fig. 4. Multipath errors on carrier phase measurement at antenna *A*.

relationship like Fig. 4. In Fig. 4 the solid line shows L1 carrier phase measurements errors and the dashed line shows L2 carrier phase measurements errors.

If the dual frequency carrier phase measurements are used, $\left(\Phi^i_{AB}\right)_{MP,L1}$, $\left(\Phi^i_{BC}\right)_{MP,L1}$, $\left(\Phi^i_{AB}\right)_{MP,L2}$, and $\left(\Phi^i_{BC}\right)_{MP,L2}$ can be obtained for each satellite. Subscript, $L1$ and $L2$ represent L1 and L2 frequencies.

The multipath parameters also have the relationships as follow:

$$S^i_{L2} = \frac{\lambda_{L1}}{\lambda_{L2}} S^i_{L1}, \quad \gamma^i_{A,L2} = \frac{\lambda_{L1}}{\lambda_{L2}} \gamma^i_{A,L1}, \tag{19}$$

where the subscript $L1$ stands for L1 carrier phase measurements, the subscript $L2$ stands for L1 carrier phase measurements.

4. UNSCENTED KALMAN FILTER

For multipath mitigation, the EKF has been a popular estimator, which uses a combination of the available information from an array antenna system to estimate various multipath parameters [11]. Although the EKF inherits the fancy feature of a linear Kalman filter under process and measurement noises, the EKF has several drawbacks due to its linearization scheme. When estimation intervals are not sufficiently small, linearization process may degrade the filter performance. The derivations of the Jacobian matrices are nontrivial in most applications and often lead to significant implementation difficulties. On the other hand, sufficiently small time step intervals usually lead to high computational overhead as the number of calculations for generating state estimates and covariance become large.

To overcome the weak points of the EKF, the UKF has been recently developed as a state estimator. When a fixed number of parameters are used, it is easier to approximate a Gaussian distribution than an arbitrary nonlinear function. The UKF uses a parameterization, which captures the mean and covariance information while permitting the direct propagation of the information through an arbitrary set of nonlinear equations. It will be shown that this can be accomplished by generating a distribution from the minimum number of points which have the same first and second moments, where each point in the discrete approximation can be directly transformed. The mean and covariance of the transformed ensemble can be computed as the estimate of a nonlinear transformation of the original distribution. On the other hand, the EKF uses linearized system dynamic equations for the state propagation. The UKF does not use the crude linearized scheme in the prediction procedure. The UKF employs the equivalent formation of filtering procedure to the EKF [12]. Fig. 5 shows the concept of the unscented transform of the UKF.

Generally, it is easier to estimate its statistical value like mean or variance than its realized value. By this reason, unscented transformation is proposed. Unscented transformation is the method to perform nonlinear transformation on the assumption that the transformed variable has a Gaussian probability distribution.

Unscented transformation has characteristics as follows:

- Standard implementation is available because it uses limited sigma points.
- It has an equivalent calculation amount with a linearized transformation, which is used in the extended Kalman filter if two filters have the same nonlinear function.
- Unscented transformations do not need to differentiate nonlinear equations for linearization.
- Unscented transformations can be applied into discontinuity functions.

The Kalman filter, which exchanges nonlinear transformations to unscented transformations, is the UKF. Construction of the UKF is as follow.

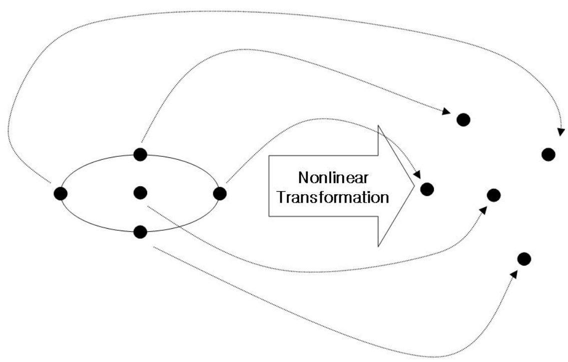

Fig. 5. Unscented transform.

4.1. Initial condition and sigma point

Equation (20) is an augmented state vector of the UKF and (21) is its sigma point matrix.

$$\begin{aligned}\hat{x}_0 &= E[x_0],\\ P_0 &= E\left[(x_0-\hat{x}_0)(x_0-\hat{x}_0)^T\right],\\ \hat{x}_0^a &= E\left[x^a\right]=\left[\hat{x}_0^T \quad 0 \quad 0\right]^T,\\ P_0^a &= E\left[\left(x_0^a-\hat{x}_0^a\right)\left(x_0^a-\hat{x}_0^a\right)^T\right]\\ &=\begin{bmatrix} P_0 & & \\ & Q & \\ & & R\end{bmatrix},\end{aligned} \tag{20}$$

$$\chi_{k-1}^a=\left[\hat{x}_{k-1}^a \quad \hat{x}_{k-1}^a \pm \sqrt{(L+\lambda)P_{k-1}^a}\right], \tag{21}$$

where x is the state vector, P is the covariance of the state vector, x^a is the mean of the augmented state vector, P^a is the covariance of the augmented state vector, Q is the covariance matrix of the process noise, R is the covariance matrix of the measurement noise, χ_{k-1}^a is a sigma point matrix, L is the dimension of the state vector, λ is the sigma point scaling parameter.

4.2. Time propagation

Equation (22) is a time propagation procedure using sigma points generated from the previous step.

$$\begin{aligned}\chi_{k|k-1}^x &= f\left(\chi_{k-1}^x,\chi_{k-1}^v\right),\\ \hat{x}_k^- &= \sum_{i=0}^{2L} W_i^{(m)}\chi_{i,k|k-1}^x,\\ P_k^- &= \sum_{i=0}^{2L} W_i^{(c)}\left[\left(\chi_{i,k|k-1}^x-\hat{x}_k^-\right)\left(\chi_{i,k|k-1}^x-\hat{x}_k^-\right)^T\right],\\ Y_{k|k-1} &= h\left(\chi_{k|k-1}^x,\chi_{k|k-1}^n\right),\\ \hat{y}_k^- &= \sum_{i=0}^{2L} W_i^{(m)}Y_{i,k|k-1},\end{aligned} \tag{22}$$

where $x_k=f(x_{k-1},v_{k-1})$ expresses system models, $y_k=h(x_k,n_k)$ expresses measurement models, $W_i^{(m)}$ is a weight for the mean, $W_i^{(c)}$ is a weight for the covariance.

4.3. Measurement update

Equation (23) is the measurement update procedure. It uses sigma points which propagated from the previous step.

$$\begin{aligned}P_{\bar{y}_k,\bar{y}_k} &= \sum_{i=0}^{2L} W_i^{(c)}\left[Y_{i,k|k-1}-\hat{y}_k^-\right]\left[Y_{i,k|k-1}-\hat{y}_k^-\right]^T,\\ P_{x_k,y_k} &= \sum_{i=0}^{2L} W_i^{(c)}\left[\chi_{i,k|k-1}-\hat{x}_k^-\right]\left[Y_{i,k|k-1}-\hat{y}_k^-\right]^T,\\ \kappa &= P_{x_k,y_k}P_{\bar{y}_k,\bar{y}_k}^{-1},\\ \hat{x}_k &= \hat{x}_k^- + \kappa\left(y_k-\hat{y}_k^-\right),\\ P_k &= P_k^- - \kappa P_{\bar{y}_k,\bar{y}_k}\kappa^T.\end{aligned} \tag{23}$$

5. SIMULATION RESULTS

Numerically simulated data with time variant parameters have been used to test the performance of the proposed method. The following figures show the circumstance of the experiment. Figs. 6 and 7 show the number of visible satellites and PDOP. In this case, the number of observable satellites must be more than four or five. In this case the visible satellite number is 8. The PDOP is about 1.72.

This simulation supposes that the signal of satellite 1 is contaminated by the multipath with the time variant parameters. Assuming the GPS array antenna system is fixed on the floor of the top of the car as in Fig. 3, Fig. 8 shows the single difference multipath

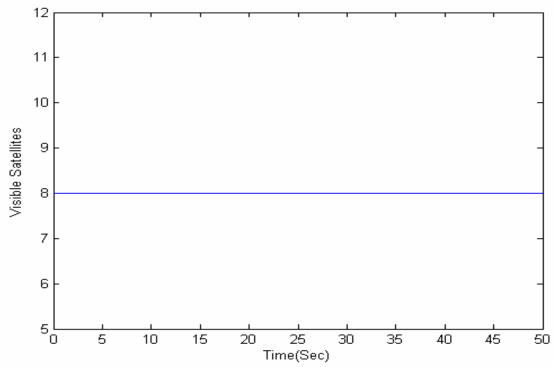

Fig. 6. Number of visible satellites.

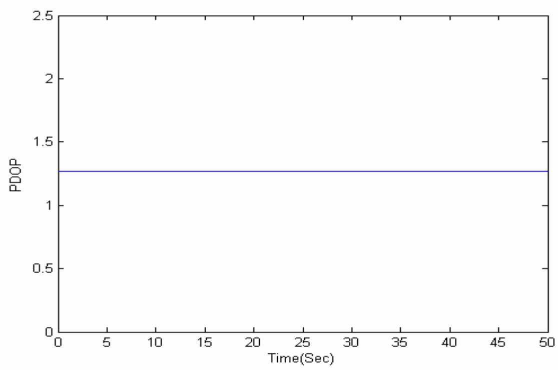

Fig. 7. Position DOP.

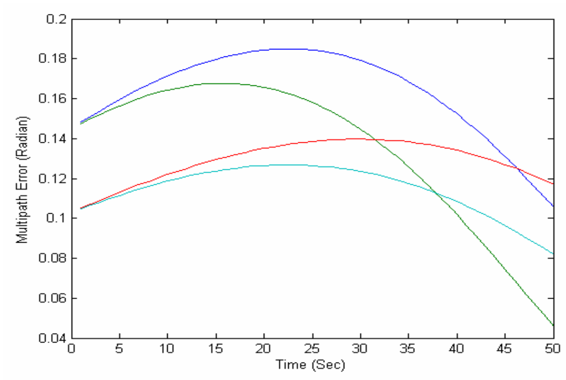

Fig. 8. Single difference multipath errors.

Table 1. Initial parameters.

Initial Parameters	Given	True
α_{L1}	0.3000	0.8000
α_{L2}	0.2000	0.7000
$\gamma_{A,L1}$	0.0331	0.0331
S_{L1}	0.1687	0.1687

errors. Because the three antennas exist, four single difference multipath errors are obtained. Table 1 expresses the initial parameters which are the input to the EKF and the UKF. Two of those parameters are far from true initial parameters.

Figs. 9 through 12 show the results of the EKF. The solid lines are estimates and the stars are the true parameters. Figs. 9 and 10 show the estimated reflection ratios (α) of the L1 and L2 carrier phase measurements respectively. Fig. 11 shows the estimated phase delay ($\gamma_{A,L1}$). Fig. 12 shows the estimated S_{L1}. The results of the EKF show that the EKF does not work properly for estimating the parameters and that the parameters are divergent. On the other hand, Figs. 13 to 17 show the results of the UKF. Figs. 13 and 14 show the estimated reflection ratios of L1 and L2 carrier phase measurements respectively. Fig. 15 shows the estimated phase delay. Fig. 16 shows the estimated S_{L1}. The results show that the UKF works well and the estimated multipath parameters follow the true parameter correctly. According to those results, the convergent time is less than about 25sec.

6. CONCLUSIONS

Multipath is the major error source in high precision GPS applications, i.e. multipath accounts for most of the total error budget especially in carrier phase measurements. This paper describes the procedure to estimate the multipath of GPS carrier measurements. An array antenna system with antennas

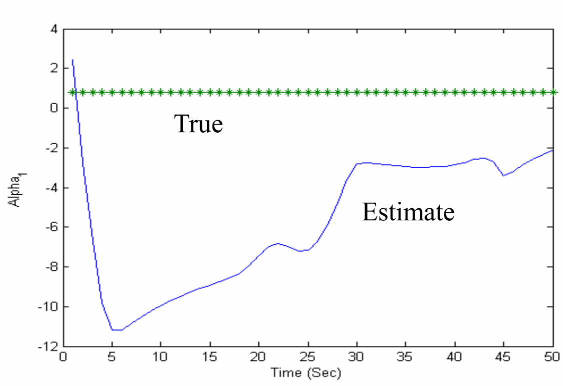

Fig. 9. Multipath parameter α_{L1} (EKF).

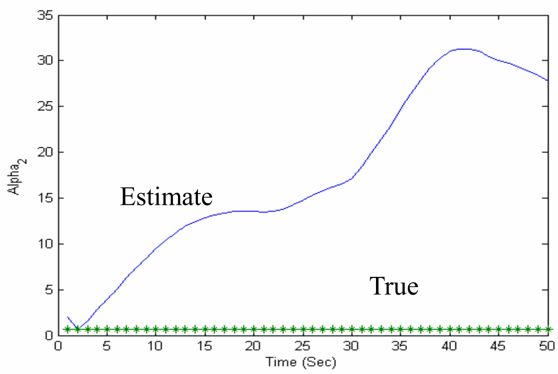

Fig. 10. Multipath parameter α_{L2} (EKF).

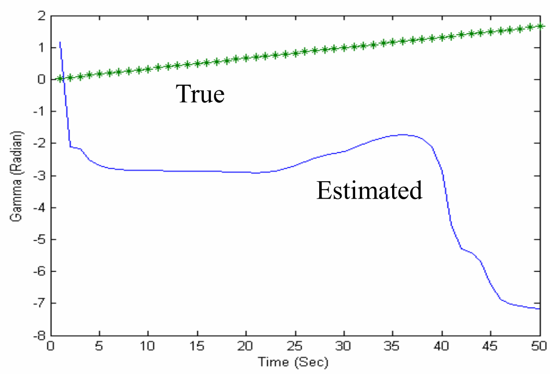

Fig. 11. Multipath parameter $\gamma_{A,L1}$ (EKF).

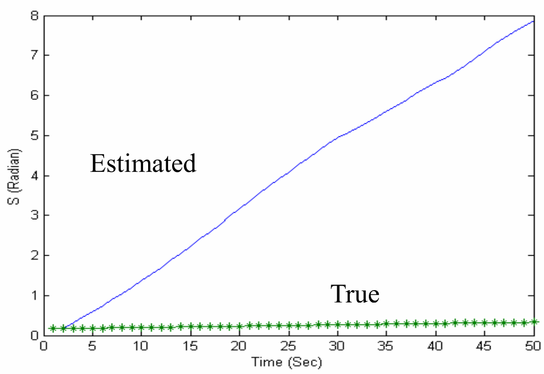

Fig. 12. Multipath parameter S_{L1} (EKF).

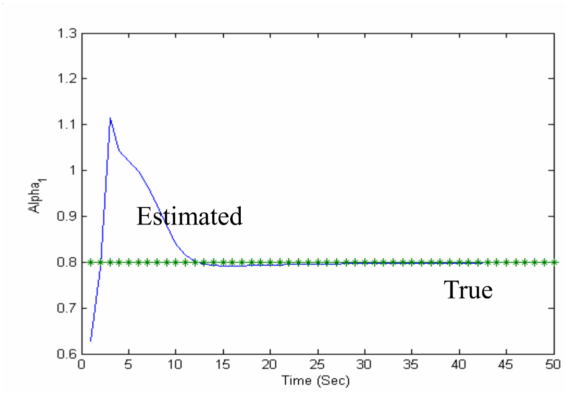

Fig. 13. Multipath parameter α_{L1} (UKF).

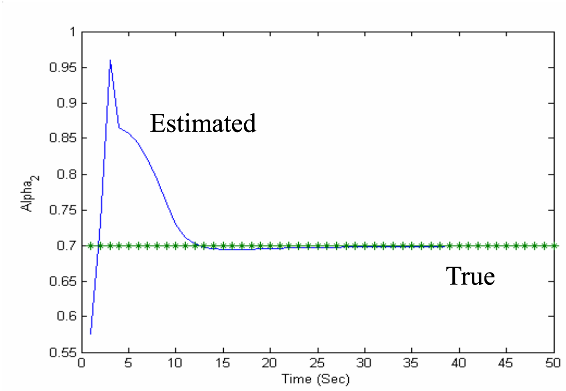

Fig. 14. Multipath parameter α_{L2} (UKF).

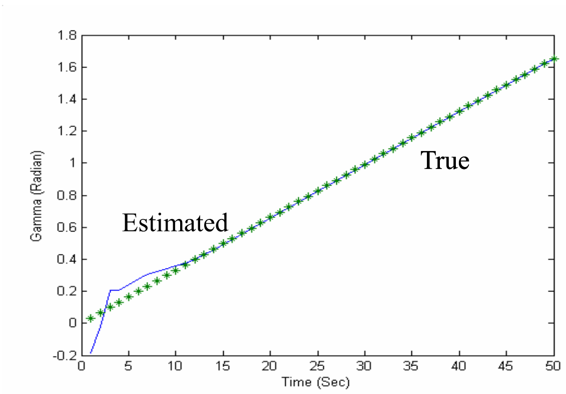

Fig. 15. Multipath parameter $\gamma_{A,L1}$ (UKF).

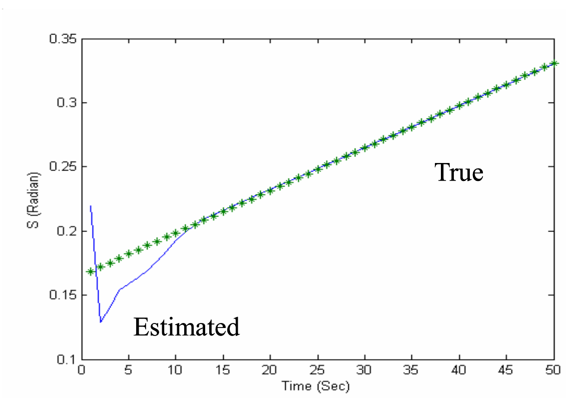

Fig. 16. Multipath parameter S_{L1} (UKF).

was used with a common external clock. Dual frequency carrier phase measurements increase the redundancy of measurements so it can reduce the number of antennas. In this paper, the EKF and the UKF are used to estimate multipath parameters and the results by the two filters are compared. Using numerical simulation data, it has been shown that the proposed method can estimate the multipath parameters in GPS carrier phase measurements effectively and the UKF shows an advantage over the EKF. This proposed algorithm can be used for real time precise positioning as well as attitude determination using GPS carrier phase measurements.

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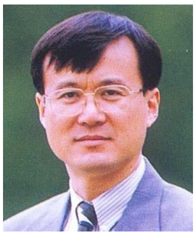

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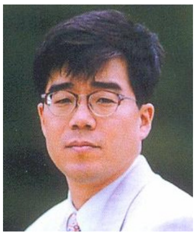

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