A Development of WAAS-Aided Flight Inspection Truth System

Euiho Kim, Uri Peled, Todd Walter, J.D Powell, *Stanford University*

***Abstract*— The FAA currently uses its Automated Flight Inspection System (AFIS) to check the accuracy of Instrument Landing Systems (ILS) and other navaids. It is desirable to measure the deviations of the ILS to within 0.015 degree accuracy. Therefore, a flight inspection system requires a high level of accuracy in determining position which is computed by a Flight Inspection Truth System (FITS). The AFIS has a navigation grade inertial navigation system (INS), a barometric altimeter, a radar altimeter, GPS, and a TeleVision Positioning System (TVPS). The AFIS is self-contained in that it does not require any facilities on the ground. The primary sensor in the AFIS is the INS whose error characteristics are limited by drifts. These drifts are measured by using a TVPS and a radar altimeter, and then the measurements from each sensor are fused with proprietary filtering techniques to result in the best possible accuracy in position. The error characteristics of the navigation grade INS causes the position computed from the current AFIS to have errors at distances far from the runway that are larger than desirable. This paper discusses techniques that will improve the accuracy and allow for better efficiency in the flight inspection procedures.**

The FAA has recently commissioned the Wide Area Augmentation System (WAAS), which provides corrections to GPS through a network of 25 reference stations throughout the U.S. WAAS accuracy (95%) over the U.S. is better than 1 meter in horizontal and 2 meters in vertical. The current standalone WAAS does not meet the ILS calibration accuracy requirements by itself, but WAAS can be used as a complementary sensor to the INS and radar altimeter for the flight inspection system because the position error in WAAS for the duration of an approach is approximately constant. This research focuses on the developments of the enhanced flight inspection system aided by WAAS, which does not require significant changes in the current AFIS. It has been found that the fusion of WAAS, radar altimeter, and INS makes it possible to obtain the required position accuracy. Another advantage is that an inspecting aircraft no longer has to fly over both ends of the runway in order to calibrate the INS drifts. The TVPS may also be eliminated for the inspection of CAT1 or CAT2 ILS. Preliminary results using the data from flight tests assure the WAAS-aided flight inspection system provides drift-free accurate positions.

I. Introduction

The Instrument Landing System (ILS) has been a primary landing guidance from early 20th century in U.S and is expected to serve additional at least 20 or more years. The ILS consists of consist of a localizer, a glide-slope, and marker beacons. A localizer and a glide-slope provide horizontal and vertical guidance to an approaching airplane to a runway. Marker beacons provide an indication to pilots of their progress on the glide path [1]. Because the ILS is the sole source of guidance to the runway, the role of the ILS is particularly important during bad weather, called Instrument Meteorological Conditions (IMC). Therefore, it is critical that the ILS must provide accurate guidance. However, because of its sensitivity to the environment, the accuracy of the ILS often degrades owing to environmental changes [1]. As a result, the ILS must be regularly checked and calibrated to adjust to the new environment and provide accurate guidance.

The calibration of the ILS is done by a flight inspection. During a flight inspection, an aircraft approaches the runway following the ILS guidance with a system that can accurately determine its true position. The system is called the Flight Inspection Truth System (FITS). From the estimated position from the FITS and the measured path from the ILS, the error of the ILS is determined. Therefore, the FITS must have enough accuracy to correctly fix the degradation of the ILS. The Federal Aviation Administration (FAA) currently uses the Automated Flight Inspection System (AFIS), whose FITS consists of a high quality inertial navigation system (INS), a barometric altimeter, a radar altimeter, and a TeleVision Positioning System (TVPS). The AFIS has these sensors on board and outputs the flight trajectory without any help from ground facilities, which is the major advantage of this system. However, a limiting factor of the AFIS is the high cost due to the navigation grade INS. Furthermore, the navigation grade INS yields large drifts far from the runway such that accuracy requirements for the ILS calibration cannot be met in those far away areas.

Another widely used flight inspection system is the Differential GPS Flight Inspection System (DGPS FIS), which uses a differential GPS as its truth system. This truth system usually provides a centimeter level of accuracy without any drifts. However, it requires a cumbersome and time-consuming procedure to set up a local reference station for each flight test. Because the FAA needs to cover several airports during one day, the FAA cannot afford this large set-up time. Therefore, the DGPS FIS is not widely used by the FAA.

The FAA has commissioned the Wide Area Augmentation System (WAAS) in 2003, which provides corrections to GPS through a network of 25 reference stations throughout the U.S as shown in figure 1. Due to the real-time correction, WAAS accuracy (95%) over the U.S. is close to 3ft in horizontal and 6 ft in vertical [2]. The WAAS is one of the Space-Based Augmentation Systems (SBAS) which includes EGNOS in Europe and MSAS in Japan. Besides, India and South Korea have recently decided to build their own SBAS. These systems have not been completed but are expected to have similar or better performance than the WAAS.

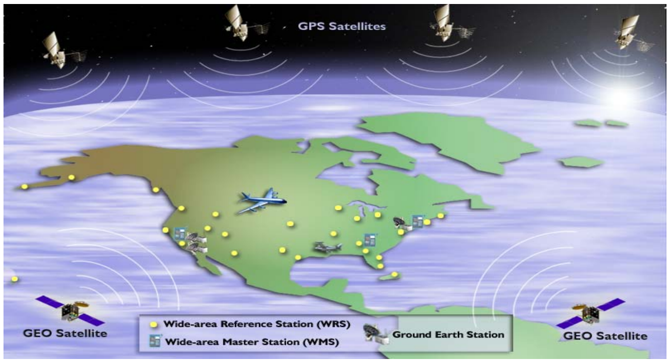

Fig. 1. Wide Area Augmentation System (courtesy of FAA)

The current standalone WAAS does not meet the ILS calibration accuracy requirements by itself, but the WAAS position can be improved by using complementary sensors such as the INS and radar altimeter. In this paper, we introduce a new design of a Flight Inspection Truth System (FITS), the WAAS-Aided FITS, which uses the WAAS as a primary sensor. This system is very similar to the AFIS, but it can use a low grade INS (tactical or less) and an airborne WAAS receiver. The WAAS-Aided FITS not only offers better performance and cheaper cost than the AFIS by fusing a tactical or lower grade INS but also allows a simpler inspection procedure since an airplane no longer has to fly level over the runway.

This paper begins by reviewing the AFIS focusing on how positions are computed in the system. Then, discussing airborne WAAS error characteristics, we describe the fusion algorithm of the WAAS and an INS and true trajectory estimation process in the WAAS-Aided FITS. Next, the test results of this algorithm with flight tests using a navigation grade INS and with simulated flight tests using a lower grade INS will be shown. Lastly, a conclusion will be followed.

II. Automated Flight Inspection System (AFIS)

The current flight inspection truth system used by the FAA is called the Automatic Flight Inspection System (AFIS). It consists of a navigation grade inertial navigation system (INS), a radar altimeter, a television positioning system (TVPS), a pilot event button and a barometric altimeter. The AFIS is a self-contained system that does not require any ground facilities to determine the trajectory of a flight path. This self-contained system makes it possible to finish flight inspection quickly and efficiently, saving considerable time in setting up and communicating with ground facilities. Due to this advantage and its high level of accuracy, the AFIS has been chosen as the main flight inspection system in U.S.

The primary sensor of the system is the INS. The barometric altimeter is coupled with the INS so that INS measurements are stable in vertical. The other sensors are used to estimate the accelerometer bias and gyro bias in the INS. Figure 2 shows the overall procedure in determining the position of an approaching airplane.

The green line in figure 2 is the typical flight path for flight inspection. Here, the FAA airplane equipped with the AFIS approaches the runway following the guidance of ILS and flies level over the runway. For the entire flight path, the INS coupled with the barometric altimeter measures the trajectory. While the airplane flies level over the runway, the radar altimeter measures the vertical distance of the airplane from the runway. The TVPS in turn measures cross-track deviations from the center line of the runway. The accuracies (95%) of the radar altimeter and the TVPS are about 30cm and 60cm respectively. Since the radar altimeter and the TVPS can only measure relative distances, the coordinates of the runways are surveyed. A pilot event button is used to measure when the airplane passes the thresholds at both ends of the runway. In this way, the position of the airplane can be accurately estimated. This accurately estimated position over the runway is used to determine the biases of the accelerometer and the gyro of the INS through a Kalman filter. Then, the final position is estimated by filtering the measurements from the INS with the determined biases on the runway in reverse time.

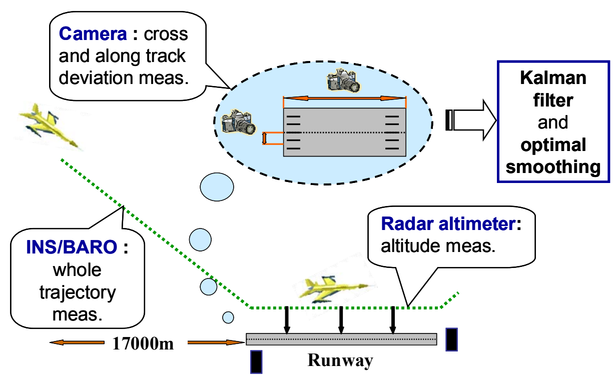

Fig. 2. Position estimation procedure in AFIS

The overall performance of the AFIS highly depends on the quality of the INS. Therefore, this system requires a high grade of INS in order to meet the accuracy requirements for the flight inspection. This constraint makes the AFIS very expensive. However, even though a navigation grade INS is used, the estimated trajectory computed from the AFIS often suffers from a large drift when the trajectory is far from the runway.

III. The WAAS and ILS Calibration Accuracy Requirements

A. WAAS Accuracy and ILS Calibration Accuracy Requirements

The WAAS accuracy (95%) is summarized in Table I[2]. These observations were taken during the period from Oct 1,2005 to Dec 31, 2005 by the FAA.

TABLE I

WAAS 95% Accuracy

Parameter	Site/Maximum	Site/Minimum
Horizontal	Washington DC 1.694 meters	Greenwood 0.788 meters
Vertical	Oakland 2.307 meters	Greenwood and Chicago 1.116 meters

Figure 3 and 4 compares the WAAS accuracy and the ILS calibration accuracy requirements in vertical and horizontal. For this comparison, the WAAS accuracy is assumed to be 3ft in horizontal and 6ft in vertical.

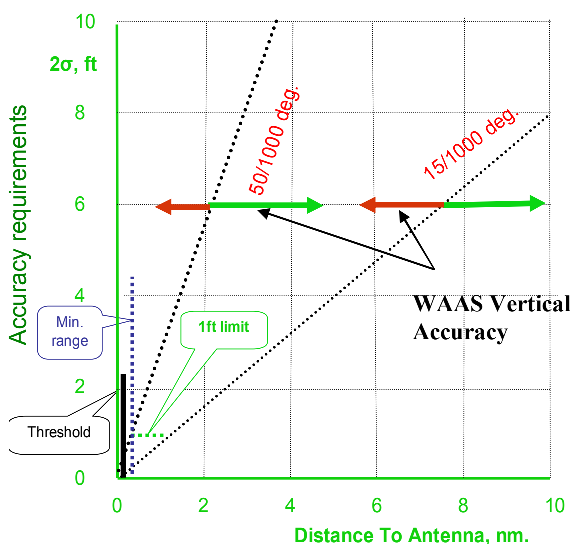

Fig. 3. Comparison of WAAS accuracy and ILS calibration accuracy requirements in vertical

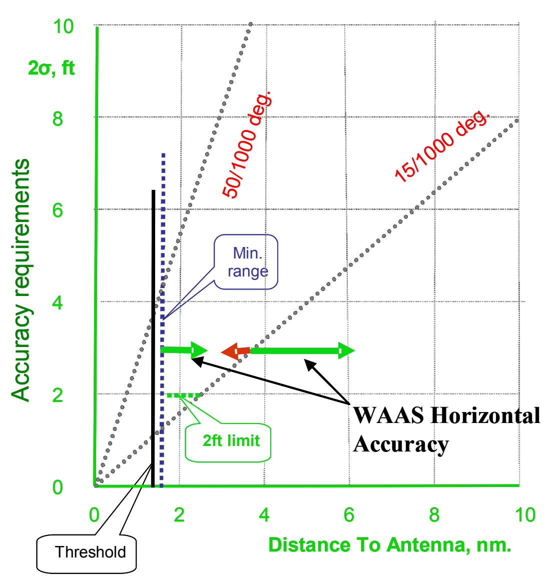

Fig. 4. Comparison of WAAS accuracy and ILS calibration accuracy requirements in horizontal

The 0.05 deg. line is the minimum acceptable accuracy requirement, and the 0.015 deg. is the desired accuracy requirement. The two accuracy requirements are limited to 1ft and 2ft in vertical and horizontal respectively. These two figures indicate that the WAAS accuracy [2] cannot meet the minimum ILS calibration accuracy requirements within 2nm of the runway. Therefore, in order to meet the requirements, it is necessary to improve the WAAS positions with other sensors and an appropriate filter. The section below discusses the error characteristics of the WAAS, which implies how the WAAS position can be improved by using other sensors.

B. WAAS Airborne Error Characteristics

Figure 5 shows the WAAS position errors obtained from flight tests taken on Apr 4, 2005. From figure 5, the WAAS error characteristics can be described as the sum of a bias and an additive noise for short periods. However, the bias could jump if a satellite constellation changes and a new WAAS ionosphere correction message comes. The noise is contributed by many factors such as multipath, thermal noise, interference, tropospheric model residuals, and WAAS correction residuals [3].

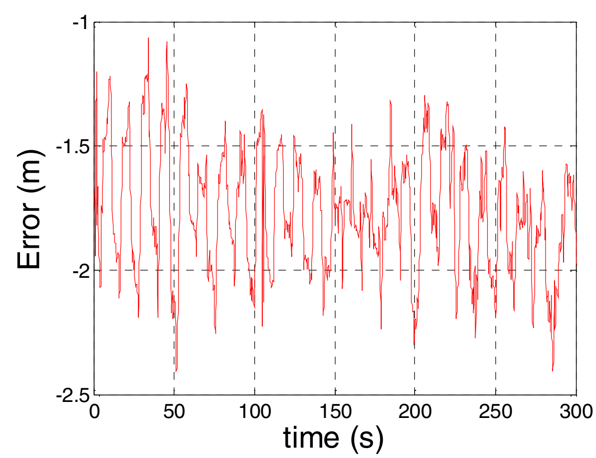

Fig. 5. WAAS airborne position error

Figure 6 shows the spectrum of the noise obtained from subtracting the mean of the error in figure 5. It is interesting to see the distinct peak in the noise. The period of the peak is 12 seconds, and this pattern of noise is clearly shown in figure 5. This cyclic noise is caused by WAAS fast correction messages Type 2-5, whose update rate is 6 seconds [4]. One example of the fast correction messages is shown in figure 7. The amplitude of the cyclic noise varies with time and is usually over 0.5 meters which is close to the ILS calibration accuracy requirements in vertical.

The bias of the WAAS error indicates that WAAS position can be significantly improved if the bias can be properly estimated with the cyclic noise. The next section discusses how the bias can be accurately estimated by using a radar altimeter and an INS in the WAAS-Aided flight inspection truth system.

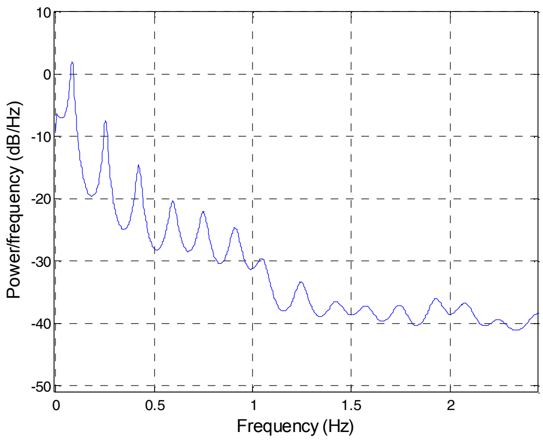

Fig. 6. Spectrum of WAAS airborne noise

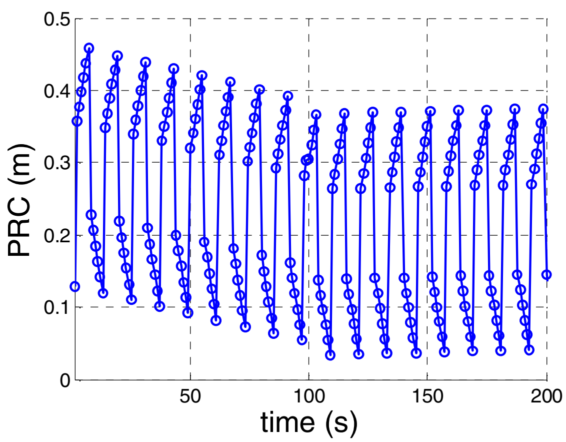

Fig. 7. WAAS fast correction messages

IV. WAAS-AIDED FLIGHT INSPECTION TRUTH SYSTEM

The WAAS-Aided flight inspection truth system (FITS) is designed for better performance as well as lower cost than the AFIS. Besides that, since this system does not require any significant changes to either the AFIS or the avionics, the AFIS can be easily upgraded to the WAAS-Aided FITS. The WAAS-Aided FITS consists of an INS, a radar altimeter, a TVPS, and an airborne WAAS receiver. Even though this system is quite similar to the AFIS, the grade and the function of the INS are quite different from the AFIS. The main function of the INS is to remove the cyclic noises of the WAAS which is the primary sensor in this system. Therefore, since the INS is mainly used to filter out the cyclic noise of the WAAS, an expensive INS is no longer required. The radar altimeter and the TVPS estimate the bias in the cyclic noise-removed WAAS measurements. Figure 8 shows the overall algorithms of the WAAS-Aided FITS. The details of the algorithms are discussed in this section.

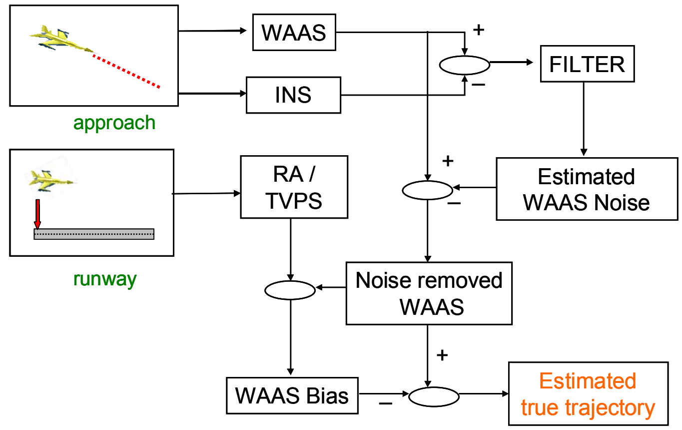

Fig. 8. Algorithm of WAAS-Aided FITS

A. *WAAS Cyclic Noise Filtering Process*

The WAAS-Aided FITS takes advantage of the bias-like position error of the WAAS over a short period of time. If the bias can be estimated correctly at one time during approach, it is possible to have accurate position solutions by subtracting the estimated bias from the WAAS position outputs. However, the amplitude of the cyclic noise is so large that it must be removed in estimating the bias in vertical and is better to be eliminated in horizontal as well. Therefore, the cyclic noise removal process is critical. The discussion below shows how to robustly remove the cyclic noise of the WAAS by using an INS.

The sensor measurements of the INS and the WAAS can be described as follows.

$$z_{ins}(t) = P_T(t) + B_i(t) + x(t) \quad (1)$$

$$z_{waas}(t) = P_T(t) + B_w(t) + N_w(t) + \eta_w(t) \quad (2)$$

where $P_T(t)$ is the true trajectory. $B_i(t)$ and $B_w(t)$ are biases in the measurements of the INS and the WAAS respectively. $x(t)$ is the inertial drift, and $N_w(t)$ is the cyclic noise in the WAAS. $\eta_w(t)$ includes other noises such multipath, receiver noise and unmodeled effects in the WAAS.

Subtracting equation (1) from (2) results in

$$\begin{aligned}\Delta z(t) &= z_{waas}(t) - z_{ins}(t) \\ &= N_w(t) + B_w(t) - B_i(t) - x(t) + \eta_w(t)\end{aligned} \quad (3)$$

Equation (3) reveals the important fact that the motion of the airplane has no impacts on the difference, $\Delta z(t)$, which make the filtering performance independent of the airplane motion assuming that the time delay of the two measurements is insignificant. Considering $\eta_w(t)$ small and making the bias terms zeros, the problem becomes how to separate the cyclic noise, $N_w(t)$, and the inertial drift, $x(t)$.

To design a filter separating $N_w(t)$ and $x(t)$, it is necessary to know the characteristics of $x(t)$. In general, the propagation of an inertial drift is very complicated and has some uncertainty [5]. However, these complexities can be simplified by considering the flight motion during the inspection: short operation time, a straight line trajectory, nearly non-rotating and non-accelerating motions. The Equation (4) shows a simplified linear error model of an INS in NED coordinates [5].

$$\begin{aligned} \ddot{x}_N &= \beta_N - g(-\phi_E) \\ -\dot{\phi}_E &= \dot{x}_N / R_e - \varepsilon_E \\ \ddot{x}_E &= \beta_E - g\phi_N \\ \dot{\phi}_N &= \dot{x}_E / R_e + \varepsilon_N \\ \ddot{x}_D &= \beta_D \\ \dot{\phi}_D &= \varepsilon_D \end{aligned} \qquad (4)$$

where

x = position error
β = accelerometer bias
ε = gyro drift rate
ϕ = platform tilt error
g = acceleration of gravity
R_e = radius of earth

Assuming that the accelerometer biases are nearly constant during the approach, Equation (4) suggests the horizontal error is nearly a jerk motion. On the other hand, the vertical error is driven by a constant accelerometer bias. Let us first look at the filtering technique in the vertical channel due to its simplicity.

From equation (4), the inertial drift in the vertical channel in continuous time can be described as follows.

$$x_D(t) = x_{Do} + v_{Do}t + \tfrac{1}{2}\beta_D t^2 \qquad (5)$$

where is x_{Do} and v_{Do} is the initial position and initial velocity respectively.

Modeling the cyclic noise $N_w(t)$ as $A_N(t)\sin(\frac{2\pi}{T}t)$ and ignoring the biases and the noise, $\eta_w(t)$, equation (3) becomes

$$\Delta z_D(t) = A_N(t)\sin(\tfrac{2\pi}{T}t) - x_D(t) + \eta_w(t) \qquad (6)$$

where $A_N(t)$ is the time-varying amplitude of the cyclic noise**.**

Equation (6) shows that $\Delta z_D(t)$ is basically the sum of the cyclic noise with a time-varying amplitude and a quadratic curve whose curvature depends on β_D. The value of β_D is significantly different from the grade of an INS and has some uncertainty during operation. Therefore, a robust filtering technique is necessary, a filter which is able to effectively select the cyclic noise regardless of the value of β_D and the time-varying amplitude from $\Delta z_D(t)$.

Since a near-real time process is allowed, a non-causal zero-phase high pass filter [6] is of our interest. A high pass filter can be easily designed by using some basic low pass filters. Considering the time-varying amplitude of the sine wave, a symmetric triangular shape is selected for a low pass filter. Equation (7) describes this low pass filter in discrete time and figure 9 shows its impulse response.

$$h[t] = \tfrac{1}{T^2}(-|t| + T), \qquad -T \le t \le T \qquad (7)$$

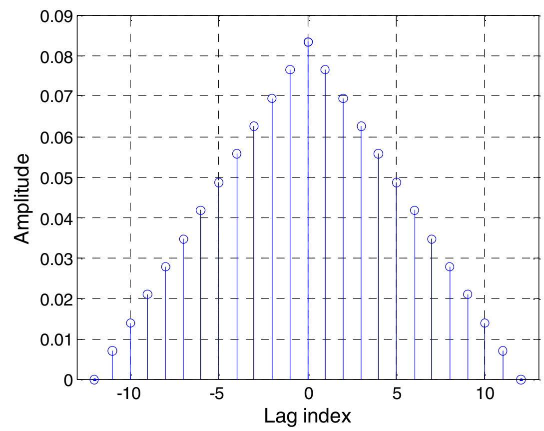

Fig. 9. Impulse response of the low pass filter

The output of the filter with input, sampled at 1Hz, $\Delta z_D[n]$, at time n is

$$\begin{aligned} y[n] &= \sum_{k=-T}^{T} h[k]\Delta z_D[n-k] \\ &= \frac{1}{T^2}\sum_{k=-T}^{T}(-|k|+T)(A_N[n-k]\sin[\tfrac{2\pi}{T}(n-k)] - \\ &\qquad x_D[n-k] + \eta_w[n]) \\ &= -x_D[n] - \tfrac{143}{T}\beta_D + \eta_{w,s}[n] \end{aligned} \qquad (8)$$

where $\eta_{w,s}[n]$ is noise due to the incomplete cancellation of the sine wave and the WAAS noise. It is interesting that, in addition to the vertical drift error, $x_D[n]$, $y[n]$ results in a constant bias term which does not depend on time, n. Therefore, subtracting $y[n]$ from $\Delta z_D[n]$ produces

$$\begin{aligned} e_D[n] &= \Delta z_D[n] - y[n] \\ &= A_N[n]\sin[\tfrac{2\pi}{T}n] + \tfrac{143}{T}\beta_D[n] + \hat{\eta}_e[n] \end{aligned} \qquad (9)$$

Filtering $e_D[n]$ with the same filter, h, results in

$$\begin{aligned} V_D(n) &= \sum_{k=-T}^{T} h[n]e_D[n-k] \\ &= \tfrac{143}{T}\beta_D[n] + \hat{\eta}_v[n] \end{aligned} \qquad (10)$$

Therefore, the cyclic noise term can be estimated as follows.

$$\begin{aligned}\hat{N}_{w,D}[n] &= e_D[n] - V_D[n] \\ &= A_N[n]\sin[\tfrac{2\pi}{T}n] + \hat{\eta}_{v,e}[n]\end{aligned} \tag{11}$$

The filtering process in a horizontal channel is the same as the vertical channel, but the low pass filter results in a slightly different term.

From equation (4), the inertial drift in the east channel can be described as follows.

$$x_E(t) = x_{Eo} + v_{Eo}t + \tfrac{1}{2}\beta_{Eo}t^2 + \tfrac{1}{6}\varepsilon t^3 \tag{12}$$

Following the similar procedure of equation (8), the filter outputs at time n

$$\begin{aligned}y[n] &= \sum_{k=-T}^{T} h[k]\Delta z_E[n-k] \\ &= -x_E[n] - \tfrac{143}{T}\beta_E[n] - 4\varepsilon + \eta_{w,s}[n]\end{aligned} \tag{13}$$

Unlike the previous case, the filter results in an additional term which is nearly linear function of time.

Now, the difference between $y[k]$ and $\Delta z_E[k]$ is

$$\begin{aligned}e_E[n] &= \Delta z_E[n] - y[n] \\ &= A_N[n]\sin[\tfrac{2\pi}{T}n] + \tfrac{143}{T}\beta_E[n] + 4\varepsilon + \hat{\eta}_e[n]\end{aligned} \tag{14}$$

Filtering $e_E[n]$ with the same filter, h, results in

$$\begin{aligned}V_E[n] &= \sum_{k=-T}^{T} h[k]e_E[n-k] \\ &= \tfrac{143}{T}\beta_E[n] + 4\varepsilon + \hat{\eta}_v[n]\end{aligned} \tag{15}$$

Therefore, the cyclic noise term can be estimated as follows.

$$\begin{aligned}\hat{N}_{w,E}[n] &= e_E[n] - V_E[n] \\ &= A_N[n]\sin[\tfrac{2\pi}{T}n] + \hat{\eta}_{v,e}[n]\end{aligned} \tag{16}$$

Figure 10 illustrates the high pass filter design process in vertical and horizontal channels.

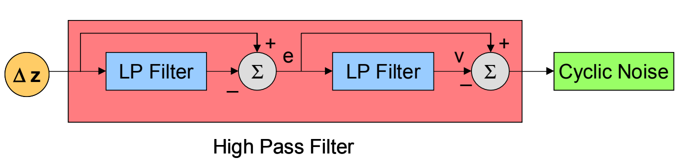

Fig. 10. High pass filtering block for the cyclic noise

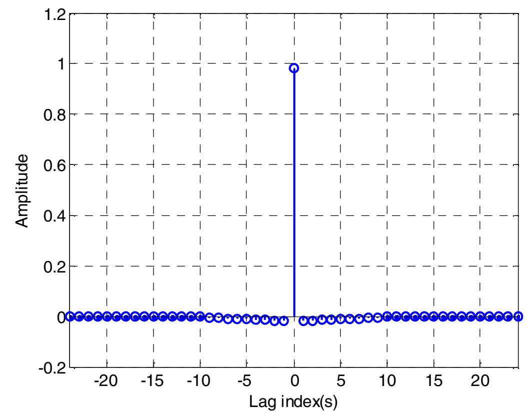

Fig. 11. Impulse response of the high pass filter

Figure 11 and 12 shows the impulse response of the high pass filter in discrete time and its frequency response.

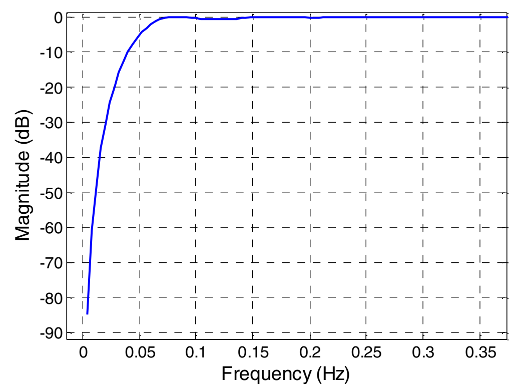

Fig. 12. Impulse response of the high pass filter

As an example, figure 13 shows the true WAAS noise and the estimated WAAS noise from the high pass filtering block. The residual errors are shown in figure 14. As shown in these figures, this filter effectively selects the periodic noise so that the residual errors are, most of time, less than 0.1 m.

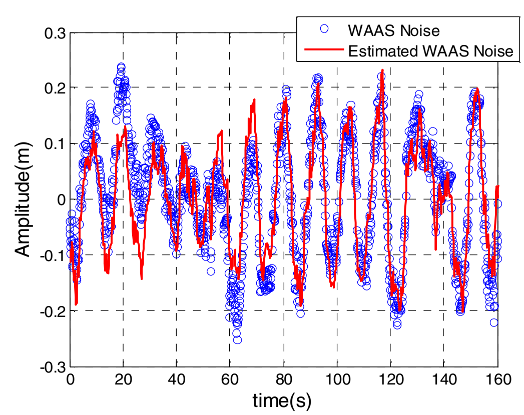

Fig. 13. Comparison WAAS noise and estimated WAAS noise

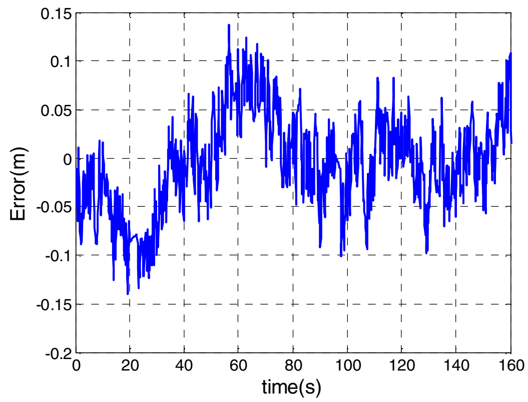

Fig. 14. The residual errors of the estimated WAAS noise

B. *Estimating true trajectory process*

After the cyclic noise process is selected, the remaining process in estimating the flight path is straightforward. First, noiseless WAAS measurements are obtained as follows.

$$\begin{aligned} z_{noiseless\_waas}(t) &= z_{waas}(t) - \hat{N}_w(t) \\ &= P_T(t) + B_w(t) + N_w(t) - \hat{N}_w(t) + \eta_w(t) \quad (17) \\ &= P_T(t) + B_w(t) + \eta(t) \end{aligned}$$

It is important to keep in mind that this noiseless WAAS position, $z_{noiseless\_waas}(t)$, not only provides smooth position outputs but also makes it possible to accurately determine the bias, $B_w(t)$, of the WAAS by using other sensors. To estimate the bias in the WAAS, it is necessary to have more accurate position measurements than the WAAS. The radar altimeter and the TVPS currently used in the AFIS have better accuracies (95%), 30cm and 60cm respectively, than the WAAS. Therefore, the WAAS bias is obtained from the position measurements of those sensors at the threshold of the runway similar to the AFIS. Let us denote this position estimate as $z_{RA\_TVPS}(t)$. Then, $z_{RA\_TVPS}(t)$ is subtracted from the noiseless WAAS position, $z_{noiseless\_waas}(t)$, on the threshold to obtain the WAAS bias, $B_w(t)$, as follows.

$$\hat{B}_w(t) = [z_{noiseless\_waas}(t) - z_{RA\_TVPS}(t)]_{\text{at threshold}} \quad (18)$$

This bias estimate, $\hat{B}_w(t)$, is usually a constant for the duration of the approach. However, $\hat{B}_w(t)$ may significantly change and be no longer useful if a satellite constellation changes or new ionospheric delay correction updates during the approach. This issue will be discussed in a later section.

By subtracting $\hat{B}_w(t)$ from $z_{noiseless\_waas}(t)$, the noise and bias removed WAAS position, $z_{true\_waas}(t)$, is estimated as follows.

$$z_{true\_waas}(t) = z_{noiseless\_waas}(t) - \hat{B}_w(t) \quad (19)$$

$z_{true\_waas}(t)$ will be used to calibrate the ILS.

The design philosophy of the WAAS-Aided flight inspection system is that this system not only can provide low costs and better performances than the current AFIS but also does not require any significant changes to either the AFIS. However, it is capable of replacing the expensive navigation grade INS to a low grade INS and adds a conventional airborne WAAS receiver. Therefore, this system can be easily installed and operated.

C. *Effect of satellite geometry changes and ionospheric delay correction updates*

Satellite geometry changes and ionospheric delay correction updates usually make a jump in position solutions. If this occurs near the runway, the bias estimation from a radar altimeter and a TVPS are no longer valid. Therefore, it is very important to detect any of these changes near the runway. Some airborne WAAS receivers output the number of satellites used to compute the positions and the updates of ionospheric corrections such that it is easy to detect these changes.

Once the satellite geometry changes and ionospheric correction updates are observed, it is necessary to compensate for the jump in the position. One possible way to do this is to use the velocity from an INS since the INS provides smooth and accurate velocity in a short term. Another way is to control the positioning algorithms of the WAAS receiver. However, this method requires an advanced receiver and adds more complexity to the system.

V. Flight Test Results with a navigation Grade Ins

The proposed algorithm is tested with flight test data taken in APR, 2005. The current AFIS flight inspection system was used to collect these data, therefore a navigation grade INS was used. The output rate of the WAAS measurements and inertial measurements are 1 Hz and 50Hz respectively. In order to compare the accuracy of the WAAS-Aided FITS, DGPS positions with 5 HZ output rate are used as truth sources. All of these measurements are sampled at 8 HZ and transformed to along-track, cross-track, and vertical coordinates with respect to the runway.

Figure 15 shows the horizontal accuracy requirements (0.05 Deg. and 0.015 Deg. lines) and the cross-track errors from the WAAS-Aided FITS. In these tests, TVPS measurements were not accurate enough to fix the WAAS bias such that they are not used to correct the biases in the errors. This figure shows that the cyclic noises are effectively removed. The biases in the error are larger than the 2σ of the typical WAAS horizontal accuracy. It appears as if the DGPS reference receiver position has some offsets for this set of data.

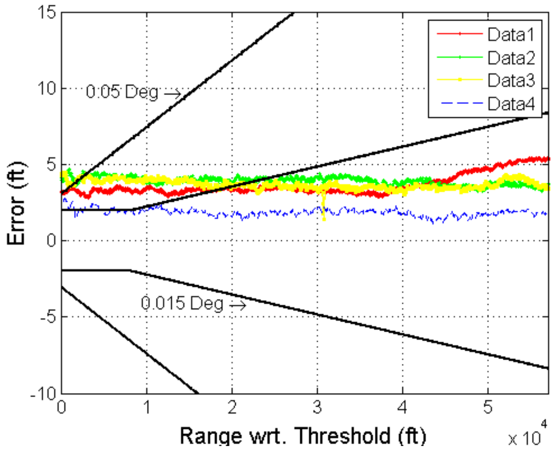

Fig. 15: Cross-track errors of the WAAS-Aided FITS

Figure 16 shows the vertical accuracy requirements (0.05 Deg. and 0.015 Deg. lines) and vertical errors obtained from the WAAS-Aided FITS. The bias of the WAAS is removed by assuming a perfect radar altimeter. The vertical error characteristics are mainly biases but have larger noise than the horizontal errors, which indicates that the filtering process for the cyclic noise in vertical is not as effective as in horizontal. The reason for this less effective filtering result is that the vertical output of the INS is coupled with a barometric altimeter, which is usually required to stabilize the vertical output of an INS. The result shows that the noise is still improved about 50% by using the filtering technique. However, since the barometric altimeter can be removed in the WAAS-Aided FITS, the performance in the vertical channel is expected to be as good as the horizontal channel.

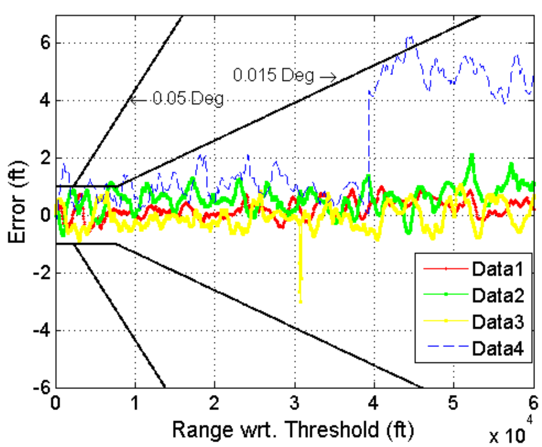

Fig. 16. Vertical errors of the WAAS-Aided FITS

VI. Simulation Results in Horizontal for a Tactical and an Automotive Grade INS

In this section, the WAAS-Aided FITS is tested with simulated horizontal measurements of a low-end tactical grade INS and an automotive grade INS. The horizontal measurements of a low grade INS are generated from adding errors to the navigation grade INS measurements. The added errors are simulated by assuming that the accelerometer and gyro errors are mainly biases with white noise. The parameters of the error model of a low-end tactical grade INS and an automotive grade INS are summarized in Table II [7].

TABLE II

Biases and Power Spectra of Accelerometer and Gyro

Sensor Parameter	**Unit**	**Tactical**	**Automotive**
Accelerometer bias	μg	500	30,000
Gyro bias	deg/hour	1	100
Accelerometer white noise	$(\mu g)^2$ / Hz	2500	5000
Gyro white noise	$(\text{deg/s})^2$ / Hz	10^{-6}	10^{-4}

Figure 17 and 18 show the simulated horizontal errors for a tactical grade INS and an automotive grade INS.

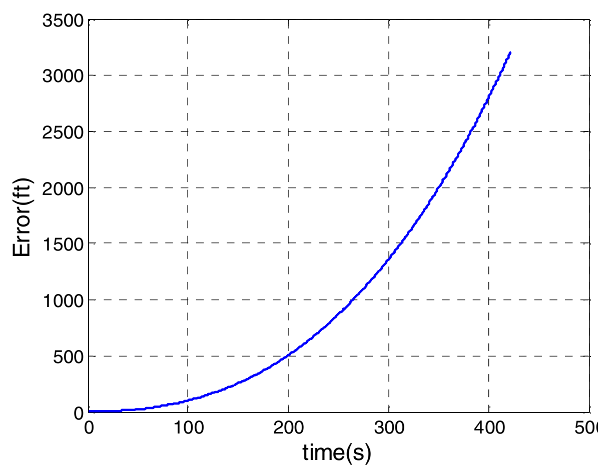

Fig. 17. Simulated horizontal error for a tactical grade INS

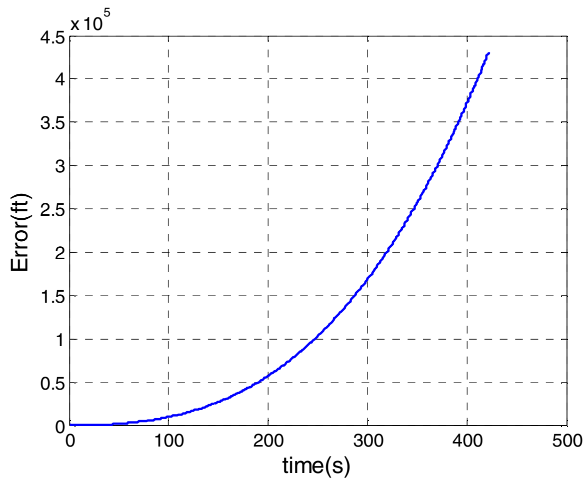

Fig. 18. Simulated horizontal error for an automotive grade INS

Figure 19 and 20 shows the cross-track errors of the WAAS-Aided FITS using the simulated low-end tactical and the automotive grade INS. In both of the results, the cyclic noise is effectively removed so that it is hard to find any difference between the two cases.

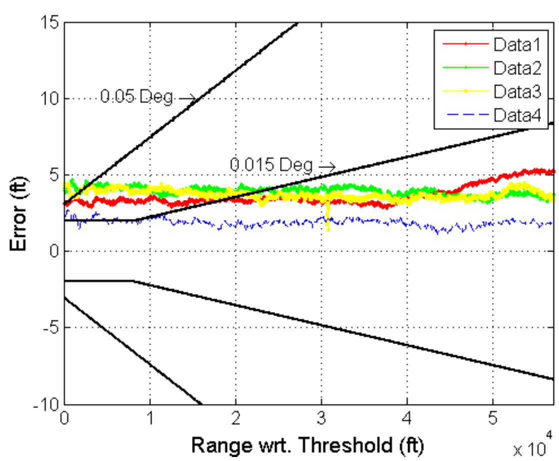

Fig. 19. Cross-track error from the WAAS-Aided FITS without a TVPS bias fix for a simulated tactical grade INS

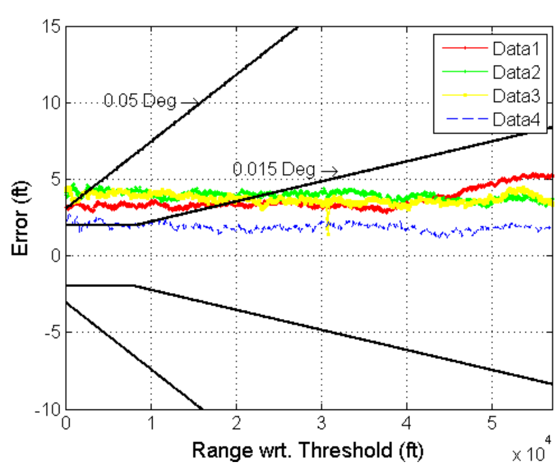

Fig. 20. Cross-track error from the WAAS-Aided FITS without a TVPS bias fix for a simulated automotive grade INS

The WAAS-Aided FITS is not tested with simulated vertical measurements for a tactical or an automotive grade INS because the measurements of a navigation grade INS are corrupted with a barometric altimeter. Test results in vertical without a barometric altimeter would provide similar performance to the horizontal channel.

VII. Conclusion

The WAAS-Aided FITS is described in this paper. This system uses the WAAS as a primary sensor with a low cost INS, and a radar altimeter, and a TVPS. The algorithms of the system are intensively discussed for fusion of the WAAS and an INS and for the bias detection process. The WAAS-Aided FITS is tested with the flight test collected from the AFIS which uses a navigation grade INS. Also, the feasibility of a low-end tactical grade INS and an automotive grade INS is tested with the simulated errors.

The results show that the cyclic noise accurately removed in horizontal with a low grade INS. But, about only 50% of the cyclic noise is removed in the vertical channel due to the use of a barometric altimeter in the AFIS. Since a barometric altimeter does not have to be in the WAAS-Aided FITS, the performance of removing the cyclic noise in the vertical channel is expected to be as good as the horizontal channel. The horizontal error has larger biases than the typical WAAS horizontal error. Since the horizontal errors are biased in a similar way, it appears that the DPGS reference receiver position has a slight offset. A TVPS is not used to fix the WAAS bias because the actual flight test shows that the TVPS measurements are not accurate enough to fix the WAAS bias even though a TVPS is claimed to have slightly better accuracy than the WAAS. This issue will be further investigated with the FAA.

Overall, the results indicate that a WAAS-Aided FITS with a low-end tactical or an automotive grade INS could meet the ILS accuracy requirements with a proper operation of a radar altimeter and a TVPS. This system would not only allows much lower costs than the AFIS by replacing a navigation grade INS with a low grade INS but also has better efficiency than the AFIS because an airplane no longer needs to fly level over the length of the runway as the current AFIS requires. A limitation of the WAAS-Aided FITS is that it is vulnerable to a sharp ionospheric gradient during approach. In this case, the error could become excessively larger farther from the runway. However, since the ILS calibration iterates a few times, one bad solution caused by the sharp ionospheric gradient would be detected and discarded. Finally, this study shows that the Space-Based Augmentation System (SBAS) could be used for a main sensor for a next generation flight inspection system.

Acknowledgment

The authors gratefully acknowledge the support of FAA flight inspection division (AVN)

References

[1] M. Kayton and F. Walter, *Avionics Navigation Systems*. New York: John Wiley and Sons, 1997

[2] *Wide-Area Augmentation System Performance Analysis Report*, FAA William J. Hughes Technical Center, Atlantic City, NJ (updated reports

issued every quarter). Available:
http://www.nstb.tc.faa.gov/ArchiveList.html
[3] P. Enge, *Wide Area Augmentation System of Global Positioning System IEEE Proc*. Volume 84, Issue 8, Aug. 1996.
[4] *Minimum Operational Performance Standards for Global Positioning System/Wide Area Augmentation System Airborne Equipment.* Washington, D.C, RTCA SC-159, WG-2, DO-229C, 28 Nov, 2001.
[5] D.H Titterton and J.L. Weston, *Strapdown Inertial Navigation System,* vol. 207 in Prog. in Astronautics and Aeronautics, 2004.
[6] Sanjit K. Mitra, *Digital Singal Processing: A computer-Based Approach, second edition,* McGraw-Hill, 2001.
[7] Yaakov Bar-Shalom et al., *Estimation with Application to Tracking and Navigation ,*New York, Wiely-InterScience, 2001