GNSS-based Flight Inspection Systems

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***Abstract*—This paper presents novel Global Navigation Satellite System (GNSS)-based flight inspection systems (FIS) that outperform current flight inspection systems in terms of cost, efficiency, and integrity. The GNSS-based FIS are the WAAS-based FIS and the stand-alone GPS-based FIS. These GNSS-based FIS are onboard and do not use an INS or external reference stations at the airport. Instead, the WAAS-based FIS requires raw GPS/WAAS measurements, and the stand-alone GPS requires only raw GPS measurements. Both systems require a radar altimeter and a TeleVision Positioning System (TVPS) for CAT II and III calibration; however, no TVPS is required for CAT I ILS calibration in the WAAS-based FIS. The stand-alone GPS-based FIS always requires both the radar altimeter and TVPS. These two systems are very similar and basically have the same positioning algorithm. Using the specialized positioning algorithm called Time-Differenced Precise Relative Positioning (T-D PRP) with those sensors, the two GNSS-based FIS meet the FIS accuracy requirements for ILS calibration. They do this efficiently because the airplane does not need to fly level over the entire runway nor does a ground unit need to be installed. The GNSS-based FIS also have several integrity features. Secure satellite health status is checked by using broadcast WAAS integrity messages in the WAAS-based FIS or by using specialized Receiver Autonomous Integrity Monitoring (RAIM) for a FIS called FIS-RAIM in the stand-alone GPS-based FIS. The T-D PRP has a built-in protection against abnormal ionospheric effects. In addition, the WAAS-based FIS can validate the integrity of the measurements from a radar altimeter and a TVPS using WAAS accuracy. These integrity features ensure sound position solutions of the two GNSS-based FIS. Therefore, the GNSS-based FIS provide high efficiency and firm integrity with low cost. The difference between the two GNSS-based FIS is that the WAAS-based FIS has better integrity features but can only be used where WAAS or other SBAS is available. On the other hand, the stand-alone GPS-based FIS can be used worldwide.**

I. INTRODUCTION

The current automated flight inspections systems (AFIS) are the Inertial-based AFIS and Differential GPS (DGPS)-based AFIS. The Inertial-based AFIS is an onboard system that has a navigation grade INS, GPS, a barometric altimeter, a radar altimeter, and a TeleVision Positioning System (TVPS). In this system, the fusion of a navigation grade INS, GPS, and a barometric altimeter provides high quality velocity during approach. A radar altimeter and a TVPS provide accurate position fixes at the runway threshold and departure end. Those position fixes are used to refine the velocity during approach by calibrating various INS biases. Then, the flight path during the flight inspection approach is estimated by integrating the velocity backward from the position fix at the runway threshold. On the other hand, the DGPS-based AFIS uses a Real-Time Kinematic (RTK) DGPS system that can provide centimeter level accuracy. An RTK system uses differential GPS techniques with two receivers and utilizes GPS carrier phase measurements as ranging sources. This system requires an installation of a local reference receiver near a runway before the flight inspection is carried out.

These two different positioning schemes result in substantial differences in the tradeoffs between cost and efficiency of the current flight inspection systems. The Inertial-based AFIS is much more expensive than the DGPS-based AFIS mainly due to the use of a navigation grade INS. On the other hand, the flight inspection procedure with the DGPS-based AFIS takes significantly more time than the Inertial-based AFIS because a flight inspection aircraft first lands on a runway to install a local reference receiver to begin flight inspection. A civil aviation administration (CAA) of a country typically chooses either one of the systems that better fits its own preference. For example, the Federal Aviation Administration (FAA) mainly uses the

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Inertial-based AFIS due to the large volume of flight inspection required.

Previously, from an effort to replace the Inertial-based AFIS with a lower cost system, the WAAS (SBAS)-aided Flight Inspection System (WAAS-aided FIS) was proposed [1]. This system uses a low (tactical or less) grade INS, a certified commercially available WAAS receiver, a radar altimeter, and a TeleVision Positioning System (TVPS). The advantages of this system are lower cost and better efficiency than the current AFIS. However, the accuracy of this system is marginal near the runway but sufficient to the flight inspection system accuracy requirements far from the runway. The WAAS-aided FIS has some vulnerability to possible accuracy degradation in rare events (e.g., a sharp ionospheric gradient or severe multipath) because it is constrained to only utilize standard positioning outputs from the WAAS receiver.

Through continuing efforts to replace the Inertial-based AFIS with a lower cost system, we present two novel Global Navigation Satellite System (GNSS)-based flight inspection systems (FIS): WAAS (SBAS)-based FIS [2] and stand-alone GPS-based FIS [3]. These systems have sufficient accuracy to meet the FIS accuracy requirement up to CAT III ILS calibration with better performance than the current flight inspection systems in terms of cost, efficiency, and integrity. These two GNSS-based systems are very similar. However, the WAAS-based FIS has better integrity features, but it can only be used where WAAS or SBAS is available in the world. On the other hand, the stand-alone GPS-based FIS can be used worldwide.

This paper is organized as follows. The system architectures of the WAAS-based FIS and the stand-alone GPS-based FIS are briefly discussed including positioning algorithm and integrity features. Then, the performance of the GNSS-based FIS is evaluated with flight test data. Lastly, conclusions follow.

II. GNSS-BASED FLIGHT INSPECTION SYSTEMS

Global Navigation Satellite System (GNSS) is a generic term indicating various satellite navigation systems. As of 2007, the global satellite-based navigation systems are GPS, GLONASS, Galileo, and more recently Compass of China. Among the systems, GPS is currently the only fully operational system. There are also several space-based augmentation systems (SBAS) such as Wide Area Augmentation System (WAAS) in the U.S., European Geostationary Navigation Overlay Service (EGNOS) in the European Union, Multi-functional Satellite Augmentation System (MSAS) in Japan, and GPS and GEO Augmented Navigation (GAGAN) in India. Korea and Brazil are investigating SBAS, also. At this time, WAAS is the only fully operational SBAS, but EGNOS and MSAS will be complete in one or two years. GPS and WAAS are undergoing modernization planning in order to meet future civil and military needs.

Since GPS and WAAS are currently available, they are used in this research; however, the concepts apply to any of the GNSS or SBAS now being developed. In this section, the highlights of the WAAS-based FIS and the stand-alone GPS-based FIS are introduced. More technical details about the WAAS-based FIS and the stand-alone GPS-based FIS can be found in [2] and [3], respectively. In these systems, the same kinds of radar altimeter and TVPS being used in the current Inertial-based AFIS are used in the GNSS-based FIS. The 95% accuracy of the radar altimeter is better than 15 cm [4]. The 95% accuracy of the TVPS is better than 15 cm in cross-track and 30 cm in along-track [5].

A. *WAAS-based Flight Inspection System*

The Wide Area Augmentation System (WAAS) is an augmentation system of Global Positioning System (GPS) in the U.S and was developed by the FAA to serve various phases of flight operation as a primary means of navigation. As of 2007, WAAS can guide an airplane down to within 200 ft above an airport's runway surface. An extensive overview of WAAS can be found in [6] and [7]. The current WAAS 95% accuracy is better than 0.935 meters in the horizontal and 1.289 meters in the vertical [8], which does not meet the ILS calibration accuracy requirements. Although WAAS cannot be directly used for the ILS calibration, WAAS still has useful features because it broadcasts accurate correction messages for GPS errors and integrity messages. The error corrections include satellite clock-ephemeris and ionospheric delay. The integrity messages include satellite anomalies, severe ionospheric disturbances, and the quality of the error corrections. These features play a very important role in helping the WAAS-based FIS have sound position solutions and firm integrity.

The WAAS-based FIS is a system that has a single frequency WAAS receiver, a radar altimeter, a TVPS, and a computer. This integrated system is optimally designed for the ILS calibration problem in terms of accuracy, cost, efficiency, and integrity.

Figure 1 illustrates the overall algorithm of the WAAS-based FIS. During approach, WAAS position and raw GPS/WAAS measurements are collected. The raw GPS/WAAS measurements include ephemeris, L1 code and carrier phase measurements, and WAAS messages. The ephemeris parameters provide GPS satellite locations at a specific time. L1 code and carrier phase measurements provide range information between a user to satellites. The WAAS messages provide GPS error corrections and satellite health. Over a runway threshold, the radar altimeter, corrected for roll and pitch angles, measures the vertical distance between the airplane and the runway threshold. At that point, the TVPS measures the cross-track and the along-track deviations of the airplane from the centerline and the threshold mark of the runway by using its camera images for CAT II and III ILS calibration. However, WAAS can substitute for a TVPS in the WAAS-based FIS for CAT I ILS calibration. Since the position of the threshold is accurately surveyed, the radar altimeter and the TVPS provide an accurate instant 3D position of the airplane over the threshold called a reference position. Again, the reference position can be given from a radar altimeter and WAAS cross-track position in the WAAS-based FIS for CAT I ILS calibration.

A specialized positioning algorithm, Time-Differenced Precise Relative Positioning (T-D PRP) method, uses the reference position and the raw GPS/WAAS measurements to compute precise relative positions. The T-D PRP utilizes the difference of GPS carrier phase measurements over a time interval as ranging sources. It removes the satellite clock-ephemeris errors by using broadcast WAAS correction and the ionospheric effects by using the first order linear regression on the time series of code minus carrier phase measurements during approach. Then, the estimated flight trajectory during approach is obtained by adding the relative positions to the reference position. The positioning performance of the WAAS-based FIS with flight test data will be shown in the next section.

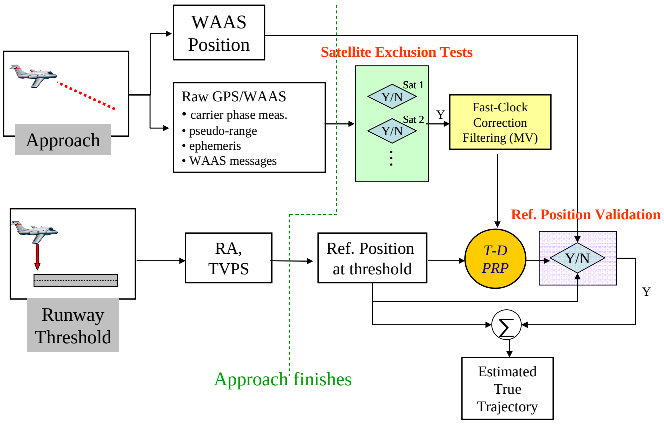

Figure 1: System architecture of the WAAS-based FIS

There are two integrity features for the soundness of the estimated flight trajectory: satellite exclusion tests and validation of the reference position from the radar altimeter and the TVPS. First, satellite exclusion tests are implemented to discard a satellite that should not be used in the T-D PRP. These exclusion tests have the following checks: unhealthy satellite status reported from GPS/WAAS, discontinuity in carrier phase measurements called cycle-slip, severe nonlinearity of ionospheric delay, and satellite outages. If any of these items is reported, the corresponding satellite is excluded in computing position solutions. Second, the integrity of a reference position from a radar altimeter and a TVPS is checked by using both WAAS position during approach and the precise relative position from the T-D PRP. Even though this validation test is limited to the level of WAAS accuracy, it is useful when a radar altimeter or a TVPS introduces an abnormally large error.

These features of the WAAS-based FIS provide high performance in terms of accuracy, cost, efficiency, and integrity by taking advantages of WAAS and the near real-time nature of flight inspection. The WAAS-based FIS can be used where WAAS (or other SBAS) is available. It should be also noted that a certified WAAS receiver may require modification to allow for the raw GPS/WAAS calculations to be available as an output quantity. Again, more technical details of the WAAS-based FIS can be further found in [2].

B. *Stand-alone GPS-based FIS*

The stand-alone GPS-based FIS has a single frequency GPS receiver, a radar altimeter, a TVPS, and a computer. Figure 2 illustrates the overall algorithm of the stand-alone GPS-based FIS. The overall algorithm of the stand-alone GPS-based FIS is very similar to the WAAS-based FIS. This system also uses the T-D PRP as a positioning algorithm except that the T-D PRP only utilizes raw GPS measurements. However, integrity features are different. First, instead of using the broadcast satellite health status from WAAS, the FIS-RAIM [3] is used to detect possible satellite failures in the stand-alone GPS-based FIS. The FIS-RAIM was designed to detect a satellite failure that may cause the violation of the required FIS accuracy requirements up to CAT I ILS calibration. Second, unfortunately, the stand-alone GPS-based FIS is not able to check the integrity of a reference position provided from a radar altimeter and a TVPS because GPS accuracy is insufficient to perform that.

Overall, the stand-alone GPS-based FIS is a very similar system to the WAAS-based FIS and provides almost the same accuracy. Its integrity features are less secure than the WAAS-based FIS, but the stand-alone GPS-based FIS is available worldwide. More technical details of the stand-alone GPS-based FIS can be found in [3].

III. EVALUATION OF GNSS-BASED FIS USING FLIGHT TEST DATA

The WAAS-based FIS and the stand-alone GPS-based FIS are evaluated with flight-test data taken on Oct 30~31, 2007 at Oklahoma City in collaboration with the FAA. The total number of ILS approaches used is 23. In this test, GPS measurements and WAAS messages were collected by using an FAA certified Garmin 480 receiver with minor changes that allowed access to the raw internal measurements. The FAA Inertial-based AFIS collected RTK DGPS positions. Unfortunately, the radar altimeter and TVPS were not used because of hardware limitations at that time. Therefore, a reference position for each approach was provided from the RTK DGPS positions in this evaluation.

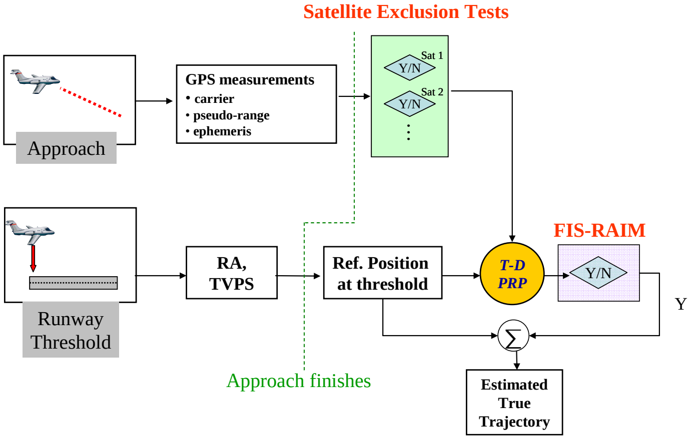

Figure 2: System architecture of the stand-alone GPS-based FIS

The position error of the GNSS-based FIS is the sum of two parts: T-D PRP error and reference position error. These two errors are not absolutely independent. The magnitude of a reference position error effects the T-D PRP errors, however, this effect is so small in the short time of approach that it can be neglected. Now, let us first look at the T-D PRP errors. Figures 3 and 4 show the T-D PRP errors of the WAAS-based FIS in the cross-track and in the vertical, respectively. Figures 5 and 6 show the T-D PRP errors of the stand-alone GPS-based FIS. The two pairs of straight lines are the FAA flight inspection system accuracy requirements for CAT I and CAT II•III ILS. For the computation of the cross-track requirements, the runway length is assumed to be 2700 meters.

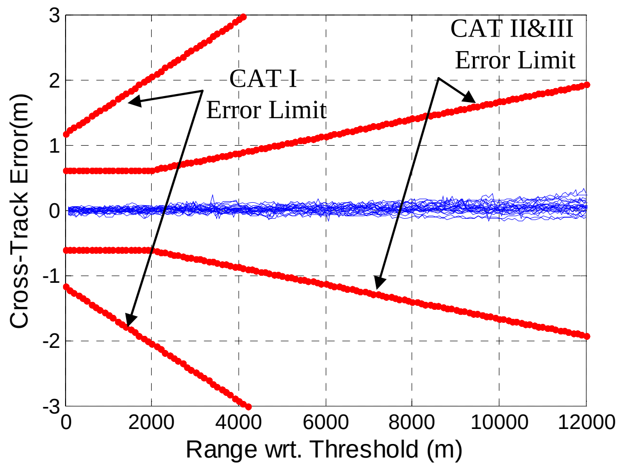

Figure 3: T-D PRP errors of the WAAS-based FIS in the cross-track

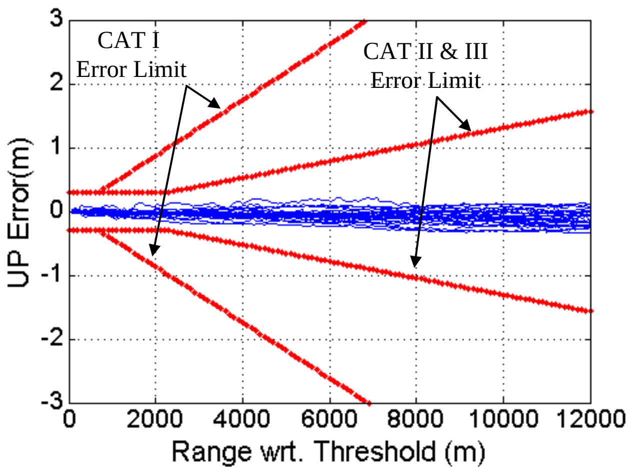

Figure 6: T-D PRP errors of the stand-alone GPS-based FIS in the vertical

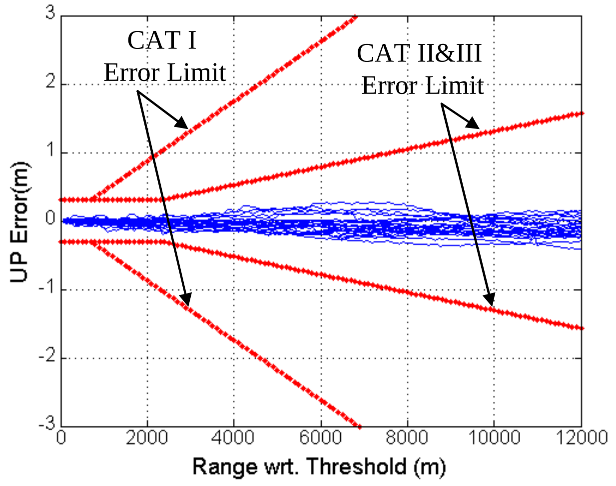

Figure 4: T-D PRP errors of the WAAS-based FIS in the vertical

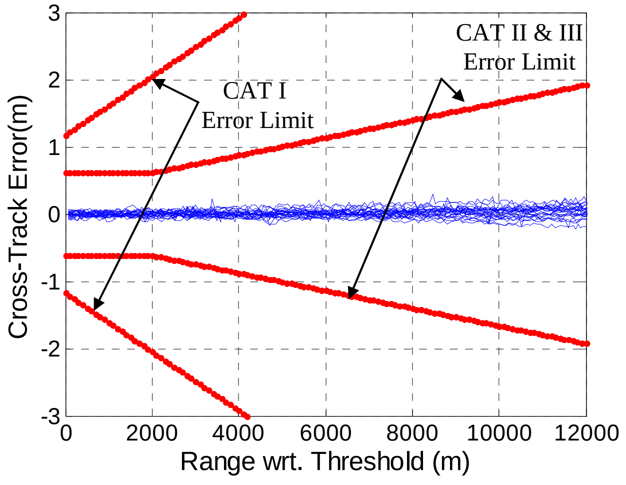

Figure 5: T-D PRP errors of the stand-alone GPS-based FIS in the cross-track

Although WAAS provides better satellite clock-ephemeris corrections, the T-D PRP error of the WAAS-based FIS looks almost identical to the stand-alone GPS-based FIS. The reason for this is that the satellite clock-ephemeris residual correction errors of WAAS and stand-alone GPS errors are highly correlated over time. Therefore, when the T-D PRP takes the time difference of carrier measurements, the satellite clock-ephemeris residual correction errors are effectively cancelled out. As a result, there is no real difference in the T-D PRP errors for the WAAS-based FIS and the stand-alone GPS-based FIS.

Based on the T-D PRP error characteristic that slowly grows over time, the total errors of the WAAS-based FIS and the stand-alone GPS-based FIS are evaluated at the critical regions. The critical regions are defined as the range from the runway threshold where the total errors most likely violate the accuracy requirements. As can be seen from the previous figures, the critical regions for CAT II•III ILS are around 2200 meters and 2000 meters in the vertical and horizontal directions, respectively. The critical regions for CAT I ILS are around 800 meters and the threshold in the vertical and in the cross-track, respectively. The total errors at those critical regions are obtained by combining the T-D PRP error statistics at the critical regions with the accuracy of a radar altimeter and a TVPS with an RSS computation. The total cross-track error of the WAAS-based FIS for CAT I ILS is obtained by using

WAAS horizontal accuracy instead of the accuracy of a TVPS.

Table 1 summarizes the 95% accuracy of the GNSS-based FIS and the FIS accuracy requirements at the critical regions. For the stand-alone GPS-based FIS, CAT II•III ILS accuracy requirements are used. The vertical accuracy of the WAAS-based FIS for CAT I ILS is evaluated at around 2200 meters instead of at around 800 meters because the performance of the WAAS-based FIS already meets the tighter requirements for CAT II•III ILS. Therefore, the WAAS-based FIS and stand-alone GPS-based FIS accuracies given from the flight data set sufficiently meet the FIS accuracy requirements at the critical regions.

Table 1: WAAS-based FIS and stand-alone GPS-based FIS accuracies at the critical regions (* RA is radar altimeter, TVPS is the TV positioning system)

	WAAS-based FIS for CAT II/III ILS	WAAS-based FIS for CAT I ILS	Stand-alone GPS-based FIS
Required components*	WAAS, RA., TVPS	WAAS, RA	GPS, RA, TVPS
Cross-track errors (m)	0.17	0.94	0.17
Cross-track Requirements (m)	0.6	1.2	0.6
Vertical errors (m)	0.18	0.18	0.18
Vertical Requirements (m)	0.3	0.9	0.3

IV. CONCLUSIONS

Two GNSS-based FIS are introduced in this paper. These systems are the WAAS-based FIS and the stand-alone GPS-based FIS. The system architectures and algorithms were briefly discussed. The performance of the two proposed systems was evaluated with flight test data and showed that these systems can meet the flight inspection system accuracy for cat III ILS calibration requirements.

The benefits of the GNSS-based FIS over the current flight inspection systems are lower cost, higher efficiency, and firm integrity. The cost reduction is especially significant for the Inertial-based AFIS because a navigation grade INS is no longer required. The WAAS-based FIS for CAT I ILS costs even less because a TVPS is also not required.

The analysis of the efficiency improvement is described in Figure 7. In this figure, it is assumed that the approach starts at 10 NM away from the runway threshold and the length of the runway is about 1.5 NM (2700 m). A simple 2D semi circle trajectory is taken in this analysis. Based on these assumptions, the GNSS-based FIS has a 20 NM straight flight trajectory plus a turning trajectory at the two ends. On the other hand, the Inertial-based FIS has a length of 23 NM straight flight trajectory plus the turning trajectories. Assuming the turning trajectory is 2 NM at each end, a flight inspection aircraft with the GNSS-based FIS will achieve 11% better efficiency over the Inertial-based AFIS when the shorter pattern is acceptable to ATC.

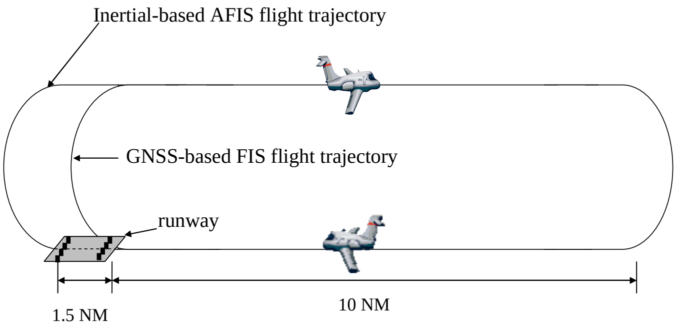

Figure 7: Comparison of flight trajectory using the GNSS-based FIS and the Inertial-based FIS

The integrity features of the GNSS-based FIS are satellite health, ionospheric disturbances, and reference positions. These features give great confidence in computed positions during flight inspection.

In the near future, when the currently developing SBAS are completed, the WAAS (SBAS)-based FIS will be possible in other places including Europe, Japan, India, Brazil, and Korea. The performance of the two GNSS-based FIS will also be strengthened due to additional civil signals and more satellites from Galileo, GLONASS, Compass, and modernized GPS. Therefore, the GNSS-based FIS introduced in this paper will have better performance and better worldwide coverage as GNSS evolves.

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