Flight Inspection of GNSS SBAS Procedures

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1. Introduction to SBAS

a. Overview

Satellite Based Augmentation Systems (SBAS) are now being implemented around the world in order to improve the accuracy and integrity of Global Navigation Satellite Systems (GNSS). One of these is the Wide Area Augmentation System (WAAS), the FAA's SBAS that was commissioned in 2003. It now provides continuous horizontal navigation throughout the national airspace system. In addition, it provides vertical guidance to most of the Coterminous United States (CONUS) greater than 99% of the time [1]. The European Geostationary Navigation Overlay Service (EGNOS) is a similar SBAS that will provide coverage for Europe. Other parts of the world (e.g., Japan and India) are also developing SBAS's. All the SBAS's will have instrument approaches that utilize their improved navigation accuracy. This paper addresses the flight inspection of SBAS approaches.

WAAS supports two types of approach procedures with vertical guidance: LNAV/VNAV (Lateral and Vertical NAVigation) and LPV (more precise lateral and vertical navigation) [2]. LNAV/VNAV was originally developed for barometric VNAV systems where the lateral guidance was supported by either stand-alone GPS or a ground based navigation aid called Distance Measuring Equipment (DME). WAAS improves upon these by supporting both the LNAV and VNAV functions itself. An LPV approach further improves on LNAV/VNAV by taking advantage of the horizontal accuracy of WAAS. The horizontal obstacle clearance zone is made more than ten times smaller, which enables LPV to achieve much lower decision altitudes. LPV is capable of bringing an airplane to within 250 feet of the ground (depending on local obstacles and runway markings). Functionally, it is very similar to a Category I (CAT I) Instrument Landing System (ILS) approach. A pilot flying an LPV approach would fly it in the same manner they would an ILS using the same displays in the cockpit for guidance.

b. How WAAS Works

WAAS is a satellite based navigation system. It uses the Global Positioning Satellites (GPS) to determine the position of an airplane. In addition, it augments the GPS position in three important ways: it improves the accuracy by sending corrections for the largest errors on the GPS signals; it provides integrity by broadcasting confidence bounds for the remaining errors; and it improves availability by providing additional satellites for use in determining position. WAAS employs a ground network of 25 reference stations throughout the U. S. These stations monitor the health of the GPS satellites. This information is then broadcast to airplanes through a Geostationary Earth Orbit (GEO) satellite that also sends a signal virtually identical to what the GPS satellites broadcast. Aircraft can incorporate this extra signal into their position solution to better guarantee the reception of the four or more satellites required. Because WAAS is a nation-wide network and uses a geostationary satellite for its data-link, it can provide service throughout the airspace without the need for local infrastructure. To use WAAS at a local airport no additional ground navigational aids need to be installed. The 25 WAAS reference stations are at precisely surveyed locations in the U. S. Each has three dual frequency GPS receivers that can be used to crosscheck the measurements. By taking measurements from two frequencies, the propagation delay caused by the signal passing through the ionosphere can be separated from the other error sources. WAAS sends corrections for the ionospheric delay as well as for the GPS satellites' clock and orbital errors. Each correction is sent to the user at least every five minutes. Because the reference stations know their location to within centimeters, they can determine what errors may be present on the ranging signals from the satellites. These errors are isolated to their individual components for efficient broadcast. Together, these corrections yield an accuracy that is a little less than one meter horizontally and a little over one meter vertically (95% of the time).

c. The WAAS Program

The WAAS initial operating capability was commissioned on July 10, 2003. The performance is very good, but it has some limitations. These issues are being addressed with a series of improvements designed to meet LPV performance over all CONUS in early 2008. Although WAAS availability has been very high, the geostationary satellites (GEOs) used are not ideally placed over the U. S. Additionally, their signal capability is limited.

Consequently, the FAA is procuring two new GEOs whose signals should be available in late 2006. These GEOs are positioned so that their signals are always available over the U.S. They will appear higher in the sky and offer overlapping coverage. The GEO signals will better emulate the GPS signals and a second civil frequency will be provided. Another improvement is the addition of 13 new reference stations in Alaska, Canada, and Mexico. These additions will expand the coverage so that the LPV approach has availability over all of CONUS more than 99% of the time. Finally, there will be enhancements made to the internal algorithms of WAAS. These will improve both the continuity and availability of the system.

In the longer term, WAAS intends to take advantage of the improvements planned for the GPS constellation. Primarily this involves the use of a new civil frequency at L5. By having both frequencies measured onboard the aircraft, ionospheric delays can be directly measured and removed. This significantly reduces the largest error source currently affecting GPS and WAAS. A dual frequency equipped airplane will have several advantages over the current WAAS. It will have significantly better performance for LPV, which will no longer be vulnerable to outages due to ionospheric disturbances. It will also have some immunity to radio frequency interference that can block either the L1 or L5 signals. Lastly, it will be able to provide availability of CAT-I service. Thus, modernizing WAAS to match the improved GPS capabilities offers significant benefits to the aviation community. Another planned improvement is to incorporate the European counterpart to GPS, called Galileo, as it becomes available. The additional measurements from the Galileo satellites will dramatically increase availability and reduce continuity breaks. The final operating capability of WAAS, which will be available in 2015 or later, will offer full availability of CAT-I throughout CONUS and a very reliable LPV service even in the presence of interference.

d. Use of WAAS

WAAS can easily be added to any aircraft. Consumer receivers have been using WAAS for years and two manufacturers offer certified WAAS receivers for aviation use. Several more are expected in the next few years. WAAS currently supports over 4400 approaches.

2. Importance of Flight Inspection

a. Overview

The FAA is responsible for the safe operation of the national airspace system in the U. S. The same is true for civil aviation authorities in all countries. If an accident happened where the cause was a faulty navigation aid or an improper landing approach procedure, the government would not have done its job adequately and would be liable for damages. As a result, specially equipped aircraft periodically inspect all ground-based navigation aids (navaids). Accuracy of the navigational aid is evaluated using flight-inspection aircraft that have equipment on board to determine their true location independently, allowing for the verification that the accuracy of the navaids is within the allowable tolerances. The FAA carries out flight inspection upon initial commissioning of the navaids and periodically thereafter. Flight inspection is also part of the commissioning process of new landing approach procedures before publication. The purpose of this inspection is to verify that 1) all data to be published for the approach are correct, 2) the flight path clears obstacles and terrain by an acceptable margin, and 3) the achieved flight path is the same as the flight path intended by the designer.

b. Determining True Position of the Flight Inspection Aircraft

In order to compute the error in a navaid, flight inspection airplanes must be equipped with an independent positioning computer that does not depend on the navaids being evaluated. The International Civil Aviation Organization recommends that the error in the positioning system used as a truth source be at least five times smaller than that of the tolerance of the parameters being measured. The flight inspection computer can use a variety of positioning truth measuring systems to determine its true 3-D position with acceptable accuracy. One system, called “Hybrid GPS” uses multiple input sources and GPS. It is also possible to use Differential GPS, which uses a ground GPS unit. Hybrid GPS is the most frequently used truth system in the day-to-day operations of the FAA flight inspection program. The selection of the truth system depends on the application as each truth system in itself provides its own unique capabilities.

Although fairly accurate and stable, the Hybrid GPS truth system by itself is not accurate enough for inspecting precision landing systems without additional data inputs to provide an improved horizontal and vertical position. A TeleVision Positioning System (or TVPS) provides this additional data.

When the flight inspection computer uses the Hybrid GPS truth system with TVPS for the precision landing systems, it combines data inputs from a specialized Inertial Reference Unit, a GPS receiver, a TVPS camera (and computer unit), a barometric altimeter, and a radio altimeter.

Position information from the onboard Inertial Reference Unit, GPS receiver, and barometric altimeter are all combined to provide an aircraft position up until the beginning of a precision approach. During level flight, the flight inspection computer uses the barometric altimeter input to calibrate the Inertial Reference Unit's vertical accelerometer bias. Once the aircraft begins the descent on the precision approach, the flight inspection computer extrapolates aircraft position using only the Inertial Reference Unit lateral velocities (N-S, E-W) and vertical velocities with all the accelerometer biases removed. This process continues until the aircraft reaches the runway end. During the approach, the TVPS camera takes pictures when the airplane crosses the runway threshold and runway end. The flight inspection computer uses the pictures to determine exactly when the aircraft crossed the runway threshold and runway end as well as the horizontal displacement from the center of the runway. The radio altimeter provides the aircraft's altitude above the runway at both fixes.

Once the flight inspection computer has processed the fixes, it extrapolates and recalculates the aircraft's path to provide improved position and velocity information for the entire preceding approach path. The flight inspection system can then accurately determine the errors of the navaid and data used for precision instrument landings at airports.

Another independent truth system is Differential GPS (DGPS). The DGPS truth system is much simpler than that of TVPS. It provides extremely accurate 3-D aircraft position throughout the approach. No runway fixes are required. Although DGPS is sufficiently accurate to update the flight inspection system, it requires that a reference receiver be set up at a surveyed location near the inspection site, which is a time consuming process.

c. Flight Inspection of an Instrument Landing System (ILS)

An Instrument Landing System consists of antenna arrays that provide an electronic beam for guidance of aircraft along their approach to landing. More specifically, it provides a signal that the aircraft is on the correct glide slope, i.e., the correct vertical path, and is on the extended runway centerline. The extended runway centerline information is provided by a signal from the "localizer" antenna (see Fig. 1) at the far end of the runway and the vertical information is provided by a signal from the "glide slope" antenna located beside the runway about 1000 ft from the approach end (see Fig. 2).

Fig. 1. Localizer Antenna

Fig. 2. Glide Slope Antenna

In some cases, the ILS electronics on the ground require adjustments to provide correct signals along the entire length of the approach. The flight inspection aircraft will complete several low approaches that fly along the runway at approximately 50 ft elevation making sure that the camera system captures the runway thresholds at both ends. After each pass, the technician on board the aircraft communicates with technicians on the ground and informs them what, if any, adjustments need be made to correct the glide slope and localizer signals within the required tolerances. A flight inspection to verify the accuracy and recalibrate the ILS is carried out every 270 days.

d. Flight Inspection of Approach Procedures

An "approach procedure" is a set of instructions to pilots that inform them of all information required to fly to a runway using a particular navigation system for guidance (see Fig 3). Many runway ends have more than one approach procedure; e.g., for a specific runway end, there might be an approach using an ILS, or a nearby en route navigation aid, or one using GPS. The data for each approach is published by the FAA (and other civil aviation authorities in other countries) and updated as required. Generally, there are some modifications published every 28 days and this information is made available to pilots through government publications and through private sources. Flight inspection identifies and corrects any problems due to poor survey data, incorrect database content, or poor design before commissioning a facility or publication of an approach. Many en route navigation aids do not have approach procedures associated with them;

however, they will be flight inspected periodically to ensure their accuracy for navigation. Because all ILS's do have a procedure associated with them, the flight inspection of the ILS accuracy and its approach procedure are typically carried out at the same time. Currently, there is a periodic flight inspection requirement to verify the accuracy of both en route navaids and ILS's. There is also an FAA requirement to flight inspect an approach procedure when it is commissioned and a periodic requirement thereafter. The periodic requirement is to assure the continued safety of the approach, primarily to assure that clearance is maintained from any new obstacles that may be introduced.

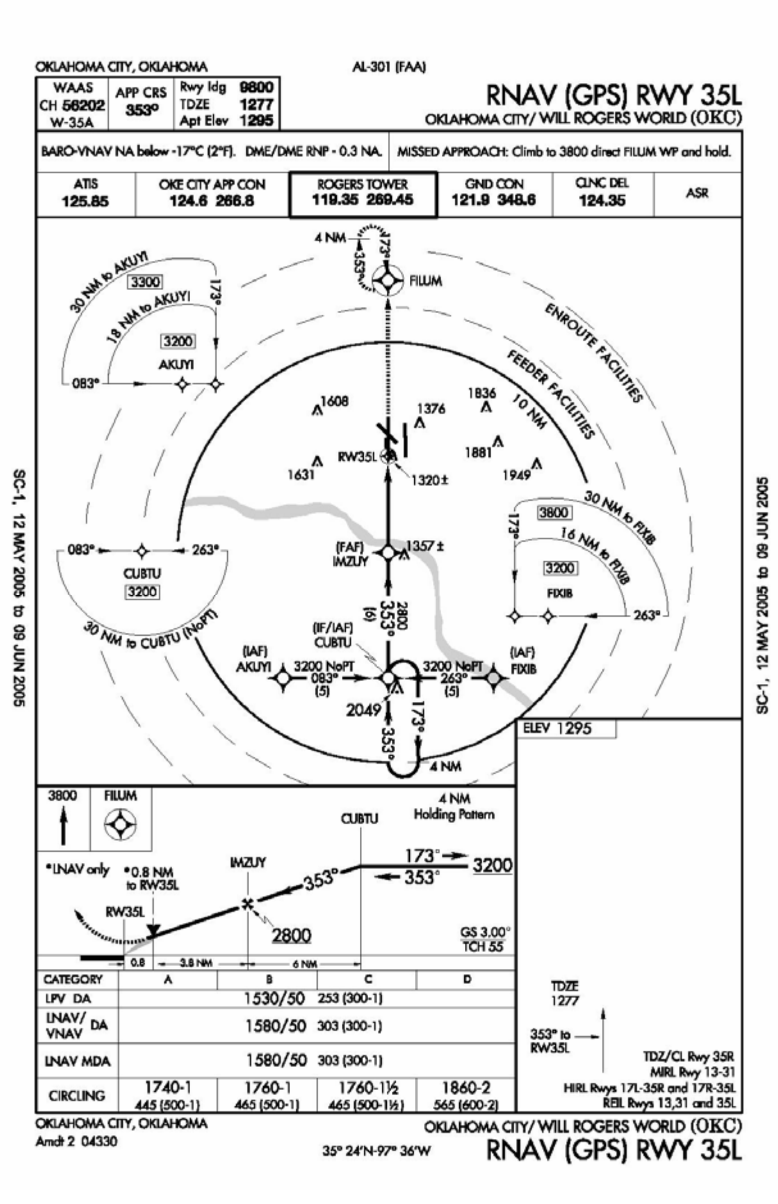

Figure 3. RNAV GPS Approach Procedure.

3. Flight Inspection of WAAS Procedures

WAAS is self-monitoring. It monitors, corrects, and bounds the errors in the system itself. This information is broadcast in real-time to the aircraft via the geostationary satellite signal. WAAS meets a six-second time-to-alarm, meaning that it will detect any violation of its confidence bounds and alert the pilot within six seconds of the error occurring. In addition, the FAA performs off-line monitoring of WAAS using a network of static ground receivers. This continual monitoring establishes the health of the overall system and ensures that the models used to form the real-time error bounds remain accurate over the life of the system. Flight inspection is not required to check the accuracy of the WAAS system.

a. Flight Inspection for Procedure Safety

It is essential to perform flight inspection prior to commissioning a new approach for data base integrity, for interference from nearby transmissions, for obstacle clearance, and for procedure flyability. A new WAAS approach is designed by using the surveyed coordinates of the runway and databases containing local terrain, obstacles, and location of landing surface. The approach designer uses databases to construct a WAAS LPV approach. The data contains critical elements used in the development of the final approach segment of the designed procedure including the data used for the descent glide path and course alignment. This information is coded into binary files by the procedure developer and the integrity is then protected with a redundancy check, a test to see whether data has been transferred without corruption. The sender of the data adds a check number to the end of the data being sent. The receiver applies the same check to the data and compares the number it gets with the check number. If they don't match, the data errors must be resolved. This process is used throughout the entire instrument approach procedure development process. This ensures the same data was used to develop, flight inspect, and chart the procedure. The approach may look very different through the windshield of the cockpit than it did on the approach designer's desk. A very important safety assessment is the qualitative evaluation of the designed approach. Flight inspection must verify the accuracy of the runway survey point. Any database error could render an approach unsafe. Figure 4 shows an actual case where an error in the database manipulations caused a substantial offset in the designed approach from the actual runway. This situation was discovered by flight inspection and corrected before the approach was commissioned.

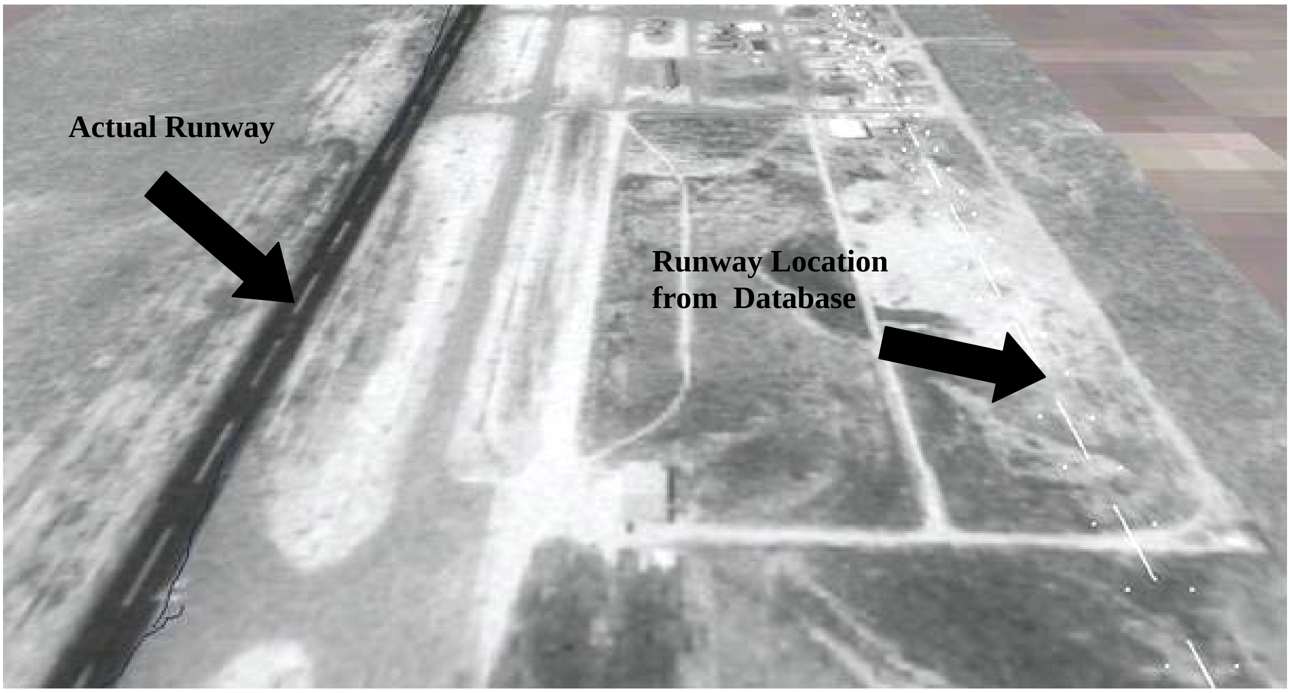

Figure 4. Moriaty NM – RWY 26/08

All procedures must be flight inspected to check the databases for errors and correct the error before publication. Flight inspection also verifies the approach data supporting the procedure and its relationship to actual obstacles and terrain. This is an important safety component of the flight inspection. Any significant obstacles not in the database or erroneously reported in the database must be identified and reassessed by raising the minimum altitudes and/or changing the final design of the approach. Finally, flight inspection verifies that the WAAS signal is received and reliable throughout the approach and that there are not any sources of interference that prevent the aircraft from receiving GPS or WAAS signals. The flight inspection aircraft identifies potential sources of interference because it is equipped to detect and locate interference sources. Illegal or unintentional interference sources are eliminated, while other sources may result in operational restrictions or even termination of the approach from planned publication. Flight inspection is essential for aviation safety of all instrument flight procedures.

4. Unique Aspects of SBAS

a. Continental Drift

SBAS's are unique in that they require no specific local infrastructure at the airport. This makes it extremely simple to plan new procedures. The performance of the system at the location is known beforehand, so procedures need only be designed for airports that are known to meet the requirements. One interesting consequence from having no local equipment arises from the fact that airports are actually in motion. Although we may not realize it directly, the surface of the Earth is composed of plates that move with respect to one another. Therefore, a particular runway may shift compared to the SBAS reference stations leading to an error in the guidance.

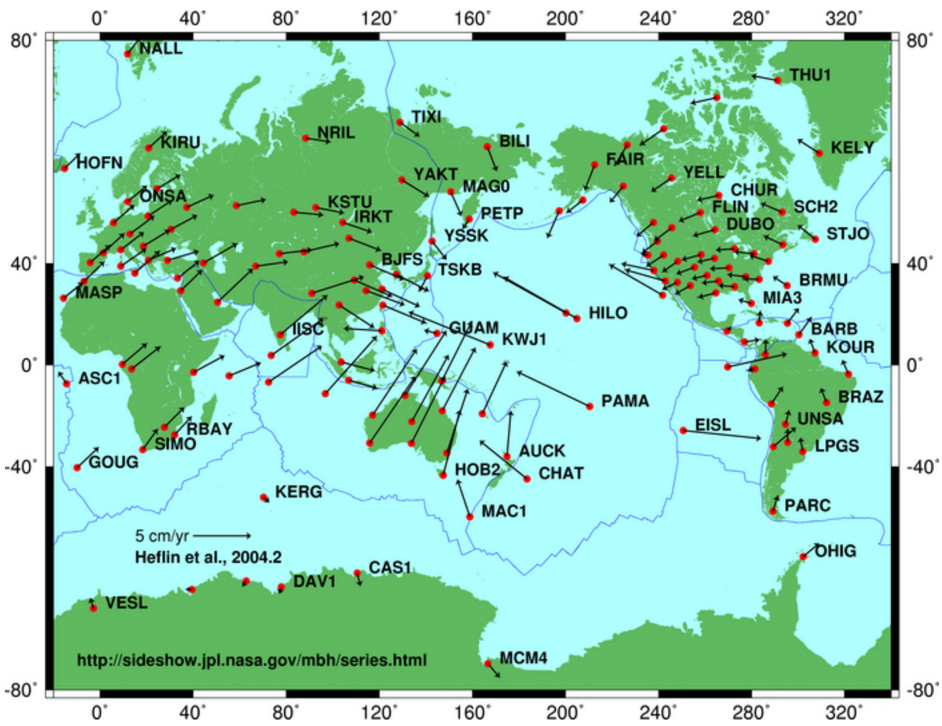

Figure 5. The velocity of various reference points around the Earth (figure courtesy of JPL: http://sideshow.jpl.nasa.gov/mbh/all/images/global.jpg)

Figure 5 shows the velocity vectors for various points around the world as well as the approximate plate boundaries. For the most part, the North American velocities are small and in the same direction. The exceptions are the western part of California and Hawaii. Here the relative velocities can reach 5 cm/year. Thus, over ten years there could be a half-meter error in the survey point for a runway in those regions. While this does not represent a hazard to an LPV approach, at some point it will be necessary to update the survey points for the runway. The vectors shown in Figure 5 are horizontal motion only. Fortunately, the vertical motion is over an order of magnitude smaller, so the height of the runway changes by only a few centimeters even over ten years. Thus, the horizontal motion will spur an update to the waypoints long before any vertical motion would require a change.

This effect is analogous to the change in magnetic variation over time. The magnetic north pole and the Earth's true north pole are not at the same place. The correction to the compass measurement to obtain true north is the magnetic variation. However, the magnetic north pole is not constant. It is in motion relative to the true pole. Therefore, the measured compass heading for a particular runway will change over time even though the orientation of the runway on the ground has not changed. If the magnetic heading changes sufficiently, the runway number and charts will need to be updated. Similarly, when the SBAS reference stations and runway drift sufficiently far apart, the waypoints for the approach procedure will need to be updated.

Because the change is small and well known in advance, an update to the station coordinates would not need to be flight inspected for a continental drift update. The update will likely be less than a meter and in a direction that is easily predicted years in advance. As long as the integrity of the database can be maintained, the new waypoint does not need to be verified by conducting approaches.

For a seismic event (earthquake), flight inspection is also probably not required. The changes are likely small and not easily discerned on approach. The runway condition and local environment will be inspected by ground crews. For a large change in position, it is possible that flight inspection could be desired. The exact shift of the waypoints is less predictable, so it would depend on the level of confidence in the new measurements. If the new waypoints have a sufficient degree of confidence, then no flight inspection is required. If the measurement process is not completely trusted, then a new flight inspection should take place.

5. Conclusions and Recommendations

SBAS approach procedures must be flight inspected prior to commissioning. The flight inspection verifies that the published approach information is correct. In particular, the acceptability of the waypoints, the obstacle clearance environment, the interference environment, the pilot workload, and the overall procedure design are assessed. Any problems due to poor survey data, incorrect database content, obstacle clearance, signal interference, or poor design are identified and corrected before commissioning. A flight check is essential to ensure the safety of the procedure.

Once a WAAS approach has been successfully commissioned, it is now FAA policy to carry out periodic flight inspections in order to ensure that no new obstacles or interference sources have been introduced. However, obstacles can be monitored by means other than flight inspection. New construction can be monitored by the airport manager's office, as is the current policy in the UK. Pilots should report problems with signal reception so that the civil aviation organization (e.g., FAA) and the office of the airport manager can investigate. With sufficient reporting by pilots and monitoring by the airport managers, it appears as if periodic inspection of SBAS approaches might not be required.

References:

[1] FAA/William J. Hughes Technical Center, "Wide-Area Augmentation System Performance Analysis Report #12 January 1 – March 31, 2005," May, 2005, available at http://www.nstb.tc.faa.gov/.

[2] Cabler, H. and DeCleene, B., "LPV: New, Improved WAAS Instrument Approach," in Proceedings of ION GPS-2002, Portland, OR, September 2002.