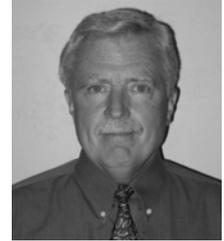


WAAS/LPV Flight Inspection and the Importance of Database Integrity and Standardization

Gary A. Flynn

Engineering Manager
Aviation System Standards
Federal Aviation Administration
Oklahoma City, Oklahoma, USA
Fax: 405 954 4740
E-mail: gary.a.flynn@faa.gov



ABSTRACT

The FAA is committed to providing Global Positioning System/Wide Area Augmentation System (GPS/WAAS) based instrument approach capability at all large and medium-sized airports throughout the U.S. As part of this initiative, Aviation System Standards (AVN) has developed a process for establishing GPS/WAAS-based instrument approach procedures; i.e., WAAS/LPV. Early during this development, it became apparent that satellite-based navigation posed new challenges for flight inspection. Two of these challenges are discussed herein.

One challenge was to accommodate the change in how cockpit guidance is derived. With the Instrument Landing System (ILS), guidance is obtained directly from the signal in space; pretty much the same principal with the Microwave Landing System (MLS). WAAS requires a more-complex solution, utilizing both runway survey data and an associated Final Approach Segment (FAS) data block definition.

A second challenge was associated with the increased criticality of runway survey data. When inspecting ILS, we are concerned only with local geometry; any error with respect to a worldwide datum is of little consequence. WAAS/LPV is a different story. Since cockpit guidance is influenced by the runway survey data, the FAS data block definition, and the GPS/WAAS signal, we must ensure that all three are accurate and can be related to the same geodetic datum.

Although AVN has successfully met the first challenge, work remains toward conquering the second.

INTRODUCTION

AVN began WAAS Research and Development (R&D) work, using experimental equipment, in 1999. By 2004, AVN had established procedures and policy deemed adequate to begin inspecting WAAS/LPV approaches.

Figure 1 is a photograph of the Engineering Lab at Oklahoma City and Figure 2 shows the WAAS installation in an FAA Learjet Model 60.



Figure 1. Engineering Lab – WAAS Simulation

After several months of flight checking WAAS/LPV approaches, flight inspection technicians began questioning our results and our evaluation criteria. Due to my prior work analyzing inspection data for the NASA Space Shuttle Microwave Scanning Beam Landing System, I was brought in as an independent consultant to the WAAS/LPV program. After a cursory review of the inspection process and logged results, I recommended halting further development of WAAS/LPV approaches pending a full-scale technical review. AVN management agreed and, in January 2005, launched a full-scale technical review.

It is not the intent of this paper to delve into the technical details of my audit of the WAAS/LPV flight inspection program but rather to focus upon two consequential topics: the determination of WAAS/LPV vertical guidance and the importance of database integrity and standardization.



Figure 2. Multi-Mode (WAAS) Receiver (MMR) Installation in Lear 60

DEFINITIONS

Along Track (ATK) – Horizontal path along runway centerline extended.

Best Fit Straight Line (BFSL) – A straight line average (using standard linear regression methodology) of the vertical guidance path. For WAAS/LPV, the guidance path is averaged over the range of 5.0 nautical miles (from threshold) to threshold.

BFSL TCH – The vertical distance from the runway surface at threshold to the BFSL path.

Geoidal Separation – At any given point, the vertical distance from the ellipsoid to the geoid. Also referred to as *geoidal undulation*.

Guidance Path – The “on course” approach path, relative to the runway, projected by the navigation system. With the aircraft (antenna) on this path, the navigation system would report zero vertical and zero lateral deviation from the desired approach path.

Height above Ellipsoid (HaE) – The vertical distance from the ellipsoid to a given point.

Threshold Crossing Height (TCH) – The vertical distance from the runway surface at threshold to the approach vertical path. In the context of this paper, TCH is relative to the WAAS/LPV vertical guidance path.

Vertical Guidance Path – The vertical component of the guidance path.

WAAS/LPV VERTICAL GUIDANCE

As mentioned within the abstract, WAAS/LPV cockpit guidance is derived using methods that differ from those used by ILS and MLS. This difference increases the importance of establishing a careful understanding of exactly what we are checking during flight inspection.

Why do we Care about Guidance? Isn't WAAS so Accurate that There's no Need to Check it?

This was one of FAA's assertions while developing the initial inspection criteria – WAAS is so accurate that there is no need to check guidance accuracy. When AVN's Automated Flight Inspection System (AFIS) reported runway threshold crossing heights (TCH) that varied from -100 feet to +300 feet above ground level (AGL), panel technicians became suspicious! As a result, this reporting of questionable TCH measurements became the catalyst that triggered AVN's in-depth technical audit of the WAAS/LPV flight inspection program.

Although the accuracy of the WAAS signal-in-space was never thought to be the cause of these anomalous TCH results, it soon became apparent that measurement of the WAAS guidance TCH was an excellent indicator as to the accuracy and integrity of the WAAS/LPV procedure and supporting data.

What is WAAS/LPV TCH? – The Simple Answer

During the early weeks of the technical audit, it became apparent that, in order to properly measure TCH, we must have a good understanding of exactly what it is and how to describe any error associated with it.

At first glance, it might appear simple to define TCH; it's simply the vertical distance from the runway surface to the WAAS/LPV guidance path at threshold. Later within this paper, we will provide a more meaningful definition; i.e., Best Fit Straight Line (BFSL) TCH. Even using the simple interpretation, we must still define the WAAS/LPV vertical guidance path.

Final Approach Segment (FAS) Data Block

Before we can describe the WAAS/LPV vertical guidance path, we must identify the desired path; i.e., the approach specification. In an effort to ensure data integrity, WAAS/LPV approach specifications are packaged into standardized data blocks that contain alteration detection in the form of a cyclic redundancy check (CRC) code. These data blocks are referred to as final approach segment (FAS) data blocks and are described in RTCA document DO-229C. [1]

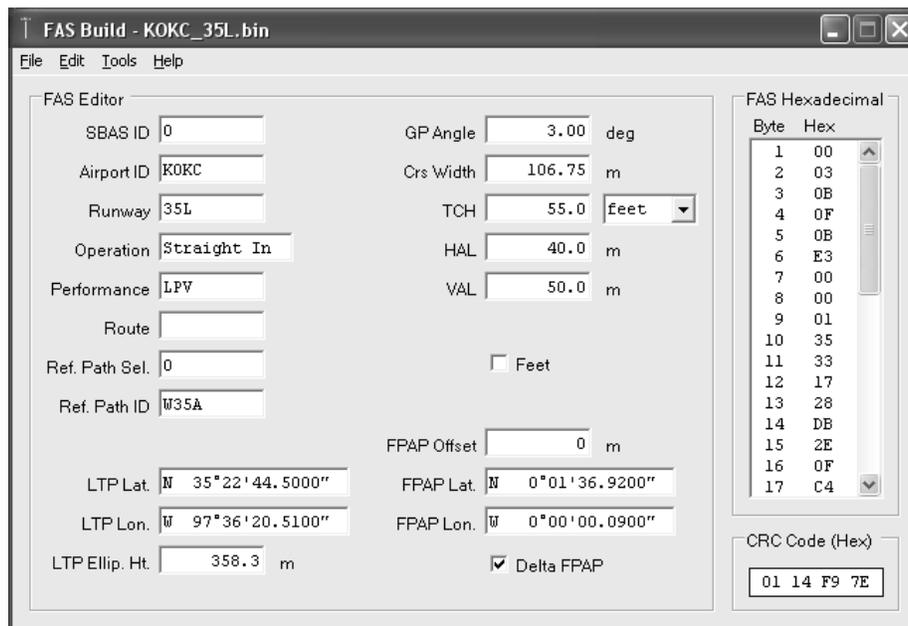


Figure 3. FAS Build Tool

Figure 3 provides a screen shot of an automated tool used to build FAS data blocks. From the figure, the reader can see the various fields that comprise the FAS data block, including the 32-bit CRC code. A few of interest:

- LTP – Landing Threshold Point. Typically, corresponds to runway threshold.
- FPAP – Flight Path Alignment Point. Used with LTP to horizontally align the approach. Typically, located on runway centerline extended, at or beyond runway end.
- FPAP Offset – Along-track distance from runway end to FPAP. A non-zero value corresponds to an FPAP beyond the runway end point.

WAAS/LPV Vertical Guidance

For reference, Figure 4 illustrates the process for deriving vertical guidance path for ILS. In simple terms, it is the

glideslope deviation (DDM in figure) superimposed upon the aircraft's actual vertical position relative to the runway. As shown in the figure, vertical error is simply the difference between the vertical guidance path and the desired approach path.

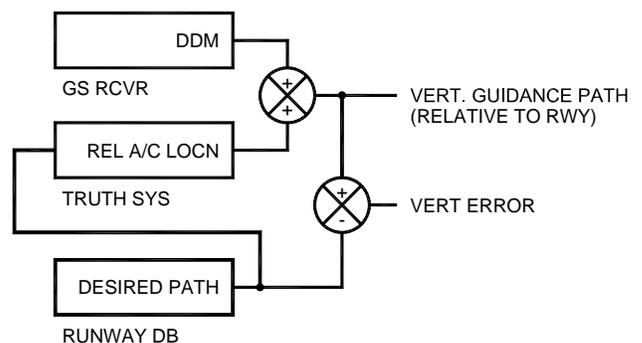


Figure 4. ILS Vertical Error and Path

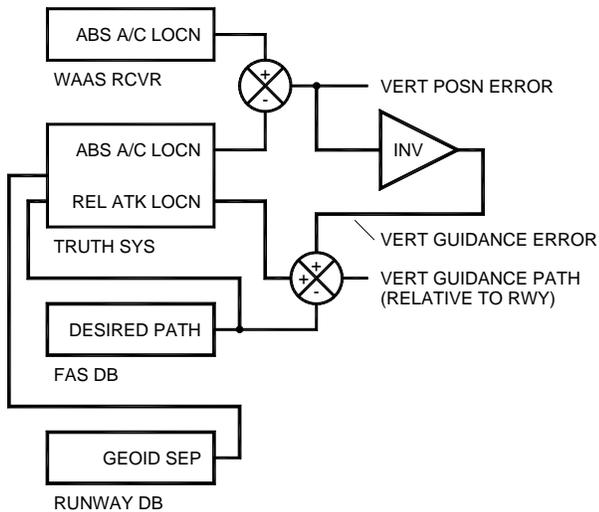


Figure 5. WAAS/LPV Vertical Error and Path

Since WAAS does not provide guidance directly, we must derive guidance based upon *perceived* WAAS positioning error.

Refer to Figure 5. Unlike glideslope, we must first calculate vertical error and then superimpose this error upon the desired path. Notice that we must invert the computed WAAS vertical positioning error in order to obtain WAAS vertical guidance error. The need to reverse the orientation of this parameter is not necessarily intuitive and was originally overlooked during the development of WAAS/LPV flight inspection requirements.

Figure 6 provides a graphical representation of this orientation reversal. Within the figure, see that the WAAS vertical guidance error \ominus is equal in magnitude but opposite in direction to the WAAS vertical position error \oplus . In order to illustrate this reasoning, let us take the case in which the system (WAAS) believes the airplane is 10 feet below path when it is actually on path (negative positioning error), it will attempt to raise the airplane 10 feet (positive guidance error).

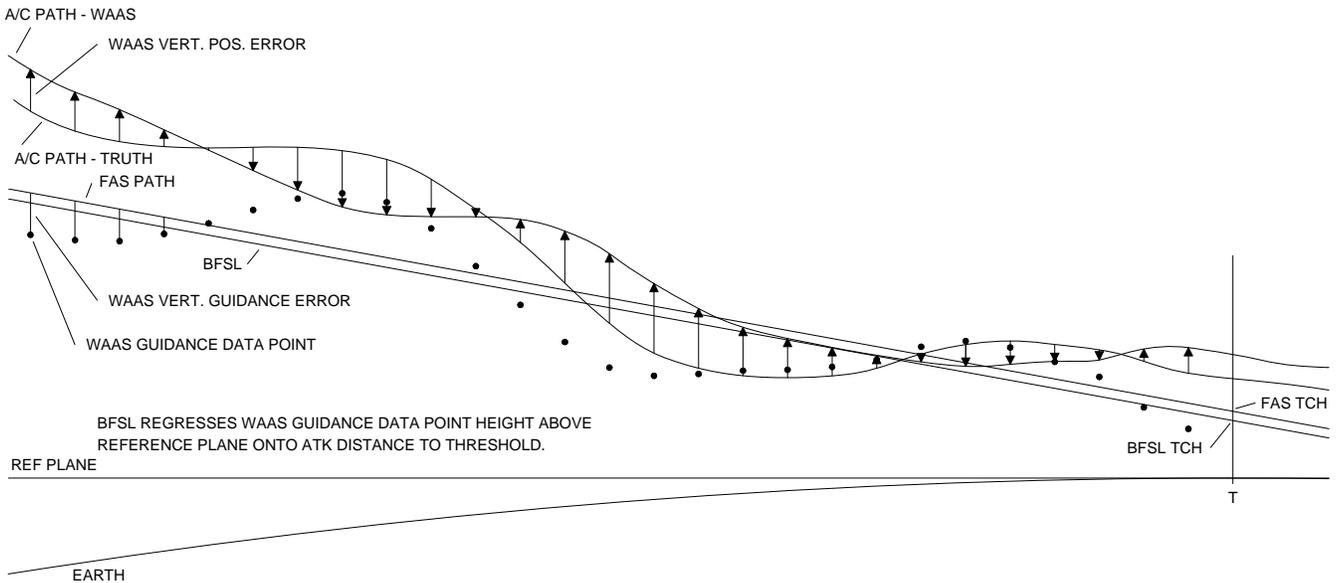


Figure 6. WAAS Vertical Guidance Data Points

Along Track (ATK) Error

Any WAAS positioning ATK error will certainly impact the WAAS vertical guidance path. A 50-foot negative error (delay) would slide the vertical guidance path (horizontally) 50 feet closer to the runway (guidance error is inversely proportional to positioning error). Two methods for compensating for ATK error are briefly discussed herein.

Note: For an in-depth discussion of the formulas used, refer to AVN Engineering Report 05-16. [2]

Along Track Error Compensation – Tangent Method

Refer to Figure 7. In this method, the distance that the WAAS forward (FWD) error (eF) displaces the data point vertically, with respect to the FAS path, is appended to the WAAS UP error (eU).

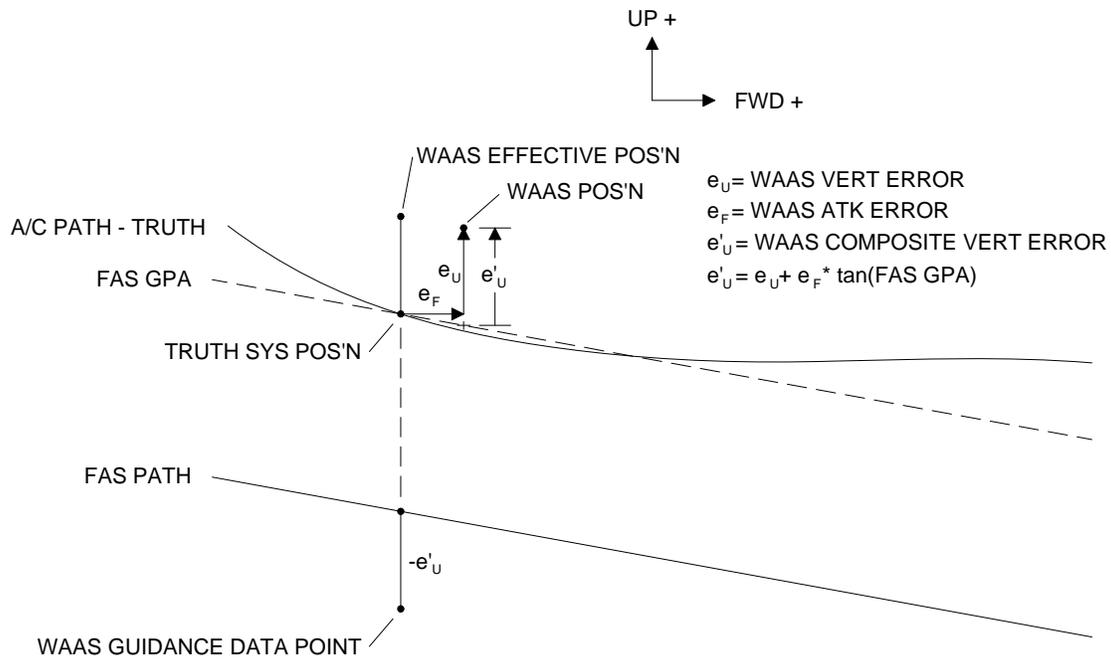


Figure 7. Compensating for ATK Error – Tangent Method

Along Track Error Compensation – Vector Method

Refer to Figure 8. In this method, the combination of WAAS FWD and UP errors is projected onto the FAS path. Although this eliminates the need for an extra tangent computation, it slightly complicates the calculation of the FWD component of WAAS guidance.

Either method for ATK error compensation should work equally well and produce an identical result. At a 3-degree glide path, the ratio of ATK error to vertical guidance error is roughly 20:1 ($\tan 3^\circ$). In other words, a 30-foot ATK error would result in a 1.5-foot vertical guidance error.

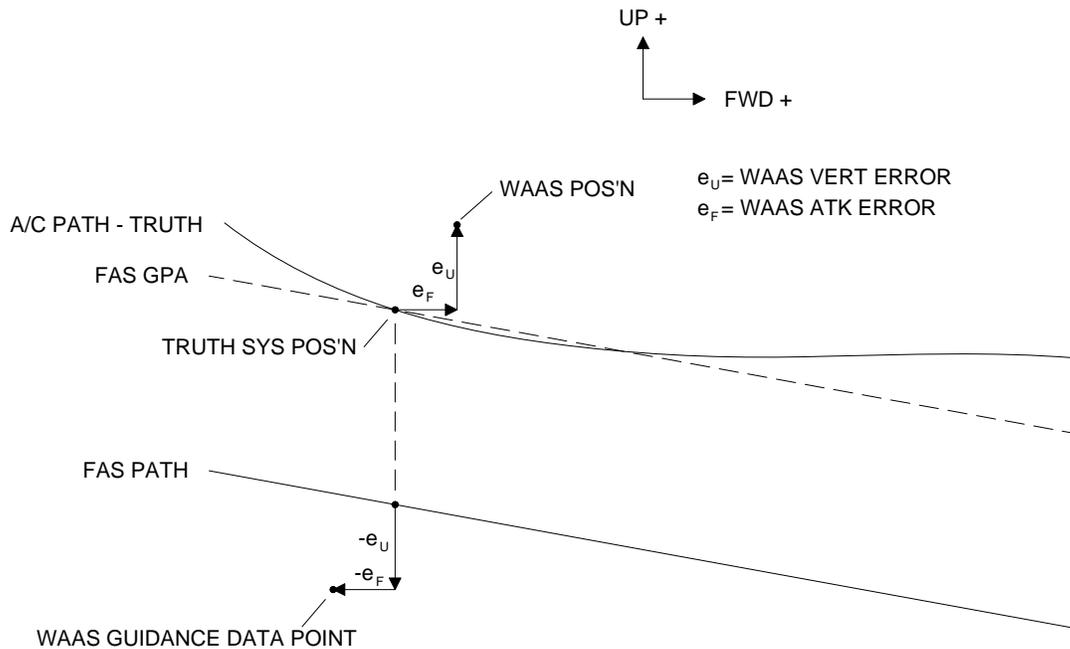


Figure 8. Compensating for ATK Error – Vector Method

Best Fit Straight Line (BFSL)

In order to obtain a more accurate assessment of the WAAS/LPV approach guidance path and remove any anomalous distortion, a straight-line average is created. For WAAS/LPV, the guidance path is averaged over the range of 5.0 nautical miles (from threshold) to threshold using standard linear regression methodology. For an in-depth discussion of the formulas used, refer to AVN Engineering Report 05-16. [2]

Figure 6 illustrates the BFSL path. Notice that the BFSL path parallels the FAS path (same vertical path angle). This is typical when inspecting WAAS/LPV approaches. Any significant difference between the two would likely point to a problem in the flight inspection truth system rather than with GPS/WAAS.

DATABASE INTEGRITY AND STANDARDIZATION

The second topic of this paper is the importance of database integrity and standardization. During development of WAAS/LPV, it became apparent that data was often a larger contributor of error than the GPS/WAAS signal in space. Whereas GPS/WAAS error is statistically bounded, data errors are not and can easily create catastrophic results.

When inspecting ILS, we are concerned only with local geometry; any error with respect to a worldwide datum is of little consequence. WAAS/LPV is a different story. Since cockpit guidance is influenced by the runway

survey data, the FAS data block definition, and the GPS/WAAS signal, we must ensure that all three are accurate and can be related to the same geodetic datum.

Database Integrity

Database integrity refers to the “correctness” of the data within the database. During my technical audit of our WAAS/LPV approach development program, I reviewed hundreds of database and flight inspection log files. Figure 9 depicts our data flow, from survey data on the left to flight inspection log files on the right. To support the technical audit, two automation efforts were performed:

- The existing *FAS Pack* tool, previously used to combine multiple FAS data blocks into a single file, was enhanced to provide extensive validation capability. This enhanced tool will detect any inconsistency that might exist among the AFIS runway database, the National Geodetic Survey (NGS) database, and the FAS data block.
- A new tool, *WAAS Extract*, was created to perform step-by-step and statistical analysis of the AFIS log files. Development of this tool required a tremendous effort since the tool had to independently duplicate most of the mathematical computations performed within AFIS for inspection of WAAS/LPV.

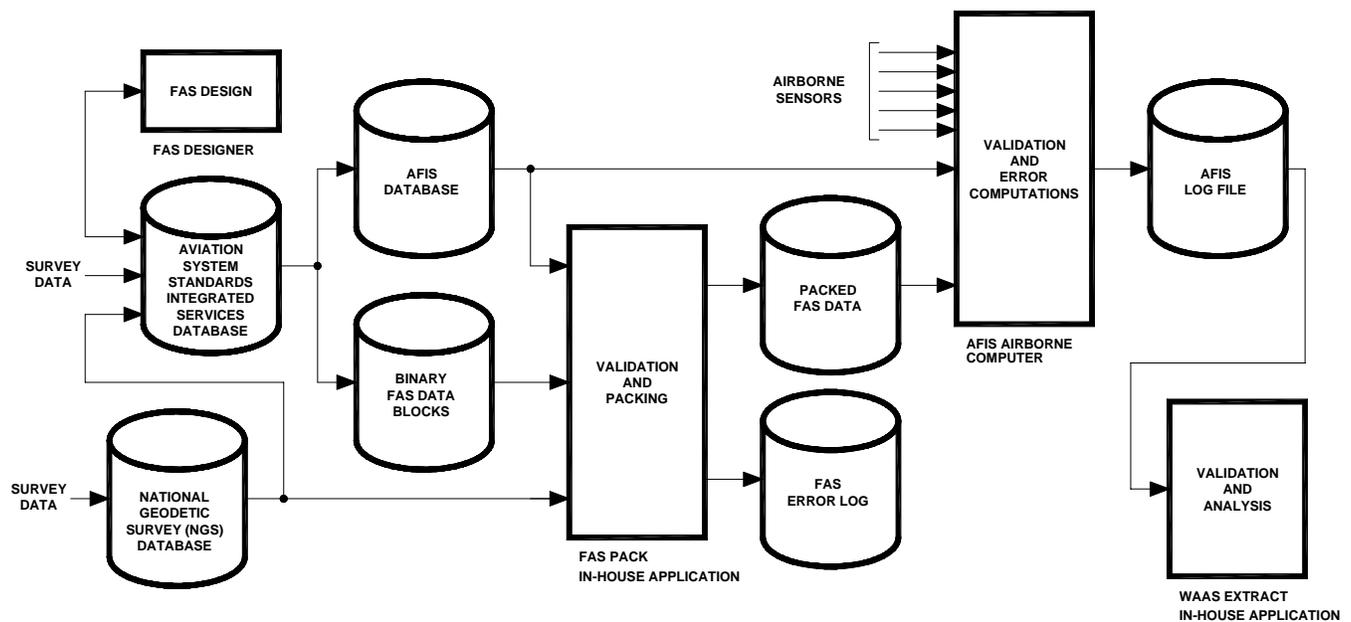


Figure 9. Data Flow – WAAS LPV Flight Inspection

Even though the focus of the technical audit was the set of computations performed within the AFIS computer, it soon became apparent that errors could arise from just about anywhere. Although most errors associated with the FAS data block were introduced during the design of the FAS, other sources were evident:

- Survey data
- Transfer of survey data into database
- Latent errors within the runway database
- Runway database filter algorithm
- Differences in geodetic datum

Note that these errors are not unique to the flight inspection process, but could very well be found in any FAS development. This fact underlines the importance of flight inspecting the approach procedure.

Figure 10 is a partial screen shot of the FAS Pack tool being used to review an actual FAS data block. In this example, the FAS data block LTP ellipsoidal height field contained a 363-foot vertical error. FAS Pack detected this error by comparing FAS geoidal separation with that from the National Geodetic Survey. The FAS geoidal separation was computed by subtracting the runway threshold orthometric height (363.4 ft) from the FAS LTP ellipsoidal height (650.9 ft), resulting in a difference of 287.5 ft. In the example, the NGS geoidal separation was reported to be -75.9 ft.

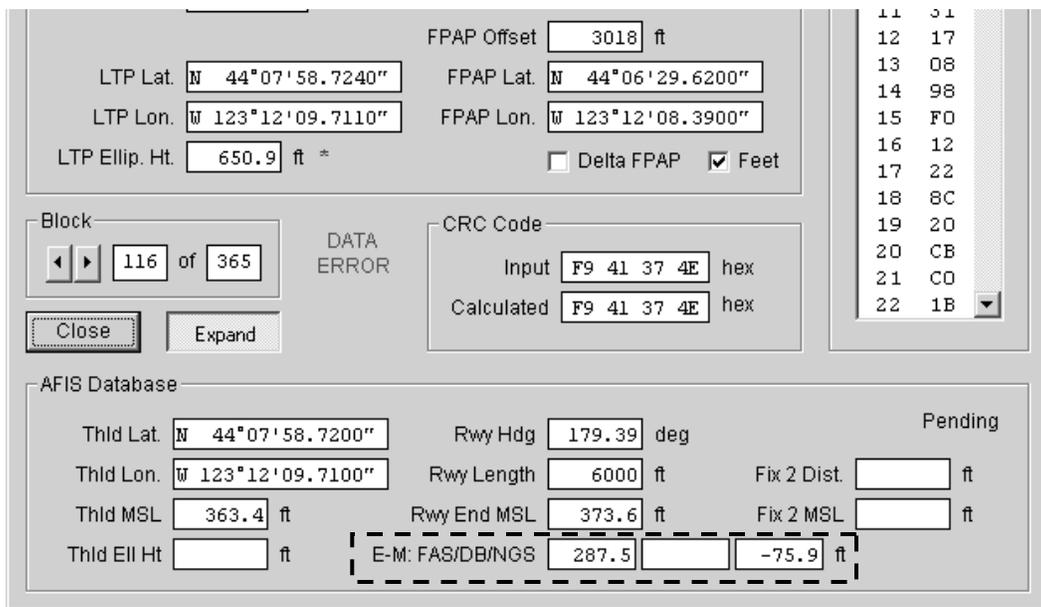


Figure 10. Partial Screen Shot from FAS Pack Tool

Database Standardization

As stated previously, the technical audit of our WAAS/LPV flight inspection program required a tremendous effort and spanned many months. Even when we felt that we had identified and eliminated each and every source of error, we continued to see an overall vertical bias of our TCH results. Although this was characterized as the “four-foot offset,” the bias changed somewhat with location.

AVN performed many tests, both in the aircraft and in the lab, in an effort to identify the source of this problem. These tests included the use of multiple truth systems, post-flight analysis, static aircraft and lab tests, as well as use of multiple WAAS receivers.

AVN was unable to reconcile this vertical bias until April 2006 when it was discovered that AVN was populating WAAS final approach segment (FAS) data blocks with NAD83 [3] based runway altitude while WAAS is using WGS-84 (ITRF 00) [4] as its reference.

NAD83 vs. WGS-84

Refer to Figure 11. When the NAD83 reference frame was originally computed, every possible effort was made to keep it exactly the same as the WGS-84 reference frame used by the GPS: the BIH Terrestrial System of 1984. [5] The two reference frames were essentially equivalent at that time. Since that time, the center of the earth's mass has been more precisely determined and, as a result, the point of origin of the WGS-84 datum has been shifted about 2 meters from its original location.

NAD83 did not move along with it. As a result, the NAD83 datum and WGS-84 datum are no longer coincident.

Note: For more information concerning this issue, refer to Ohio University report 06-27. [6]

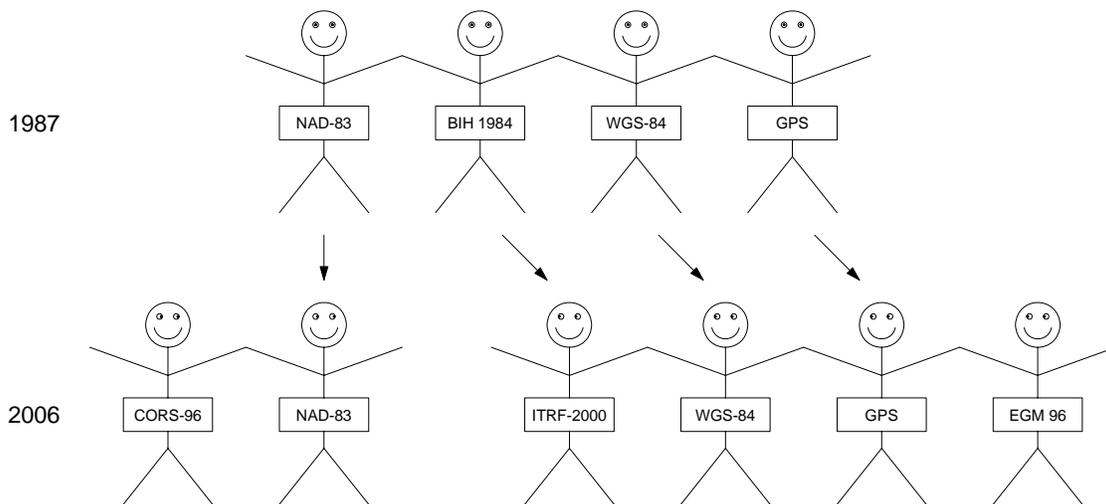


Figure 11. NAD83 and WGS-84 Drift Apart

FAA’s Dilemma

FAA document 405, [7] which provides standards for performing U.S. aeronautical surveys, specifies NAD83 to be used for surveys. RTCA DO-229C [1] states that FAS data blocks shall contain runway threshold elevation based upon WGS-84.

Table 1 lists the difference between WGS-84 height above ellipsoid (HaE) and that of NAD83, for various points across the U.S. As can be seen from the table, this difference is approximately 4 feet for Oklahoma City.

Analysis verified that the orientation of this difference is consistent with the vertical bias reported during flight test in and around the Oklahoma City area.

Discussion continues within the FAA as to whether or not FAS data blocks should contain WGS-84 coordinates rather than NAD83. As of the writing of this paper, FAA continues to populate the FAS data blocks using NAD83 coordinates. The recent reduction of the WAAS/LPV approach minimum decision height, from 250 feet to 200 feet, strengthens the argument for WGS-84.

Table 1. NAD83 vs. WGS-84 HaE Sample Data Points

Airport	Ident	Runway	Latitude Longitude	NAD83 Vertical Error
Will Rogers World (Oklahoma City, OK)	KOKC	17R	N 35° 24' 21.4200" W 097° 36' 20.6000"	3.7 ft
Daytona Beach International (Daytona Beach, FL)	KDAB	07R	N 29° 10' 33.7160" W 081° 03' 24.6303"	5.0 ft
Denver International (Denver, CO)	KDEN	07	N 39° 50' 27.4000" W 104° 43' 35.9700"	2.9 ft
Los Angeles International (Los Angeles, CA)	KLAX	06L	N 33° 56' 56.7900" W 118° 25' 52.1600"	2.3 ft

Other Survey References

The previous discussion might imply that there are only two coordinate systems at play when concerning ourselves with consistency of FAS data. Nothing could be further from the truth. Many of the WAAS/LPV approaches produced by the FAA are based upon legacy

survey data. Many of these surveys were performed using orthometric coordinate systems such as the North America Vertical Datum 1988 (NAVD88) and the National Geodetic Vertical Datum 1929. [8] Figure 12 illustrates the cumbersome processes that must be followed when converting altitude information from one coordinate system to another.

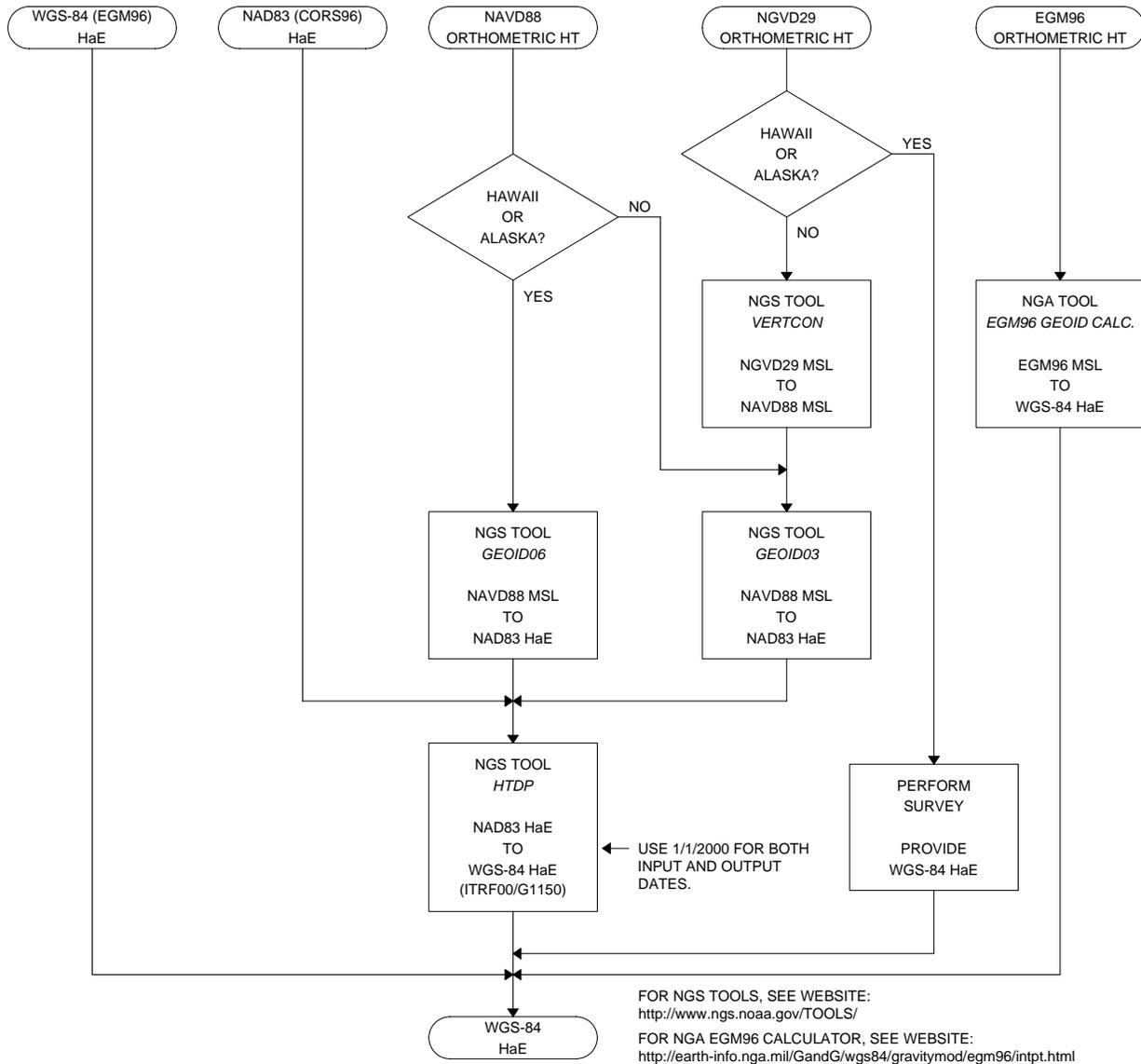


Figure 12. Mixed Datum Altitude Transformations

CONCLUSIONS

This paper touched upon two topics: WAAS/LPV TCH and pitfalls surrounding databases. My concluding points:

a. It is imperative that flight inspection policy establish exactly what is being checked.

b. BFSL TCH provides a good figure of merit for the WAAS/LPV approach.

c. Database accuracy and standardization are larger contributors to WAAS/LPV approach problems than the actual signal in space.

- d. Due to the susceptibility of the WAAS/LPV to survey errors and the multiplicity of opportunities for errors to enter the development process, it is imperative that an end-to-end check be performed to ensure correctness (i.e., flight inspection).

REFERENCES

- [1] RTCA, 28 November 2001, Minimum Operational Performance Standards for Global Positioning System/Wide Area Augmentation System Airborne Equipment, DO-229C
- [2] FAA/AVN, 4 April 2005, WAAS LPV Best-Fit Straight Line, Engineering Report 05-16
- [3] National Geodetic Survey, National and Cooperative CORS,
<http://www.ngs.noaa.gov/CORS/coordinates/>
- [4] National Geospatial-Intelligence Agency (NGA), 3 January 2000, Department of Defense World Geodetic System 1984, NIMA TR8350.2, Third Edition, Amendment 1
- [5] B. Guinot, History of Bureau International de l'Heure, Polar Motion: Historical and Scientific Problems, ASP Conference Series, Vol. 208,
<http://adsabs.harvard.edu/abs/2000ASPC..208..175G>
- [6] Ohio University, June 2007, Investigation of Threshold Crossing Height Variations for Wide Area Augmentation System (WAAS) Localizer Performance with Vertical Guidance (LPV) Approach Procedures, Technical Memorandum OU/AEC 06-27 TM15689/0001-2,
http://avn.faa.gov/content/fioo/pdf/06-27_Official_Final_Report_Body.pdf
- [7] Federal Aviation Administration, September 1996, Standards for Aeronautical Surveys, FAA No. 405, Fourth Edition, <http://www.ngs.noaa.gov/AERO/FAA405.htm>
- [8] National Geodetic Survey, NGS Geodetic Tool Kit,
<http://www.ngs.noaa.gov/TOOLS/>

Biography – Gary Flynn, FAA:

Gary Flynn began work for the Federal Aviation Administration immediately upon graduation from Oklahoma State University in 1974. Gary began as an Avionics Engineer, supporting FAA's flight inspection fleet.

In the late 70's, Gary was a key engineer in the upgrade of FAA's Semi-Automatic Flight Inspection System (SAFI). This required interfacing 1950's technology with a Motorola M6800 microprocessor.

In the late 80's, Gary was lead engineer for development of a new TACAN System, currently in use today.

In 2003, Gary was involved with incorporating flight inspection capability for NASA's Microwave Scanning Beam Landing System (MSBLS) into FAA's Challenger fleet.

Recently, Gary has been actively involved with development of FAA's Next Generation Automated Flight Inspection System.

In January of this year, Gary was promoted to Engineering Branch Manager.