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A TOOL FOR ESTIMATING AIRPORT ACCESS BENEFITS FROM GPS-BASED INSTRUMENT APPROACHES

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ABSTRACT

The MITRE Corporation developed a computer-based tool that estimates the Height Above Touchdown (HAT) and visibility minima for Global Positioning System (GPS) instrument approaches using electronic databases of terrain and obstacles. The model uses criteria from the U.S. Federal Aviation Administration (FAA) Terminal Instrument Procedures (TERPS) developed for GPS approaches, but can be modified to use different criteria. The design of the model allows the evaluation of a large number of runways, with subsequent analysis of the benefits of a particular approach procedure.

The development of wide area systems to augment the GPS has long promised the capability of providing or improving the instrument approach capability at many airports. In particular, one of the objectives of the Wide Area Augmentation System (WAAS) is to provide, where possible, straight-in instrument approaches with vertical guidance to all instrument capable runways in the USA.

There are over 5000 airports in CONUS that have at least one runway over 3000 ft long. At present, the minima for approaches with vertical guidance that would result from the development of WAAS are known for only a few runways. Using the present FAA approach design apparatus to estimate the minima for all the possible runways would be an impossibly long task.

Application of the MITRE Corporation computer model enables a timely high-level evaluation of HAT estimates for a large number of runway ends, and will eventually include considerations for airport infrastructure. This paper provides a statistical summary of preliminary results showing HAT and visibility benefits for approaches to a large number of airports in the USA, and also provides a comparison of approach minima between different classes of augmented GPS approaches. The intent of the analysis is to assist in the final design criteria for GPS approaches in the USA.

This paper is based on system analysis studies performed by the Center for Advanced Aviation System Development (CAASD), the MITRE Corporation for the FAA Satellite Program Office (AND-730). This paper reflects the views of the authors, who are responsible for the accuracy of the facts, analyses and suggestions presented herein, and does not reflect the official views or policy of the FAA.

BACKGROUND

The U.S. Federal Aviation Administration (FAA) and many other countries have declared the Global Positioning System (GPS) suitable as a supplemental means of navigation and have published criteria for use of the system. GPS can currently be used for oceanic, en route, terminal, and non-precision instrument approach navigation. At present, there are approximately 2500 GPS instrument approach procedures to airports in the U.S.

Nonprecision approaches provide horizontal guidance to the aircraft, but vertical profiles are flown using the aircraft barometric altimeter. Typically, the aircraft flies level at HAT until visually acquiring the runway or approach lights, after which the aircraft begins a descent to land.

An FAA goal is to improve aircraft safety by providing instrument approaches with horizontal *and* vertical guidance. These approaches provide a stabilized descent path for the aircraft, in addition to the horizontal guidance. This allows a constant rate of descent down the approach path—there is no need to level off, as in the nonprecision approach. Approaches with vertical guidance are currently performed by using ground-based Instrument Landing System (ILS). However, due to cost and other considerations, only about 1100 of the 4000+ instrument approach runways in the U.S. have ILS. Also, many airports and runways

do not have instrument approach capability at all. To address these concerns, the FAA is developing the Wide Area Augmentation System (WAAS). WAAS will augment GPS, and allow primary means satellite-based navigation in the U.S., including approaches with vertical guidance to nearly all instrument capable runways. For larger airports, the FAA is also developing the Local Area Augmentation System (LAAS). LAAS will provide approaches at individual airports with vertical guidance similar to WAAS, but with the very high availability necessary for larger airports, in addition to very low landing minima associated with Category II and III approaches. This paper will not consider Category II or III approaches.

An important consideration for GPS approaches is airport access. The presence of an instrument approach can significantly benefit airport users and enhance safety.

Currently, the FAA has published design criteria for three types of area navigation (RNAV) approaches using GPS. The *LNAV* approach provides horizontal guidance only, and is a nonprecision approach. Approximately 2000 LNAV approaches have currently been designed for U.S. airports. The *LNAV/VNAV* approach has a similar size area over which obstruction clearance criteria are evaluated, but provides horizontal and vertical guidance to the pilot during the approach. Only a few hundred LNAV/VNAV approaches have currently been developed. The *GLS* approach uses vertical and horizontal guidance of higher quality, and therefore has reduced obstruction clearance criteria. GLS approach criteria are essentially identical to criteria currently used to design Category I ILS approaches. Few GLS approaches have been developed.

The design of the approach dictates how low the pilot can legally descend without visual reference to the runway or approach lights. The lowest height, called the Height Above Touchdown (HAT), is determined by applying the criteria for the approach to terrain and obstacles that surround the airport. Different approach criteria (e.g., LNAV, LNAV/VNAV, or GLS) can produce different HATs for approaches to the same runway.

Although HAT is an important criterion for instrument approaches, current U.S. regulations use the flight visibility, expressed in statute miles, as the limiting factor for landing from an instrument approach. Typically the aircraft will arrive at HAT during the approach; if the pilot can see the runway or approach lights, then s/he may continue the approach. If not, then a missed approach must be initiated.

The required visibility minimum is computed in different ways for nonprecision approaches (i.e., LNAV) than for approaches with vertical guidance (i.e., LNAV/VNAV and GLS). For an LNAV approach, a table is used to determine the required visibility by using HAT and the aircraft category.* See Figure 1. The limiting visibility varies with HAT, but Category A and B aircraft can attain the lowest visibility (without approach lights†) of one mile if the HAT is 740 ft or less. Category C aircraft require an HAT of 400 ft or less to attain one-mile visibility. An LNAV approach normally results in the aircraft descending to HAT and flying level until the runway is in sight. For Category A/B, the descent gradient to the runway could be quite steep if the visibility is near the minimum (e.g., as steep as 740 ft per statute mile). However, these are generally small aircraft that have high maneuverability, and can also land farther down the runway if necessary. Category C aircraft, which are generally less maneuverable than Category A/B aircraft, would have a lower maximum descent gradient (e.g., 400 ft/statute mile), which is closer to the three-degree descent path normally flown on most approaches.

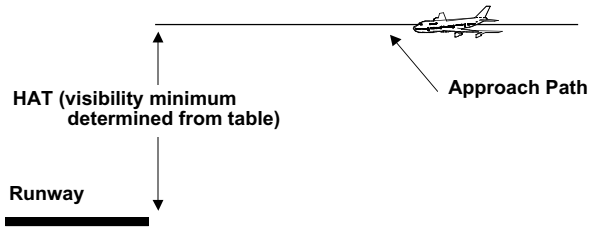

Figure 1. LNAV Visibility Minimum

The visibility minimum for an approach with vertical guidance (i.e., an LNAV/VNAV or GLS) is determined using a geometric method. In a vertically-guided approach, when the aircraft arrives at the HAT, the pilot must be able to see the runway and continue on the same descent path. Thus the horizontal distance from the point at which the descent path reaches HAT to the runway threshold determines the visibility minimum. See Figure 2. Like a nonprecision approach, the visibility minimum can be reduced with approach

* Aircraft category is based on the stalling speed of the aircraft. General aviation and commuter aircraft are usually Category A or B, while most airliners are Category C. Large airliners are usually Category D.

† The visibility can also be affected by airport infrastructure. For example, approach lights can reduce the required visibility, while runway length, pavement, and taxiway placement can increase the required visibility.

lights, or may be increased by other airport infrastructure considerations.

In general, we will measure airport access benefits primarily by the improvements to the visibility minimum of the instrument approach, with improvements to HAT as an important secondary benefit.

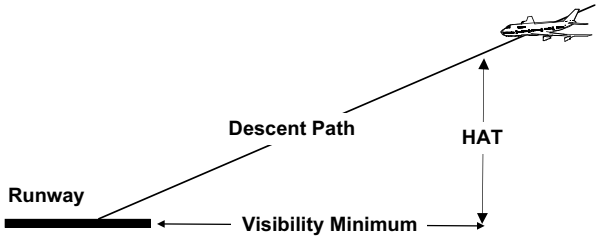

Figure 2. LNAV/VNAV or GLS Visibility Minimum

How can we estimate the airport access benefits of WAAS approaches? We can compare the HATs and visbilities of LNAV approaches to those of LNAV/VNAV and ILS (same criteria as GLS) approaches developed to the same runway. However, this would not provide estimate for the thousands of runways that have no vertically-guided approach, nor the runways that have no GPS approach at all. The current process used for developing instrument approaches, which is semi-automated and is performed by the FAA, takes weeks of elapsed time to develop an approach and determine the minimum visibility and HAT for one runway end. Estimating minima for thousands of runways is clearly impractical with this system.

Also, the FAA is still developing WAAS. The first phase WAAS Vertical Alert Limit (VAL) of 50 m will support LNAV and LNAV/VNAV approaches, but not GLS. There is active research to determine how to reduce the VAL performance limit. However, it is not clear what the access benefits will be from a reduced integrity limit. Evaluation of new instrument approach criteria is necessary to estimate the access benefits of proposed changes to the WAAS system—and the estimation for a large number of runways would be just as impractical using the current system.

THE GPS APPROACH MINIMA ESTIMATOR (GAME) MODEL

In order to assist the FAA in estimating airport access benefits for GPS approaches and to assess new criteria for approaches, The MITRE Corporation's Center for Advanced Aviation System Development (CAASD) developed the GPS Approach Minima Estimator (GAME). This computer model is based on a Unix workstation and is written in the C computer language. The output is ported to a PC, where results are analyzed in Microsoft Access.

The Model uses Digital Terrain Elevation Data (DTED) from the National Imagery and Mapping Agency (NIMA) to provide information on terrain features. Obstacle and runway data are contained in Exchange Files provided by the National Geodetic Survey's Aeronautic Survey Program for 1534 airports in the U.S. Additional obstacle data are provided by the FAA National Aeronautical Charting Office (NACO) in the Digital Obstacle File (DOF).

GAME first selects an Exchange File for an airport, locating the position and elevation of all of the runway ends at the airport. A terrain grid is constructed, and all obstacles within 11 miles of the airport center are identified.

After selecting one of the runway ends, GAME then selects a terrain point and evaluates the contribution of that terrain point towards the HAT of an LNAV, LNAV/VNAV, and a GLS approach to that runway. The three values are then stored, and the next terrain point is selected. After completing all the terrain points, GAME then performs similar calculations on each obstacle associated with the airport.

The evaluation of HAT is performed using FAA Order 8260.48, which provides the criteria for GPS instrument approaches. However, simplifications were made to GAME to reduce development, processing, and analysis time. As such, the model does not attempt to adjust or adapt an approach to optimize for terrain and obstacle locations, as would a human procedure developer. For example, the GAME analysis assumes that all approaches will use a 5 nautical mile final approach segment, and the model constructs approaches aligned with the runway centerline. This is a normal assumption, but a human procedure developer could make the final segment longer or vary the alignment slightly to avoid certain obstacles. Also, GAME does not yet calculate the contribution of terrain and obstacles on the missed approach path. Therefore, it is possible for an obstacle in the missed approach segment to cause the approach to have a higher HAT than the GAME estimate, although discussions with procedure designers indicate that these increases would usually be small. Also, GAME estimates of HAT for LNAV approaches do not employ step-down fixes to avoid obstacles or terrain in the final approach segment.

Also, GAME may be further limited by not having all data that a procedure developer may have. For

example, GAME is dependent on digital obstacle data for locations and elevations of man-made obstacles. FAA procedure developers use a detailed map in addition to digital data, which is inspected and validated for each approach.

Lastly, the current version of GAME does not account for limitations of airport infrastructure. For example, if the airport has approach lights, the visibility can be reduced over GAME's estimated values. If the airport runway is short, then the procedure developer will increase the visibility minima, but GAME will not. The lack of airport infrastructure can produce significant differences in visibility minimum for an approach to a runway.

We are currently improving GAME to include the initial portion of the missed approach segment, use step-down fixes in LNAV, and to include the limitations of airport infrastructure.

VALIDATION

In order to develop an estimate of the accuracy of the HATs produced by GAME, MITRE obtained data from the FAA that gave HATs for LNAV, LNAV/VNAV, and ILS for a set of runways for which FAA procedures have already been developed. MITRE then computed HATs for LNAV, LNAV/VNAV, and GLS approaches to those runways using GAME.

Figure 3 provides Box Plots for the differences between the FAA developed HAT, which we considered to be 'truth,' and the GAME HAT. Figure 3 is based on 62 runways for ILS/GLS and approximately 100 runways for LNAV and LNAV/VNAV. GLS HAT differences have the least overall spread, with the median difference equal to zero, and the 75th percentile at 50 feet. LNAV/VNAV are also quite satisfactory, with a median difference of -15 feet and a 75th percentile of -4 feet. The LNAV minima were more scattered, with a median difference of -30 feet and a 75th percentile of 2 feet. Other validation analyses are available on request.

Clearly GAME would be inadequate for actual design of instrument approaches. However, we believe that the current results indicate that GAME can estimate HATs for runways with accuracy suitable for a macro analysis. The slightly negative bias (i.e., the GAME HAT tends to be lower than the FAA HAT) is to be expected, since GAME calculations include neither the missed approach nor obstacles from maps, both of which will tend to increase the HAT.

Although we believe that GAME is working adequately, one must note that GAME is completely dependent on the accuracy of data files. FAA procedure developers routinely validate locations and elevations of obstacles and terrain, including trees and other vegetation. Due to the large number of airports, this is not possible for estimates using GAME. Thus, if an obstacle is missing, in the wrong place, has incorrect elevation, or has been removed, GAME may give incorrect estimates of HATs for approaches to that runway. Also, airports routinely conduct a detailed survey when installing an ILS or GLS approach. This survey may identify terrain and obstacles not contained in or different from the data used by GAME. This could also affect HAT.

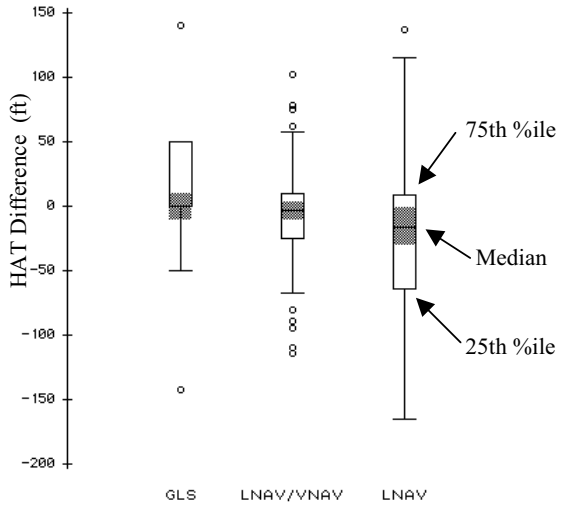

Figure 3. GAME HAT minus FAA HAT (ft) for GLS, LNAV/VNAV, and LNAV Approaches

The results presented in Figure 3 indicate that GAME provides adequate macro estimates of the HATs for approaches. Future plans include obtaining additional HATs from the FAA in order to provide a larger data set for validation.

PRELIMINARY ESTIMATES OF THE AIRPORT ACCESS BENEFITS OF LNAV/VNAV APPROACHES COMPARED TO LNAV APPROACHES

We used GAME to estimate the HAT and visibility for LNAV, LNAV/VNAV, and GLS approaches to 5147 runway ends at 1534 U.S. airports. As discussed previously, these results do not currently include the effects of airport infrastructure on visibility. Thus, they should be considered preliminary. However, we believe that the results presented are instructive and demonstrative the utility of GAME.

Figure 4 presents the estimated HAT for an LNAV approach to each of the 5147 runway ends. Each vertical bar shows the number of approaches with HAT in the range shown on the horizontal axis.

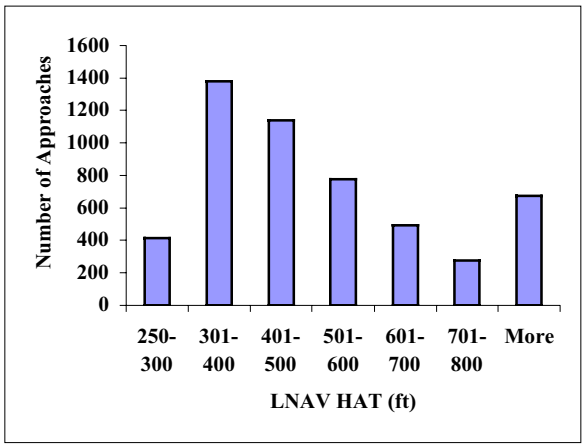

Figure 4. GAME HATs for LNAV Approaches

LNAV approaches are available with unaugmented GPS and are currently flown to many airports. When WAAS is initially commissioned (currently planned for 2003), LNAV/VNAV approaches will be available for public use. A natural question is: what improvement will LNAV/VNAV bring to airport access? Figure 5 shows GAME estimates of the difference between the HATs of an LNAV approach and an LNAV/VNAV approach to the same runway.

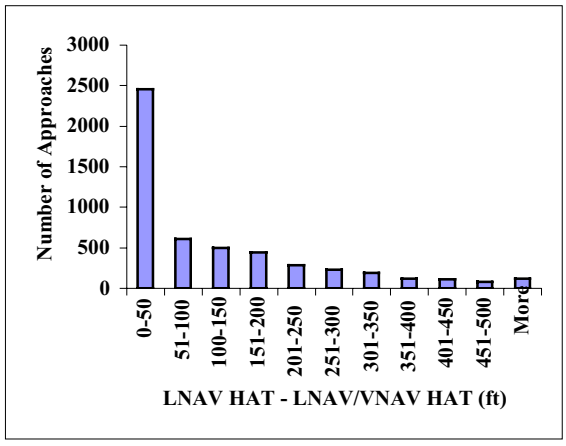

Figure 5. GAME Estimates of Improvement in HAT of LNAV/VNAV over LNAV

The data presented in Figure 5 show that LNAV/VNAV will provide lower HATs for instrument approaches than the currently available LNAV approaches. This is, of course, in addition to the safety benefit of a stabilized approach with vertical guidance. This is a clear benefit for WAAS and LNAV/VNAV.

However, HAT is only a secondary benefit for airport access. Figure 6 shows the difference in visibility between LNAV and LNAV/VNAV approaches for Category A and B aircraft. Recall that the current version of GAME does not include airport infrastructure considerations for visibility. However, airport considerations should affect LNAV and LNAV/VNAV minima in a similar manner, so the difference in visibility presented in Figure 6 should be reasonably accurate.

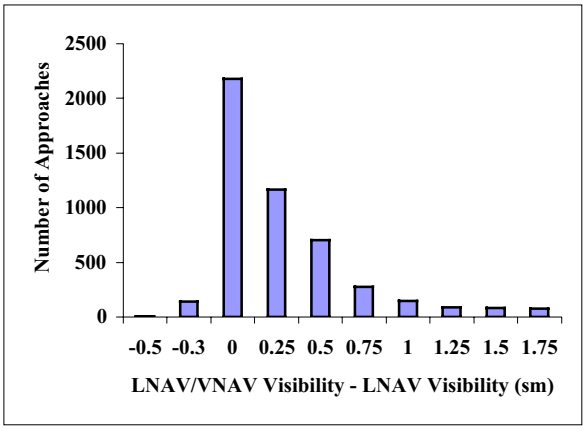

Figure 6. GAME Estimates of Improvement in Visibility for Category A/B Aircraft for LNAV/VNAV versus LNAV Approaches

We can note that for about 45% of the runway ends, GAME estimates that LNAV/VNAV will provide equal (~2300 runways) visibility to LNAV, with a few hundred runways providing lower visibility minima. Unfortunately, approximately 55% of the runways will have higher visibility minima for LNAV/VNAV than for the currently available LNAV.

Although LNAV/VNAV will provide a stabilized approach to a lower HAT, the fact that the visibility minimum will increase in more than half of the cases only gives LNAV/VNAV a marginal airport access benefit over LNAV. When the weather is really bad, the pilot will be forced to fly the nonprecision LNAV approach to land legally, rather than the vertically-guided LNAV/VNAV. We have already observed adverse comments in the general aviation press where pilots have noted the higher LNAV/VNAV minima with respect to LNAV minima.

Figure 7 shows a similar comparison of visibility minima for Category C aircraft. One can note that the

LNAV/VNAV visibility minima are equal or better to the LNAV minima a majority of the time (about 67%). This is a positive benefit for Category C aircraft. Unfortunately, most Category C aircraft will be flying approaches to runways equipped with ILS or LAAS equipment. As we will see in the next section, these approaches (i.e., GLS and ILS) provide even lower visibility minima than LNAV/VNAV. Thus, the improved access benefit of LNAV/VNAV for Category C aircraft may not be significant.

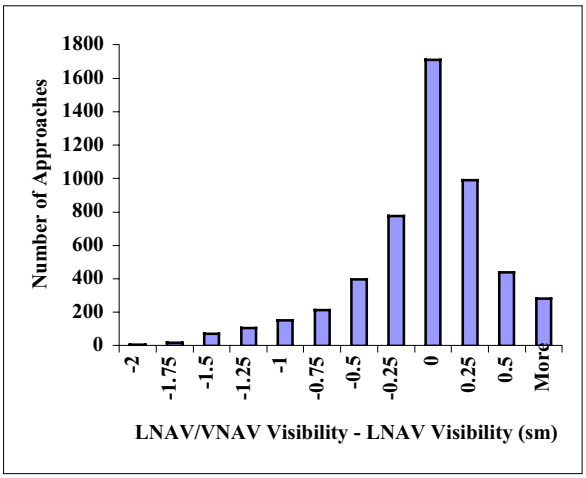

Figure 7: GAME Estimates of Improvement in Visibility for Category C Aircraft for LNAV/VNAV over LNAV Approaches

In summary, when WAAS is commissioned, LNAV/VNAV approaches will provide a stabilized instrument approach to a lower HAT at most airports. This is a positive benefit. However, the regulatory visibility minima for the LNAV/VNAV approaches will be worse than the associated LNAV approaches at most runways for the small aircraft that will likely be the main users of the approaches. This is a marginal airport access benefit.

IMPROVEMENTS IN INSTRUMENT APPROACHES AND APPROACH CRITERIA

As noted earlier, the obstacle clearance criteria for LNAV/VNAV are very similar to LNAV. In fact, the horizontal dimensions of the obstacle clearance surfaces are identical. This design was originally developed to service airlines with Flight Management Systems (FMSs) that could fly LNAV/VNAV but may not be equipped with WAAS equipment. At that time, the FAA planned to provide an LNAV, LNAV/VNAV, and a GLS approach at nearly every runway. The GLS approaches would have had HATs near 200 ft and provide much lower visibility minima than the associated LNAV and LNAV/VNAV approaches.

Unfortunately, technical difficulties with WAAS have probably delayed the ubiquitous use of GLS approaches until a second civil frequency can be provided on most of the GPS satellites, which may be 2015 or later. Now the FAA is relying on LNAV/VNAV as the vertically-guided approach capability for WAAS until approximately 2006, when a possible new criteria is introduced, called the Approach Procedure with Vertical guidance (APV).

LNAV/VNAV will be flown with WAAS available, and WAAS can provide significantly better horizontal performance than unaugmented GPS. For example, the Horizontal Alert Limit (HAL) for unaugmented GPS approaches (i.e., LNAV) is 556 m. However, WAAS may be able to achieve a HAL of only 40 m when first commissioned (presently scheduled for 2003). Thus, there seems to be potential to develop approach criteria with narrower horizontal obstacle clearance surfaces than LNAV/VNAV. These improved approaches could be available immediately upon commissioning of WAAS, although the time to actually develop the procedures could be significant.

The APV approach criteria being developed for 2006 will use the WAAS HAL of 40 m, and may use a reduced Vertical Alert Limit (VAL) of 20 m. (LNAV/VNAV uses the 50 m VAL that will be available in 2003). Thus, the APV criteria should provide lower HATs than LNAV/VNAV or LNAV/VNAV with a reduced HAL. However, improving WAAS performance to support a reduction in VAL from 50 m to 20 m could be an expensive effort, and the airport access benefits should be carefully examined to determine if the investment in WAAS is worth the money and effort.

When new candidate approach criteria are developed, GAME can be used to estimate the airport access benefits of each procedure, allowing an informed decision both on the criteria, and on the investment required to attain the WAAS capability necessary to implement the criteria.

Figure 8 illustrates the potential for improvements in HAT by comparing the HAT of a GLS approach with the HAT of the associated LNAV/VNAV approach. Figure 8 is optimistic, since the WAAS performance necessary for GLS may not be available until 2015 or later. Also, limitations of airport infrastructure are not included in the current calculations, and this could affect visibility estimates. However, the estimates of

GLS minima do give some indication of the potential for lower HATs with improved criteria.

Similar improvements in visibility minima can be seen in Figures 9 and 10, showing the improvements in visibility minima with GLS as compared to LNAV/VNAV and LNAV approaches.

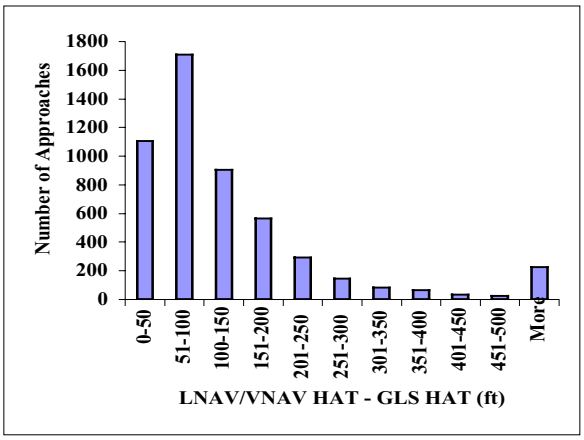

Figure 8. Estimates of the Improvement of the HAT of GLS over LNAV/VNAV Approaches

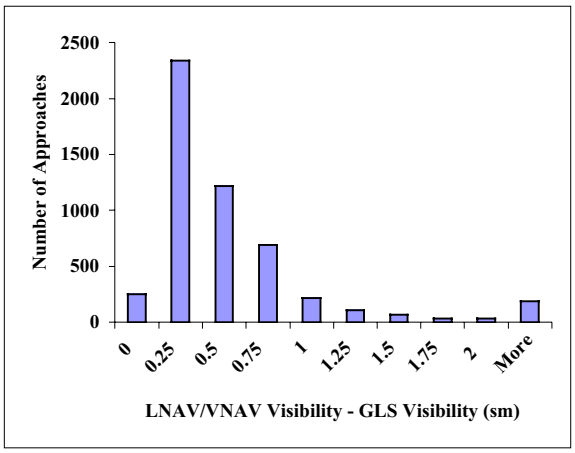

Figure 9. Estimate of the Improvement in Visibility Minima of GLS Approaches over LNAV/VNAV Approaches

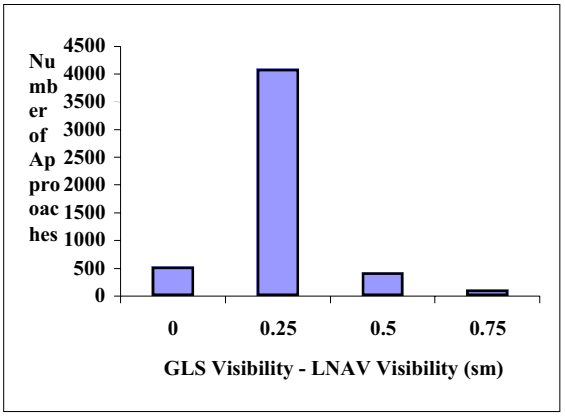

Figure 10. Estimate of the Improvement in Visibility Minima of GLS Approaches over LNAV Approaches (Category A/B Aircraft)

FUTURE WORK

MITRE is currently gathering data and modifying GAME to include airport infrastructure considerations, missed approaches, and step-down fixes. These new capabilities will provide improved insight into the effects of airport infrastructure on airport access benefits. Additionally, we are gathering data to allow larger samples for validation of GAME against approaches developed by the FAA.

CONCLUSIONS

GAME allows calculation of airport access benefits for various types of instrument approaches, including new instrument approach criteria that may be developed. The preliminary results depicted in this paper demonstrate the potential for assisting the development of the WAAS program.

When improvements are completed to GAME, we will be able to better estimate the benefits of LNAV, LNAV/VNAV, GLS, and new instrument criteria on airport access. Additionally, GAME results can assist in determining the benefits of improving WAAS performance.