Technical Report for Operational Evaluation of Transponder Landing System Vertically Guided Offset Approaches in a Category A Aircraft

Flight Systems Laboratory
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Technical Report for Operational Evaluation of Transponder Landing System Vertically Guided Offset Approaches in a Category A Aircraft

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Flight Systems Laboratory
Flight Technologies and Procedures Division
Flight Standards Service

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Date

February 2009

Technical Report
This report presents the results of an operational evaluation of Transponder Landing System (TLS) vertically guided offset approaches using a Local Area Augmentations System (LAAS) as installed and flown in a Category A aircraft, a Piper PA34. The evaluation was sponsored by the Federal Aviation Administration (FAA), Technical Operations Navigation Services Office, Chief System Engineer Group (AJW-41), and performed by the Flight Systems Laboratory (AFS-450). The School of Electrical and Computer Engineering and School of Aviation at the University of Oklahoma (OU) conducted the flight test and processed the data. These processed data were provided to the Flight Systems Laboratory for analysis and evaluation. This evaluation was part of a TLS evaluation effort that included a Boeing 737 simulator, Category D; a Bombardier Q400 simulator, Category C; and a Beechcraft B200 aircraft, Category B, performed jointly by AFS-450 and the FAA’s William J. Hughes Technical Center at Atlantic City, New Jersey. This report focuses on the Category A evaluation results that support FAA decision making for developing vertically guided offset approach criteria for Terminal Instrument Approach Procedures (TERPS), with emphasis on the visual segment.
Executive Summary

This report presents the results of an operational evaluation of Transponder Landing System (TLS) vertically guided offset approaches using a Local Area Augmentation System (LAAS) as installed and flown in a Category A aircraft, a Piper PA34. The evaluation was sponsored by the Federal Aviation Administration (FAA) Technical Operations Navigation Services Office, Chief System Engineer Group (AJW-41), and performed by the Flight Systems Laboratory (AFS-450). The School of Electrical and Computer Engineering and School of Aviation at the University of Oklahoma (OU) conducted the flight test and processed the data. These processed data were then provided to the Flight Systems Laboratory for analysis. This Category A evaluation was one segment of a TLS Offset Approach Test that also included a Boeing 737 simulator, Category D; a Bombardier Q400 simulator, Category C; and a Beechcraft B200 aircraft, Category B. These three evaluations were performed jointly by AFS-450 and the FAA’s William J. Hughes Technical Center at Atlantic City, New Jersey.

This report focuses on the Category A evaluation results that support the development of vertically guided offset approach criteria for Terminal Instrument Approach Procedures (TERPS), with emphasis on the visual segment.

The offset approach test project was initiated in response to a request for a TLS approach into Hailey, Idaho, that would require an offset final segment. Since the TERPS criteria for this type approach did not exist, the test project was expanded to include the general classification of vertically guided offset approaches. The project used flight simulators and actual aircraft flight tests. The tests were conducted in two phases: Phase I, using a broad range of conditions, and Phase II, using specific conditions derived from Phase I. The results of Phase I, and Phase II Approach Categories B, C, and D, are contained in Reference 1.

The purposes of the present test were:

- To evaluate transitioning from instrument flight to the visual segment, aligning the aircraft from the offset course with the runway centerline, and landing, i.e., the segment between the point at which the aircraft becomes visual and the runway threshold
- To evaluate any missed approaches or rejected landings
- To determine the required lateral and vertical airspace in which the probability of an aircraft being laterally outside of or vertically below this airspace is less than $10^{-5}$ in the visual segment.
- To determine the flyability, acceptability, and workload associated with the offset configurations flown in this approach Category A aircraft.
A LAAS developed by OU provided the lateral and vertical guidance for this test. From a previous test, the LAAS lateral and vertical Navigation System Error (NSE) for both Category A and Category B aircraft was well within applicable requirements contained in RTCA DO-245, ‘Minimum Aviation System Performance Standards for the Local Area Augmentation System.” Thus, the OU LAAS demonstrated the lateral and vertical NSE performance necessary for a Category I vertically guided approach system. For a detailed description of the OU LAAS and the results of that test, refer to Reference 2.

The vertically guided offset approaches flown at approach Category A speed in this aircraft proved to be flyable by pilots with a broad range of experience. This was demonstrated by very accurate lateral course and glidepath tracking at Decision Height (DH), the ease of aligning the aircraft to land well within the touchdown zone of the runway, coupled with the pilot questionnaire responses indicating the ease of identifying the runway and aligning with it to land. No missed approaches or rejected landings occurred during this testing.
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1.0 Introduction

This report presents the results of an operational evaluation of Transponder Landing System (TLS) vertically guided offset approaches using a Local Area Augmentation System (LAAS) as installed and flown in a Category A aircraft, a Piper PA34. The evaluation was sponsored by the Federal Aviation Administration (FAA) Technical Operations Navigation Services Office, Chief System Engineer Group (AJW-41), and performed by the Flight Systems Laboratory (AFS-450). The School of Electrical and Computer Engineering and School of Aviation at the University of Oklahoma (OU) conducted the flight test and processed the data. These processed data were then provided to the Flight Systems Laboratory for analysis. This Category A evaluation was part of a TLS Offset Approach Test that also included a Boeing 737 simulator, Category D; a Bombardier Q400 simulator, Category C; and a Beechcraft B200 aircraft, Category B. These three evaluations were performed jointly by AFS-450 and the FAA’s William J. Hughes Technical Center at Atlantic City, New Jersey.

This report focuses on the Category A evaluation results that support the FAA’s development of vertically guided offset approach criteria for Terminal Instrument Approach Procedures (TERPS), with emphasis on the visual segment. For details of the test prior to the visual segment, refer to Reference 3.

1.1 Purpose

The purposes of the present test were:

- To evaluate transitioning from instrument flight to the visual segment, aligning the aircraft from the offset course with the runway centerline, and landing, i.e., the segment between the point at which the aircraft becomes visual and the runway threshold
- To evaluate any missed approaches or rejected landings
- To determine the required lateral and vertical airspace in which the probability of an aircraft being laterally outside of or vertically below this airspace is less than $10^{-5}$ in the visual segment.
- To determine the flyability, acceptability, and workload associated with the three different offset configurations flown in this aircraft

1.2 Background

The offset approach test project was initiated in response to a request for a TLS approach into Hailey, Idaho, that would require an offset final segment. Since the TERPS criteria
for this type approach did not exist, the test project was expanded to include the general classification of vertically guided offset approaches. The project used flight simulators and actual aircraft flight tests. The tests were conducted in two phases: Phase I, using a broad range of conditions and Phase II, using specific conditions derived from Phase I. The results of Phase I and Phase II Approach Categories B, C, and D, are contained in Reference 1. For a graphic depiction of a vertically guided offset approach, see Figure 1.

![Figure 1: Graphic Depiction of Vertically Guided Offset Approach](image)

The TLS is composed of both ground and airborne equipment, and it is designed to provide approach guidance using the existing Instrument Landing System (ILS), localizer, glideslope, and transponder equipment in the aircraft. Ground equipment consists of a transponder interrogator, sensor arrays to detect the lateral and vertical position of the aircraft, a manned remote control unit, and ILS frequency transmitters.

The TLS facility interrogates the transponder of an aircraft and upon receiving a reply, determines the aircraft’s location using two sets of direction-finding antenna arrays, one for horizontal position and the other for vertical. It then calculates the signal that the aircraft would receive if it were approaching a conventional ILS and broadcasts a signal that is indistinguishable from a normal ILS signal to the aircraft. The aircraft ILS
receivers display this information on the aircraft ILS Course Deviation Indicator (CDI) and Vertical Deviation Indicator (VDI).

A drawback to the tested TLS is that the system uses the transponder of the aircraft utilizing the TLS intended approach path and transmits lateral and vertical signals that are specific to that particular aircraft’s location relative to the approach path. Hence, only one aircraft at a time can fly the approach. Any other aircraft in the area tuned to that TLS broadcast frequency receives the same guidance as the aircraft utilizing the TLS regardless of their location in the TLS service volume or direction of travel relative to the TLS approach path.

LAAS is also composed of both ground and airborne equipment. The ground equipment typically includes four reference receivers, a LAAS Ground Facility (LGF), and a VHF Data Broadcast (VDB) transmitter. Signals from Global Positioning System (GPS) satellites are received by the LAAS GPS reference receivers at the LGF. These receivers and the LGF work together to determine errors in the GPS-derived position. The LGF produces a LAAS correction message. This message is sent to the VDB transmitter, which broadcasts the LAAS signal throughout the LAAS service volume. The service volume (a cylinder of approximately 23-nautical-mile (NM) radius and a height of 10,000 feet above the LGF elevation) is designed to support aircraft transition from en route airspace into and throughout terminal area airspace. See Reference 4 and Reference 5.

The LAAS equipment in the aircraft uses the correction message to provide ILS look-alike signals to the CDI and VDI for use by the pilot in maintaining the desired lateral and vertical path. Figure 2 shows the CDI/VDI that was flown in the test aircraft. It is an older, “windshield wiper” design, and typical of many CDI/VDI instruments installed in General Aviation single-engine and multi-engine aircraft.

Figure 2: Course Deviation/Vertical Deviation Indicator (CDI/VDI)
Windshield wiper instruments operate by swinging each deviation indicator, or needle, through an arc. In later versions of the instruments, the deviation indicators operate by displacing the entire needle horizontally or vertically.

1.3 Terminology

In the international arena, the term “Ground-Based Augmentation System” (GBAS) identifies an augmentation system on the ground in a localized area around an airport. LAAS is the United States nomenclature for its implementation of GBAS. LAAS may also be referred to as a GNSS Landing System (GLS). A GLS implies a system, such as ILS or Microwave Landing System (MLS), which possesses the necessary accuracy, integrity, and continuity to serve as a vertically guided approach landing system.

2.0 Description of the Evaluation

This study used LAAS ground equipment, LAAS airborne equipment, and fourteen subject pilots to evaluate the transition from instrument flight to the visual segment. The study used three vertically guided offset approach configurations to determine the required lateral and vertical airspace in which the probability of an aircraft being vertically below or laterally outside this airspace is less than $10^{-5}$. In addition, this study used subjective and objective performance measures to assess the flyability, acceptability, and workload of the three different offset configurations.

2.1 LAAS Ground Equipment

In a previous test, the OU LAAS demonstrated the lateral and vertical Navigation System Error (NSE) performance necessary for a Category I vertically guided approach system, equivalent in accuracy to either an ILS or a TLS. A detailed description of the OU LAAS and the results of that test are contained in Reference 2. The LAAS lateral and vertical NSE for Category A aircraft is well within requirements contained in RTCA DO-245, “Minimum Aviation System Performance Standards for the Local Area Augmentation System,” Reference 4.

2.2 LAAS Airborne Equipment

The airborne equipment for this study consisted of the aircraft itself and the LAAS airborne subsystem. The LAAS airborne subsystem worked in tandem with the ground equipment to provide approach guidance to the aircraft.
2.2.1 Aircraft

The aircraft for this test was the OU School of Aviation’s Piper, PA34 Seneca, a light twin engine, 6 place aircraft, and it is typical of General Aviation aircraft. The aircraft was flown at approach Category A airspeeds. It provided space and payload capability for a subject pilot, a safety pilot, an observer, two data specialists, and the airborne subsystem. (See Figure 3.)

![Figure 3: OU School of Aviation's Piper PA34 Seneca](image)

2.2.2 LAAS Airborne Subsystem

The aircraft is equipped with GPS antennas to receive the GPS satellite information and VHF antennas to receive the LAAS VDB broadcasts. A Rockwell Collins GNLU 930 Multi-Mode Receiver (MMR), which provided navigation information from ILS, VHF Omni-Directional Range (VOR), marker beacon, MLS, and GPS including LAAS was used. It was developed to help the aviation industry migrate from conventional landing systems to satellite-based landing systems. This unit has been issued a limited supplemental-type certificate for LAAS approaches. The MMR applies the locally determined corrections received from the LGF to the pseudo-ranges it has received from GPS satellites and computes corrected Position, Velocity, and Time (PVT) information. Since LAAS had not received operational approval at the time of this test, the MMR was not permanently mounted in the aircraft, but it was temporally installed prior to takeoff on each evaluation flight. The MMR output was connected to the aircraft’s CDI/VDI, as shown in Figure 2, via an analog interface.

To select the desired offset approach configuration, an MMR control unit, as shown in Figure 4, was used to interface with the MMR. The unit tunes to the correct VDB frequency for the desired airport and allows a choice of approaches defined by the Runway Path Data Selector (RPDS) entered in the control unit to acquire runway information from the LAAS message.
2.3 Data Acquisition Equipment and Methodology

Real-time LAAS PVT data were recorded from the Rockwell Collins GNLU 930 MMR via a Toshiba Libretto 50 CT computer to the MMR’s RS-422 bus. The software program TMON version 21d, also developed by Rockwell Collins, was used to interface with the MMR and store the PVT data for later analysis.

To record the position of the aircraft in space, a separate “truth” system that determined the true position of the airplane during the offset procedures was used. The truth system in this study was a set of two Ashtech Z-Xtreme GPS receivers working in differential mode. One receiver was carried onboard the aircraft and recorded dynamic GPS data through the same antenna as the MMR. The other receiver was stationed at the LGF and simultaneously recorded GPS data. The data from both receivers were used as inputs to a post-flight processing program. Since the true location of the stationary receiver was known, the post-processing program was able to determine the GPS errors present at any given time during a flight. These errors were then applied to the aircraft-recorded GPS data to provide a highly accurate indication of the aircraft’s true position. (See Figure 5.)
2.4 Subject Pilots

Prior to the flight tests, each subject pilot completed a pre-briefing questionnaire. (See Appendix A.) Fourteen subject pilots, (two FAA pilots and twelve OU School of Aviation instructor pilots) participated in the tests. Total flight time of the pilots varied from 500 hours to 6,200 hours. Two pilots held type ratings in jet aircraft, and four held type ratings in turboprop aircraft. The PA34 does not require a type rating. The fourteen pilots were all multi-engine rated. Total time in the PA34 varied from 0 hours to 368 hours. Three held Airline Transport Pilot (ATP) certificates, and twelve held Certified Flight Instrument Instructor (CFII) certificates. Actual Instrument Flight Rules (IFR) hours flown in the last 90 days varied from 0 hours to 20 hours.
Table 1: Subject Pilot Qualifications and Experience

<table>
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<tr>
<th>Pilot</th>
<th>Aircraft Type Ratings</th>
<th>Airman Certificates</th>
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<th>Time in PA34</th>
<th>Actual IFR Hours in Last 90 Days</th>
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</table>

* Pilot numbers are not sequential, because pilots were assigned numbers across all aircraft tested, i.e., the PA34, BE200, Q400, and the B737. (See Section 1.0, Introduction.)

The primary task of the subject pilots was to follow the lateral and vertical guidance as displayed on the CDI/VDI and to visually acquire the runway at the Decision Height (DH), align the aircraft, and land. Prior to the test, the pilots were briefed on each approach that would be flown and on the objective of the test, which was to evaluate the visual segment of the approach. They were instructed to fly in a professional manner as though passengers were on board and not to maneuver the aircraft in an unsafe manner at any time. If they felt they were in an unsafe condition to land or if they felt the success of the landing was questionable, they should miss the approach or execute a go-around from any point. It was emphasized that a missed approach or rejected landing was an acceptable result of the approach and that this information was important to the evaluation.

Pilots were instructed to rely strictly on the instruments and refrain from looking outside the aircraft during the instrument portion of the approach. They were briefed on the design of the approaches and on the technique inside the DH that would best result in a successful approach and landing. The technique briefed was as follows: once the pilots became visual and identified the runway of intended landing, they were to maintain the indicated airspeed and rate of descent used to maintain the flight path prior to the DH, then to establish a 15° bank angle to align with the runway until at a position and height above
the runway where power, speed, and descent adjustments were necessary to make a successful landing.

A safety pilot accompanied the subject pilot to reposition the aircraft for subsequent approaches while the subject pilot was completing the post-run questionnaire, to alert the subject pilot to any traffic conflicts during the approach, and to handle communication with air traffic control. In addition to the subject and safety pilots, an observer and either one or two data technicians were aboard as needed.

2.5 Instrument Approach Procedures

The offset configurations tested are listed in Table 2. All approaches were conducted with the offset placed left of centerline and with a glidepath of 3.5°. Previously collected data during Phase I indicated only a small difference in the quality of approaches based upon left or right offset, with left offsets being slightly poorer in quality. Additionally, approaches with a glidepath of 3.5° were also poorer in quality than approaches with 3.0° or 3.2° glidepaths. See Reference 1. To reduce the number of approach configurations tested and to increase the number of data runs per configuration, the configurations were limited to these more difficult conditions.

<table>
<thead>
<tr>
<th>Table 2: Vertically Guided Offset Approach Configurations</th>
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<tr>
<td>Approach Category A</td>
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<td>Glidepath</td>
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<tr>
<td>3.5°</td>
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</table>

Figure 6 shows a vertically guided offset Instrument Approach Procedure (IAP) to Runway 17 at Westheimer Airport (KOUN) in Norman, Oklahoma, used for this evaluation. It is a LAAS procedure designed with a 10° offset course intercepting the runway centerline extended at a point 1,000 feet from the runway threshold. The IAP is designed with a DH of 199 feet Height Above Threshold (HATH) based on a glidepath angle (GPA) of 3.5° and a Threshold Crossing Height (TCH) of 58 feet.

Figure 7 shows the vertically guided offset instrument approach procedure to Runway 35 at KOUN used for this evaluation. It is designed with a 20° offset course intercepting the runway centerline extended at a point 2,000 feet from the runway threshold and with a DH of 279 feet HATH. The threshold elevations used for this test are 1,181.7 feet for Runway 17 and 1,177.3 feet for Runway 35. The ellipsoid elevations are 1,094.5 feet for Runway 17 and 1,090.3 feet for Runway 35.
During this evaluation, the fourteen subject pilots flew each of the three offset approaches twice for a total of 84 approaches. The approaches were flown to either Runway 17 or Runway 35 depending on the prevailing wind. There were no missed approaches.
Figure 6: KOUN Runway 17 Vertically Guided Offset Instrument Approach
Figure 7: KOUN Runway 35 Vertically Guided Offset Instrument Approach
2.5.1 Calculations to Determine the Decision Heights

To compute the DHs in Table 2, the following diagram, Figure 8, and the associated calculations were used to generate the values based on offset angle, centerline intercept point, glidepath angle, aircraft approach speed, aircraft bank angle, pilot response time and aircraft response time. The Turn Point, (TP) was calculated with both pilot and aircraft response times set to zero. The final DH was then determined by adding 3 seconds of pilot response time and 3 seconds of aircraft response time, for a total of 6 seconds of flight time, prior to the TP as explained below.

These calculations were not intended to be a rigorous analysis of the dynamics of the offset approaches or to give the exact DH. Rather, they were used to give a close approximation for testing. A more exact approach would have computed the DH using the arc length of the designed ground track. Using the computations below, the results differ by approximately 1%. For example, in the worst case situation, i.e., the 2,000 feet, 20° offset case, the DH is computed as 279.01 feet. Using the theoretical turn radius of the aircraft at 100 knots true airspeed (KTAS) and a bank angle of 15°, the computed DH is 276.09 feet, a difference of only 2.93 feet, which is unreadable on the aircraft altimeter, and is traversed in much less than 1 second.

For the purposes of this test, several assumptions were made regarding aircraft flight dynamics and offset geometry. In establishing the TP, the following assumptions were made:

- The aircraft turns with a bank angle of 15°.

- The time for the plane to roll from wings level to 15° and from 15° to wings level is set to 0 seconds. (International standards assume a roll rate of 5 deg/sec and the roll time to be 3 seconds.)

- Pilot reaction time is set to 0 seconds. (International standards assume this time to be 3 seconds.)

- The distance from DH to the runway centerline crossing point (DTA) is the same as the distance from the runway centerline crossing point to the wings level point (SD).

In concert with harmonizing with ICAO, the maximum final approach speed specified in ICAO Doc 8168 Volume I, for a Category A aircraft was used. Volume I, Section 4, Chapter 1, Table I-4-1-2, *Speeds for procedure calculation in knots (kt)*, specifies speeds by category of aircraft for the different segments of an instrument approach procedure. The speed specified for a Category A aircraft at threshold is specified as <91 knots and is specified as 100 knots in the final approach segment. See Reference 7.
The DH was then established by adding 6 seconds of flight time prior to the TP as explained above.

Figure 8 shows the geometrical relationships for these offset approaches.

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**Figure 8: Offset Geometry**

TP = Point at which the turn onto runway centerline begins
DH = Decision Height point (determined by adding 3 seconds of pilot reaction time and 3 seconds of aircraft roll time prior to the TP)
RP = Point at which the turn is complete; wings are level and the aircraft is on centerline
SD = Distance along centerline from RP to centerline intercept point
DTA = Distance along offset final approach path from centerline crossing point to TP
GPI = Glidepath Intercept distance from threshold
h = Height of the aircraft at RP
d = Distance from threshold to RP
dc = Distance from threshold to centerline crossing point
φ = Offset angle of final approach path from runway centerline
θ = Glidepath angle
TCH = The height at which the glidepath crosses the threshold.

The following equations were used to calculate the minimum DH. Note: all angles are in degrees and all distances are in nautical miles.

First, calculate the radius of curvature:
\[a_{\text{centripetal}} = \frac{v^2}{R},\]

where \(R = \text{Radius of curvature (NM)}\)

\(v = \text{Speed of aircraft (KTS)}\)

\(a = \text{Centripetal acceleration of the aircraft}\)

and setting:

\[a_{\text{centripetal}} = g \tan \omega,\]

where \(g = \text{Acceleration due to gravity (68,625 NM/hr}^2)\)

\(\omega = \text{Bank angle of the aircraft (15°)}\)

gives:

\[R = \frac{v^2}{g \tan \omega}\]

Now calculate \(DTA + SD\):

\[DTA + SD = R \tan \phi\]

assume \(DTA = SD\)

and substituting for \(R\) gives:

\[DTA = \frac{v^2 \tan \phi}{2g \tan \omega}\]

Now calculate \(DH\):

\[DH = (DTA + d_x) \tan \theta\]

substituting:

\[DH = \left[\frac{v^2 \tan \phi}{2g \tan \omega} + d_x\right] \tan \theta\]

This gives a decision height in units of nautical miles. To convert to feet, multiply DH by 6,076 ft/NM. This DH does not account for pilot reaction time, aircraft roll time and threshold crossing height. Therefore, 3 seconds of pilot reaction time, 3 seconds of aircraft roll time and the threshold crossing height were added. The additional height to the DH is calculated by the following equation:

\[\Delta DH = (vt) \sin \theta + (GPI) \tan \theta\]

where \(\Delta DH = \text{additional height correction (feet}\)
\[ v = \text{True airspeed (feet/second)} \]
\[ t = \text{Reaction and roll time (seconds)} \]

2.6 Human Factors Analysis

The human factors portion of this evaluation used both subjective and objective measures. Subjective performance measures included post-run and post-simulation session questionnaires designed specifically to elicit comments and opinions from the subject pilots. A numerical weighting procedure was used to provide an overall score rating on several human factor issues. Focus was on any potential changes in either mental or physical workload manifested from the vertically guided offset approach operation as it differed from other approach operations. Objective crew performance measures were accomplished through observation of pilot performance by the test observer.

2.6.1 Subjective Post-Run and Post-Test Analysis

Following each test run, the subject pilot completed a post-run questionnaire. (See Appendix B). From a human-in-the-loop perspective, there did not appear to be any appreciable increase or change in workload (physical or mental) directly resulting from the use of vertically guided offset approaches. Figure 9 through Figure 14 represent subjective pilot responses across the three different trial scenarios. Figure 9 represents total response for all pilots for all scenarios by question. Total scores all fell into the higher end of the scoring spectrum (i.e., responses indicating “Strongly Agree”). A breakdown of each question by pilot (Figure 10 through Figure 14) revealed one pilot whose subjective responses were consistently lower than the other subjects. Hence, the average overall scores were lower. Even so, the high scores indicated that pilots felt that these approaches induced no additional workload or no special physical or mental requirements to successfully perform the vertically guided offset approach and align to land.
Figure 9: Average Pilot Responses (All Pilots Total)

Figure 10: Question 1: Visual Easy (By Individual Pilot)
Figure 11: Question 2: Path/Centerline (By Individual Pilot)

Figure 12: Question 3: IMC to Visual (By Individual Pilot)
Figure 13: Question 4: Stabilized (By Individual Pilot)

Figure 14: Question 5: Workload (By Individual Pilot)
Concurrently, each pilot responded to six additional questions, each addressing a different characteristic of workload, after each run. These questions were based on the National Aeronautics and Space Administration (NASA) Task Load Index (TLX), a subjective, post-hoc workload assessment tool. (See Appendix C.) The NASA TLX allows users to perform subjective workload assessments on operator(s) working with various human-machine systems. The NASA TLX is a multi-dimensional rating procedure that derives an overall workload score based on a weighted average of ratings on six subscales. The subscales are Mental Demands, Physical Demands, Temporal Demands, Own Performance, Effort, and Frustration.

Those responses are represented in Figure 15 and Figure 16. All scores, across all six dimensions, were in the very low range, indicating that pilot perception of performance was high and perception of workload was low.
Pilot post-simulation comments corroborated pilot subjective responses concerning perceived ability to perform the approaches and pilot perception of both mental and physical workload. Pilots generally felt that these approaches were easily performed although the offset did make it a bit more challenging, albeit not enough to make a safety case against them. Several pilots mentioned that adverse weather and wind conditions might make these procedures more difficult.

2.7 Composite Lateral Plots

There were 28 flights per offset configuration for a total of 84 flights. The lateral flight tracks of each of the three different offset configurations are shown in Figure 17, Figure 18, and Figure 19. In each plot, the runway threshold and the procedure design parameters of Roll-Out Point (RP) (wings level), the Turn Point (TP), and the DH point are marked. Note that the distance from the intercept point to both the RP and the TP are equal (see Figure 8). Due to the differences in the scale of the axes in these plots, the distance to the TP appears greater than the distance to the RP and both the angle of intercept, and the GPA appear greater than they actually are. As can be seen, the pilots tended to turn inside the intended flight track, and this became more pronounced with an increasing offset angle. All three offset configurations had some tracks which overshot the runway centerline extended. It is not apparent that this overshoot increased with an increasing offset angle, as there were few overshoots at the 2,000 feet/15° offset. The observed tendency was for the pilots to visually acquire the runway, to fly toward the runway threshold, and to intercept the extended runway centerline at a point where they
felt comfortable in aligning with the centerline as in a normal visual approach. In doing so, they abandoned the technique previously briefed of maneuvering the aircraft along the designed path by maintaining speed, descent rate, a 15° bank, and reverted to visual cues to maneuver the aircraft to obtain the sight picture they were familiar with in Visual Meteorological Conditions (VMC).

The observed bank angles were consistently in the 10° to 12° range, with an occasional 15° bank angle. The maximum bank angle observed was 20°, and the minimum was 5°.

Note in this figure, the one track which is significantly to the right of the others. At 2500 feet Centerline Distance to Threshold, the track deviation is decreasing and is 42 feet inside of full scale lateral deviation. However, at 3000 feet the track is 2 feet beyond full scale lateral fly left deviation. This would require the pilot to execute a missed approach, but he did not do so. The observer log notes, "lost glideslope - high - recovered for landing." In Figure 20, the highest track corresponds to this lateral track. At 3000 feet Centerline Distance to Threshold the track is 19 feet beyond full scale fly down deviation. This, too, would require the pilot to execute a missed approach. Since the pilot chose to continue this approach outside of normal operating parameters, this track has been deleted from the data analysis.
Figure 18: 2,000 Feet/15° Offset Composite Lateral Tracks
Note in this figure, the one track which is significantly to the left of the others. At 1 NM Centerline Distance to Threshold, (not included in Figure 19) the track is 172 feet to the right of the course. At 5000 feet, the track is 74 feet right of course. At 4000', the track is 47 feet left of course. At the DH, (3514 feet) the track is 109 feet left of course and at 2000 feet, the track is 278 feet left of course. The observer log has the note, "cheated a bit on turn anticipation." It is apparent that the pilot did not obey the rules of the test, which was flown in daylight VMC conditions, chose to go visual i.e., he looked out of the cockpit, before reaching the DH, abandoned the procedure and flew directly toward the threshold. Since the pilot chose to fly this approach outside of normal operating parameters, this track has been deleted from the data analysis.

2.8 Composite Vertical Plots

The vertical flight tracks of each of the three different offset configurations are shown in Figure 20, Figure 21, and Figure 22.

On close examination of these tracks, it is apparent that there are two separate groupings of tracks inside the threshold, one being approximately 10 feet above the other. There were five flight test periods in which the aircraft did not touchdown, but instead flew a low approach over the runway. Hence, there are 10 tracks on each of the vertical profiles
that are higher inside the threshold than the rest of the tracks. Since the primary purpose of this study was to evaluate the visual segment, these low approach profiles had no impact on the analysis and outcome of the study.

In Figure 21, there is one flight on the 2,000 feet/15° offset that is significantly above the rest inside the threshold. This was due to an unsafe landing gear indication on that particular flight. The flight was flown as it would normally be flown to the threshold, so it too, had no impact on the analysis. The lowest track at DH is 7 feet below full scale fly up and this track has been deleted from the data analysis.

From the beginning of their training, General Aviation (GA) pilots are trained to land the aircraft by “putting it on the numbers.” They are taught that any portion of the runway behind the aircraft is useless for landing. By contrast, FAR, Part 135 and FAR, Part 121 crews are trained to acquire a stabilized approach (to have the aircraft configured inside the Final Approach Fix, to be within required path tracking margins, airspeed, and descent rates, etc.), to maintain airspeed and descent rates, to aim for the 1,000-foot bar on the runway, and to expect the TCH to be on the order of 50 feet. This difference in training and pilot performance was apparent in the offset testing with the other three aircraft, and comparative plots are contained in Reference 1.

This GA training is evident in examining the vertical composite plots of this test. The design TCH for all of these approaches was 58 feet, based on a 3.5° GPA. This is depicted by the blue line on the plots. The on-path descent rate at 100 knots is 618 feet per minute. Above the DH, the pilots were tracking the GPA very well. Below the DH, in all three offset configurations, most of the pilots were well below the intended path, and many had already reached the 58 feet TCH by as much as 500 feet to 800 feet prior to the runway threshold. In one instance, the pilot had to increase power and pitch to avoid touching down prior to the threshold.

The result of this tendency to depart from the stabilized descent rate and to “put it on the numbers” resulted in an initial increase in the descent rate to a height of between 30 to 50 feet HATH where the rate was decreased. On the 1,000 feet/10° offset, there is an apparent change that can be seen shortly after DH. This apparent change in the established rate of descent to a rate greater than the procedure design rate of descent is delayed until approximately 200 feet HATH in the two 2,000-feet offset configurations.
Figure 20: 1,000 Feet/10° Offset 3.5° GPA Composite Vertical Tracks

Figure 21: 2,000 Feet/15° Offset 3.5° GPA Composite Vertical Tracks
3.0 Vertically Guided Offset Approach Data Analysis Methodology

To quantify the lateral and vertical extent of airspace required about the design path of an Instrument Approach Procedure to provide obstacle protection, probability distributions must be determined. The data required for the establishment of probability density functions were generated by flight test approaches of an actual aircraft. The flight tests resulted in lengthy data files containing the aircraft position and other parameters recorded at discrete time intervals (5 hertz). The flight test data files were analyzed by finding the aircraft position when it passed through evenly spaced imaginary planes placed at regular intervals (100 feet) perpendicular to the ground plane and perpendicular to the intended ground track of the aircraft. (See Figure 23.) Each plane contains points that represent the places where each aircraft’s center of gravity passed through the plane. An x-y coordinate system was imposed on the plane with its origin at the point where the lateral course and glidepath pass through the plane. Thus, each point has x-y coordinates assigned to it.
The $x$-$y$ coordinates can be divided into two sets, the set of $x$-coordinates and the set of $y$-coordinates. For systems such as ILS and MLS, these two sets have been shown to be independent. Thus, an aircraft that has deviated a large distance laterally has not necessarily deviated a large distance vertically. This means that separate probability density functions can be developed for the lateral and vertical deviations. It was assumed that lateral and vertical data generated by this study were independent.

Statistical tests verified that neither the lateral or vertical data sets could be modeled using a normal or Gaussian distribution. Therefore, the Johnson family of curves developed by N. L. Johnson in 1949, was used to fit probability curves to the lateral and vertical data sets. The Johnson family includes three types of curves: the Johnson $S_L$ family, the Johnson $S_B$ family, and the Johnson $S_U$ family. The curves of the $S_L$ family are bounded at one end with an infinite tail at the other end. The curves of the $S_B$ family are bounded at both ends. The curves of the $S_U$ family are unbounded, i.e., they have infinite tails at both ends. Each family of curves is based on a transformation of the observed data into a set of data that could be generated by a standard normal curve with mean zero and variance 1 ($N(0,1)$). A test based on the statistics of the data determines which type of curve will best fit the data. It was found that only two of the Johnson families, the $S_B$ and $S_U$, were required to fit curves to the data sets.

Each Johnson family is a transformation of the standard normal $N(0,1)$ curve. Therefore, probabilities defined by a particular realization of a Johnson curve are easily computed from the standard normal probability density curve. The transformation that determines the Johnson $S_B$ family of curves is given by the following equation:

$$z = \gamma + \delta \ln \left( \frac{x - \varepsilon}{\lambda + \varepsilon - x} \right), \varepsilon < x < \lambda + \varepsilon$$  

(1)
The transformation that determines the Johnson $S_U$ family of curves is given by the following equation:

$$z = \gamma + \delta \sinh^{-1}\left(\frac{x - \epsilon}{\lambda}\right), \quad -\infty < x < \infty. \tag{2}$$

In Equation 1 and Equation 2, $x$ represents a sample observation such as a lateral deviation from the runway centerline or a vertical distance from the intended glidepath, and $z$ represents the transformation of $x$ into a number from a normal $N(0,1)$ distribution. The variables $\gamma$, $\delta$, $\lambda$, and $\epsilon$ represent parameters that fit the curve to the data. The parameters $\gamma$, $\delta$, $\lambda$, and $\epsilon$ were determined from the data via an iterative numerical process.

By multiplying the two density functions for a given plane, a bivariate density function of the total deviation of the aircraft about the glidepath was obtained. This bivariate density function represents a snapshot of the aircraft position when it passes through that particular plane. The Johnson functions defining the bivariate density functions were used to compute closed curves (isoprobability contours) such that the probability of being outside the curve was a given value of $2 \times 10^{-5}$. Then the probability that an aircraft is below the part of the curve under the horizontal line through the glidepath is approximately $1 \times 10^{-5}$. (See Figure 24.) The aircraft must fly through several planes during the instrument approach, so the aggregate of closed curves formed a kind of tunnel that the aircraft flew through during the approach. (See Figure 34, Figure 48, and Figure 60.)
In Figure 25 through Figure 60, the isoprobability contours are plotted individually along and perpendicular to the intended ground track. The plots begin just outside the DH and proceed along and around the flight path to the runway threshold. Figure 34, Figure 48, and Figure 60 are three-dimensional composite plots of each offset configuration. Although the analysis was accomplished at each 100-foot interval, for visual clarity only each 200-foot isoprobability contour is plotted, forming a tunnel around and along the intended flight path.

Due to the small number of flights (28) on each offset, each flight had a significant influence on the statistical results. Hence, significant deviations from the intended track resulted in the isoprobability contours being expanded at those points along the flight track at which those deviations occur. For example, see Figure 17 and Figure 31, and observe that two tracks between the RP and the threshold are to the right of course, but regain the course just at the threshold. The effect on the isoprobability contour in Figure 31 is obvious, as it shows the contour to contain an area considerably to the right of the intended course, i.e., the runway centerline.

Next, see Figure 19 and Figure 55 at 800 feet from threshold. In Figure 19, three tracks deviate significantly from the rest at this distance, overshooting the runway centerline.
extended. In Figure 55, the contour significantly expands laterally to the right at this point.

A similar effect in the vertical dimension is seen in Figure 21 and Figures 45 and 46. Note in Figure 21, that every track is below the procedure vertical path beginning at approximately 400 feet prior to threshold. In Figures 45 and 46, almost all of the contour falls below the flight path. From the observer logs, no extenuating circumstances were observed that caused these deviations, hence, they cannot be ignored since it can be expected that some pilots will take this action.

The reader is cautioned to observe the variation on the scaling on the axes of the following figures containing the isoprobability contours, as the lateral and vertical scales were adjusted to allow the contours to be presented in this report and to maintain proportionality. Compare Figure 25 and Figure 26 to get a clear presentation of this necessity. The three-dimensional plots are also influenced by this necessity. The difference is noticeable in Figure 60, in which the offset angle is 20°, but compared to the 15° offset in Figure 48, it appears to be at a smaller offset angle.

For proper orientation, the individual isoprobability contour plots should be viewed from the viewpoint of the pilot, as though flying through the contour, i.e., looking toward the runway. The horizontal axis intersects the vertical axis at an HATh of 0 feet. The centerline of designed approach path is depicted at 0 feet on the horizontal axis. The runway width is 100 feet (± 50 feet).

3.1 1,000 Feet/10° Offset Approach Results

The results of this configuration are presented in Figure 25 through Figure 34. Table 3 contains tabulated values

3.1.1 Lateral Results

At the DH, the mean of the contour is at 34 feet left of the intended course, extending from 178 feet left of course to 110 feet right of course. At the TP, which is 1,011 feet inside the DH, representing 6 seconds of flight at 100 knots, the mean of the contour is at 50.7 feet to the left of course, extending from 61.3 feet to the left and 40.9 feet to the right. The contours continue to be centered to the left of course as they progress around the turn and to the centerline. At 4° of turn, the mean of the contour is at 30.1 feet left and extends from 97.4 feet left to 37.3 feet right of course. At 6° of turn, the mean of the contour is at 32.2 feet left and extends from 103 feet left to 38.6 feet right of course. At the RP (709 feet from threshold), the mean of the contour is at 22 feet to the left of course extending from 84.9 feet to the left and 40.9 feet to the right. At 600 feet from threshold, the mean of the contour is at 1.0 feet right and extends from 58 feet left to 59.9 feet right of course. At 400 feet from threshold, the mean of the contour is at 4.9 feet right of centerline extending from 20.5 feet to the left to 30.3 feet to the right. At 200 feet from threshold,
the mean of the contour is at 2.2 feet right of centerline extending from 18.1 feet to the left to 22.4 feet to the right. The mean of the contour at the threshold is at 3.2 feet right of centerline and extends from 26.5 feet left to 33.0 feet right of centerline.

3.1.2 Vertical Results

At the DH, the mean of the contour is at 38.3 feet below the vertical path, extending 101.1 feet below the path. The contours continue to be centered below the path to the threshold. At the TP, the mean of the contour is at 32.88 feet below the vertical path and extends to 80.48 feet below the vertical path. At 4° of turn, the mean of the contour is at 31.53 feet below the path and extends to 74.93 feet below. At 6° of turn, the mean of the contour is at 34.8 feet below the path and extends to 80.9 feet below. At the RP, the mean of the contour is at 38.35 feet below the vertical path and extends to 89.15 feet below the vertical path. At this point, the contour lies just 12.2 feet above the elevation of the runway threshold. At 600 feet from threshold, the mean of the contour is at 46 feet below path and extends to 14.3 feet below threshold. At 400 feet from threshold, the mean of the contour is at 43.17 feet below the vertical path and extends to 38.7 feet below the threshold. At 200 feet from threshold, the mean of the contour is at 30.6 feet below path and extends to 59.5 feet below threshold. At the threshold, the mean of the contour is at 12.6 feet below the vertical path and extends to 24.3 feet below the threshold.
Figure 25: 1,000 Feet/10° Offset 1,300 Feet From Intercept (DH)
(DH to Intercept [SD] = 1,302 Feet)
$1 \times 10^{-5}$ Probability Under the Curve
Figure 26: 1,000 Feet/10° Offset at Turn Point (TP)
(TP to Intercept [SD] = 291 Feet)
$1 \times 10^{-5}$ Probability Under the Curve
Figure 27: 1,000 Feet/10° Offset at 4° Heading Change

$1 \times 10^{-5}$ Probability Under the Curve
Figure 28: 1,000 Feet/10° Offset at 6° Heading Change

$1 \times 10^{-5}$ Probability Under the Curve
Figure 29: 1,000 Feet/10° Offset at 10° Point (Roll Out) (RP)
(708.7 Feet from Threshold)
$1 \times 10^{-5}$ Probability Under the Curve
Figure 30: 1,000 Feet/10° Offset at 600 Feet from Threshold

$1 \times 10^{-5}$ Probability Under the Curve
Figure 31: 1,000 Feet/10° Offset at 400 Feet from Threshold

$1 \times 10^{-5}$ Probability Under the Curve
Figure 32: 1,000 Feet/10° Offset at 200 Feet from Threshold

$1 \times 10^{-5}$ Probability Under the Curve
Figure 33: 1,000 Feet/10° Offset at Threshold
1 × 10⁻⁵ Probability Under the Curve
Figure 34: 1,000 Feet/10° Offset—3D Composite
(DH to Intercept (SD) = 1,302 Feet, TCH = 58 Feet, GPA = 3.5° RP = 708.7 Feet from Threshold)
$1 \times 10^{-5}$ Probability Under Each Curve

Note: Scaling on the axes of this figure was adjusted to allow the contours to be presented in this report and to maintain proportionality. Compare Figure 48 and Figure 60. Due to the significant differences in the axes scaling, although the isoprobability contours are orthogonal to the course, they do not appear so until near to and on the runway centerline.
3.2 2,000 Feet/15° Offset Approach Results

The results of this configuration are presented in Figure 35 through Figure 48. Table 3 contains tabulated values.

### 3.2.1 Lateral Results

At the DH, the mean of the contour is at 11.7 feet left of the intended course, extending from 186.6 feet to the left of course to 163.2 feet right of course. At the TP, the mean of the contour is at 48.7 feet to the left of course, extending from 148.2 feet to the left and 50.8 feet to the right. The contours continue to be centered to the left of course as they progress around the turn and to the centerline. At 6° of turn, the mean of the contour is at 41.6 feet left of course and extends from 124.5 feet left to 41.4 feet right of course. At 9° of turn, the mean of the contour is at 35.5 feet left of course and extends from 107.9 feet left to 36.8 feet right of course. At the RP (1,557 feet from threshold), the mean of the contour is at 21.6 feet to the left of course extending from 74.6 feet to the left and 31.4 feet to the right. At 1,400 feet from threshold, the mean of the contour is at 14 feet left of centerline and extends from 52.3 feet left to 24.4 feet right of centerline. At 1,200 feet from threshold, the mean of the contour is at 20 feet left of course extending from 86.7 feet left to 46.6 feet right of centerline. At 1,000 feet from threshold, the mean of the contour is at 3.6 feet left of centerline and extends from 58.9 feet to the left to 51.6 feet to the right. At 800 feet from threshold, the mean of the contour is at 2.5 feet right of centerline, and extends from 45.0 feet left of course to 50.1 feet to the right. At 600 feet from threshold, the mean of the contour is at 3.7 feet right of centerline and extends from 32.6 feet left to 39.9 feet right of centerline. At 400 feet from threshold, the mean of the contour is at 1.8 feet right of centerline and extends from 30.3 feet left to 34.0 feet right of centerline. At 200 feet from threshold, the mean of the contour is at 3.4 feet left of centerline and extends from 22.4 feet to the left and 16.1 feet to the right. The mean of the contour at the threshold is at 5.6 feet left of centerline and extends from 20.7 feet left to 9.4 feet right of centerline.

### 3.2.2 Vertical Results

At the DH, the mean of the contour is at 8.08 feet above the vertical path, extending 95.92 feet below the intended path. At the TP, the mean of the contour is 22.5 feet below the vertical path and extends to 96.5 feet below the vertical path. At 6° of turn, the mean of the contour is at 25.32 feet below the path and extends to 115.62 feet below. At 9° of turn, the mean of the contour is at 39.14 feet below the path and extends to 156.64 feet below. At the RP, the mean of the contour is at 18.24 feet below the vertical path, and extends to 83.64 feet below the vertical path. At this point, the contour lies just 69.6 feet above the elevation of the runway threshold. At 1,400 feet from threshold, the mean of
the contour is at 20.9 feet below the path and extends to 75.7 feet below. At 1,200 feet from threshold, the mean of the contour is at 24.7 feet below the path and extends to 71.2 feet below. At 1,000 feet from threshold, the mean of the contour is at 28.56 feet below the vertical path and extends to 72.56 feet below the vertical path. At 800 feet from threshold, the mean of the contour is at 32.33 feet below the vertical path and extends to 75.33 feet below. At 600 feet from threshold, the mean of the contour is at 34.5 feet below the path and extends to 78.1 feet below. At 400 feet from threshold, the mean of the contour is at 34.37 feet below path and extends to 71.57 feet below. At 200 feet from threshold, the mean of the contour is at 33.6 feet below the vertical path and extends to 68.2 feet below the vertical path. At the threshold, the mean of the contour is at 31.8 feet below the vertical path and extends to 6.7 feet below the threshold.
Figure 35: 2,000 Feet/15° Offset, 1,500 Feet From Intercept (DH)
(DH to Intercept = 1,453 Feet)
$1 \times 10^{-5}$ Probability Under the Curve
Figure 36: 2,000 Feet/15° Offset at Turn Point (TP)
(TP to Intercept = 443 Feet)
$1 \times 10^{-5}$ Probability Under the Curve
Figure 37: 2,000 Feet/15° Offset at 6° Heading Change

$1 \times 10^{-5}$ Probability Under the Curve
Figure 38: 2,000 Feet/15° Offset at 9° Heading Change

$1 \times 10^{-5}$ Probability Under the Curve
Figure 39: 2,000 Feet/15° Offset at 15° Point (Roll Out) (RP)
(1,557.3 Feet to Threshold)
$1 \times 10^{-5}$ Probability Under the Curve
Figure 40: 2,000 Feet/15° Offset at 1,400 Feet from Threshold

$1 \times 10^{-5}$ Probability Under the Curve
Figure 41: 2,000 Feet/15° Offset at 1,200 Feet from Threshold

$1 \times 10^{-5}$ Probability Under the Curve
Figure 42: 2,000 Feet/15° Offset at 1,000 Feet from Threshold
$1 \times 10^{-5}$ Probability Under the Curve
Figure 43: 2,000 Feet/15° Offset at 800 Feet from Threshold

$1 \times 10^{-5}$ Probability Under the Curve
Figure 44: 2,000 Feet/15° Offset at 600 Feet from Threshold
1 × 10⁻⁵ Probability Under the Curve
Figure 45: 2,000 Feet/15° Offset at 400 Feet from Threshold

$1 \times 10^{-5}$ Probability Under the Curve
Figure 46: 2,000 Feet/15° Offset at 200 Feet from Threshold

$1 \times 10^{-5}$ Probability Under the Curve
Figure 47: 2,000 Feet/15° Offset at Threshold
1 × 10^{-5} Probability Under the Curve
Figure 48: 2,000 Feet/15°—3D Composite
(DH to Intercept = 1,453 Feet, TCH = 58 Feet, GPA = 3.5°, RP = 1,557.3 Feet to Threshold)
$1 \times 10^{-5}$ Probability Under the Curve

Note: Scaling on the axes of this figure are adjusted to allow the contours to be presented in this report and to maintain proportionality. Compare Figure 34 and Figure 60. Due to the significant differences in the axes scaling, although the isoprobability contours are orthogonal to the course, they do not appear so until near to and on the runway centerline.
3.3 2,000 Feet/20° Offset Approach Results

The results of this configuration are presented in Figure 49 through Figure 60. Table 3 contains tabulated values.

3.3.1 Lateral Results

At the DH, the mean of the contour is at 132.6 feet left of the intended course, extending from 452.4 feet to the left of course to 187.2 feet right of course. At the TP, the mean of the contour is at 58.9 feet left of course, extending from 143.5 feet to the left and 25.6 feet to the right. They continue to be weighted to the left of course as they progress around the turn and to the centerline. At 10° of turn, the mean of the contour is at 57.5 feet left of course, and extends from 117.3 feet left to 23 feet right of course. At the RP (1,399 feet from threshold), the mean of the contour is at 4 feet left of course extending from 69.0 feet to the left and 61.0 feet to the right. At 1,200 feet, the mean of the contour is at 31.0 feet left of centerline and extends from 29.0 feet left to 91.1 feet right of course. At 1,000 feet from threshold, the mean of the contour is at 1,54.8 feet to the left of centerline and extends from 19.1 feet left to 128.8 feet right of course. At 800 feet from threshold, the mean of the contour is at 26.9 feet right of centerline and extends from 13.1 feet to the left to 66.9 feet right of centerline. At 600 feet from threshold, the mean of the contour is at 60.0 feet right of centerline, and extends from 12.8 feet left of course to 132.9 feet to the right. At 400 feet from threshold, the mean of the contour is at 49.3 feet right of centerline and extends from 12.4 feet left to 111.1 feet right of course. At 200 feet from threshold, the mean of the contour is at 32.2 feet right of centerline and extends from 11.4 feet to the left and 75.9 feet to the right. The mean of the contour at the threshold is centered at 24.0 feet right of centerline.

3.3.2 Vertical Results

At the DH, the mean of the contour is at 7.23 feet below the intended vertical path, extending 38.97 feet below the intended path and they continue to be centered below the path to the threshold. At the TP, the mean of the contour is at 17.71 feet below the vertical path and extends to 58.81 feet below the intended vertical path. At 10° of turn, the mean of the contour is at 27.88 feet below path and extends to 99.68 feet below. At the RP, the mean of the contour is at 26.25 feet below the vertical path, and extends to 101.45 feet below. At this point, the contour lies 42.1 feet above the elevation of the runway threshold. At 1,200 feet from threshold, the mean of the contour is at 27.1 feet below the path and extends to 94.6 feet below. At 1,000 feet from threshold, the mean of the contour is at 27.46 feet below path and extends to 80.76 feet below. At 800 feet from threshold, the mean of the contour is at 24.63 feet below the vertical path, extends to 78.33 feet below the path. At 600 feet from threshold, the mean of the contour is at 13.8 feet below path and extends to 73.4 feet below. At 400 feet from threshold, the mean of the contour is at 21.1 feet below path and extends to 70.3 feet below. At 200 feet from
threshold, the mean of the contour is at 21.2 feet above the vertical path, extends to 68.7 feet below the vertical path and is at 1.5 feet below the threshold. At the threshold, the mean of the contour is at 6.8 feet above the vertical path and extends to 59.7 feet below, which is 1.7 feet below the threshold.
Figure 49: 2,000 Feet/20° Offset at 1,600 Feet from Intercept (DH)  
(DH to Intercept (SD) = 1,612 Feet)  
$1 \times 10^{-5}$ Probability Under the Curve
Figure 50: 2,000 Feet/20° Offset at Turn Point (TP)
(TP to Intercept = 601 Feet)
$1 \times 10^{-5}$ Probability Under the Curve
Figure 51: 2,000 Feet/20° Offset at 10° Heading Change
1 × 10⁻⁵ Probability Under the Curve
Figure 52: 2,000 Feet/20° Offset at 20° Point (Roll Out) (RP)
(1,399 Feet from Threshold)
$1 \times 10^{-5}$ Probability Under the Curve
Figure 53: 2,000 Feet/20° Offset at 1,200 Feet from Threshold
$1 \times 10^{-5}$ Probability Under the Curve
Figure 54: 2,000 Feet/20° Offset at 1,000 Feet from Threshold
$1 \times 10^{-5}$ Probability Under the Curve
Figure 55: 2,000 Feet/20° Offset at 800 Feet from Threshold
1 × 10⁻⁵ Probability Under the Curve
Figure 56: 2,000 Feet/20° Offset at 600 Feet from Threshold

$1 \times 10^{-5}$ Probability Under the Curve
Figure 57: 2,000 Feet/20° Offset at 400 Feet from Threshold
1 × 10^5 Probability Under the Curve
Figure 58: 2,000 Feet/20° Offset at 200 Feet from Threshold
1 × 10⁻⁵ Probability Under the Curve
Figure 59: 2,000 Feet/20° Offset at Threshold

$1 \times 10^{-5}$ Probability Under the Curve
Figure 60: 2,000 Feet/20° Offset—3D Composite
(DH to Intercept = 1,612 Feet, TCH = 58 Feet, GPA = 3.5°, RP = 1,399 Feet from Threshold)
$1 \times 10^{-5}$ Probability Under the Curve

Note: Scaling on the axes of this figure are adjusted to allow the contours to be presented in this report and to maintain proportionality. Compare Figure 34 and Figure 46. Due to the significant differences in the axes scaling, although the isoprobability contours are orthogonal to the course, they do not appear so until near to and on the runway centerline.
### Table 3: Location of Procedure Track, Glidepath, and 1 × 10⁻⁵ Isoprobability Contour Mean, Left (-), Right (+) and Low Values from both the Flight Path and the Threshold Elevation in Feet

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*Note: Track is the location of the course from the RCL at each listed point along the approach, left of the RCL is negative; Glidepath is the HATh of the GPA at that same point. Mean is the location of the mean value of the contour, laterally and vertically. Left of course is negative and above threshold is positive. Left & Right are the left extreme and right extreme lateral values of the contour from the procedure course. Low is the low extreme HATh value of the contour, negative is below the threshold.
4.0 TERPS Offset Visual Area

The lateral and vertical dimensions of the offset visual area for this approach were calculated in accordance with FAA Order 8260.3B, *United States Standard for Terminal Instrument Procedures (TERPS)*, Change 20, Volume I, Chapter 3, Paragraph 3.3.2.d.(1)(c), Reference 6.

4.1 Lateral Visual Area Comparison

The TERPS Offset Visual Area (OVA) dimensions were calculated at the DH, the RP, 200 feet prior to threshold, and at the threshold for the three offset configurations. The dimensions are depicted in Table 4. As can be seen, the lateral extremes of the $1 \times 10^{-5}$ isoprobability contours are contained well within in the lateral confines of the offset visual area. At the DH, the 1,000 feet/10° offset contour is 545 feet inside the OVA, the 2,000 feet/15° offset is 658 feet inside and the 2,000 feet/20° offset is 620 feet inside. At the RP, the 1,000 feet/10° offset contour is 188 feet inside the OVA, the 2,000 feet/15° offset is 385 feet inside and the 2,000 feet/20° offset is 480 feet inside the OVA. At the 200 foot point, the 1,000 feet/10° offset contour is 188 feet inside the OVA, the 2,000 feet/15° offset is 177 feet inside and the 2,000 feet/20° offset is 188 feet inside the OVA. At the threshold, the 1,000 feet/10° offset contour is 173 feet inside the OVA, the 2,000 feet/15° offset is 179 feet inside and the 2,000 feet/20° offset is 186 feet inside the OVA.

4.2 Vertical Visual Area Comparison

The two (20:1 and 34:1) Offset Visual Area Obstacle Identification Surface (OIS) dimensions in FAA Order 8260.3B, Change 20, were calculated at the DH, the RP, 200 feet prior to threshold, and at the threshold for the three offset configurations. The dimensions are depicted in Table 4. As can be seen, at DH, the vertical extremes of the $1 \times 10^{-5}$ isoprobability contours are all above the OIS except for the 1,000 feet/10° offset, which is 8.3 feet below the 20:1 OIS. At the RP, the 1,000 feet/10° offset lies below both the 20:1 and 34:1 surfaces by 13.2 feet and 2.7 feet respectively. The 2,000 feet/15° offset lies above both by 1.7 feet and 30 feet respectively and the 2,000 feet/20° offset lies below the 20:1 surface by 27.9 feet. At 200 feet from threshold, both of the OIS are at threshold elevation, and the 1,000 feet/10° offset is below both by 59.5 feet, while the 2,000 feet/15° and the 2,000 feet/20° offsets are within 2.0 feet above both. At the threshold, the 1,000 feet/10° offset lies below both OIS by 24.3 feet, the 2,000 feet/15° offset is below both by 6.7 feet and the 2,000 feet/20° offset is below both by 1.7 feet.
Table 4: TERPS Offset Visual Area versus the $1 \times 10^5$ Isoprobability Contours in Feet

Negative values are to the left of RCL

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<th>2,000/20°</th>
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<td>Contour Lateral Extremes</td>
<td>-26.5/33.0</td>
<td>-20.7/9.4</td>
<td>-14.0/61.9</td>
</tr>
<tr>
<td>Contour Vertical Extreme</td>
<td>-24.3</td>
<td>-6.7</td>
<td>-1.7</td>
</tr>
<tr>
<td>TERPS 3.3.2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lateral</td>
<td>-200</td>
<td>0/0</td>
<td>0/0</td>
</tr>
<tr>
<td>**Vertical 20/34</td>
<td>0/0</td>
<td>0/0</td>
<td>0/0</td>
</tr>
<tr>
<td>Contour versus 20/34</td>
<td>-24.3/-24.3</td>
<td>-6.7/-6.7</td>
<td>-1.7/-1.7</td>
</tr>
</tbody>
</table>

* RCL is runway centerline extended.
** These vertical OCS values from TERPS begin at 200 feet prior to threshold and rise at either 20:1 or 34:1 along the RCL to the associated distance.
5.0 Results and Conclusions:

1. The OU LAAS as installed at Max Westheimer Field and operated in a Category A light, twin-engine aircraft demonstrated the flexibility of operation to easily design and broadcast multiple offset procedures with vertical guidance. Previous testing, see Reference 2, had shown the guidance to be equivalent to ILS localizer and glide slope guidance and was flyable in this test by pilots with a broad range of experience.

2. Vertically guided offset approach procedures require a change in pilot technique at the DH from the normal ILS transition to visual conditions. The pilot must visually acquire the runway, which is not directly ahead as it is in an ILS approach, but is offset to one side of the approach course. Only six approaches with a left offset angle, were made by each pilot in this test, but the learning curve was very steep, and the pilots had little to no problem with the visual transitions.

3. Though the pilots were briefed on the proper procedure to fly the design flight path, i.e., to maintain speed and descent rate, and establish a 15° bank angle to align with the runway, the observed tendency was once the pilots had visually acquired the runway, they abandoned this technique and the design approach path, and flew toward the runway threshold directly, establishing a new aiming point and altitude which felt comfortable to them.

4. The training of GA pilots to land on the numbers was apparent in these tests. Once visual, the pilots abandoned the descent rate required to maintain the glidepath prior to the DH and established a new visual descent point. This resulted in a pronounced negative impact on the vertical extremes of the $1 \times 10^{-5}$ isoprobability contours.

5. From the post run and post-test pilot inputs, all of the pilots felt all of the offset procedures to be easy to fly and that the procedure should benefit access to airports where obstacles might reduce access in IMC conditions. The majority of the pilots expressed concern for two items, those being the potential impact of winds, and in conducting an offset approach to real minimums. All of the test runs were day VMC, with little crosswind, and the runways were chosen to provide the best wind conditions for the tests. Other comments repeated were that training for these approaches would be beneficial, and that the offset angles could likely be increased.

6. All of the lateral extremes of the $1 \times 10^{-5}$ isoprobability contours are well within the lateral confines of the TERPS Offset Visual Area, which is expanded on the offset side of the approach.

7. The 1,000 feet/10° offset vertical extreme of the $1 \times 10^{-5}$ isoprobability contour penetrated both the TERPS Visual Segment 20:1 and 34:1 OIS except at the DH, where it was 35.7 feet above the 34:1. The 2,000 feet/15° offset contour was above both OIS except at the threshold where it was 6.7 feet below. The 2,000 feet/20° offset was 27.9 feet below the 20:1 at the RP and was 1.7 feet below both at threshold.
8. The transition from the instrument flight segment to the visual segment, aligning the aircraft from the offset course with the runway centerline and landing did not pose a problem and no missed approaches or rejected landings were necessary.
Appendix A: Vertically Guided Offset Pre-Briefing Questionnaire

SUBJECT PILOT PRE-BRIEFING QUESTIONNAIRE

First Name____________________   Date _________________

Company ____________________________________________

Experience ___________________________________________

_____________________________________________________

Approximate total flight hours __________________________

Approximate hours in PA34A____________________________

Last time flying PA34A_________________________________

Number of actual weather IFR approaches in last 90 days ____

Does your company have guidelines that define a stabilized approach? If so, what are they? ______________________

_____________________________________________________

Does your company or rating authorize circling approaches?

   Y or N
Appendix B: Vertically Guided Offset Post-Run Questionnaire

Date: ___/___/___   Pilot Number:______   File: ______
Start Time: _____   Stop Time: _____   Wind:_____/_____

Approach:   Rwy 17____   1000/10___  1500/10___  2000/15___  2000/20___
Approach:   Rwy 35____   1000/10___  1500/10___  2000/15___  2000/20___

Please indicate your agreement or disagreement with the following statements. You may also write a comment below the item if you would like to explain your response.

General Items

1. The VISUAL segment of this approach was easy for me to fly.
   1 2 3 4 5
   Strongly Disagree Somewhat Neither Agree Somewhat Strongly Agree
   Disagree Disagree Nor Disagree Agree

2. I was able to successfully coordinate flying an appropriate descent path with capturing and maintaining the extended runway centerline during the VISUAL segment.
   1 2 3 4 5
   Strongly Disagree Neither Agree Somewhat Strongly Agree
   Disagree Nor Disagree Agree

3. It was easy to transition from IMC to Visual conditions.
   1 2 3 4 5
   Strongly Disagree Neither Agree Somewhat Strongly Agree
   Disagree Nor Disagree Agree

4. The VISUAL segment of this approach was stabilized based on my organization’s guidance for a stabilized approach.
   1 2 3 4 5
   Strongly Disagree Neither Agree Somewhat Strongly Agree
   Disagree Nor Disagree Agree
5. The workload I experienced in performing the VISUAL segment of this approach was acceptable.

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<tbody>
<tr>
<td>Strongly Disagree</td>
<td>Somewhat Disagree</td>
<td>Neither Agree</td>
<td>Somewhat Agree</td>
<td>Strongly Agree</td>
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</table>
Appendix C: NASA TLX Workload Scale

For the approach that you just flew, please provide a rating on each workload dimension on a scale of 0 to 100.

Mental demand: How much mental and perceptual activity was required (e.g., thinking, deciding, calculating, remembering, looking, searching, etc.)? Was the task easy or demanding, simple or complex, exacting or forgiving?

Rating: ________ (0 = Low Workload, 100 = High Workload).

Physical demand: How much physical activity was required (e.g., pushing, pulling, turning, controlling, activating, etc.)? Was the task easy or demanding, slow or brisk, slack or strenuous, restful or laborious?

Rating: ________ (0 = Low Workload, 100 = High Workload).

Temporal demand: How much time pressure did you feel due to the rate or pace at which the tasks or task elements occurred? Was the pace slow and leisurely or rapid and frantic?

Rating: ________ (0 = Low Workload, 100 = High Workload).

Performance: How successful do you think you were in accomplishing the goals of the task set by the experimenter (or yourself)? How satisfied were you with your performance in accomplishing these goals?

Rating: ________ (0 = Good Performance, 100 = Poor Performance).

Effort: How hard did you have to work (mentally and physically) to accomplish your level of performance?

Rating: ________ (0 = Low Workload, 100 = High Workload).

Frustration Level: How insecure, discouraged, irritated, stressed and annoyed versus secure, gratified, content, relaxed and complacent did you feel during the task?

Rating: ________ (0 = Low Workload, 100 = High Workload).
Appendix D: Vertically Guided Offset Post-Test Questionnaire

Please indicate your agreement or disagreement with the following statements.

Please write a comment in the space below the item to explain your response. Your comments are very valuable. Please take the time.

1. It was easy to see the runway environment at DH on all approaches.

   1  2  3  4  5
   Strongly Somewhat Neither Agree Somewhat Strongly Agree
   Disagree Disagree Nor Disagree Agree

   Comment:

2. The transition to the VISUAL segment did not interfere with scanning the runway environment.

   1  2  3  4  5
   Strongly Somewhat Neither Agree Somewhat Strongly Agree
   Disagree Disagree Nor Disagree Agree

   Comment:
3. Offset approaches require no more effort than visual approaches that I typically fly.

<table>
<thead>
<tr>
<th>Strongly Disagree</th>
<th>Somewhat Disagree</th>
<th>Neither Agree</th>
<th>Somewhat Agree</th>
<th>Strongly Agree</th>
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Comment:

4. My awareness of own aircraft position relative to the runway was uninterrupted by the transition to the VISUAL segment.

<table>
<thead>
<tr>
<th>Strongly Disagree</th>
<th>Somewhat Disagree</th>
<th>Neither Agree</th>
<th>Somewhat Agree</th>
<th>Strongly Agree</th>
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Comment:

5. Visual acquisition of the landing environment during the offset approaches was no more difficult than acquiring the landing environment during the straight in procedures.

<table>
<thead>
<tr>
<th>Strongly Disagree</th>
<th>Somewhat Disagree</th>
<th>Neither Agree</th>
<th>Somewhat Agree</th>
<th>Strongly Agree</th>
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Comment:

6. Maneuvering the aircraft to align with the runway was easily accomplished.

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<thead>
<tr>
<th>Strongly Disagree</th>
<th>Somewhat Disagree</th>
<th>Neither Agree</th>
<th>Somewhat Agree</th>
<th>Strongly Agree</th>
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Comment:
7. A successful landing from the approaches was never in doubt.

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<tbody>
<tr>
<td>Strongly Disagree</td>
<td>Somewhat Disagree</td>
<td>Neither Agree</td>
<td>Somewhat Agree</td>
<td>Strongly Agree</td>
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Comment:

8. When I reached DH I had time to execute my decision to land or go around.

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<td>Somewhat Disagree</td>
<td>Neither Agree</td>
<td>Somewhat Agree</td>
<td>Strongly Agree</td>
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Comment:

9. My landing touchdown point was acceptable.

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<td>Neither Agree</td>
<td>Somewhat Agree</td>
<td>Strongly Agree</td>
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Comment:

10. I was comfortable with my perceived descent rate on the VISUAL segment.

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<td>Somewhat Disagree</td>
<td>Neither Agree</td>
<td>Somewhat Agree</td>
<td>Strongly Agree</td>
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Comment:
11. The offset angle impacted my performance most.

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<td>Somewhat Disagree</td>
<td>Neither Agree</td>
<td>Somewhat Agree</td>
<td>Strongly Agree</td>
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Comment:

12. The centerline intersect distance (thus time to line up) impacted my performance most.

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<tr>
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<td>Somewhat Disagree</td>
<td>Neither Agree</td>
<td>Somewhat Agree</td>
<td>Strongly Agree</td>
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Comment:

13. Descent rate impacted my performance most.

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<td>Somewhat Disagree</td>
<td>Neither Agree</td>
<td>Somewhat Agree</td>
<td>Strongly Agree</td>
</tr>
</tbody>
</table>

Comment:

14. Please tell us your thoughts about the potential uses of offset approaches and any concerns that you may have about their use. If you flew wind approaches, please also describe any concerns about their use.
15. Please tell us your thought or concerns or about the effects of wind on the approaches you flew and on these types of approaches in general.
References


