Federal Aviation Administration

Phase I Helicopter Test Flight Evaluation of Instrument Flight Rules Approaches to a Heliport Under Global Positioning System/Wide Area Augmentation System Guidance

Flight Systems Laboratory
DOT-FAA-AFS-450-60

August 2010

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OK-11-0218

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Flight Systems Laboratory
Flight Technologies and Procedures Division
Flight Standards Service

PHASE I HELICOPTER TEST FLIGHT EVALUATION OF INSTRUMENT FLIGHT RULES APPROACHES TO A HELIPORT UNDER GLOBAL POSITIONING SYSTEM/WIDE AREA AUGMENTATION SYSTEM GUIDANCE

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August 2010

Technical Report

Technical Report Documentation Page

1. Report No. DOT-FAA-AFS-450-60	**2. Government Accession No.**	**3. Recipient's Catalog No.**
4. Title and Subtitle **PHASE I HELICOPTER TEST FLIGHT EVALUATION OF INSTRUMENT FLIGHT RULES APPROACHES TO A HELIPORT UNDER GLOBAL POSITIONING SYSTEM/WIDE AREA AUGMENTATION SYSTEM GUIDANCE**		**5. Report Date** August 2010
6. Author(s) Sherri S. Avery, AFS-450 David Stapleton, ISI Mark A. Reisweber, AFS-440		**7. Performing Organization Code**
8. Performing Organization Name and Address Flight Systems Laboratory, AFS-450 6500 S. MacArthur Blvd, STB Annex, RM 217 Oklahoma City, Oklahoma 73169		**9. Type of Report and Period Covered** Technical report
10. Sponsoring Agency Name and Address Federal Aviation Administration Flight Operations Branch, AFS-410 470 L'Enfant Plaza, SW Washington DC 20024		
11. Supplementary Notes		
12. Abstract There exists a need for development of Global Positioning System/Wide Area Augmentation System (GPS/WAAS) Instrument Flight Rules (IFR) Terminal Instrument Procedures (TERPS) criteria for helicopter approaches to a heliport; Helicopter Localizer Performance with Vertical Guidance (HLPV). Twenty helicopter test flights, resulting in 151 approaches, were performed with the Sikorsky S-76A helicopter at the FAA William J. Hughes Tech Center Airport in Atlantic City, New Jersey using LPV guidance. The results presented in this document are the quantitative portion of analysis, which includes the final approach segment with TSE/NSE/FTE components, flight tracks, mean, ±2 SD's, ±6 SD's (lateral and vertical); the missed approach segment with existing TERPS protected surfaces, flight tracks, mean, ±2 SD's, ±6 SD's (lateral and vertical); height loss analysis; turn segment with existing TERPS protected surfaces, flight tracks, mean, ±2 SD's, ±6 SD's (lateral and vertical).		
13. Key Words Helicopter, WAAS, LPV, PinS	**14. Distribution Statement** Controlled by AFS-450	
15. Security Classification of This Report Unclassified	**16. Security Classification of This Page** Unclassified	

Executive Summary

The need for development of Global Positioning System/Wide Area Augmentation System (GPS/WAAS) Instrument Flight Rules (IFR) Terminal Instrument Procedures (TERPS) criteria for helicopter approaches to a heliport was identified [1] because of the growing use of WAAS guidance in recent years. Approaches developed with these criteria are called Localizer Performance with Vertical Guidance (LPV). WAAS provides navigation accuracy equivalent to an Instrument Landing System (ILS) localizer and glideslope performance standards.

A data collection effort at the FAA William J. Hughes Tech Center Airport using LPV guidance using a 7.5° final approach Glide Path Angle (GPA) was Phase I in the Helicopter LPV project. The primary objectives were to validate display scaling requirements, to determine the flyability of the procedures, and to determine if pilot workload was acceptable when flying these procedures.

Generally, the lateral dispersion of these flights shows containment within TERPS protected surfaces. However, there were several incidences of large vertical dispersion. Observer comments noted that several pilots had difficulty maintaining the 7.5° GPA (mostly above the GPA). While flying above the GPA does not pose additional risk in the final approach segment, it either caused an overshoot of the landing area or a late execution of the missed approach.

Phase II of the Helicopter LPV project is currently underway. Data collection efforts are scheduled to begin September 2010. In Phase II, AFS-400 will be collecting and analyzing data for Approach, Missed Approach, Landing, Departure and Enroute Segments. The Glide Path Angle for the Final Approach Segment will be 6°.

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1.0 Introduction

The need for development of Global Positioning System/Wide Area Augmentation System (GPS/WAAS) Instrument Flight Rules (IFR) Terminal Instrument Procedures (TERPS) criteria for helicopter approaches to a heliport was identified [1] because of the growing use of WAAS guidance in recent years. Approaches developed with these criteria are called Localizer Performance with Vertical Guidance (LPV). WAAS provides navigation accuracy equivalent to Instrument Landing System (ILS) localizer and glideslope performance standards.

It was determined that criteria should be developed in three phases to support such procedures. In the first phase, engineering evaluation of test flights conducted at the FAA William J. Hughes Tech Center (WJHTC) Airport, in Atlantic City, New Jersey would be used to recommend possible modifications to approach procedures and determine pilot workload. The FAA Flight Navigation Performance and Flight Program Teams were tasked to conduct test flights and reduce the data for analysis by the FAA Flight Systems Laboratory and Flight Procedure Standards Branches (AFS-450 and AFS-420). This report summarizes that analysis for the Phase I testing in terms of evaluation of the LPV criteria, helicopter, and pilot performance.

2.0 Test Procedures

The test helicopter was the FAA Sikorsky S-76A helicopter shown in Figure. 1.

Figure 1: The Sikorsky S-76A (Courtesy WHTC)

The S-76A is a twin engine helicopter capable of speeds up to 155 knots, with a maximum takeoff gross weight of 10,300 lbs, and is certificated for steep angle approaches using a GPA of less than or equal to 7.5^{o}.

During the tests, the S-76A, through its digital system, provided recorded full rate ARINC 429 data from its UNS-1F flight management system from WAAS inputs provided by a Rockwell Collins multimode navigation receiver at 5 Hz. It also carried an Ashtech Z-Extreme truth receiver which worked in coordination for data merge with another Z-Extreme receiver located on the ground at a surveyed position.

Twenty helicopter test flights were performed with this test vehicle at the WHTC using WAAS guidance, from Sept. 16 through November 26, 2008 using a 7.5° final approach GPA. During

these flights, 151 helicopter LPV Point in Space (PinS) approaches were made along two different approach courses of 145° and 310° magnetic, of which 142 had completely retrievable data sets (Table 1) and 138 could be used for analysis. The two approaches required a turn of 15° at the DA to a visual segment to the heliport to land. Note: Table 1 shows that the first 7 sorties were Autopilot. These runs are noted as "Autopilot" because the autopilot was engaged for the majority of the run. However, the autopilot was not engaged for the entire run.

Table 1: Sikorsky S-76A Final Approach Data Sets

Date and AM or PM	Piloting Type	Approaches at 145°	Approaches at 310°
Sept. 16, AM	Autopilot	0	10
Sept. 17, AM	Autopilot	2	8
Sept. 18, AM	Autopilot	0	5
Sept. 18, PM	Autopilot	8	0
Sept. 19, AM	Autopilot	2	2
Sept. 24, AM	Autopilot	0	5
Sept. 24, PM	Autopilot	5	0
Sept. 30, AM	Flight Director	0	8
Sept. 30, PM	Flight Director	0	8
Oct. 1, AM	Flight Director	1	5
Oct. 2, AM	Flight Director	0	10
Oct. 6, AM	Flight Director	0	10
Oct. 6, PM	Flight Director	6	0
Oct. 8, AM	Flight Director	0	4
Oct. 8, PM	Flight Director	0	11
Oct. 30, AM	Flight Director	0	8
Nov. 12, AM	Flight Director	0	8
Nov. 13, AM	Flight Director	8	0
Nov. 26, AM	Flight Director	0	1
Nov. 26, PM	Flight Director	0	7
Totals		32	110

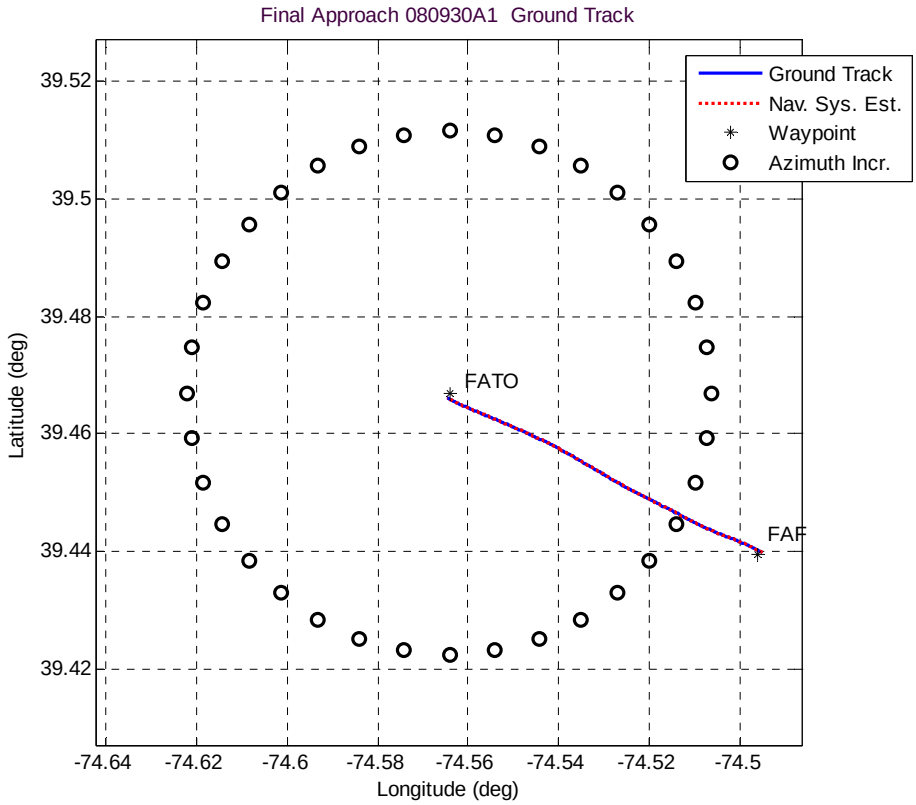

Figure 2: Top View of a Typical Final Approach at 310°

In these tests, the test pilot flew an IVH approach (IFR to a VFR Heliport; Proceed Visually). They were instructed to fly instruments only with no visual cues (although they were not hooded), at a fixed altitude along initial and intermediate approach segments and then continued along a final approach segment either by using the flight director or by using the autopilot. The helicopter descended along a constant-gradient (ILS-like) final approach segment toward a fictitious helipoint using GPS/WAAS lateral and vertical guidance. The system provided pilot navigation information during the final approach by means of Flight Director, a Cross-track Deviation Indicator (CDI), and a Vertical Display Indicator (VDI) until reaching the decision altitude/height (DA/H), at which point, the pilot was able to transition to visual guidance, or execute a missed approach. Most approaches ended with a planned missed approach.

Approaches were performed with a nominal final approach speed of 70 KIAS (Knots Indicated Air Speed), at a glide path angle of 7.5°, and if visual at DA/H, with a nominal helicopter deceleration rate) of 0.085 g, to arrive at the helipad at a hover height of 15 feet (if landing). Tests were performed under day Visual Meteorological Conditions (VMC) and with a maximum tailwind of 10 knots.

The navigation receiver data sets from the final approaches were stored in files according to the

naming convention of the two-digit year (08), followed by the two-digit month, the two-digit day of the month, A or P (for AM or PM flight), a one-digit hexadecimal approach sequence number within the flight, and the string '.dat'. For example, file 080917A5.dat contained the data from the 5th approach of the 09/17/08 AM test flight. Files 081008A4 and 080918A4 were eliminated because of interruptions during the test; file 081030A1 was eliminated because a crosswind lead to a change in direction (and a computer malfunction was reported in the flight log), and file 081112A7 was eliminated because vertical guidance was lost.

3.0 Computations Relating Pilot Instruments to Helicopter Position

Cross-track positioning during final approach, shown in Figure 3, used a full-scale deflection limit of 1.15° from a point located 17,436 ft (5,314 m) behind the fictitious helipoint) from a minimum width of 350 ft (106.68 m) to a maximum width of 1 nm (1852 m). In all plots in this paper, the fictitious helipoint (if present) will appear at the origin.

Computation of Cross-Track Position y and Cross-Track Full-Scale Deflection fsd_L Limit From Lateral Difference in Depth of Modulation (DDM_L) and Along-Track Position x

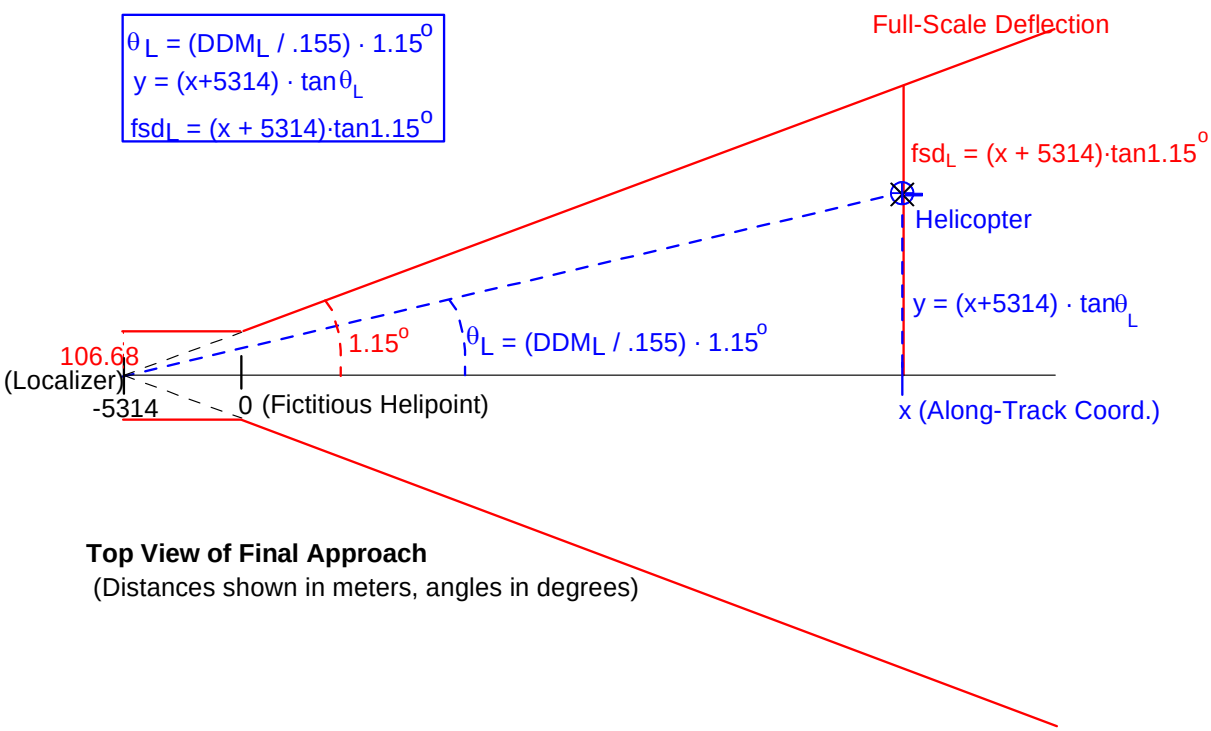

Figure 3: Helicopter LPV Cross-Track Positioning

The WAAS-derived lateral position of the helicopter relative to the procedure track was displayed as a left or right deviation on the CDI display for the pilot, in which full-scale deflection corresponded to a .155 DDM (difference in depth of modulation) localizer equivalent.

Hence, during the angular portion of the course the angle of the helicopter from the origin of the splay was $\theta_L = \frac{D}{0.155} 1.15^o$, where D was the DDM value for the CDI presentation, and the cross-track helicopter position was y = (x + 5,314) × tan(θ_L), where x was the along-track position of the helicopter. Full-scale lateral deflection (in meters) was fsd_L = (x + 5,314)× tan(1.15°) cross-track.

Vertical positioning on the VDI is illustrated in Figure 4, and was computed based upon deviation from a GPA of 7.5° originating 1,000 ft (304.8 m) behind the fictitious helipoint, using an ILS-based 0.175 DDM full-scale deflection to represent a deviation of one fourth of the GPA from the glide path. This angular full-scale deflection was used between a minimum value of 49.2 ft (15 m) and a maximum value of 492 ft (150 m).

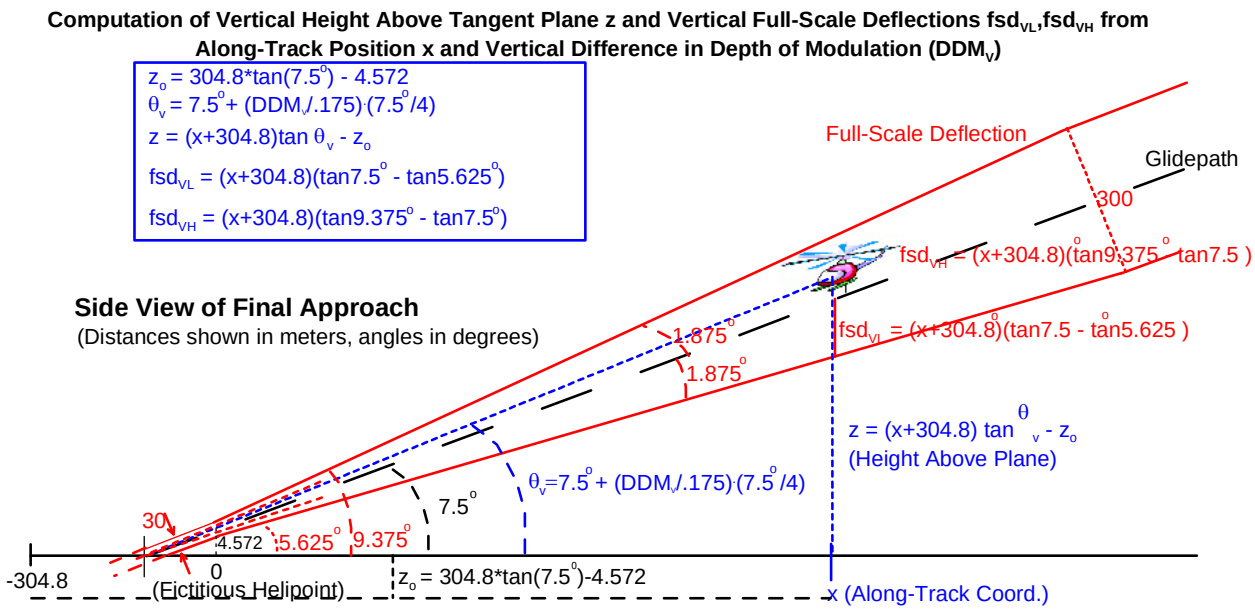

Figure 4: Helicopter LPV Vertical Positioning

The glide path was required to pass over the fictitious helipoint at a height of 15 ft (4.572 m), and this put the origin of the vertical splay below ground. If z was the helicopter's height above the tangent plane to the earth at the fictitious helipoint and D was the DDM value for VDI presentation, the angle of the helicopter from the GPA was then $\theta_V = 7.5° + \frac{D}{0.175} 1.875°$ and the corresponding vertical height was z = (x + 304.8)(tan(θ_V)-tan(7.5°)) + 4.572 m. Full-scale vertical deflection limits (z-widths) were therefore fsd_{VL} = (x+304.8)(tan7.5° - tan5.625°) and fsd_{VU} = (x+304.8)(tan9.375° - tan7.5°) between a minimum of 15 m and a maximum of 150 m.

4.0 Compilation/Reduction of Data

After review of the 138 flight director and autopilot HLPV test approaches, it was determined

that there was a subset of flight tracks which differed significantly from the other approaches. Figure 5 shows the final approach segment and missed approach for all approaches flown with the flight director. The tracks in red or blue reached full-scale vertical deflection at some portion of the final approach. These approaches were designated "High". The "High" runs were flown by two different subject pilots. According to observer comments, these two pilots (of 11 total subject pilots) had difficulty maintaining glide path and airspeed ["1 dot high", "High on GS", "Fast Airspeed"]. The flight tracks also showed instances of high lateral error.

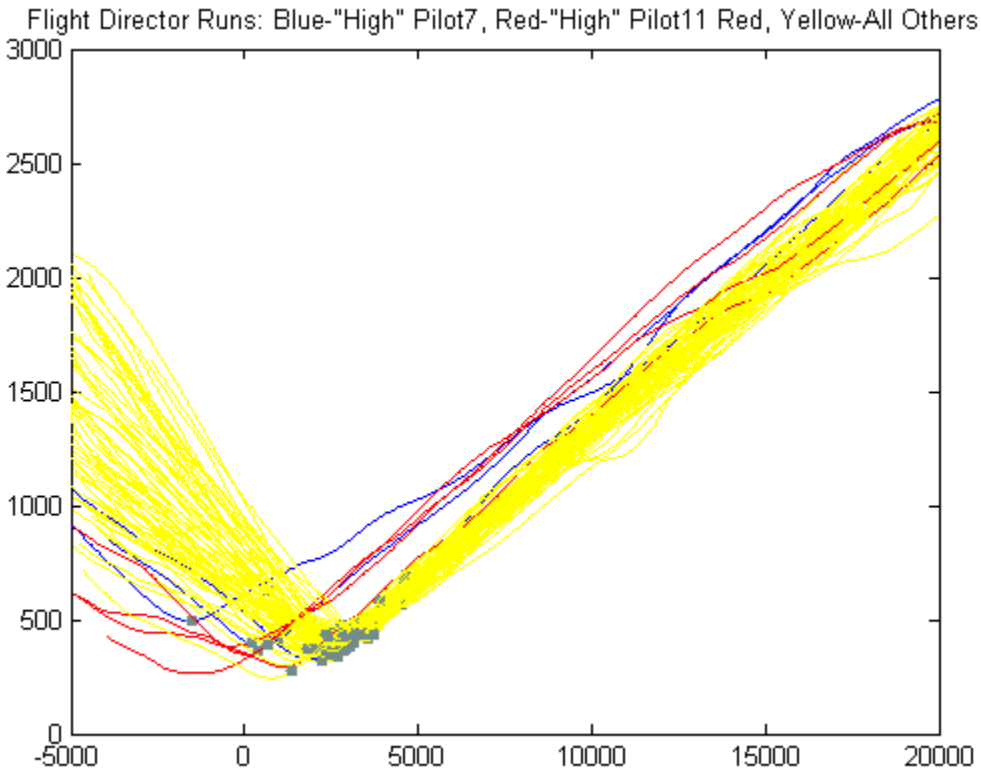

Figure 5: High and Non-High Approaches

Inclusion of the high approaches with the other approaches would lead to large vertical standard deviations that may consequently lead to overestimates of penetrating obstacles below the TERPS W-Surface protection underneath the glide path (if vertical symmetry of flight paths is assumed). The W-Surface is shown in gray in Figures 47-49. In fact, the pilots were flying conservatively with respect to the TERPS W-surface. Consequently, as seen in Table 2, data was separated and statistics were collected for autopilot, flight director High, flight director Non-High approaches.

The determination if these High tracks are representative of what would be flown in the National Airspace System (NAS) is of significant interest in further testing. Importantly, as seen in Figure 5, the execution of missed approach and subsequently lowest point in the miss occurs

much later in the High approaches. This is another topic of concern in subsequent testing.

Table 2: Final Approaches with Usable Data Sets In Six Test Categories

Pilot Type \ Azimuth	145°	310°
Autopilot	17	29
Flight Director – Non-High	14	70
Flight Director - High	1	7

Statistics of flight performance are collected via slices (windows or bins) orthogonal (perpendicular to the tangent) to the theoretical track. For the straight portion of the approach, the data for the slices are combined that are a specific along track distance (increments of 1000 ft) from the fictitious helipoint. For the turn portion of analysis, the orthogonal data is combined also by increments of along track distance. However, the along track distance is approximated by the length of an arc in a circle. As there is no precise theoretical track for a flyby waypoint, turn analysis "slices" [at the Intermediate Fix (IF) and after the miss], were calculated by dividing the 90°degree arc into slices, at angular increments (approximately 1000 ft. along track). That is, a theoretical RF leg (center and radius) was approximated to best-fit the data. The mean, $\pm$ 2SD, and $\pm$ 6SD statistics are not affected by this center and radius chosen for slice analysis. Figure 6 shows an example of the slices orthogonal to the course in planform view.

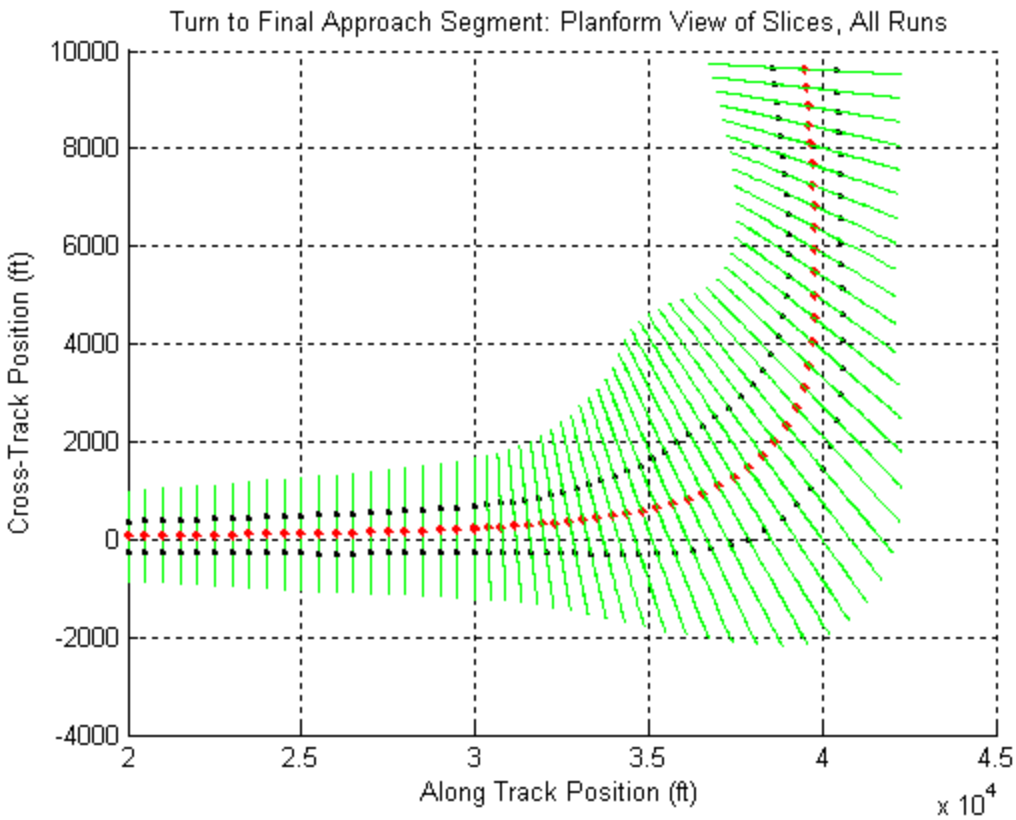

Figure 6: Planform View of Slices

5.0 Evaluation from Start of Turn to Final Approach Segment

As the vertical dispersion occurred initially during descent in the High approaches, flight director High and Non-High were combined for analysis from start of turn to the final approach segment. Additionally, approaches at 310° and 145° were identical but mirror images of one another. When possible the data from these two approaches were combined. Figure 7 shows a "far-view" of the TERPS primary and secondary protection areas for the turn. In the turn tracks were well within containment areas.

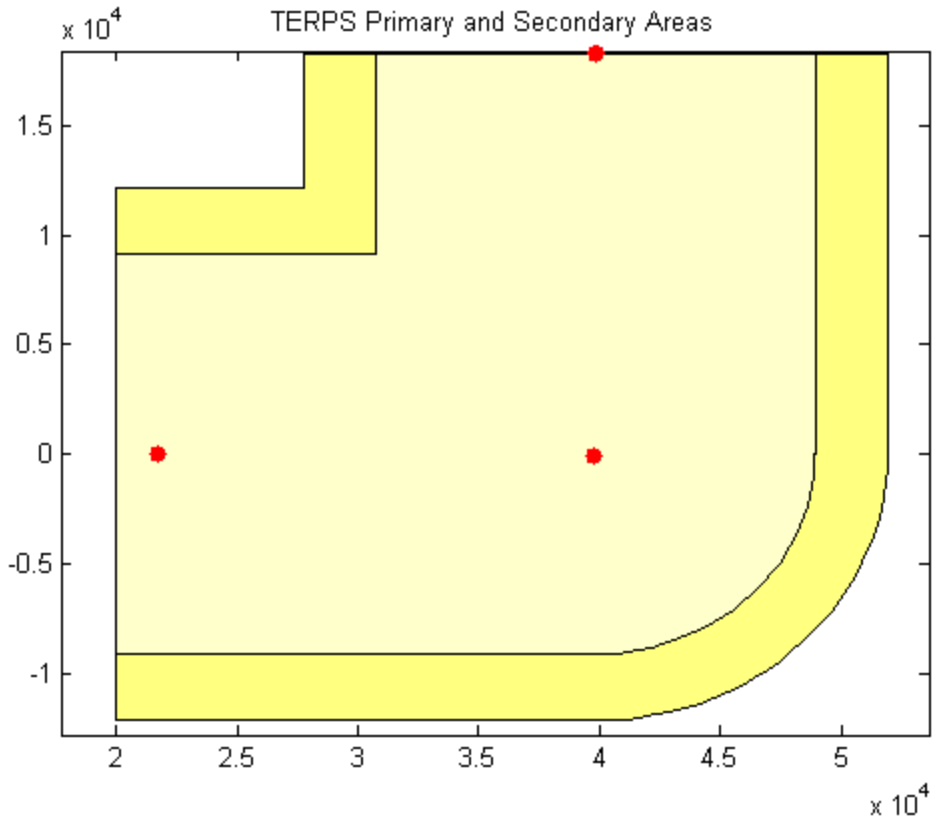

Figure 7: TERPS surface area in the turn

Figures 8-13 are enlarged about the track/SD data and show start of turn to final approach; flight director, autopilot and all tracks [Figures 8-10 Planform and Figures 11-13 Profile]. Note: There are several tracks in Figure 12 in which it is appears as if the autopilot was not engaged during the turn portion of the test. The figures show Truth Position, mean track, ± 2SD, and ± 6SD tracks. Lateral and vertical statistics from start of turn to final approach segment appear in Tables A1-A6 of the Appendix. Figures A1-A8 depicting start of turn to final approach segment tracks/SD's at 310° and 145° are also shown in the Appendix. Table 3 shows a sample of the presentation of the lateral and vertical dispersion tables in the Appendix. Figure 14 shows the 2-Sigma Total System Error (TSE) elliptical cross-sections in 3D all flight tracks from start of turn to final approach segment.

Table 3: Sample of Presentation of Lateral Error

Along-Track Position	Lateral Total System Error				
	Mean	Mean-2σ	Mean+2σ	Mean-6σ	Mean+6σ
20000	75	-338	488	-1164	1314
19000	-3	-365	358	-1088	1082
18000	-80	-398	238	-1033	874
17000	-139	-481	203	-1165	886

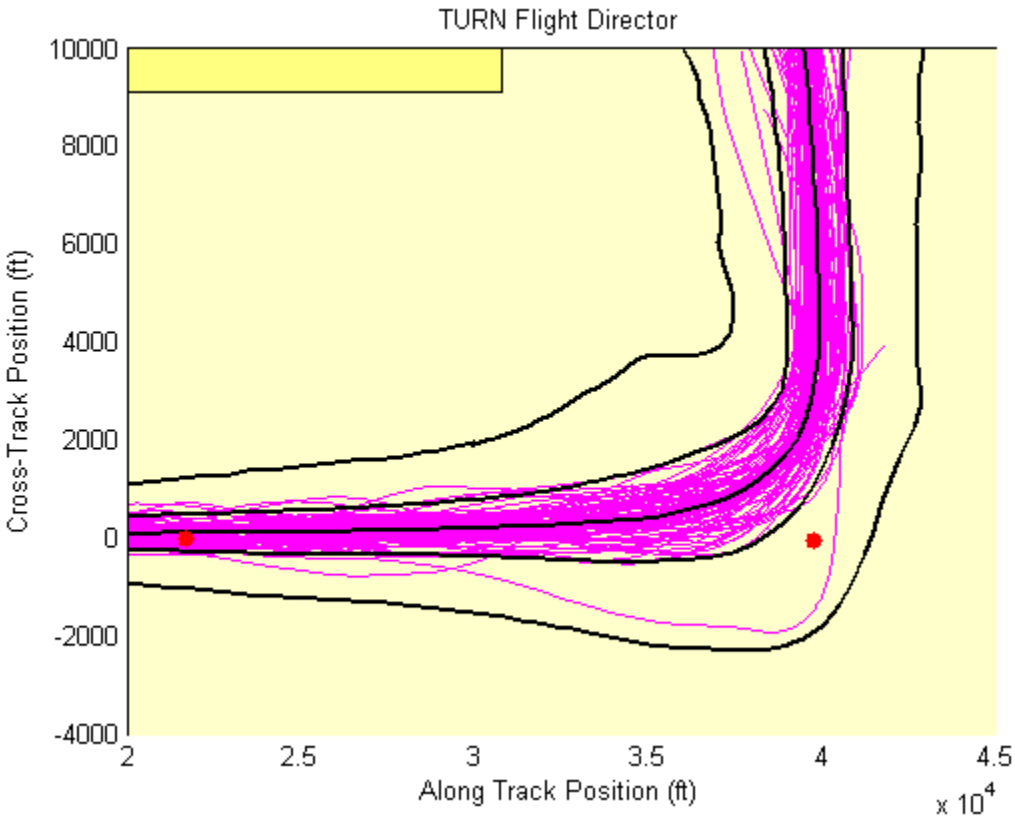

Figure 8: Planform View Start of Turn to Final Approach Segment Flight Director

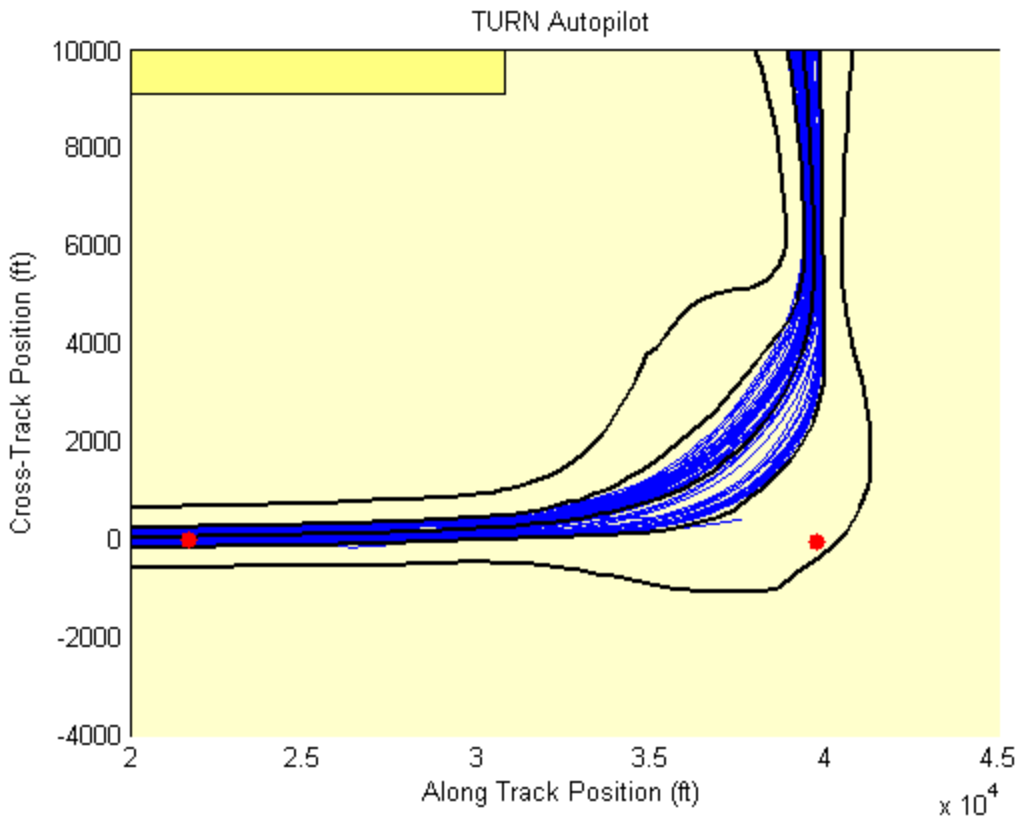

Figure 9: Planform View Start of Turn to Final Approach Segment Autopilot

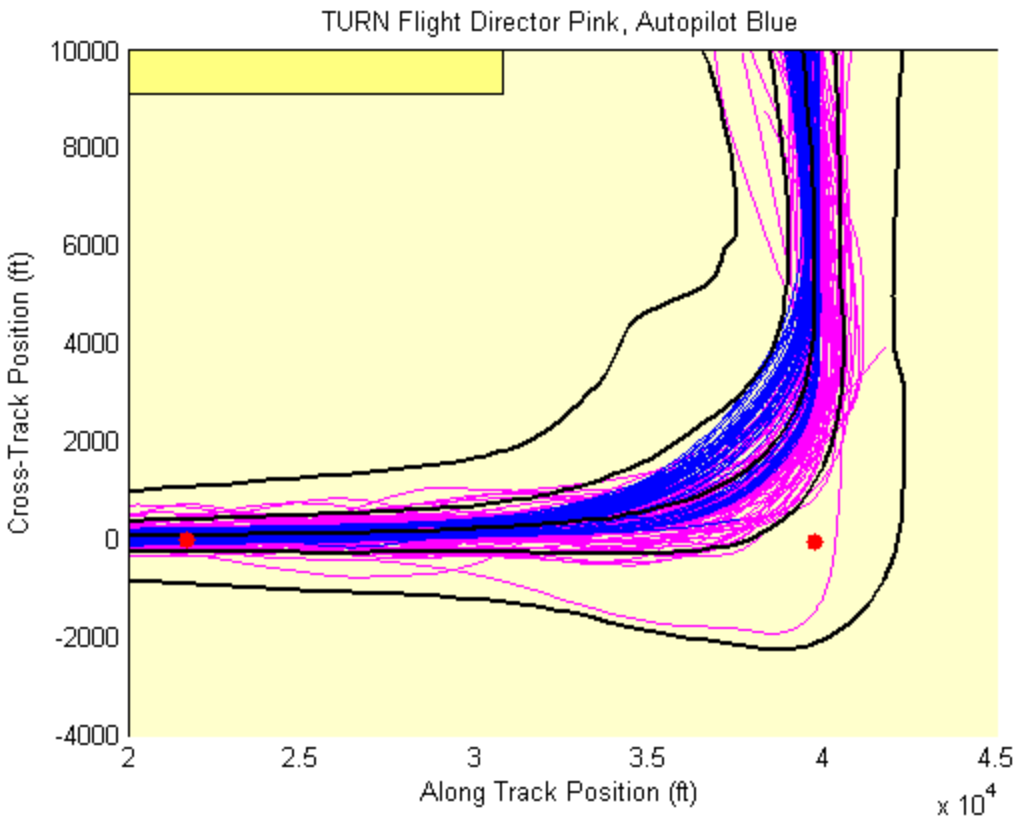

Figure 10: Planform View Start of Turn to Final Approach Segment

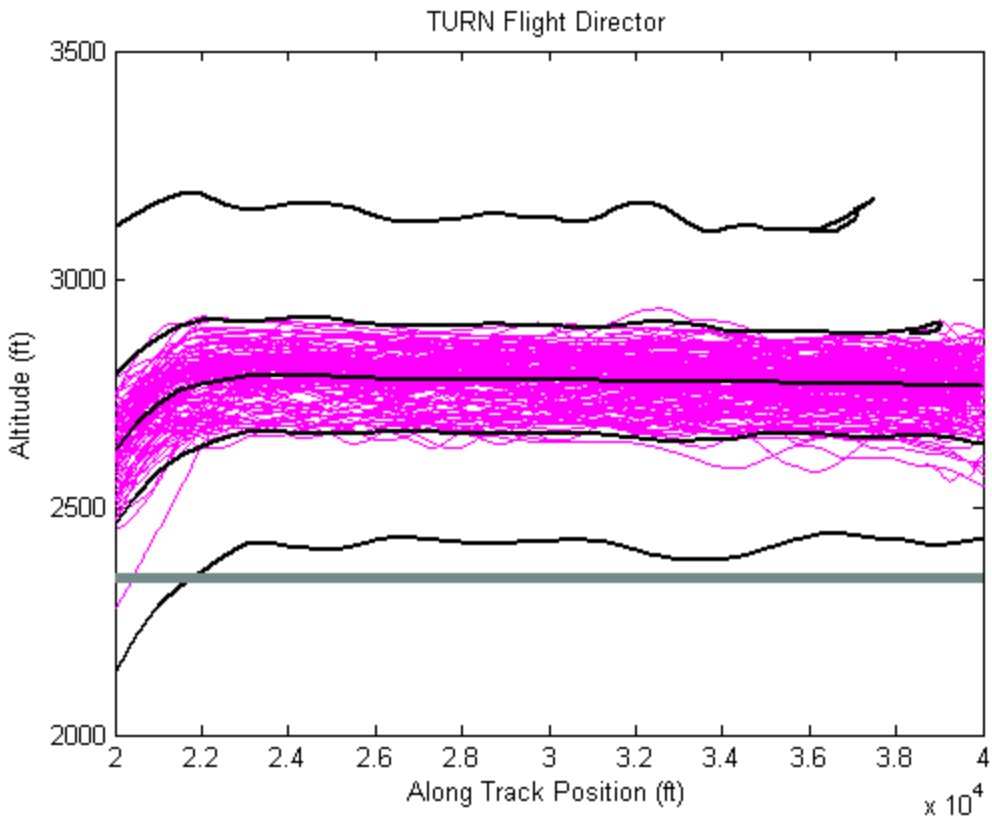

Figure 11: Profile View Start of Turn to Final Approach Segment Flight Director

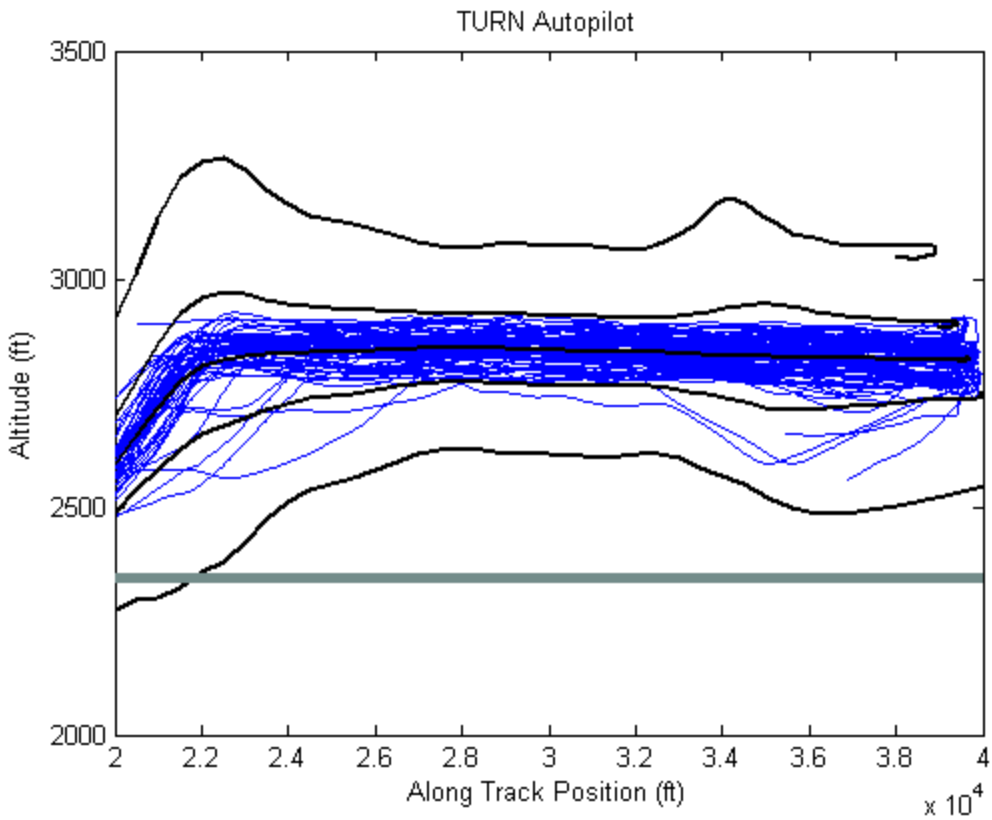

Figure 12: Profile View Start of Turn to Final Approach Segment Autopilot

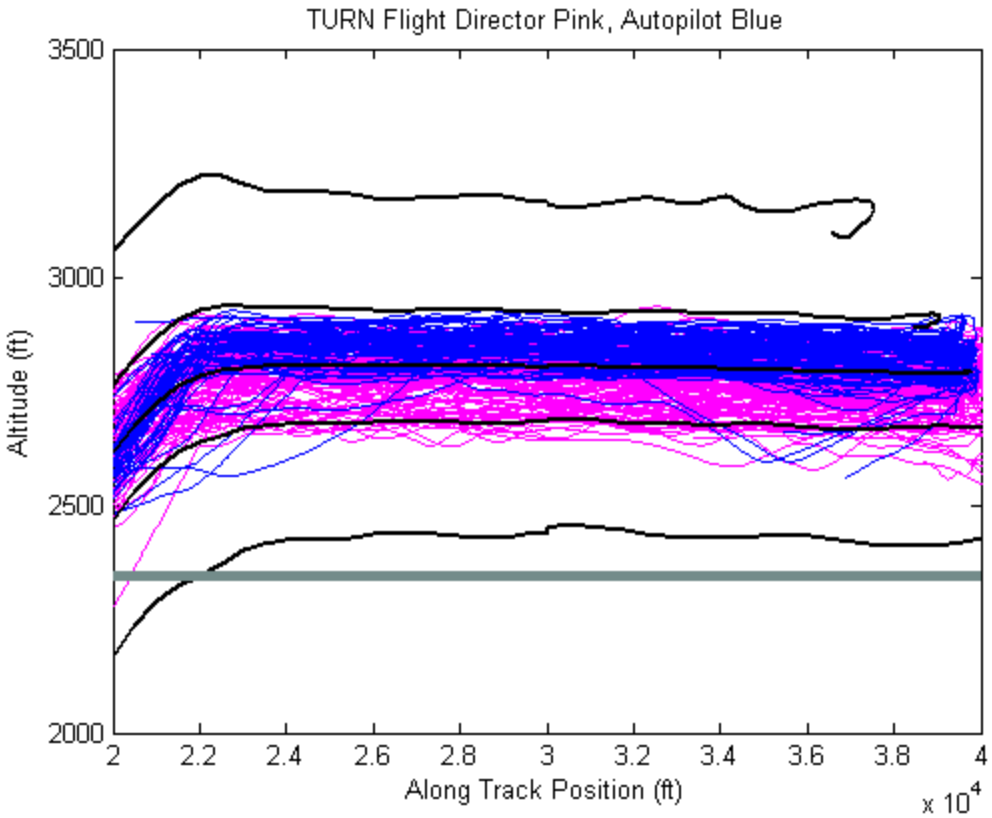

Figure 13: Profile View Start of Turn to Final Approach Segment

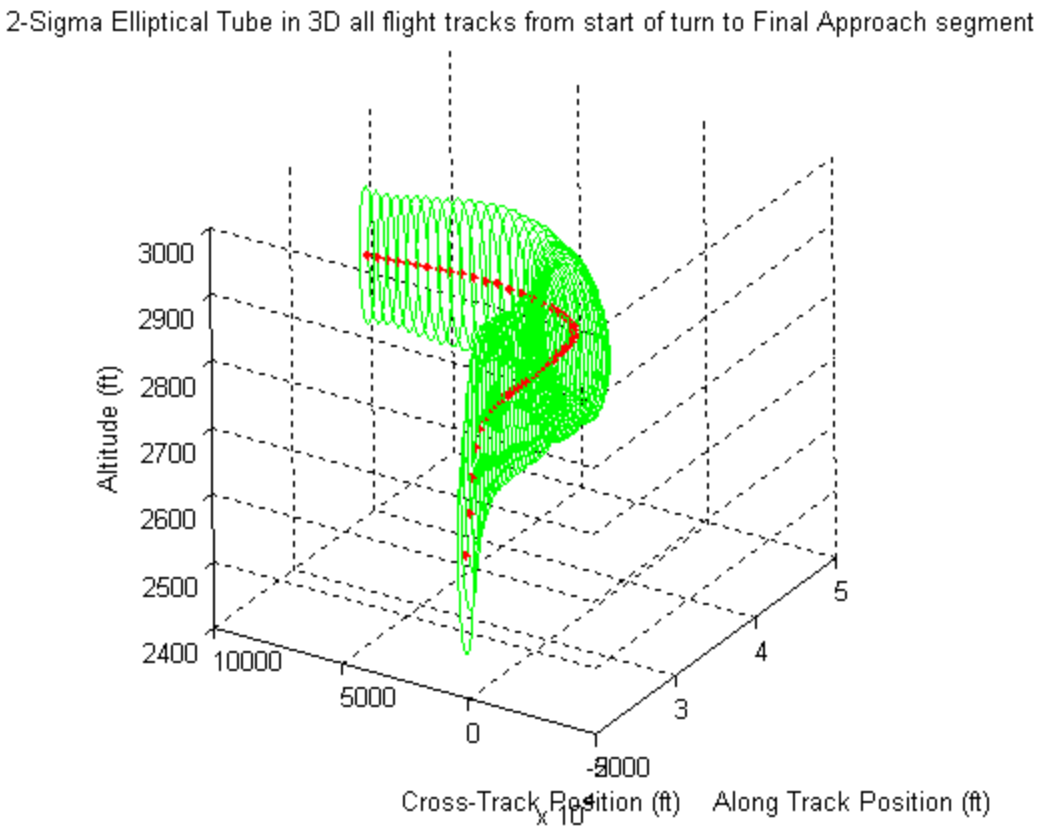

Figure 14: 2-Sigma TSE Elliptical Cross-Sections in 3D Start of Turn to Final Approach Segment

6.0 Evaluation of the Final Approach Test Cases Including WAAS NSE and NSE contribution by FMS

There were six flight test cases considered (as shown in Table 2) which will now be evaluated in Sections 6.1 through 6.6. In each, the NSE (Navigation System Error), FTE (Flight Technical Error,), and TSE (total system error = NSE + FTE) is considered.

The NSE shown herein, however, will refer only to the error in the position calculated by the navigation receiver itself (as differenced from the truth receiver position) and does not include the latency of pilot display, error in the pilot's instruments, or errors in user input of the antennae offsets, waypoints, or other data. Latency effects were omitted because the test equipment did not permit its evaluation. Pilot instrumentation was a significant factor omitted, as shown in Figure 15 (where NSE denotes only navigation receiver error) and the CDI and VDI together with the navigation receiver's along-track position estimate were used to calculate cross-track and vertical position errors. Figure 15 shows a close up view of the TSE, FTE, NSE, and CDI. Full-Scale Deflection is outside the scale of the graph.

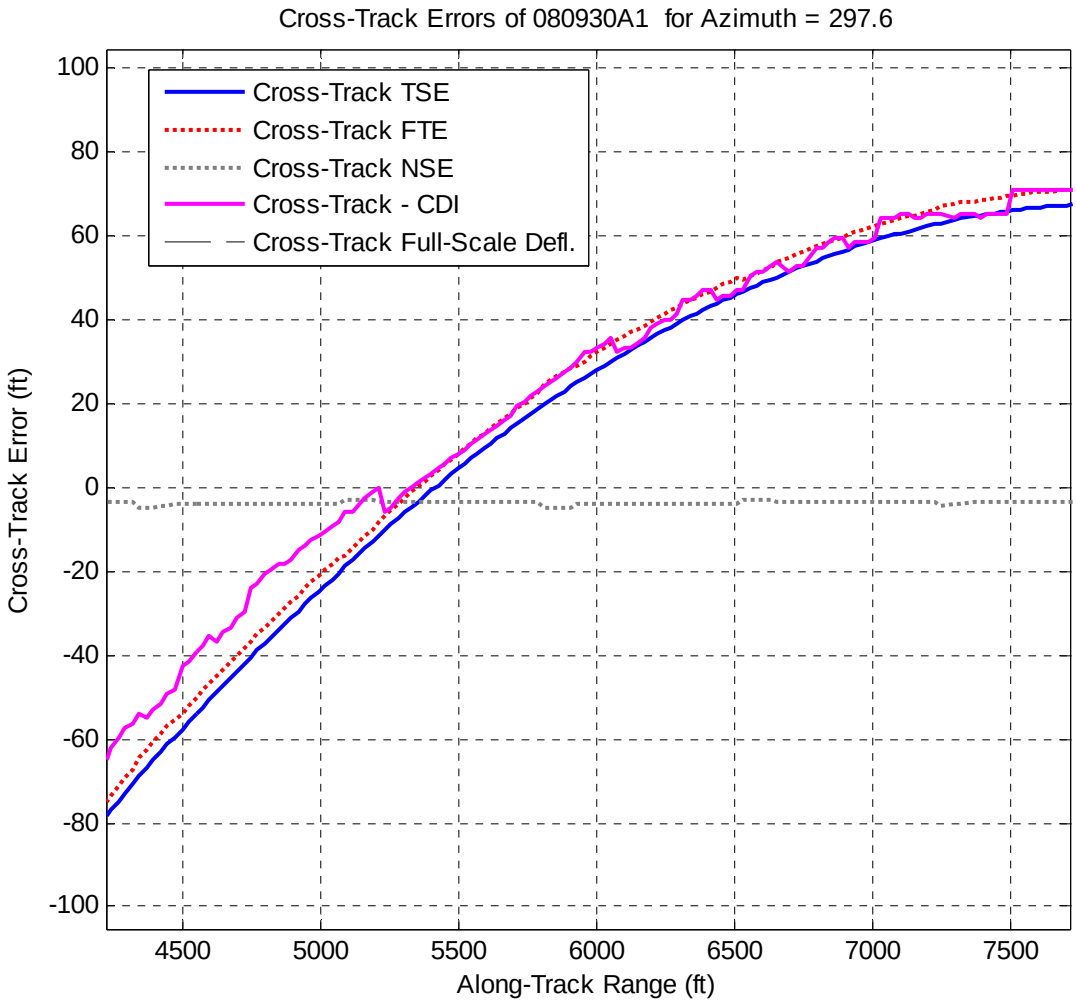

Figure 15: Typical Differences Between the Navigation Receiver Position Estimates and Pilot Instrument Position Estimates

6.1 The 310° Non-High Flight Director Approaches

The 310° flight director approaches constituted the only group (of the six groups in Table 2) large enough to calculate 95% confidence intervals for comparison with Normal 95% confidence intervals (approx. 2-sigma intervals). Figure 16 shows vertical error during a typical flight director approach – with FTE and TSE evidently characterized by an oscillation about centerline.

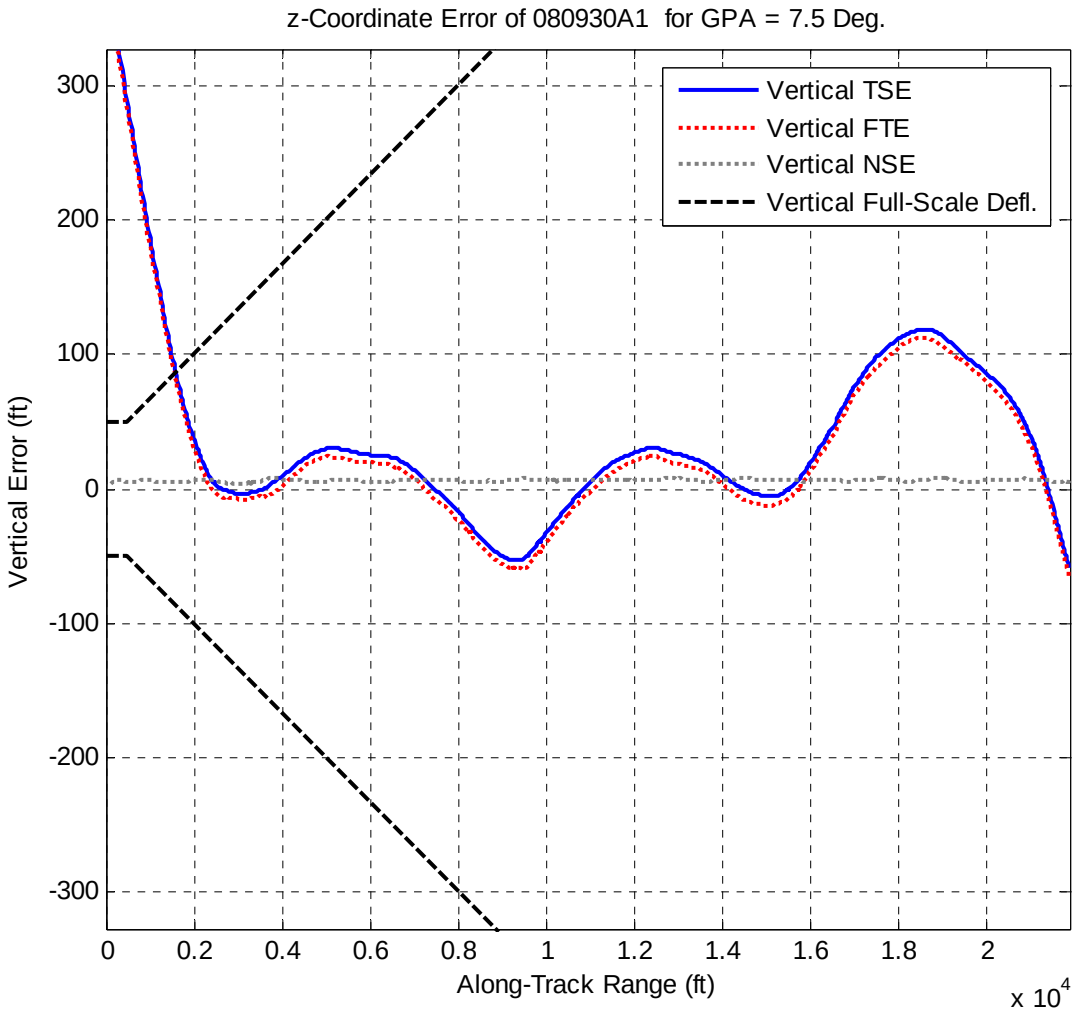

Figure 16: Planform View of a Typical Approach at 310°

The NSE also oscillates about a relatively constant value of (e.g. 6 ft for vertical NSE), as shown in Figure 17.

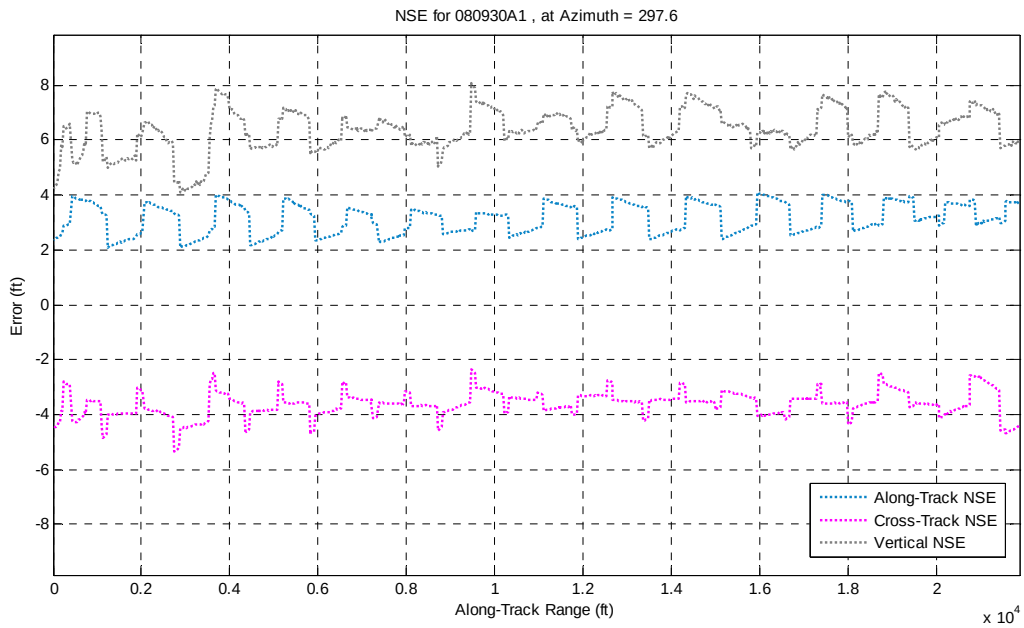

Figure 17: NSE Components During a Typical Approach

The 70 usable approach data sets produce the plots and statistics of Figures 18 and 19.

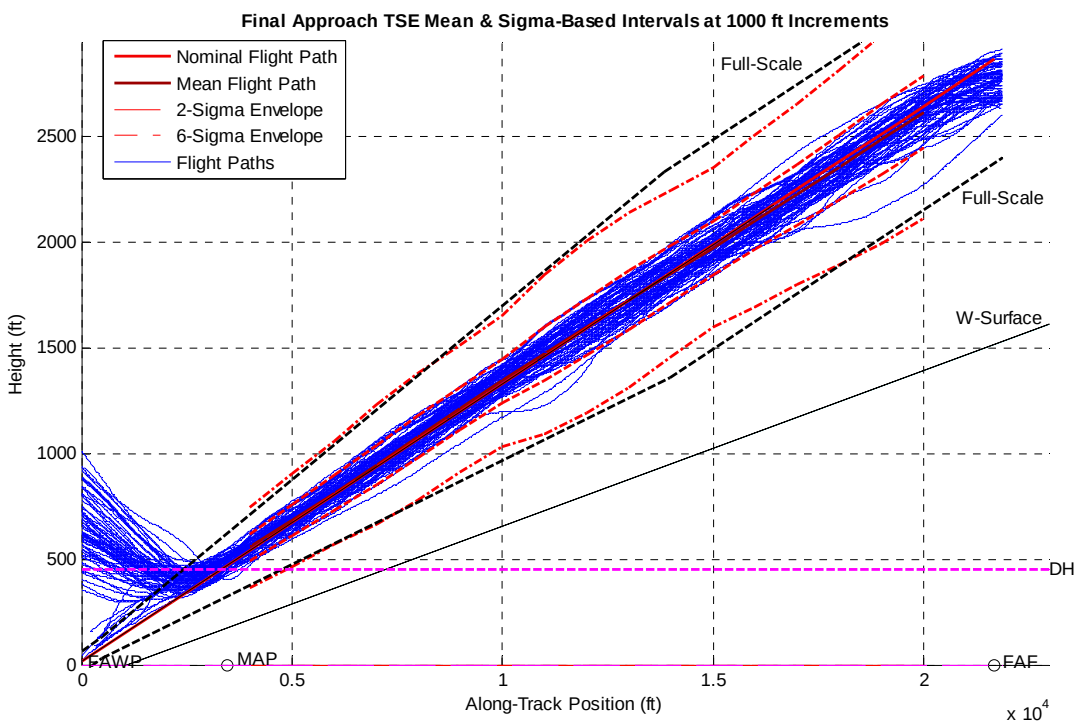

Figure 18: Profile of the 70 Non-High 310° Approaches With Statistics

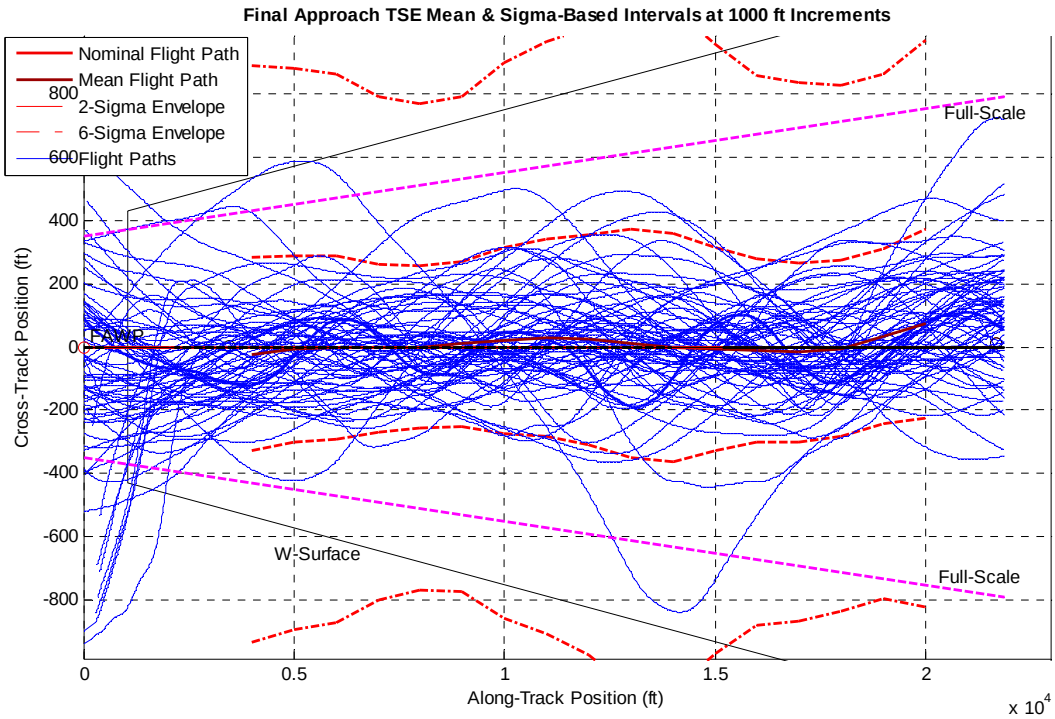

Figure 19: Planform View of the 70 Non-High 310° Approaches With Statistics

On one approach the pilot weaves back and forth between lateral full-scale deflection limits, substantially contributing to the wide 6-sigma interval near the fictitious helipoint. According to observer comments, the pilot for this run had "hard time staying on GS (glide slope)" for this run and throughout the sortie. It is likely that the effort to stay on glide path caused the pilot to deviate laterally as well.

The 3-dimensional view of the corresponding 2-sigma ellipses appears in Figure 20.

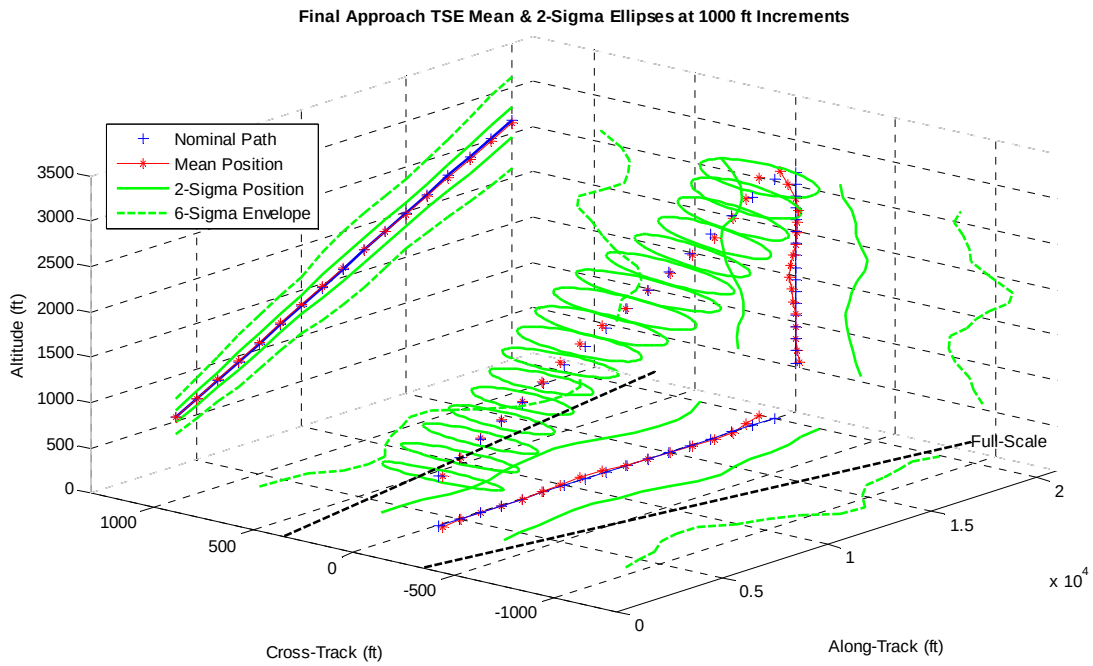

Figure 20: Elliptical Cross-Sections of the 2-Sigma TSE Tube in 3D
For Non-High Final Approaches at 310°.

Looking up the glide path (with the glide path perpendicular to the figure at (0,0)) at these 2-sigma ellipses constitutes the first plot of Figure 21, in which ellipse colors are varied so that individual ellipses can be resolved.

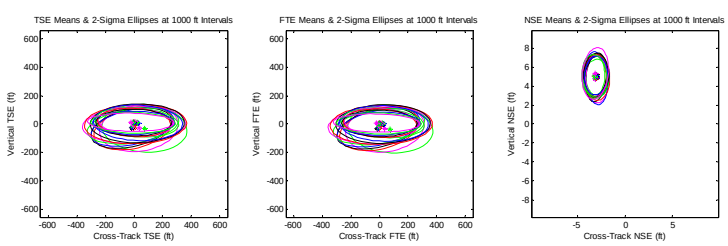

Figure 21: 2-Sigma TSE, FTE, and NSE Ellipses for 310° Non-High Approaches

Analogous views up the glidepath for FTE and NSE appear in the 2nd and 3rd plots of Figure 21. The NSE ellipses remain relatively constant, as expected, since they are computed only of errors from the GPS/WAAS navigation receiver, with vertical NSE about twice as large as lateral NSE; and in contrast, FTE and TSE ellipses reduce somewhat as width of full-scale deflection narrows. The NSE vertical and lateral bias is evident as the center of the NSE ellipses. In all

cases, lateral and vertical error components are relatively uncorrelated since the ellipses' axes are approximately parallel to the coordinate axes. Lateral and vertical statistics for Non-High final approaches at 310°appear in Tables A9-A10 of the Appendix.

Since this was the biggest sample group, plots of errors were compared with Normal distributions having the same mean and standard deviation to see if errors appeared to be Normal (i.e. have a bell-shaped normal distribution). The result at the two test ranges of 4,000 ft and 14,000 ft (corresponding roughly to the test distances of 1,200 m and 4,200 m taken in the Collision Risk Model [3]) is shown in Figure 22.

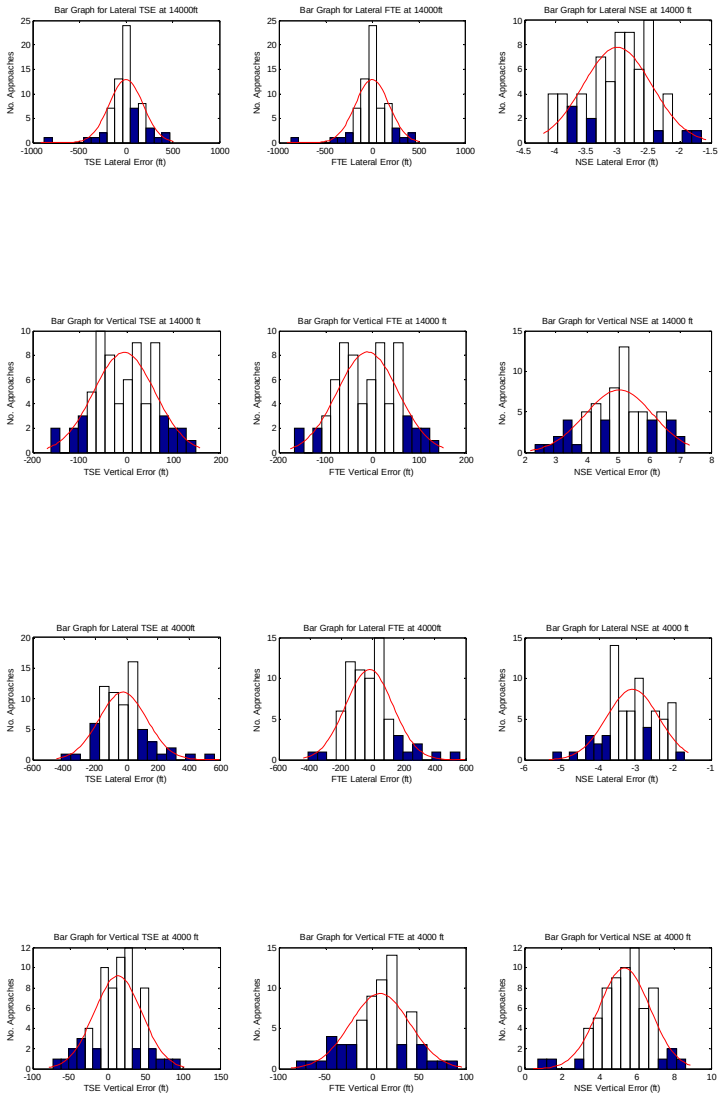

Figure 22: 310° Non-High Lateral and Vertical TSE, FTE and NSE Error Distributions Compared With Normal (Bell-Shaped) Distributions Having the Same Statistics

It appears that all distributions are somewhat bell-shaped, but probably not Normal. Scatter plots of pierce points, in which the points show where the helicopter paths intersect a vertical plane at a given along-track position with the glide path through the origin, were also constructed.

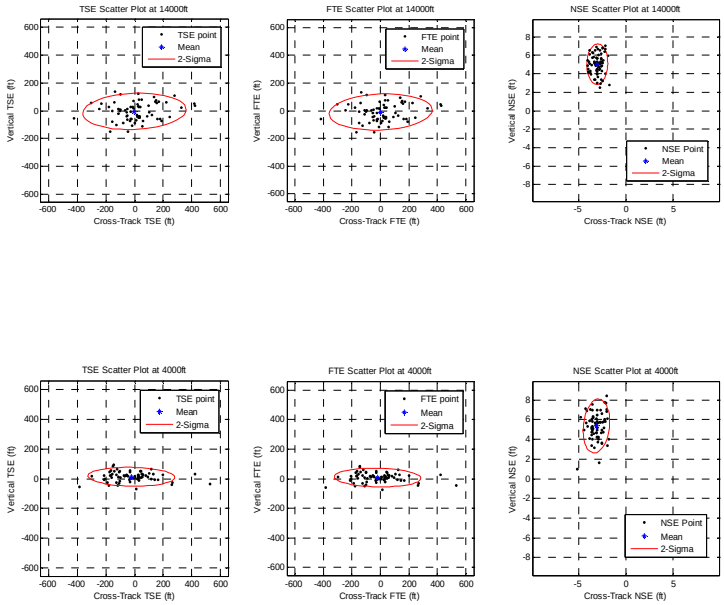

Figure 23: Pierce Points in Vertical Planes at 4,000 ft and 14,000 ft Along-Track with the Glide Path passing through (0,0), for 310° Non-High Approaches

If distributions were Normal, only about 5% of the pierce points would lie outside of the ellipses, but in each case above at least 10% lie outside.

Symmetric 95% confidence intervals could be constructed from this data (these require at least 40 approaches) and appear in Figure 24 together with 95% Normal confidence (about 2-sigma) intervals for comparison. For Normal error distributions the intervals would match.

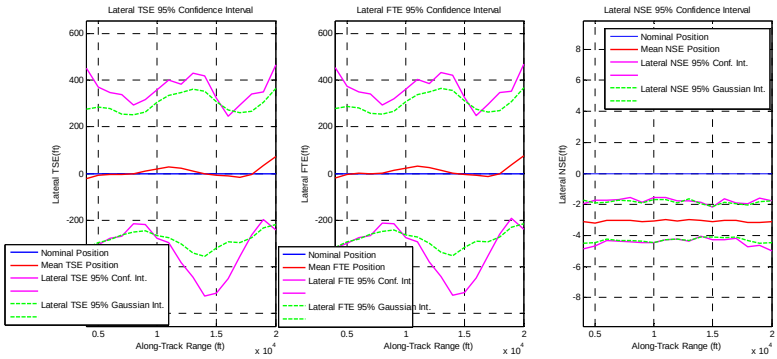

Figure 24: Confidence Intervals Vs. Normal 95% Intervals for 310° Non-High Approaches

6.2 The 145° Non-High Flight Director Approaches

Statistics for 145° Non-High hand-flow approaches appear in Figures 25-27. Lateral and vertical statistics for Non-High final approaches at 145°appear in Tables A11-A12 of the Appendix.

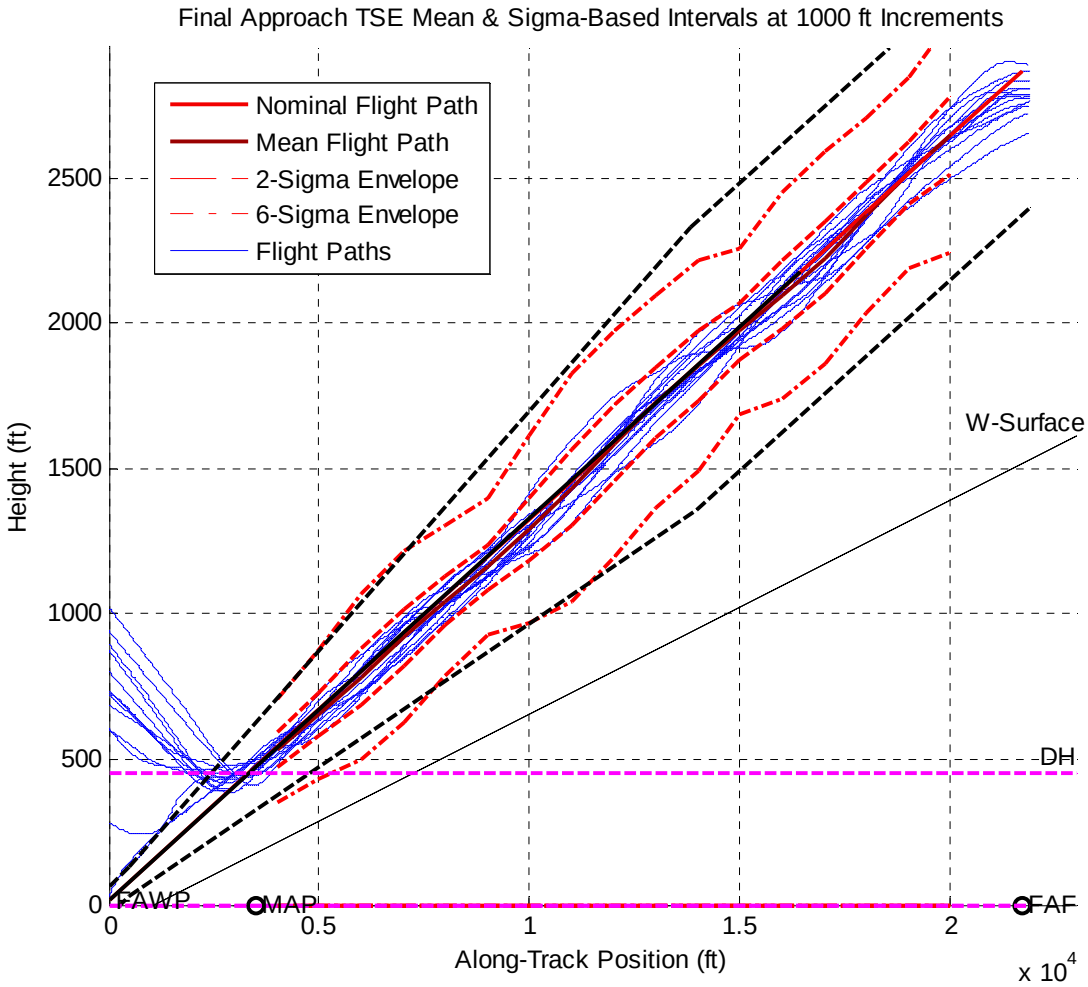

Figure 25: Profile of the 14 Non-High Approaches at 145° With Statistics

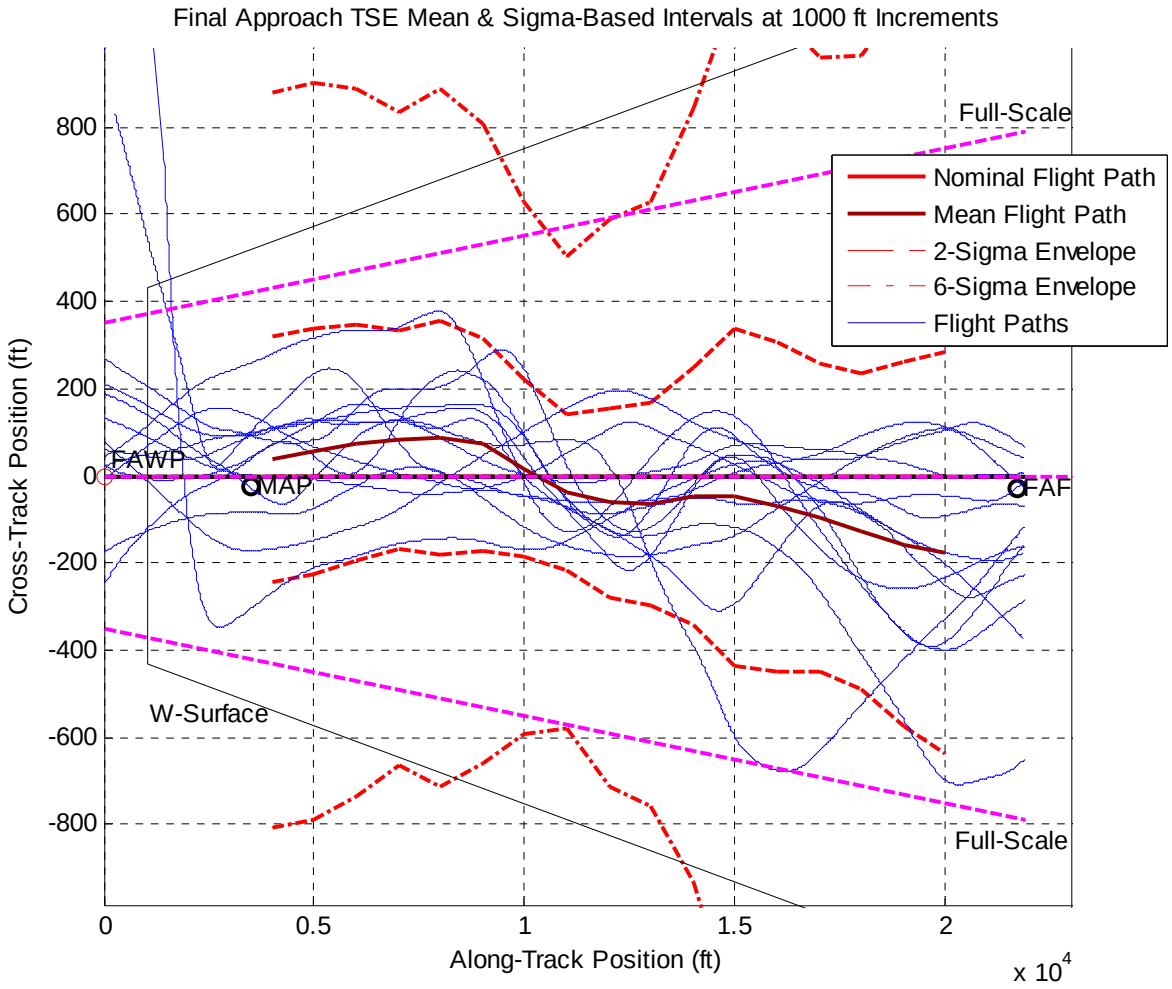

Figure 26: Top View of the 14 Non-High 145° Approaches With Statistics

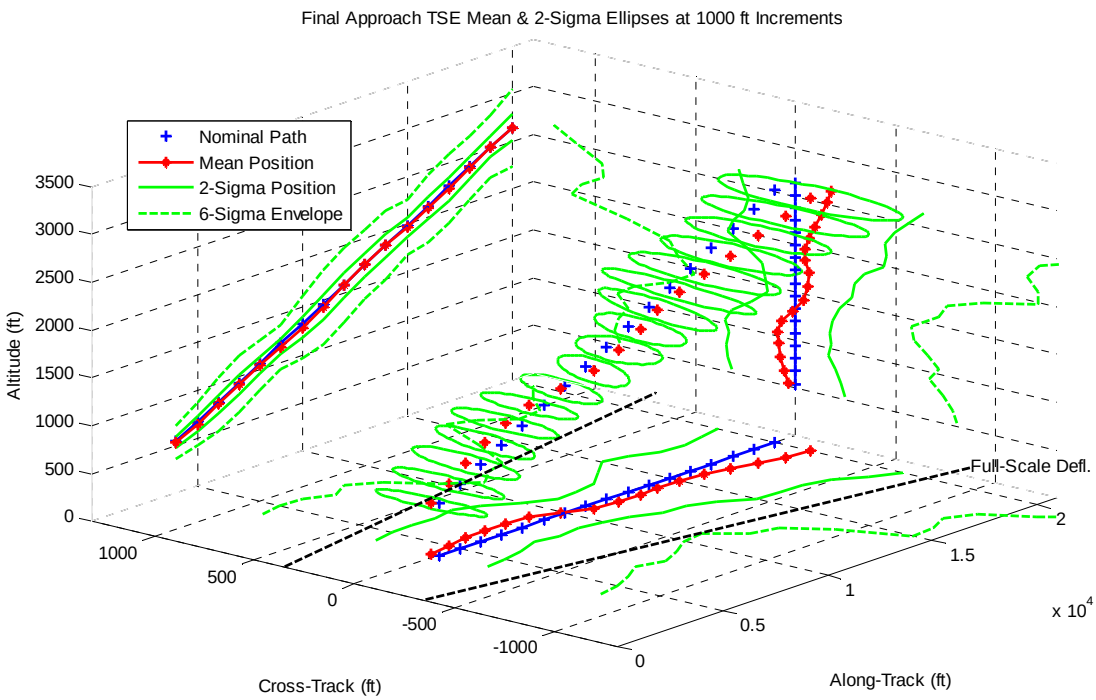

Figure 27: 2-Sigma TSE Elliptical Cross-Sections of the 2-Sigma TSE Tube in 3D For Non-High Flight Director Approaches at 145°

It is observed from these that pilots consistently flew to the left of the FAF (Final Approach Fix) and this is also observed in the 145° autopilot approaches TBD. Perhaps a rounding difference in waypoint coordinates entered into different flight systems could have led to this result, but the cause was not pursued.

6.3 Autopilot Approaches at 310°

The autopilot had lower lateral FTE and TSE on both runways than its flight director counterparts. It also had no "high" approach cases. Figure's 28-30 show the 310° autopilot tracks with statistics. Lateral and vertical statistics for autopilot final approaches at 310°appear in Tables A13-A14 of the Appendix.

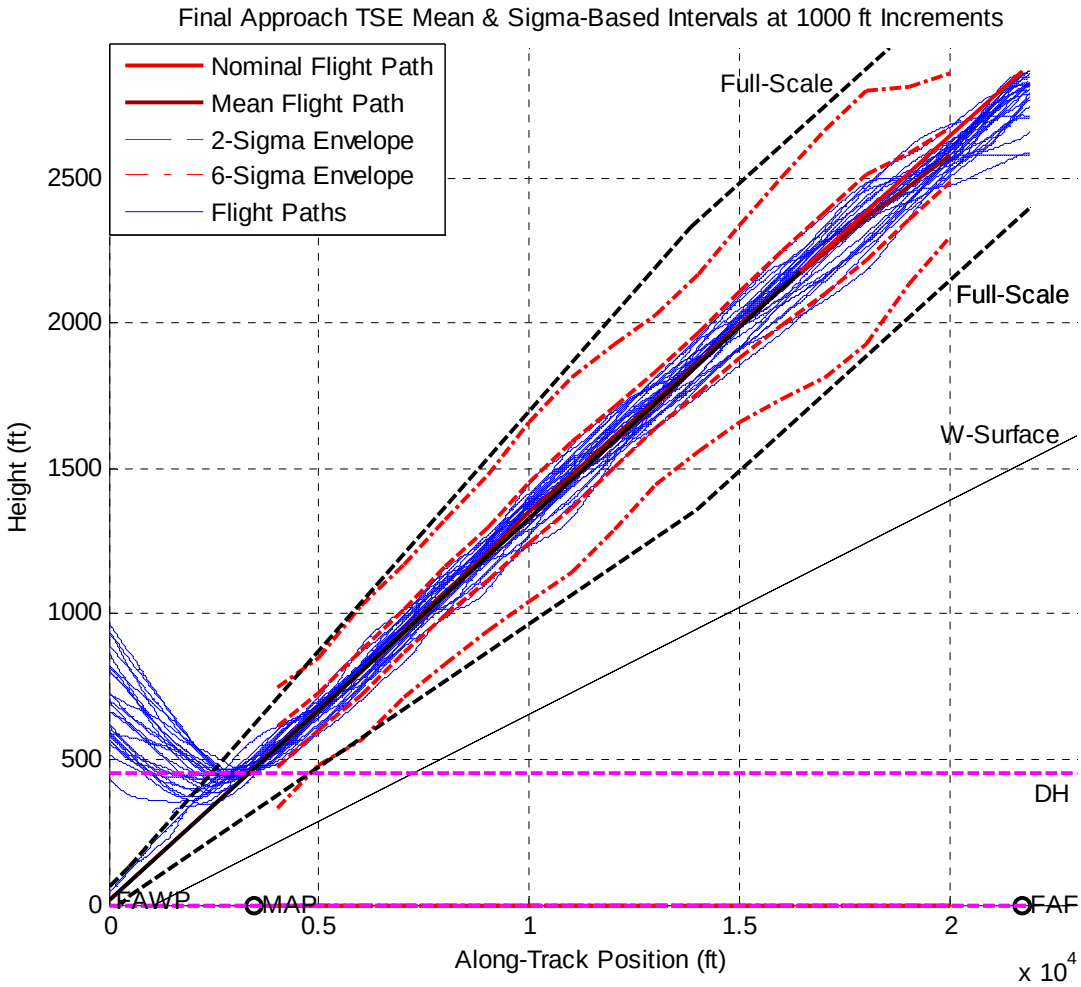

Figure 28: Profile of the Autopilot Approaches at 310° With Statistics

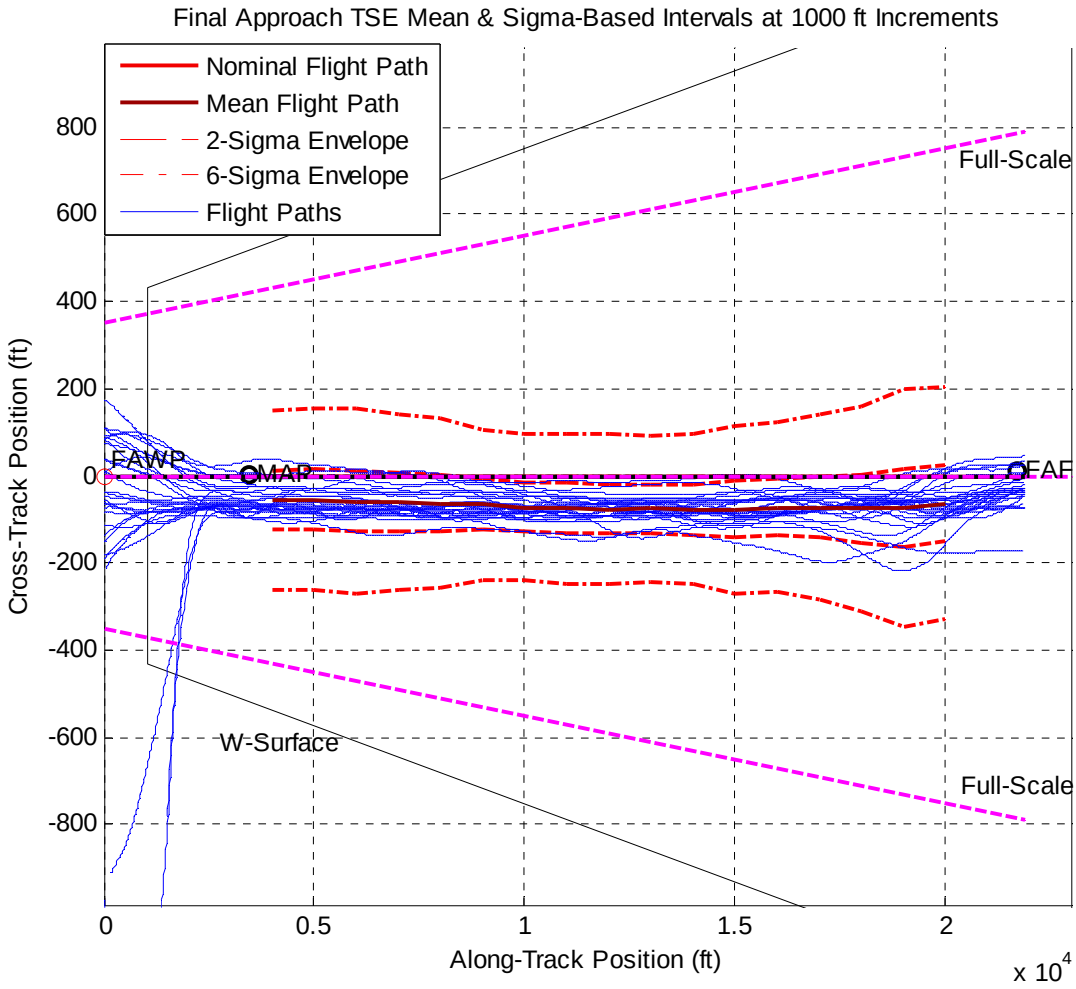

Figure 29: Planform View of the Autopilot 310° Approaches With Statistics

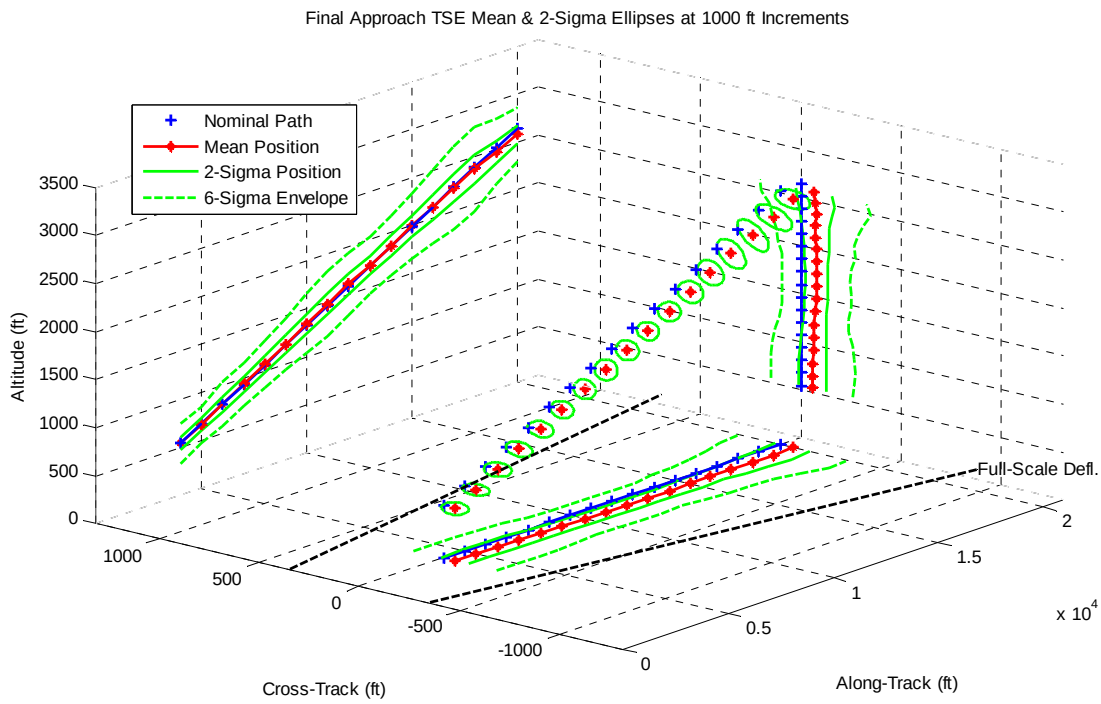

Figure 30: 2-Sigma TSE Elliptical Cross-Sections of the 2-Sigma TSE Tube in 3D For Autopilot Approaches at 310°

6.4 Autopilot Approaches at 145°

Figures 31-33 show the 145° autopilot tracks with statistics. Lateral and vertical statistics for autopilot final approaches at 145°appear in Tables A15-A16 of the Appendix.

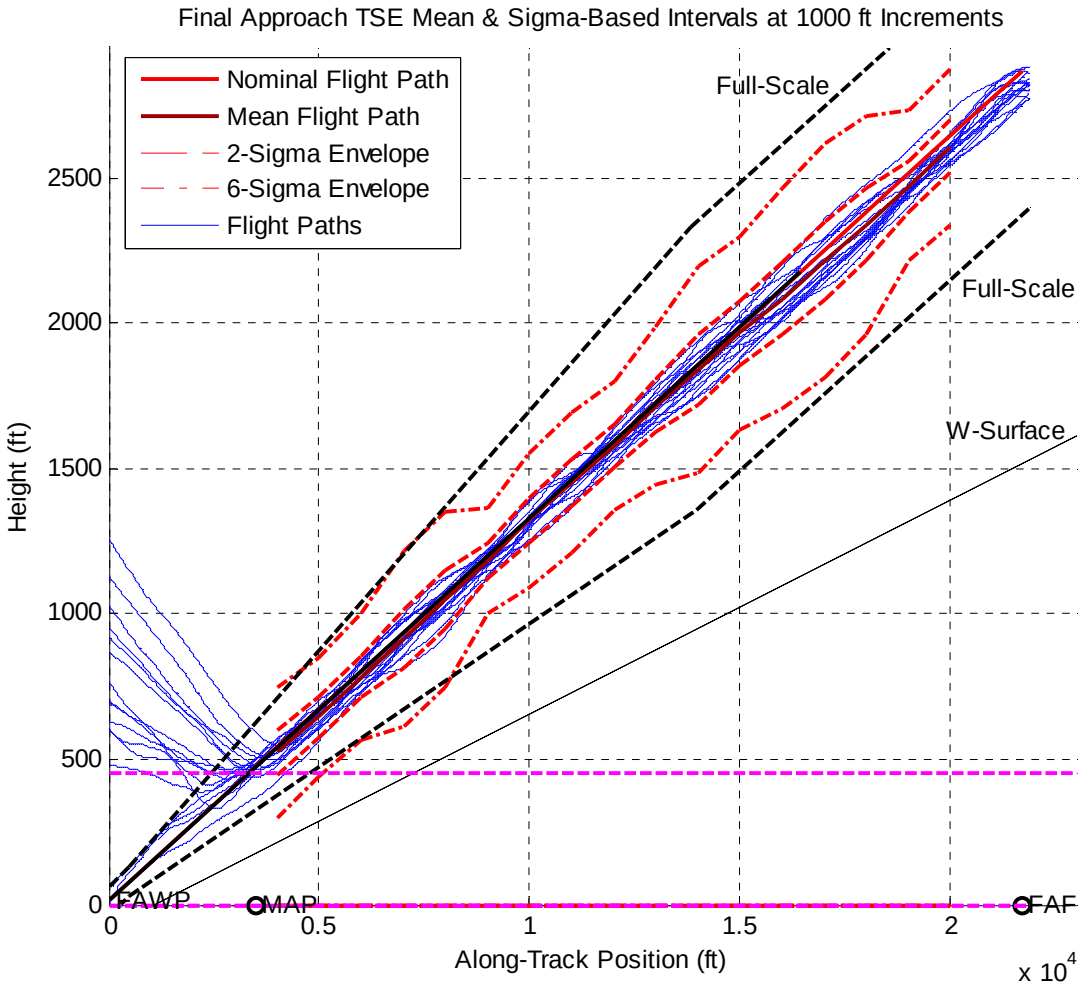

Figure 31: Profile of the Autopilot Approaches at 145° With Statistics

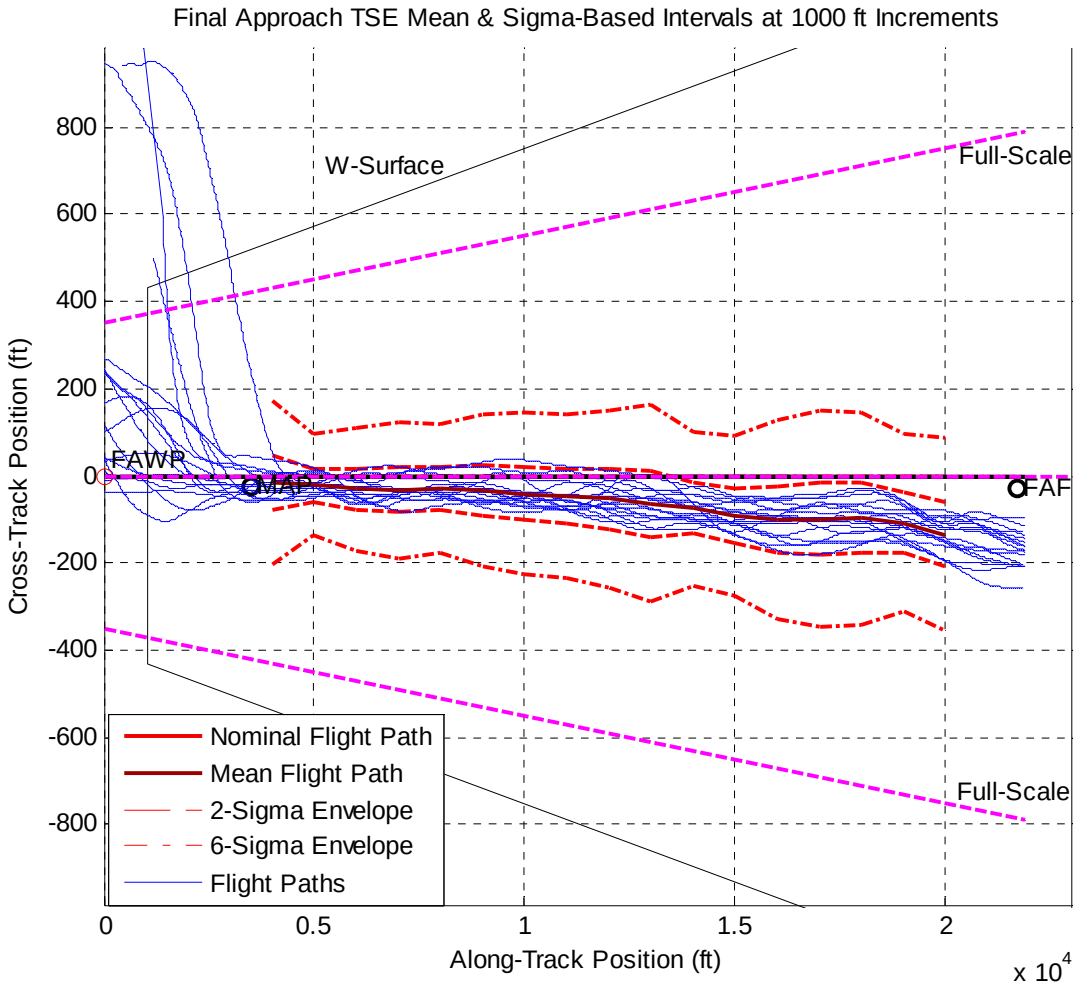

Figure 32: Planform View of the Autopilot 145° Approaches With Statistics

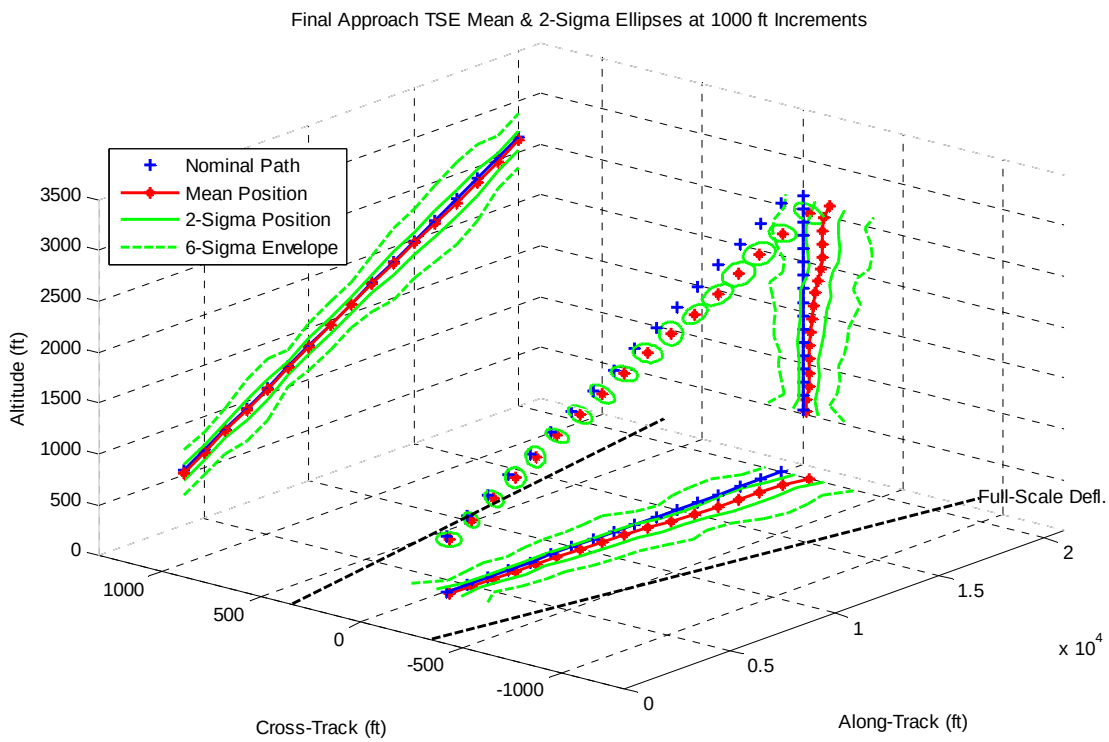

Figure 33: 2-Sigma TSE Elliptical Cross-Sections of the 2-Sigma TSE Tube in 3D For Autopilot Approaches at 145°

6.5 The High Flight Director Approaches at 310°

Seven of the eight high approaches occurred at 310° (since most approaches were performed at this azimuth) and Figures 34 and 35 show these together with 2-sigma and 6-sigma (2- and 6-standard deviations from the mean position) vertical intervals.

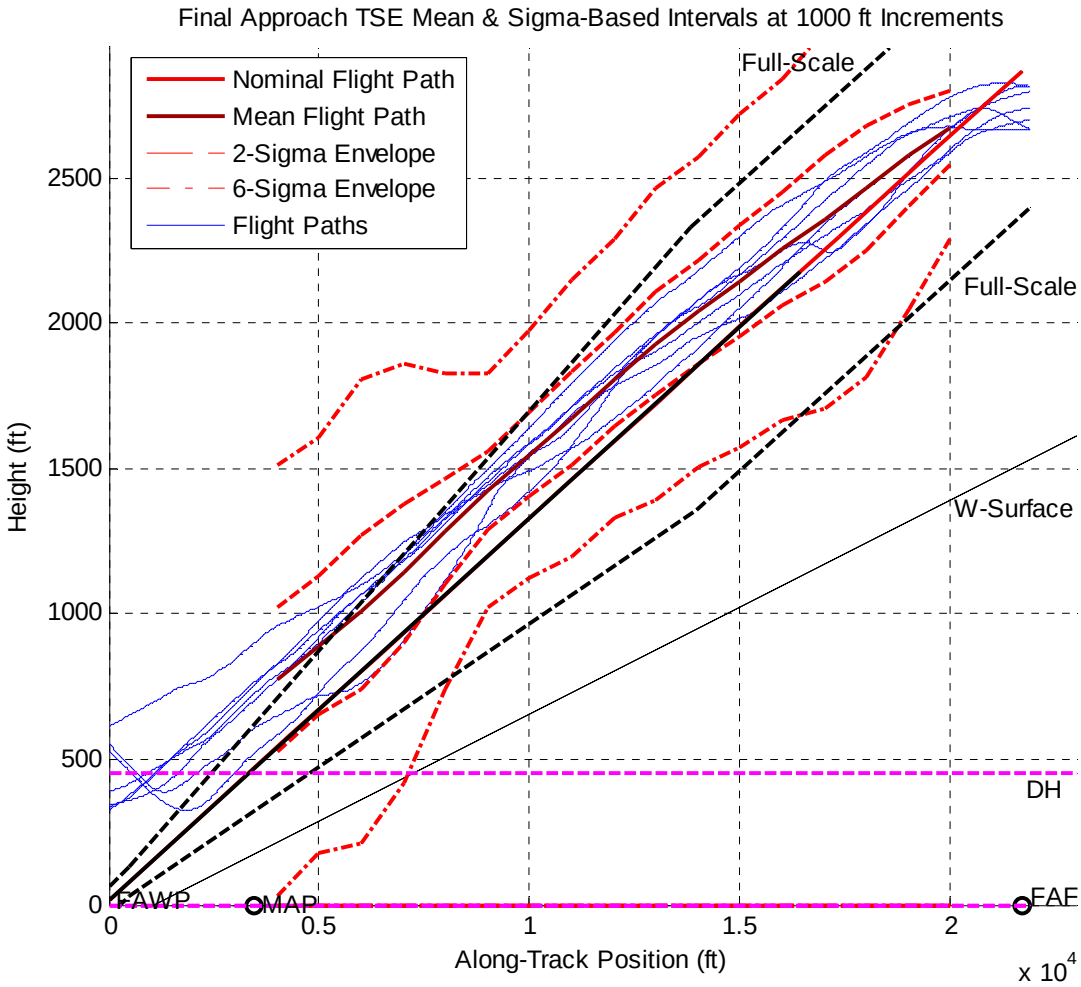

Figure 34: Profile of the 7 High Approaches at 310° With Statistics

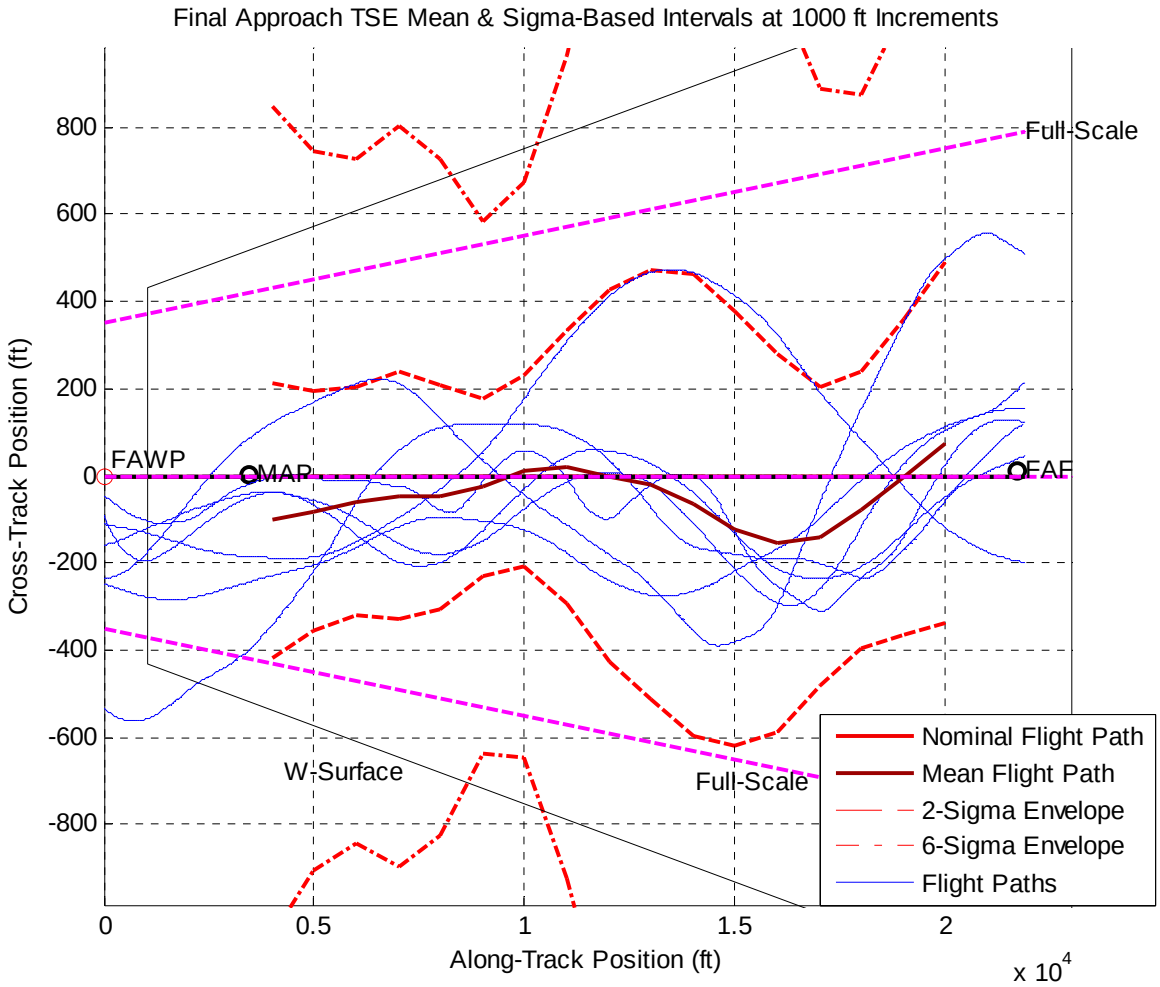

Figure 35: Top View of the 7 High Approaches at 310° With Statistics

The 2-sigma intervals are cross-sections taken from 2-sigma ellipses in three dimensions. In other words, there is a 2-sigma tube about the mean flight path that can be constructed and its cross-sections are shown as ellipses in Figure 36.

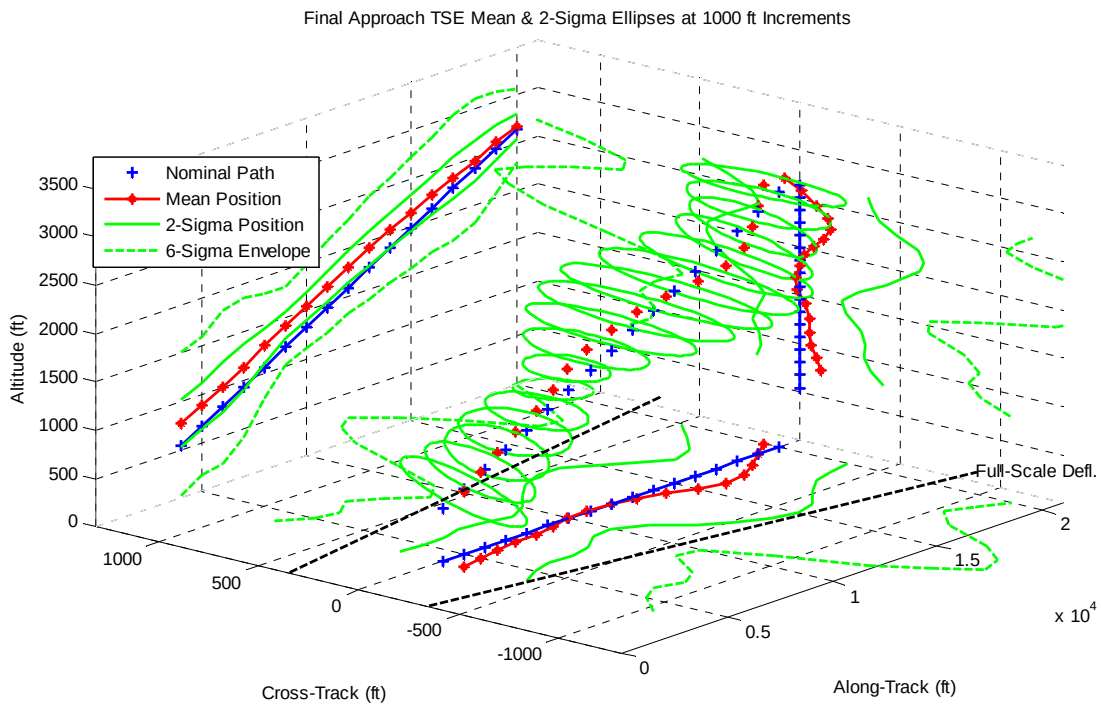

Figure 36: 2-Sigma TSE Elliptical Cross-Sections of the 2-Sigma TSE Tube in 3D For High Approaches at 310°.

The 2-sigma interval corresponds to a 95% confidence interval for vertical position (2.5% chance of being low) if the distribution of paths is Normal (Gaussian) with the same statistics and the 6-sigma interval corresponds to a 99.9999998% Normal confidence interval (10^{-9} chance of being low); however, the intervals are not reliable for probability calculations because:

- There are only seven samples – not nearly enough to estimate sigma accurately,
- The method of deciding which samples were "high" and whether they should be grouped is subjective, and
- The distribution of samples is probably not Normal.

The intervals are intended only to give a very crude estimate of the high approach dispersions.

What can be concluded from these paths, however, is:

- The average of these high-flying pilots reached full-scale vertical deflection outside 5,000 ft along-track, at which time a missed approach would normally be executed,
- When missed approach was not executed by the pilots who reached full-scale vertical deflection, the *missed approach appears to have began upon reaching DH (Decision Height). Five of the missed approaches appear to have initiated inside 2,000 ft along-track and in one case at negative along-track coordinates. Such missed approaches have much higher likelihood of penetrating the missed approach surface* (not shown here) than missed approaches executed at the nominal along-track range of nearly 5,000 ft.

- Since seven out of the 77 (9% of) flight director approaches on Runway 31 were deemed to be “high” there appears to be a significant likelihood of pilots flying either the early or late part of this procedure in a high position.

The lateral and vertical statistics of High Approaches at 310°appear in the Appendix Tables A7-A8.

6.6. A High Flight Director Approach at 145°

One out of 15 (7% of) approaches at 145° was deemed in the high category and is plotted in Figure 37, with its late missed approach executed inside 2,000 ft along-track. Since there was only one 145° high final approach no measure of dispersion could be calculated.

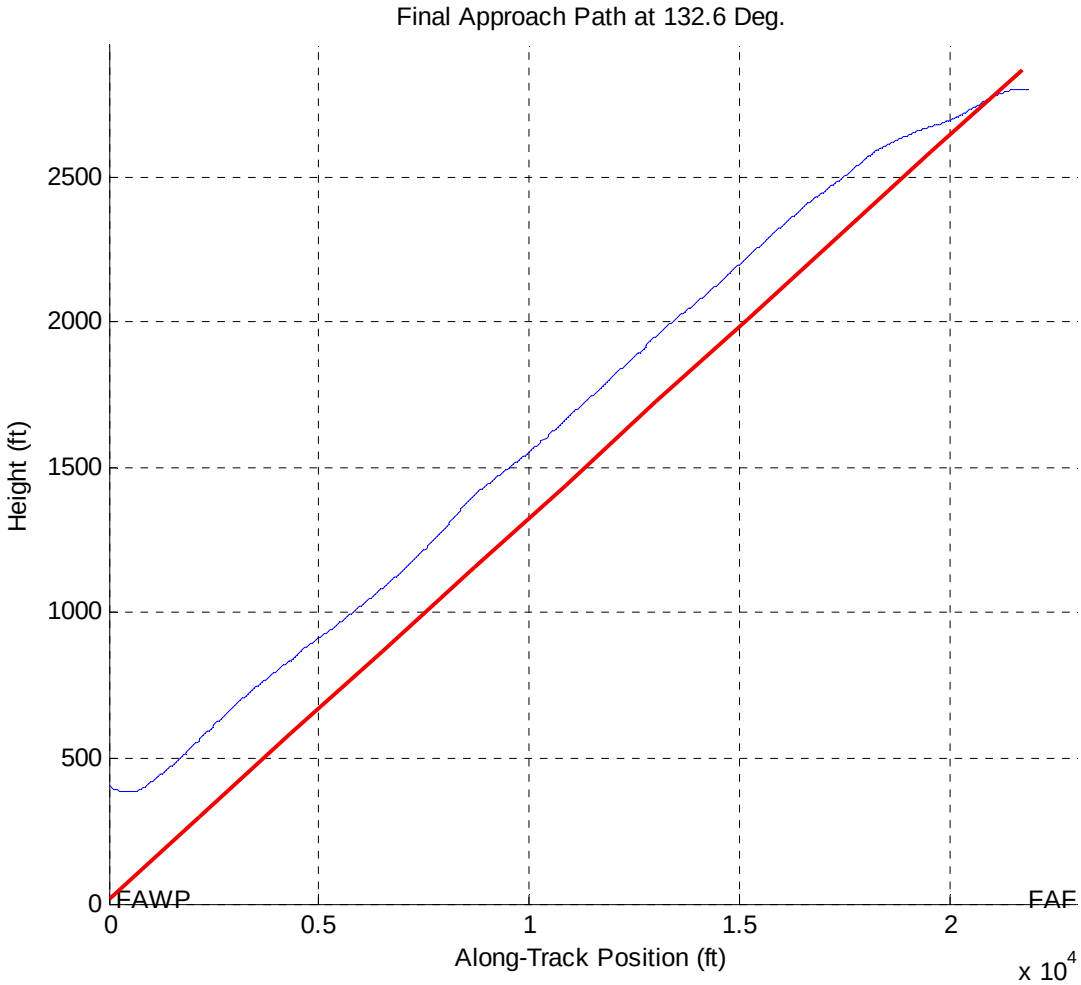

Figure 37: A High Flight Director Approach at 145°

6.7. Comparison of Lateral and Vertical Dispersions by Approach Configuration

Tables 4 and 5 show standard deviation in lateral and vertical error total system error separated by approach, autopilot, flight director high and flight director non-high.

Table 4: Lateral TSE Standard Deviation During Final Approach As a Function of Along-Track Position (ft)

Along-Track Position	Standard Deviation in Lateral Total System Error				
	310° High (7 runs)	310° Non-High (70 runs)	145° Non-High (14 runs)	310° Autopilot (29 runs)	145° Autopilot (17 runs)
20000	206	151	231	44	37
19000	181	139	209	46	34
18000	159	138	182	39	41
17000	171	140	176	36	41
16000	217	142	190	33	38
15000	249	158	194	32	30
14000	265	180	148	29	29
13000	246	179	115	28	38
12000	214	166	108	29	34
11000	157	156	90	29	31
10000	110	147	102	28	31
9000	102	131	122	29	29
8000	129	129	134	33	24
7000	142	133	125	34	26
6000	131	145	135	35	23
5000	138	148	141	35	19
4000	158	152	141	34	32
Average	175	149	150	34	32

Table 5: Vertical TSE Standard Deviation During Final Approach As a Function of Along-Track Position (ft)

Along-Track Position	Vertical Standard Deviation in Total System Error				
	310° High (7 runs)	310° Non-High (70 runs)	145° Non-High (14 runs)	310° Autopilot (29 runs)	145° Autopilot (17 runs)
20000	64	84	68	47	45
19000	88	83	55	57	43
18000	108	77	56	73	63
17000	109	71	61	71	67
16000	98	68	59	64	63
15000	95	64	48	56	56
14000	89	66	60	51	59
13000	90	69	61	49	45
12000	80	68	65	53	37
11000	80	63	65	56	40
10000	71	52	54	52	39
9000	67	50	39	45	30
8000	90	49	43	42	50
7000	120	47	49	38	50
6000	133	40	47	39	37
5000	119	35	37	31	35
4000	124	31	30	35	38
Average	96	60	53	50	47

7.0 Evaluation of from Start of Missed Approach to Final Approach Segment

7.1 Height Loss Analysis

It has already been noted that there were several incidences of large vertical dispersion. A set of extreme cases has been separated from the final approach analysis due to the fact that flying above the glide slope in the final approach segment is "conservative". However, flying above the glide slope will cause a "late" missed approach (along track distance past the Missed Approach Point (MAP)). Figures 38 -41 show the profile view of the missed approach categorized by along track distance of low point from the MAP. MAP and Decision Altitude (DA) are shown in gray. As the primary objectives of the evaluation were to validate display scaling requirements, to determine the flyability of the procedures; and to determine if pilot workload was acceptable when flying these procedures, there was likely limited training with regard to timing of Missed Approach declaration. Autopilot tracks are blue and flight director tracks are pink. However, the autopilot was most likely disengaged prior to the DA. TOGA engagement is shown with and red dot. Several tracks in Figure 38, showing low point within 500 feet along track of the MAP, demonstrate that the pilot began initiating the missed approach before the MAP. Figure 41 which show low point greater than 1500 feet along track of the MAP contains the "High" approaches in cyan. The low point in these tracks is significantly further from the MAP. However, one High approach initiated the missed approach above the DA, still clearly much later than the MAP.

Figure 38 shows bar graphs pertaining to the location of lowest point in missed approach and TOGA engagement.

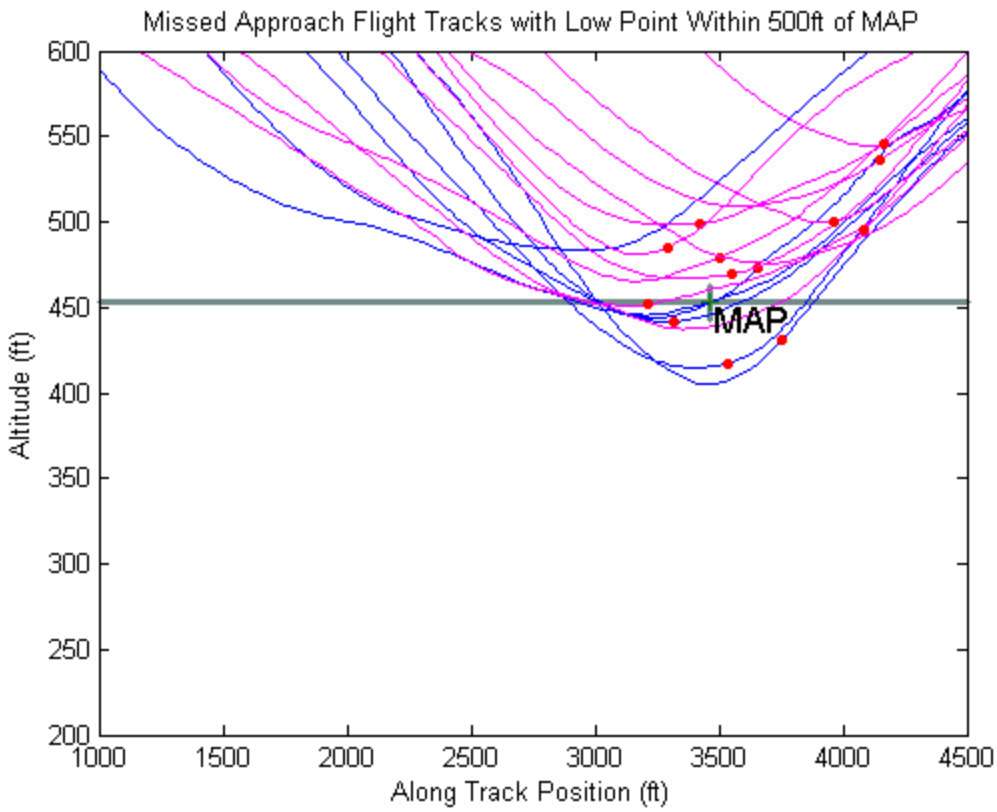

Figure 38: Missed Approach Tracks Low Point within 500 feet of MAP

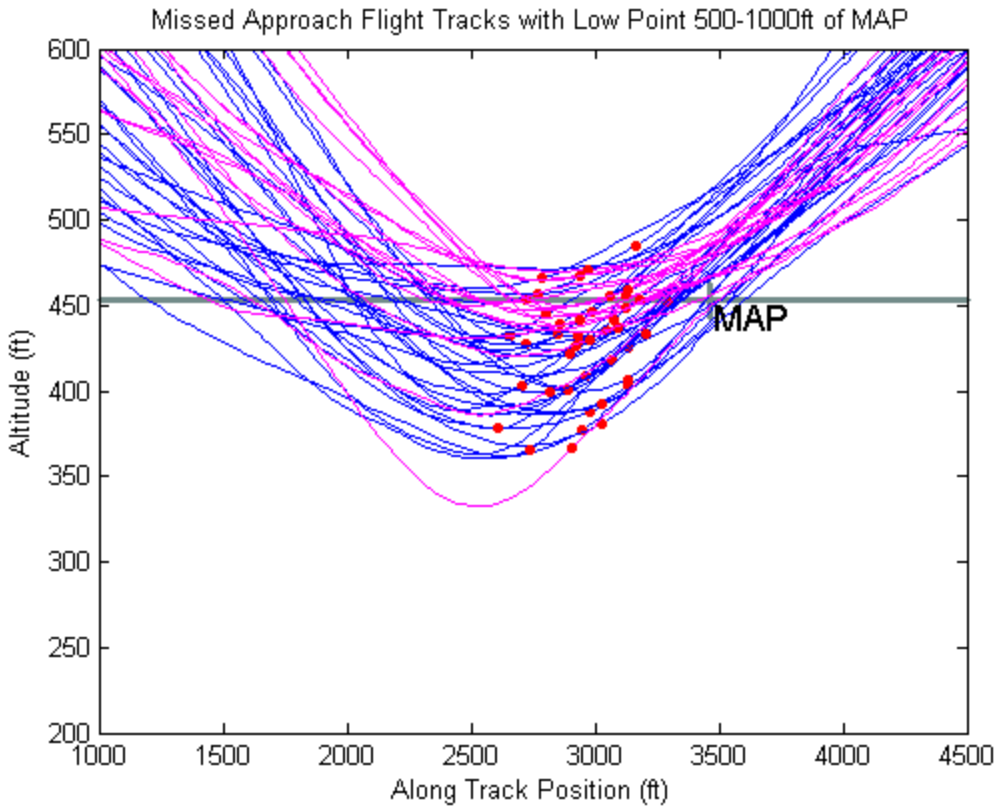

Figure 39: Missed Approach Tracks Low Point 500-1000 feet from MAP

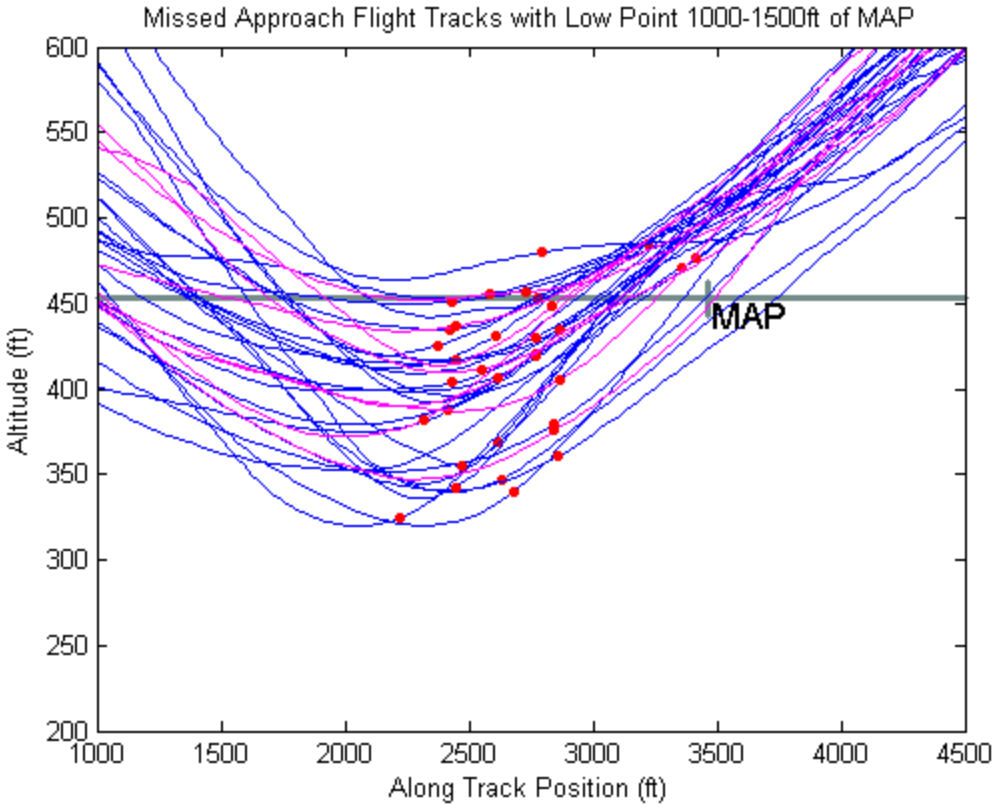

Figure 40: Missed Approach Tracks Low Point 1000-1500 feet from MAP

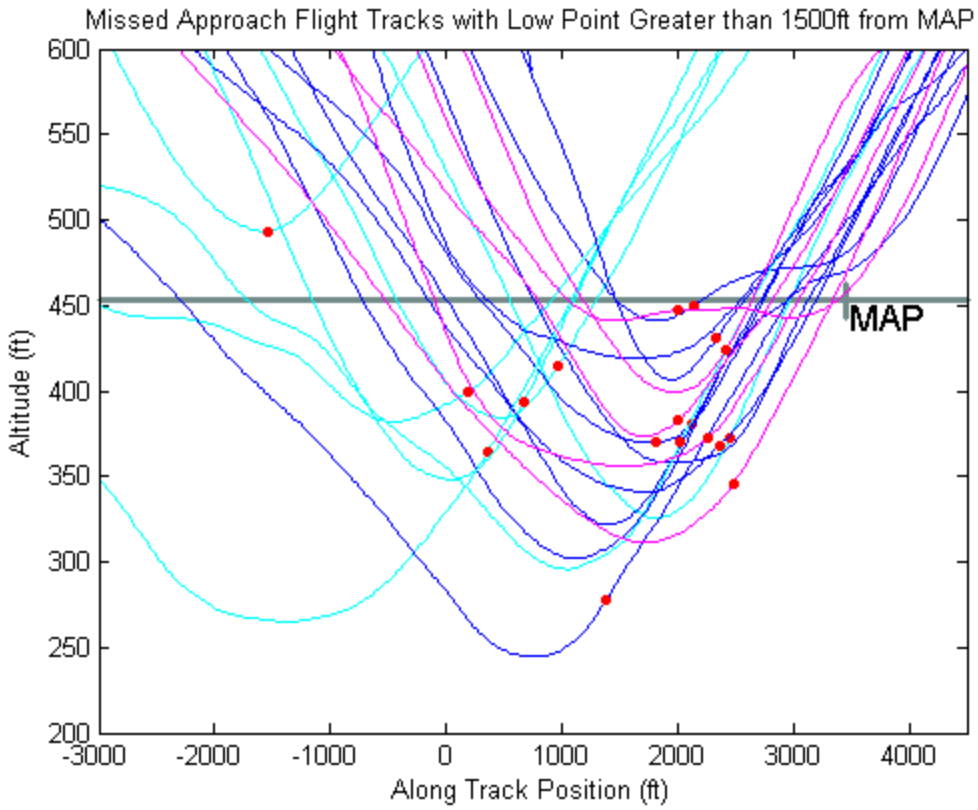

Figure 41: Missed Approach Tracks Low Point Greater than 1500 feet from MAP

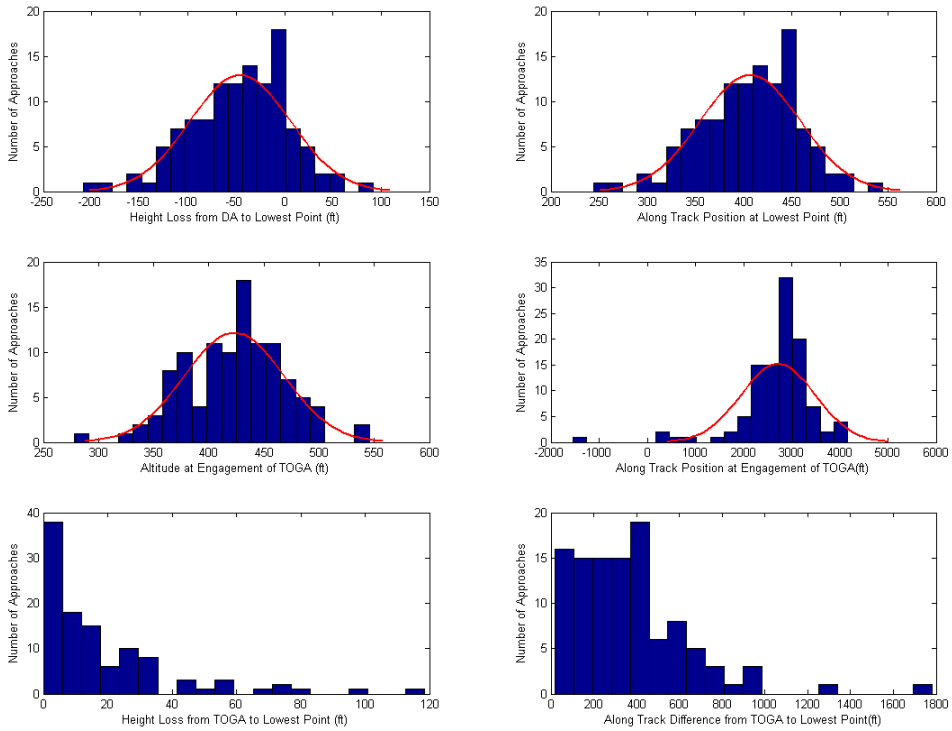

Figure 42: Bar Graphs of Height Loss and TOGA by Height and Along Track Position

7.2 Evaluation of Flight Tracks in Missed Approach

Figure 43 shows a "far-view" of TERPS surface in the missed approach. Figures 44-49 are enlarged about the track/SD data and show flight director, autopilot and all tracks planform view. Figures 44-46 show profile view. Note that, laterally the ± 6SD are within TERPS Primary Surface for autopilot runs and combined autopilot/ flight director High/ flight director Non-High (Figures 44 and 45). Figure 46 shows the 6SD penetration of the Secondary Surface at the left side. The standard deviation at this point is 153.09 ft. mean -20.57 ft. The width of the primary surface is 1354.78 ft. Thus at 5.6 SDs, (876.97-20.57)/153.09, the left edge of the primary surface is NOT penetrated. The 6SD metric is used to loosely approximate a risk of 1.0×10^{-07}. For a normal distribution, the probability of being outside of 5.6 SD's is 1.1×10^{-08}, which is well within the 1.0×10^{-07}. Additionally, the missed approach surface is protected to 1.0×10^{-05} which, assuming Normal, is approximately 4.25 SD's.

Figures 47-49 show the vertical dispersion in the missed approach for autopilot, flight director and all approaches combined. The Obstacle Clearance Surface (OCS) is shown in gray. The OCS is penetrated in all cases at 2 SD's below mean. The vertical penetration of the OCS in Phase I testing, is of interest and will be further evaluated in subsequent testing. Figure 50

shows the 3D Isoprobability contours of the missed approach for all approaches with mean track and 2 SD and 6SD ellipses. Lateral and vertical standard deviations of the missed approach segment are shown in Tables A17-A18 of the Appendix.

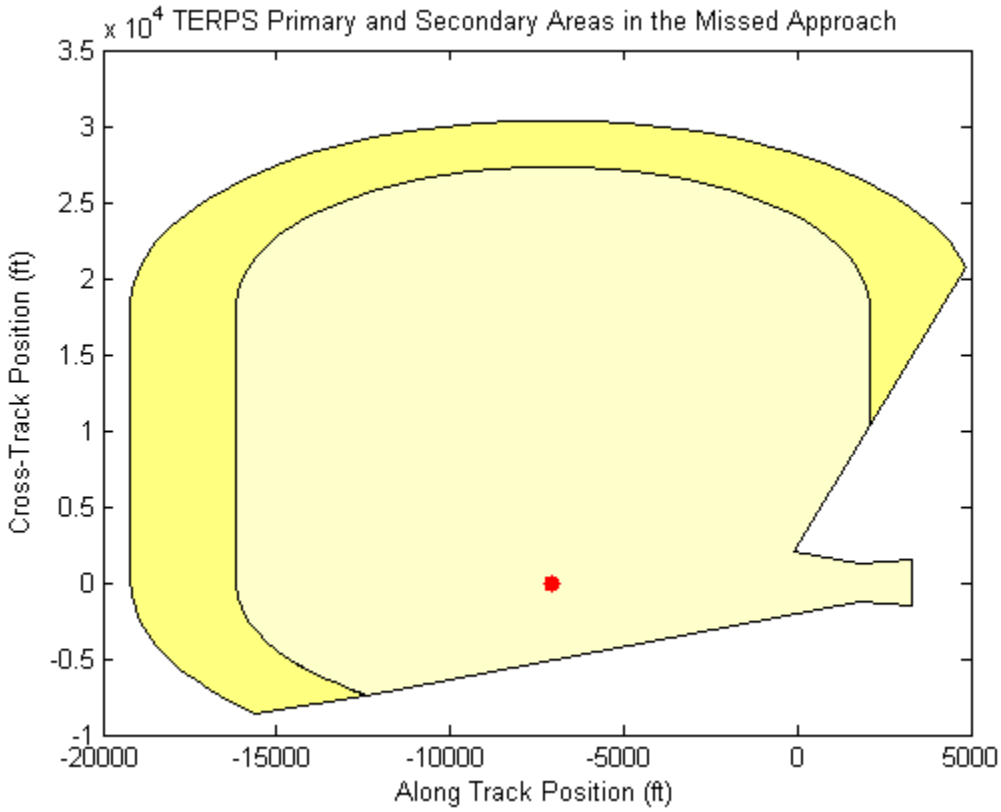

Figure 43: Planform View TERPS Primary and Secondary Surfaces

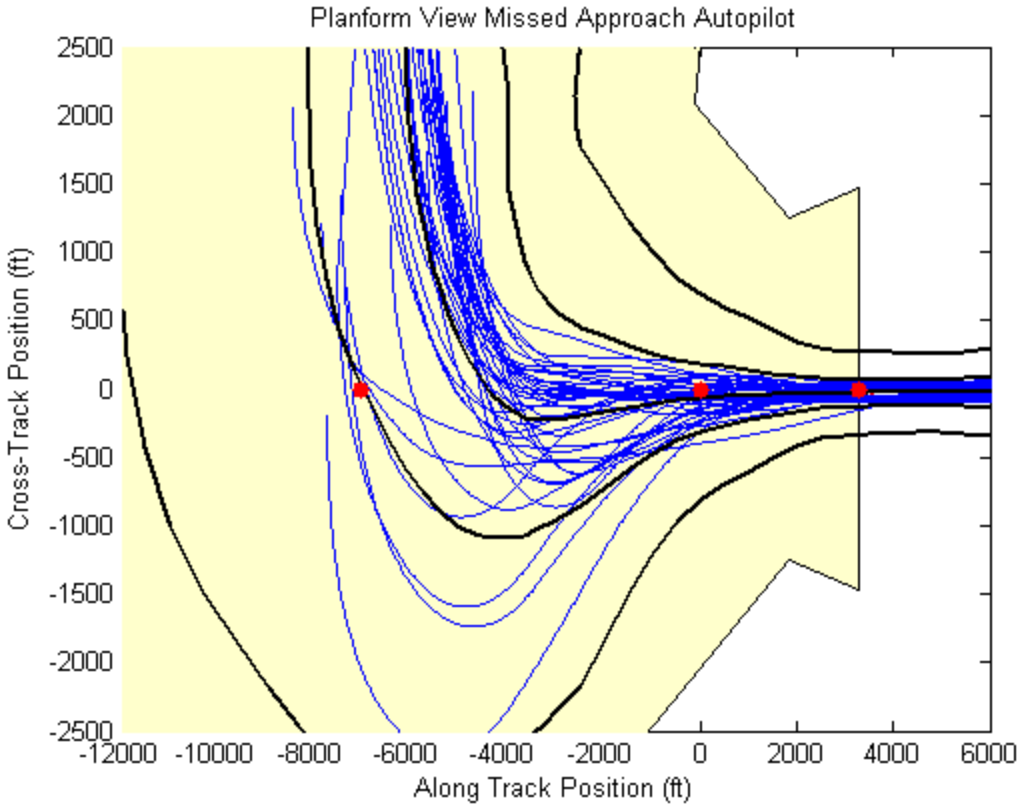

Figure 44: Planform View Missed Approach Autopilot

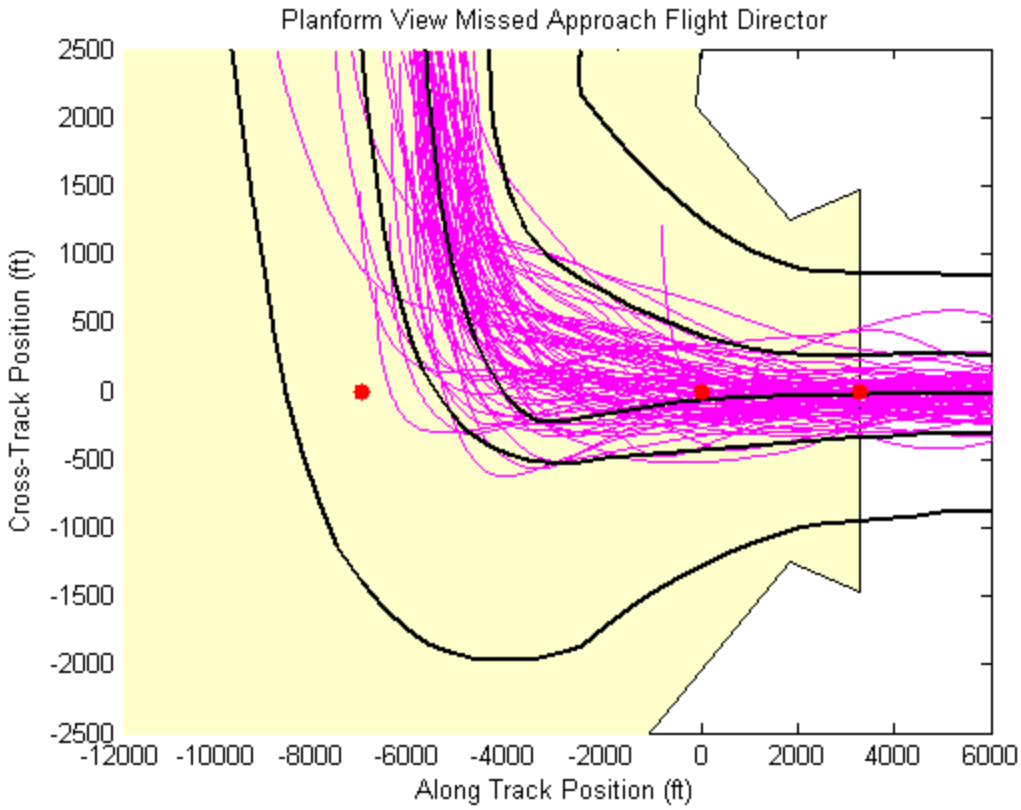

Figure 45: Planform View Missed Approach Non-High Flight Director

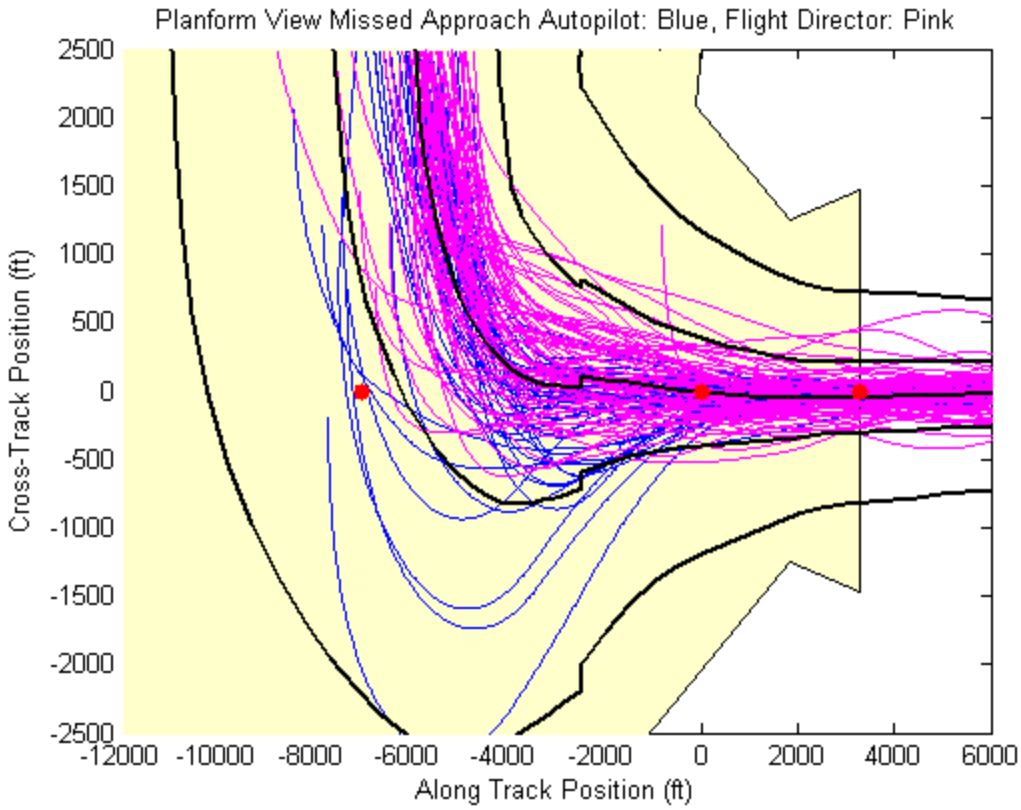

Figure 46: Planform View Missed Approach All Approaches

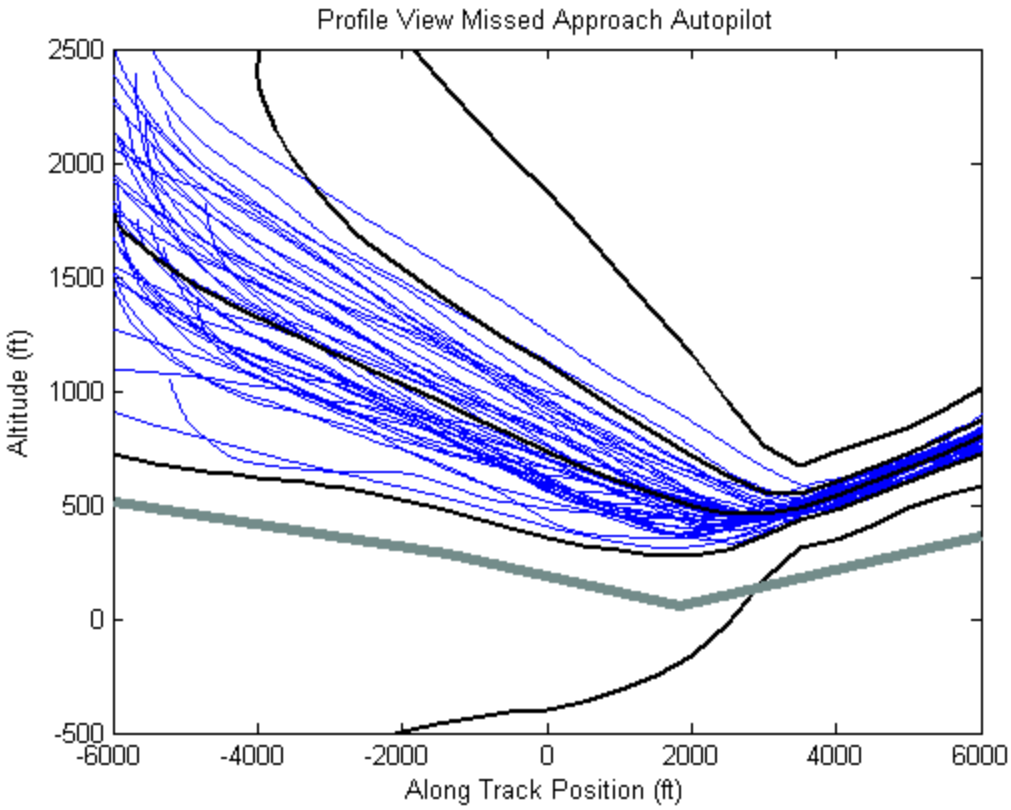

Figure 47: Profile View Missed Approach Autopilot

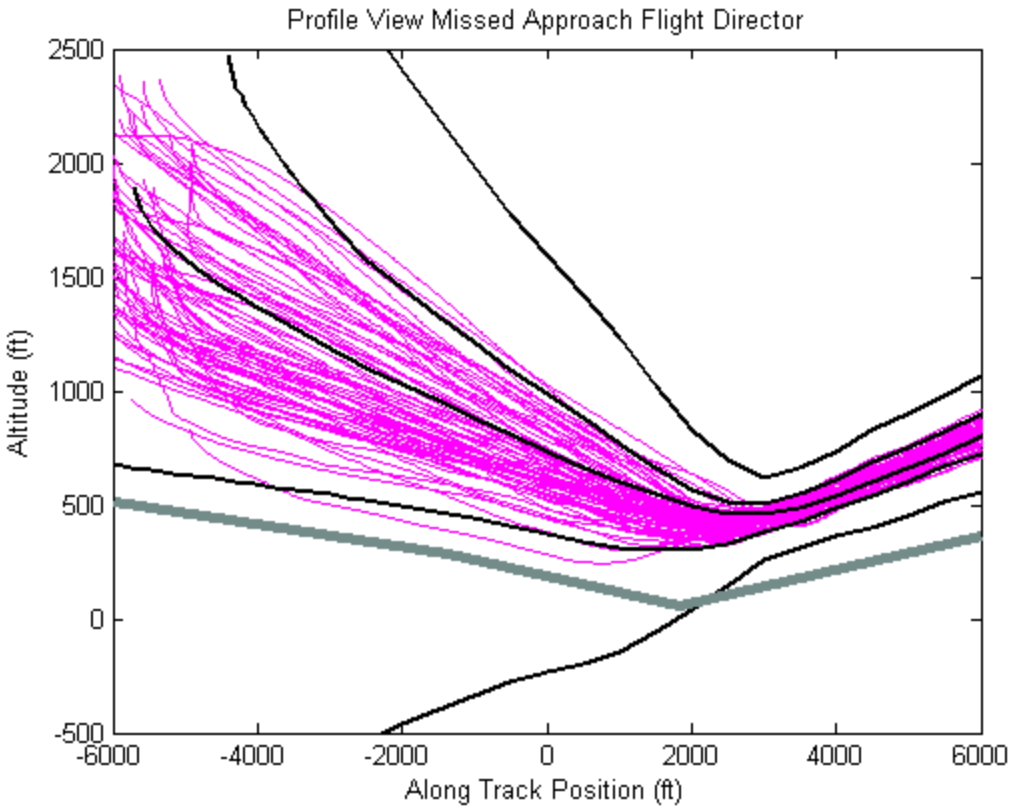

Figure 48: Profile View Missed Approach Flight Director

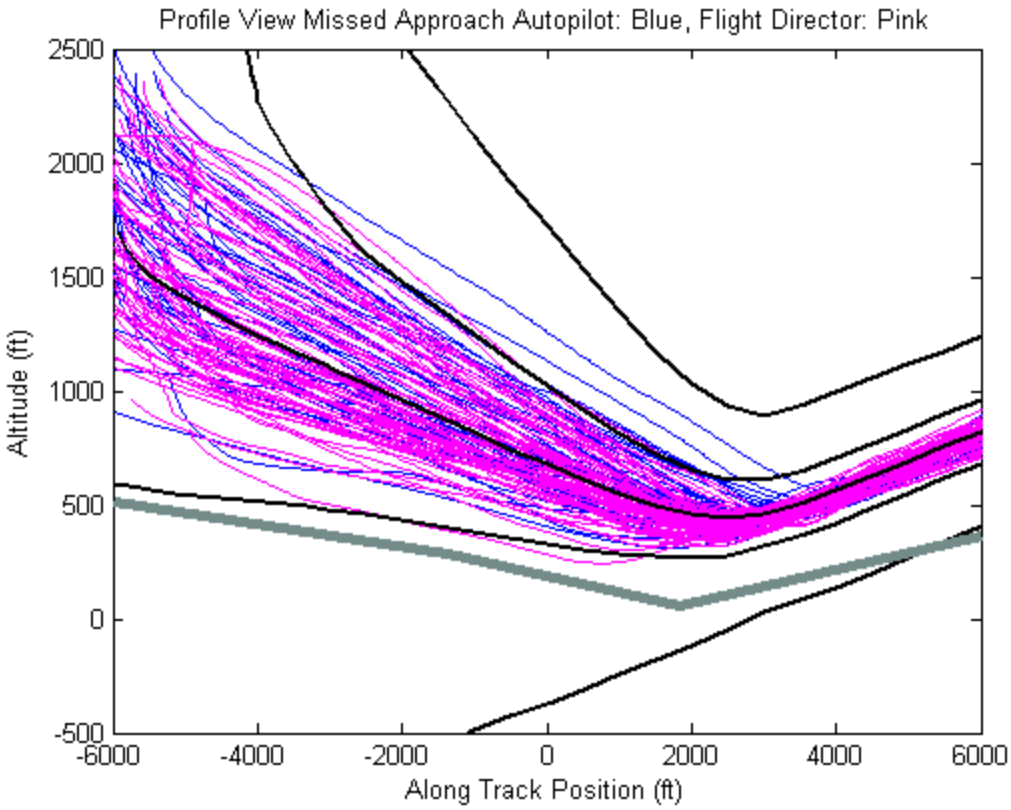

Figure 49: Profile View Missed Approach All Approaches

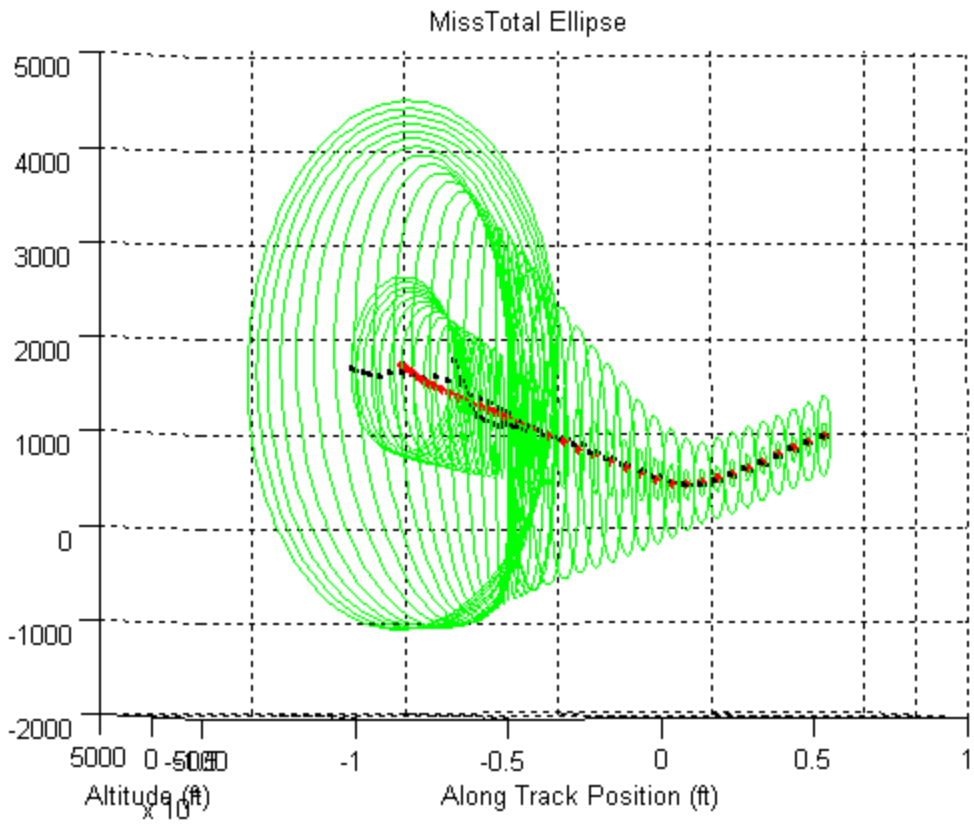

Figure 50: Missed Approach 3D Isoprobability 2 SD and 6SD Ellipses; All Approaches

8.0 Landing.

Figures 51 and 52 show the planform and profile view of landing tracks.

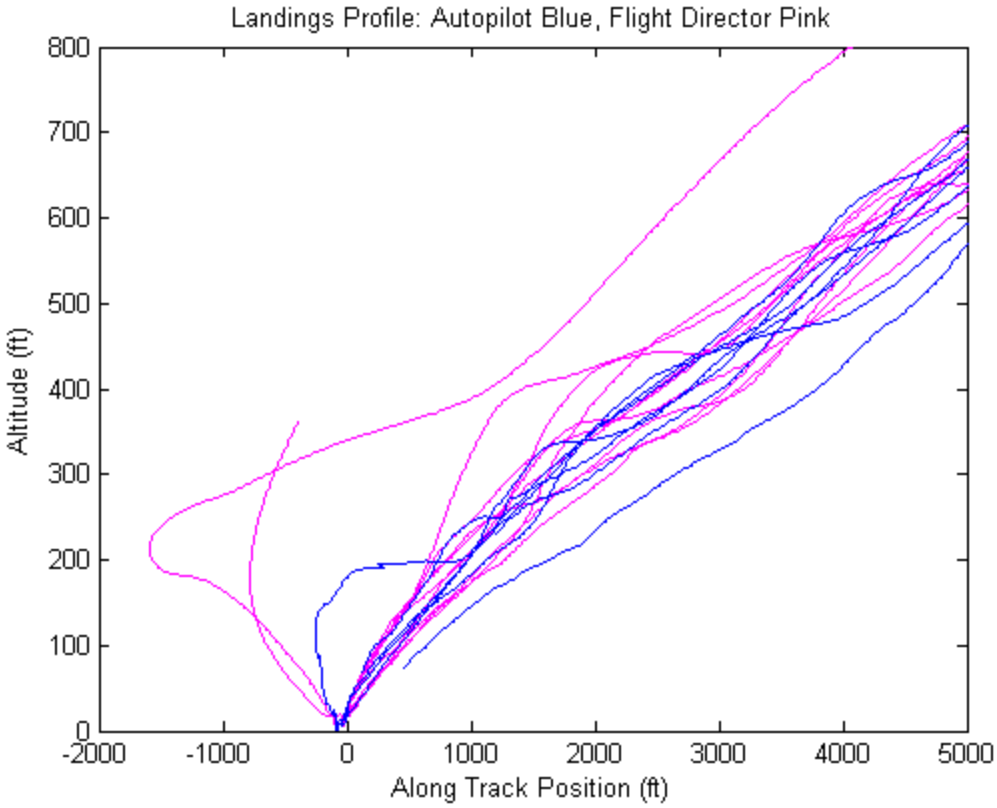

Figure 51: Landings Profile View

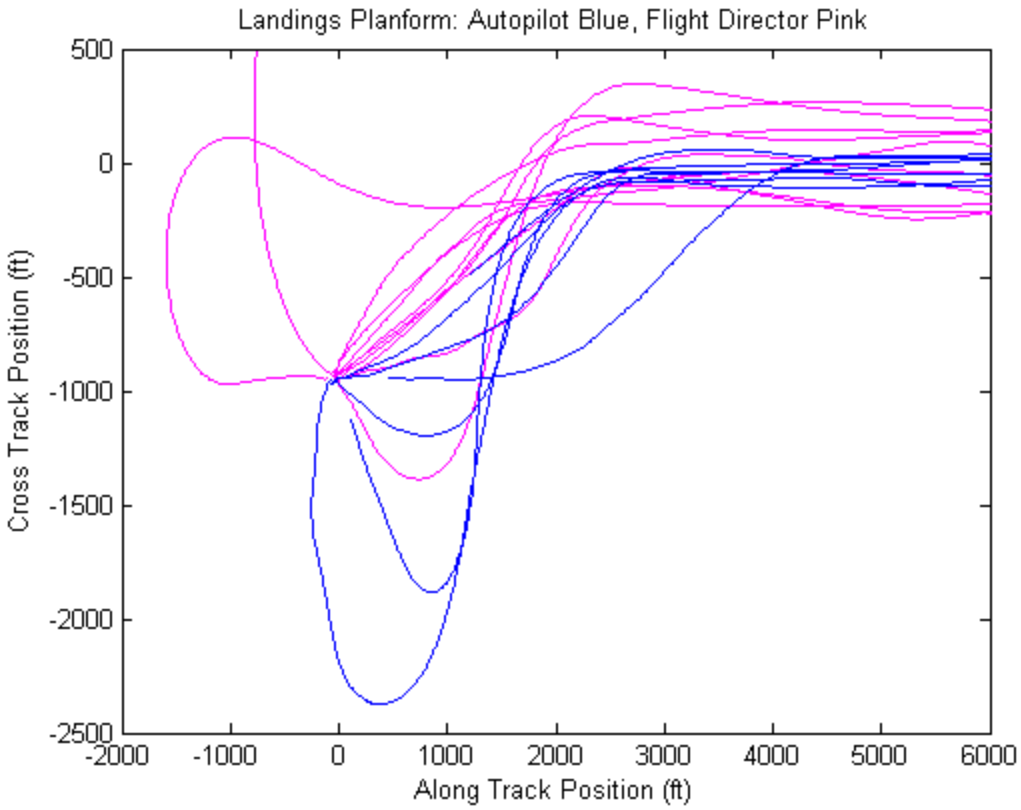

Figure 52: Landings Planform View

9.0 Human Factors

Each subject pilot completed post approach and post test questionnaires during the flight testing. Following each approach the pilot was asked to complete a Post Approach Questionnaire that addressed:

a) Workload on these procedures compared to other instrument approach procedures.
b) Overall workload on the approach.
c) Safety of the procedure.
d) Level of difficulty without autocoupling.
e) Workload as a function of mental demand.

Following completion of the test each subject pilot completed a Post Test Questionnaire. This questionnaire addressed the overall perceptions that the subject pilot had following his flight test experience. Specific topics addressed included:

a) Perception of workload
b) Procedure flyability
c) Procedure safety.

The general perceptions by the subject pilots were supportive of the procedure design, safety, workload level and flyability.

Pilot subjective responses from the post-run questionnaires have been tabulated and are graphically portrayed in Figures 53 through 55.

Concern for subject pilot anticipation of a missed approach was discussed with the safety pilots, who reported they felt very comfortable in saying that the subjects did not anticipate the miss. The subject pilots were briefed beforehand that the safety pilot would call “pad in site, land” or “no pad, miss” at DA.

In Figure 53, it can be seen that the majority of the pilots indicated this approach was easy for them to accomplish, and differed little from current approach procedures being flown.

In Figure 54, three of the subject pilots felt the steep angle approach and the offset did not cause the workload of the approaches to be more than normally experienced. Most of the comments concerned energy management, and not having the pad appear where it was expected when going visual.

In Figure 55, four of the subject pilots felt that flying the approaches on the Flight Director was more difficult than normal. Contributing to this is the fact that in the test helicopter, the vertical command in FD mode is not for collective, since the guidance being provided is two dimensional and the command is to have the helicopter descend to the MDA, since there is no electronic Glide Slope signal. This will not be the situation in follow on testing.

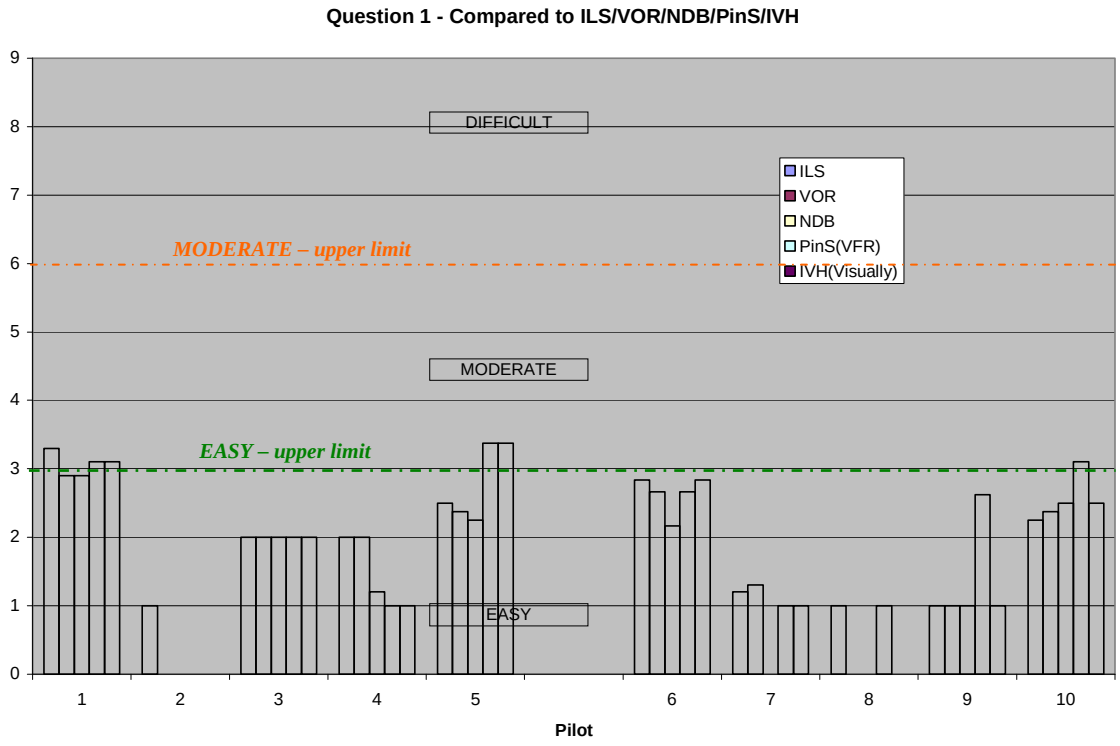

Figure 53: Pilot Evaluation of the Overall Difficulty of the Approach Compared to Other Approaches Typically Flown.

Figure 54: Pilot Evaluation of Workload Imposed by 7.5° GPA and 15° Offset to Heliport

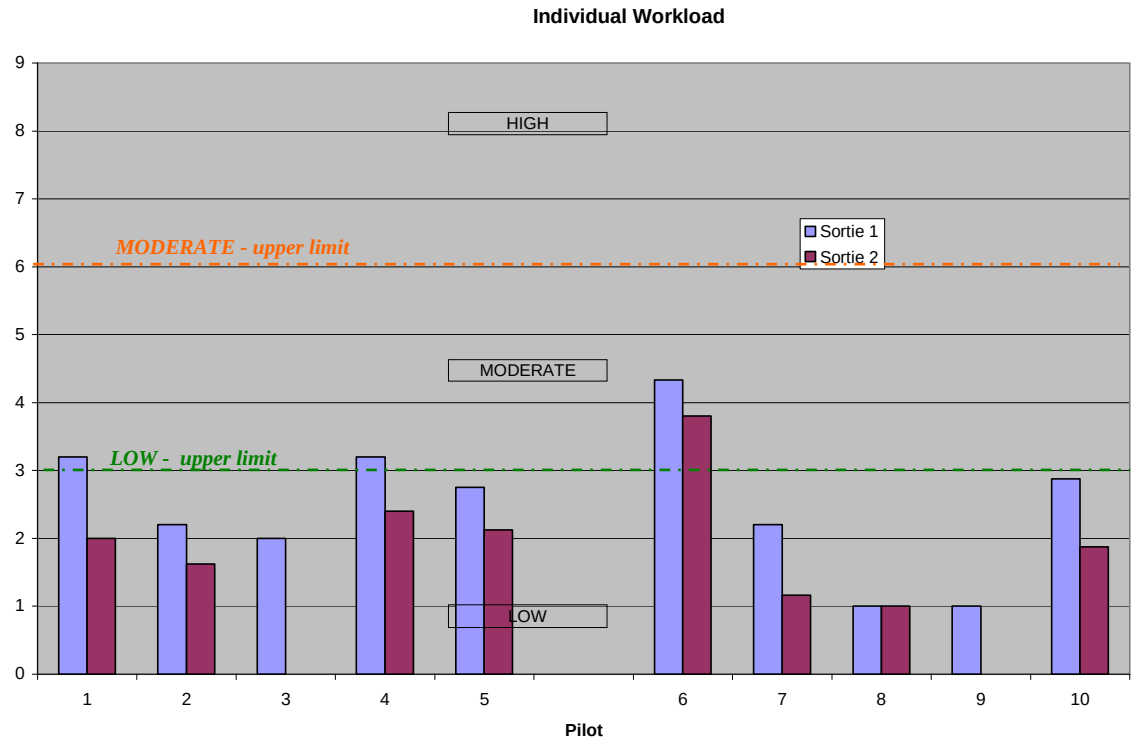

Figure 55: Pilot Evaluation of Personal Workload Perceived

In Figure 53, three of the subject pilots felt the overall personal workload was above "LOW", again mostly due to energy management, the heliport not being where expected at DA and the FD two dimensional queueing. However, these results of perceived workload are below the moderate level.

Note that in Figures 54 and 55, the ratings for the second sortie flown are all less than the upper limit of the workload difficulty ratings. This indicates the learning of the subject pilots on how these approaches are flown, how the helicopter behaves and what to expect at DA when going visual.

10.0 Summary

There were 138 usable helicopter LPV PinS approaches made to the FAA Tech Center Helipad in Atlantic City, NJ in 2008 utilizing the FAA's Sikorsky S-76A helicopter. These were broken into six categories (Table 2) according to pilot case: autopilot, flight director non-high, or flight director high and magnetic approach azimuth case: 310° or 145°. An evaluation of the TSE, FTE, and NSE was made for each case, in which NSE calculation included only the error of the navigation receiver – omitting instrumentation, latency, and input errors.

Unusually high final approach paths occurred in eight of the 92 flight director cases and in seven of these cases the helicopter consequently experienced a late (along-track) missed approach initiation point. These cases were treated separately during final approach so as not to affect statistics for penetration of the W-surface, since these pilots were flying conservatively with respect to this surface. There were not enough samples to generate accurate statistics for the high cases.

For the non-high approach cases, the autopilot was a much more accurate lateral navigator since its standard deviation in lateral total system error during final approach averaged only about 34 feet while Flight Director (non-high) standard deviation averaged about 150 ft. The difference in vertical navigation variation between autopilot and flight director was much smaller; with non-high flight director approaches averaging nearly 60 ft in standard deviation and the autopilot averaging nearly 50 ft in standard deviation. In all cases TSE became somewhat smaller near the fictitious helipoint.

In the final approach phase TSE, FTE, and NSE distributions appear to be somewhat non-Normal, but the proper distribution to fit was not investigated. The 95% TSE confidence interval for the case with the largest number of samples was computed and found to generally be only 10% to 20% larger than the 2-sigma interval that provides 95% confidence for a Normal distribution. NSE statistics were approximately equal all along the approach, as expected.

Inspection of non-high 6-sigma TSE intervals shows that the W-surface is more than adequately outside. Lateral full-scale deflection occurred in at least one approach and upward vertical full-scale deflection occurred in at least seven approaches. The height loss after the missed approach in Phase I testing is of interest and will be further evaluated in subsequent testing.

References

[1] Helicopter WAAS Localizer Performance With Vertical Guidance (LPV) IFR To a Heliport (IVH) Approach and Missed Approach Engineering Evaluation, FAA William J. Hughes Technical Center Navigation System Performance Team, Atlantic City, NJ., 8/08.