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Angles of Deviation from Localizer Course during Simultaneous Independent Approaches to Parallel Runways

Flight Systems Laboratory
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September 2010

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NOTICE

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Flight Systems Laboratory
Flight Technologies and Procedures Division
Flight Standards Service

Angles of Deviation from Localizer Course during Simultaneous Independent Approaches to Parallel Runways

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12. Abstract The MITRE Corp. was tasked by the FAA to examine approach data at 12 major airports where parallel approach operations are conducted during IFR conditions. The study was conducted during fiscal years 2008 and 2009. From 785,203 approach operations 34 were found with deviations from the final approach course where the aircraft entered or nearly entered the NTZ. Problems such as radar noise made it difficult to estimate the specific angle of deviation. The FAA obtained the 34 flight tracks for the Flight Systems Laboratory, AFS-450, in Oklahoma City for further analysis. The Flight Systems Laboratory employed least squares polynomial curves to estimate the deviation angles. The results reflected deviation angles varied from 5 to 31 degrees. The report also provides estimates of rates of blunder based on deviation angle as well as confidence intervals for the rates.		
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EXECUTIVE SUMMARY

The purpose of this study was to collect and analyze data on closely spaced parallel independent ILS approaches flown in actual instrument meteorological conditions (IMC) to determine the frequency and angle of blunders (unexpected turns by one of the aircraft toward the other stream of traffic). The overall goal is to reduce the runway separation standards and allow operations to runways more closely spaced than can be done today.

Several key assumptions or parameters control those separation standards, principally the blunder angle and rate and the target level of safety. The values agreed upon for the blunder assumptions in the approval of prior parallel operations were intentionally conservative because no operational data was available on actual blunders.

Operational data is now available via databases which provide large amounts of data to examine both the rate and angle of blunders during actual approaches. Using those databases, MITRE examined radar track data, meeting weather and arrival rate metrics, from 12 major airports conducting parallel approach operations for 2008 and 2009. From 785,203 approaches, they identified 34 approaches with lateral deviations from the final approach course significant enough to be considered blunders.

Both MITRE and the FAA Flight Systems Laboratory (FSL), AFS-450, evaluated the 34 tracks. The MITRE analysis is covered in their reports [6, 7]. This report covers the FSL analysis. The results support significant reductions in the blunder rate assumption and changes to the blunder angle assumption. These new assumptions are defensible and will make current and future studies more representational of operations in the NAS today. The results are already being used in the FSL's Monte Carlo simulation tools to determine runway separations likely to be successful in scenario-specific, real-time, human-in-the-loop blunder studies to evaluate controller and pilot response times using modern aircraft and air traffic facility equipage and training. Once these scenario-specific controller and pilot response times distributions are determined, the FSL's Monte Carlo simulation tools will allow rapid evaluation of the risk level of each scenario-specific parallel runway configuration. These blunder evaluation studies and analyses will result in the determination of performance based closely spaced parallel operations standards and criteria for airport design and air traffic procedure development.

This study recommends the MITRE data collection effort be continued to gather data that will determine the effects of new technologies coming online, their impact on the safety of parallel operations and allow future refinement to the blunder evaluation assumptions and parameters.

Although the updated blunder assumptions are valid for operational implementation, their net effect are partially offset by the increase to the target level of safety value. This increase is due to the acceptable risk level within the FAA’s ATO Safety Management System manual.

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1.0 INTRODUCTION AND BACKGROUND

The use of parallel instrument landing system (ILS) approaches to increase aircraft arrival rates dates back to the late 1950's. The Federal Aviation Agency, the predecessor of the Federal Aviation Administration (FAA), sponsored several studies to determine the possible hazards of parallel operations and evaluate the risk associated with those hazards. The Franklin Institute gathered track data of 2,000 final approaches to 10 airports in 1959 and analyzed the distributions of the approaches. Other studies published in 1961 and 1962 included some field data collection, theoretical analysis and a field flight test program at Chicago O'Hare. The flight test was intended to verify the pilot and controller response times in the event of a blunder by one aircraft toward an aircraft on the adjacent approach. The agency was satisfied with the results and issued regulations in 1963 permitting simultaneous independent parallel approaches to runways with centerlines spaced at least 5000 feet apart.

By the late 1960's, increases in air traffic spurred inquiries into the possibility of further reduction in runway spacing requirements. This was the goal in the Air Traffic Control Advisory Committee Report in 1969. Following a data collection and analysis supported by MITRE and Resalab, Inc., the minimum spacing requirement was reduced by the FAA in 1974 to 4300 feet. The analysis conducted by MITRE used the MITRE model, an early computer simulation model. At the time these studies were conducted, ASR 4/5/6 radars with an update rate of 4.0 seconds and ARTS displays were being used. MITRE recommended that a 2700 feet No Transgression Zone (NTZ) should be used for 4300 feet runway spacing. In 1975, MITRE recalibrated their model based on the assumption that a 2000 feet NTZ would be acceptable for 4300 feet runway spacing. The parameters (of the model) were adjusted so as to provide a rational explanation of the distances required for a controller to detect and react to a blunder when the runway spacing is 4300 feet. The model presumes that the 4300 feet rule is acceptable. Therefore, it is obvious that in the 1960's and 1970's there was concern about the possibility of a blunder and the ability of controllers and pilots to react with sufficient speed to avoid a collision or very near miss.

Another MITRE study in 1981 evaluated the benefits of improved surveillance and concluded that the minimum runway spacing for independent parallel approaches could be reduced to 3400 feet with a 4 second update rate and 3000 feet with a 1 second update rate. Again, the emphasis of the study was to determine the ability of the controllers and pilots to recover from the occurrence of a blunder.

The FAA formed the Precision Runway Monitor Program in 1988. The principal objective of this program was to develop improved radar, the Precision Runway Monitor (PRM), and the associated procedures necessary to lower the minimum required spacing between parallel runways for simultaneous independent ILS operations. In addition, an equivalent level of safety with approaches to single runways was required. The investigators and participants in the study agreed to use blunders that turned 30 degrees off the localizer toward the other parallel approach course. This choice of blunder angle had been used in previous studies.

To demonstrate an equivalent level of safety, a target level of safety was determined from accident data provided by the National Transportation Safety Board (NTSB). The target level of safety is deemed the maximum acceptable probability of a collision. The real-time and computer based simulations could produce the probability of a collision once a 30 degree blunder is initiated, but to find the total probability of a collision due to a 30 degree blunder it is necessary to know the probability of a 30 degree blunder. In addition, the probability that the blundering aircraft would not respond to controller directions to return to the localizer course was needed. However, at the time of the study there were no data available to estimate any blunder rate. The probability of a non-responding blunder was estimated to be no more than one per one hundred 30 degree blunders. To compensate for these shortcomings, the investigators computed a blunder rate that when combined with the ability of the PRM to resolve them attains the target level of safety. If that rate is well above an intuitive sense of experts of how often blunders occur, then the system could be considered to have met the desired target level of safety. The PRM study adopted a target level of safety of 4×10^{-8} per approach. The Precision Runway Monitor Report (1991) established the maximum blunder rate that would satisfy the target level of safety to be one in 2000 approaches or one in 1000 dual approaches. This blunder rate was based on a key assumption there would be no more than one non-responding blunder per one hundred 30 degree blunders. It was observed in the PRM report that if blunders were occurring at one in 1000 dual approaches, Chicago would have about ten 30 degree blunders per year during instrument meteorological conditions and Atlanta would have about fourteen. Since anecdotal evidence suggested the actual rate at Chicago was no more than one per year it was assumed that the target level of safety was met. The risk analysis adopted during the PRM study was very conservative. It guaranteed that the target level of safety was met, but it was felt that the actual risk of the operation was less than the target level of safety.

Since the PRM Monitor Program and the Multiple Parallel Approach Program (MPAP) that followed it, several data sources have become available that either did not exist or were not mature. The National Offload Program (NOP) was initiated by the FAA in the 1990s. Radar tracks are recorded that include the position and altitude for each aircraft during approaches and departures. Since most surveillance radar used today in terminal airspace update at 4.8 second intervals, the NOP data are mostly recorded at 4.8 second intervals. A necessary adjunct to NOP is the Aviation System Performance Metrics (ASPM) data base. ASPM includes weather data and arrival rates. From ASPM the date and times that Instrument Meteorological Condition (IMC) operations were conducted at the airports of interest can be ascertained as well as likely periods of simultaneous operations.

1.1 MITRE BLUNDER STUDIES

With the advent of data bases such as NOP and ASPM, it has become possible to obtain large amounts of data to examine for both the rate of blunders and the approximate angle of deviation from the approach course. MITRE was tasked by the FAA to examine approach data at 12 major airports where parallel approach operations are conducted during IFR weather conditions. The study was conducted during fiscal years 2008 and 2009. MITRE developed a program to determine which approaches were conducted during IFR weather conditions. MITRE found 405,035 simultaneous independent approaches in 2008 and 380,168 simultaneous independent approaches in 2009. From the 785,203 approaches MITRE found 34 approaches with deviations from the final approach course where the aircraft entered or nearly entered the NTZ. MITRE obtained voice recordings of the events to verify that the aircraft were instructed to return to the localizer. MITRE provided a compilation of the deviation angles they determined to the FAA.

The radar data in the NOP are subject to various forms of “noise” primarily caused by radar errors. Therefore the points that the radar recorded do not lie on smooth curves. Furthermore, the aircraft tended to vary the deviation angle as they flew through the deviation. These problems make it difficult to estimate an exact angle of deviation. The FAA requested that MITRE forward the 34 flight tracks to the Flight Systems Laboratory, AFS-450, in Oklahoma City for further analysis.

2.0 FLIGHT TRACK AND DEVIATION ANGLE ANALYSIS

The flight tracks supplied by MITRE have two primary paired variables, the distance x from the runway threshold and the distance y from the localizer course of the recorded radar position of the aircraft. The radar has various errors, some are random, but there may be a bias as well. During a deviation it is likely that the aircraft may wander or change headings somewhat during the deviation. The radar track of an aircraft when plotted will be a series of points or hits of the radar. The points are somewhat erratic and from a cursory examination of a given track one might not expect an aircraft to be able to fly some segments of the indicated course.

A similar situation often occurs in statistical applications. A set of data consists of points having two variables, an x coordinate and a y coordinate. When the data points are plotted on a graph the investigator is able to see a distinct pattern. The data points might form what appears to be a straight line or possibly a parabolic curve, but further investigation reveals that the data points do not lie on a straight line or a parabolic curve. The investigator then proceeds to fit a curve (straight line or some other curve) that best fits the data using some criteria even though the curve might not pass through any of the data points.

A common approach to this problem is the least squares or regression approach. The idea is to consider a mathematical function f(x) that could be adapted to the shape of the plotted data. The function f(x) has constants in it that can be computed to make the function conform to the shape of the plotted data. Each x value of the data has a corresponding y value. Given a set of constants in the function f(x), a value y of the function can be computed and compared to the corresponding y value in the data. Normally the two y values will be different. The difference of the two y values represents the error between function value of y and the data value of y. The error value can be either positive or negative. If the error is squared, then negative errors become positive and positive errors remain positive. Then one sums the squares of the errors and works to minimize this sum by adjusting the constants in the function f(x). This process is called the least squares method or regression.

The deviations from the localizer course resemble curves produced by polynomials. A polynomial is a function of the form:

$$f(x) = c_0 + c_1 x + c_2 x^2 + \ldots + c_n x^n$$

where n is the degree of the polynomial. The investigator knows the general shape of the function that will result from a given value of n. Therefore the investigator chooses a value of n that will result in a curve that resembles the shape of the plotted data points. Then the values of the polynomial coefficients $c_0, c_1, c_2, \ldots, c_n$ are computed using the least squares method to find the best fit curve. The “goodness” of the fit can be ascertained from the coefficient of determination or “R^2” value. This value will be used to optimize the curve fit but the investigator will plot the curve on the data plot to visually confirm how well the curve fits the data.

After the best fit polynomial has been determined, an estimate of the deviation angle can be computed using calculus. The derivative of a polynomial is another polynomial function and it can be used to compute the deviation angle at any point on the best fit curve f(x). The investigator can examine the best fit curve to determine the predominant deviation angle from the localizer course. Then the investigator selects an x value from that segment of the curve and computes the corresponding value of the derivative. The value of the derivative is the trigonometric tangent of the angle the line tangent to the curve f(x) makes with the localizer course (x axis). The investigator then computes the trigonometric inverse tangent of the derivative value to find the estimate of the deviation angle.

At this point, it is required to select a range within the polynomial curve fit as the region of interest. This range usually includes the start of the blunder to the start of recovery, trimming the ends to avoid obvious polynomial fit errors. The goal is to select a range of time that is sufficient to represent the blunder. This is at least the same amount of time as the average radar hit interval of 4.8 seconds. This necessitates the conversion of the polynomial along track distance vs. cross track distance graph into a graph of time vs. deviation angle; which is performed using linear piecewise sampling of the region of interest. The interpolation is square, so that limited errors are present and only the nearest time value is selected.

Figure 1 illustrates the five-step process used to find the blunder or deviation angle that was found at KDEN, row 10 in Table 1. First, the section of the flight track that represents the blunder is determined, making sure that the suspected area deviates toward a parallel localizer course, and extends far enough toward the parallel localizer to enter or nearly enter the NTZ. The suspected blunder section must occur where the aircraft should be established on the glide slope and not in the turn-on phase of the approach. Second, the values in the suspected blunder region are "normalized" to facilitate the polynomial curve fit, i.e., the zero x-value is selected to be the midpoint of the endpoint x-values of the selected section. In Figure 1 and from Table 1, the x-values of the endpoints of the selected section are -17.8 and -13.7. The midpoint value -15.75 is renamed zero and the remaining x-values are relabeled accordingly. Therefore, -17.8 becomes -2.05 and -13.7 becomes 2.05. Then, the coefficients of the appropriate polynomial are computed using the polynomial least-squares regression method. This is represented by the first inset in Figure 1. Third, a range of the polynomial curve is selected that best represents the blunder region of interest. Note that the vertical and horizontal scales are different, so the apparent deviation angle is larger than the actual angle. Fourth, the region selected is converted to represent real time in seconds versus deviation angle; from which the investigator must select a range of time. The deviation angles are computed by using the derivative of the polynomial curve over the time region of interest. Fifth, the deviation angle is selected from the time range. Note that the curve might not fit the data well in the entire area selected to compute the angle, but does fit well in the area of interest. The curve in the inset of Figure 1 does not fit well at the endpoints, but the curve fits well in the area of interest.

3.0 FINDINGS AND CONCLUSIONS

The FAA received thirty four flight tracks from MITRE for AFS-450 to further analyze. AFS-450 was able to extract 33 angles. One track was unusable due to the length and variation in the data points. Table 1 contains the track number, the airport identifier, the runway, the calculated deviation angle in degrees, the x-values of the endpoints of the selected segment, the smaller region of interest minimum and maximum for the regression curves, and the length of time over which to calculate the deviation angle. This length of time is also reflected in the time graphs in the appendix. From Table 1 the smallest deviation angle was estimated to be 4 degrees and the largest deviation angle 31 degrees.

Figures 2 through 4 are histograms of the deviation angles determined by the five-step process from the Flight Track and Deviation Angle Analysis section. Figure 2 is a histogram with bins one unit wide showing the frequency and distribution of the deviation angles over the selected regions of time. Figure 3 is a histogram with bins 5 units wide. Figure 4 is a histogram with bins 10 units wide.

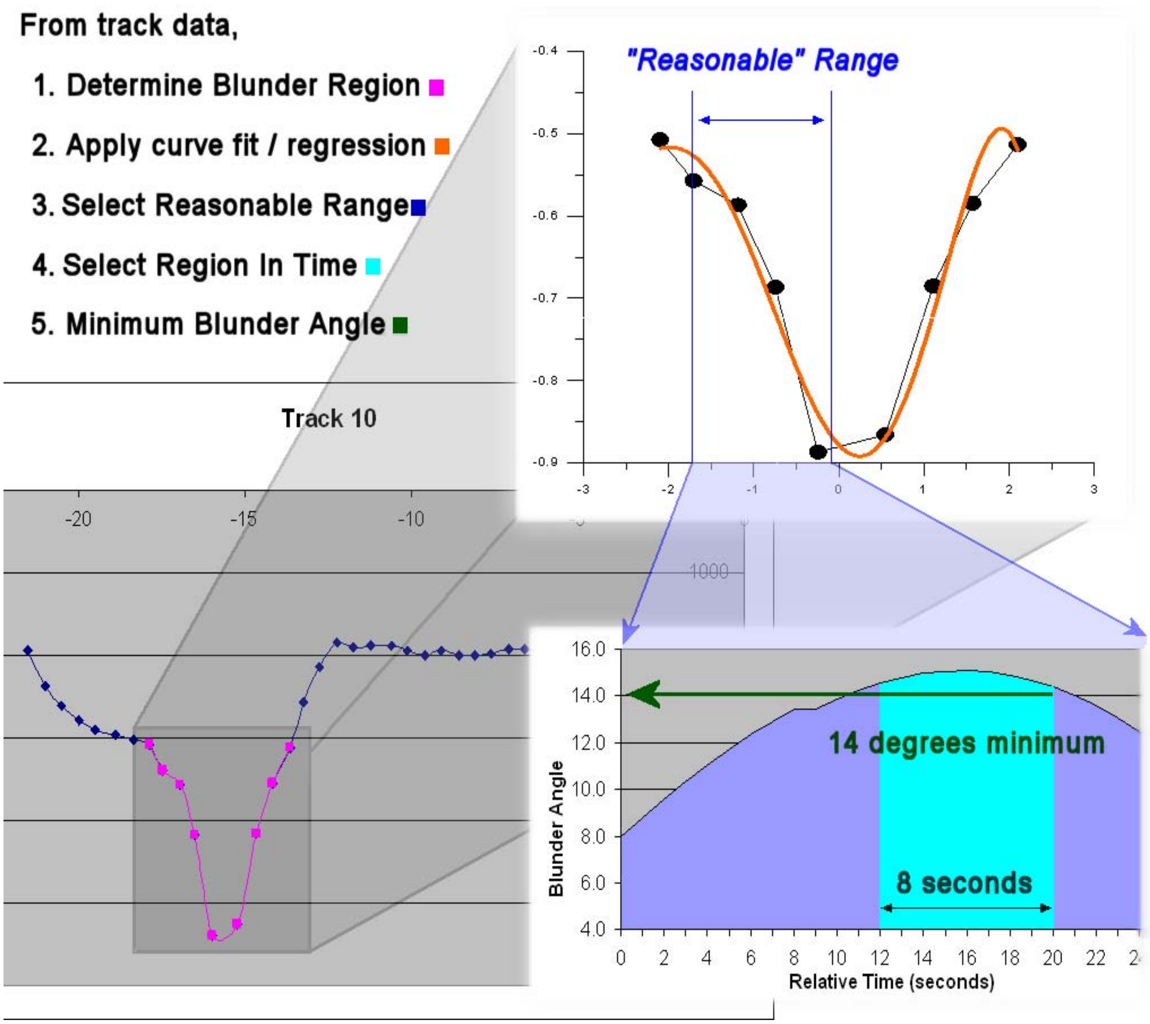


Figure 1: Illustration of Computation of a Deviation Angle

Table 1: Airport Identifiers and Deviation Angles

Track	Airport	Runway	Angle	Max X	Min X	ROI Min	ROI Max	ROI Time
0	XAAA	09L	16º	-1.96987	-3.82536	-0.80	0.45	5
1	XAAA	27L	5º	-3.03023	-4.41621	-0.65	0.75	6
2	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
3	XAAA	27R	19º	-7.87196	-9.44689	-0.70	0.30	6
4	XAAA	28	10º	-9.72144	-13.0615	-1.40	0.00	6
5	XBBB	36C	6º	-10.8472	-14.4078	-1.50	0.00	12
6	XCCC	18R	12º	-10.5707	-15.0049	-2.00	0.00	9
7	XCCC	18R	7º	-5.67042	-7.98767	-1.00	-0.40	6
8	XCCC	18R	24º	-9.06806	-12.0231	-1.30	-0.20	5
9	XDDD	18R	9º	-10.4832	-14.2488	-1.85	-0.70	5
10	XEEE	34L	14º	-13.6533	-17.8531	-1.50	0.00	9
11	XFFF	19L	13º	-9.20935	-12.2981	-0.30	0.30	9
12	XFFF	19L	12º	-5.32995	-8.05773	-1.35	-0.80	6
13	XGGG	26L	10º	-7.84952	-11.4544	-1.60	0.00	10
14	XGGG	27	5º	-9.3696	-13.659	-1.80	0.60	6
15	XGGG	26L	17º	-10.456	-15.068	-2.20	-1.00	8
16	XGGG	08L	5º	-11.1086	-15.8644	-0.80	0.40	8
17	XGGG	26L	5º	-9.50158	-16.2853	-1.30	0.40	9
18	XGGG	08R	10º	-9.52046	-15.341	-2.80	-0.40	7
19	XGGG	26R	31º	-3.33564	-4.23627	-0.40	0.00	10
20	XGGG	26L	19º	-1.59566	-6.16591	-1.55	-0.20	7
21	XHHH	24L	4º	-9.42221	-13.0404	0.50	1.40	6
22	XHHH	25L	8º	-5.07994	-8.31549	-1.50	-0.80	7
23	XHHH	25L	6º	-7.95434	-11.9313	-1.00	0.00	7
24	XDDD	18R	22º	-7.23346	-9.11472	-0.80	0.00	11
25	XDDD	18R	8º	-8.45176	-11.1486	-1.10	-0.30	9
26	XDDD	18R	11º	-5.21974	-12.0408	-3.30	-2.00	8
27	XDDD	18R	7º	-9.54958	-12.6232	-1.40	-0.90	7
28	XDDD	18R	16º	-7.77919	-10.1401	-1.00	-0.50	7
29	XDDD	18R	12º	-8.55607	-11.473	-1.40	-0.20	9
30	XDDD	36L	18º	-9.37933	-12.1029	-1.30	-0.20	9
31	XIII	09R	25º	-7.96933	-15.1751	-3.20	-0.40	7
32	XIII	09R	6º	-5.98853	-10.9184	-2.00	0.30	9
33	XJJJ	35	15º	-3.43101	-11.6756	-3.80	-2.00	9

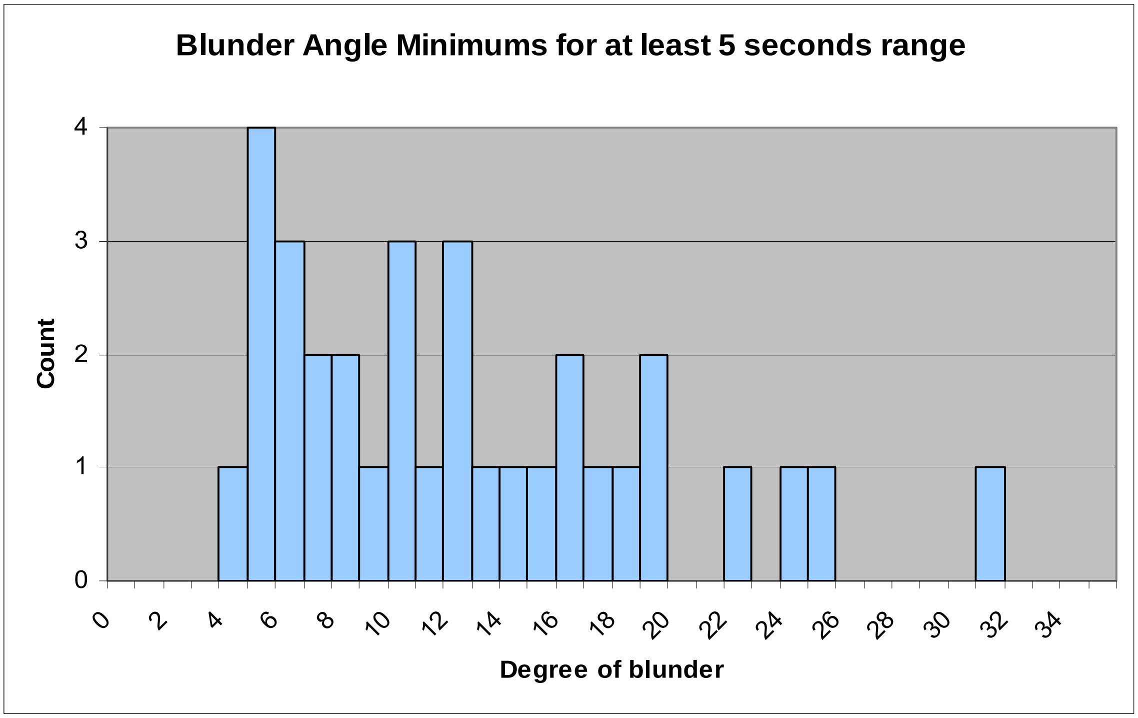


Figure 2: Histogram with One Degree Bins

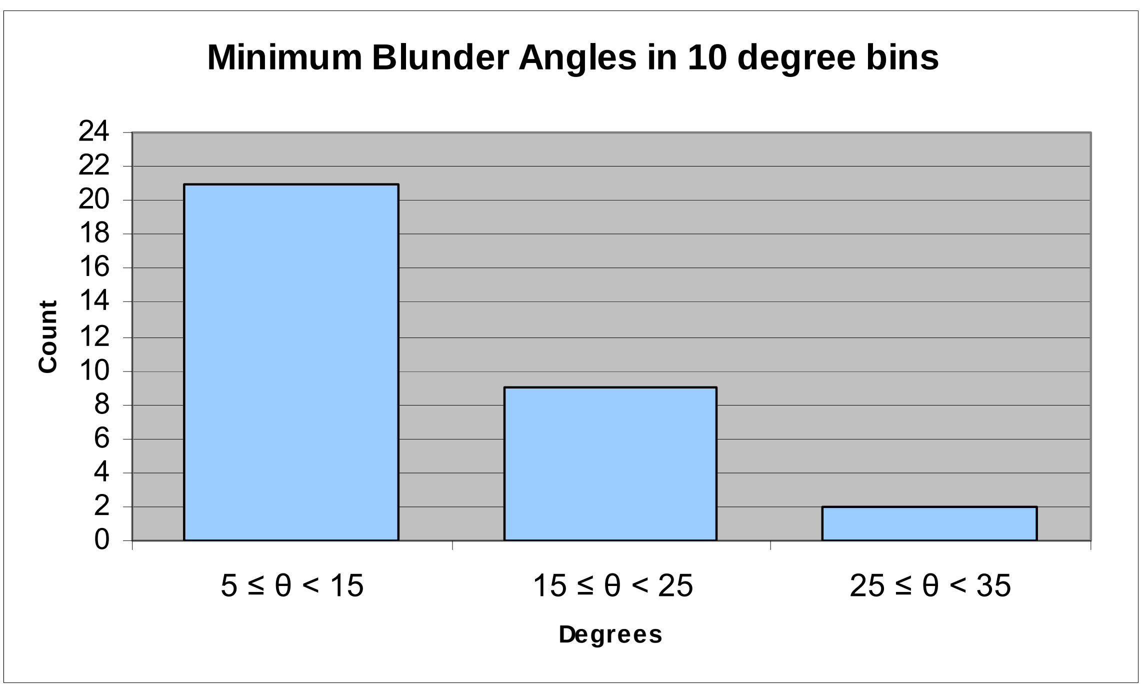


Figure 3: Histogram with Ten Degree Bins

MITRE examined 785,203 simultaneous approaches conducted in less than visual approach conditions to obtain the 34 approaches with deviations exceeding five degrees. The deviation angles derived by AFS-450 can be used with the MITRE estimate of the number of approaches to derive deviation rates. The rates were partitioned over 10 degree intervals, i.e., angles equal to or greater than 5 degrees and less than 15 degrees, angles equal to or greater than 15 degrees and less than 25 degrees, and angles equal to or greater than 25 degrees and less than 35 degrees. Even though the number of approaches that were examined is a large number, it is still only a sample of the total population of simultaneous IFR approaches. To indicate the uncertainty associated with the rates, even though the data set is large, confidence intervals were computed. The confidence intervals were based on a theoretical description of the population as a binomial distribution. Since the sample data set was believed to represent a large fraction of the entire population during the sampling period, a Finite Population Correction Factor (FPCF) was generated to adjust the size of the confidence intervals. In calculating the FPCF it was assumed that the total population size during the sampling period was no more than twice the sample size of 785,203 approaches. Table 2 displays 99% confidence intervals including Low and High Confidence Intervals and Low and High Confidence Intervals with FPCF adjustments. Exact requirements for the applicability of the FPCF are still under consideration.

Table 2: 99% Confidence Intervals for NTZ Penetration Rates

99% Confidence Intervals for NTZ Penetration Rates Assuming Blunder Events are Binomial in Nature

Deviation Degrees	Approaches per Penetration	Low Confidence Limit	Low Confidence Limit w/ Adjustment	Observed Penetration Rate	High Confidence Limit w/ Adjustment	High Confidence Limit
$5 \leq \Theta < 15°$	37,391	1.41×10^{-5}	1.94×10^{-5}	2.68×10^{-5}	3.77×10^{-5}	4.58×10^{-5}
$15 \leq \Theta < 25°$	87,244	3.99×10^{-6}	7.15×10^{-6}	1.15×10^{-5}	1.95×10^{-5}	2.55×10^{-5}
$25 \leq \Theta < 35°$	392,601	1.32×10^{-7}	1.15×10^{-6}	2.55×10^{-6}	7.9×10^{-6}	1.18×10^{-5}

The deviation or blunder rate is an essential factor in the equation used to estimate the collision risk associated with a blunder. The confidence intervals demonstrate that there is significant uncertainty in the magnitude of the blunder rate even though the sample size is large. Since the consequences of a collision are so severe, the prudent use of a confidence interval would be to use the right endpoint or largest value of the confidence interval as the estimate of the blunder rate

4.0 RECOMMENDATIONS

The primary result or benefit associated with decreasing the minimum separation of parallel runways for the implementation of independent parallel approaches is the potential of increased capacity at airports having runways too closely spaced under current criteria. However, the intolerable consequences of a collision require that the estimation of the risk of a collision be made in a conservative, prudent manner. Current and future risk analyses should use the upper bound of a 99% confidence interval. It is also recommended that the data collection of possible blunder events be continued. This should allow further refinement of the confidence interval in the future.

REFERENCES

1. Department of Transportation, Air Traffic Control Advisory Committee, Final Report, December 1969.

2. Fantoni, J.A. and Rudich, R.D., Evaluation of Parallel Runway Spacing, FAA, Aviation Research and Development Service, Atlantic City, New Jersey, July 1961.

3. Federal Aviation Agency, An Operational Evaluation of the Parallel ILS System – O'Hare International Airport, November 1962.

4. Haines, A. L., Reduction of Parallel Runway Requirements., The MITRE Corp., MTR-6282, January 1973.

5. Haines, A. L., Requirements for 3500 Foot Spacings for Simultaneous Parallel IFR Approaches., The MITRE Corp., MTR-6841, January 1975.

6. Massimini, S. V., McNeill, G. C., Tene, N., Frequency and Severity of Deviations During Simultaneous Independent Approaches to Parallel Runways., The MITRE Corp., MP080164, September 2008.

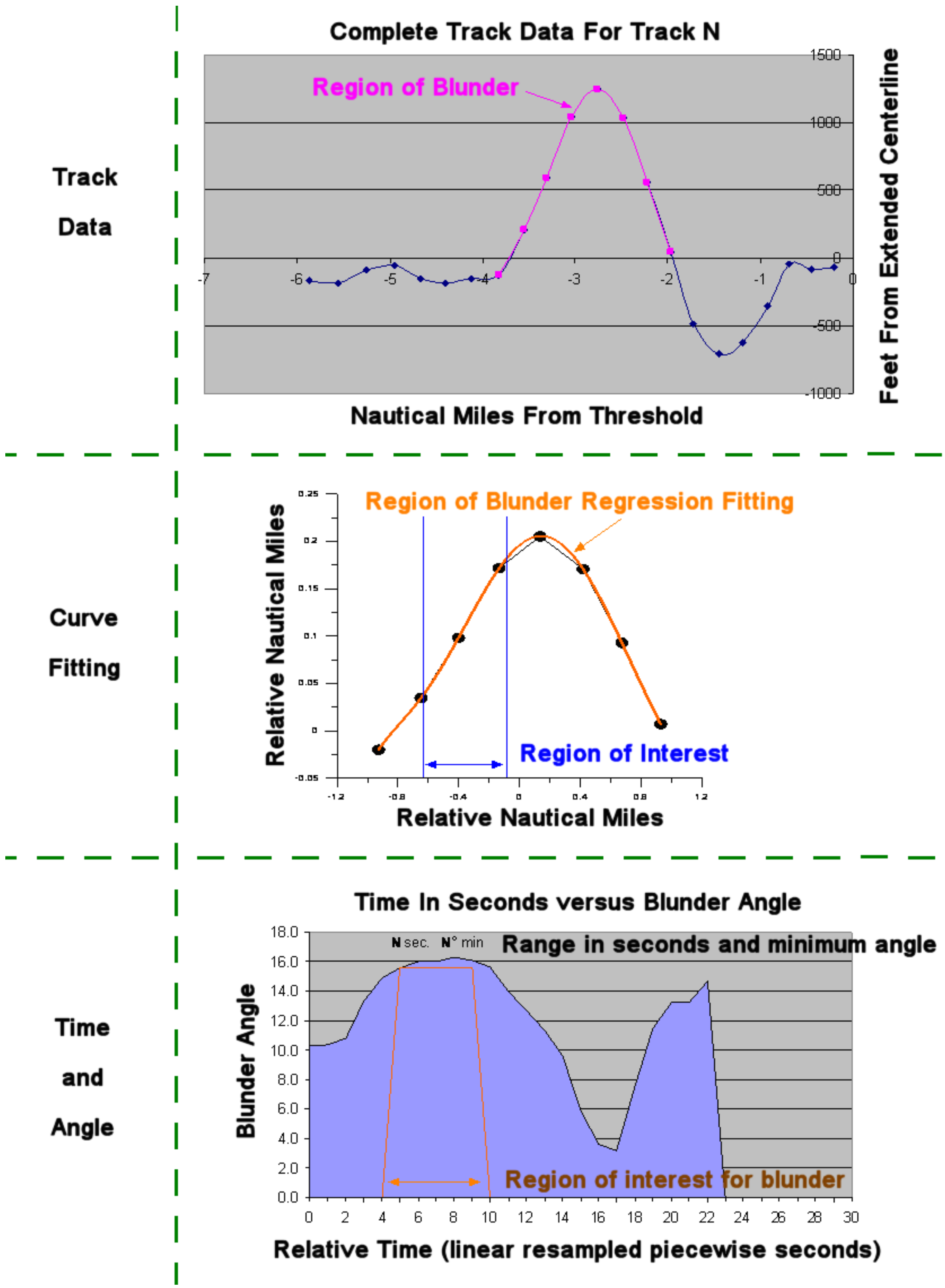
7. . Massimini, S. V., McNeill, G. C., Tene, N., Frequency and Severity of Deviations During Simultaneous Independent Approaches to Parallel Runways – A 2009 Update., The MITRE Corp., MP090245, September 2009.

8. McLaughlin, Francis X., Navigational Accuracy Demonstrated with the Instrument Landing System, Franklin Institute Labs, FAA/BRD-14, June 1959.

APPENDIX A

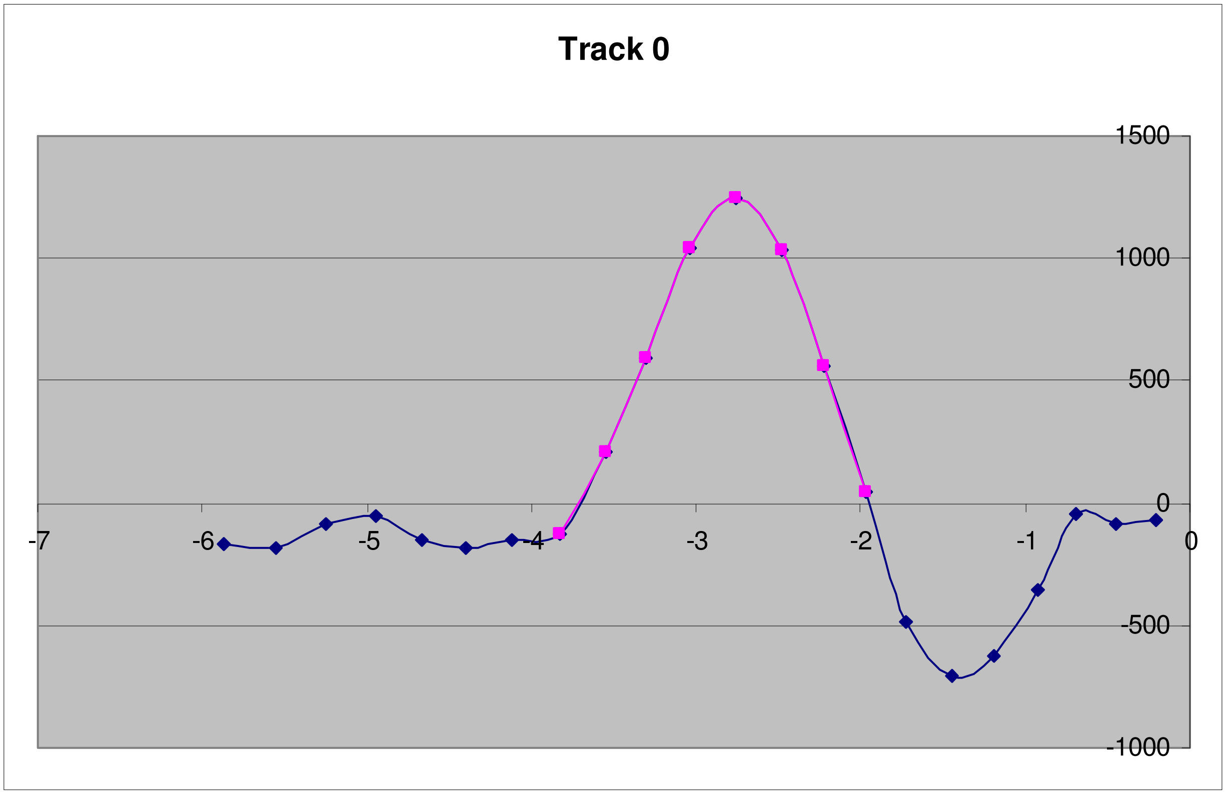
AIRCRAFT FLIGHT TRACKS

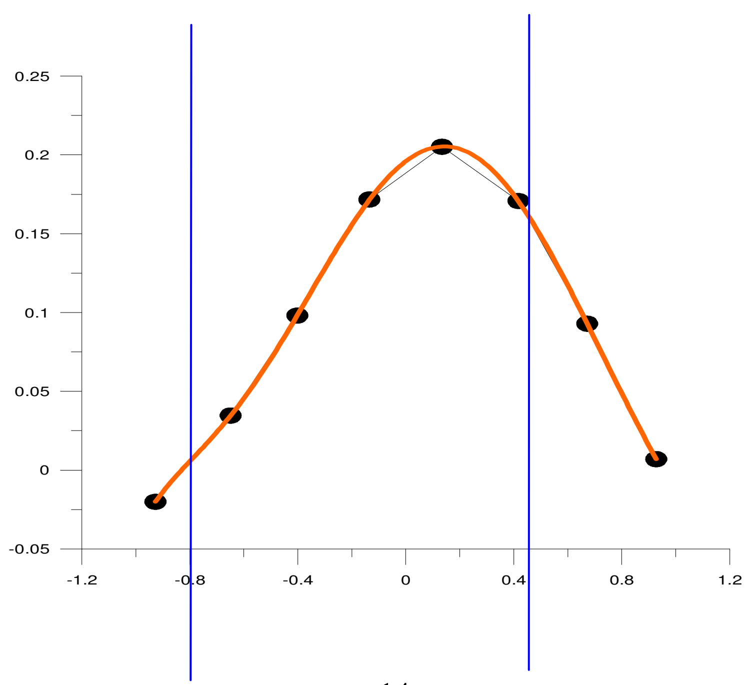
Legend for Interpreting Appendix Data

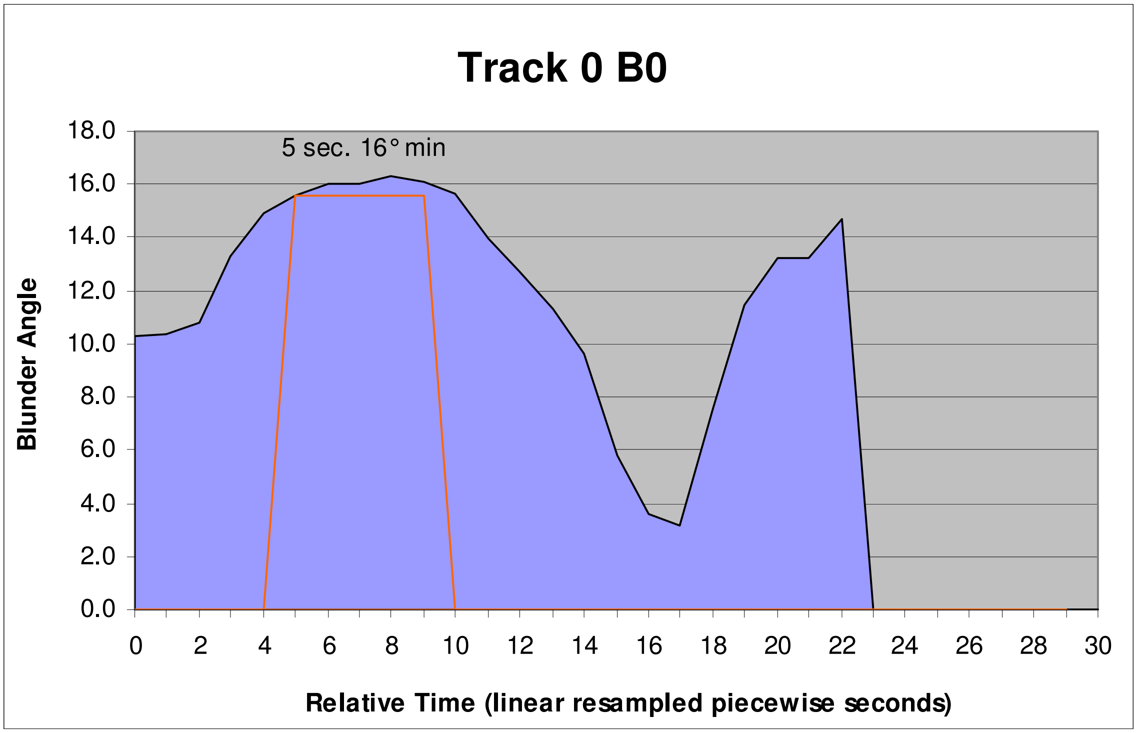


TRACK 0

- **AIRPORT:** XAAA
- **RUNWAY:** 09L
- **ANGLE:** 16º

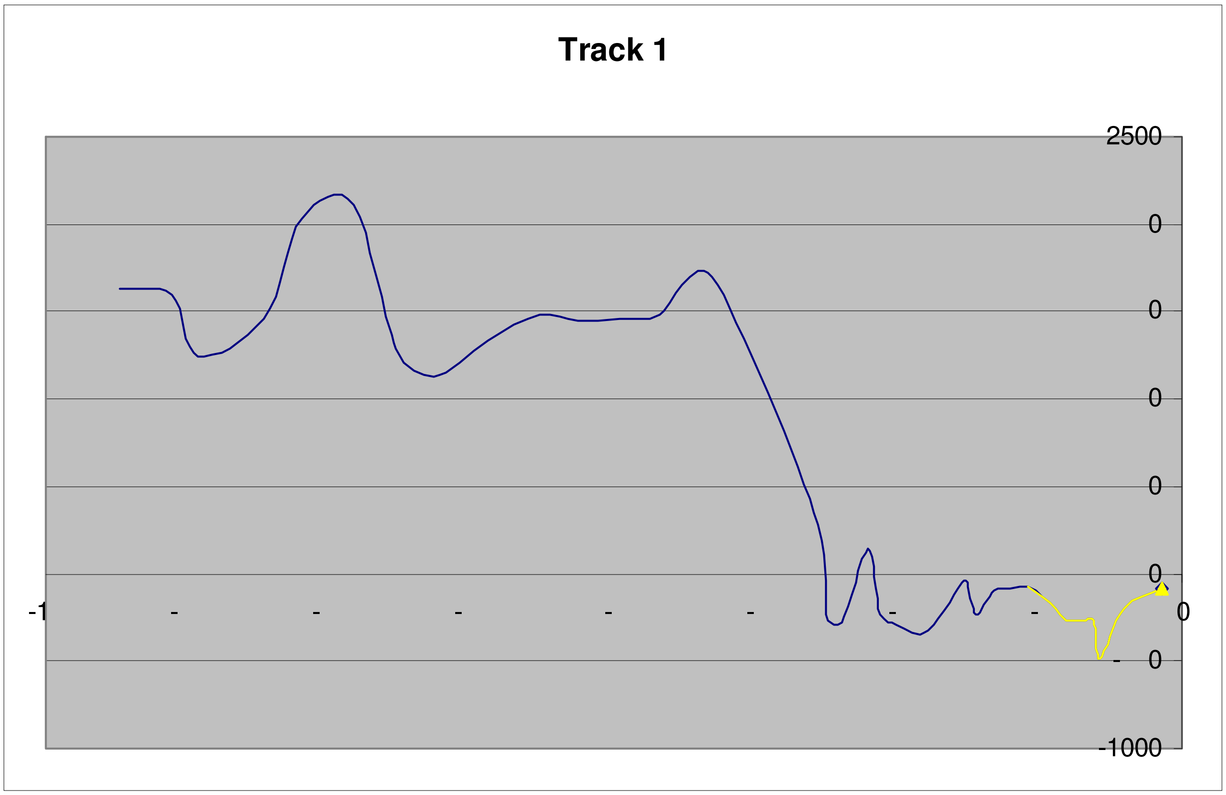


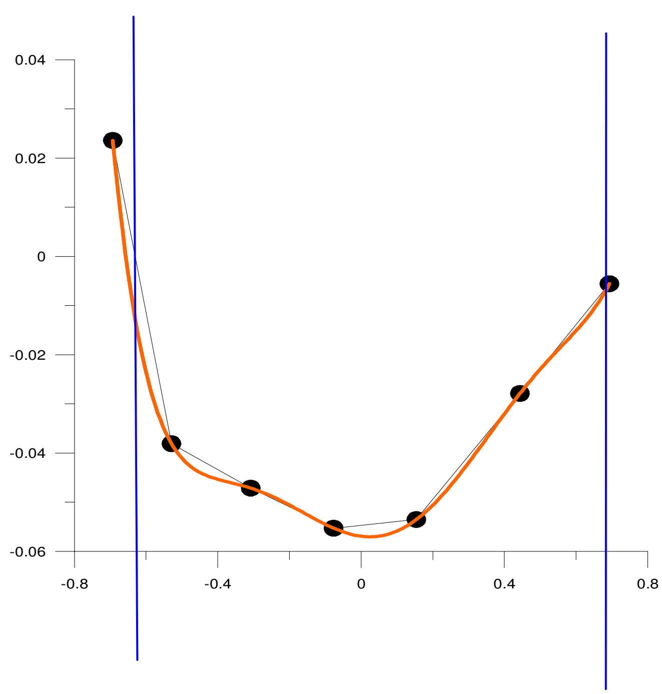


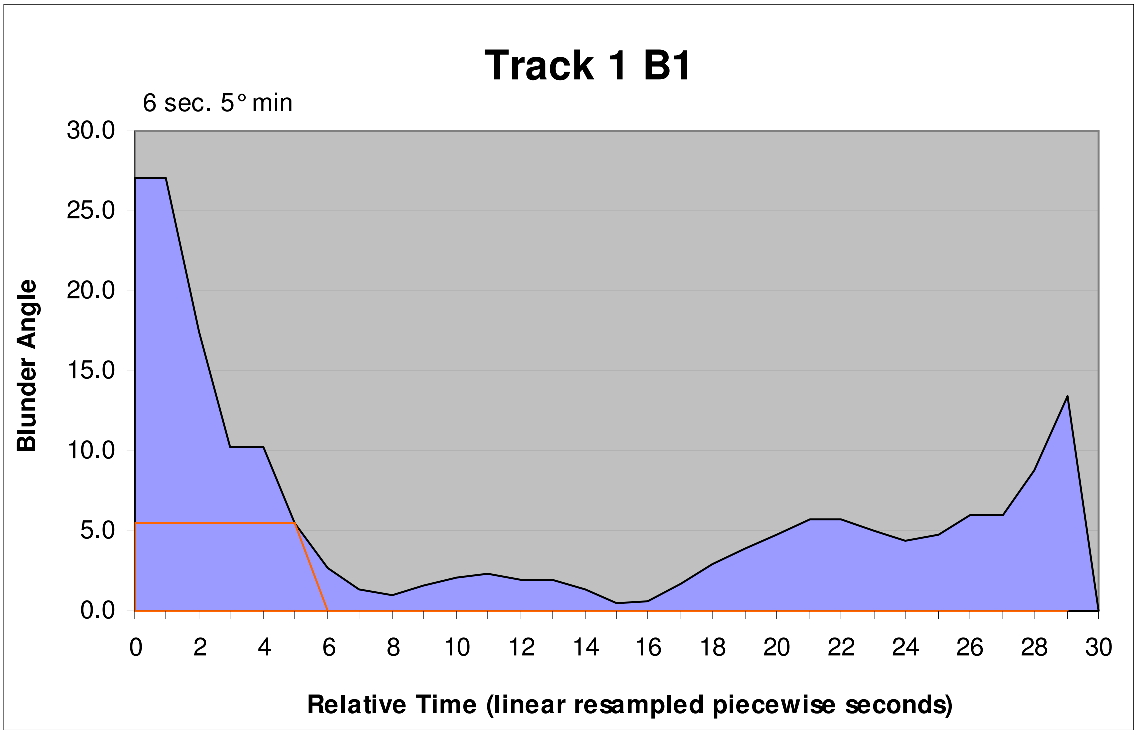

Track 0 B0
5 sec. 16° min
Blunder Angle
18.0
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
Relative Time (linear resampled piecewise seconds)

TRACK 1

- **AIRPORT:** XAAA
- **RUNWAY:** 27L
- **ANGLE:** 5º

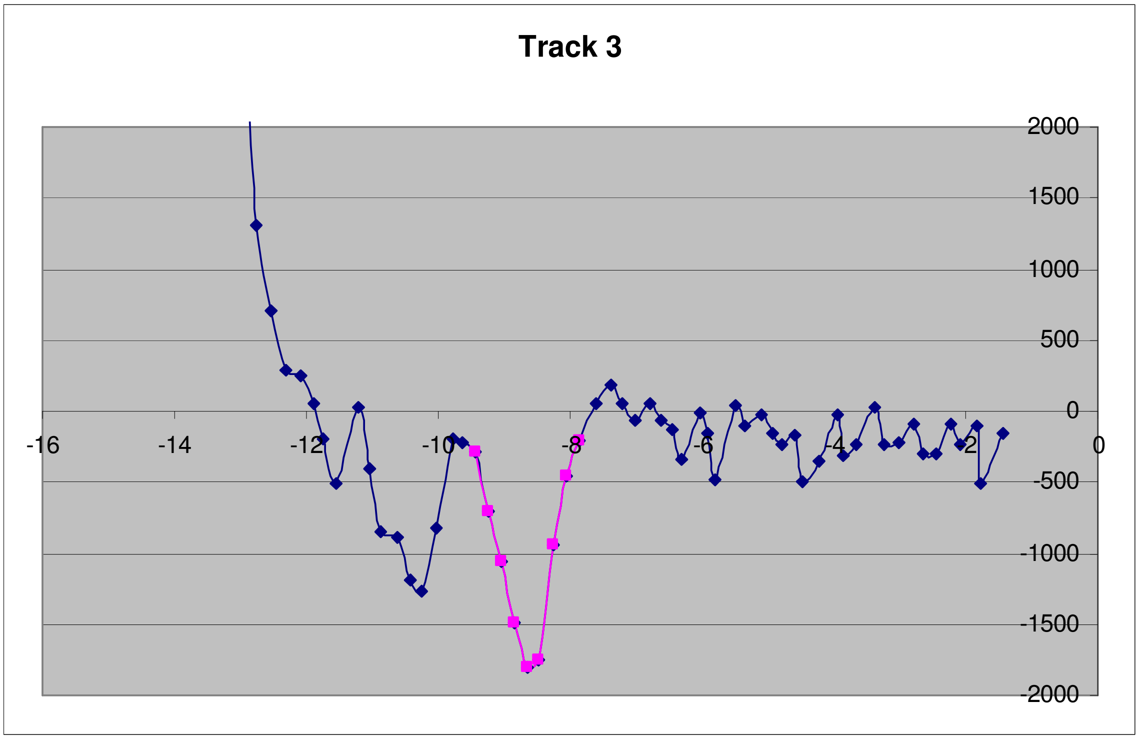


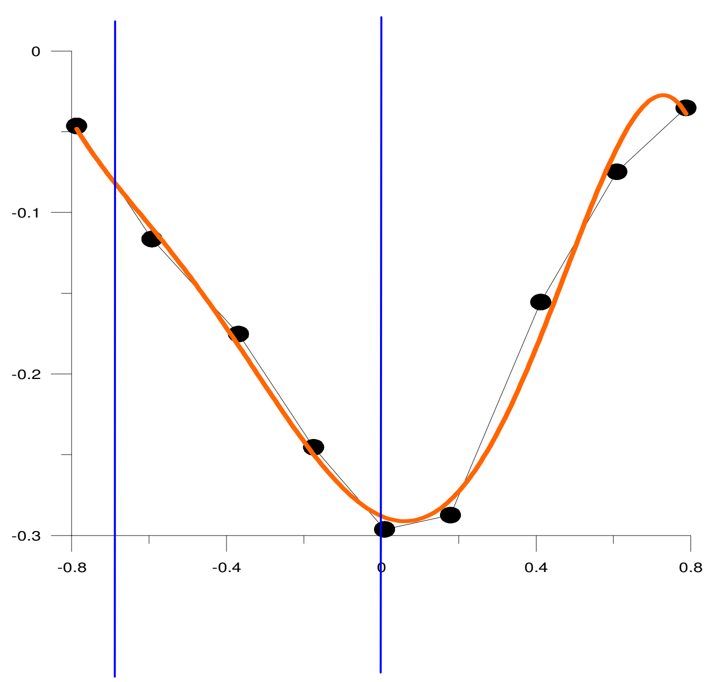


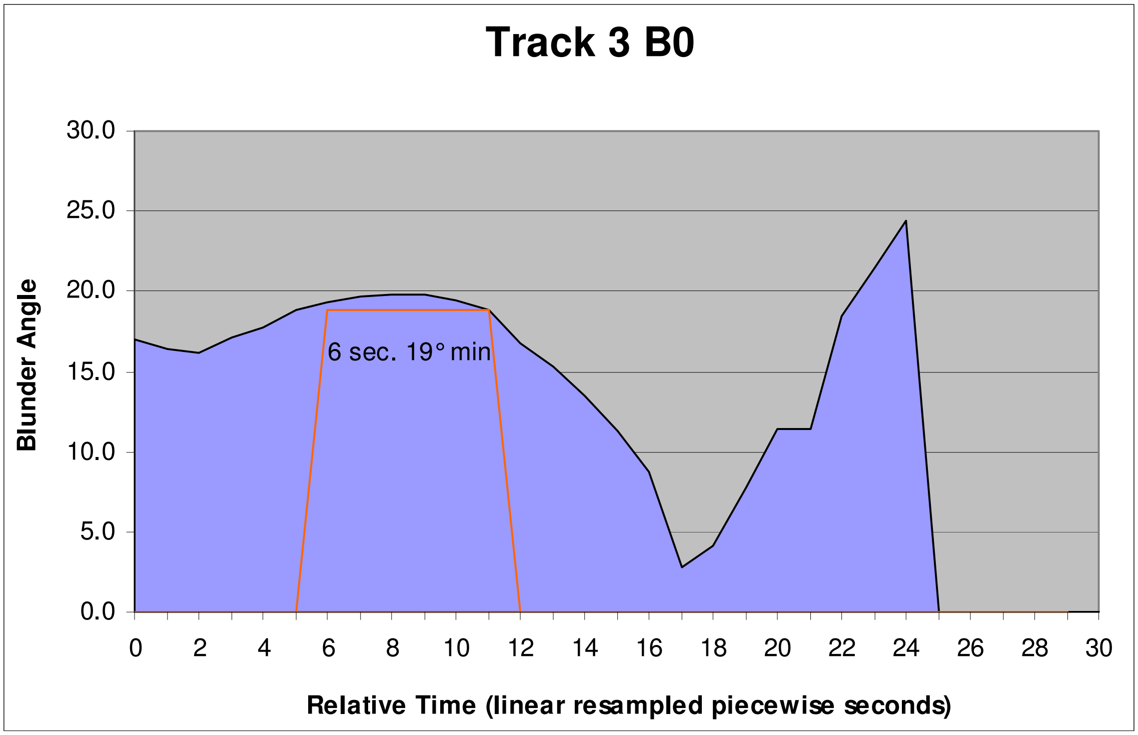

Track 1 B1
6 sec. 5° min
30.0
25.0
20.0
15.0
10.0
5.0
0.0
Blunder Angle
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
Relative Time (linear resampled piecewise seconds)

TRACK 3

- **AIRPORT:** XAAA
- **RUNWAY:** 27R
- **ANGLE:** 19º

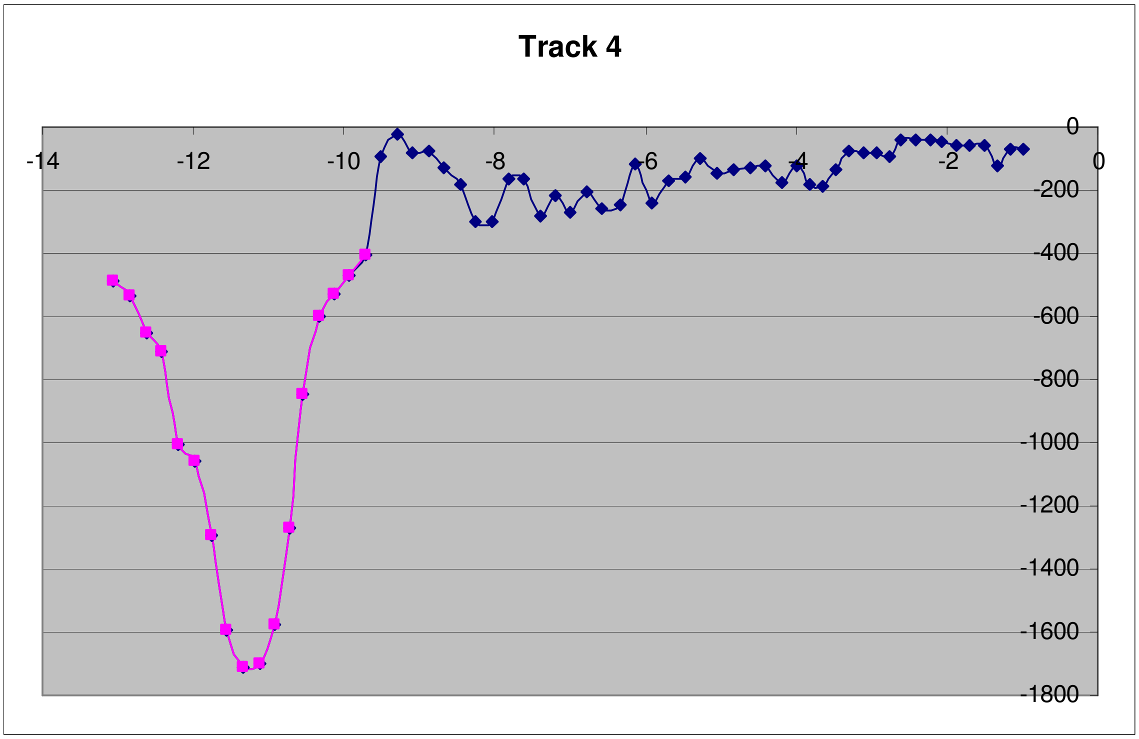


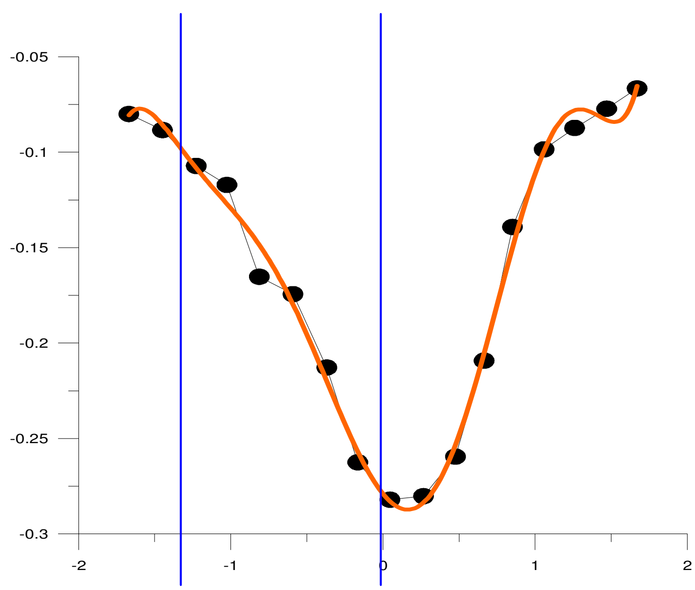


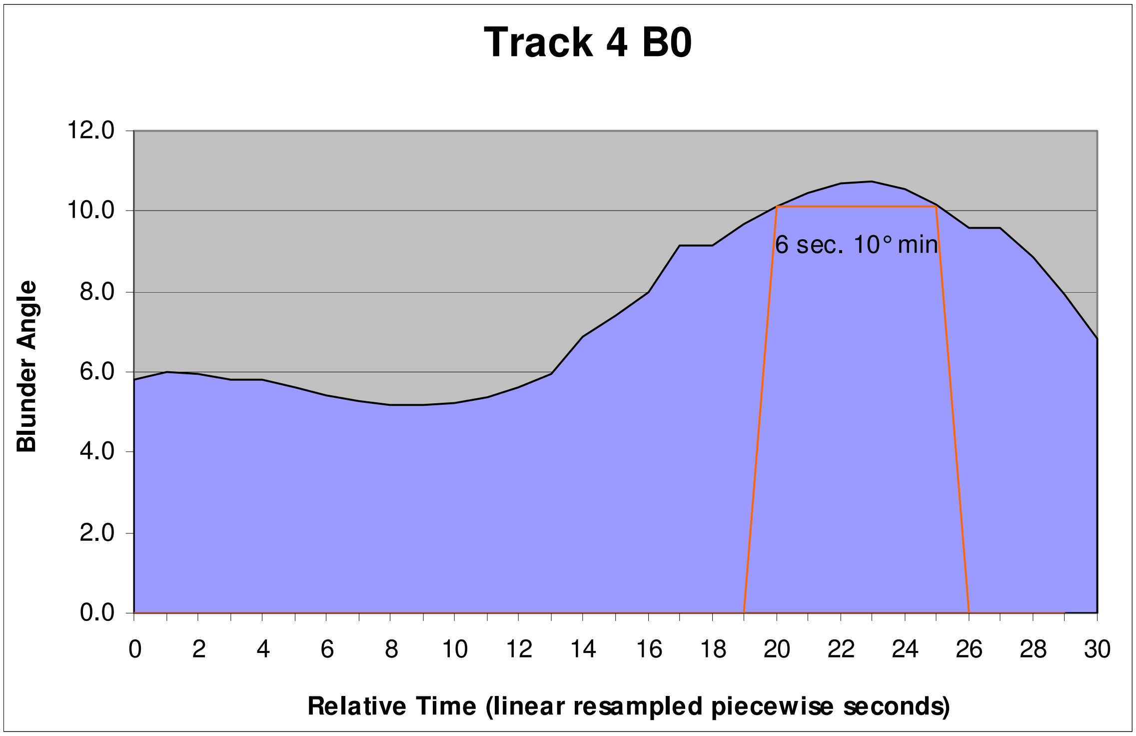

Track 3 B0
Blunder Angle
30.0
25.0
20.0
15.0
10.0
5.0
0.0
6 sec. 19° min
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
Relative Time (linear resampled piecewise seconds)

TRACK 4

- **AIRPORT:** XAAA
- **RUNWAY:** 28
- **ANGLE:** 10º



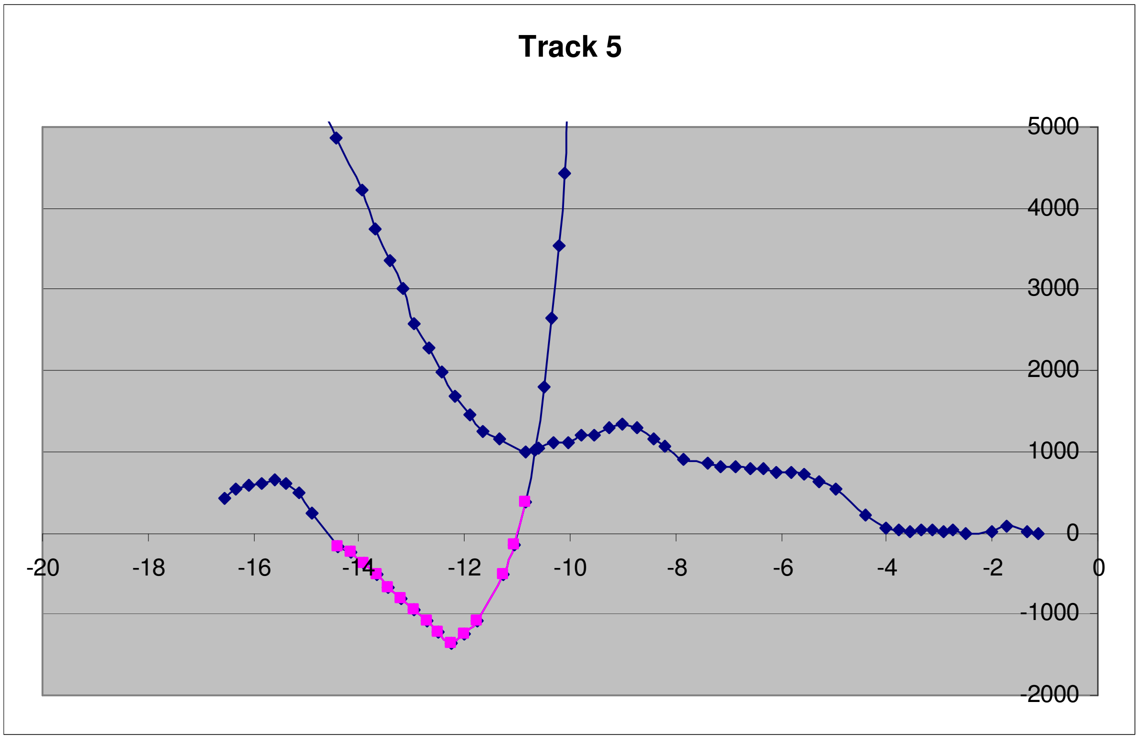


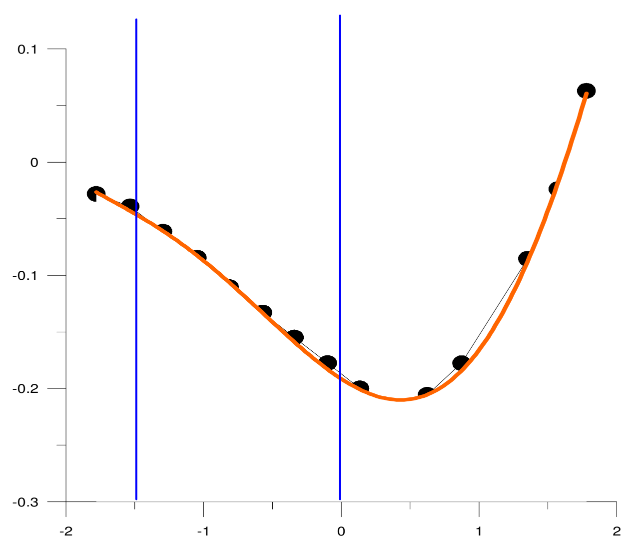

Track 4 B0
Blunder Angle
12.0
10.0
8.0
6.0
4.0
2.0
0.0
6 sec. 10° min
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
Relative Time (linear resampled piecewise seconds)

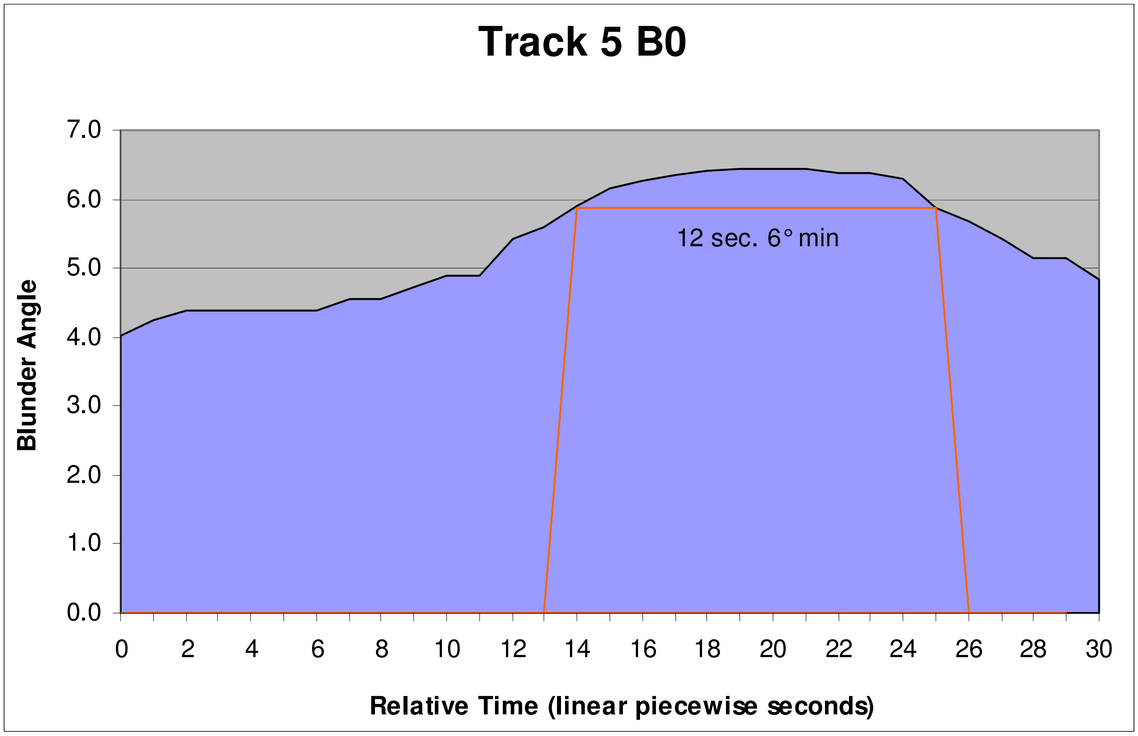
TRACK 5

- **AIRPORT:** XBBB
- **RUNWAY:** 36C
- **ANGLE:** 6º

Note: Track goes around then lands, blunder occurs on first attempt

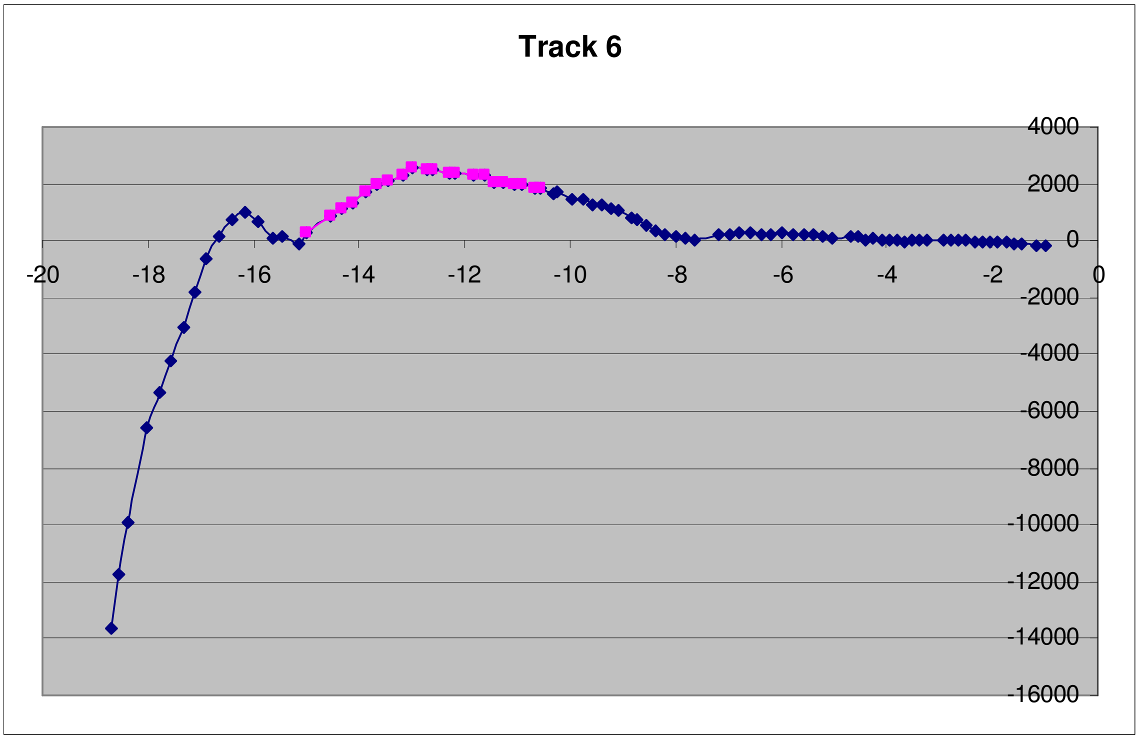


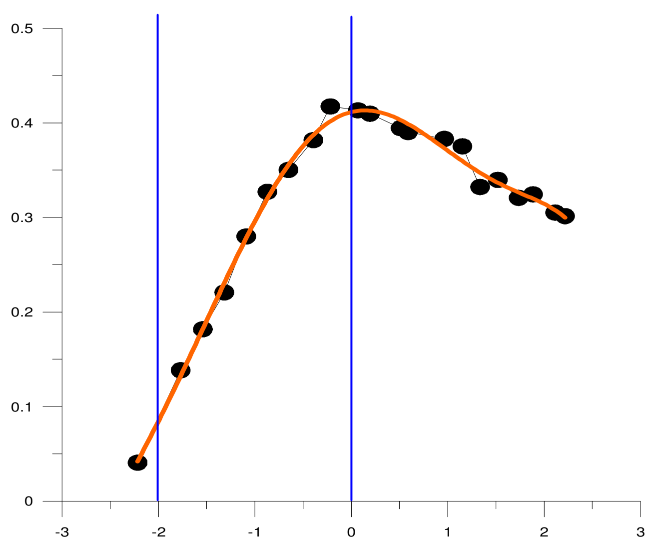


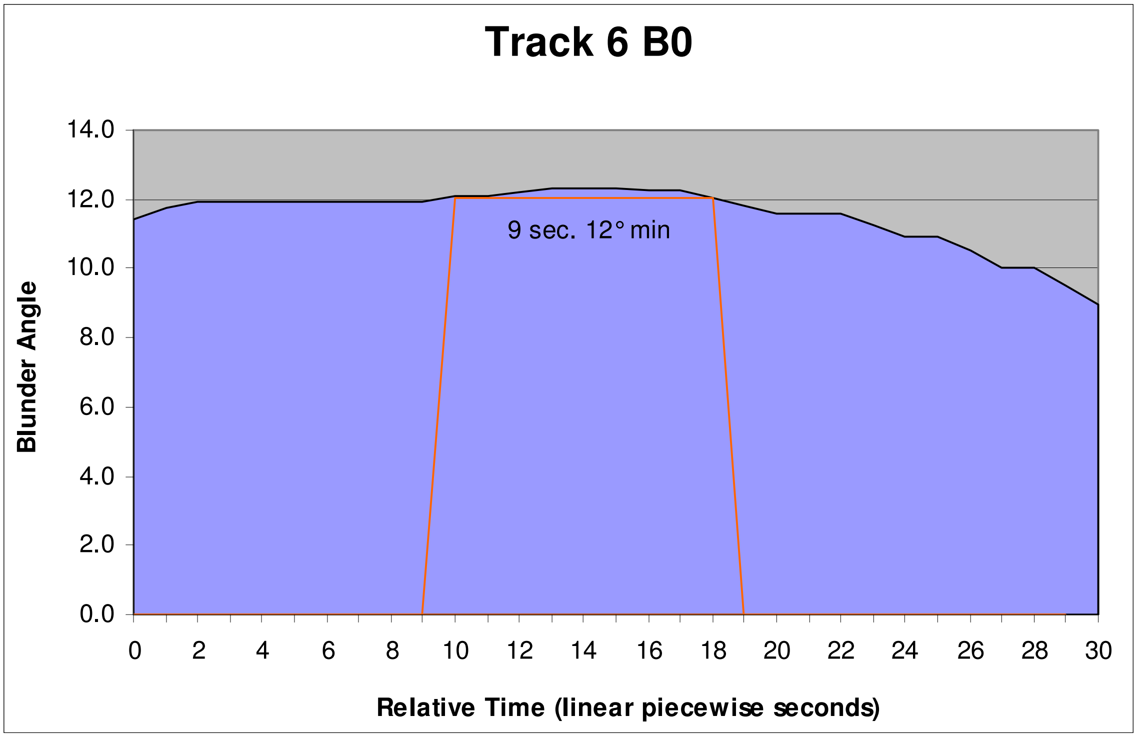

Track 5 B0
12 sec. 6° min
Blunder Angle
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
Relative Time (linear piecewise seconds)

TRACK 6

- **AIRPORT:** XCCC
- **RUNWAY:** 18R
- **ANGLE:** 12º



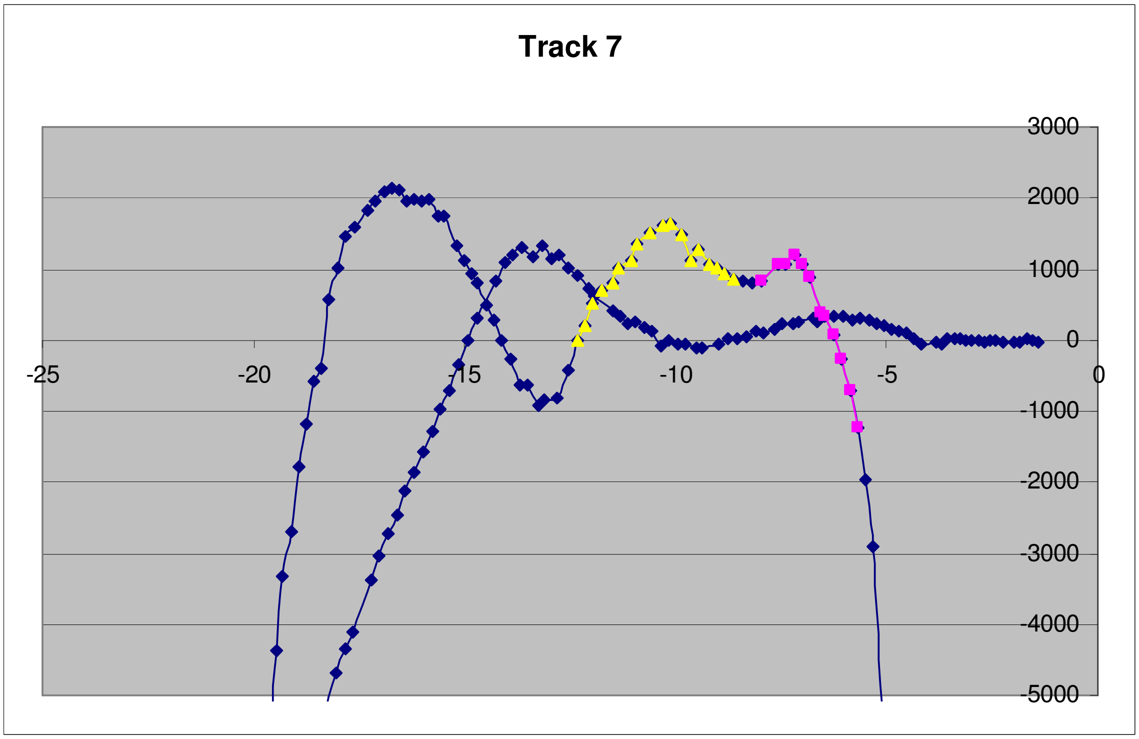


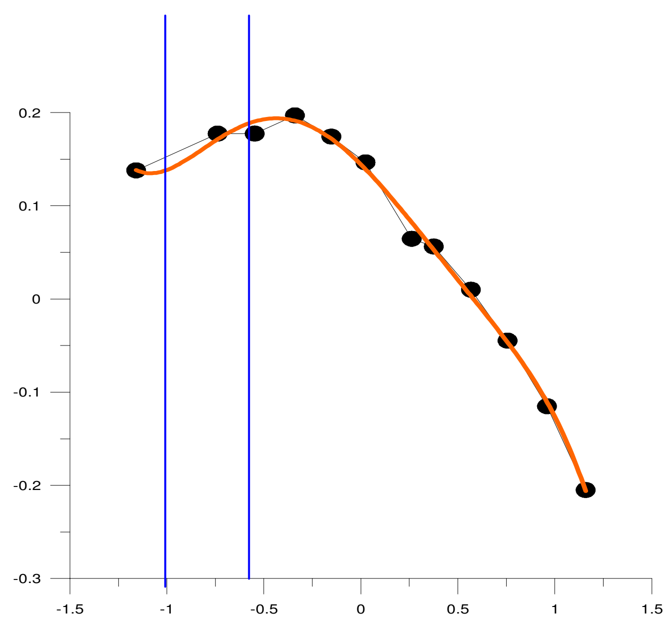

Track 6 B0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
Blunder Angle
9 sec. 12° min
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
Relative Time (linear piecewise seconds)

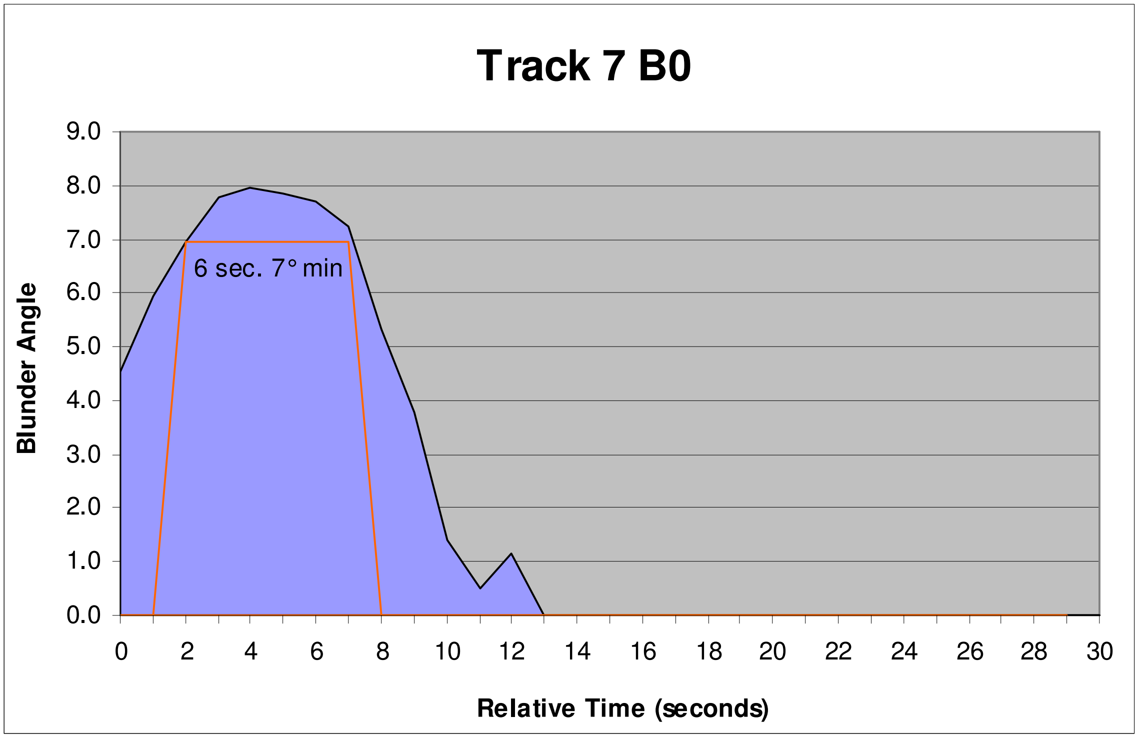
TRACK 7

- **AIRPORT:** XCCC
- **RUNWAY:** 18R
- **ANGLE:** 7º

Note: Track goes around then lands, blunder occurs on first attempt

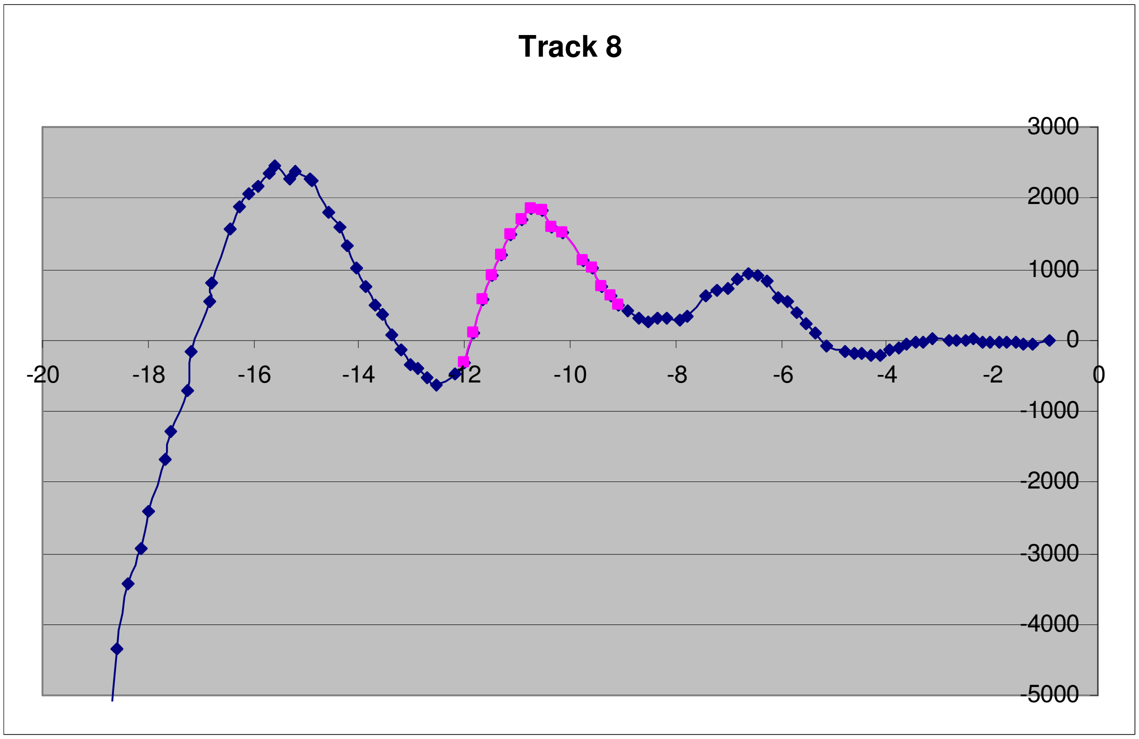


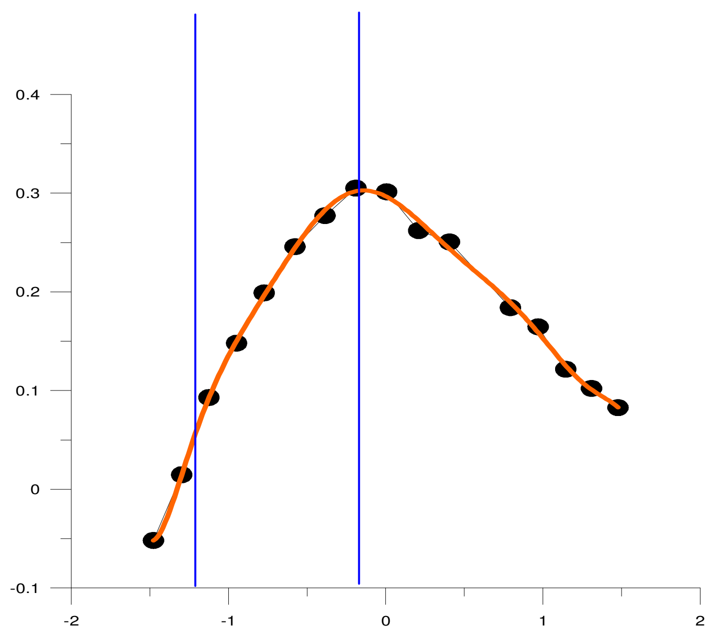


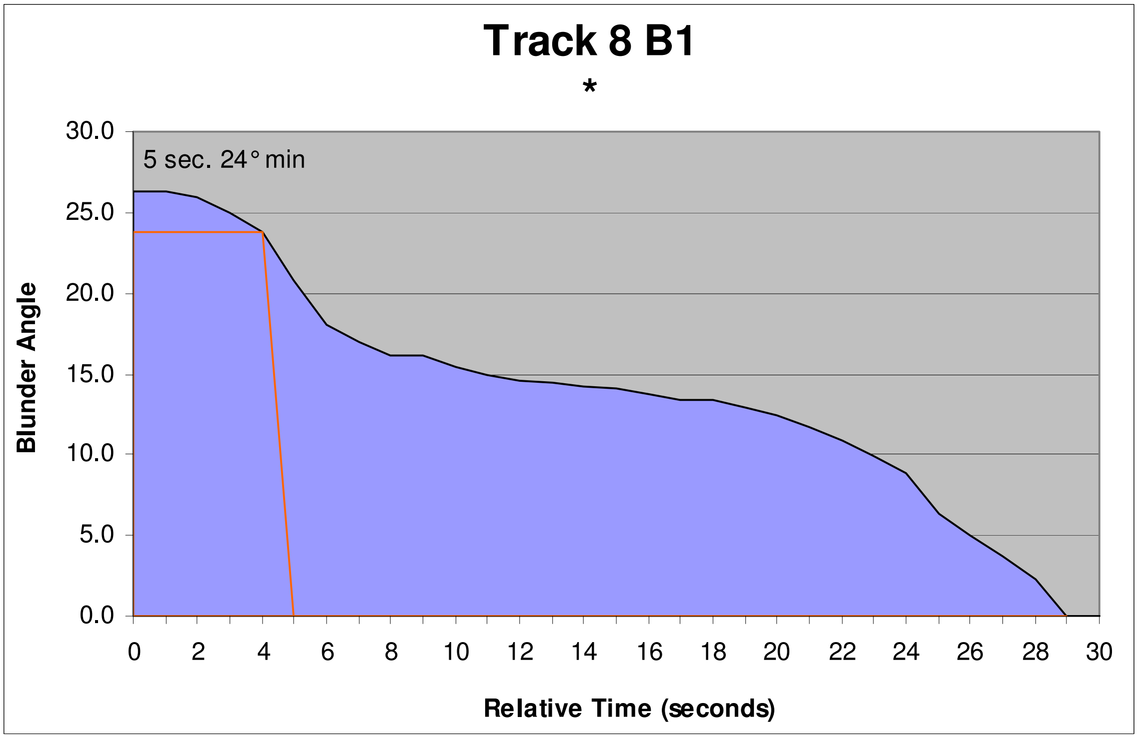

Track 7 B0
Blunder Angle
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
6 sec. 7° min
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30
Relative Time (seconds)

TRACK 8

- **AIRPORT:** XCCC
- **RUNWAY:** 18R
- **ANGLE:** 24º

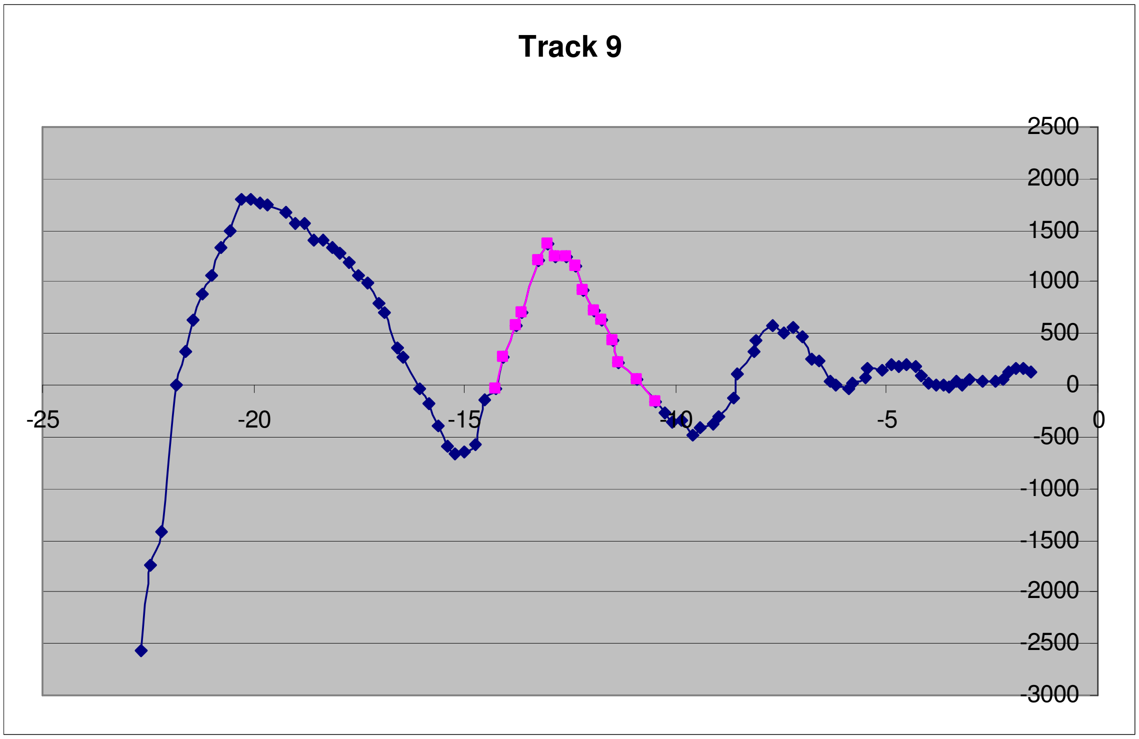


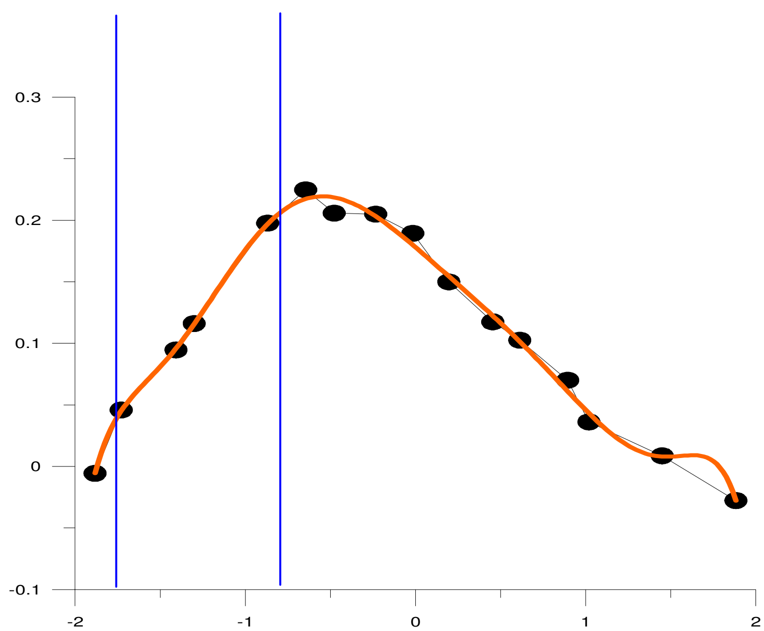


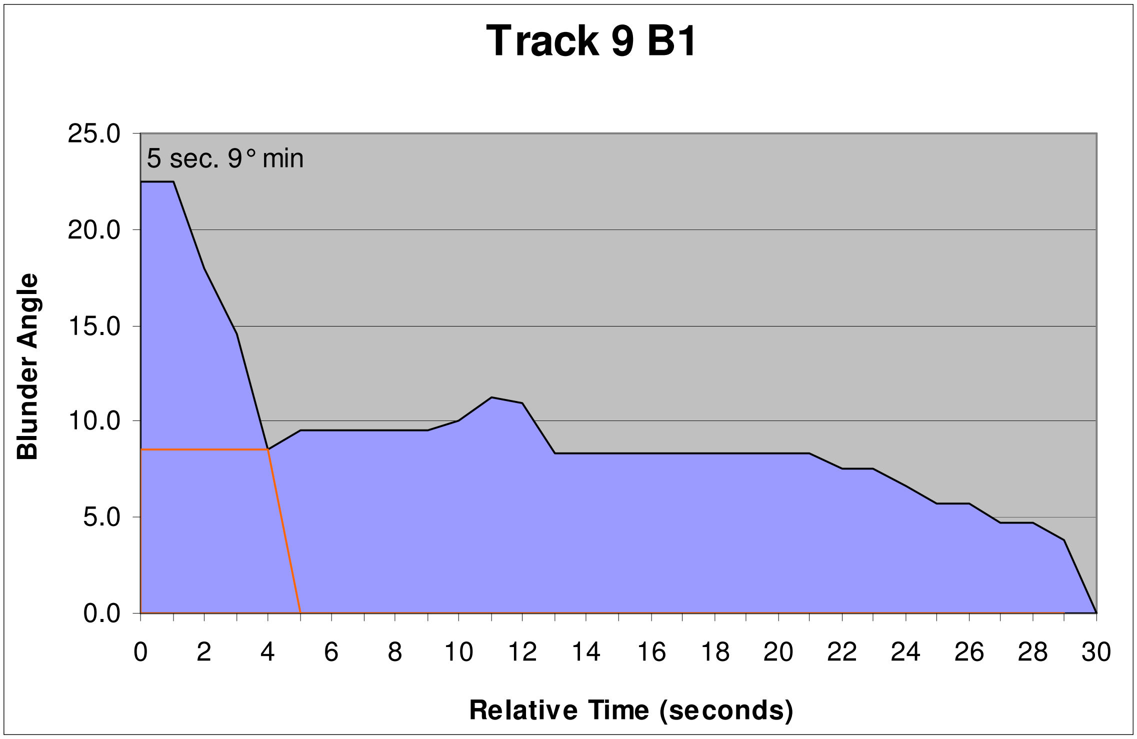

Track 8 B1
*
5 sec. 24° min
Blunder Angle
30.0
25.0
20.0
15.0
10.0
5.0
0.0
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30
Relative Time (seconds)

TRACK 9

- **AIRPORT:** XDDD
- **RUNWAY:** 18R
- **ANGLE:** 9º

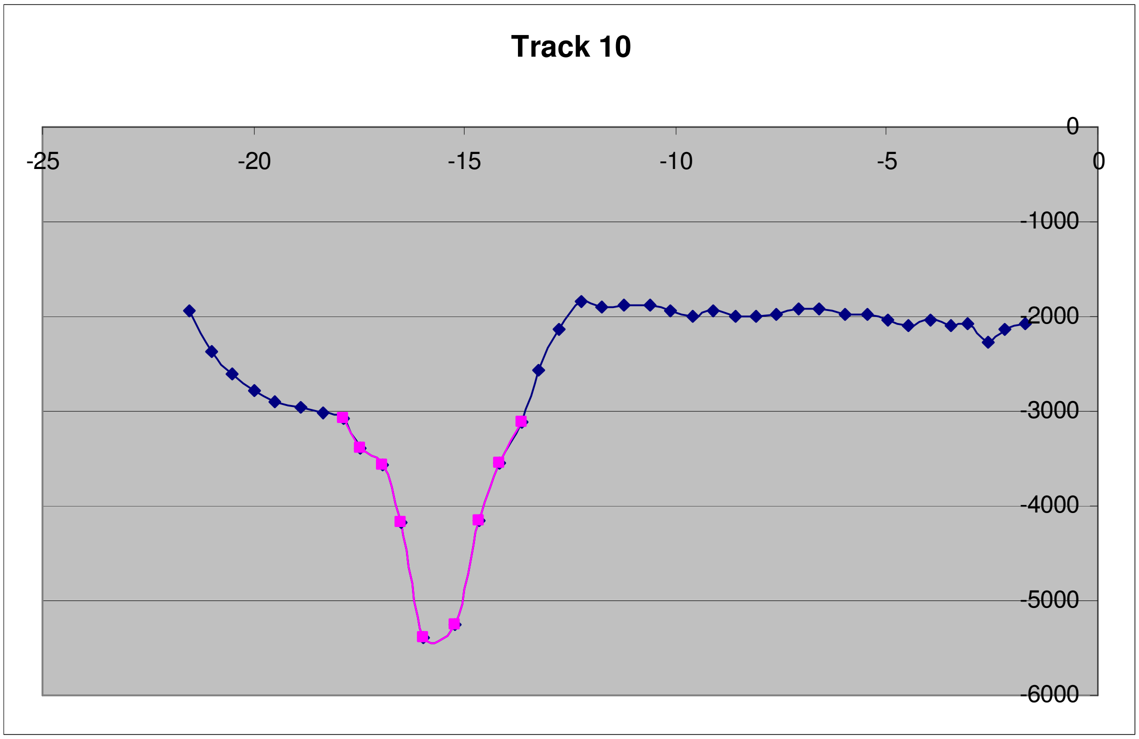


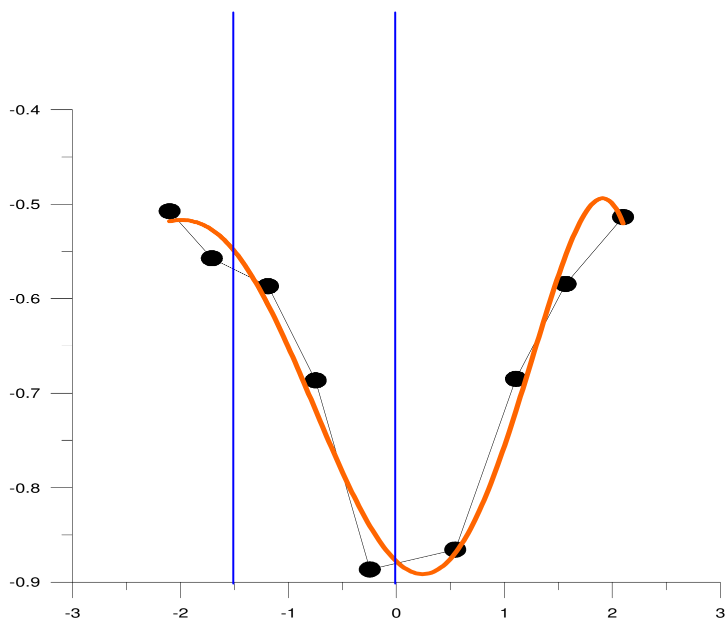


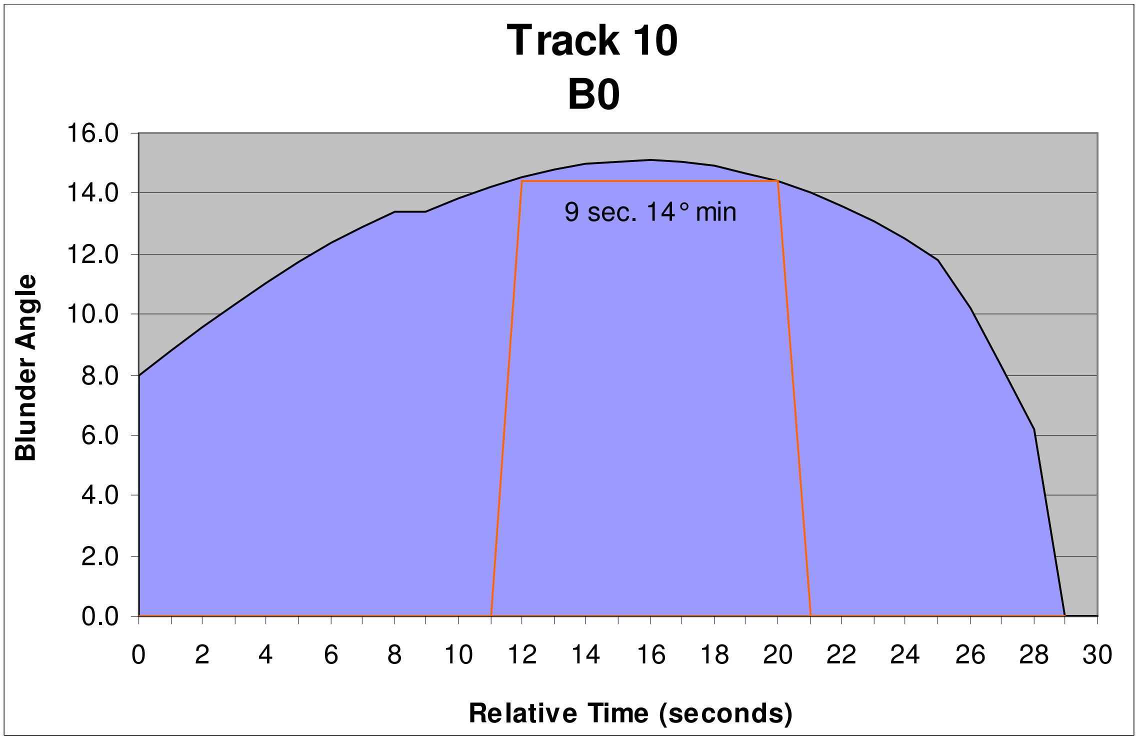

Track 9 B1
5 sec. 9° min
25.0
20.0
15.0
10.0
5.0
0.0
Blunder Angle
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
Relative Time (seconds)

TRACK 10

- **AIRPORT:** XEEE
- **RUNWAY:** 34L
- **ANGLE:** 14º

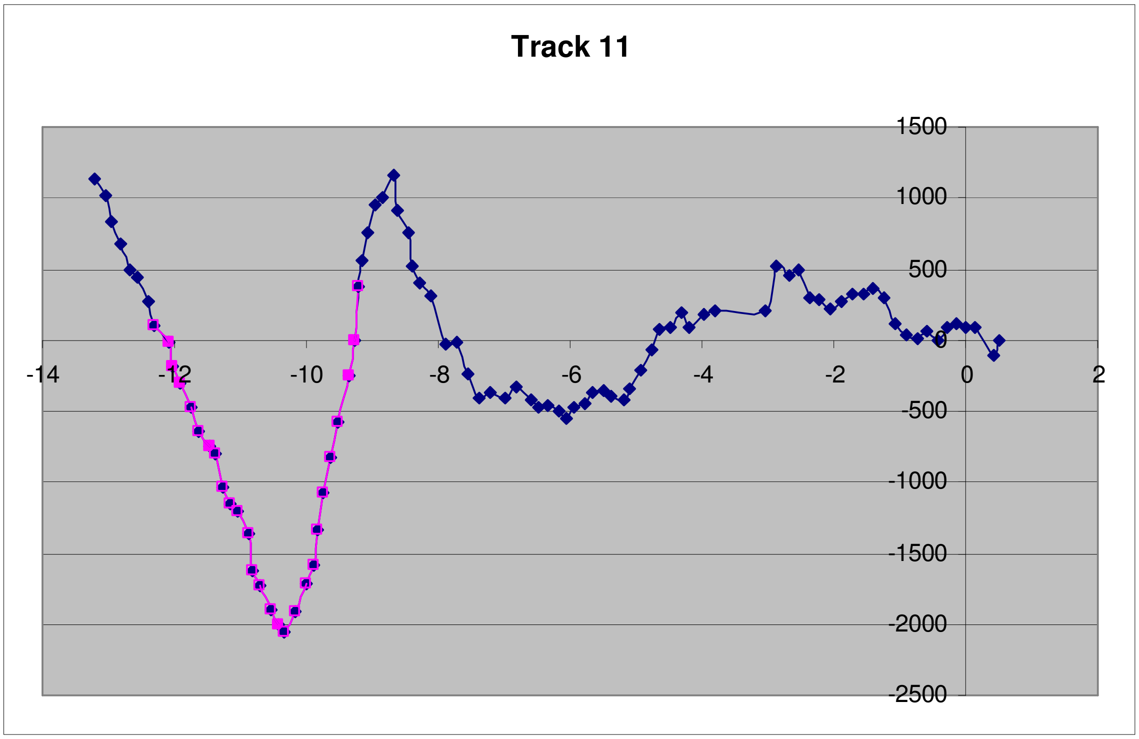


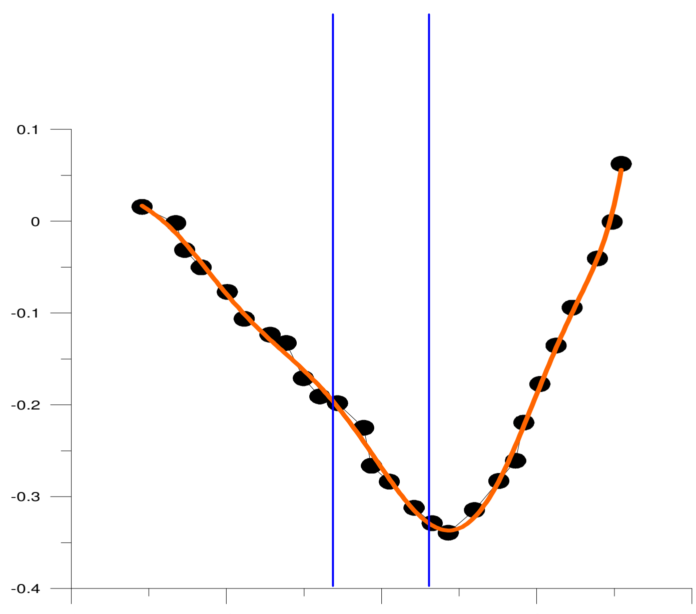


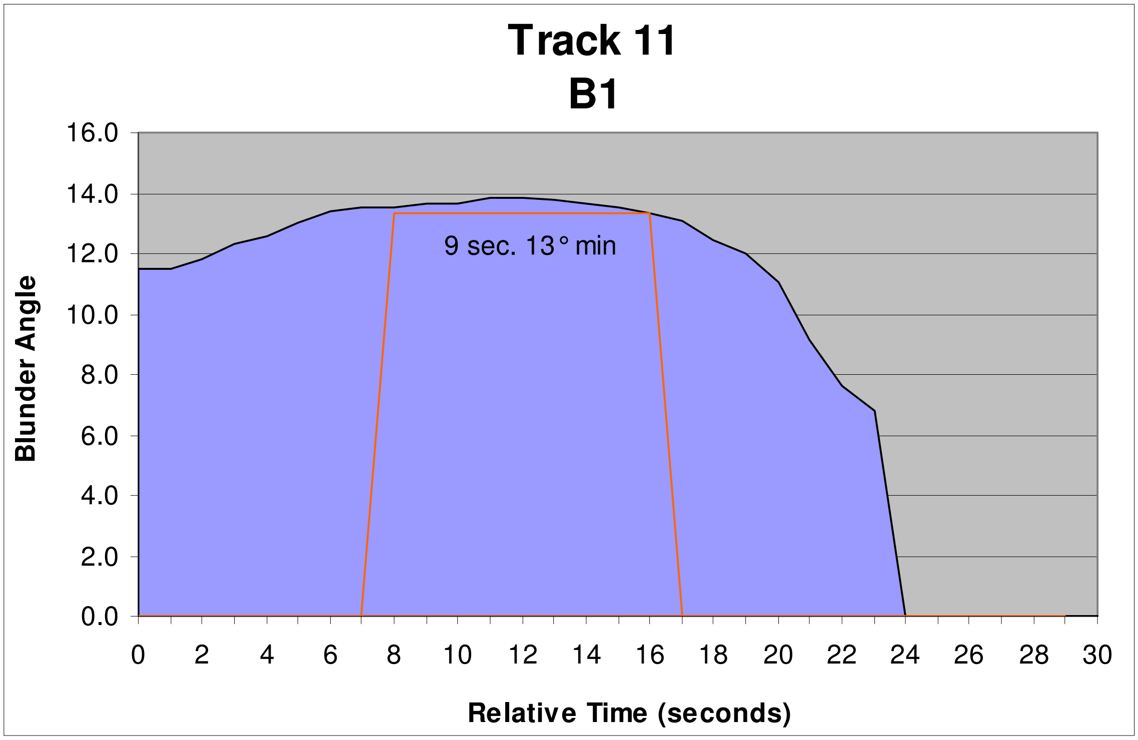

Track 10
B0
9 sec. 14° min
Blunder Angle
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
Relative Time (seconds)

TRACK 11

- **AIRPORT:** XFFF
- **RUNWAY:** 19L
- **ANGLE:** 13º

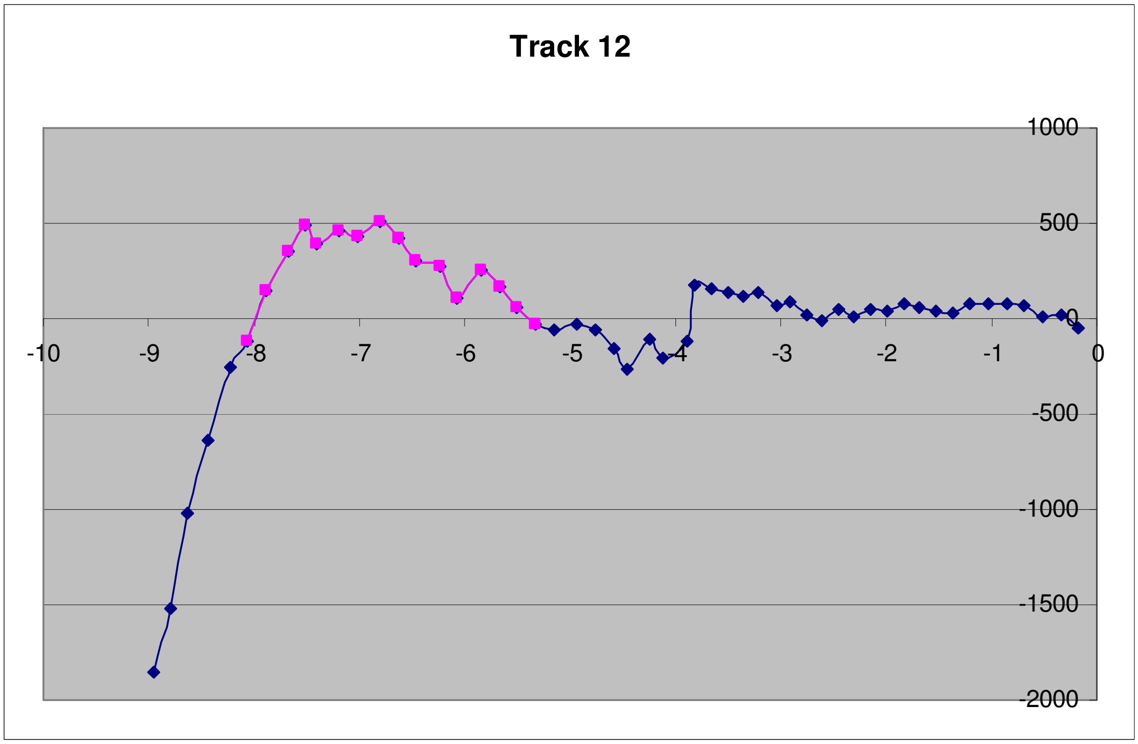


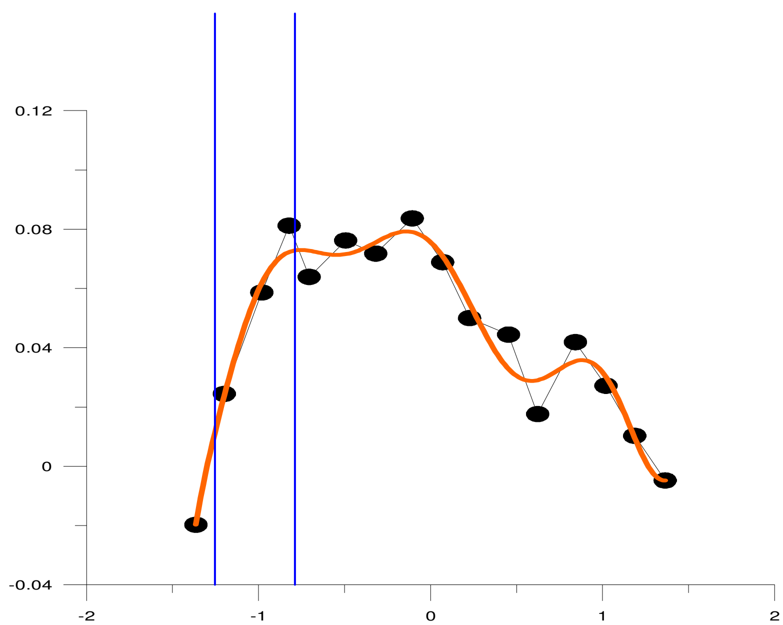


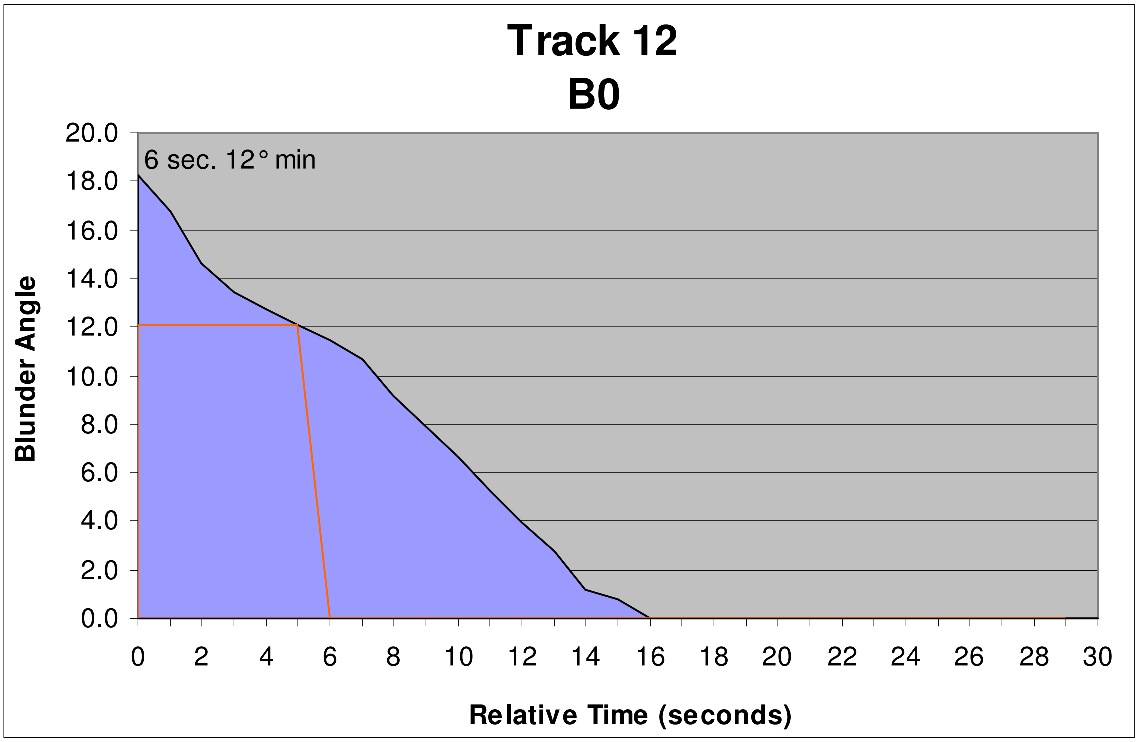

Track 11
B1
9 sec. 13° min
Blunder Angle
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
Relative Time (seconds)

TRACK 12

- **AIRPORT:** XFFF
- **RUNWAY:** 19L
- **ANGLE:** 12º

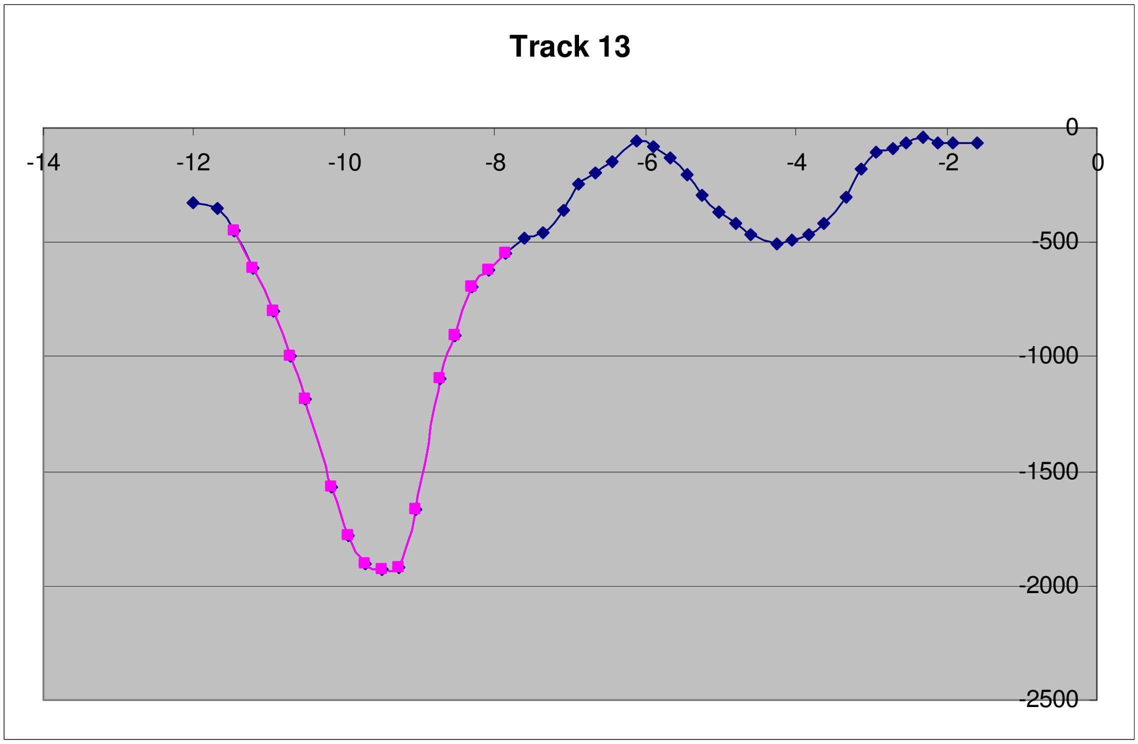


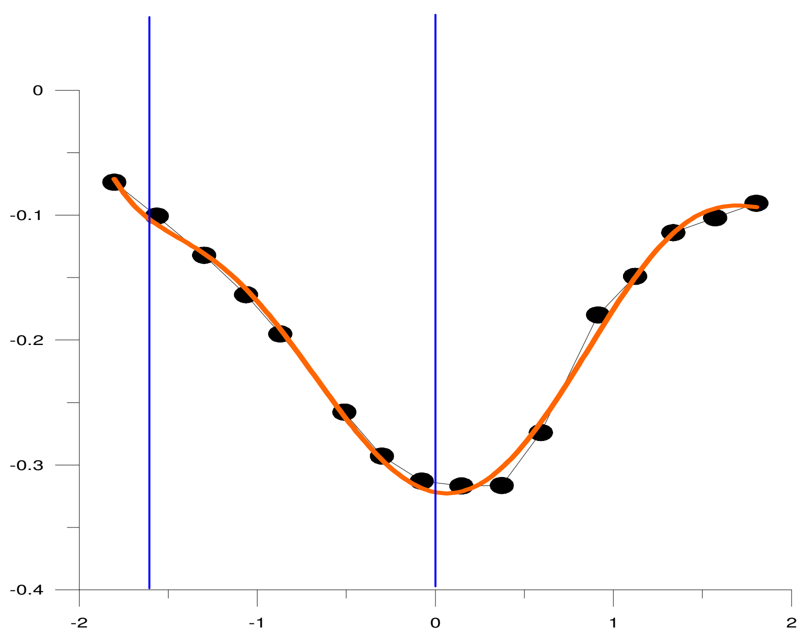


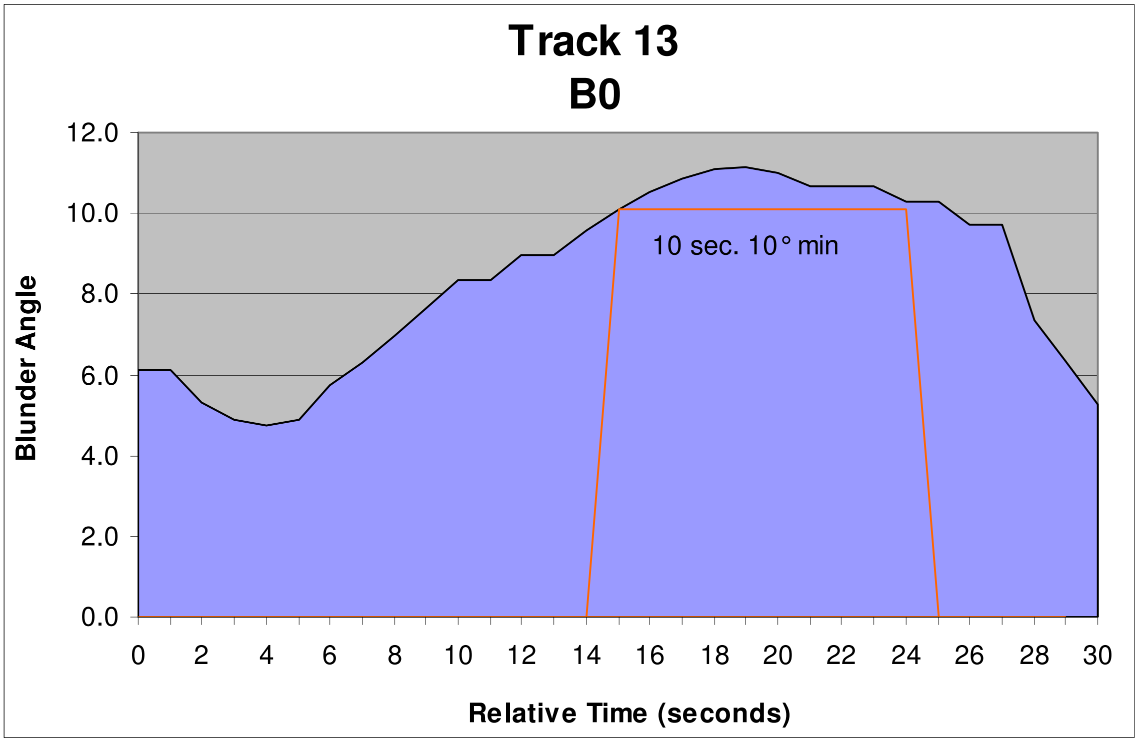

Track 12
B0
6 sec. 12° min
Blunder Angle
20.0
18.0
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
Relative Time (seconds)

TRACK 13

- **AIRPORT:** XGGG
- **RUNWAY:** 26L
- **ANGLE:** 10º

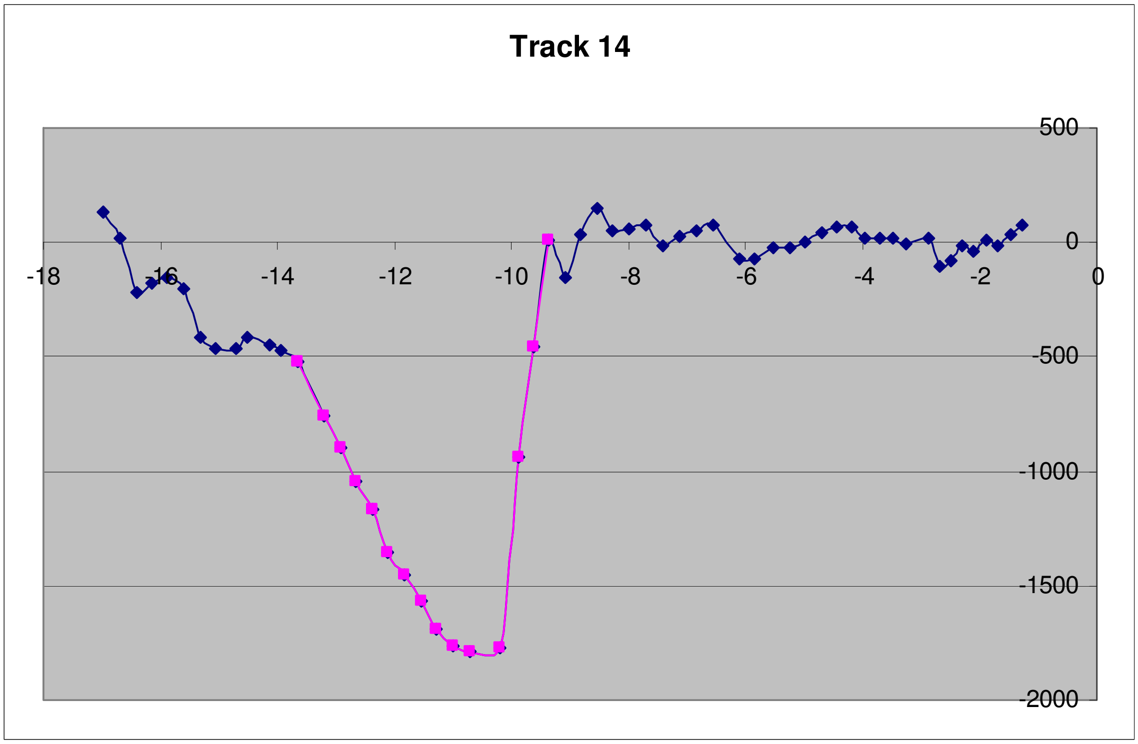


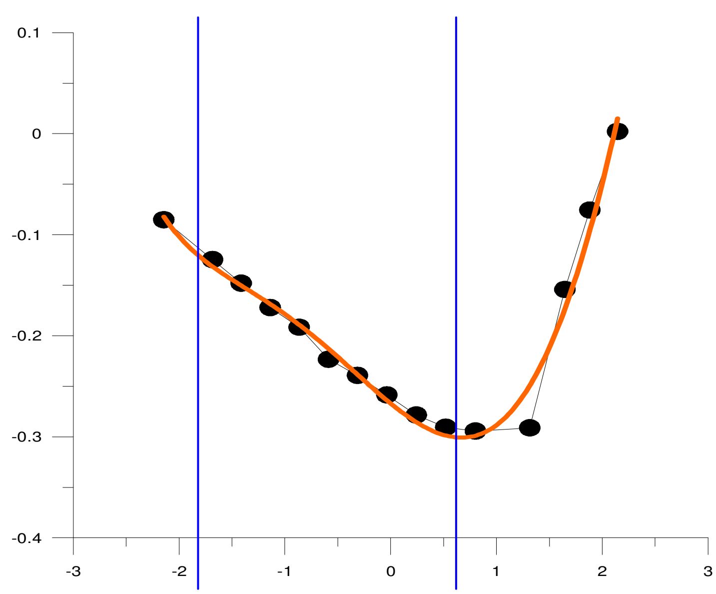


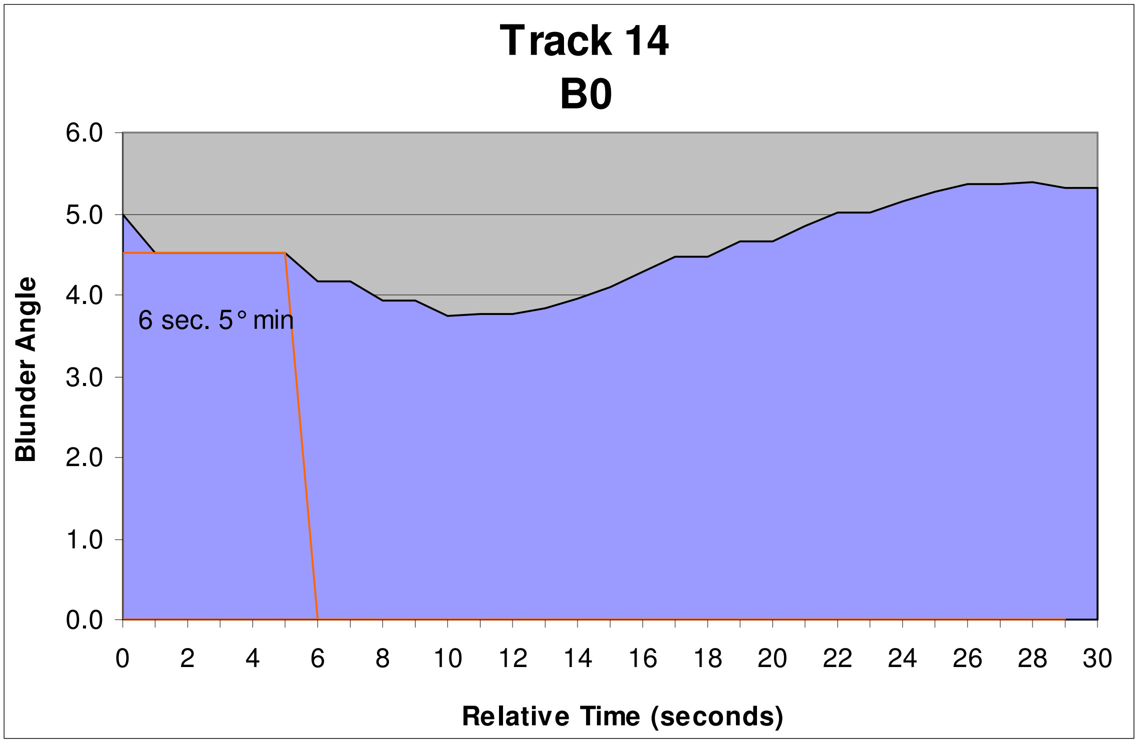

Track 13
B0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
Blunder Angle
10 sec. 10° min
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
Relative Time (seconds)

TRACK 14

- **AIRPORT:** XGGG
- **RUNWAY:** 27
- **ANGLE: 5º**

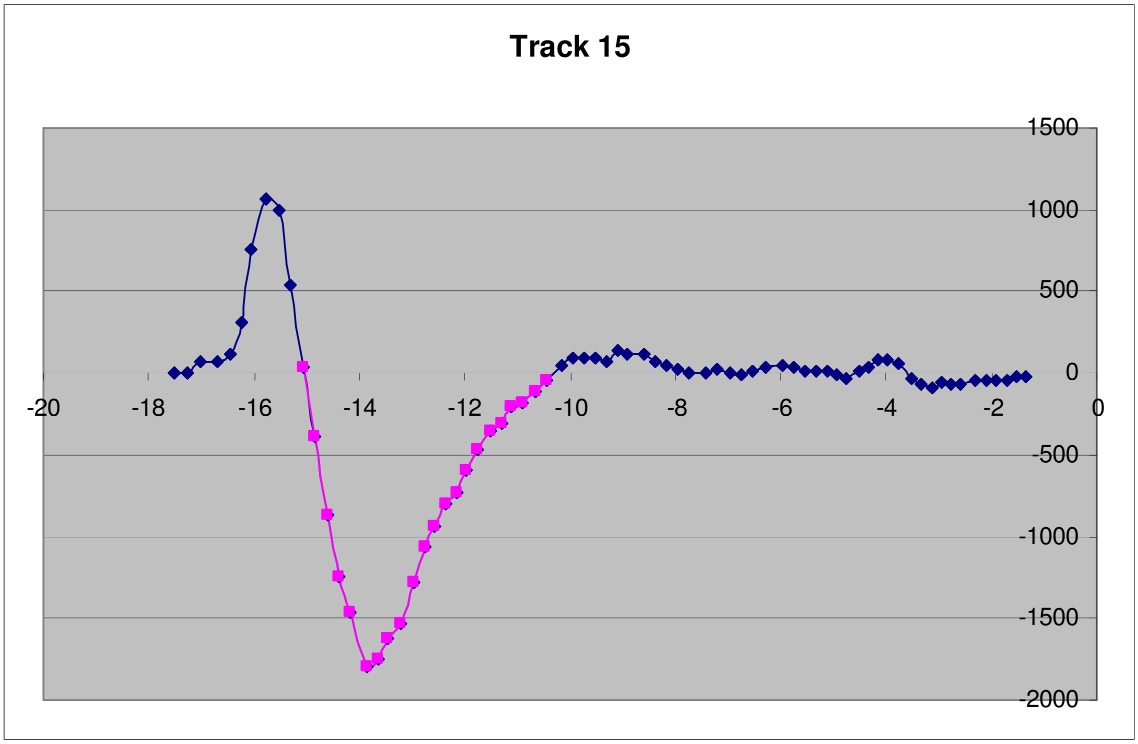


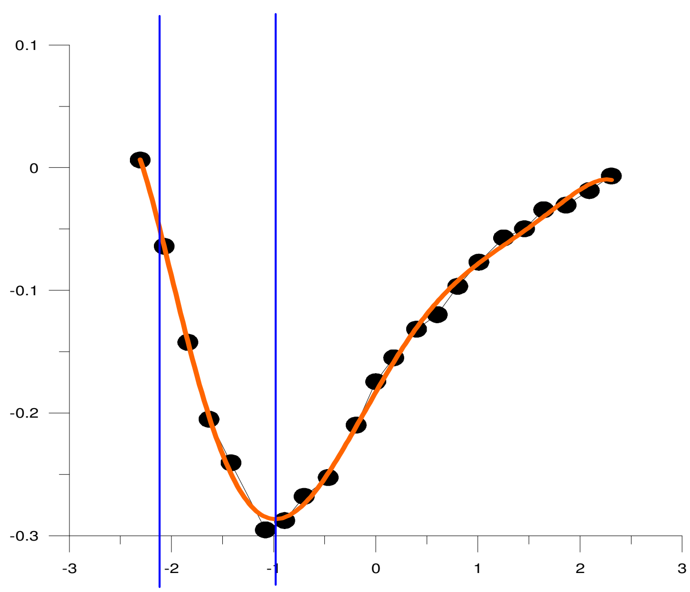


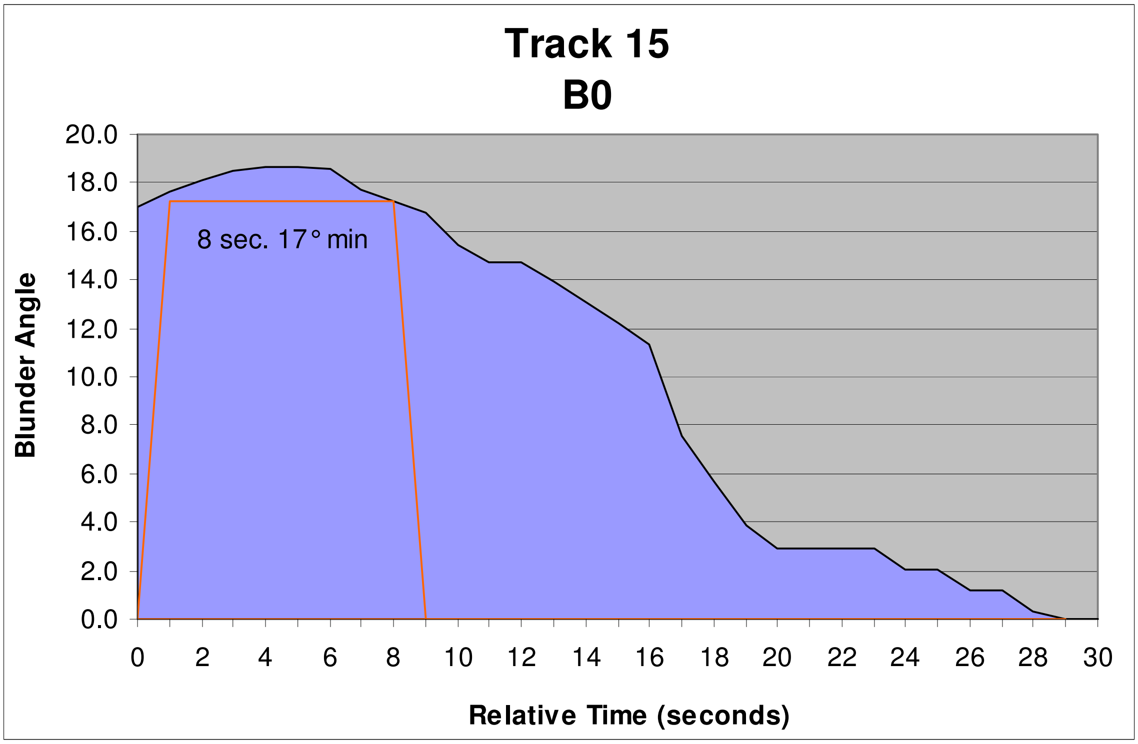

Track 14
B0
Blunder Angle
6.0
5.0
4.0
3.0
2.0
1.0
0.0
6 sec. 5° min
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
Relative Time (seconds)

TRACK 15

- **AIRPORT:** XGGG
- **RUNWAY:** 26L
- **ANGLE:** 17º

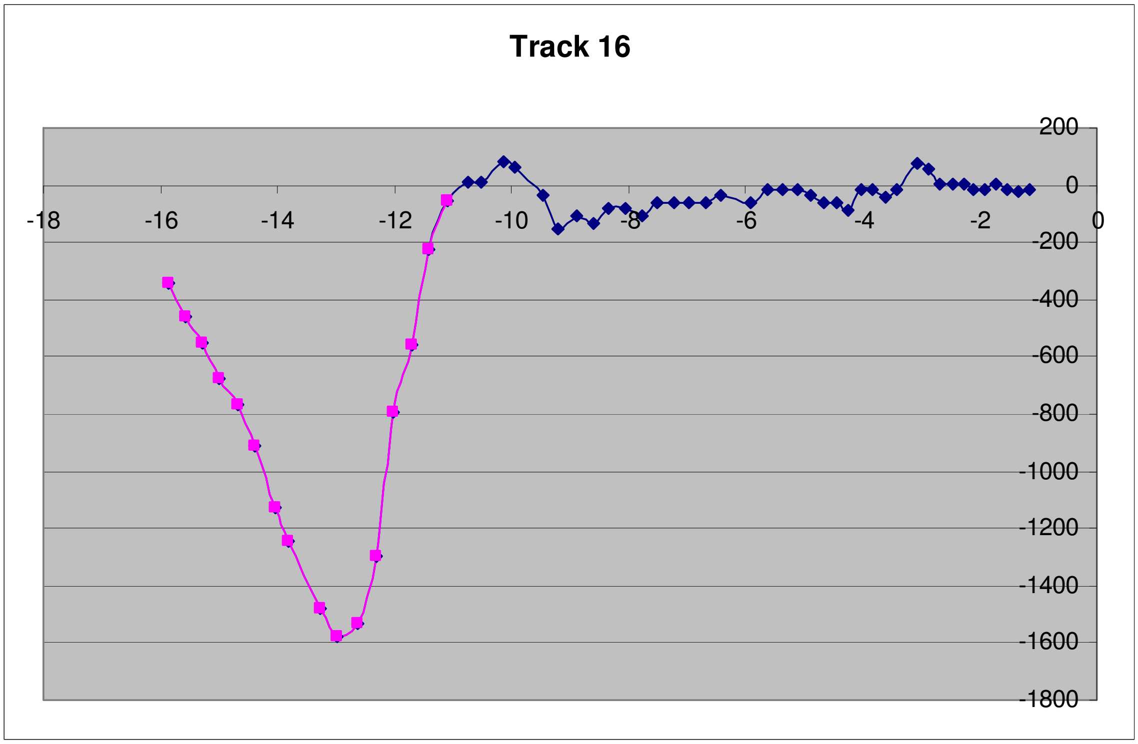


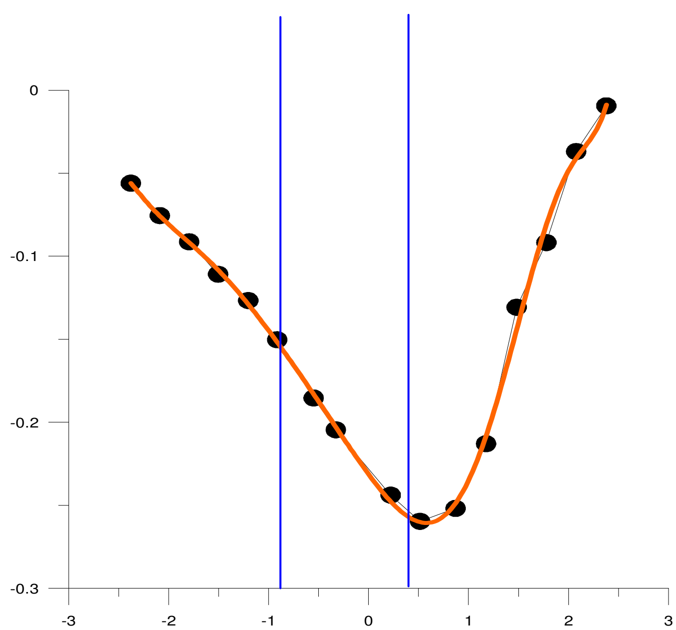


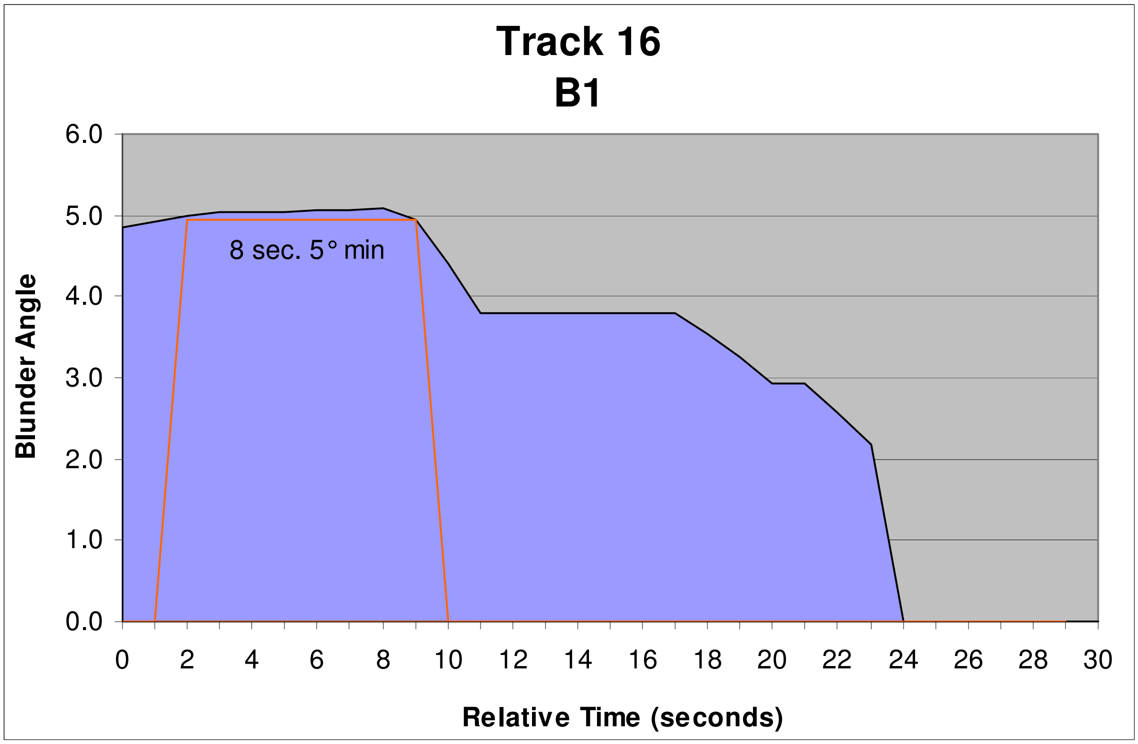

Track 15
B0
Blunder Angle
20.0
18.0
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
8 sec. 17° min
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
Relative Time (seconds)

TRACK 16

- **AIRPORT:** XGGG
- **RUNWAY:** 08L
- **ANGLE:** 5º

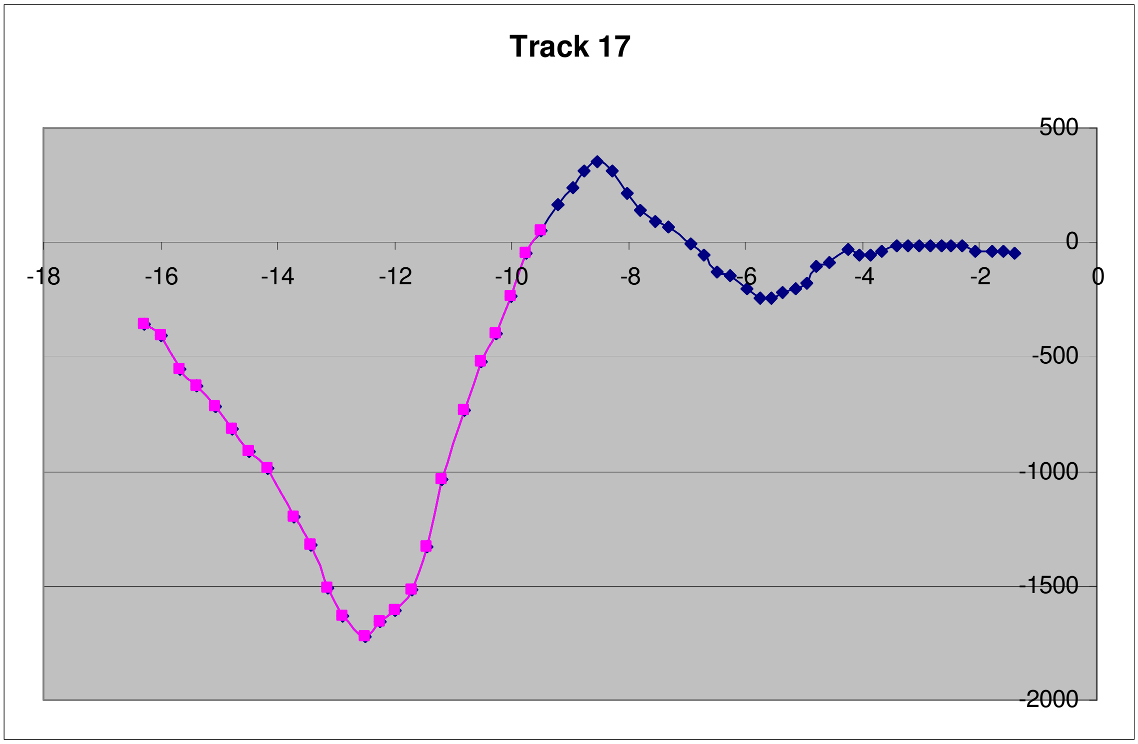


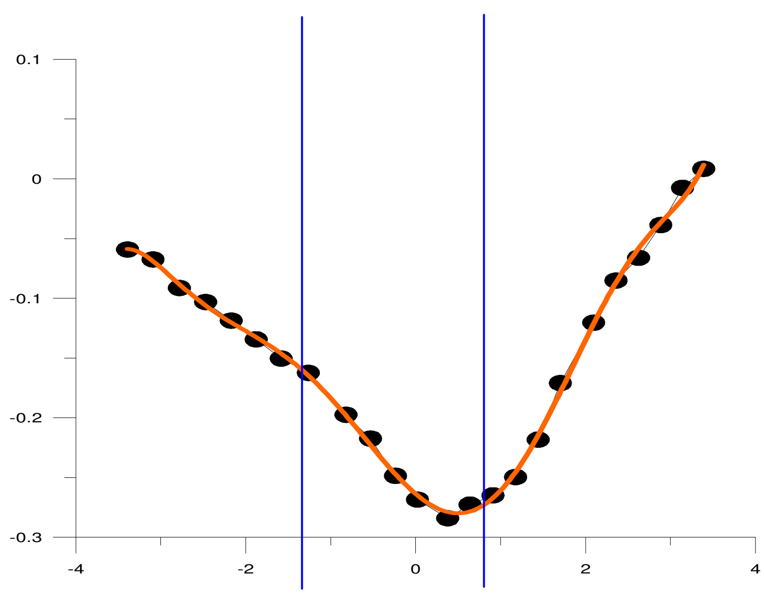


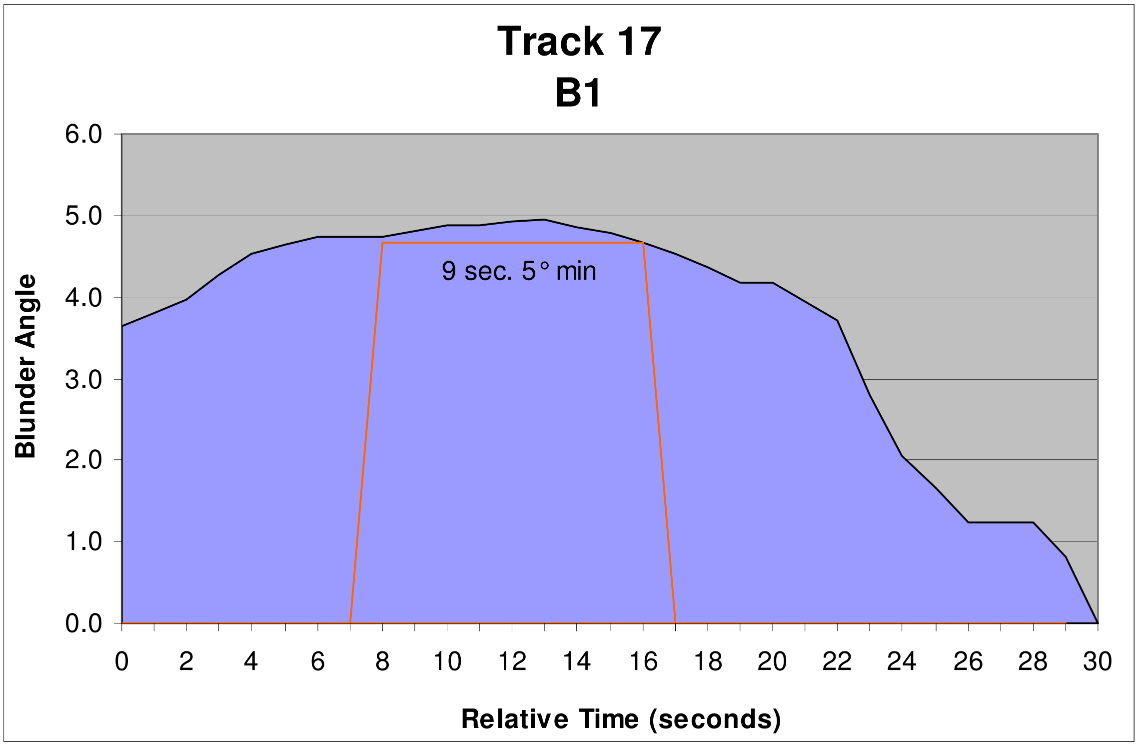

Track 16
B1
8 sec. 5° min
Blunder Angle
6.0
5.0
4.0
3.0
2.0
1.0
0.0
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
Relative Time (seconds)

TRACK 17

- **AIRPORT:** XGGG
- **RUNWAY:** 26L
- **ANGLE:** 5º

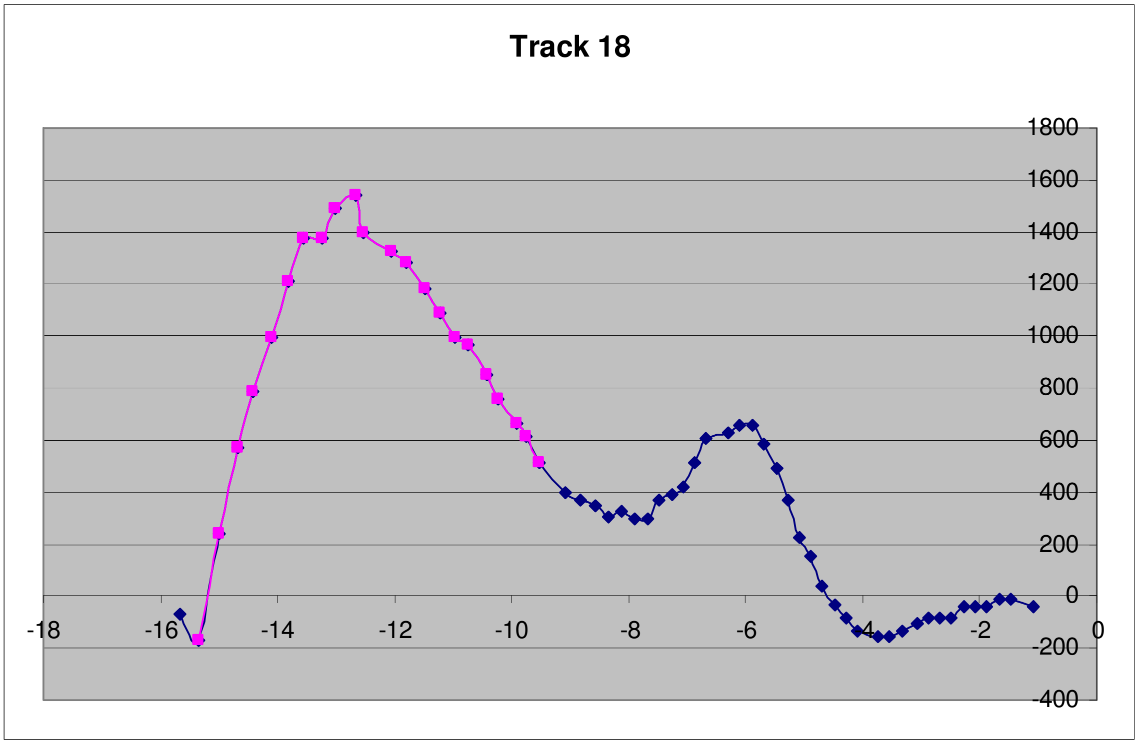


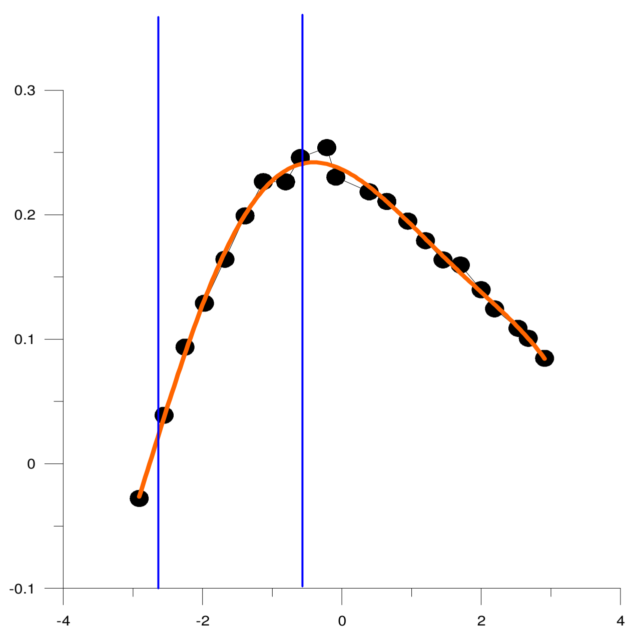


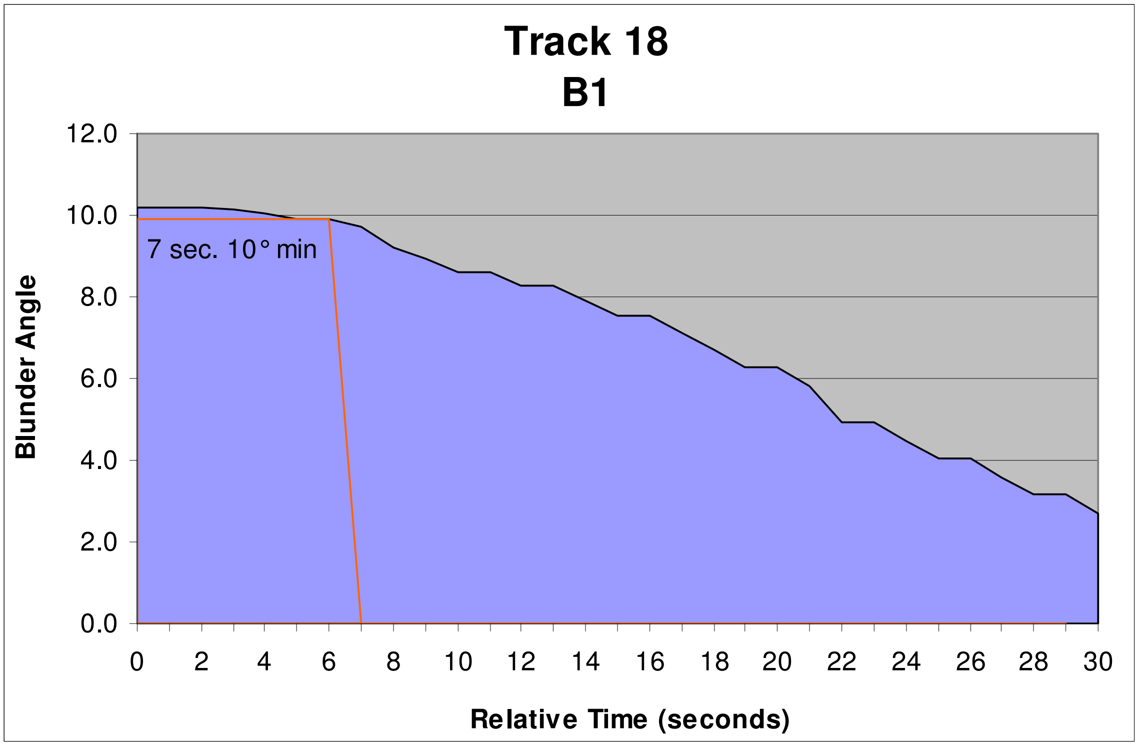

Track 17
B1
Blunder Angle
9 sec. 5° min
Relative Time (seconds)
6.0
5.0
4.0
3.0
2.0
1.0
0.0
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30

TRACK 18

- **AIRPORT:** XGGG
- **RUNWAY:** 08R
- **ANGLE:** 10º

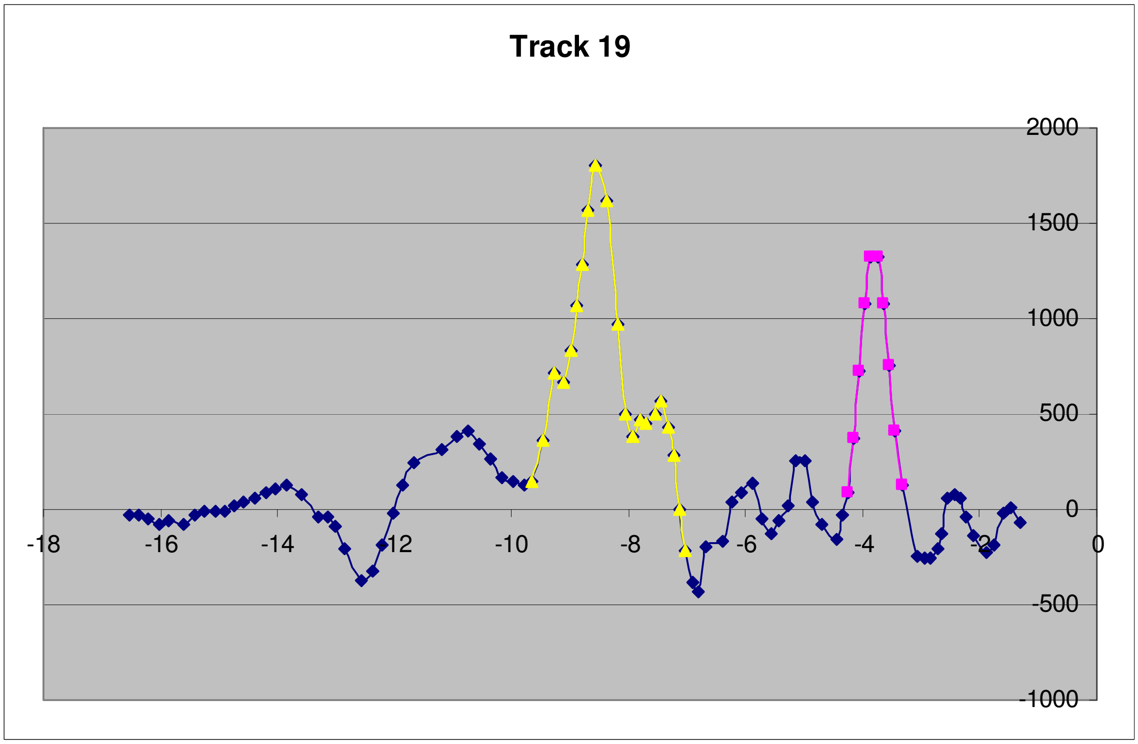


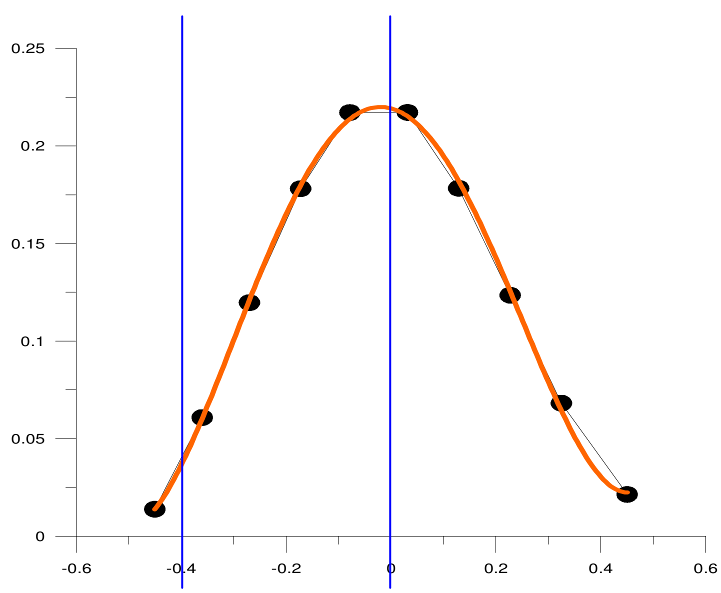


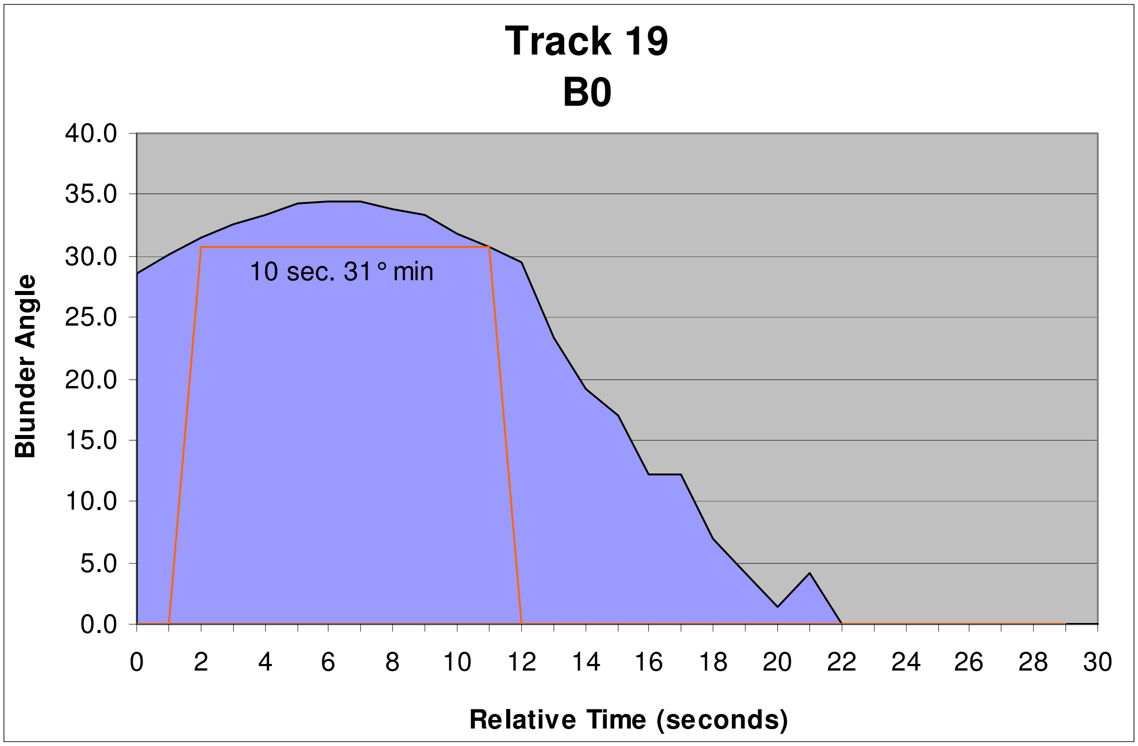

Track 18
B1
Blunder Angle
Relative Time (seconds)
7 sec. 10° min
12.0
10.0
8.0
6.0
4.0
2.0
0.0
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30

TRACK 19

- **AIRPORT:** XGGG
- **RUNWAY:** 26R
- **ANGLE:** 31º

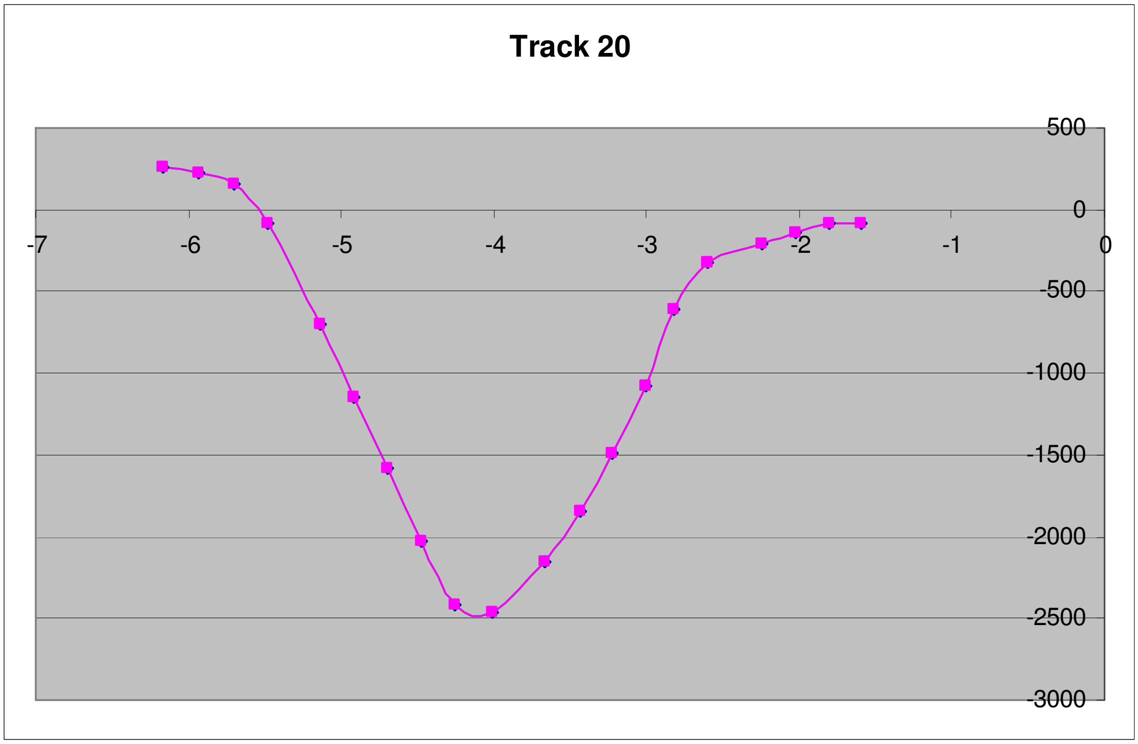


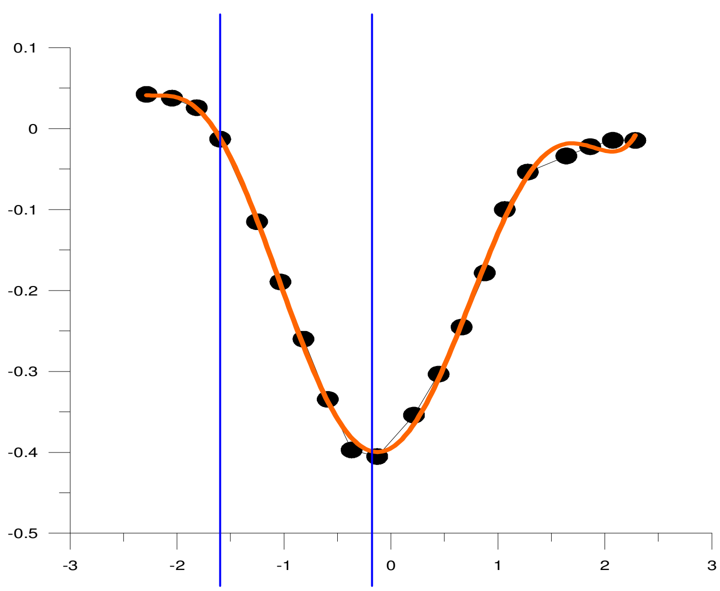


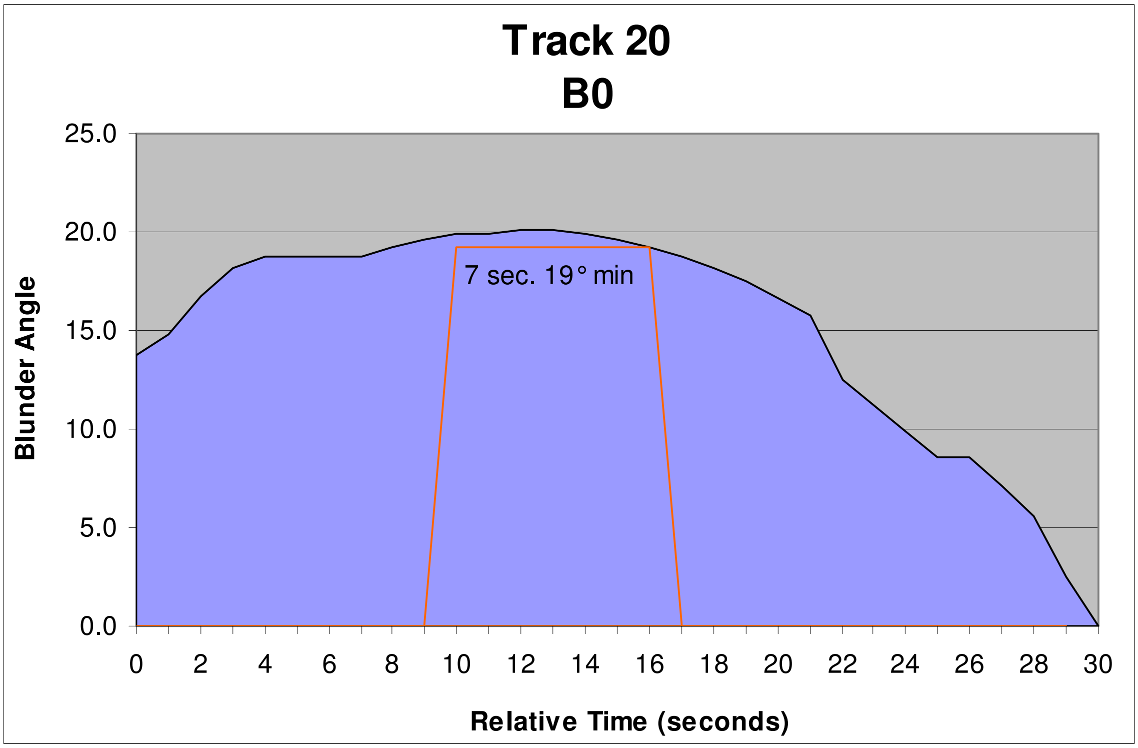

Track 19
B0
Blunder Angle
40.0
35.0
30.0
25.0
20.0
15.0
10.0
5.0
0.0
10 sec. 31 ° min
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
Relative Time (seconds)

TRACK 20

- **AIRPORT:** XGGG
- **RUNWAY:** 26L
- **ANGLE:** 19º

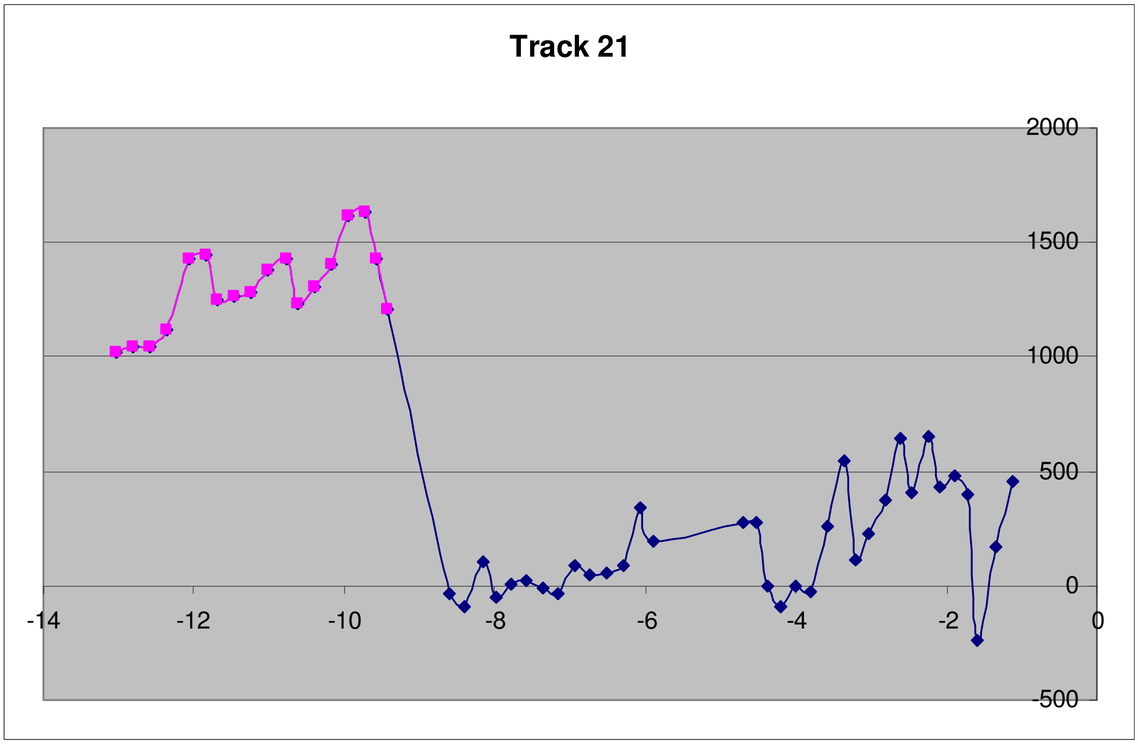


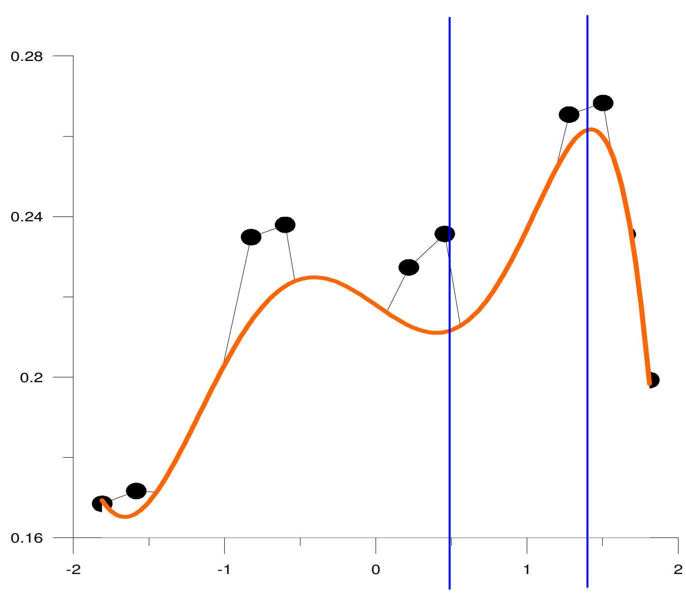


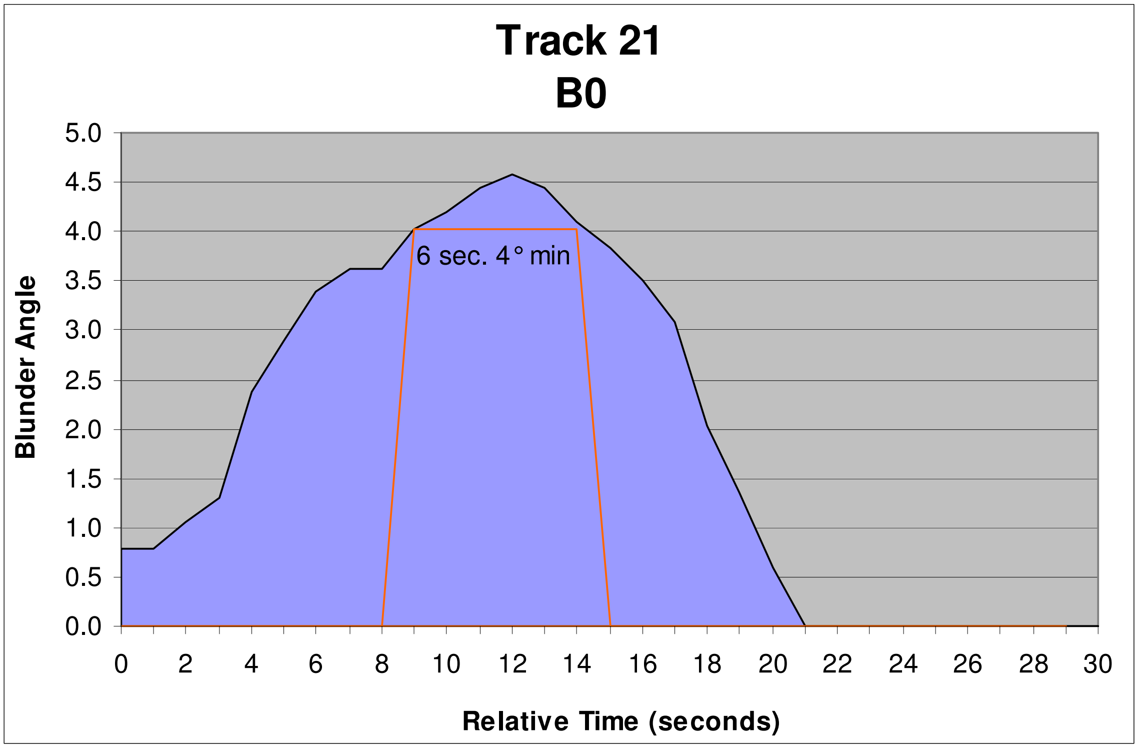

Track 20
B0
7 sec. 19° min
Blunder Angle
25.0
20.0
15.0
10.0
5.0
0.0
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
Relative Time (seconds)

TRACK 21

- **AIRPORT:** XHHH
- **RUNWAY:** 24L
- **ANGLE:** 4º

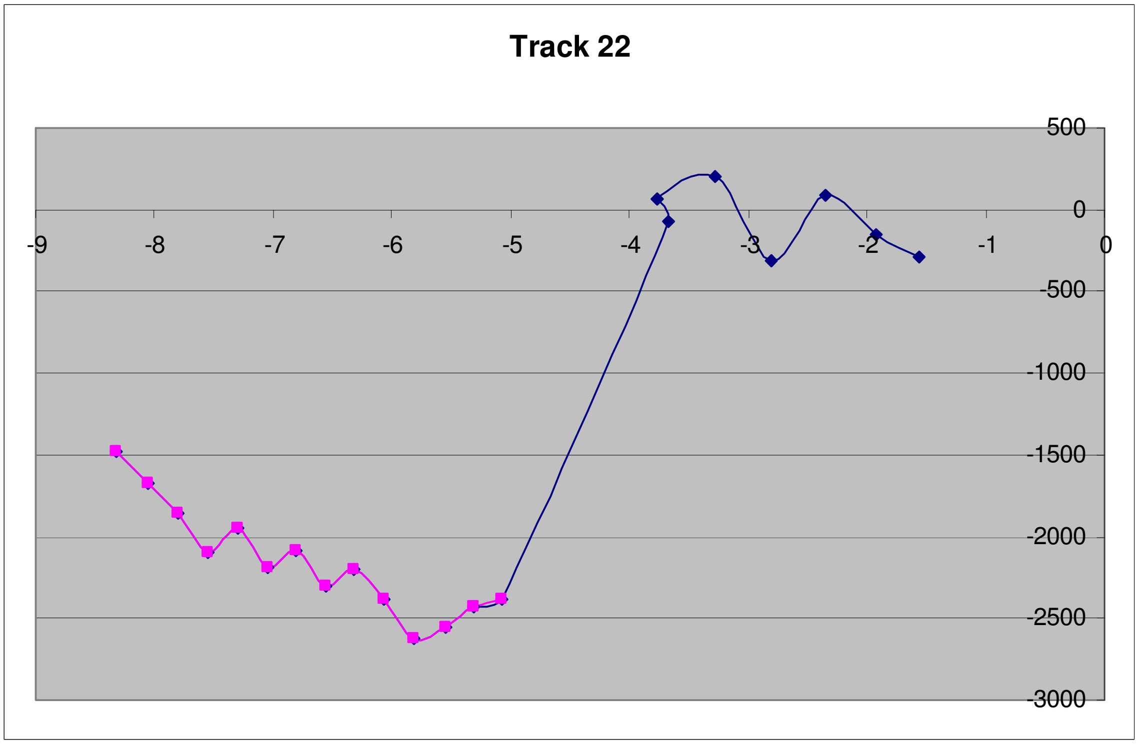


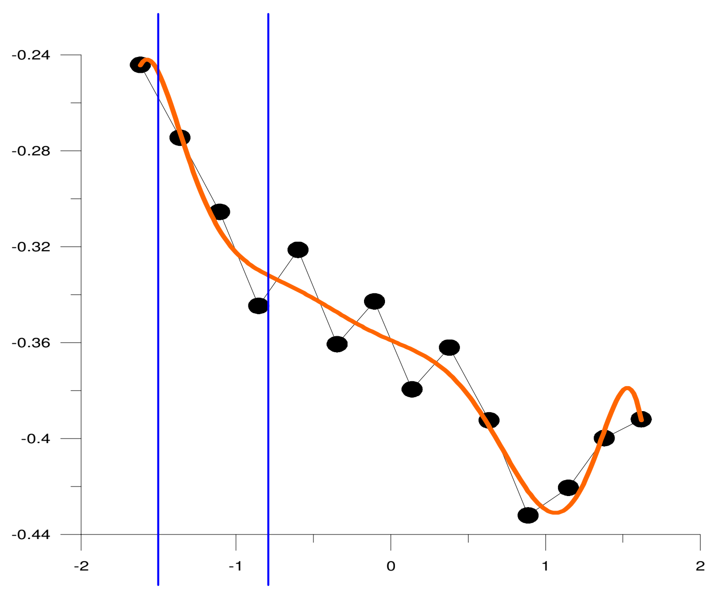


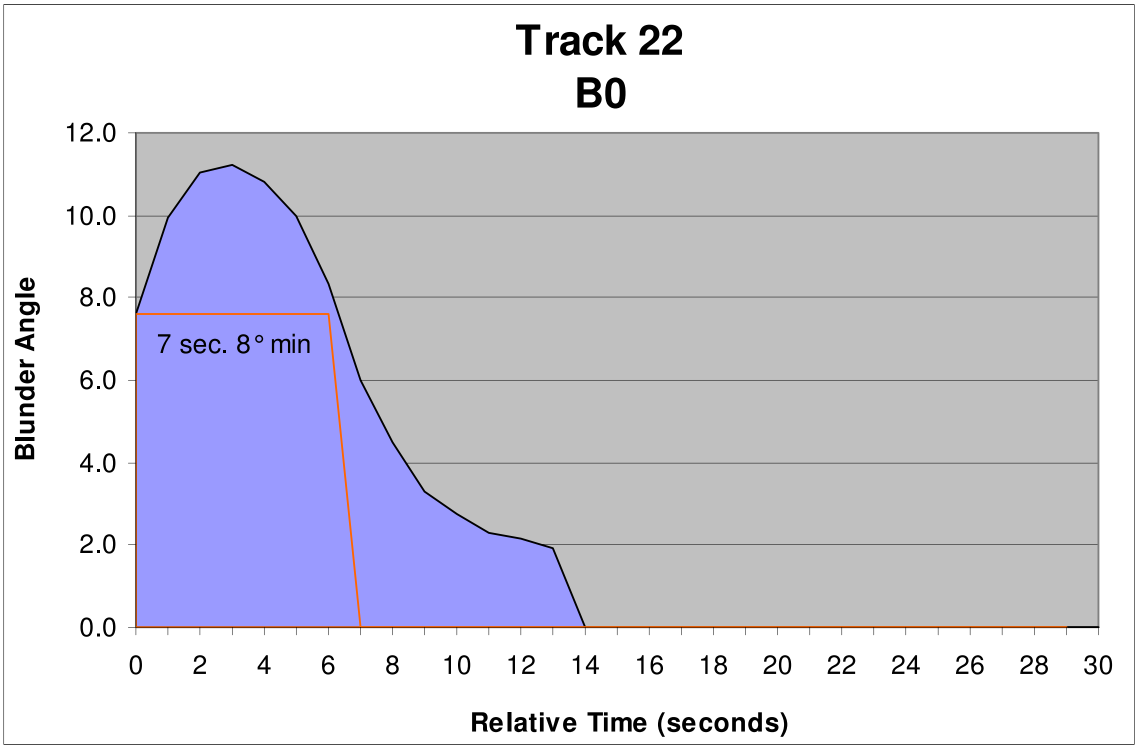

Track 21
B0
Blunder Angle
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
6 sec. 4° min
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
Relative Time (seconds)

TRACK 22

- **AIRPORT:** XHHH
- **RUNWAY:** 25L
- **ANGLE:** 8º

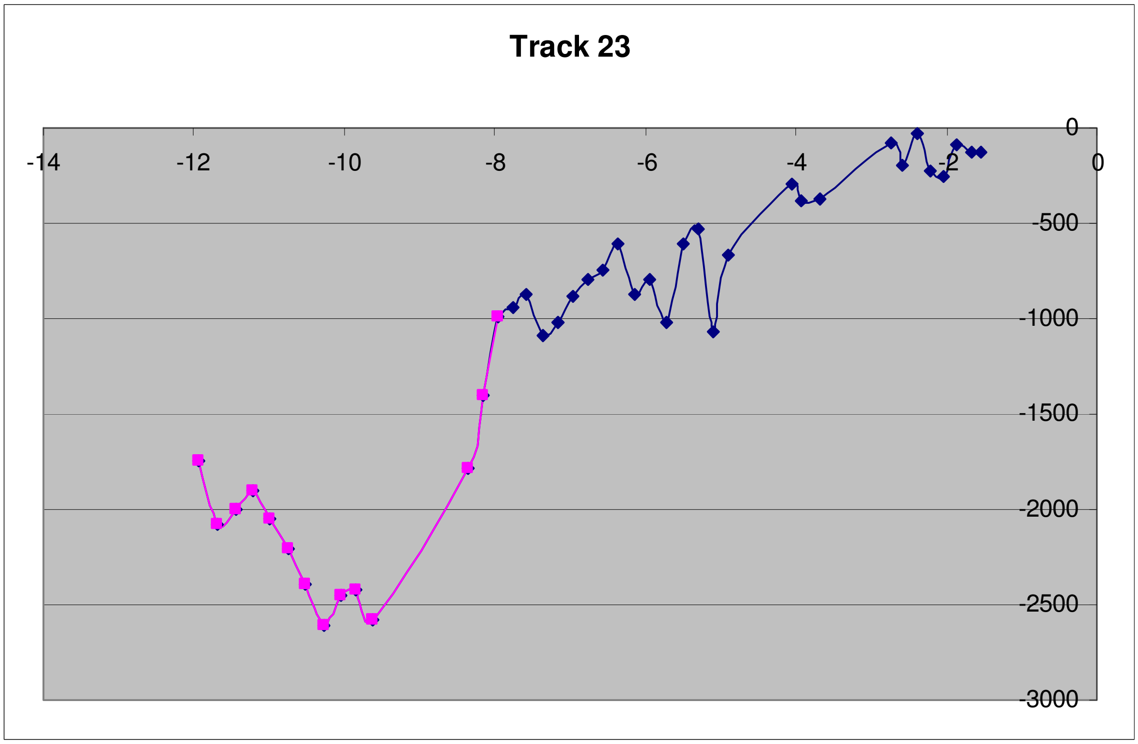


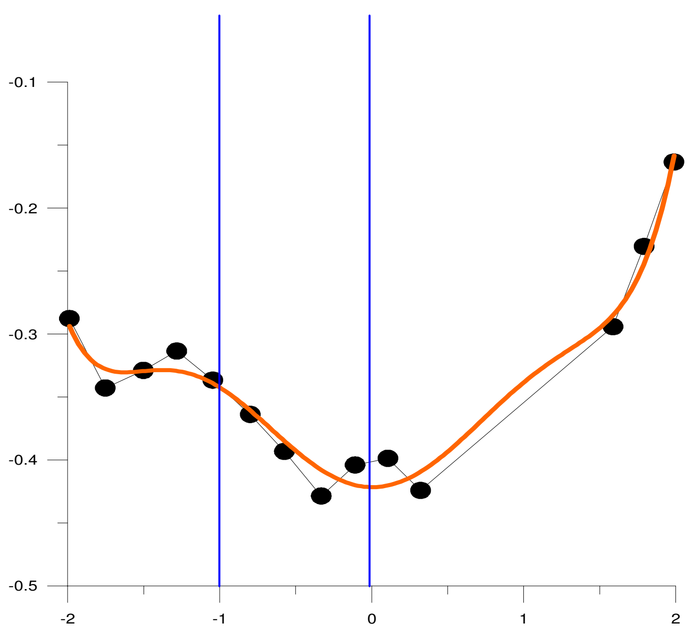


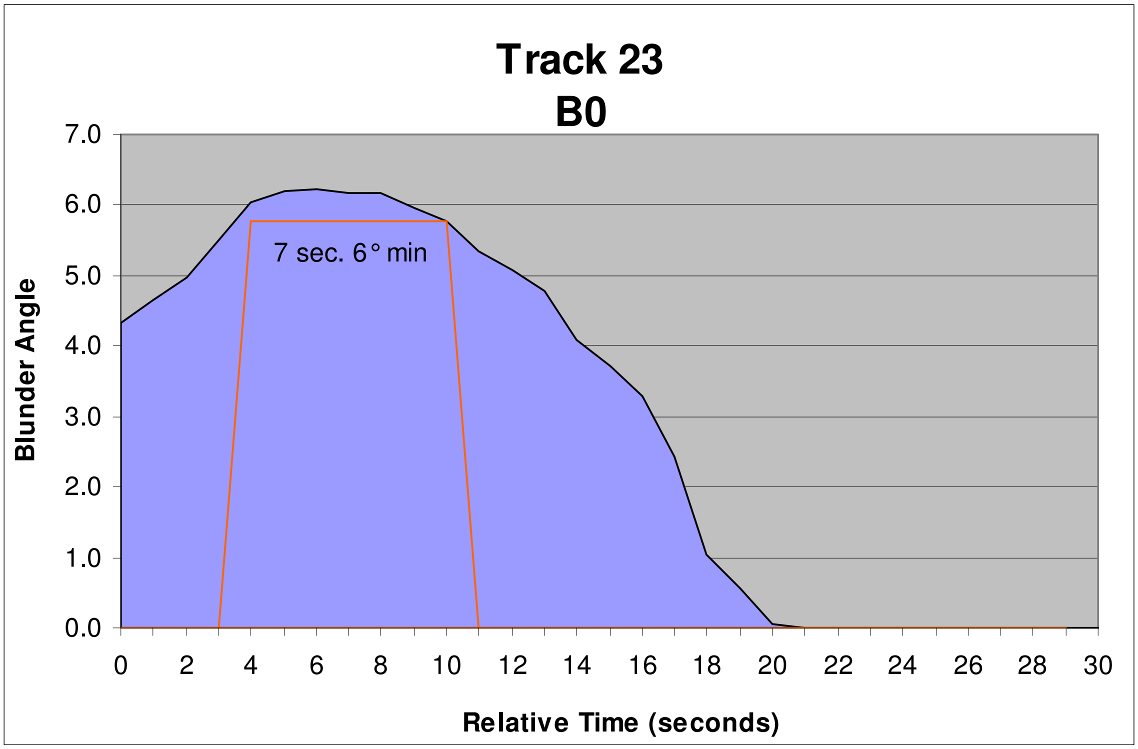

Track 22
B0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
Blunder Angle
7 sec. 8° min
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30
Relative Time (seconds)

TRACK 23

- **AIRPORT:** XHHH
- **RUNWAY:** 25L
- **ANGLE:** 6º

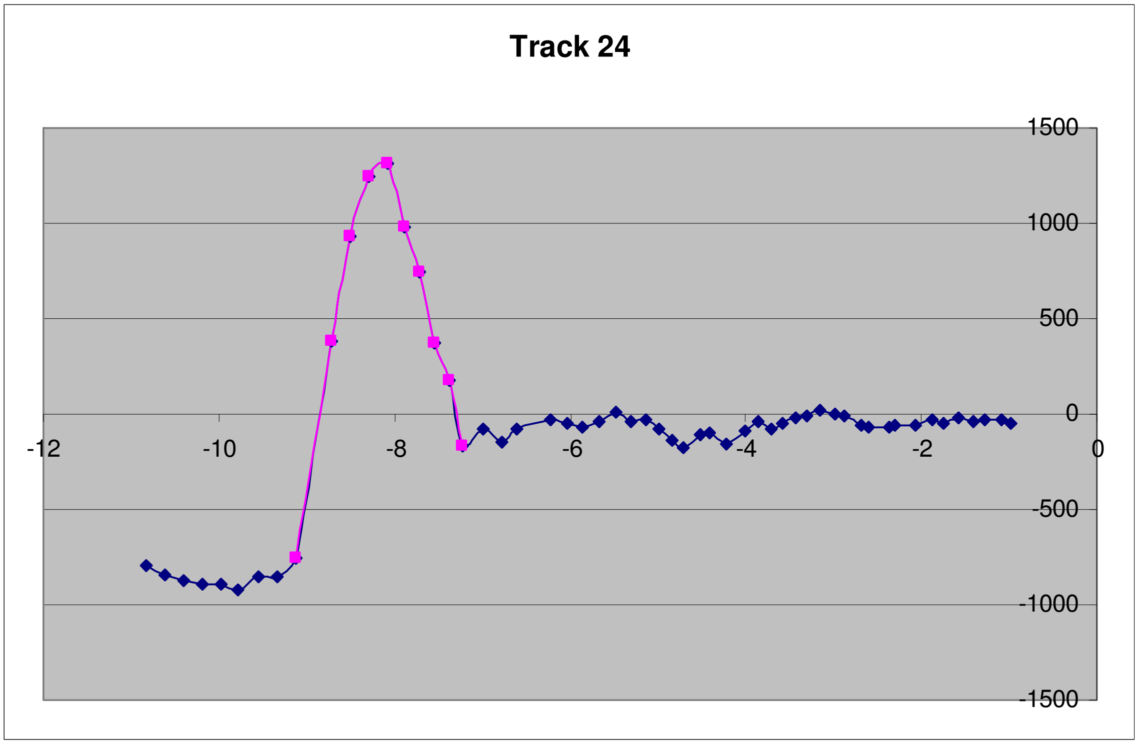


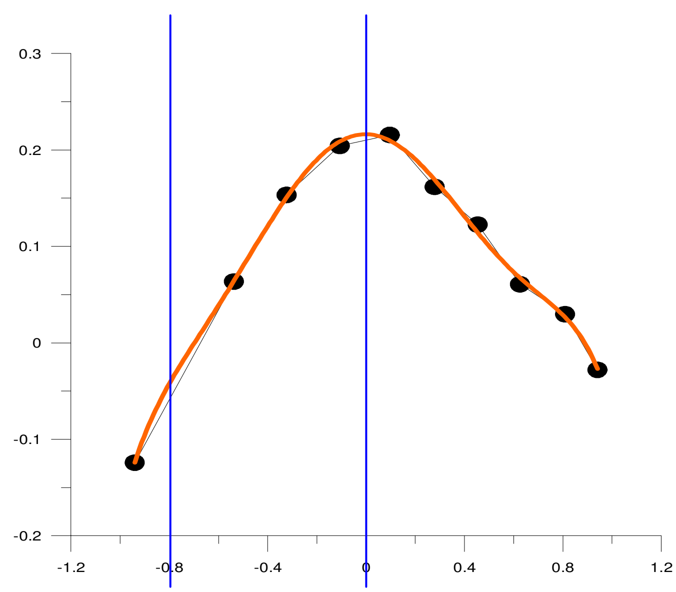


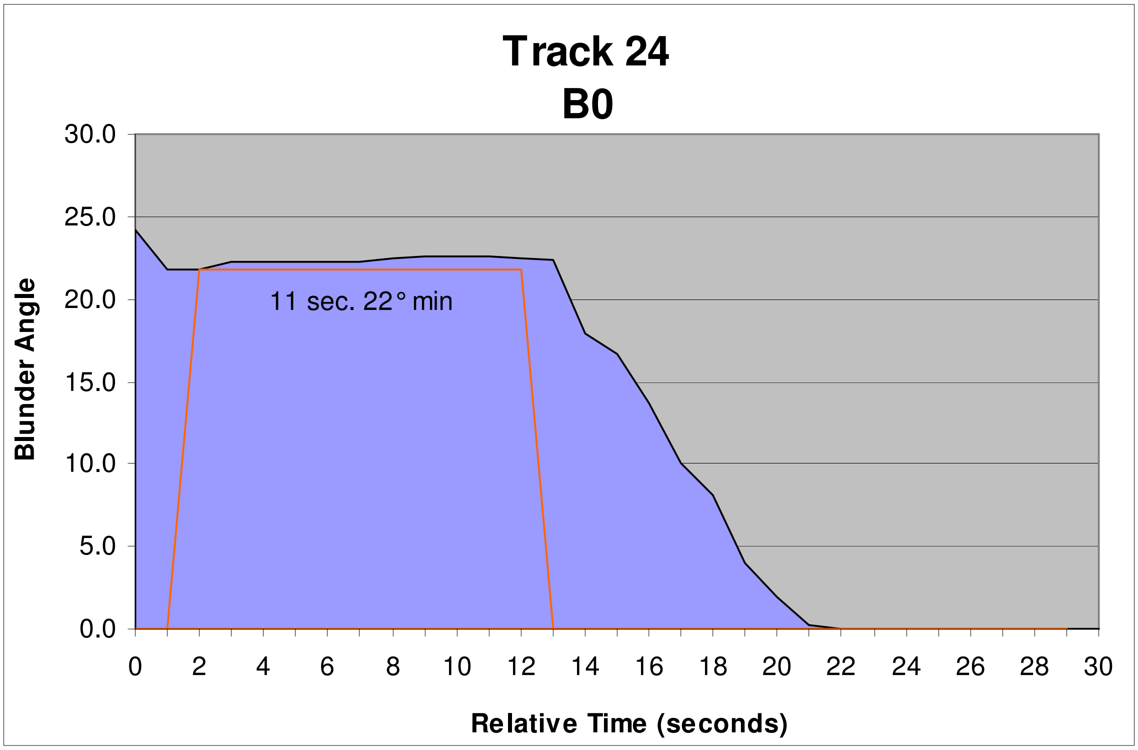

Track 23
B0
7 sec. 6° min
Blunder Angle
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
Relative Time (seconds)

TRACK 24

- **AIRPORT:** XDDD
- **RUNWAY:** 18R
- **ANGLE:** 22º



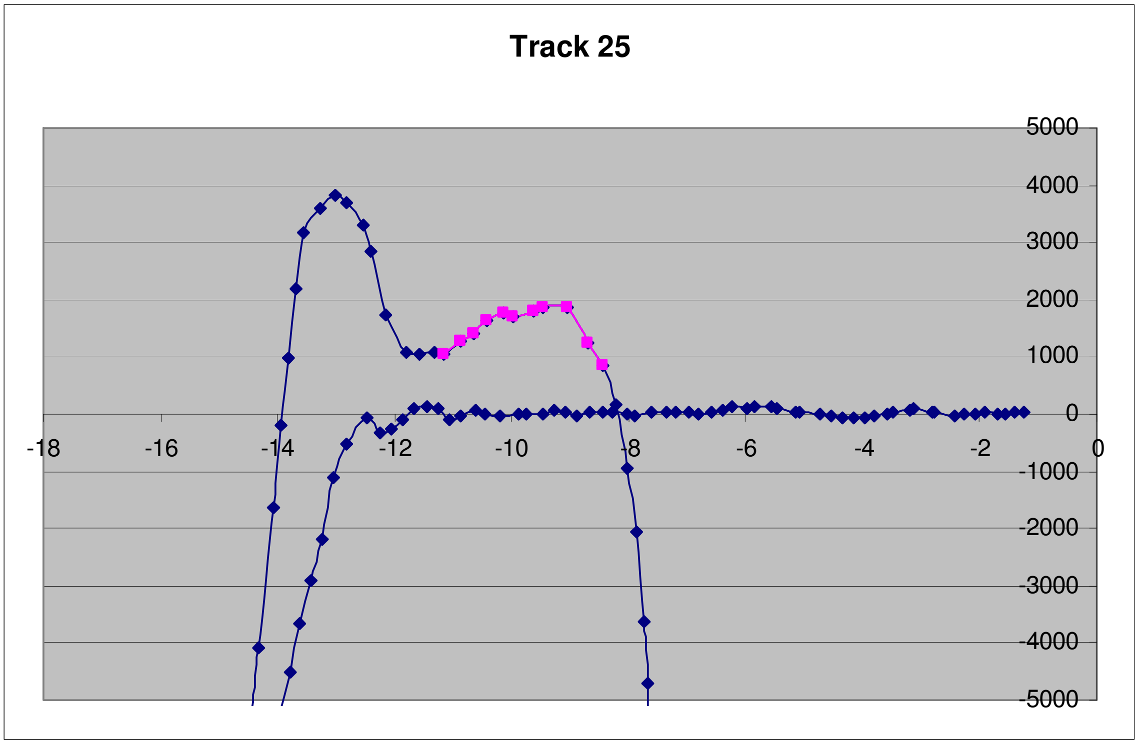


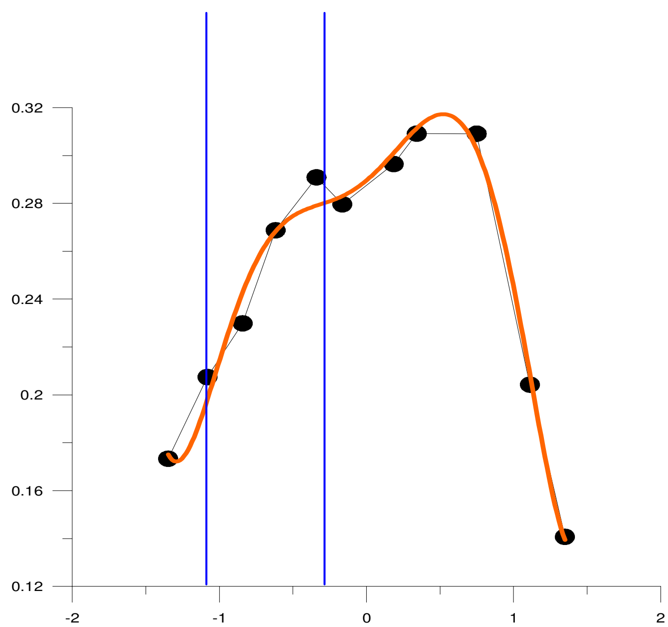

Track 24
B0
30.0
25.0
20.0
15.0
10.0
5.0
0.0
Blunder Angle
11 sec. 22° min
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
Relative Time (seconds)

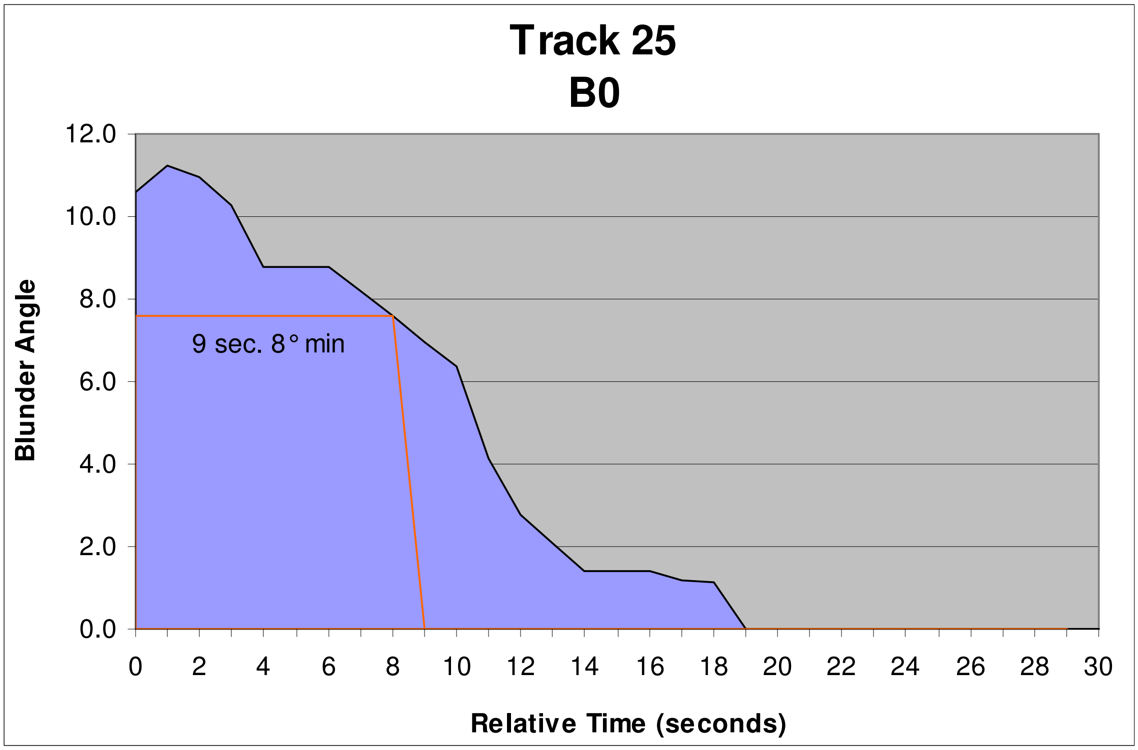
TRACK 25

- **AIRPORT:** XDDD
- **RUNWAY:** 18R
- **ANGLE:** 8º

Note: Track goes around then lands, blunder occurs on first attempt

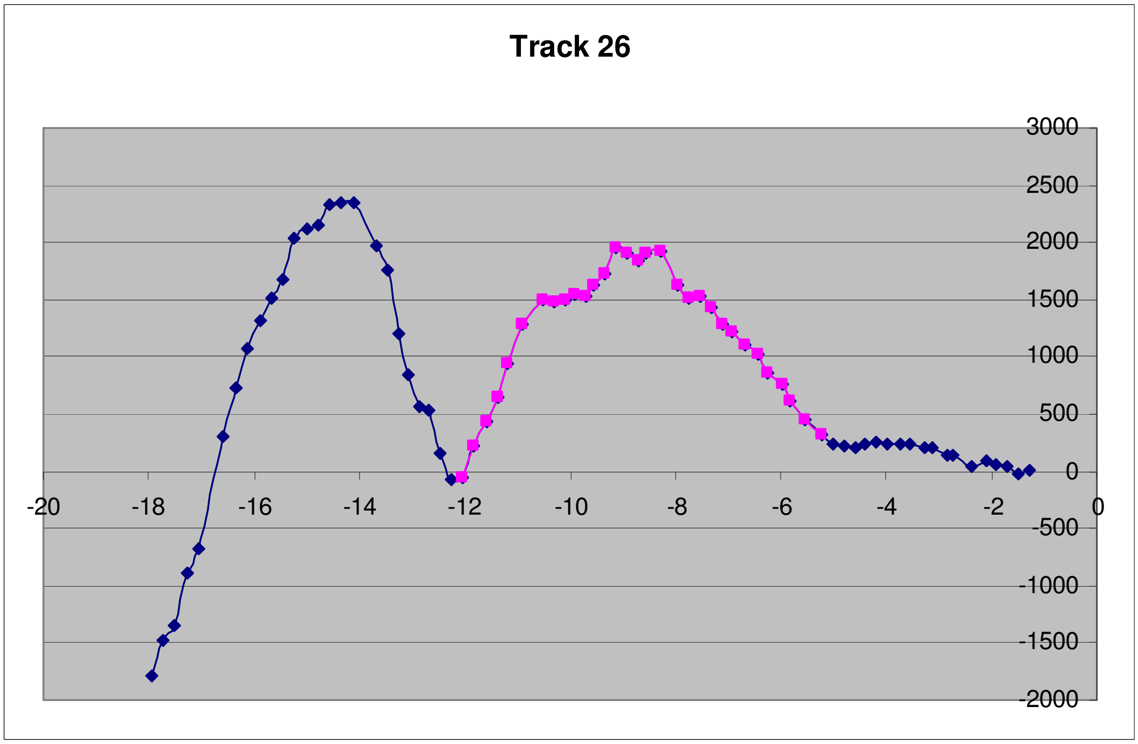


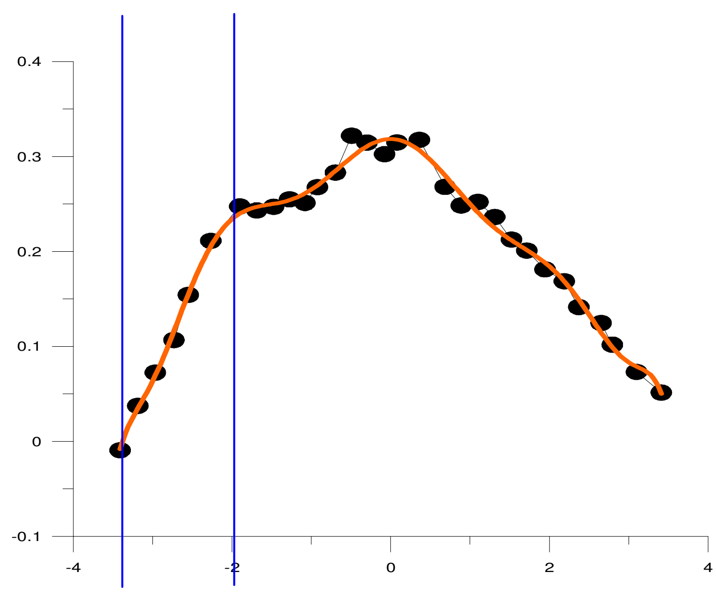


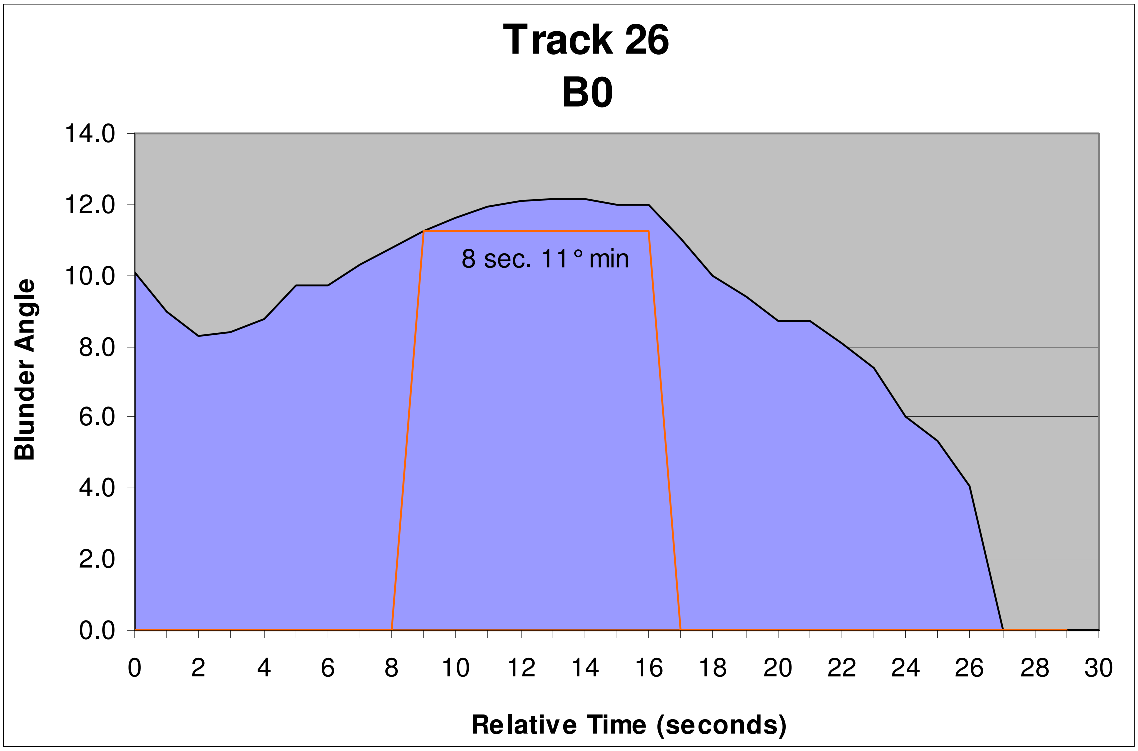

Track 25
B0
Blunder Angle
12.0
10.0
8.0
6.0
4.0
2.0
0.0
9 sec. 8° min
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
Relative Time (seconds)

TRACK 26

- **AIRPORT:** XDDD
- **RUNWAY:** 18R
- **ANGLE:** 11º

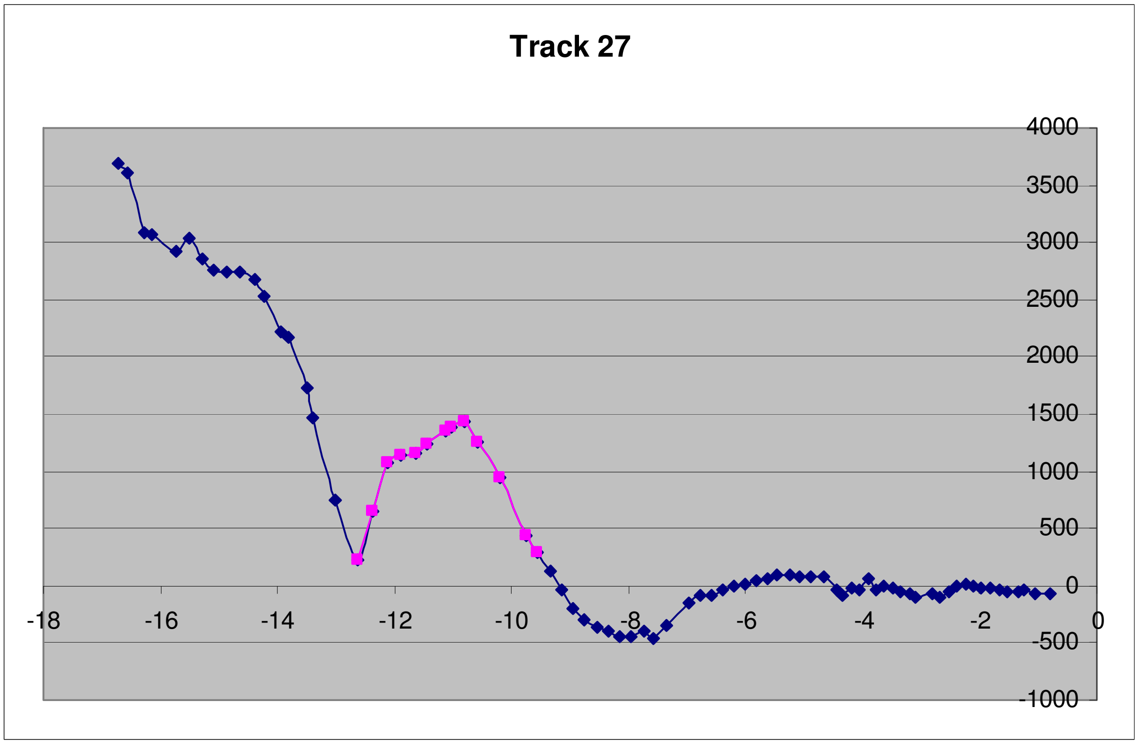


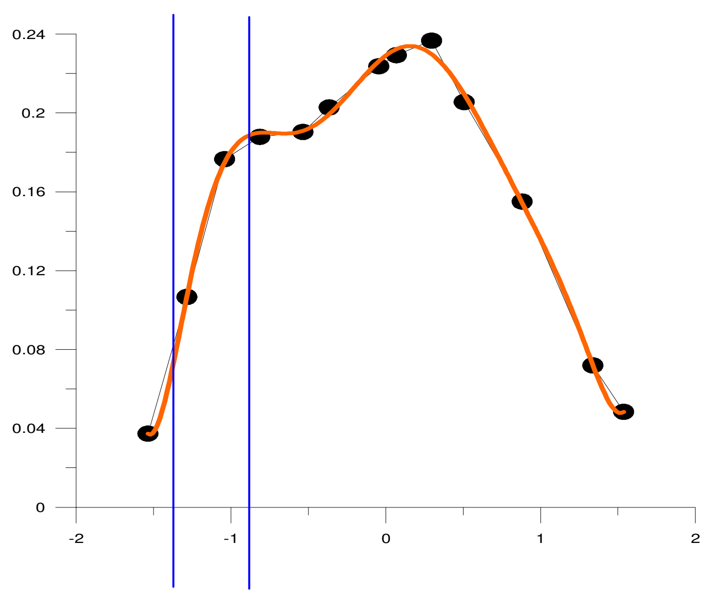


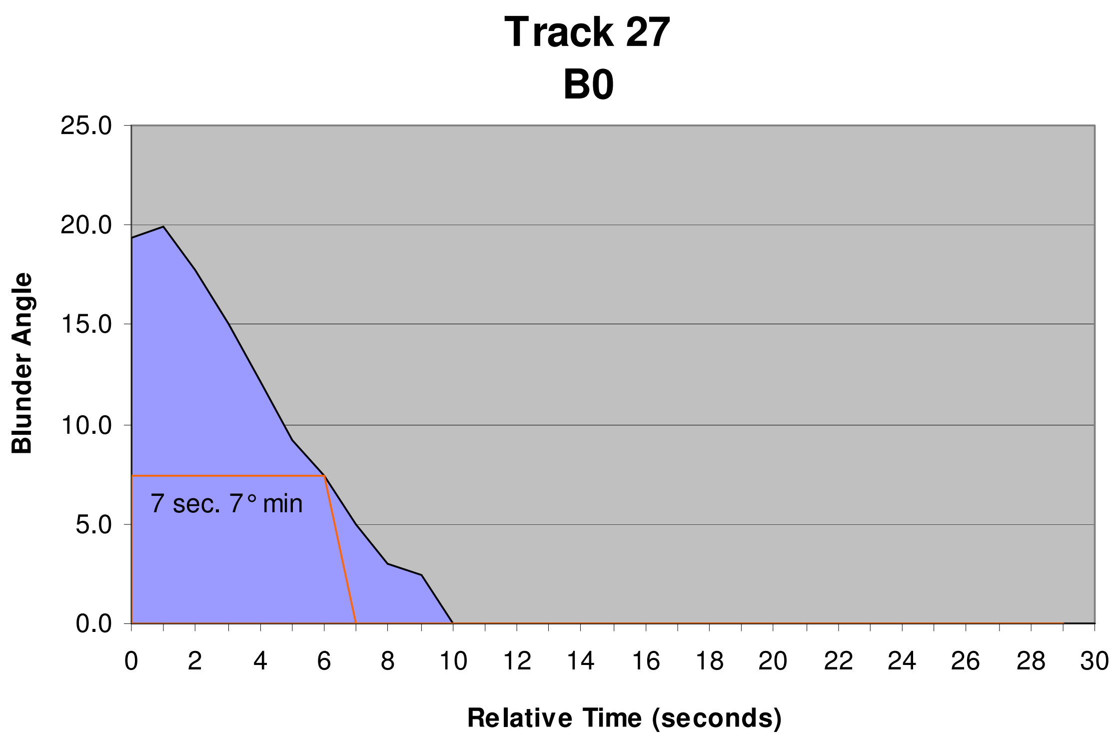

Track 26
B0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
Blunder Angle
8 sec. 11° min
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30
Relative Time (seconds)

TRACK 27

- **AIRPORT:** XDDD
- **RUNWAY:** 18R
- **ANGLE:** 7º



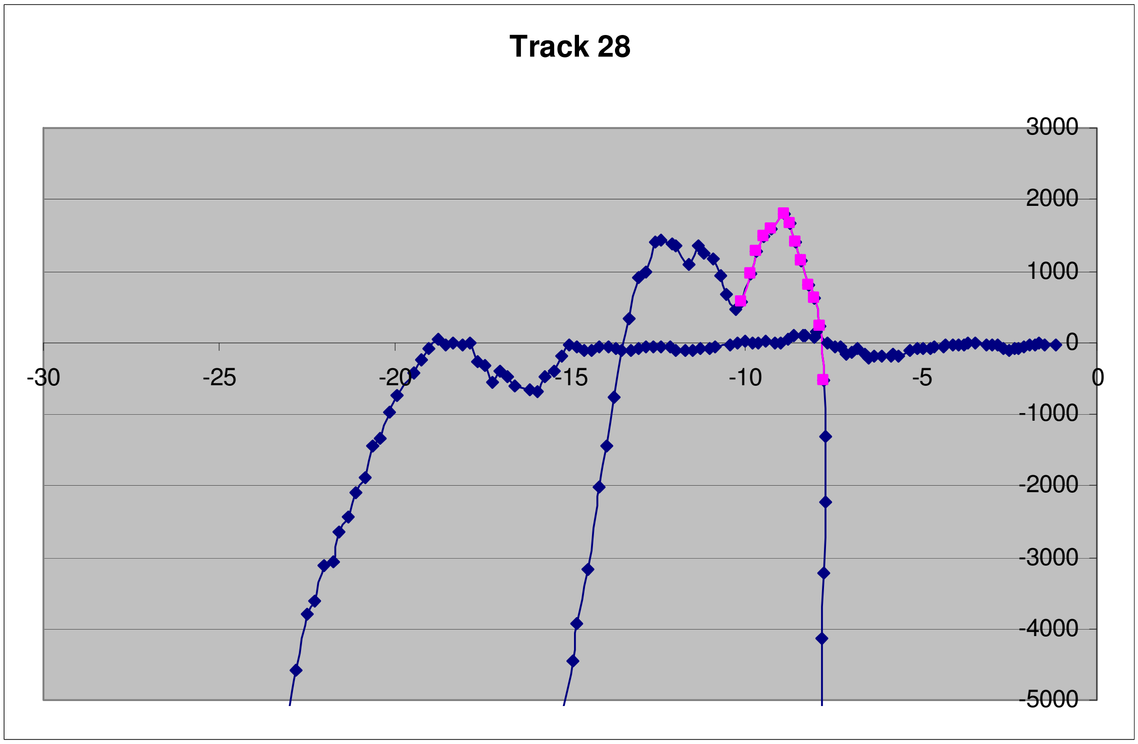


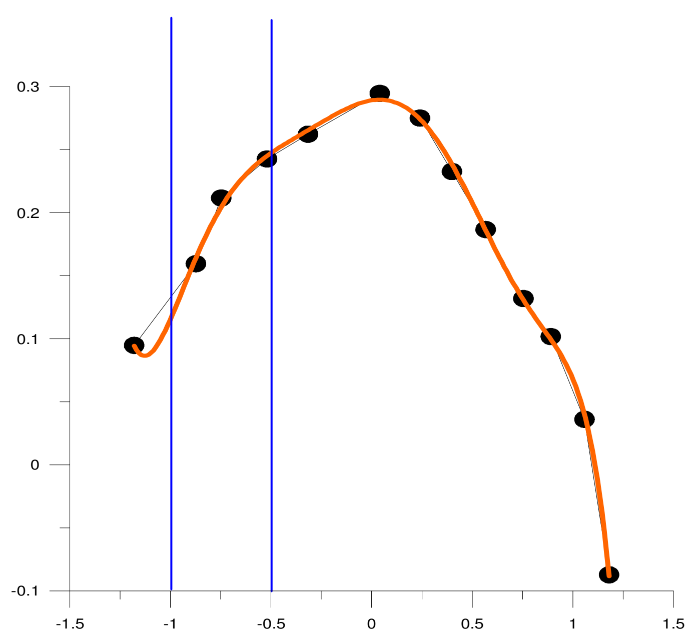

Track 27
B0
25.0
20.0
15.0
10.0
5.0
0.0
Blunder Angle
7 sec. 7° min
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30
Relative Time (seconds)

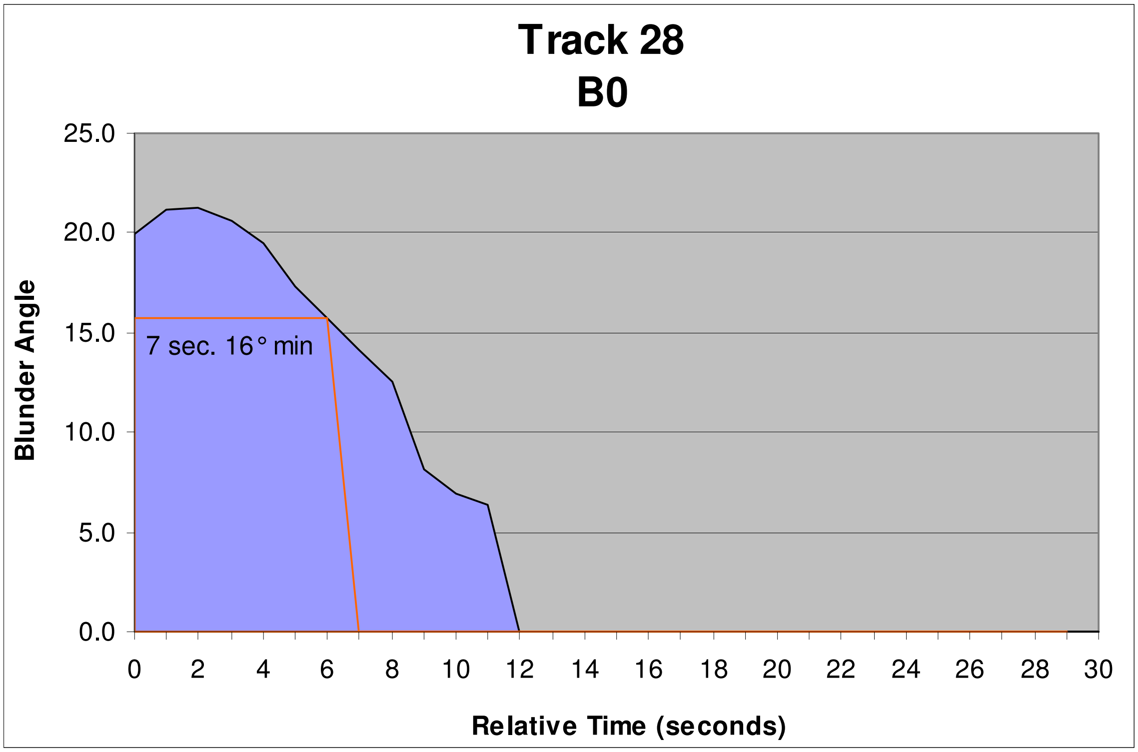
TRACK 28

- **AIRPORT:** XDDD
- **RUNWAY:** 18R
- **ANGLE:** 16º

Note: Track goes around then lands, blunder occurs on first attempt

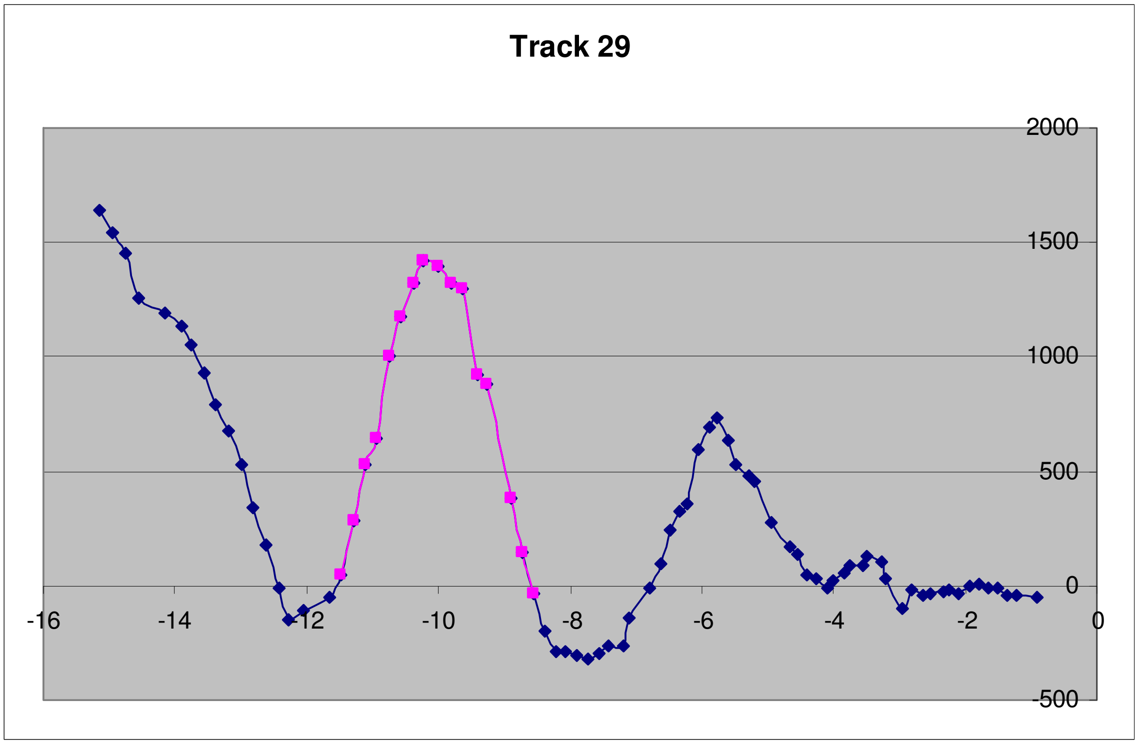


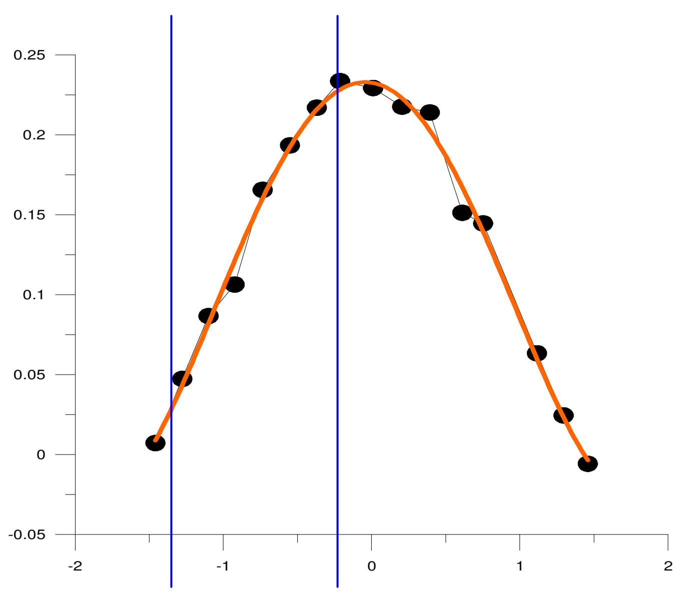


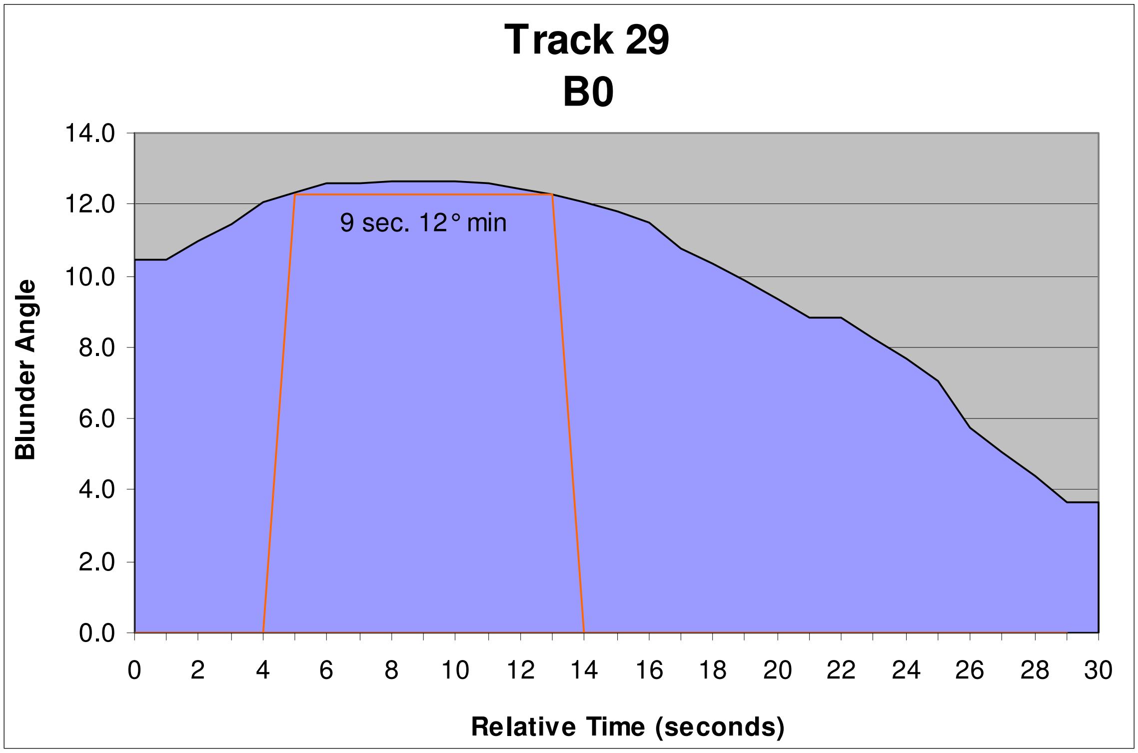

Track 28
B0
25.0
20.0
15.0
10.0
5.0
0.0
Blunder Angle
7 sec. 16° min
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30
Relative Time (seconds)

TRACK 29

- **AIRPORT:** XIII
- **RUNWAY:** 09R
- **ANGLE:** 12º

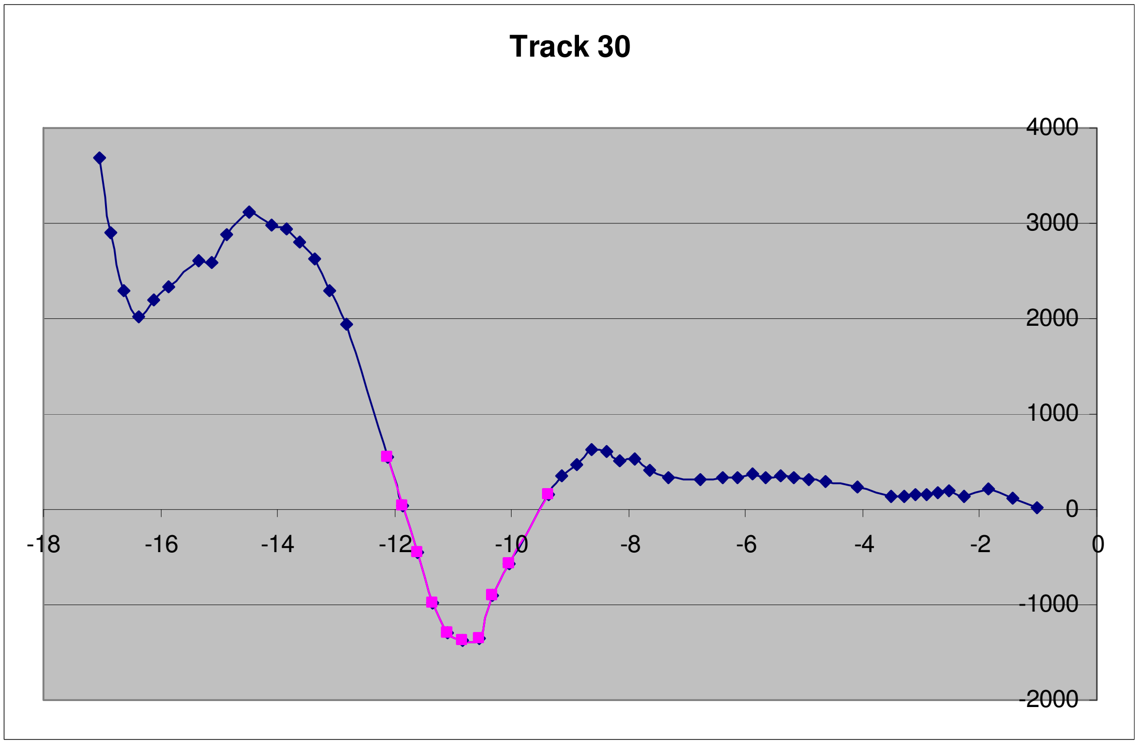


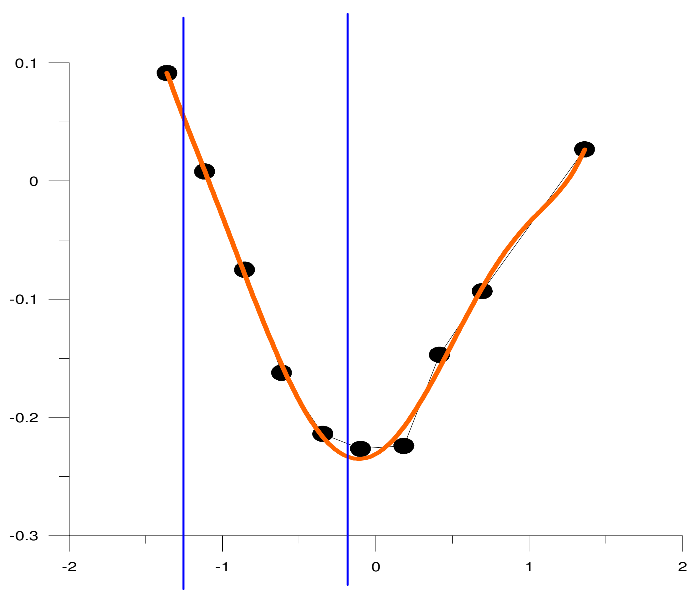


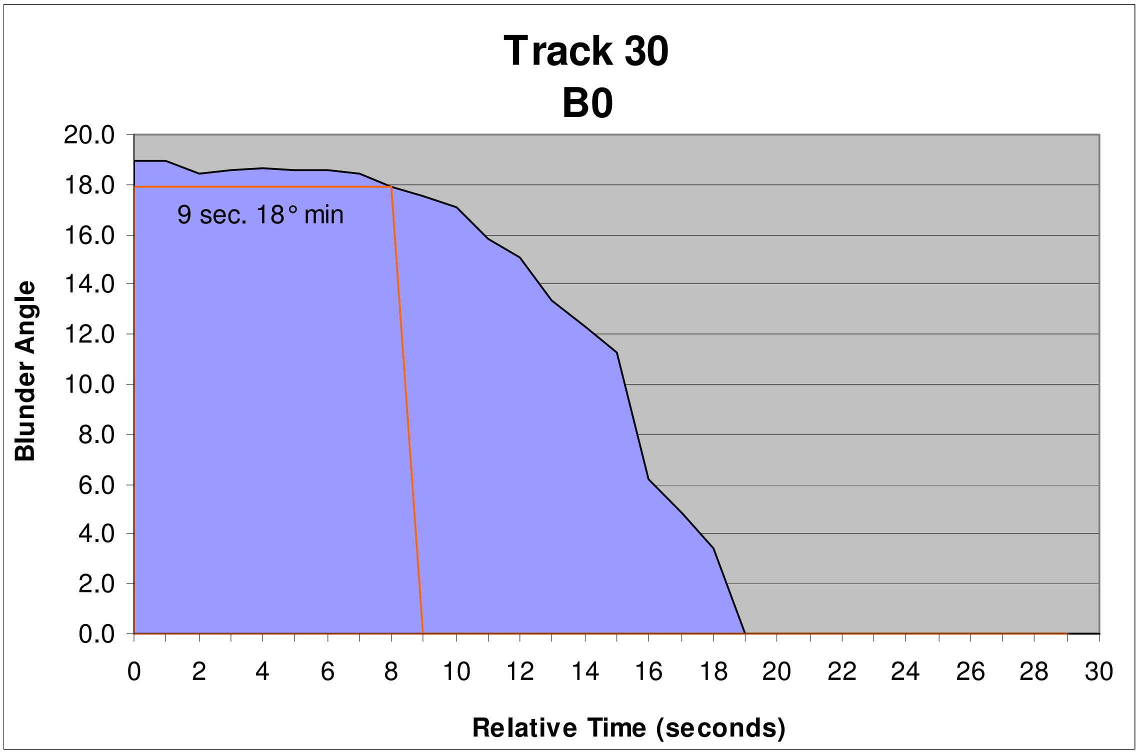

Track 29
B0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
Blunder Angle
9 sec. 12° min
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30
Relative Time (seconds)

TRACK 30

- **AIRPORT:** XDDD
- **RUNWAY:** 36L
- **ANGLE:** 18º

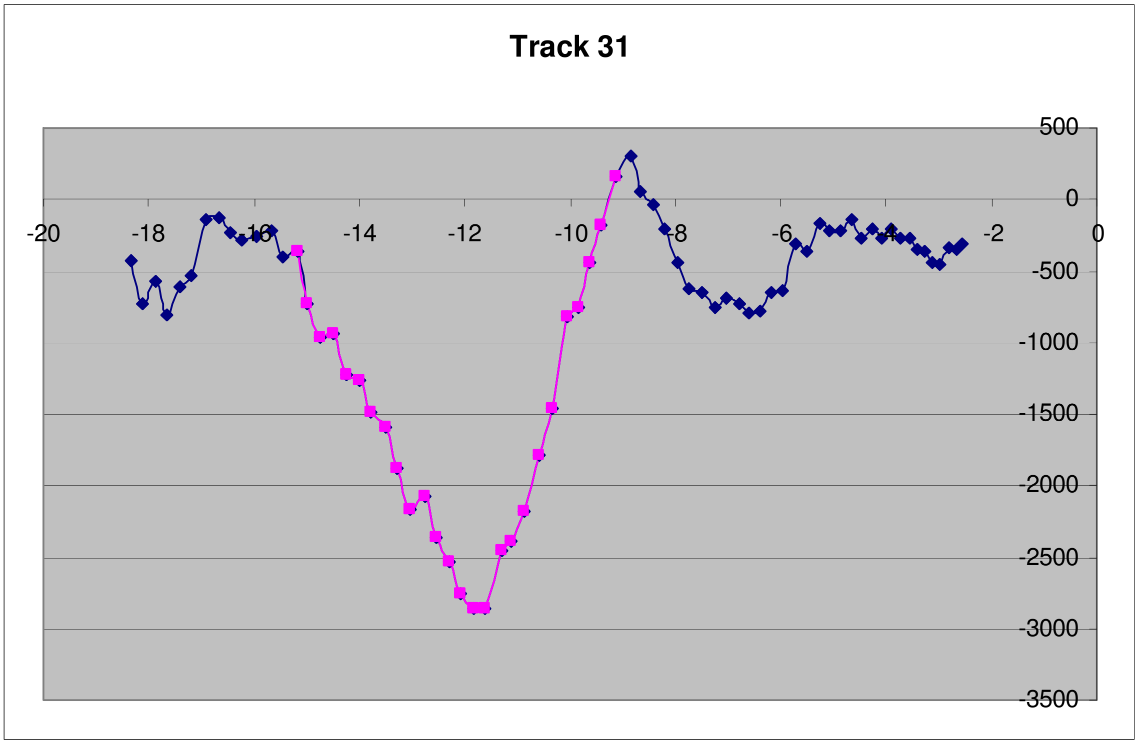


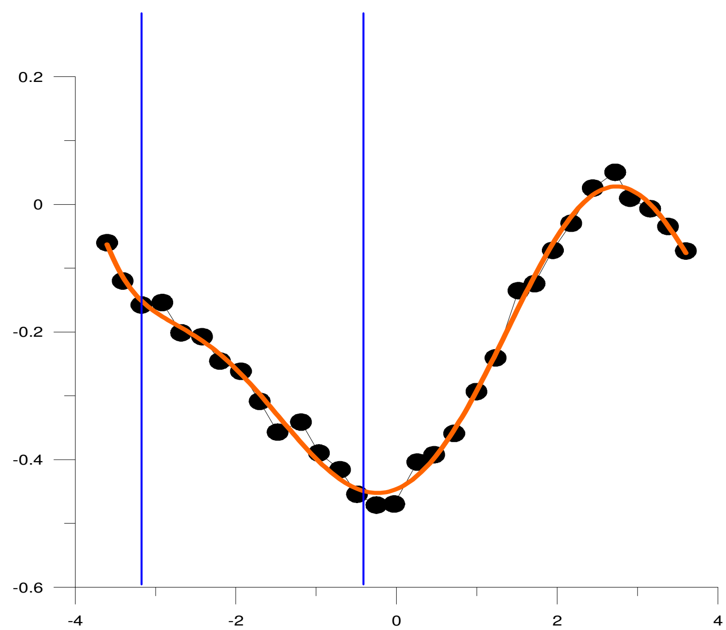


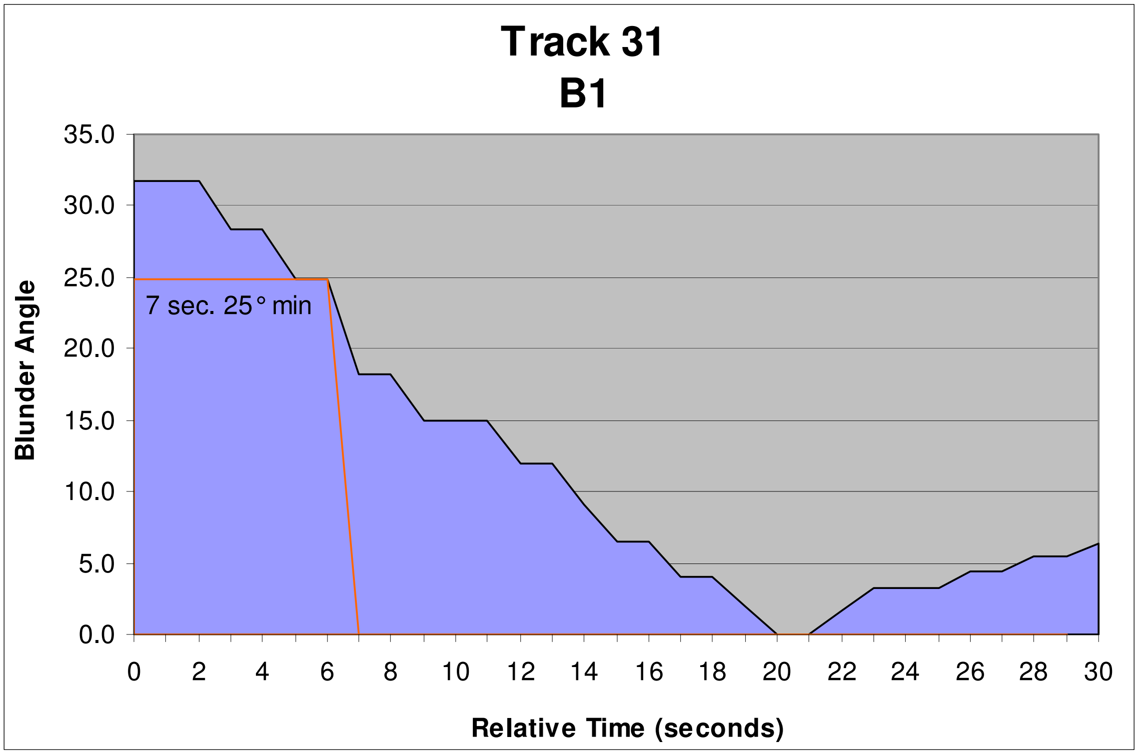

Track 30
B0
9 sec. 18° min
Blunder Angle
20.0
18.0
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
Relative Time (seconds)

TRACK 31

- **AIRPORT:** XIII
- **RUNWAY:** 29R
- **ANGLE:** 25º

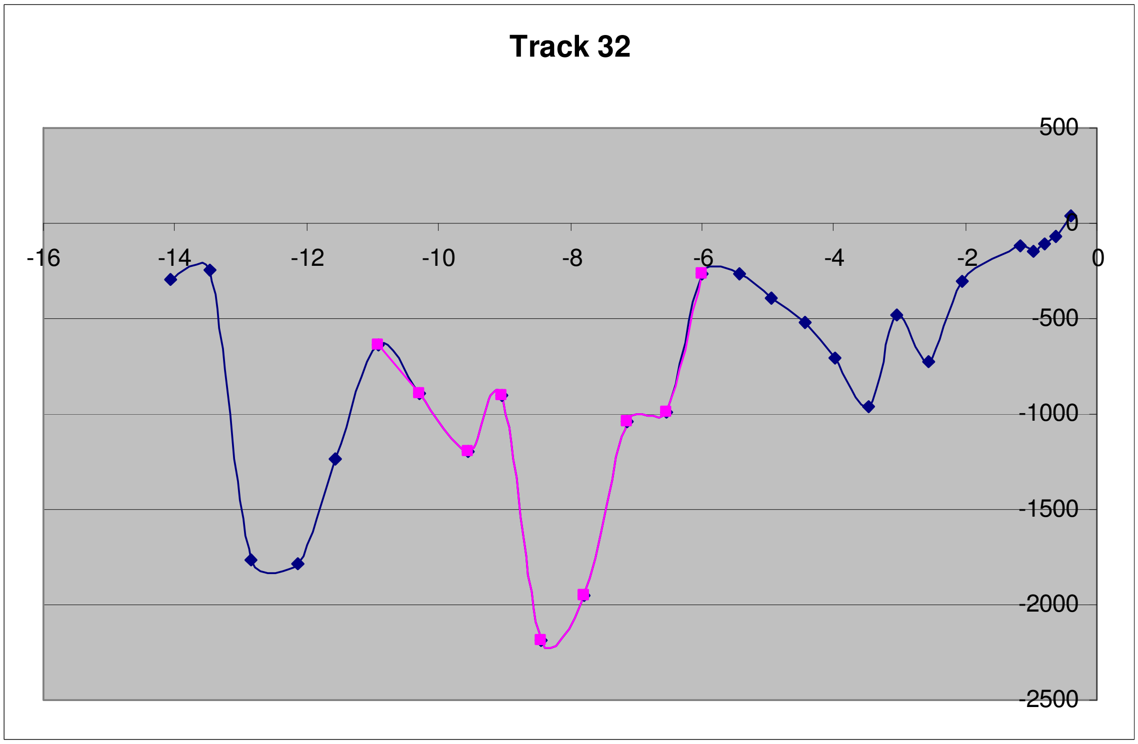


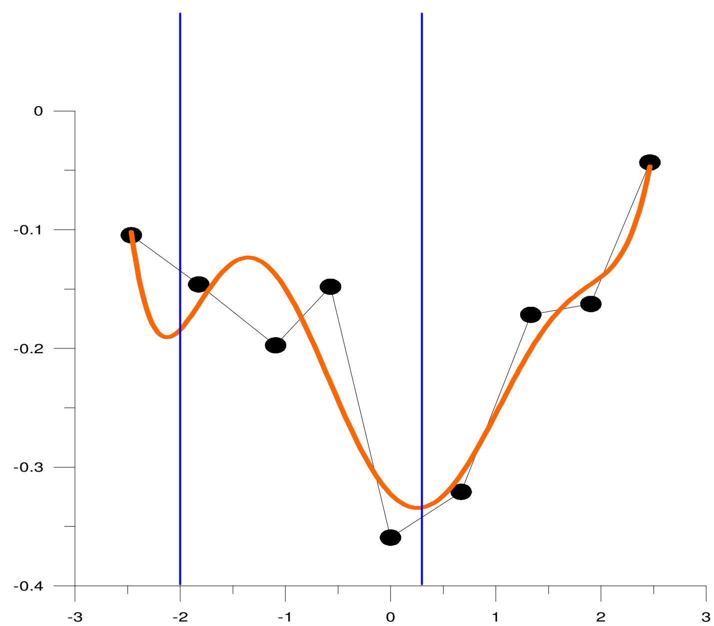


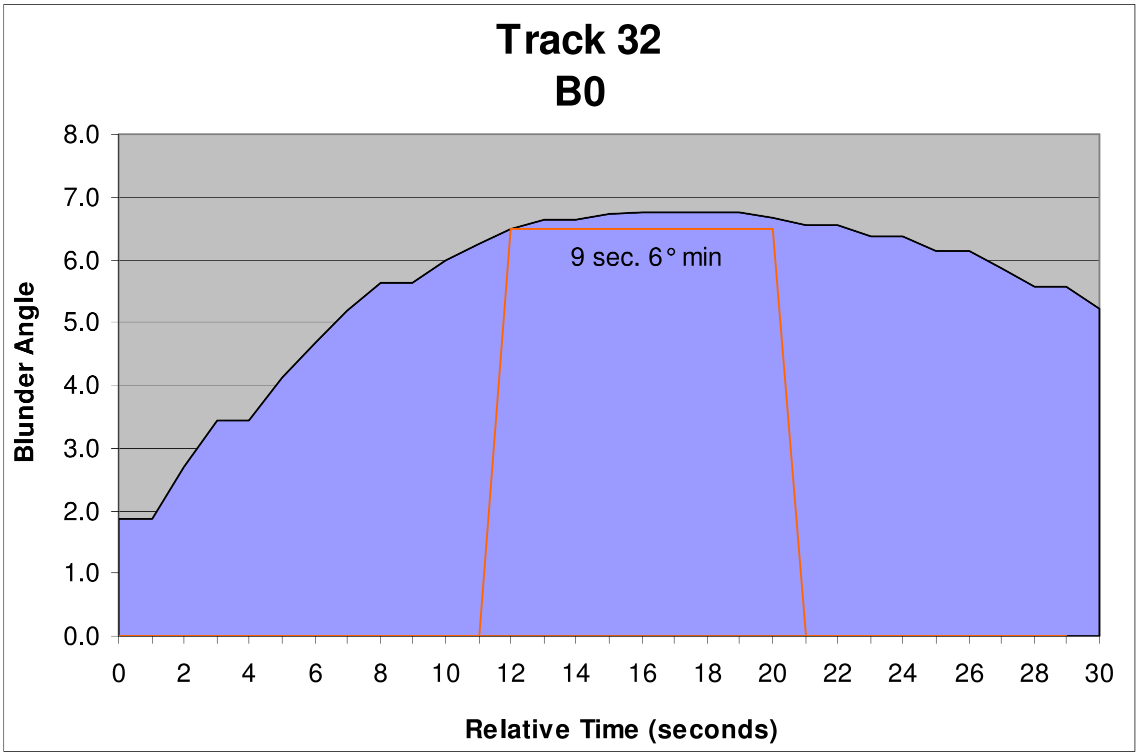

Track 31
B1
35.0
30.0
25.0
20.0
15.0
10.0
5.0
0.0
Blunder Angle
7 sec. 25° min
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30
Relative Time (seconds)

TRACK 32

- **AIRPORT:** XIII
- **RUNWAY:** 09R
- **ANGLE:** 6º

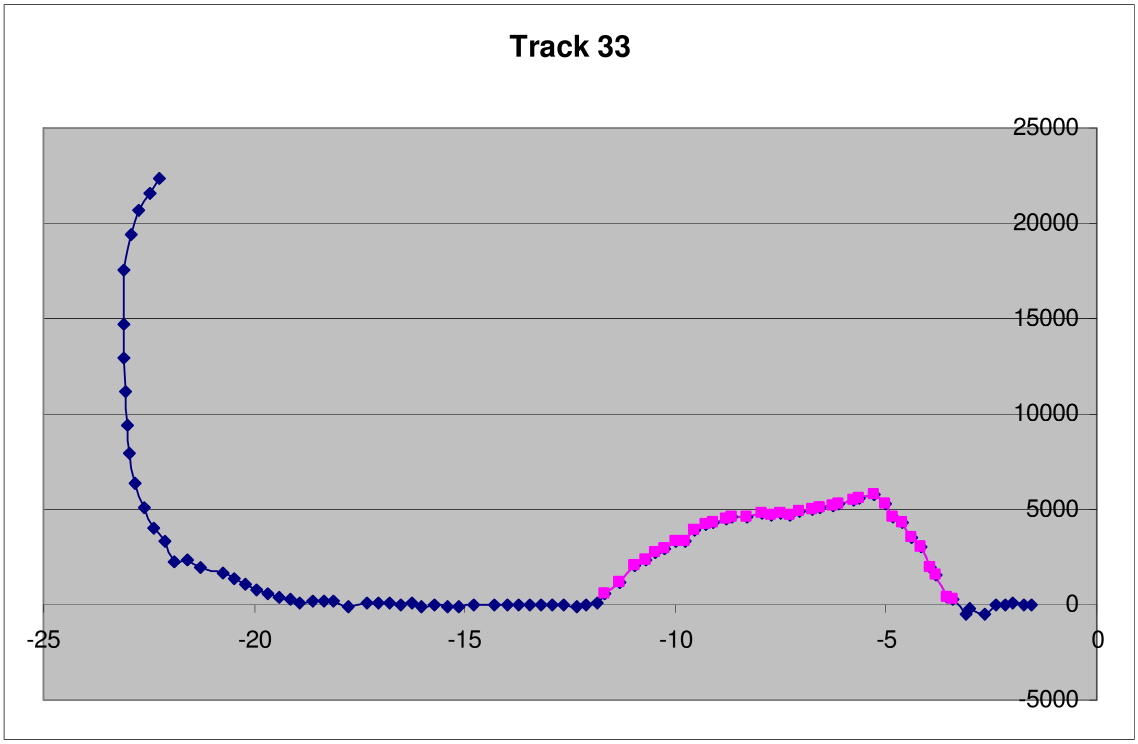


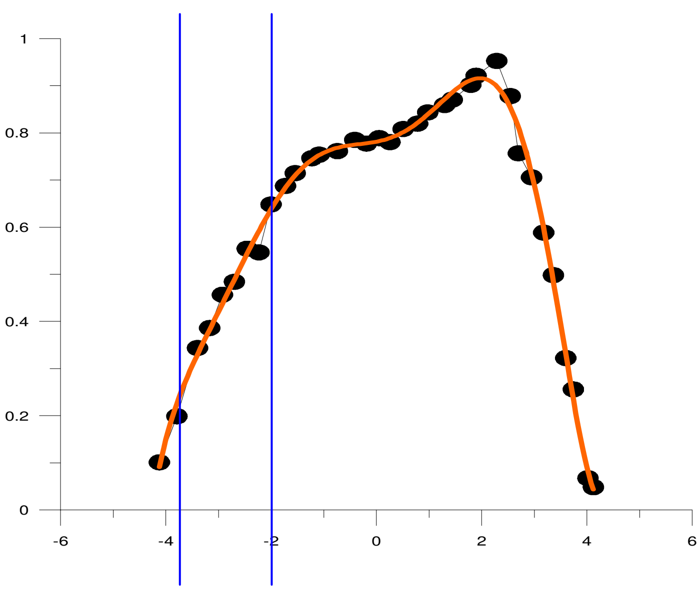


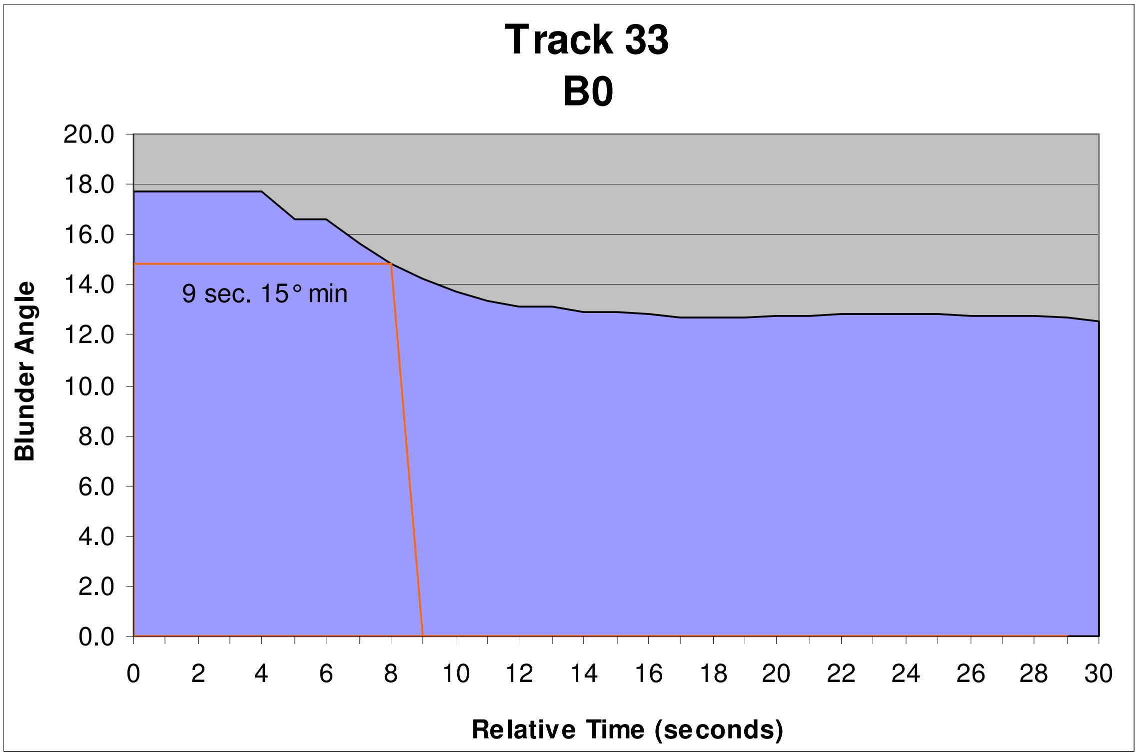

Track 32
B0
9 sec. 6° min
Blunder Angle
Relative Time (seconds)
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30

TRACK 33

- **AIRPORT:** XJJJ
- **RUNWAY:** 35
- **ANGLE:** 15º






Track 33
B0
Blunder Angle
20.0
18.0
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
9 sec. 15° min
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30
Relative Time (seconds)

APPENDIX B

UNUSEABLE TRACK

UNUSABLE TRACK

- **AIRPORT:** XAAA
- **RUNWAY:** Unknown
- **ANGLE:** Unknown
- **SOURCE FILENAME:** XXX_AAAAAAA_Jul08.csv

Note: This particular track is missing the time information needed to calculate the blunder angle and all other relevant track information. This plot is in latitude/longitude since we cannot convert this track into XYZ coordinates due to the lack of required time data. Using a visual-only rough estimate, the angle is near 9 degrees.