

Browse > Conferences> Digital Avionics Systems Conf

Analysis of localizer and glide slope Flight Technical Error

Hall, T. Soares, M.
US DOT/RITA/Volpe Center, Cambridge, MA

This paper appears in: Digital Avionics Systems Conference, 2008. DASC 2008. IEEE/AIAA 27th

Issue Date : 26-30 Oct. 2008

On page(s): 2.D.2-1 - 2.D.2-9

Location: St. Paul, MN

Print ISBN: 978-1-4244-2207-4

INSPEC Accession Number: 10412239

Digital Object Identifier : 10.1109/DASC.2008.4702786

Date of Current Version : 09 December 2008

ABSTRACT

A new wake turbulence procedure has been developed that permits two dependent arrival traffic streams during instrument meteorological conditions to runways with centerline separations less than 2500 ft. For the proposed procedure, aircraft approaching both runways of a closely-spaced pair under limited ceiling/visibility conditions utilize instrument landing system (ILS) localizer and glide slope guidance. A critical safety analysis building block was to quantify the risk posed by aircraft flight technical error (FTE), a measure of the deviations from the localizer/glide slope centerlines, under ceiling/visibility conditions when non-visual ILS approaches are normally performed. Flight track data from Lambert-St. Louis international airport (STL) under severe IMC conditions, when strict adherence to navigation aide guidance would most likely occur, were used to quantify the aircraft dispersion characteristics.

INDEX TERMS

Available to subscribers and IEEE members.

REFERENCES

Available to subscribers and IEEE members.

CITING DOCUMENTS

Available to subscribers and IEEE members.

Analysis of Localizer and Glide Slope Flight Technical Error

Timothy Hall, Melanie Soares

US DOT/RITA/Volpe Center, Cambridge, Massachusetts USA

Abstract

A new wake turbulence procedure has been developed that permits two dependent arrival traffic streams during instrument meteorological conditions to runways with centerline separations less than 2500 ft. For the proposed procedure, aircraft approaching both runways of a closely-spaced pair under limited ceiling/visibility conditions utilize Instrument Landing System (ILS) localizer and glide slope guidance. A critical safety analysis building block was to quantify the risk posed by aircraft Flight Technical Error (FTE), a measure of the deviations from the localizer/glide slope centerlines, under ceiling/visibility conditions when non-visual ILS approaches are normally performed. Flight track data from Lambert-St. Louis International Airport (STL) under severe IMC conditions, when strict adherence to navigation aide guidance would most likely occur, were used to quantify the aircraft dispersion characteristics.

The position sensors were the STL Airport Surface Detection Equipment, Model X (ASDE-X), the on-airport Surface Measurement Radar (SMR), multilateration subsystem sensors, and by Riegl laser range-measurement sensors near the runway thresholds.

In general, the FTE found in this analysis were significantly tighter than the International Civil Aviation Organization (ICAO) navigation tolerances commonly used in safety simulations.

Background

Current Air Traffic Control (ATC) regulations require that, under Instrument Meteorological Conditions (IMC), aircraft approaching parallel runways spaced less than 2500 feet apart, i.e., Closely-Spaced Parallel Runways (CSPR), be separated longitudinally as though in a single stream. This restriction results in IMC arrival capacity being essentially half the capacity during visual conditions at several major U.S. airports, for some configurations. It causes delays when traffic

is heavy, as flights are scheduled based on capacity under visual conditions.

A new procedure [1] has been developed that permits two arrival traffic streams during IMC to runways with significant stagger but whose centerline separation is less than 2500 ft. This procedure includes restrictions on participating aircraft weights and geometries. Aircraft are arranged in pairs, with the first (lead) aircraft on the same or lower glide slope and the second aircraft trailing by at least 1.5 NM. The safety risk evaluation of this procedure involved analyzing aircraft surveillance data collected at Lambert - St. Louis International Airport (STL) during the winter of 2006.

The primary position sensor was the STL Airport Surface Detection Equipment, Model X (ASDE-X). In addition to the on-airport Surface Measurement Radar (SMR) and multilateration subsystem sensors, the STL ASDE-X system was augmented by off-airport multilateration sensors adjacent to the approach corridors at both ends of runways 12L/R and 30L/R, and by Riegl laser range-measurement sensors near the 12L and 12R runway thresholds. ASDE-X provides horizontal position information of sufficient accuracy for this analysis (errors typically 25 ft or less). However, ASDE-X is not intended to accurately measure aircraft vertical position (height). Instead ASDE-X collects aircraft-provided barometric altimeter information (similar to secondary surveillance radar), which was used to determine deviations from the glide slope and was supplemented by Riegl data when an aircraft was close to the ground.

For the proposed procedure, aircraft approaching both runways of a closely-space pair under IMC utilize Instrument Landing System (ILS) localizer and glide slope guidance. Aircraft track and associated weather data for 10,505 operations underwent extensive quality assurance screening, including filtering Navigation System Error (NSE) from the position data (which is actually Total System Error (TSE) data), and adjustments for individual variations in aircraft barometric altimeter

readings, and were analyzed to quantify the risk posed by aircraft Flight Technical Error (FTE), which is a measure of the deviations from the ILS centerline/glide slope under ceiling/visibility conditions when non-visual operations are normally performed at STL, and when strict adherence to ILS centerline/glide slope guidance would most likely occur. Data are analyzed in terms of the distribution of the lateral and vertical perturbations from the ideal path as a function of distance from the runway.

ICAO ILS Specification Tolerances

According to [2], Chapter 3, Sections 3.1.3.3.1 and 3.1.5.3.1 (see also Attachment C, page C-25, Figures C-7 and C-10), the conforming ILS localizer signals produce a Proportional Guidance Region (LPGR) and Clearance Regions (CR) according to the dimensions found in Figure 1. For STL Runway 12R/30L, which is 10,019 ft long, the localizer LPGR will be 350 ft at the beginning of the 12R arrival threshold.

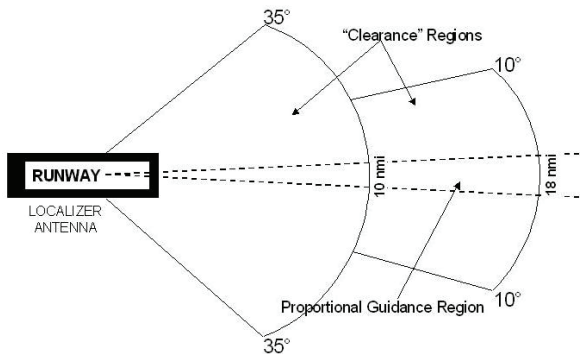


Figure 1: ICAO Localizer Regions

The half-width of the LPGR at various distances from the 12R arrival threshold is indicated in Table 1. For example, when an aircraft is 2 nautical miles (nmi) from the 12R arrival threshold, there would be a “full needle deflection” in the cockpit indicator when the aircraft reaches 705 ft on either side of the ILS localizer centerline. While Table 1 only shows the LPGR to 10 nmi, the actual ILS signals extend as far as the signal strength allows, with corresponding half-width distances.

Table 1: ICAO LPGR Full Deflections

Distance**	Full Deflection***
1 nmi	± 525 ft
2 nmi	± 705 ft
5 nmi	± 1235 ft
7 nmi	± 1588 ft
10 nmi	± 2120 ft

** From Arrival Threshold
 *** Distance From LOC Centerline

Similarly, the conforming ILS Glide Slope (GS) signals produce a guidance region (GSPGR) according to the dimensions found in Table 2. Note that the heights listed are above/below the glide slope centerline, and are corrected for the curvature of the earth.

Table 2: ICAO GS Full Deflections

Distance*	Full Deflection**
1 nmi	± 89 ft
2 nmi	± 166 ft
5 nmi	± 396 ft
7 nmi	± 549 ft
10 nmi	± 779 ft

* From Arrival Threshold
 ** Height Above/Below GS Centerline (corrected for curvature of earth)

Within the LPGR and GSPGR are sub-regions where aircraft are actually expected to fly once established on the localizer. These sub-regions are formed by the intent of the cockpit crew and coupled avionics systems to adhere to the localizer and glide slope centerlines, but, due to various navigation system and human factors, actually deviate from these paths. According to [3], et seq., prior extensively-monitored ICAO flight tests and simulations for ILS and Area Navigation (RNAV) straight-line approaches under varying wind speeds and directions, and for various size aircraft models, have led to the common use of an autopilot-coupled FTE of one-eighth (0.125) nmi with 95% probability. This means the ICAO FTE tolerances are approximately 380 feet on either side of the localizer centerline. The ICAO FTE value for

manual straight-line approaches is twice as large, namely 760 feet on either side of the localizer centerline.

The ICAO FTE tolerance for the glide slope is three-fourths (0.75) of the full deflections listed in Table 2.

These ICAO tolerances will be compared to the FTE found in the ASDE-X track and Riegl data analyses.

The Riegl Laser Rangefinder

The Riegl Model LD90-3300VHS-FLP laser Rangefinder (LRF) (see Figure 2) was used as a sensor for measuring the height of aircraft passing over the approach to runways 12L and 12R. The LRF uses a Class 1 laser which is eye-safe and does not pose any hazard. The wavelength of the laser is approximately 900nm.



Figure 2: Model LD90-3300VHS-FLP Riegl Laser Rangefinder

The internal block diagram of the LRF consists of a laser transmitter, a laser receiver, a clock, and a microprocessor. The LRF can operate at 200 Hz, 2 KHz, and even up to 12 KHz pulse rate. The LRF was set to 200-Hz pulse rate for the STL test site. The LRF sends out infrared light pulses through the transmitter lens which hit the aircraft, and part of the laser is reflected back to the receiver lens of the LRF and therefore generates an electrical signal. The LRF has a built-in clock, which measures the time from when the signal was transmitted to the time the signal was received.

The microprocessor then uses the measured time and the speed of the laser to calculate the distance and level of the aircraft. The LRF was placed along the extended runway centerlines of both the 12L and 12R runways and it was pointed upwards (see Figure 3).



Figure 3: Riegl Rangefinder

When the aircraft passes above the LRF (see Figure 4), the laser beams will reflect from under the plane, therefore the LRF can measure the range, in this case height of the aircraft from the ground.



Figure 4: Aircraft over Riegl Rangefinder

The Analysis Data

ASDE-X CAT-11 MSDP

All ASDE-X data used in this analysis was recorded from the ASTERIX Category 11 (CAT-11) output from the Multi-Sensor Data Processor (MSDP) at Lambert-St. Louis International Airport (STL) from December 1, 2005 00:00:00 UTC through February 28, 2006 23:59:59 UTC (ninety 24-hour periods). During this period, 42,655 arrivals were observed on four runways (12L/R and 30L/R), with track files recorded from 10 nmi from threshold to arrival threshold. However, due to data quality issues that called into doubt the track's veracity, e.g., continual large jumps in position, backwards flight, impossibly steep turns, missing data for significant periods (6 seconds or more), etc., 32,005 of these track files were complete enough to facilitate FTE analysis.

Altitudes in CAT-11 data are reported in 25 ft increments, based on a base MSL altitude. The base MSL altitude was assumed to be the altitude reported by a calibrated and conforming barometric altimeter when the aircraft was on the ground at the arrival runway threshold. However, since the analysis track data clearly showed that different aircraft report significantly different altitudes at the arrival threshold, a Riegl laser rangefinder was used to determine the actual height above ground for the arrivals used in the FTE analysis.

Based on the Mode S ID reported in each track position report, the make, model, and series of each arrival aircraft was available by pairing the Mode S ID with the manufacturer ID, found in the Aircraft Registration List (MASTER) file available from the FAA Civil Aviation Registry in Oklahoma City, OK, and online at <http://registry.faa.gov>. The manufacturer ID was then paired with the make, model, and series information in the Aircraft Reference (ACFTREF) file. The make, model, and series information was used to classify the aircraft into its appropriate wake-related weight classes, namely General Aviation (GA), Small, Large, B757, and Heavy. In particular, only track files for Large, B757, and Heavy aircraft were used in the FTE analysis.

Riegl Data

The LRF 200-Hz raw data contain time, height of return and amplitude of return. The real-time identification of arrival events required a minimum of three hits. Because of signal degradation during bad weather, this requirement had to be reduced to one hit, with the additional requirement that the height be above 33 feet.

The measurements for the event are saved and processed to obtain the arrival parameters listed in Table 3.

Table 3: Sample Range Finder Arrival Data

Parameter	Arrival
StartDate	4/20/2004
StartTime	19:08:04.0
StopDate	4/20/2004
StopTime	19:08:04.3
RefDate	4/20/2004
RefTime	08:04.2
Duration	00:00.3
MaxRange (m)	32.53

Parameter	Arrival
MinRange (m)	30.913
AvgRange (m)	31.4812
MaxAmplitude	56
MinAmplitude	28
AvgAmplitude	48
Samples	47
Gated Samples	47
Runway	12R

Additional event filtering was carried out off line and was necessary during bad weather periods. Height limits on the raw data were assigned into two bins: (a) >150 ft for 12L, and (b) between 90 and 160 ft for 12R. If there were many events within seconds of each other, only one was accepted, based on manual screening of the number of samples and the number of continuous samples (termed “gated” samples). Typically the event with the largest number of samples (usually near 50) was accepted. This further filtration was only necessary on bad weather days when the LRF measurements were noisy. Otherwise, the hits were clean, occurring a few minutes apart during peak traffic times.

Analysis Tiles

To meaningfully compare the positions of different aircraft at different times to the ILS localizer and glide slope centerlines at various distances from the arrival threshold, ten Analysis Tiles were defined. See Figure 5.

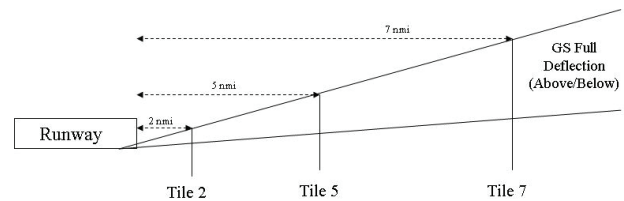


Figure 5: Analysis Tiles

For example, Tile 5 is the vertical plane whose face is exactly 5 nmi from the arrival threshold, where the distance is corrected for the curvature of the earth. For each arrival runway, there is one analysis tile at each nautical mile from the arrival threshold, from Tile 10 to Tile 0 (the threshold itself). When an aircraft “punctures” an analysis tile, the lateral distance from the ILS localizer centerline and the vertical distance above or below the ILS glide slope centerline were recorded. These

are the measures of FTE at various distances from the arrival threshold.

Weather Condition Binning

The positions of the aircraft in each analysis tile were classified according to the current terminal-area based weather conditions (which were assumed to be the same in each analysis tile). The specific conditions available were (a) wind speed, (b) wind direction, (c) minimum ceiling, and (d) visibility, all available from Automated Surface Observing System (ASOS) data at the KSTL station that was updated every five minutes.

The wind speeds were divided into four ranges, or “bins.” Those bins were (i) 0-5 kt, (ii) 5-10 kt, (iii) 10-15 kt, and (iv) 15+ kt. The wind directions were binned at two levels. The general direction of the wind was either a (i) headwind, or a (ii) tailwind. Furthermore, each type of wind direction was either (i) dominant (the incident angle of the wind direction to the aircraft heading is less than 45 degrees in absolute value; colored as yellow in Figure 6), or (ii) non-dominant (the incident angle is more than 45 degrees in absolute value; colored as red in Figure 6).

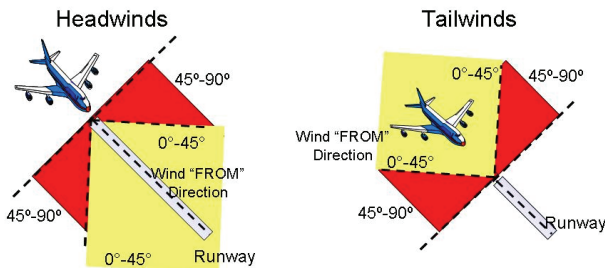


Figure 6: Wind Direction Binning

The minimum ceiling value was binned into (i) Under 1,200 ft, (ii) Between 1,200 and 4,000 ft, and (iii) Above 4,000 ft

Finally, visibility was binned into (i) 0-4 statute miles (smi), (ii) 4-8 smi, and (iii) More than 8 smi.

Therefore, each track could be classified into one of 144 bin combinations. However, to limit the complexity of so many distinct analysis groups, the ceiling and visibility bin combinations were grouped into three categories: (1) Visual (when the minimum ceiling is above 4,000 ft and the visibility is more than 8 smi), (2) Marginal Visual Meteorological Conditions (VMC) (when the minimum ceiling is above 1,200 ft and the visibility

is more than 4 smi, but the conditions are not Visual), and (3) “Hard” Instrument Meteorological Conditions (all minimum ceiling and visibility combinations that are not Visual nor Marginal VMC). See Figure 7.

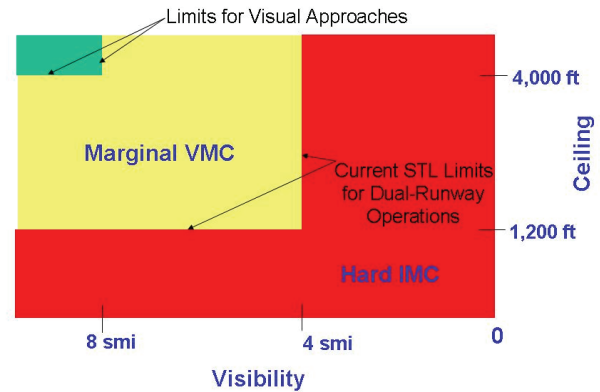


Figure 7: Minimum Ceiling/Visibility Categories

“Hard” IMC

The so-called “Hard” IMC minimum ceiling/visibility conditions are the situations under which non-visual operations are normally performed at STL, and when the strictest adherence to ILS localizer/glide slope guidance would be expected. Therefore, this FTE analysis uses only track files fulfilling all data quality requirements and which completely occur under “Hard” IMC conditions.

Data Organization

Table 3 shows the distribution of the FTE analysis data according to the weather condition binning.

Table 3: Classification of FTE Analysis Data

Direction Speed	Headwind		Tailwind		Totals
	MVMC	HIMC	MVMC	HIMC	
0 – 5 knots	511	377	189	175	1,252
5 – 10 knots	2,899	2,507	225	88	5,719
10 – 15 knots	1,774	1,002	220	56	3,052
15+ knots	301	66	115	0	482
Totals	5,485	3,952	749	319	10,505

The most frequently occurring weather condition bin under “Hard” IMC is for headwinds

(relative to the aircraft heading) between 5 and 10 kt. Although not shown in Table 3, 90.1% of these headwinds were dominant. Furthermore, since there are more than 25 times more tracks with headwinds under “Hard” IMC than with tailwinds (dominant and non-dominant), all tailwind tracks were combined with the headwind tracks to perform the definitive FTE analysis (while still maintaining the wind speed binning).

Final Data Adjustments

The following final data adjustments were performed before the FTE analysis was completed.

1. All track data are converted to a common reference plane, regardless of arrival runway. In ASDE-X CAT-11 MSDP output, the ATC tower is used as the origin of the rectangular grid coordinates, i.e., x- and y-coordinates representing horizontal and vertical distances (in feet) from the origin. These coordinates were translated and rotated so that the origin was at the arrival threshold centerline, regardless of the particular arrival runway.
2. Altitude corrections are made for the curvature of the earth.
3. Further altitude corrections were made for the Mean Sea Level (MSL) altitudes reported for each aircraft so that a common Height Above Terrain (HAT) is reported for each position report in the track data.

Calculations were then made for each analysis tile to record the lateral distances from the ILS localizer centerline and the vertical distances from the ILS glide slope centerline.

The ASDE-X Data Results

Regardless of weather condition bin, including wind speed and direction, the analysis data strongly supports the conclusion that the FTE observed for arrivals under “Hard” IMC is significantly tighter than the ICAO navigation tolerances commonly used in safety simulations.

For example, in Tile 5 (Figure 8) under the “hardest” of the “Hard” IMC arrivals, in particular, for the 368 arrivals on Runway 30R when the minimum ceiling was less than 200 ft and the visibility was less than 1 smi, the localizer FTE and glide slope FTE (shown as a blue point representing

the position report for a single aircraft) are significantly less than those allowed under the 380/760 ft ICAO tolerances. The red dotted rectangle depicts the LPGR (horizontal) and the GSPGR (vertical) for the particular tile.

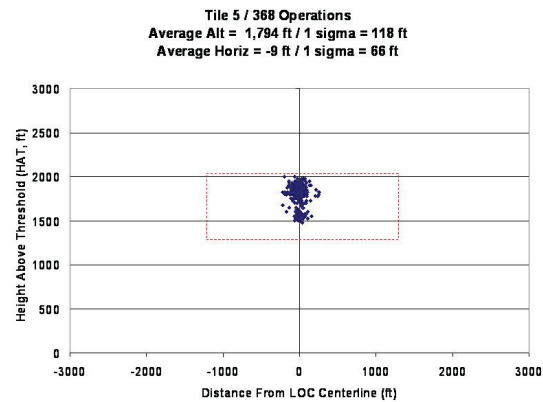


Figure 8: FTE Results at Tile 5

By Tile 3 (Figure 9), there is now data for 384 arrivals, and the localizer FTE has remained approximately the same. The glide slope FTE is now “riding high,” yet still within the GSPGR red rectangle except for 5 operations (at the very top of the main cluster). This barometric altitude data most likely did not represent the real altitudes of the arriving aircraft, as the following results indicate that Tile 3 show the first effects of discrete stratification, i.e., the data is only reported in 25 ft increments, and therefore cannot be used to make arbitrarily precise calculations.

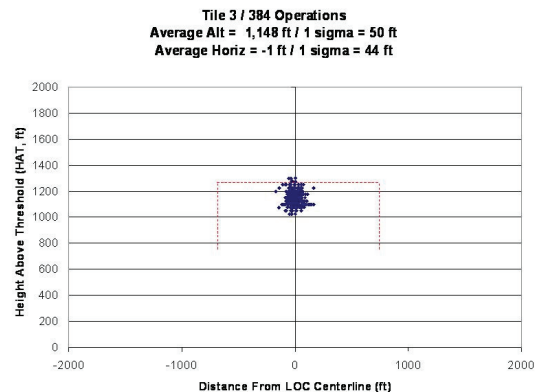


Figure 9: FTE Results at Tile 3

By Tile 1 (Figure 10), the HAT values have stratified into discrete values and show almost all aircraft descending far above the GS centerline. This demonstrates that the barometric altitude

becomes less and less reliable as the HAT value decreases. However, the localizer FTE has remained the same as before.

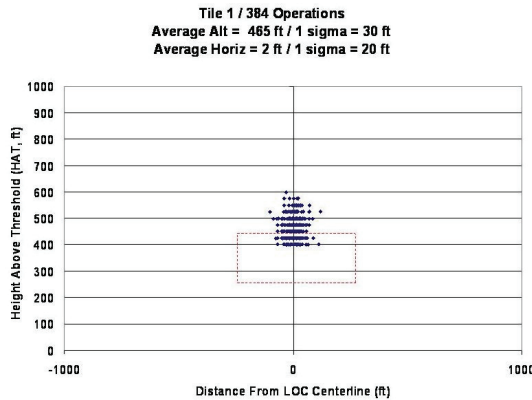


Figure 10: FTE Results at Tile 1 Showing HAT Stratification

Finally, at Tile 0 (Figure 11), the arrival threshold, the HAT stratification has overwhelmed the resolution of the data, which clearly shows that, as was the case from Tile 5, Riegl data is needed to evaluate glide slope FTE in general, and especially at such close proximity to the arrival threshold.

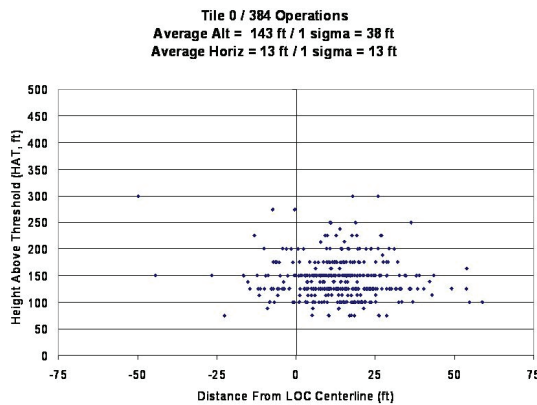


Figure 11: FTE Results at Tile 0 Showing HAT Variability

Similar results were found of every subgroup of data, regardless of wind speed or direction, and regardless of specific sub-range of “Hard” IMC.

In particular, Table 4 shows the sample average and unbiased sample standard deviation estimate of the population horizontal mean and standard deviation (localizer FTE mean/1-sigma) at each analysis tile for STL Runway 30R during “Hard” IMC. Note that a negative average value means “to the left of the localizer centerline,” while a positive average value means “to the right of the

localizer centerline” as viewed by the flight crew during arrival. Similar results apply from this analysis for all other runways during “Hard” IMC.

Table 4: STL Runway 30R Localizer FTE Mean/1-Sigma (ft) During “Hard” IMC

Tile #	Average	1- σ
10*	-36	450
9*	-14	315
8*	-65	235
7*	-104	139
6*	-90	124
5	-9	66
4	-7	50
3	-1	44
2	4	30
1	2	20
0	1	14

* NSE significant part of TSE

Note that for Tiles 6-10 of Table 4, the NSE was a significant part of the observed TSE data due to extensive missing and clearly impossible ASDE-X position data at those distances from an arrival threshold. This means the certainty of any analysis results for the localizer FTE for Tiles 6-10 is highly suspect.

However, the fundamental result of the analysis based on ASDE-X CAT-11 track data is that the observed localizer FTE within 5 nmi of the arrival threshold is significantly tighter than the ICAO tolerances, while the glide slope FTE data is too subject to error for conclusive results.

Riegl Data Results

The Riegl HAT calculations augment the inconclusive glide slope FTE analysis results from the ASDE-X CAT-11 track data. For example, for all arrivals on Runway 12L under the same “Hard” IMC as for the ASDE-X data (Figure 12), the average height of the aircraft over the Riegl is 190.5 ft with a standard deviation of 16.7 ft. The Runway 12L GS centerline HAT is 193 ft, so these results are well within the ICAO tolerances.

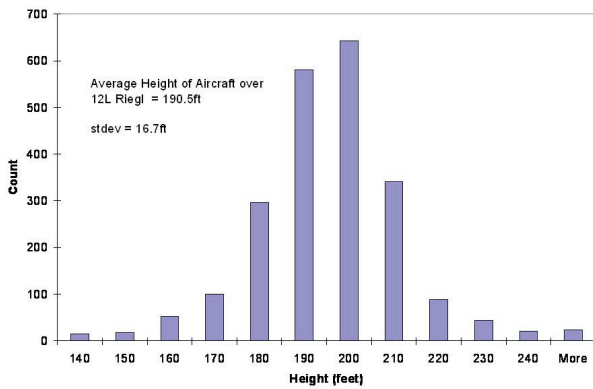


Figure 12: STL Runway 12L HAT Distribution

In addition, the same type of results applies for all arrivals on Runway 12R under the same “Hard” IMC as for the ASDE-X data (Figure 13), where the average height of the aircraft over the Riegl is 139.4 ft with a standard deviation of 12.2 ft. In this case, the GS centerline HAT is 141 ft, which demonstrates even tighter adherence to the ILS glide slope centerline than for arrivals on Runway 12L.

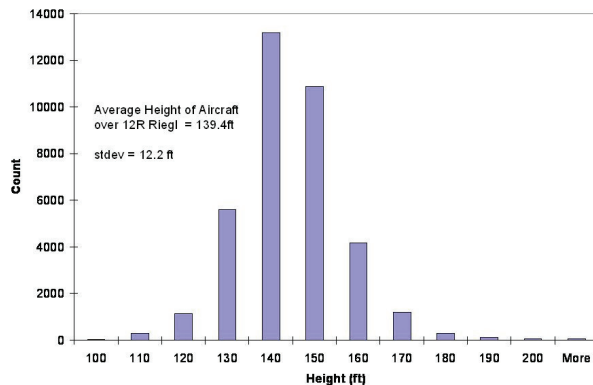


Figure 13: STL Runway 12R HAT Distribution

As with ASDE-X data, similar Riegl results were found of every subgroup of data, regardless of wind speed or direction, and regardless of specific sub-range of “Hard” IMC.

Conclusions

Through both ASDE-X CAT-11 track position data, carefully filtered for data quality, and through Riegl laser rangefinder technology that more accurately measures height above terrain than is available from a barometric altimeter, the actual

localizer and glide slope FTE of arrivals to STL were significantly tighter than the ICAO tolerances.

In conclusion, the FTE found in this analysis, which occurred under IMC weather that would most likely imply the strictest adherence to ILS localizer/glide slope guidance, were significantly tighter than the International Civil Aviation Organization (ICAO) navigation tolerances commonly used in safety simulations. This result is an important element in the safety analysis of the development of the new CSPR procedure with runway stagger.

References

- [1] Bryant, W., Lang, S., Tittsworth, J., and Darr, S., “Wake Vortex Avoidance System”, 1st CEAS European Air and Space Conference, CEAS-2007-175, Berlin, September 2007.
- [2] International Civil Aviation Organization, International Standards and Recommended Practices, *Aeronautical Telecommunications, Annex 10 to the Convention on International Civil Aviation, Volume 1: Radio Navigation Aids, Sixth Edition*, July 2006 (Revised November 23, 2006)
- [3] ICAO Document 9613-AN/937, *Manual on Required Navigation Performance (RNP)*, First Edition, 1994

Acknowledgments

The authors wish to thank Wayne Bryant of NASA Langley Research Center, Steven Lang of the FAA Air Traffic Organization, Rod Collins and Jeff Legge of the Sensis Corporation, Kevin Clark of the Volpe Center, Leo Jacobs of Titan SRC, and the information technology department at Lambert-St. Louis International Airport for their assistance and cooperation in collecting, delivering, organizing and interpreting the ASDE-X/Riegl data used in this analysis.

Email Addresses

Timothy Hall: Timothy.Hall@dot.gov

Melanie Soares: Melanie.Soares@dot.gov

27th Digital Avionics Systems Conference
October 26-30, 2008