# LOCALIZER FLIGHT TECHNICAL ERROR MEASUREMENT AND UNCERTAINTY

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## Abstract

Recent United States Federal Aviation Administration (FAA) wake turbulence research conducted at the John A. Volpe National Transportation Systems Center (The Volpe Center) has continued to monitor the representative localizer Flight Technical Error (FTE) associated with Instrument Landing System (ILS) arrivals. This work complements, extends, and improves on previously published localizer FTE results by calculating FTE from more recent Airport Surface Detection Equipment – Model X (ASDE-X) datasets with improved data quality characteristics, as well as providing a quantification of the FTE measurement uncertainty due to the geometry of the Remote Unit (RU) sensor array that provides the analysis data. The technical description of the ASDE-X system is published as [**1**].

This paper presents additional FTE results and improved uncertainty calculations for ILS arrivals at John F. Kennedy International Airport (JFK) and Detroit Metropolitan Wayne County Airport (DTW), as well as comparisons with previous documented FTE results from Lambert – St. Louis International Airport (STL).

The measurement uncertainty assessment provided insight on the level of confidence that can be placed in each runway specific dataset, and these localizer FTE results confirm the previously published observation that the observed FTE performance is consistently much tighter than the International Civil Aviation Organization (ICAO) navigation tolerances commonly used in safety simulations.

***Keywords: Localizer FTE, CSPR, Cross-track Component of FTE, Best-fit Closest-point Distance Regression***

## Introduction

United States Air Traffic Control (ATC) regulations require aircraft approaching parallel runways spaced less than 2500 feet apart, i.e., Closely-Spaced Parallel Runways (CSPR), during IMC to be either separated horizontally as if all traffic were in a single arrival queue, or to not use the parallel runway at all. As a direct consequence, arrival capacity during IMC is at best half the capacity during Visual Meteorological Conditions (VMC). This promotes arrival delays, as flights are scheduled based on capacity under VMC.

A National CSPR Rule Change, otherwise known as the FAA Order 7110.308 [**7**], was recently implemented in the National Airspace System (NAS). The rule allows for separate arrival streams, during Instrument Flight Rules (IFR), to CSPR runways. This procedure included restrictions on participating aircraft weights and geometries. Aircraft were arranged in pairs, with the lead aircraft on the same or lower glide slope and the second aircraft trailing by at least 1.5 nautical miles (nmi) diagonally. A part of the safety risk analysis for this procedure included FTE results using aircraft surveillance data collected from STL during the winter of 2006, and published as [**2**].

Additional ASDE-X surveillance data was collected from DTW and JFK to supplement, expand on, refine, and confirm the FTE calculations found in [**2**]. The ASDE-X system for STL differed from DTW and JFK by an enhanced “outer ring” of sensors during an experimental phase (no longer operational) which allowed for better aircraft tracking beyond 5 nmi of the airport. This was accomplished by off-airport multilateration sensors adjacent to the approach corridors at both ends of runways 12L/R and 30L/R. ASDE-X provides horizontal position information relative to a “System Plane” Euclidean coordinate grid (a stereographic projection onto the tangent plane to the Earth at an origin in the terminal area) whose accuracy depends, in part, on the particular geometry of the Remote Unit (RU) sensors array that provides the position data.

### *Analysis Context*

An aircraft arriving on a CSPR utilizes (if available, and at airports authorized to conduct operations under FAA Order 7110.308) an Instrument Landing System (ILS) which guides the crew to align the aircraft with the arrival runway extended centerline (which is assumed to be the same as the centerline of the ILS guidance region). The calculated FTE values represent the lack of adherence of the aircraft track to this ILS centerline. JFK ASDE-X data were processed to provided individual aircraft tracks separated by arrivals/departures and runways. Only arrival tracks for approaches conducted to ILS equipped runways and conducted during “Hard” IMC (HIMC) weather conditions, to be defined in section I.C, were included. The filtering criteria of HIMC were used to ensure that the possibility of the aircraft actually being on the ILS centerline is maximized. The tracks underwent adjustments for individual variations in barometric altitude readings, and for the curvature of the Earth relative to the System Plane. These corrections were used to calculate the track’s FTE, a function of the observed deviations from the ILS extended centerline. The FTE is a statistic of the distribution of the lateral perturbations, or dispersion from the ideal arrival path (once established on the localizer) as a function of the distance from the arrival runway threshold. In the context of wake turbulence analysis, FTE is combined with the probability of the spatial distribution of the vortices, at a given time frame and runway geometry, to allow the assessment of wake encounter probabilities. The observed FTE is a combination of (a) horizontal deviations from the arrival centerline due to the actual flight path, plus (b) the position error due to signal processing limitations due to the sensitivity and processing accuracy of the sensor array, and (c) the unavoidable error introduced by the geometry of the RU sensor positions. This paper presents a method for quantifying the uncertainty in the FTE due to RU geometry (part (c) of the FTE) through a statistical variance/covariance calculation that is based on the ideal arrival track for a particular runway. This calculation shows that the uncertainty in the FTE due to RU geometry is very sensitive to RU placements, and in order to have meaningful FTE statistics, these uncertainties must be kept small relative to the observed FTE values.

In particular, the FTE results presented in this paper confirm the observation previously published in [**2**] that the observed FTE performance is consistently tighter than the International Civil Aviation Organization (ICAO) navigation tolerances commonly used in safety simulations. These results continue to play an important role in aviation safety analyses involving CSPR operations.

### *ICAO Full Deflections*

According to [**3**], conforming ILS localizer signals produce a localizer Proportional Guidance Region (PGR) according to the dimensions found in Table 1.

For example, when an aircraft is 2 nautical miles (nmi) from the arrival threshold (regardless of the length of the runway itself), 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 deflection widths to 10 nmi, the actual ILS signals extend as far as the signal strength allows, with corresponding deflection distances.

**Table 1: ICAO Localizer PGR Full Deflections**

| Track Distance** | Full Deflection*** |
|---|---|
| 1 nmi | ± 525 ft |
| 2 nmi | ± 705 ft |
| 5 nmi | ± 1,235 ft |
| 7 nmi | ± 1,588 ft |
| 10 nmi | ± 2,120 ft |

** Distance from arrival threshold
*** Distance from LOC Centerline

Furthermore, it will be assumed that the ILS is sufficiently calibrated and maintained so that the ILS centerline agrees with the runway centerline, as assessed by the sensor systems that produce the position data.

### *“Hard” IMC*

The so-called HIMC minimum ceiling/visibility is defined within the present analysis framework as less than 1,200 ft ceiling and less than 4 statute mile visibility. See Figure 1. HIMC values are the meteorological conditions under which non-visual operations are expected to be performed, and when the strictest adherence to ILS localizer guidance would be necessary and expected. Therefore, the FTE calculations only use track data which completely occur under HIMC conditions, and that fulfill all data quality requirements. Therefore, without access to the details of the crew intent for each arrival in the ASDE-X data, the HIMC filter is used to maximize the likelihood that the associated flight tracks were conducted under ILS approaches.

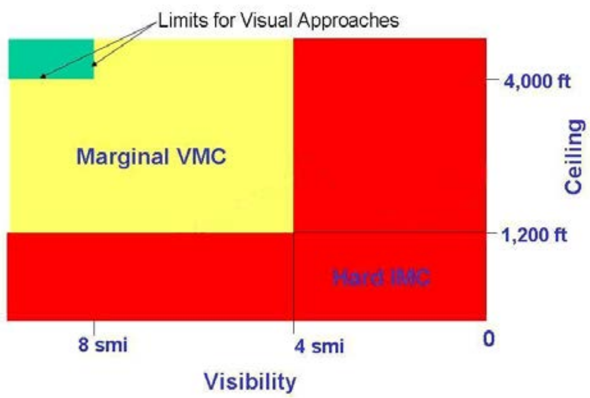



**Figure 1: Minimum Ceiling/Visibility Categories**

## Best-Fit FTE Calculation Methods

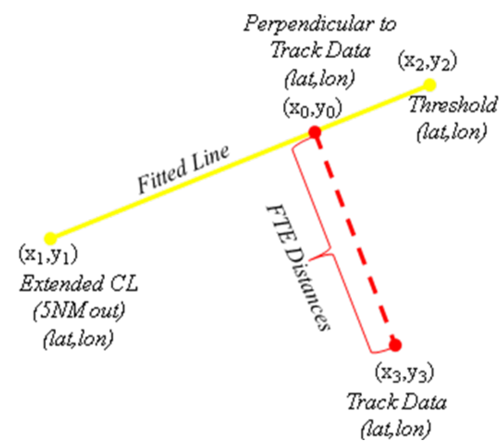
The following analytical methods provide elementary formula (solving a fourth-degree polynomial) for automatically calculating "best fit" FTE values for a given set of track data.

A commonly used measure of “best fit” is finding the minimum sum of squared FTE distances for all track data points. This is the approach used in finding regression and correlation coefficients. Such an automatic calculation requires mathematically parameterizing the ILS localizer centerline in terms of a single parameter, then finding the value of that parameter that minimizes the sum of squared FTE distances.

Given an aircraft's position reports throughout its arrival path (the “track data”) the reference coordinates are translated so that arrival runway’s threshold is the origin. The goal is to find the unique line $y=m*x$ (the “fitted line”) so that the sum of squared distances from this line to the track data is minimized. In particular, we want to find the value of $m$ that minimizes the sum of all squared minimum straight-line distances (the “FTE distances”) from the fitted line to the track positions values based *only* on the track data. This formulation results in a fourth-degree polynomial in $m$ with coefficients that are functions of the track data exclusively. In fact, the real solutions to this polynomial contain the minimizing *and* maximizing value of $m$, so that the calculation implementation procedure must take care to choose the minimizing value of $m$ among all solutions. This minimizing value of $m$ generates the “best-fit” FTE distances.

The FTE distance can then be calculated by finding the distance between the point $(x_0,y_0)$ on the Fitted Line (defined by (x1,y1) and (x2,y2)) that is perpendicular to the Track Data point and the Track Data point $(x_3,y_3)$. See Figure 2 and Equations 1 and 2, for the explicit calculation methods.

**Figure 2: FTE Distance Calculation**



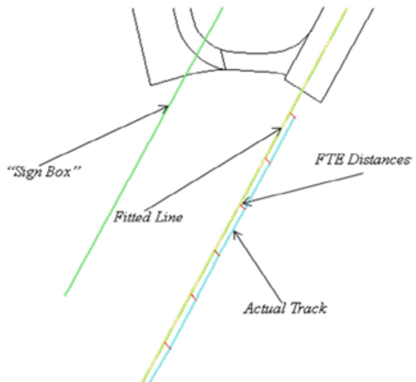

**Equations 1, 2: Point Perpendicular to Track Data**

$$x0 = -\left(\frac{y2 - y3 - \frac{y1-y2}{x1-x2}x2 - \frac{x1-x2}{y1-y3}x3}{\frac{y1-y2}{x1-x2} + \frac{x1-x2}{y1-y2}}\right)$$

$$y0 = y2 + \frac{y1-y2}{x1-x2}(x0 - x2)$$

Since the calculated FTE Distances are always absolute, it is necessary to determine which side of the extended centerline the aircraft resides. This is accomplished by placing a sign box on the left side of the extended centerline and aircraft inside the box are considered negative and outside positive. See Figure 3.

**Figure 3: FTE Sign Box**




## FTE Uncertainty Due To RU Geometry

Originally developed for LOng RAnge Navigation (LORAN) terrestrial radio navigation applications, but more recently extended to geomatic engineering in general, and Global Positioning System (GPS) in particular, the concept of the Cross-track Component of Flight Technical Error (XTE) is a measure of the precision to which the particular geometry of a differential positioning system, such as a ground-based terminal-area multilateration system, can calculate the position of a target at a particular point in the detection volume of the RU sensor array. The XTE calculation also measures the extent to which this precision "dilutes" as the target moves relative to the sensor positions. Since XTE takes into account an aircraft's horizontal and altitude positions at each point in time along a perfectly-executed localizer and glide-slope guided arrival approach, it may be used to comprehensively measure the minimum FTE value that a particular arrangement of sensors may achieve regardless of an aircraft's position. Furthermore, since it is a function of the covariance matrix of relative distances from the target to the sensors (in a three-dimensional Euclidean plane frame of reference, such as that found in System Plane coordinates), the XTE units correspond to the units of distance in its calculations.

### *Calculation Methods*

The following analytical development is consistent with the GPS-related precision dilution calculation methods found in [**4**], [**5**], and [**6**], based on a System Plane coordinate system provided by ASDE-X processors.

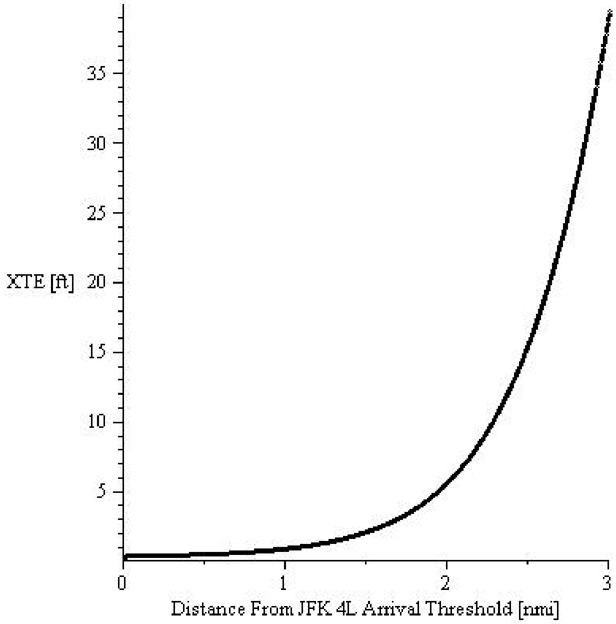
Suppose there were N(d) sensors that receive an aircraft's multilateration signal at distance d (along the ILS centerline) from the arrival threshold, and suppose that position is given by (x(d),y(d),z(d)) at distance d. The value of z(d) is the reported Mode-C altitude corrected for the actual terminal-area barometric pressure, as well as for the curvature of the Earth relative to the System Plane. Since at least four sensors must detect a target signal to calculate a multilateration position in three dimensions, then N(d) must be at least 4 for all distances d. Let (x[i],y[i],z[i]) be the (static) position of sensor i, for i=1,2,…,N(d).

Define M(d) to be the standardized, i.e., re-scaled to a common distance unit, variance/covariance matrix of the differences between the sensor positions (x[i],y[i],z[i]) and the positions an aircraft would be in at distance d from the arrival threshold if it were following a perfectly-aligned localizer and glide slope track along the extended arrival runway centerline. There would be one row in M(d) for each of the N(d) sensors that detect an aircraft's track. For completeness, it will be assumed that N(d) is always the same value regardless of distance d, namely, the full number of RU sensors in the terminal area. This assumption produces the smallest XTE number possible. The square root of the sum of the first two main diagonal elements (the horizontal elements) of the inverse of the matrix square of M(d) is the XTE value for an arrival on the particular runway in the analysis. The XTE units are the same as for the distances used in the calculations.

### *JFK XTE*

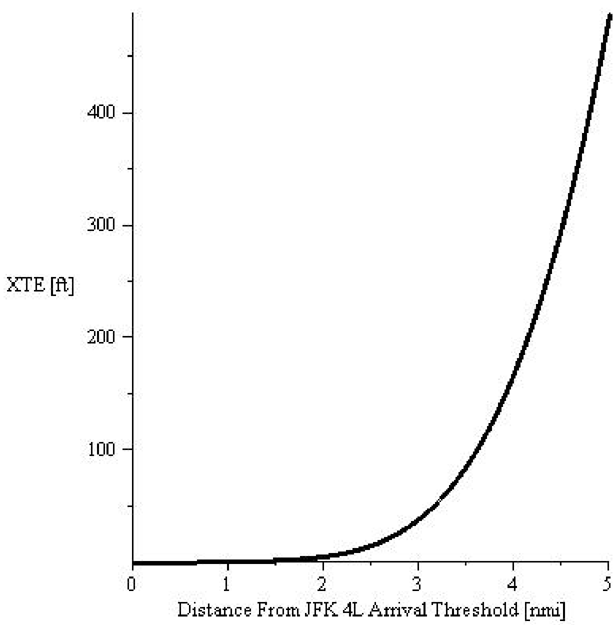
Figure 4 shows the XTE for arrivals on JFK 4L from the arrival threshold to 3 nmi along the extended runway centerline. The XTE is less than 1 foot from 0 – 1 nmi, but then rises rapidly to more than 5 feet at 2 nmi, and to 40 feet by 3 nmi. This means, for example, at 2 nmi from the arrival threshold along the 4L extended centerline, the ASDE-X RU sensor array at JFK produces position reports that have an XTE of approximately 5 feet, i.e., the system is incapable of meaningfully providing a statistically relevant FTE distribution relative to the localizer centerline that has less than 5 feet of error.

**Figure 4: XTE for JFK 4L 0 – 3 nmi**




For distances from 0 – 5 nmi from the 4L arrival threshold (along the extended centerline), Figure 5 shows that the XTE explodes quickly to almost 500 ft, which is slightly less than half of the half-width of the localizer PGR at 5 nmi.

**Figure 5: XTE for JFK 4L 0 – 5 nmi**




It is clear from these calculations that, for arrivals on JFK 4L, the closer to the arrival threshold the position reports occur, the more accurate the position report can be, hence the more meaningful the associated FTE statistics.

### *STL XTE*

Compare the XTE results at JFK with those found at STL (with the entire set of RU sensors). Figure 6 shows the XTE for arrivals on 12R from 0 – 5 nmi. Note that throughout this range, the XTE remains under 1 foot. This is the consequence of the outer ring RU sensors, which encircle the arrival track from as far out as 17 nmi.

**Figure 6: XTE for STL 12R 0 – 5 nmi**

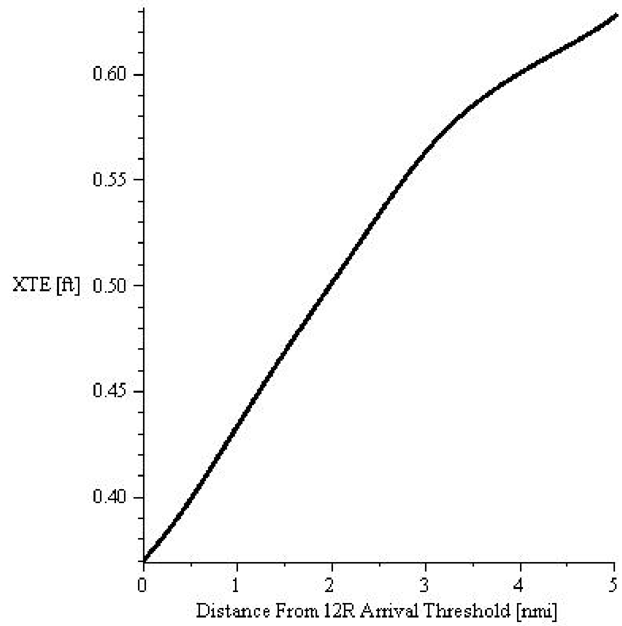
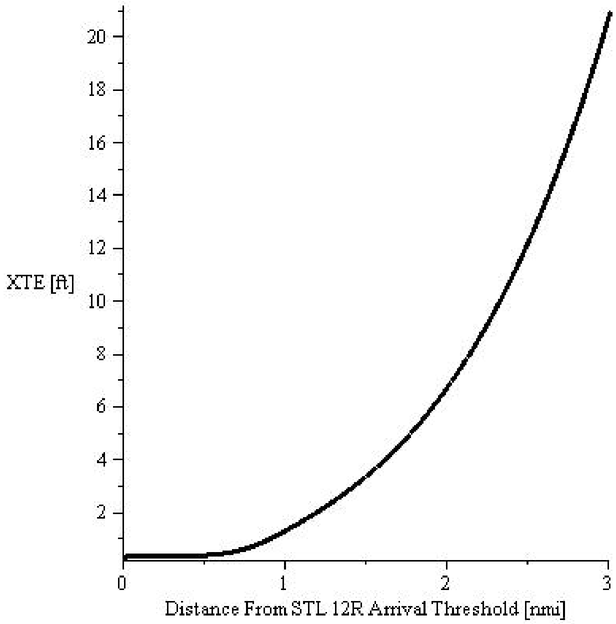


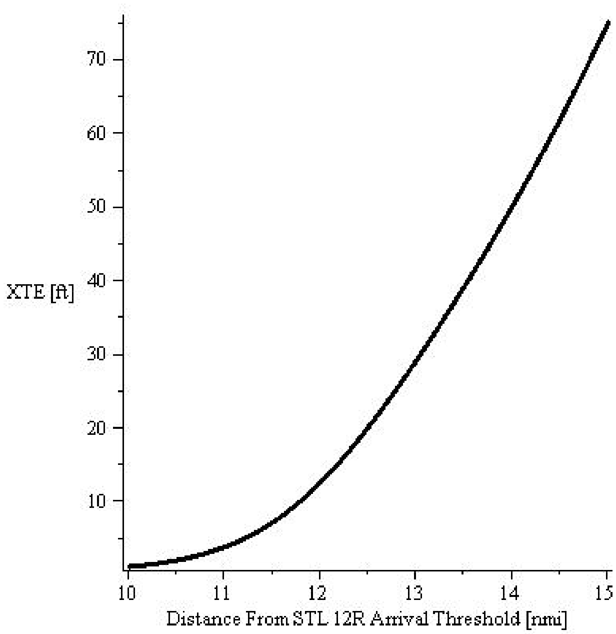

Figure 7 shows the effect of removing the outer ring RU sensors (out of 18 total) from the calculation. Note how the XTE remains relatively low within 0 – 3 nmi, as was the case for JFK; however, the XTE has increased to 21 ft at 3 nmi without the benefit of the outer ring RU sensors.

**Figure 7: XTE for STL 12R 0 – 3 nmi (No Outer Ring)**




Note also that when all RU sensors are considered, for distances even as great as 15 nmi, the XTE for STL 12R arrivals is still less than 80 feet, and the rate of increase is approximately linear after 12 nmi. See Figure 8.

**Figure 8: XTE for STL 12R 10 – 15 nmi**




In summary and as a basis of comparison, Table 2 shows the calculated XTE values at several high-capacity United Stated airports (and a frequently used arrival runway) at various distances from the arrival threshold.

Although we will not be showing FTE results for Chicago O'Hare International Airport (ORD) or Newark Liberty International Airport (EWR) we can conclude, for example, that at 3 nmi, ORD would provide more reliable data than JFK and JFK would provide more reliable data than EWR.

Also, we are not presenting XTE results for DTW since this site used a pre-certification RU arrangement whose geometric details were not accessible to the authors.

**Table 2: Comparison XTE Values**

| Distance | Rwy | 0 ft | 1K ft | 2K ft | 3K ft | 1 nmi | 2 nmi | 3 nmi | 4 nmi | 5 nmi |
|---|---|---|---|---|---|---|---|---|---|---|
| STL | 12R | < 1 | < 1 | < 1 | < 1 | < 1 | < 1 | < 1 | < 1 | < 1 |
| ORD | 28 | < 1 | < 1 | < 1 | < 1 | < 1 | 2 | 16 | 64 | 185 |
| JFK | 4L | < 1 | < 1 | < 1 | < 1 | 1 | 6 | 40 | 170 | 489 |
| STL (w/o Outer Ring) | 12R | <1 | <1 | <1 | <1 | <2 | 7 | 21 | 52 | 109 |
| EWR | 22R | < 1 | < 1 | < 1 | < 1 | 2 | 70 | 495 | 1,770 | 4,613 |

At STL there were 18 total RU sensors used in calculating the XTE for arrivals on runway 12R as far out as 17 nmi from the arrival threshold. At Chicago O'Hare International Airport (ORD) and at JFK there were 13 RU sensors used in calculating the XTE for arrivals on runways 28 and 4L, respectively, and at Newark Liberty International Airport (EWR) there were 12 RU sensors used in calculating the XTE for arrivals on runway 22R.

Note that, in general, the XTE for arrivals on a particular runway is *not* the same as the XTE for arrivals on the same runway in the opposite direction. For example, the XTE for arrivals at EWR on runway 22R is not the same (at any distance from the arrival threshold) as for arrivals on runway 4L.

Note also the differences in XTE values at STL when the outer ring (the RU sensors furthest from the origin) was excluded from the calculation. The STL FTE values at further distances away from the airport would essentially be unusable without the benefit supplied by the functioning outer ring RU sensors.

## The Analysis Data

All JFK data used in this analysis were collected from April 2, 2009 – April 4, 2010 from the ASDE-X system in ASTERIX Category 011 (CAT-11) format, which were then filtered for quality purposes, specifically

- Removing tracks with time gaps exceeding 5 seconds;
- Excluding position, speed, and acceleration reports from tracks that were either physically impossible or were significantly inconsistent with the prior track of an aircraft; and
- Deleting position reports from tracks with redundant or contradictory identifications.

Additional filtering of the track data produced an analysis dataset for arrivals that occurred under HIMC only, and were within 3 – 5 nmi of the arrival runway threshold. Currently there is no method available to discern the intent of the flight crew. Therefore, these restrictions on the analysis data maximize the likelihood that the aircraft are flying the ILS (with the possible exception of RNAV/RNP approaches), thus maximizing the likelihood that the aircraft are intended to be aligned with the localizer centerline throughout its final approach.

There were 76,788 arrival tracks available at JFK that occurred on runways 4L, 4R, and 31R. Of these, only 5,115 occurred during HIMC and passed the quality filtering criteria for usable tracks.

The STL data contained 32,005 arrival tracks (collected from December 1, 2005, through February 28, 2006), of which 10,505 occurred during HIMC and passed the same quality filtering criteria as was used for JFK data (see [**2**]).

There were also 705 arrival tracks available at DTW (collected from January 14 – 16, 2003, and February 1, 2, 7 – 9, 2003), which occurred on runways 4L/R, 22L/R. Of these, only 78 occurred during HIMC and passed the same quality filtering criteria as were used for JFK data.

## The FTE Results

Table 3 reports the 3σ (population) standard deviation, and the ICAO full deflection distances for JFK, DTW, and STL arrivals during HIMC at various distances from the arrival threshold. All reported values are in feet.

Note that the one-sided FTE values found in Table 3 for JFK 3σ do not include entries at 4 and 5 nmi. The analysis data at these distances did not pass the data quality filters imposed for FTE calculations, which is consistent with the relatively high XTE values (from 287 – 719 feet, see Table 2) found at 4 and 5 nmi at JFK for over-water straight-line arrival approaches (4L/R, 31R).

Note also that the entries in Table 3 at 1K, 2K, and 3K for STL 3σ are missing, as FTE calculations at those distances were not included in the original STL FTE calculations (see [**2**]). However, the STL 3σ FTE values at the arrival threshold and at 1 nmi may be used to interpolate corresponding FTE values at 1K, 2K, and 3K distances. These values would still be smaller than the full deflection distances.

**Table 3: FTE at JFK (4L/R, 31R) During HIMC with Comparisons to DTW and STL**

| Distance | 0 ft | 1K ft | 2K ft | 3K ft | 1 nmi | 2 nmi | 3 nmi | 4 nmi | 5 nmi |
|---|---|---|---|---|---|---|---|---|---|
| JFK 3σ | 81 | 88 | 96 | 103 | 112 | 156 | 185 | n/a | n/a |
| DTW 3σ | 17 | 25 | 22 | 30 | 49 | 63 | 85 | 23 | 68 |
| STL 3σ | 43 | N/A | N/A | N/A | 62 | 94 | 133 | 157 | 207 |
| Full Def. | 345 | 375 | 405 | 434 | 525 | 705 | 882 | 1,062 | 1,235 |

Table 4 reports the calculated average (mean) one-sided FTE values for JFK arrivals during HIMC by aircraft weight class. Note that "Jumbo" in this case refers exclusively to the Airbus 380 (and includes only one track). The term "Large/RJ" refers to a subset of the Large weight class containing regional jets (see [**8**] for an explicit listing of aircraft in each weight class).

**Table 4: Mean FTE at JFK (4L/R, 31R) During HIMC by Aircraft Weight Class**

| Distance | 0 ft | 1K ft | 2K ft | 3K ft | 1 nmi | 2 nmi | 3 nmi |
|---|---|---|---|---|---|---|---|
| B-757 | 20 | 14 | 16 | 20 | 21 | 33 | 5 |
| Heavy | 19 | 16 | 18 | 22 | 22 | 31 | -5 |
| Jumbo | -2 | 6 | 10 | 1 | 4 | -1 | -11 |
| Large | 19 | 17 | 20 | 24 | 22 | 28 | -1 |
| Large/RJ | 20 | 19 | 21 | 27 | 28 | 43 | 13 |
| S | 21 | 3 | 1 | 3 | -2 | 25 | 8 |
| S+ | 12 | 10 | 12 | 17 | 9 | 42 | 17 |

Other than Jumbo (which includes only one track), there appears to be no real difference between weight class categories. These results are expected since all aircraft should be adhering to the ILS guidance system regardless of their weight class.

Table 5 reports the calculated 3-σ (population) standard deviation one-sided FTE values for JFK arrivals during HIMC by aircraft weight class. This value represents the upper bound on FTE distances for approximately 99.7% of the track data used in the analysis.

**Table 5: 3-σ FTE at JFK (4L/R, 31R) During HIMC by Aircraft Weight Class**

| Distance | 0 ft | 1K ft | 2K ft | 3K ft | 1 nmi | 2 nmi | 3 nmi |
|---|---|---|---|---|---|---|---|
| B-757 | 79 | 90 | 93 | 105 | 111 | 171 | 183 |
| Heavy | 81 | 88 | 94 | 101 | 112 | 148 | 171 |
| Jumbo | 58 | 77 | 103 | 97 | 104 | 99 | 94 |
| Large | 82 | 84 | 93 | 99 | 106 | 150 | 179 |
| Large/RJ | 78 | 92 | 102 | 112 | 126 | 165 | 212 |
| S | 65 | 78 | 77 | 87 | 80 | 225 | 217 |
| S+ | 119 | 99 | 105 | 96 | 97 | 179 | 200 |

Again, there appears to be no real difference between weight class categories. These results are expected since all aircraft should be adhering to the ILS guidance system regardless of their weight class.

## Conclusions

The calculated FTE values found for JFK data are slightly larger than those found in STL (reflecting, in part, the larger XTE values generally present at JFK compared to STL – see Table 2), however, JFK, DTW, and STL FTE values are significantly lower than the ICAO standard for full deflection distances, sometimes by as much as an order of magnitude. This confirms the conclusions reached in [**2**], with the additional merit of ensuring that (a) the FTE distances are the minimum such distances detected in the data due to the use of best-fit FTE calculation methods, and (b) such small FTE values are not the results of the particular sensor geometry at a particular terminal environment, rather the result of close adherence to the localizer centerline throughout the final approach phase of flight.

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[**2**] Hall, T., Soares, M., "Analysis of Localizer and Glide Slope Flight Technical Error," The 27th Digital Avionics Systems Conference (DASC), St. Paul, Minnesota, USA, October 26-30, 2008

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[**8**] United States Department of Transportation, Federal Aviation Administration, Air Traffic Control, Washington, DC, "FAA Order 7110.65 (Change 1), Appendix A: Aircraft Information, Fixed-Wing Aircraft," July 31, 2008


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## Glossary

**ASDE-X** – Airport Surface Detection Equipment – Model X

**ATC** – United States Air Traffic Control

**CSPR** – Closely-spaced parallel runways

**DTW** – Detroit Metropolitan Wayne County Airport

**EWR** – Newark Liberty International Airport

**FAA** – United States Federal Aviation Administration

**FTE** – Flight Technical Error

**GPS** – Global Positioning System

**HIMC** – "Hard" IMC

**ICAO** – International Civil Aviation Organization

**IFR** – Instrument Flight Rules

**ILS** – Instrument Landing System

**IMC** – Instrument Meteorological Conditions

**JFK** – John F. Kennedy International Airport

**LORAN** – Long Range Navigation

**ORD** – Chicago O'Hare International Airport

**PGR –** Proportional Guidance Region

**RNAV –** Area Navigation

**RNP –** Required Navigation Performance

**RU** – Remote Unit

**SMR** – Surface Measurement Radar

**STL** – Lambert – St. Louis International Airport

**The Volpe Center** – John A. Volpe National Transportation Systems Center

**XTE** – Cross-track Component of Flight Technical Error

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