

Gate-to-Gate with Modernized GPS, GALILEO and GBAS – Harmonization of Precision Approach Performance Requirements

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BIOGRAPHY

Wolfgang Schuster is a Research Fellow at Imperial College London, working on a European Commission project (ANASTASIA) to develop a flight management system (FMS) for the future. His contributions are mainly in the navigation unit which exploits multi-frequency satellite navigation systems including regional and local augmentations. He is also working in the transport telematics research area by developing innovative sensing technologies to monitor erratic driving and driver fatigue. Dr. Schuster obtained his B.A. in Physics and D.Phil. (PhD) in High-Energy Physics both from the University of Oxford (UK). He also holds a commercial pilot license.

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ABSTRACT

Satellite Navigation has become increasingly important in the optimization of the efficiency and safety within the aviation industry. ANASTASIA (Airborne New and Advanced Satellite techniques and Technologies in A System Integrated Approach) is a European Commission project within the Sixth Framework Program, with the basic objectives to define and implement future (beyond 2010) communication and navigation avionics based on satellite services, exploiting the multi-constellation and multi-frequency architectures in combination with multiple onboard sensors, to provide a worldwide gate-to-gate service. Included in the objectives are the preliminary development of advanced airborne systems for flight trial evaluation and the dissemination of results for standardisation activities. Studies have shown that stand-alone Global Navigation Satellite Systems (GNSS - GPS and GALILEO) or stand-alone GNSS augmented by Space Based Augmentation Systems (SBAS) cannot satisfy the demanding performance requirements of Category-II/III precision approaches or of surface

movement. To satisfy these requirements, Ground Based Augmentation Systems (GBAS) are needed.

To date, performance requirements have only been firmly established for the various phases of flight up to Category-I precision approach. Two methods have been used to derive the performance requirements for Category-II and III precision approaches: the "ILS (Instrument Landing System) Look-Alike Method" and the "Autoland Method". The "ILS Look-Alike Method" is based upon the concept of matching system performance at the Navigation System Error (NSE) level through linearization of the ILS performance specifications at a given height. The "Autoland Method" is based on the idea of evaluating the required performance to protect the safety of the landing operation, rather than by extrapolating the equivalent NSE performance from existing ILS specifications. Both methods lead to significant discrepancies in the performance requirements. This paper analyses each method, and identifies key differences. Potential solutions to harmonize the performance requirements obtained from these two methods are proposed.

INTRODUCTION

Defining the performance requirements for a particular phase of flight is a key element of operational safety. It is a pre-requisite to determining whether a given navigation system is suitable for this particular phase of flight. Defining these requirements for precision approach phases is the foundation of research in ANASTASIA (www.anastasia-fp6.org).

Originally, navigation capability was associated with the mandatory carriage and use of specific navigation equipment. More recently, the International Civil Aviation Organization (ICAO) developed the Performance Based Navigation (PBN) concept. PBN specifies system performance in terms of accuracy, integrity, continuity, availability (the parameters used depend on whether RNP or RNAV is specified) and functionality required for the proposed operation in the context of a particular airspace concept. Table 1 shows the latest values of the required navigation system performance for precision approaches.

Phase of Flight	Accuracy	Integrity			Continuity	Availability
	SIS (2 σ)	Alert Limits	Integrity Risk	TTA	Continuity Risk	
Cat-I	16 m (L) 4 m (V)	40 m (L) 10 m (V)	2E-7/150 s	6 s	8E-6/15 s	0.99 – 0.99999
Cat-II	6.9/6.1 m (L) 2.0/1.4 m (V)	17.3/17.9 m (L) 5.3/4.4 m (V)	1E-9/15 s	2 s	4E-6/15 s	0.99 – 0.99999
Cat-IIIa	6.2/3.6 m (L) 2.0/1.0 m (V)	15.5/10.4 m (L) 10.0/2.6 m (V)	1E-9/15 s	2 s	4E-6/15 s	0.99 – 0.99999
Cat-IIIb	6.2/3.6 m (L) 2.0/1.0 m (V)	15.5/10.4 m (L) 10.0/2.6 m (V)	1E-9/30 s (L) 1E-9/15 s (V)	2 s	2E-6/30 s (L) 2E-6/15 s (V)	0.99 – 0.99999

Table 1: Signal-in-Space Performance Requirements for the various phases of aircraft operation [1]

While the Signal-In-Space (SIS) performance requirements for Category-I approaches are well established, those for Category-II and III approaches have been under debate by the two main regulatory agencies – the EUROpean Organization for Civil Aviation Equipment (EUROCAE – EU) and the Radio Technical Commission for Aeronautics (RTCA – USA) - for several years. Two separate methods were used in the derivation of these requirements, with significantly different results, as shown in Table 1. (Note, as an example for Cat-IIIb accuracy requirements, 6.2 m was derived by the RTCA and 3.6 m by EUROCAE).

Early attempts by the Federal Aviation Administration (FAA) in the USA and the International Civil Aviation Organization (ICAO) All Weather Operations Panel (AWOP) to develop requirements for GNSS to support Category-II and III operations were based on the concept of matching system operational performance at the Navigation System Error (NSE) level through linearization of the ILS performance specifications (errors) at a given height. This resulted in the so-called *ILS look-alike* approach that was originally used to define the performance requirements for Category-I approaches and was adopted by EUROCAE to derive the allowed Navigation System Error (NSE) and the Alert Limits (AL) for Category-II and III approaches. The synthetic model in the ILS Collision Risk Model (CRM) was used to validate these results [2]. The RTCA adopted the performance requirements derived from the touchdown-requirements laid out in [3, 4], defining the maximum probabilities with which an aircraft is allowed to land outside the touchdown box. This so-called *Autoland* method aims at deriving performance requirements for GBAS equivalent to ILS in terms of operational safety.

This paper attempts to reconcile the two approaches and to explain any differences between them, with emphasis on the vertical performance requirements as these constitute the requirements that will ultimately determine the GBAS architecture that will be needed to satisfy Category-III approaches and landings.

ILS LOOK-ALIKE METHOD

The Instrument Landing System (ILS) uses two carriers (one for the localizer and one for the glide-slope) each of which is amplitude modulated by two tones. The depth of modulation (DM) of these two tones is a function of the angle of displacement from the centreline. The ILS aircraft receiver measures the difference in DM (DDM) between the two tones to compute the angular position. Any change in the transmission of the ILS signal that causes a change in the DDM at a given angle with respect to the nominal (expected) DDM at that angle (either due to transmitter or receiver failures) contributes towards the navigation system error (NSE). The various sources of error that can be identified from [5, 6] are:

- course alignment (variation in the mean ILS course line from the intended geometric approach centreline)
- beam bends (causing the ILS course line to fluctuate around the mean ILS course line)
- angular displacement sensitivity, corresponding to variations in the rate of change of DDM (as picked up by the aircraft receiver)
- the receiver centring error and
- various other sources of error such as the polarization of the carrier, receiver displacement sensitivity and receiver displacement linearity as well as noise as a result of RF interference and power supply interference.

The rationale for using the ILS performance specifications in the derivation of the GBAS performance requirements is the validation of ILS through many years of operational service, GBAS being intended to meet the same operational requirements as, with equivalent performance to, ILS.

Accuracy – Navigation System Error (NSE)

The errors in [5, 6] are expressed in terms of angles and were conservatively assumed to be given as 3-sigma values in [2]. Various assumptions about the geometry of the runway and location of the localizer and glide-slope transmitters are made to convert the angular errors into

linear errors at a given distance from the landing threshold (and therefore at a given height above the threshold – assuming a nominal glide-path angle of 3 degrees). Figure 1 illustrates these considerations.

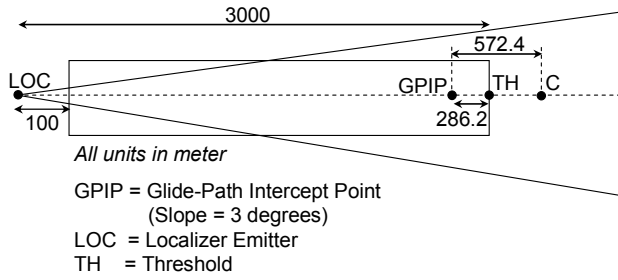


Figure 1: ILS Dimensions [2]

Error sources were assumed to be independent and Gaussian distributed, and the overall errors are calculated at 95% by taking the root of the sum-squared of the individual errors. The results are shown in Table 2.

Point of linearization	Errors at 95%
All points	0.1337 deg
TH (50 ft)	0.69 m
C (100 ft)	1.36 m

Table 2: ILS Errors

The point at which the vertical performance is required to be most stringent corresponds to the point at which the aircraft equipment makes the transition from using the glide-slope to using the radar-altimeter as the main instrument in the flare manoeuvre. The point at which this occurs is variable: most Airbus aircraft will not make use of the glide-slope below 60 ft, with the glide-slope typically being phased out below 100 ft [7].

Integrity – Alert Limits (AL)

In order to guarantee the integrity of the information output at the aircraft ILS receiver under both nominal and faulted conditions, errors greater than a given value (expressed in terms of an alert limit) that are not detected and annunciated within a given time (the time-to-alert – TTA) from the onset of the failure, may only occur with a limited probability – the Integrity Risk (IR), as shown in Table 1. For each of the errors described above, the alert limit requirements in [2] were derived based upon the ILS monitor limits specified in [5, 6], assumed to be given at the 5-sigma level. The same ILS geometrical considerations as above were used. The monitor limits were assumed to correspond to the maximum permissible errors without an alert. Bend and receiver centring errors were calculated at the limit of the displacement sensitivity defined by the monitor. The overall alert limit (shown in Table 3) was derived as the sum of the individual alert limits.

Point of linearization	VAL
All	0.436 degrees
TH (50 ft)	2.21 m
C (100 ft)	4.43 m

Table 3: Vertical Alert Limits derived from ILS Monitor Limits [2]

Choice of Linearization Height

In order to help determining the linearization height in [2], requirements to land within a given ‘landing box’ (LB) (set out in [3] and shown in Figure 2), were used in addition to the ILS specifications.

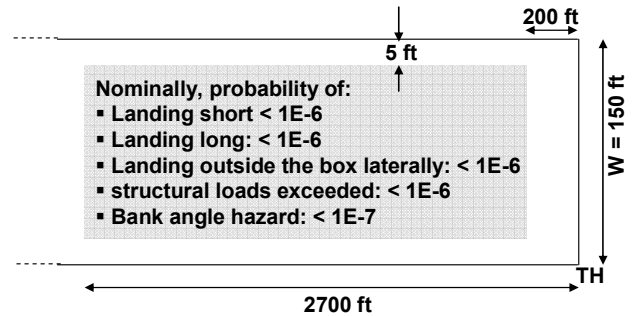


Figure 2: Landing Box Requirements [3]

By using the half-length of the touchdown-box as the nominal touchdown point (NTDP) at 1450 ft, the maximum allowable total system error along the runway ($TSE_{RWY,ILS}$) is computed as 1250 ft. Under the assumption that the flight technical error along the glide-path ($FTE_{GP,ILS}$) and the $NSE_{GP,ILS}$ are independent and that the statistical distribution of errors along the glide-path can be converted to a statistical distribution of errors along the runway through the flare manoeuvre, [2] relates the $TSE_{RWY,ILS}$ to the FTE along the glide-path ($FTE_{GP,ILS}$) by (see Figure 3):

$$TSE_{RWY,ILS} = \frac{FTE_{GP,ILS}}{\sin(\alpha - \epsilon_{NSE})} \quad (1)$$

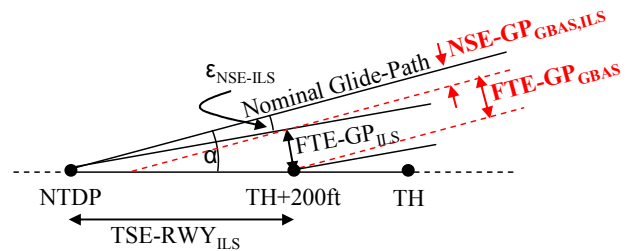


Figure 3: Alternative Derivation of GBAS NSE [2]

where ϵ_{NSE} corresponds to the angular error derived from the ILS performance specifications. By subtracting the $FTE_{GP,ILS}$ from the total $TSE_{GP,ILS}$ at $TH+200ft$, [2] extracts the $NSE_{GP,ILS}$ as:

$$NSE_{GP,ILS} = TSE_{RWY,ILS} \times (\sin \alpha - \sin(\alpha - \epsilon_{NSE})) \quad (2)$$

Using a nominal GPA = 3 degrees and $\epsilon_{NSE} = 0.1337$, the $NSE_{GP,ILS}$ is derived as 0.89 m. This value lies in between the values obtained from the 50 ft and 100 ft linearization heights and, being consistent with a typical height at which many aircraft cease to use the glide-path, was therefore selected in [2] as the minimum requirement. Note that a factor of 3.28 must be included to convert metres into feet.

Validation – Accuracy and Alert Limits

The accuracy and integrity values derived were validated using the synthetic model in the ILS Collision Risk Model (CRM), as described in detail in [2]. The difference with the simple RSS addition of the individual errors is that in this model, the total error is based upon a convolution of the individual errors. Table 4 shows a comparison of the RSS and CRM derivation of the NSE-GBAS errors and the VAL.

Point of linearization	Error – RSS (95%)	Error – CRM (95%)	VAL – SUM (5- σ)	VAL – CRM (6- σ)
Angle-deg	0.1337	0.1310	0.436	0.3931
At 100 ft	1.36 m	1.33 m	4.43 m	4.00 m
At 50 ft	0.69 m	0.67 m	2.22 m	1.99 m
Beta to Bias	0.89 m	0.87 m	N/A	2.62 m

Table 4: CRM Validation of Errors and VAL [2]

EUROCAE used Automatic Landing simulations with conservative assumptions on the FTE to further validate these requirements. The results thereof suggest that a NSE-GBAS of 1 m and a VAL of 2.6 m provides equivalent operational performance to ILS.

AUTOLAND METHODOLOGY

An alternative approach to the *ILS Look-Alike* method was developed as a joint program between Boeing [9] and the FAA, and adopted by the RTCA: *the Autoland* method. This method aims to establish requirements such that GBAS provides *operational safety* equivalent to current ILS systems, using current airworthiness certification criteria [3, 4] as a basis to establish these conditions. Whilst the ILS-LA method attempts to provide generic, architecture-independent, NSE requirements, the *Autoland* method (as interpreted in [9]) considers a specific architecture for GBAS Category-III with monitors, based upon the current proposed architecture for GBAS Category-I. The *Autoland* method assumes that, in addition to satellite navigation equipment, conventional aircraft equipment is used, such as a radar altimeter and autopilot, in the transition to the flare and touchdown manoeuvre.

Airworthiness Requirements

As shown in Figure 2, current airworthiness certification mandates that aircraft touch down inside the landing box with the given probabilities. These probabilities correspond to the ‘nominal’ conditions. Landings outside this box constitute a risk, and should occur at most with the given probability. In other words, the total system error (TSE) must be such that it only exceeds the landing box the fraction of landings corresponding to this probability. The total system error is composed of the Flight Technical Error (FTE) and the Navigation System Error (NSE), which are assumed to follow Gaussian distributions and to be uncorrelated. The variance of the TSE along the runway (RWY) is expressed as:

$$\sigma_{TSE-RWY}^2 = \sigma_{FTE-RWY}^2 + \sigma_{NSE-RWY}^2 \quad (3)$$

where the variances of the FTE and NSE are also both measured along the runway. In [9], the airworthiness requirements are specified in terms of the probabilities of landing inside the landing box for three cases:

- the fault-free case (shown in Figure 2)
- the case of a single malfunction or a combination of malfunctions (without monitors in place), and
- the limit case, computing the worst case error assuming that bias-errors are limited by monitors.

All three cases were analyzed in detail in [9, 10] and an overview of the analysis is given below. For each case and a given NSE, the maximum allowed FTE was computed as a function of the aircraft nominal touchdown point (NTDP), and compared to the performance of current Boeing aircraft.

Fault-Free Case

As shown in Figure 4, under the assumption of a normal distribution, the probability of landing short P_{LS} or of landing long P_{LL} can be related to the total system error by:

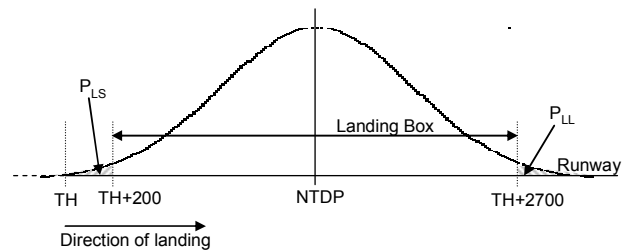


Figure 4: Probability of landing outside box - Fault-free case

$$P_{LS}^{FF} = \frac{1}{\sqrt{2\pi}\sigma_{TSE-RWY}} \int_{-\infty}^{TH+200} e^{-\frac{(x-NTDP)^2}{2\sigma_{TSE-RWY}^2}} dx \quad (4)$$

$$P_{LL}^{FF} = \frac{1}{\sqrt{2\pi}\sigma_{TSE-RWY}} \int_{TH+2700}^{+\infty} e^{-\frac{(x-NTDP)^2}{2\sigma_{TSE-RWY}^2}} dx \quad (5)$$

with the requirements that, under nominal (fault-free) conditions

$$\begin{aligned} P_{LS} &\leq 10^{-6} \text{ and} \\ P_{LL} &\leq 10^{-6} \end{aligned} \quad (6)$$

Assuming that σ_{FTE} and σ_{NSE} are uncorrelated, the following relations are obtained:

$$\sigma_{FTE-RWY,LS}^{FF} \leq \left\{ \left[\frac{NTDP - 200 - TH}{\sqrt{2} \times \operatorname{erfc}^{-1}(2 \times 10^{-6})} \right]^2 - \sigma_{NSE-RWY,LS}^2 \right\}^{1/2} \quad (7)$$

$$\sigma_{FTE-RWY,LL}^{FF} \leq \left\{ \left[\frac{2700 - NTDP + TH}{\sqrt{2} \times \operatorname{erfc}^{-1}(2 \times 10^{-6})} \right]^2 - \sigma_{NSE-RWY,LL}^2 \right\}^{1/2} \quad (8)$$

where

$$\operatorname{erfc}(x) = \frac{2}{\sqrt{\pi}} \int_x^{+\infty} e^{-t^2} dt \quad (9)$$

The $\sigma_{NSE-RWY}$ is related to the VAL in [9] by:

$$\sigma_{NSE-RWY} = \frac{3.28 \times VAL}{K_{md,H0} \times \tan(GPA)} \quad (10)$$

where $K_{md,H0}$ is the fault-free missed detection multiplier, equal to 6.9 (vertically) and GPA is the glide-path angle of the approach.

Malfunction Case

In the case of a malfunction, airworthiness certification states that ‘‘the probability of any single or combination of malfunctions that prevents a safe landing must be extremely improbable...’’. This applies to any malfunction with a probability larger than 1E-9. Furthermore, the ‘‘longitudinal touchdown should be no earlier than a point on the runway 200 ft from the threshold and the longitudinal touch down should be no further than 3000 ft from the threshold’’. Finally, it is stated that ‘‘malfunction cases may be considered under nominal environmental conditions’’. In [9], nominal environmental conditions were interpreted as meaning all variations resulting in the middle 95% of the touchdown dispersion. Using a similar approach to the fault-free case, the probability of landing-short or -long under malfunction conditions was derived as:

$$\sigma_{FTE-RWY,LS}^{MF} \leq \left\{ \left[\frac{NTDP - 200 - TH - E * 3.28 / \tan \alpha}{2} \right]^2 - \sigma_{NSE-RWY}^2 \right\}^{1/2} \quad (11)$$

and

$$\sigma_{FTE-RWY,LL}^{MF} \leq \left\{ \left[\frac{3000 - NTDP + TH - E * 3.28 / \tan \alpha}{2} \right]^2 - \sigma_{NSE-RWY}^2 \right\}^{1/2} \quad (12)$$

where E is the additional bias-like error [in metres] in the vertical and is transformed during the flare manoeuvre into $E * 3.28 / \tan \alpha$ along the RWY [in feet].

Limit Case

[3] specifies limit risk, with respect to landing within the ‘box’, as the probability of occurrence if one variable is held at its most adverse value, while the other variables vary according to their probability distributions. The probabilities of landing short or long are given as 1E-5. The most adverse value of the error is assumed to depend upon various factors in [9]:

- the probability of occurrence of a bias-like error E_B , $P(E_B)$, equal to 1 given the hypothesis of a fault.
- the probability of this error not being detected (by a monitor), $P_{MD}(E_B)$, and
- the conditional probability that, given such error, the aircraft makes an unsafe landing (UL), i.e. lands outside the landing box, $P(UL|E_B)$.

The total probability of an UL with a given E_B is then

$$P_{UL}(E_B) = P(E_B) \times P_{MD}(E_B) \times P_{UL|E_B}(E_B) \quad (13)$$

The overall probability of an unsafe landing is thus assumed to be a trade-off between the probability of missed-detection given an error E_B , which decreases with increasing E_B (due to the existence of monitors) and the probability of landing outside the landing box given an error of size E_B , which increases with increasing error. In analogy to the malfunction case, the probability of UL given a worst bias error of value E_B on the short-side can be written as:

$$P_{LS|E_B}^{Lim}(E_B) = \frac{1}{\sqrt{2\pi}\sigma_{TSE-RWY}} \int_{-\infty}^{TH+200} e^{-\frac{(x-NTDP+E_B*3.28/\tan\alpha)^2}{2\sigma_{TSE-RWY}^2}} dx \quad (14)$$

where E_B is a function of the monitor used. The probability of missed detection depends upon the error size and the monitors used. In [10], three different error sources for GBAS are addressed:

- Reference Receiver (RR) faults – VPL_{H1} test and B-value test
- Ephemeris faults and
- Signal deformation faults.

Each of these errors is being monitored, limiting the bias-error that is transmitted to the aircraft to a value determined by the monitor threshold, with a probability that depends on the ‘goodness’ of the monitor (e.g. noise will affect monitor performance). Take as an example the B-value test (producing the worst-case E_B [10]). The protection level under the hypothesis of a single faulted RR is [8]:

$$VPL_{H1,j} = \operatorname{MAX} \left\{ |B_{vert,j}| + K_{md,H1} \sigma_{vert,H1} \right\} \quad (15)$$

for each of the j RRs. In order to satisfy the integrity risk allocated to the H_1 hypothesis, [9] requires that

$$|B_{vert,max}| + K_{md,H1} \sigma_{vert,H1} = VAL \quad (16)$$

This is rewritten as

$$|B_{vert,max}| = VAL \times \left(1 - \frac{K_{md,H1} \sigma_{vert,NSE,H1}}{K_{md,H0} \sigma_{vert,NSE,H0}} \right) \quad (17)$$

$$= 0.344 \times VAL$$

under some general assumptions about the residual errors (see [10]) and the assumption that VPL_{H0} and VPL_{H1} are both equal to VAL at the worst geometry. A threshold is thus set at $B_{vert,max}$ and the risk of an unsafe landing as a function of E_B is computed using the derivation presented in [10]. The value of E_B corresponding to the maximum probability of an unsafe landing is then used to compute the FTE versus NTDP bound as in Eqs. 7 and 8:

$$\sigma_{FTE-RWY,LS}^{Lim} \leq \left\{ \frac{NTDP - 200 - TH - E_{B-RWY}^{max} * 3.28 / \tan \alpha}{\sqrt{2} \times \operatorname{erfc}^{-1} \left(\frac{2 \times 10^{-5}}{P_{md}(E_{B-RWY}^{max})} \right)} \right\}^2 - \sigma_{NSE-RWY}^2 \quad (18)$$

and

$$\sigma_{FTE-RWY,LL}^{Lim} \leq \left\{ \frac{3000 - NTDP + TH - E_{B-RWY}^{max} * 3.28 / \tan \alpha}{\sqrt{2} \times \operatorname{erfc}^{-1} \left(\frac{2 \times 10^{-5}}{P_{md}(E_{B-RWY}^{max})} \right)} \right\}^2 - \sigma_{NSE-RWY}^2 \quad (19)$$

The denominator takes into account the fact that the total probability of landing outside the box is the combined probability of the ‘limit case error’ not being detected and the TSE exceeding this box.

Results of Autoland Method

In the autoland method in [9], the approach is taken to compute the maximum allowed FTE for select maximum allowed NSE and compare the FTE to the FTE currently achieved by (Boeing) aircraft. The fault-free condition is shown to constrain the maximum tolerable NSE for the land-long case whilst the malfunction and limit-case conditions are shown to limit the maximum tolerable NSE for the land-short case. For all three cases, the conclusion is reached that a VAL of 10 m results in FTE requirements that can be met by current Boeing Aircraft for a landing under Category-III weather conditions.

ILS-LA VERSUS AUTOLAND METHOD

EUROCAE derived the VAL requirements using the *ILS Look-Alike* method as 2.6 m and the RTCA adopted the VAL derived from the *Autoland* method as 10 m. To date, no consensus has been found to harmonize these two approaches and results they provide. In this paper, each method is reviewed in detail. The analysis focuses on the

differences between the two approaches, especially regarding the assumptions made in the two derivations.

ILS-LA Method Analysis

As a first step, a detailed review of the performance specifications for ILS was carried out in this paper, similarly to the approach used in [2]. In addition to the error sources identified in [2], various other error sources were taken into consideration (as described in [11]). Table 5 compares the results obtained for the vertical accuracy of ILS with and without these additional errors (all added in quadrature).

Point of linearization	Error at 95% (EUROCAE)	Error at 95% (revised error sources)
All	0.1337 deg	0.1391 deg
TH (50 ft)	0.69 m	0.70 m
C (100 ft)	1.36 m	1.39 m

Table 5: Revised glide-slope error sources

The values are very similar, showing that the impact of taking into account the additional error sources is not significant.

One of the assumptions in the derivation of the errors shown in Table 5 is that the *monitor limits* in [5, 6] correspond to the 5-sigma limit and that the *adjust-maintain limits* can be interpreted as NSE errors and are given at 3-sigma level. The more stringent of these two values when converted to 1-sigma is interpreted as the ILS-NSE requirement. However, given that for some of the variables no probabilities were specified, it is not clear that the *adjust-maintain limits* correspond to the 3-sigma limit [12]. In order to investigate the impacts of this, the assumption was made in this paper that the *adjust-maintain limits* correspond to the 2- σ limit rather than the 3- σ limit. The effect of this is that it relaxes the performance requirements. The results are shown in Table 6 and are compared to those where the *adjust-maintain limits* were assumed to correspond to the 3- σ limit.

Point of linearization	Error at 95% (3-sigma limit)	Error at 95% (2-sigma limit)
All	0.1391 deg	0.1523 deg
TH (50 ft)	0.70 m	0.76 m
C (100 ft)	1.39 m	1.52 m

Table 6: Different Interpretations of [5, 6] Performance Specifications

The difference in results is at the level of 10% and can clearly not explain the large discrepancy between the RTCA and EUROCAE results.

The alert limits were derived separately although not independently from the NSE, by adding the monitor limits

specified for the various error sources. For those error sources where no monitor was specified, a 5-sigma value of the NSE was assumed. Independently to the derivation in [2], this paper derives the VAL using the results from the NSE derived in this paper (see Table 5, column 3), requiring the total integrity risk to be less than or equal to the required $0.5E-9$ (assuming that the total allowed integrity risk is allocated equally between the horizontal plane and the vertical direction). Table 7 compares the results of the vertical alert limits derived using this method and those derived in [2].

Point of linearization	VAL	VAL – IR = $0.5E-9$	VAL = $\sigma_{NSE} * K_{md,H0}$
All	0.436 degrees	0.433 degrees	0.480 degrees
TH (50 ft)	2.22 m	2.18 m	2.42 m
C (100 ft)	4.43 m	4.32 m	4.80 m

Table 7: GBAS VAL – Different Derivation Methods

Both results are in very good agreement. If the same ratio between the VAL and σ_{NSE} as in [9] is considered (shown in the last column of Table 7), the difference is approximately 11%.

Translation of ILS into GBAS errors

One of the differences between the ILS and the GBAS is the angular nature of the errors in the former and the bias-like nature in the latter. As a validation of the derived performance requirements, [2] derives the GBAS NSE using the *Autoland* landing box requirements by projecting the landing box requirements onto the approach path using a model based on the Collision Risk Model (CRM). From this, a so-called “beta-to-bias” NSE for GBAS was obtained and used to extract the so-called linearization height. In addition to requiring that the TSE-RWY is the same for GBAS and ILS the derivation in [2] makes the assumption that FTE-GP is the same for both ILS and GBAS. Furthermore, an implicit correlation between NSE-GP_{GBAS} and FTE-GP_{GBAS} was assumed (see Eq. 2) and the NSE was computed perpendicular to the GP rather than vertically. Figure 5a and Figure 5b give a slightly modified picture of Figure 3.

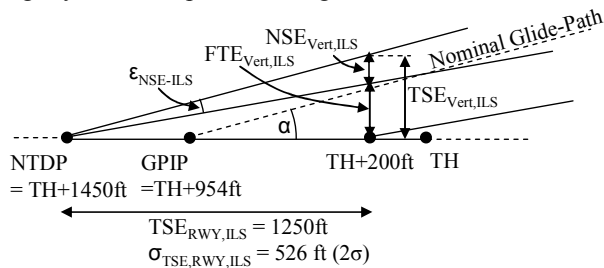


Figure 5a: Beta-to-Bias method revised (ILS)

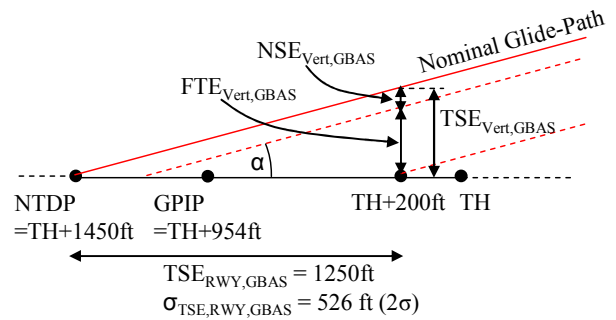


Figure 5b: Beta-to-Bias Method revised

First of all, it should be noted that the GPIIP does not coincide with the NTDP of the ‘landing box’. In order to compare the box requirements with the ILS specifications, the GPIIP needs to be shifted to the NTDP. As a result, given the angular nature of the ILS error, the NSE error at TH+200 is effectively computed at a distance of 1250 ft from the GPIIP, corresponding to a linearization height of 65.5 ft. Let T be the parameter along the runway, a function of F (the vertical parameter at TH+200) and α (the GPA), simple differential calculus yields:

$$dT \times \tan \alpha = dF - \frac{T}{\cos^2(\alpha)} d\alpha \quad (20)$$

If F and α are uncorrelated, making the appropriate associations, we can rewrite the above equation as

$$\sigma_{TSE,RWY,ILS}^2 \times \tan^2 \alpha = \sigma_{FTE,Vert,ILS}^2 + \frac{T^2}{\cos^4 \alpha} \sigma_{\alpha}^2 \quad (21)$$

The second term on the right-hand-side can be associated with the $\sigma_{NSE,Vert,ILS}$.

$$\sigma_{NSE,Vert,ILS} = \frac{1250}{\cos^2(3)} \times 0.1391 \times \frac{\pi}{180} = 0.928 m (2\sigma) \quad (22)$$

In the small-angle approximation, this result is equivalent to saying that:

$$\sigma_{NSE,Vert,ILS} \approx T \sigma_{\alpha} \quad (23)$$

For equivalent performance to ILS, this value corresponds to the required $\sigma_{NSE,Vert,GBAS}$. In order to satisfy the total integrity risk of $0.5E-9$ per 15 seconds (vertically), the VAL can be derived as:

$$VAL = \sigma_{NSE-vert,GBAS} \times \sqrt{2} \times \text{erfc}^{-1}(0.5E-9) = 2.89 m \quad (24)$$

A similar computation was carried out, assuming that the original ILS *adjust-maintain* (AM) limits were given at $2-\sigma$. The results are shown in Table 8.

VAL – IR= $5E-10$ (AM limit = $3\sigma/2\sigma$)	VAL = $\sigma_{NSE} * K_{md,H0}$ (AM limit = $3\sigma/2\sigma$)
2.89 m / 3.16 m	3.20 m / 3.51 m

Table 8: VAL - Different interpretations of ILS ICAO specifications and VAL

Using the interpretation of the ILS-errors at 3σ (in [2]) produces a VAL = 2.89 m (using the interpretation of VAL in this paper) or a VAL = 3.20 m (using the interpretation of VAL in [9]). Both values are of the same order of magnitude and clearly different from the 10 m VAL obtained from the Autoland analysis. Table 9 summarizes the results obtained from the ILS-LA method in this paper.

Vertically (1σ)	Longitudinally (along RWY - 1σ)
$\sigma_{\text{NSE,Vert,GBAS}} = 0.464 \text{ m}$	$\sigma_{\text{NSE,RWY,GBAS}} = 8.85 \text{ m}$
$\sigma_{\text{FTE,Vert,GBAS}} = 13.70 \text{ ft}$	$\sigma_{\text{FTE,RWY,GBAS}} = 261.36 \text{ ft}$
$\sigma_{\text{TSE,Vert,GBAS}} = 13.78 \text{ ft}$	$\sigma_{\text{TSE,RWY,GBAS}} = 262.97 \text{ ft}$
VAL = 2.89 m	N/A

Table 9: Results from ILS-LA (this paper)

Since the NSE is assumed to be a bias for GBAS and the FTE is assumed to be constant over the approach, the vertical values are assumed to be independent of height and distance from the threshold. The similarity between the values of the σ_{FTE} and σ_{TSE} shows that for the ILS, nearly all of the tolerable error is allocated to the FTE.

Autoland Method Analysis

In [9], a distinction is made between fault-free, malfunction [4] and ‘limit’ [3] conditions. For the malfunction condition, nominal environmental conditions are interpreted as referring to all variations resulting in the middle 95% of the touchdown dispersion. The ‘limit’ case condition is interpreted as an NSE with the largest probability of landing outside the box. This is the convolution of the conditional probability of having an error of a given size, that this error is not detected (by a monitor) and that given such error, the aircraft will land outside the landing box. [4] makes a distinction between fault-free and malfunction conditions only, where specifications for the malfunction conditions do not mention any allowed probability of landing outside the revised landing box. In comparison, [3] distinguishes between ‘average’ and ‘limit’ cases. To reconcile the requirements from those two ‘Airworthiness Requirements’ sources, the requirements are interpreted as follows in this paper:

- *Fault-Free*: Corresponding to the ‘average’ case, with a landing box between TH+200 ft and TH+2700 ft and a probability of not landing either before or after those limits less than $1\text{E-}6$ (same interpretation as in [9]).
- *Malfunction*: with a landing box between TH+200 ft and TH+3000 ft and a probability of not landing either before or after those limits less than $1\text{E-}5$. The malfunction was initially interpreted as a bias-error corresponding to the VAL and ‘nominal

environmental conditions’ are interpreted as conditions of the fault-free scenario.

- *Limit Case*: with a landing box between TH+200 ft and TH+3000 ft and a probability of not landing either before or after those limits less than $1\text{E-}5$. As specified in [3], “the ‘limit’ column is the probability of occurrence if one variable is held at its most adverse value, while the other variables vary according to their probability distributions”.

If the approach is taken to keep the performance requirements generic, and no specific architecture is assumed, the limit and malfunction cases are identical. This was one of the potential approaches taken in this paper. As in the malfunction case, the ‘most adverse value’ was therefore initially interpreted as a bias-error of magnitude VAL.

Using a similar derivation (as shown in Figure 6) to that in [9], the probability of landing-short or –long under malfunction conditions was derived as:

$$P_{\text{LS}}^{\text{MF}} = \frac{1}{\sqrt{2\pi}\sigma_{\text{TSE-RWY}}} \int_{-\infty}^{\text{TH}+200} e^{-\frac{(x-\text{NTDP}+E*3.28/\tan\alpha)^2}{2\sigma_{\text{TSE-RWY}}^2}} dx \quad (25)$$

and

$$P_{\text{LL}}^{\text{MF}} = \frac{1}{\sqrt{2\pi}\sigma_{\text{TSE-RWY}}} \int_{\text{TH}+3000}^{+\infty} e^{-\frac{(x-\text{NTDP}-E*3.28/\tan\alpha)^2}{2\sigma_{\text{TSE-RWY}}^2}} dx \quad (26)$$

where E is the additional bias-like error [in metres] in the vertical and is transformed during the flare manoeuvre into $E\text{-RWY}$ [in feet] scaled by the glide-slope angle α .

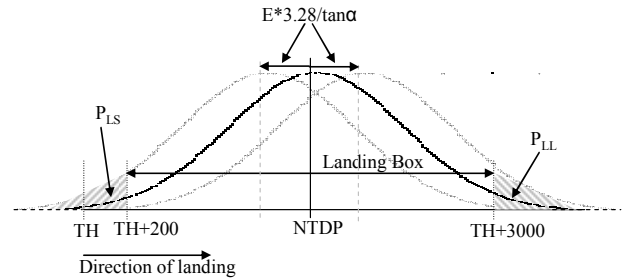


Figure 6: Probability of landing-short and long – Malfunction case

The σ_{FTE} were derived as:

$$\sigma_{\text{FTE-RWY,LS}}^{\text{MF}} \leq \left\{ \frac{\left[\frac{\text{NTDP} - 200 - \text{TH} - E * 3.28 / \tan \alpha}{\sqrt{2} \times \text{erfc}^{-1}(2 \times 10^{-5})} \right]^2}{-\sigma_{\text{NSE-RWY}}^2} \right\}^{1/2} \quad (27)$$

$$\sigma_{\text{FTE-RWY,LL}}^{\text{MF}} \leq \left\{ \frac{\left[\frac{3000 - \text{NTDP} + \text{TH} - E * 3.28 / \tan \alpha}{\sqrt{2} \times \text{erfc}^{-1}(2 \times 10^{-5})} \right]^2}{-\sigma_{\text{NSE-RWY}}^2} \right\}^{1/2} \quad (28)$$

where the $\sigma_{NSE-RWY}$ in this paper was originally assumed to correspond to the maximum NSE error along the runway allowed by the VAL in the fault-free case. However, for reasons explained later in this section, the $\sigma_{NSE-RWY}$ may have to be interpreted differently to be in line with integrity requirements.

Under the initial assumptions on the $\sigma_{NSE-RWY}$, the difference of this paper with [9] lay in the interpretation of nominal environmental conditions, which in this paper were interpreted as referring to conditions identical to the fault-free case except for the addition of a bias-error to the nominal NSE. The reason for this approach is that it preserves the allowed probability of landing short or long. A choice of 95% effectively limits the probability of landing within the ‘box’ to 95% rather than the required 99.999% ($1 - 1E-5$). Additionally, the approach in this paper allows the requirements in [3] and [4] to be reconciled.

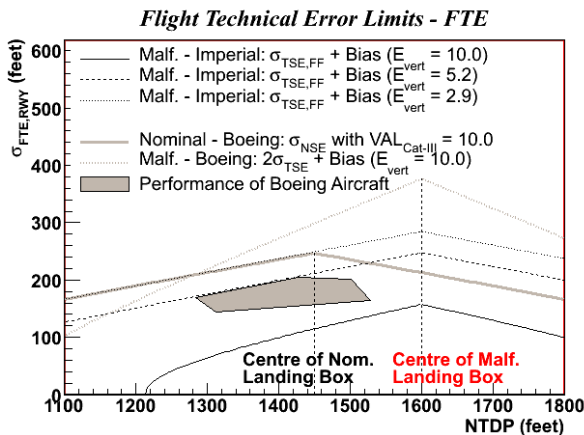


Figure 7: Comparison of Malfunction Cases

Figure 7 shows the FTE as a function of NTDP derived for the malfunction conditions using the interpretation in [9] and the malfunction conditions using the initial interpretations in this paper. The fault-free case with a VAL=10 m is also shown. In order to satisfy the touchdown requirements, the FTE of the aircraft with the worst-case performance (i.e. of the aircraft with the largest FTE for a given NTDP) must lie below the respective curve for all conditions. Current Boeing aircraft performance corresponds to the grey area (extracted from [9]). Whilst under fault-free and malfunction conditions as interpreted in [9] a VAL of 10 m can satisfy current Boeing aircraft performance, the initial interpretation of malfunction conditions in this paper, suggested a VAL = 5.2 m was required to satisfy the malfunction condition. However, further research identified that the assumption of a bias at the alert limit essentially imposes an actual limit on the maximum tolerable NSE that is larger than the VAL and is therefore inconsistent with the integrity requirements. The malfunction condition must thus be interpreted differently. An option would be to interpret the

malfunction requirement as a landing inside the box with a probability of $1 - 1E-5$ in the presence of a NSE at the alert limit, rather than a bias-error at the alert limit. Such interpretation would be consistent with the integrity definition.

However, the interpretation of the malfunction condition should not be needed in the derivation of the performance requirements for the following reason: the geometry of the landing requirements (i.e. the landing box), together with the probability of landing inside the box, determine the allowed NSE (for a given FTE), irrespective of whether the NSE is composed of a bias and noise or only of noise. The integrity requirements of the landing operation then determine the required VAL. In other words, the VAL is determined by the operation only (under the assumption of a given FTE). Moreover, given that the TSE requirements for the malfunction case are less stringent than for the nominal conditions, the VAL in the malfunction case is expected to be larger than the VAL derived from the nominal conditions (assuming that the NSE malfunction does not affect the FTE). Nominal conditions therefore are expected to impose the limiting constraint.

Monitoring

The derivation in the above section made no assumptions about the architecture of the ground subsystem. One of the questions to be addressed is whether it is acceptable to derive performance requirements based upon the use of monitors and how this may affect the performance requirements of a Category-III landing. The total performance requirements (a combination of FTE and NSE performance requirements) should depend only upon the operation itself and not upon any specific architecture. However, a possible approach is to assume a specific ground architecture to derive the NSE that can be achieved with the given monitors, and adopt this as the NSE requirement. This would then impose a limit on the FTE requirements that aircraft would have to meet in order to satisfy the operational TSE requirement. The specific architecture thus allows to trade the required NSE for the required FTE, but should not affect the total performance requirements of the landing operation. Therefore, if we considered an architecture- independent derivation using the FTE requirements from the architecture-dependent approach, identical maximum NSE requirements would be expected (which is effectively only saying that the TSE should be defined by the operation only).

However, irrespective of which approach is used in deriving the NSE performance requirements, ultimately ground monitors will be required to meet the integrity requirements. Of the monitors analyzed in [10], the one with the largest threshold was used in [9] to determine the limit case condition. By lowering the thresholds of the monitors, theoretically the VAL derived in [9] for the limit-case could be increased while still providing the

overall same performance (at least in terms of integrity). In practice this would only be possible up to the limit imposed by the fault-free requirements.

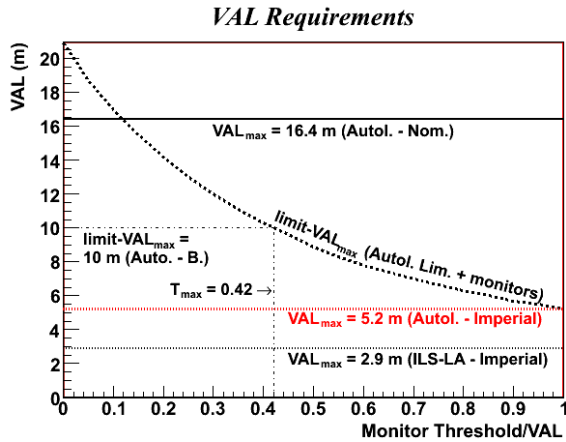


Figure 8: Maximum VAL versus monitor threshold

Figure 8 summarizes these results. The curve was derived (based upon Eqs. 18 and 19) by computing the maximum limit-VAL (explained later in this section), for a given threshold that would satisfy the FTE versus NTDP requirements of current Boeing aircraft (shown as a grey-shaded area in Figure 7). As expected, the curve intersects the malfunction-case curve when $B/VAL=1$, i.e. when there is effectively no monitor. At the point where $B/VAL = 0$, there is no bias and, with the assumptions made in [9], the result would be expected to correspond to the nominal case. The reason why it does not is that the allowed probability of landing outside the box in the limit case condition is $1E-5$ rather than $1E-6$. It was shown that $VAL_{max} \approx 21$ m under nominal autoland conditions with a probability of $1E-5$.

What is interesting to note in the above derivation is that for a given FTE and NTDP, the VAL appears to be variable and dependent upon the monitor threshold. This appears to be inconsistent with the idea that the total system performance should be operation-dependent only. Therefore, this variable cannot correspond to the VAL and was termed limit-VAL in this paper. The relationship with the VAL is the subject for further research.

Furthermore, a comparison of monitor versus no-monitor cases seems to show that the existence of monitors relaxes the NSE performance requirements for a given FTE. This result would imply that the TSE is architecture dependent. However, as discussed before, the TSE should not depend upon any architecture. To explain this result, it should be noted that the total residual NSE is essentially composed of a bias-term and a noise factor, and the maximum allowed residual NSE can be expressed as:

$$\sigma_{NSE}^{max} = VAL = Bias + \sigma_{noise}^{max} \quad (29)$$

where the σ_{noise} includes noise both at ground level and aircraft level. By imposing monitor thresholds, the bias-error is limited. This allows the system to perform better

than in the absence of monitors, i.e. it is possible to satisfy lower VAL requirements. Alternatively, one may be tempted to say that the maximum ‘noise’ is allowed to be larger than if there was no threshold (because the overall GBAS system performance is better than without monitors), up to a limit imposed by the monitor:

$$\sigma_{noise}^{max} = VAL - Bias \quad (30)$$

This appears to be the approach taken in [9], with the exception that the larger noise-allowance appears to have been interpreted as a larger NSE allowance. This would explain why [9] obtained more relaxed VAL (rather than more relaxed ‘maximum noise’) in the presence of monitors. However, relaxing noise-requirements is not necessarily an option as the noise under malfunction conditions and nominal conditions may be linked and may result in the integrity requirements of the nominal conditions not to be met.

Key issues of ILS-LA and Autoland Results

Unless ILS NSE performance specifications were too stringent with respect to the Airworthiness Certification requirements, both methods should derive similar performance requirements for GBAS. However, it appears that they do not. Table 10 gives an overview of the essential differences between the *ILS Look-Alike* and the *Autoland* methods results.

ILS Look-Alike (Eurocae /Imperial)	Autoland (Imperial)	Autoland (Boeing /RTCA)
Architecture independent		Modified Cat-I GBAS architecture
Equivalent performance to ILS	Equivalent safety to ILS	
Based on ILS Performance Specifications [5, 6]	Based on Airworthiness Certification [3, 4]	
No assumptions on user error model		Assumptions on user error model
Varying assumptions on ‘adverse error’		
Implicit assumption on A/C FTE performance	Assumption of Boeing A/C FTE performance	
VAL = 2.6 – 3.5 m	VAL = 5.2 m (initial interpretation of ‘most adverse error’)	VAL = 10 m
No monitors		Max. monit./ limit-VAL threshold = 0.42

$\sigma_{\text{NSE,Vert,GBAS}} = 0.445 - 0.507 \text{ m}$	$\sigma_{\text{NSE,Vert,GBAS}} = 0.84 \text{ m}$	$\sigma_{\text{NSE,Vert,GBAS}} = 1.45 \text{ m}$
$\sigma_{\text{FTE,RWY,GBAS}} = 261.36 \text{ ft}$	$\sigma_{\text{FTE,RWY,GBAS}} = \sim 211 \text{ ft (with NTDP = 1450ft)}$	
$\sigma_{\text{TSE,RWY,GBAS}} = 262.97 \text{ ft}$		

Table 10: Differences between ILS Look-Alike and Autoland methods

From the discussions in this paper, three key issues were identified with the methods used to derive the NSE performance requirements:

- the existence or not of monitors,
- the interpretation of ‘most adverse error’ and
- the assumptions on the maximum tolerable aircraft FTE.

The Autoland method of Boeing assumes the existence of monitors in the derivation of the performance requirements whilst the Autoland method by Imperial and the ILS-LA method do not. It should be noted that this should not be confused with the use of monitors as a means of achieving the performance requirements, which GBAS will need, irrespective of which method is used in the derivation of the performance requirements. The use of a specific architecture with monitors imposes a limit on the bias-error of the differential corrections sent by the ground subsystem to the aircraft, and will allow the GBAS system to perform better (i.e. with more stringent values of VAL) than in the absence of monitors. Aircraft with less good FTE performance may therefore be able to perform landings under Category-III weather conditions. In [9], monitors appeared to relax the VAL requirements, rather than allowing them to be tightened for reasons explained earlier.

The interpretation of ‘most adverse error’ as a bias-error with a value of VAL resulted in VAL requirements that were apparently more stringent than the VAL under nominal conditions. However, given that the operational requirements in the malfunction case or the limit case are more relaxed than those under nominal conditions, the NSE and VAL are expected to be larger than under nominal conditions. The reason why a smaller VAL was obtained is an incorrect interpretation of the bias-error as an error with magnitude VAL, since this interpretation does not allow the integrity requirements to be met. An alternative interpretation of ‘most adverse error’ as a NSE at the alert limit (rather than a bias-error at the alert limit) results in a VAL under malfunction conditions that is larger than the VAL under nominal conditions.

A significant difference between the ILS-LA method and the Autoland method is the assumption made with respect to the maximum allowable FTE. As shown in Table 10, the ILS-LA method implicitly assumes that the $\sigma_{\text{FTE,RWY,GBAS}}$ may be anything up to 261.36 ft (with a NTDP = 1450 ft). In comparison, the Autoland method assumes a maximum $\sigma_{\text{FTE,RWY,GBAS}}$ determined by the

current Boeing aircraft performance up to $\sim 211 \text{ ft}$ (at a NTDP = 1450 ft). Figure 9 shows the maximum VAL that can be supported as a function of the FTE at the NTDP = 1450 ft.

The significantly smaller FTE assumed on Boeing aircraft allows for a significantly larger VAL. If the Boeing FTE is assumed in the ILS-LA method, a VAL = 17.2 m would be derived (instead of the VAL = 2.9 m derived in this paper). The essential difference between the ILS-LA method and Autoland method without monitors is thus the assumption made on the maximum allowed FTE. This may suggest that the NSE requirements of ILS, whilst appropriate for the FTE performance of aircraft at the time when these performance requirements were derived, may be too stringent for the performance of modern aircraft.

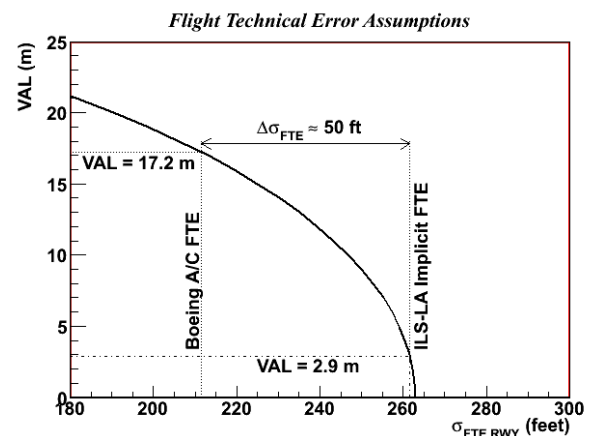


Figure 9: VAL versus FTE at NTDP = 1450 ft

CONCLUSION

In order to harmonize the NSE performance requirements for Category-III landings, two approaches may be taken:

- the use of a specific GBAS architecture with specific monitor thresholds in the allocation of the performance requirements, or
- the definition of aircraft FTE requirements.

If a specific GBAS architecture is used in the derivation of the performance requirements, monitors will determine the NSE performance that can be achieved with the GBAS system. This performance could then be imposed as the NSE requirement, hence implicitly imposing specific FTE requirements upon the aircraft. If on the other hand the assumption is made that FTE of current aircraft must be supported, this would impose a limit on the performance requirements that monitors must be able to support. If more stringent performance requirements than this limit can be met by the specific architecture, it would allow the FTE requirements to be relaxed.

Based upon the landing box requirements, this paper has shown that nominal conditions impose the limiting constraint on aircraft landing under Category-III weather conditions. If the current FTE implicitly assumed in the

ILS performance specifications is used, a VAL = 2.9 m is required. If instead the Boeing aircraft FTE performance is considered, a VAL ~ 17 m would provide the required safety for a Cat-III landing. The difference in FTE assumptions thus results in significantly different NSE requirements. The establishment and validation of FTE requirements is thus another possible approach towards the harmonization of the NSE performance requirements. If this approach is taken, both the ILS-LA and the Autoland method would essentially agree on the NSE performance requirements that should be applied, irrespective of whether monitors are used or not.

In addition to these two main issues, various other issues need to be addressed, such as:

- The validation of the assumption that the vertical NSE and FTE normal distributions translate into normal distributions along the runway during the flare manoeuvre.
- The impact of using individual monitors for specific failures in the presence of simultaneous multiple failures.
- The impact of a decorrelation of the NSE residual errors between the ground station and the aircraft.
- The design and optimization of ground monitors [14, 15].

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