Total System Performance in GBAS-based Landings

M. Felux, *German Aerospace Center – DLR, Germany*
J. Lee, *Korea Advanced Institute of Science and Technology, South Korea*
F. Holzapfel, *Technische Universität München, Germany*

ABSTRACT

The requirements for a CAT-II/III capable GBAS (the so-called GBAS Approach Service Type (GAST) D) are derived from the definition of a safe landing. The respective performance requirements are given in terms of touchdown performance of the aircraft which has two main influencing parameters: the flight technical error (FTE) and the navigation system error (NSE). In the process of deriving and standardizing the GBAS requirements a fixed value for the FTE is assumed. In this paper we show potential benefits from using the deviations from the nominal approach path to assess the FTE performance during an approach instead of using conservative assumptions. Depending on the prevailing wind conditions, the FTE performance is typically better than the value which is derived in the certification of an aircraft. This opens the potential to either improve availability of the GBAS service or optimize the landing with respect to runway capacity or risk minimization for a runway overrun.

INTRODUCTION

The Ground Based Augmentation System (GBAS) provides precision approach guidance for aircraft. It is based on a differential GNSS architecture and provides additional integrity information in order to enable error bounding and an assessment, if the current navigation performance is sufficient to support the approach. In contrast to the currently used Instrument Landing System (ILS) GBAS operations bear the potential for many improvements with respect to advanced approach procedures which are currently developed to reduce noise in the vicinity of airports [1]. This includes enabling new and shorter approaches and increaseing the runway capacity.

In 2012 the first GBAS ground station in Bremen, Germany became operational. Since then several stations including Newark and Houston in the US, Sydney in Australia, Malaga in Spain, Frankfurt in Germany and Zurich in Switzerland were approved for operation. All those stations enable approach guidance under weather conditions up to CAT-I, i.e. with a certain minimum visibility. In order to support approaches and automatic landings also under CAT-II/III weather conditions (i.e. visibility below CAT-I conditions) the international community has been developing requirements which ensure safety not only during the approach but also to meet the touchdown requirements given in the Certification Specifications for All-Weather Operations (CS-AWO) and the Advisory Circular AC 120-28D. It is expected that these requirements will be accepted by the International Civil Aviation Organization (ICAO) later this year.

The method of assuring the safety of GBAS-based automatic landings is largely driven by the requirement to land in the touchdown box with a very high probability. The touchdown box is an area on the runway where it is safe to land, i.e. not too close to the runway threshold to not land short of the runway, not too far down the runway to avoid the risk of an overrun and not too close to the edges. Note, however, that this requirement relates to the total aircraft performance, where only one part of the overall error budget is allocated to the GBAS Navigation System Error (NSE). Another big part of the error budget is attributed to the Flight Technical Error (FTE) which describes how well the aircraft can follow a predefined track and land at a desired spot. In the process of deriving the GBAS requirements a choice has to be made how much of the overall budget is allocated to either system. Currently, one single value for the FTE describing the dispersion of the touchdown point on the runway is assessed during aircraft certification. This is done based on simulations for each aircraft type with a variety of influencing parameters, especially with different wind scenarios since that is the driving factor for the FTE.

It is clear, however, that the one single value for the touchdown performance of the aircraft cannot be representative of all conditions encountered during normal operations and thus has to be a conservative parameter. Especially in foggy conditions for example there is typically almost no wind present. Thus the touchdown performance will be better than the value derived during certification. The variation of the FTE performance is currently not exploited in the tradeoff between NSE and FTE or used for advanced landings.

In this paper we suggest to estimate the FTE performance of a specific approach based on the deviations during an approach. In calm wind conditions a reduced touchdown dispersion can then safely be assumed. This opens the potential for a variety of improvements which are enabled by GBAS through leveraging the actual performance instead of conservative assumptions.

These improvements are made possible by GBAS because an error bound on the NSE is continuously estimated. With the knowledge about the FTE (deviations from the desired track) the total system error (TSE) at aircraft level is known at all times and can be exploited and predicted in terms of touchdown performance.

REQUIRED TOUCHDOWN PERFORMANCE

The relevant high-level requirements are given in the Certification Specifications for All Weather Operations (CS-AWO) [2] and the Advisory Circular AC 120-28D, Appendix 3 [3]. A landing is considered to be safe according to those documents if the aircraft touches down not less than 200 ft behind the runway threshold and not more than 2700 ft behind the threshold. In case of a limit case or malfunction condition (described in the next sections) the touchdown box extends to 3000 ft behind the threshold. The lateral limit of the box is implicitly given as not less than 5 ft from the edge of the runway. An illustration of this region is given in Figure 1. Note that the requirement relates to the total system error (TSE) of the aircraft and not only to the navigation system. It is a generally accepted assumption that the NSE and FTE are stochastically independent and thus the standard deviation of the TSE can be expressed in terms of NSE and FTE as

$$\sigma_{TSE} = \sqrt{\sigma_{NSE}^2 + \sigma_{FTE}^2} \quad (1)$$

From Equation (1) it becomes clear that the NSE performance required to land safely depends on the FTE performance of the aircraft. In order to accommodate the very different performance levels of aircraft there is some freedom in the definition of the monitoring requirements to allow manufacturers to leverage better FTE performance in the geometry screening process. The details are described in the following sections.

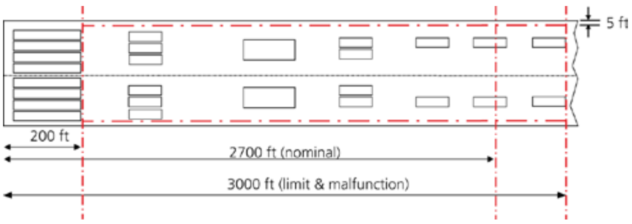

Figure 1 Illustration of the touchdown box

NOMINAL CASE

In the nominal case all parameters vary according to their nominal distributions. From an airworthiness perspective this again refers to the navigation system as well as to all other conditions, such as the aircraft configuration (e.g. flap settings). In the nominal case the GBAS NSE is bounded by the fault-free protection levels as given in [4] as

$$VPL_{H0} = K_{ffmd} \cdot \sigma_{vert} + D_v \quad (2)$$

which are representing nominal conditions. The K_{ffmd} is a missed detection multiplier which is defined by the allocated integrity risk, σ_{vert} is the expected standard deviation of the vertical position uncertainty in the GBAS solution and D_v is the difference in vertical position solutions based on 30 s and 100 s smoothed pseudoranges. The vertical uncertainty is given as

$$\sigma_{vert} = \sqrt{\sum_{i=1}^{N} s_{Apr,vert,i}^2 \cdot \sigma_i^2} \quad (3)$$

where N is the number of satellites used in the position solution, $s_{Apr,vert,i}$ is the projection factor for satellite i from the pseudorange domain into the vertical position and σ_i is the residual uncertainty associated with the corrected and smoothed pseudorange measurement from satellite i. The NSE performance is bounded by the vertical alert limit (VAL), which is a limit for the vertical protection level (VPL). If $VPL < VAL$ the system is available, otherwise GBAS cannot be used for guidance. The value for VAL can be chosen depending on the conditions of a specific approach but may not be larger than 10 m for the final approach and landing. With a $K_{ffmd} = 5.847$ (the case for four GBAS reference receivers from Table 2-16 in [4]) and $D_v = 0$ as most conservative assumption this gives an NSE performance which can be described by an uncertainty in the vertical position as

$$\sigma_{vert} \le {VAL}/{K_{ffmd}} = {10m}/{5.847} = 1.71m \quad (4)$$

This vertical NSE performance now has to be related to an along-track touchdown performance σ_{NSE} which can be used in Equation (1). The relation is given by a simple geometric projection based on the glide path angle (GPA) of the approach as

$$\sigma_{NSE} = {\sigma_{vert}}/{\tan(GPA)} \quad (5)$$

In the most conservative case a GPA of 2.5° is in the range of possible values which leads to $\sigma_{NSE} = 39.17m$. A value for σ_{FTE} has to be determined by the aircraft manufacturer. In the derivation of the standards [5] a value of $\sigma_{FTE} = 150\,ft = 45.72m$ was used. Going back to the touchdown requirements the condition to not land short can be formulated as

$$NTDP - k \cdot \sigma_{TSE} \ge 200\,ft \quad (6)$$

where $NTDP$ is the nominal touchdown point, i.e. the point on the runway where the autopilot would land in ideal conditions. In the derivation of the standards [6] a value of 1290 ft behind the runway threshold was chosen. The k-factor depends on the allocated probability with which the aircraft may land outside the box. In the nominal case the risk has to be smaller than 10^{-6} which leads to

$$k = Q^{-1}(10^{-6}) = 4.75 \quad (7)$$

where $Q(x) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{x} e^{\frac{t^2}{2}} dt$. Taking all the above given parameters for σ_{FTE}, σ_{NSE}, GPA and NTDP the touchdown condition (6) is fulfilled. In case the FTE of the aircraft is too large to fulfill the condition, an internal value for VAL can be set in the aircraft which is equivalent to limiting the nominal σ_{NSE} in Equation (4) to a smaller value.

LIMIT CASE

In the limit case one parameter is "held at its most adverse value, while the other parameters vary according to their" [2] nominal distributions. The land-short condition can then be formulated in a similar way as for the nominal case with the same notation as

$$NTDP - k_1 \cdot \sigma_{TSE} - E_v / \tan(GPA) \geq 200\,ft \qquad (8)$$

where E_v is an additional vertical error resulting from the limit case condition. In the limit case the allocated probability of not landing in the box is 10^{-5} and thus

$$k_1 = Q^{-1}(10^{-5}) = 4.26 \qquad (9)$$

In the limit case E_v must be bounded in order to comply with the touchdown requirements. This bound defines the requirement which has to be fulfilled by each monitor in the GBAS system. The probability of exceeding the touchdown limits is a conditional probability. It consists of the probability $P_{md}(E_v)$ that a certain vertical error E_v occurs and is not detected by any monitor and the probability $P_{UL|fault\_undetected}(E_v)$ that the landing is unsuccessful given that undetected error. This can be stated as

$$P_{UL|fault}(E_v) = P_{md}(E_v) \cdot P_{UL|fault\_undetected}(E_v) \leq 10^{-5} \quad (10)$$

The relation between a vertical error in the position domain and a maximum pseudorange error is given by the projection matrix S. When there is a limit on the projection factors $s_{Apr,vert,i}$ as before in the nominal case, a condition for an individual largest pseudorange error $E_{r,max}$ can be formulated as

$$E_{r,max} = \frac{E_v}{s_{Apr,vert,max}} \qquad (11)$$

The condition from Equation (10) in the pseudorange domain with the relationship from Equations (11) and based on Equation (8) is shown in Figure 2 in red. The parameters for this curve were chosen as $NTDP = 1290\,ft$ $GPA = 2.5°$, $\sigma_{FTE} = 150\,ft$ and $s_{vert.max} = 4$. The blue curve is a linear approximation of the red curve and is the actual monitoring requirement as given in the standards [6].

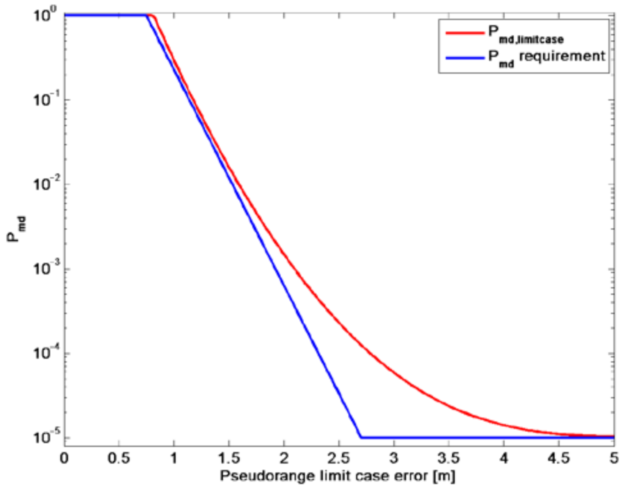

Figure 2 Limit case monitoring requirement. Shown in red is the performance requirement when assessing the touchdown performance. The linear approximation as defined in the standards is shown in blue.

While the blue curve approximates the red curve, this does not mean that the parameters (e.g. σ_{FTE} and $s_{vert,max}$) used to derive these curves are limited to the values mentioned above. It rather has to be ensured that the monitoring requirement is fulfilled at all times, given a certain performance. A $\sigma_{FTE} = 180\,ft$ together with a more stringent $s_{vert.max} = 2$ for example would be an acceptable combination of parameters which still bounds the errors in an acceptable way.

MALFUNCTION CASE

In the malfunction case it has to be shown that the aircraft can land safely in the box given a malfunction occurs. In a similar way as in the nominal and the limit case, this condition could be written as

$$200\,ft \leq NTDP - \frac{k_2 \cdot \sigma_{NSE,vert}}{\tan(GPA)} - \frac{E_v}{\tan(GPA)} - k_2 \sigma_{FTE} \quad (12)$$

for the land short case. However, the requirement as it is written has to be met with complete certainty for every possible error source which affects a GBAS user with a probability larger than 10^{-9}. Of course this is not possible if NSE and FTE are varying according to a Normal distribution. Instead, NSE and FTE are taken at their 95th percentiles and regarded as having fixed values. Then it is possible to derive a limit on the largest vertical error E_v (and thus again largest residual pseudorange error by using a limit on the S-factors) resulting from a malfunction condition. Fixing the nominal TSE (excluding the malfunction case error) at the 95th percentile yields

$$k_2 = Q^{-1}((1 - 0.95)/2) = 1.96 \qquad (13)$$

for the k-factor in Equation (12). With the assumptions as in the previous cases ($NTDP = 1290\,ft$, $GPA = 2.5°$, $\sigma_{NSE,vert} = VAL / K_{ffmd} = 1.72m$, $S_{vert,max} = 4$), however with $\sigma_{FTE} = 180\,ft$ (instead of the previously used

$\sigma_{FTE} = 150\,ft$) the bound for the largest tolerable residual pseudorange error $E_{r,\max}$ in the malfunction case becomes

$$E_{r,max} = \frac{E_v}{S_{vert,max}} = \frac{6.4\text{m}}{4} = 1.6\text{m} \qquad (14)$$

This limit is given in the draft SARPS [5], however without an explanation why a larger FTE value was assumed. While the assumption is conservative it is not clear why the FTE performance should be worse in case of a navigation system malfunction. Recall that one central assumption was that NSE and FTE are statistically independent (see Equation (1)). When assessing the total risk that such a fault occurs a prior probability of an effect leading to such a situation may be taken into account. Hence, the malfunction case condition is given such that the total probability of landing outside the touchdown box is limited. This condition applies for faults due to signal deformation, code/carrier divergence, excessive acceleration and erroneous ephemeris data broadcast. Figure 3 shows the resulting monitoring condition with a given a priori probability p_{fault} of a fault occurring which is given by an assumed failure rate of the satellites at 10^{-4} per hour, a duration of the approach of 15 seconds (from the CAT-I minimum to touchdown) and a maximum of 18 satellites used for positioning such that

$$p_{falut} = \frac{10^{-4} \cdot 15 \cdot 18}{3600} = 4.2^{-6} \qquad (15)$$

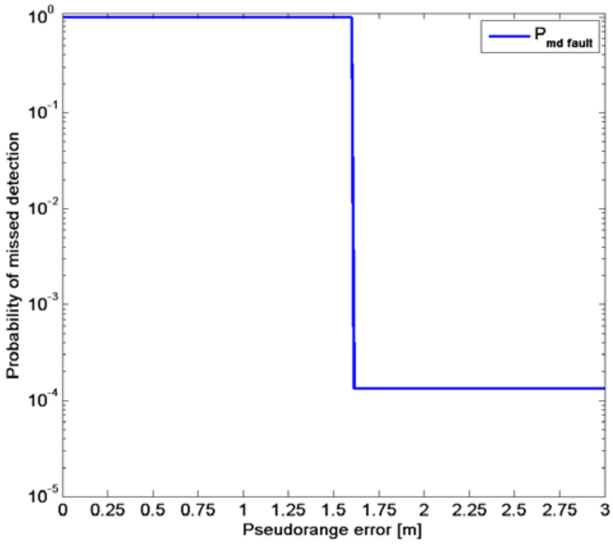

Figure 3 Malfunction case monitoring requirement

The previously described conditions form the basis for all low-level monitoring requirements in a GAST D GBAS. Note that the conditions have different constraint regions and have to be met at all times for all monitors. The combined monitoring condition is shown as the black dashed line in Figure 4. The combination of monitors in the ground and airborne systems has to ensure that any potential errors are detected with the required probability.

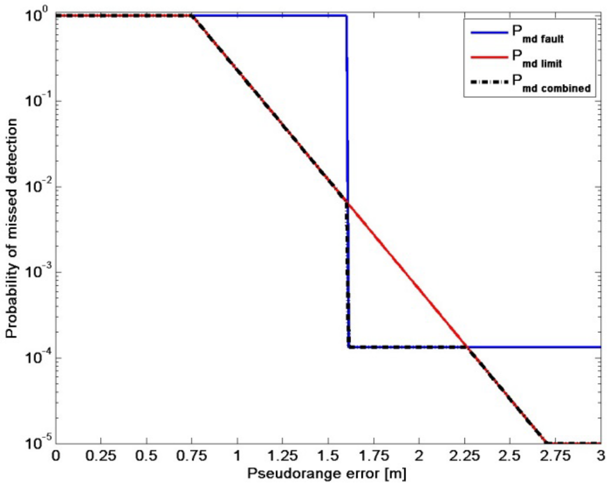

Figure 4 Total constraint region (black dased line) by combining the limit case and the malfunction case conditions.

FTE PERFORMANCE

The FTE performance of an aircraft depends on a variety of different parameters such as its mass and speed but mainly on the wind conditions encountered during landing. During certification the σ_{FTE} of an aircraft is determined. In this context σ_{FTE} describes the along-track dispersion of the touchdown point on the runway which was also used in the requirement derivation. It has to be demonstrated in a combination of Monte-Carlo simulations and flight tests that the aircraft can safely land in the touchdown box in various configurations (i.e. flap settings) and under a wide variety of wind scenarios.

In the previous sections we gave a short summary of the derivation process for the navigation requirements. In that process certain fixed values for the FTE performance were assumed. In case during certification of a specific aircraft a σ_{FTE} is determined which is larger than the values used to derive the navigation requirements, a limitation on σ_{NSE} by setting tighter internal Alert Limits and/or the projection factors of the S matrix has to be imposed.

In all the previous steps, however, only one single fixed value for σ_{FTE} is assumed which holds in all wind conditions. This does not recognize the fact that often the conditions encountered during landing are much less constraining (e.g. low visibility conditions due to fog typically coincide with very little wind) which results in better touchdown performance (i.e. smaller σ_{FTE}) than the value derived during certification.

Instead of taking this one single value, we suggest to use a σ_{FTE} which corresponds more to the actual conditions during an approach. By bounding the NSE and FTE during a specific approach it is possible to bound the TSE of the aircraft for the given conditions. Note that this is a significant difference to an ILS approach where it is not possible to bound the actual position error and thus the

TSE. This advantage is unique to GBAS and can be used to demonstrate that it is possible to fly parallel approaches [7] or to optimize the landing operation as we will describe in a later section.

FTE CATEGORIZATION AND MONITORING

For being able to take advantage of better expected touchdown performance it is essential to have reliable information about the prevailing conditions. During an approach the deviations from the desired and predefined approach track are continuously calculated and used as input to the autopilot. These deviations represent the instantaneous FTE on the approach. The parameter of interest in the GBAS autoland context is, however, the FTE describing the touchdown performance. We therefore propose to use the history of the deviations during the approach to predict the expected touchdown performance. For practical reasons it is not desirable to dynamically change the prediction of the σ_{FTE} at touchdown but rather to use a classification scheme e.g. in a more optimistic low wind scenario with a smaller σ_{FTE} than the one determined during certification, and the current standard scenario.

For the low wind scenario the same kind of Monte-Carlo simulations to evaluate touchdown performance should be performed but with restricted parameters in the wind models. The standard models are given in Book 2 of the CS-AWO [2] and consist of three contributions: the mean wind at the airport, wind shear and turbulence. The mean wind is typically measured at the airport at a height between 6 m and 10 m above the ground. Wind shear describes a change of the mean wind speed depending on altitude. The wind speed typically decreases with decreasing height above ground due to terrain, vegetation and other obstacles which reduce the wind speed when approaching the surface of the earth. Depending on the type of aircraft and performance of its autopilot the effect of wind during the approach will differ. However, the deviations encountered under a specific wind scenario can be used as a measure to decide if a low wind or the nominal scenario is to be considered for a specific approach. The decision should be made at a stage of the approach where it is still easily possible to change parameters, such as e.g. the touchdown point the aircraft is aiming for.

Once a decision was made which conditions prevail, there is still a slight chance that unusually strong turbulence and/or wind shear occurs at a later stage during the approach such that the actual FTE performance might be worse than the expected performance of the assumed wind scenario. For that reason the deviations are continuously monitored and tested for any exceedance of the deviation bounds which were determined for a specific aircraft type in the given wind scenario. Upon exceeding the maximum deviation values the approach could be continued if all safety criteria are still met, otherwise a go-around has to be initiated. When defining the scenarios and the boundaries of course it is necessary to ensure a go-around rate low enough that the proposed method is still operationally beneficial.

DISCUSSION AND OUTLOOK ON POSSIBLE BENEFITS

Taking a more realistic view on the actual aircraft performance, rather than using conservative assumptions can bring benefits in different ways. For the GBAS monitoring requirements, however, it is very difficult to take advantage of this method since the monitoring effort is shared between the ground and airborne subsystems. As knowledge about the FTE (and thus the TSE) of a specific aircraft is not known to the ground station and not just one specific but all aircraft have to be supported, there is no way to relax ground monitoring requirements with the current GBAS architecture. Thus only in the airborne system a benefit can be realized. However, again it is not practical to use the margin resulting from improved FTE performance to relax navigation requirements for the same reason that different monitors in the ground and airborne systems address different parts of the threat space.

If the navigation requirements are left unchanged, the requirement to land within the touchdown box in the nominal, limit and fault case can also be regarded with a fixed NSE performance but with varying FTE. This can be done by solving Equations (6), (8) and (12) which were describing the condition to land inside the touchdown box for σ_{FTE}. The resulting boundary conditions arising from the different cases are shown in Figure 5. The curves for the limit and fault case are shifted slightly to the right from the nominal case constraint due to the larger land long limit which was shown in Figure 1. The total constraint region as a function of the nominal touchdown point and the FTE performance is shown by the black dashed curve. Any combination of σ_{FTE} and NTPD which lies below the curve is acceptable.

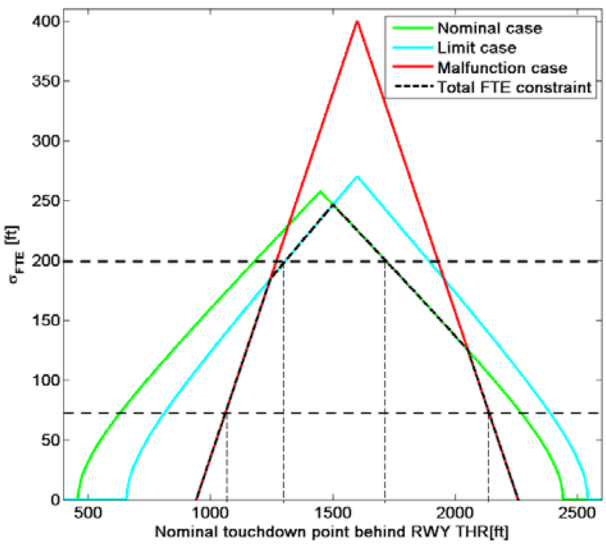

Figure 5 Constraints on the touchdown performance as a function of the FTE performance.

Assuming now fixed values for the NSE (given by the shape and magnitude of the curves) and an expected σ_{FTE} for touchdown which was derived from the history of the deviations throughout the approach, the parameter which can be varied is the NTDP. For a σ_{FTE} of 75 ft the possible values for the NTDP range from about 1085 ft to 2116 ft behind the runway threshold. If the σ_{FTE} is as large as 200 ft (and thus larger than in the derivation of the requirements) the NTDP can only range from 1331 ft to 1715 ft behind the threshold.

On short runways the NTDP could be shifted more towards the beginning of the runway in order to minimize the risk of runway overruns, especially in the case of water or snow contaminated runways. This situation is illustrated in Figure 6. It could also be beneficial to choose the NTDP in such a way that the landing aircraft reaches an exit as quickly as possible and thus the runway occupancy time is minimized. This can increase the capacity of a runway at congested airports. Another way to realize a benefit could be the integration of the proposed method with the brake to vacate automatic braking system. That system optimizes braking such that the wear of the wheel brakes is minimized. A flexible NTDP could improve the system by providing a longer rollout.

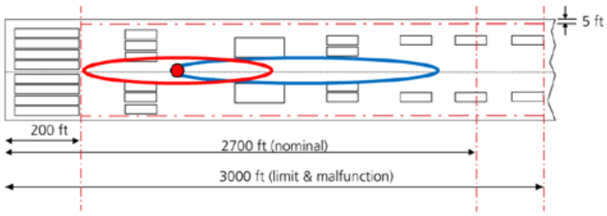

Figure 6 Expected touchdown dispersion within the touchdown zone. Shown in blue is the classical TSE bounding, while the red area illustrates a reduced uncertainty due to FTE prediction and the possibility to shift the NTDP.

CONCLUSIONS

In this paper we showed the process of deriving requirements for GBAS navigation performance from the need to land safely within a certain area on the runway. In the derivation one certain fixed value for the performance of the autopilot is assumed. However, with a continuous monitoring of the deviations of the aircraft during the approach it is possible to show that during the majority of approaches the FTE performance of the aircraft is better than conservative value for touchdown performance derived during certification. This margin can then be used to optimize the landing e.g. in conjunction with the automatic braking.

REFERENCES

[1] Geister, Robert und Hanses, Christian und Becker, Hayung (2012) *CURVED APPROACH PROCEDURES ENABLED BY A GROUND BASED AUGMENTATION SYSTEM.* IEEE Xplore. 31st DASC 2012, 14. - 18. 10. 2012, Williamsburg, VA, USA

[2] EASA 2003, Certification Specifications for All Weather Operations, (CS-AWO)

[3] FAA 1999, CRITERIA FOR APPROVAL OF CATEGORY III WEATHER MINIMA FOR TAKEOFF, LANDING, AND ROLLOUT, AC 120-28D

[4] RTCA DO-253C (2008), Minimum operational performance standards for GPS local area augmentation system airborne equipment

[5] Eurocae ED-114A, Minimum operational performance specification for global navigation satellite ground based augmentation system ground equipment to support category I operations

[6] Burns J, et al. (2009) Conceptual framework for the proposal for GBAS to support CAT-III operations, ICAO Navigation Systems Panel

[7] Geister, Robert und Dautermann, Thomas und Felux, Michael (2014) *Total System Error Performance During Precision Approaches.* ICRAT 2014, 26.05.14 - 30.05.14, Istanbul, Turkey