Total Sytem Error Performance During Precision Approaches

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***Abstract*—This paper gives an overview of the error performance of different navigation sensors used in an A320 research aircraft. In particular, the Total System Error (TSE) performance during precision approaches is investigated. Different approaches based on the Instrument Landing System (ILS) as well as based on the GNNS Landing System (GLS) were conducted manually with a research aircraft of the German Aerospace Center (DLR). The main focus of the work is put on comparing the TSE during the two different types of approaches. The goal is to show that the TSE performance is equivalent for both guidance systems and that GLS could therefore be used for simultaneous approach operations onto parallel runways. In addition, the position accuracy in the vertical domain of different sensors is investigated. Here we compare a Ground Based Augmentation System (GBAS) and the barometric altitude sensor of the basic aircraft.**

Keywords-GBAS; ILS; Total System Error Performance; VNAV

I. Introduction

Since the 1940s the traditional form of guidance of aircraft on final approach was provided by the Instrument Landing System (ILS). It consists of two transmitters which provide guidance in the horizontal and vertical planes. A localizer, situated behind the runway end to which approach service is provided, gives lateral guidance on the approach and during roll out on the runway [1]. For vertical guidance a glide slope transmitter is placed next to the runway abeam the touchdown point at a safe distance [2]. Both systems transmit narrow beams with different modulations: slightly left and right to the extended centerline for the localizer; and slightly above and below the desired glide path for the glide slope. This enables the aircraft to determine its instant deviation from the predefined approach track. However, the fixed antenna installation can only provide one single straight reference path and does not support optimized curved approach tracks in terms of noise abatement or reduced fuel consumption.

Since the introduction of Global Navigation Satellite Systems (GNSS) in the 1990s, the aviation community has been very interested in its further use for this purpose. The ICAO identified GNSS as one of the main enablers for progress in Air Traffic Management (ATM) with the potential to greatly increase capacity of airspace systems [3]. Despite its great nominal performance, however, standalone GPS is not able to provide sufficient accuracy and integrity for approach and landing operations. The imaginable impact of several potential sources for significant positioning errors, including ionospheric disturbances (see [4], [5] and [6]) Radio Frequency Interference (RFI) and several others requires additional techniques or systems that can provide a means to detect errors or provide corrections, together with integrity information. Receiver Autonomous Integrity Monitoring is a technique in which redundant GNSS measurements are used to check plausibility of the navigation solution and to identify potentially faulty satellites or associated measurements. This method can guarantee a certain level of integrity and in combination with inertial navigation supports operations with Required Navigation Performance (RNP). However, it only monitors and does not correct any potential errors. Corrections for GNSS measurements are provided by Space Based Augmentation Systems (SBAS) such as the US Wide Area Augmentation System (WAAS) and the European Geostationary Navigation Overlay Service (EGNOS). Both operate a wide area network of ground stations which monitor the GNSS satellites and ionospheric conditions and provide this information to users via geostationary satellites. A user is thus able to correct for a great part of the ionospheric disturbance and place a significant amount of trust in the correctness of navigation signals. WAAS is capable of providing lateral and vertical approach guidance down to a decision height of 200ft and EGNOS to a minimum decision height of 250ft (see [7], [8]).

However, not all effects can be detected and reflected in the transmitted parameters within the required time to alarm for approaches with a lower or no decision height. In current operating systems this can only be achieved by means of a Ground Based Augmentation System (GBAS). A GBAS, or Local Area Augmentation System (LAAS) as it is referred in the US, consists of typically four reference receivers which are located at the airport to which approach service is provided. They generate locally relevant differential GNSS corrections and provide integrity parameters which allow arriving aircraft to navigate with the required level of accuracy and integrity. Currently, systems supporting CAT-I operations (i.e., instrument guidance to a decision height of not less than 200ft, visual continuation afterwards) have been certified and the first stations have become operational (Bremen, Newark, Houston) or are in the process of obtaining approval (Malaga, Zürich). The standards for GBAS supporting CAT-II/III operations are currently undergoing validation and are expected to be fully adopted by ICAO in 2018 [9].

The introduction of the GNSS Landing System (GLS) in addition to ILS poses several new questions in terms of operations, especially regarding mixed operations at airports operating both systems simultaneously. This will likely become the nominal situation for the foreseeable future as ILS will not be decommissioned for many years. Especially for parallel approaches a detailed look on the performance of both systems has to be taken in order to ensure that simultaneous approaches based on different systems does not pose any safety risks. Currently, ILS and MLS are the only guidance systems which can be used for simultaneous parallel approach operations [10]. GLS could be used as another guidance system for such parallel approach operations provided that approaching aircraft using GLS follow the desired flight path like they would in the ILS case. In addition, some research is made to investigate whether GLS could even enable segmented parallel approaches to use the runway capacity more efficiently [11]. Below, the Total System Error (TSE) performance of GLS operations is compared to the performance of ILS before the decision height (visual part of an instrument approach starts afterwards). The analysis is based on flight data which was collected during several approaches with an Airbus A320 research aircraft to the airport of Brunswick, Germany, which is equipped with an ILS and a GBAS ground station. Similar GLS flight trials were performed in [12] with smaller aircraft. In this work a single transport category aircraft is used for ILS and GLS approaches.

There are different components which add up to the TSE. The error that is made in defining the flight path (resolution limits of digital data systems) is called Path Definition Error (PDE). It is usually negligible and is not considered in this study. The error between the actual aircraft position and the estimated position from the navigation system is called the Navigation System Error (NSE). Finally, the difference between the estimated flight path and the defined flight path is called Flight Technical Error (FTE). This part of the TSE is attributed to the pilot or autopilot and the capability to follow a predefined path. The errors are illustrated in Figure 1. They are usually divided into their lateral and the vertical components. In this paper, we show the NSE performance of different sources.

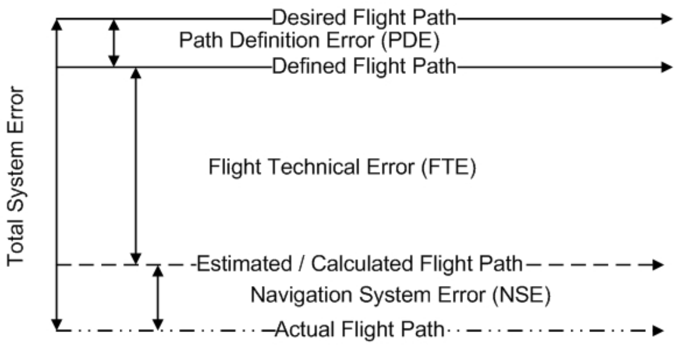

Figure 1: Flight Path Error Types

In addition, the TSE of precision approaches is below compared, i.e. during ILS approaches and GLS approaches. This includes the NSE as well as the FTE during these types of approaches. The goal is to determine if the TSE during GLS approaches is comparable to the TSE of the well-established ILS approaches. At the moment simultaneous operations onto a parallel runway system are only allowed when using ILS for the approach. The paper details collected data from flight trials that indicate that the TSE is in the same range as from ILS approaches, and therefore GLS could be used for simultaneous operation into a parallel runway system.

II. METHODS

A. Setup of experimental hardware

The presented data were gathered during different flights with the A320 research aircraft of the German Aerospace Center, the Advanced Technology Research Aircraft (ATRA). The aircraft is equipped with a basic flight test instrumentation that records data from the different sensors and systems of the basic (unmodified) aircraft. This includes data from the barometric altitude system, aircraft attitude data and ILS receiver deviations. Additionally, experimental equipment was integrated for these flight trials. First, an experimental cockpit display was integrated on the right side of the cockpit. On this display, a Primary Flight Display (PFD), a Navigation Display (ND) and an Engine Display (ED) were shown (see Figure 2). Secondly, two racks were integrated in the cabin. In these racks, a Septentrio GNSS receiver and a Rockwell Collins Multi Mode Receiver (MMR) were used to gather GNSS data. The Septentrio receiver is capable to receive SBAS data. The MMR is capable to receive GBAS messages from a GBAS ground station [13]. Both GNSS receivers were connected to the same antenna through a power divider.

The Septentrio data was used for post processing of a carrier phase solution after each flight which serves as the true reference position. The MMR is a standard avionics device and as such does not output its GBAS corrected position online, but only deviations from a reference flight path [14]. During the data analysis we found that the MMR data was not usable for all investigations presented in this paper, as there were reception problems due to the antenna wiring in the aircraft during one flight. Therefore, only the Septentrio data were used and processed in the same way the MMR would in order to have all investigated data from a single source.

Figure 2: ATRA experimental cockpit display

The GNSS receivers were connected to an experimental antenna on top of the fuselage. The sensors for the barometric altimetry system are located on the lower fuselage. The antennas for the ILS system are located at the nose of the aircraft (see Figure 3).

B. *Flight Trial Setup*

The results from the flight trials conducted with ATRA were all obtained during manual flight with a flight director shown to the pilot on the experimental cockpit display (see Figure 2). The approaches shown here were either ILS or GLS approaches. They were all conducted at Braunschweig-Wolfsburg airport (ICAO: EDVE) and they were conducted onto both runway ends (26 and 08).

The flight trials were conducted over a period of two years. During this time, the runway at the airport was extended and the Glide Path Angle (GPA) of the ILS system was changed from 3.5° to 3.0°. The GLS approaches were designed to be an exact copy of the ILS approach and were verified as such [15]. As both GPAs are permitted by ICAO for an ILS Category I (CAT I) approach, flight trials with both GPAs are considered in this work and it is not differentiated between them in the analysis.

From an operational point of view, the approaches were conducted in a similar fashion. During both types of approaches, the aircraft was intercepting the localizer with a certain offset (usually 30°) and afterwards the glideslope was intercepted. However, some of the GLS approaches considered here had a curved leg at the beginning of the approach. These legs were neglected here to compare only straight in ILS and "ILS-look-alike" approaches.

The data presented were obtained from the flights shown in TABLE I. In total, six ILS approaches as well as fourteen GLS approaches, all manually conducted, were evaluated. Due to the mentioned reception problems of the MMR, the flights from the 4th flight could not be used for analysis. Therefore, only data from eight GLS approaches are used for the investigations.

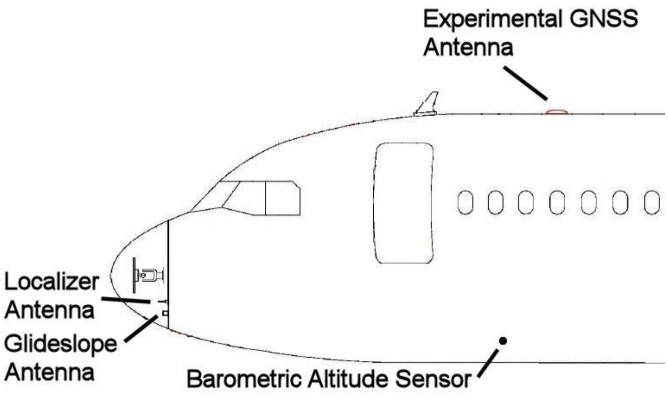

Figure 3: Approximate antenna and sensor positions

In order to evaluate the NSE during the flights, the Dilution of Precision (DOP) was considered. The DOP is an indication of how well the aircraft's position can be estimated by GNSS as a result from the prevailing satellite geometry. TABLE II. shows the minimum and maximum values of the Horizontal and Vertical DOP during each flight.

TABLE I. DATES OF FLIGHT TRAILS

Flight No. #	**Dates of Flights**		
	Date	***No. of ILS Appr.***	***No. of GLS Appr.***
1	10/06/2011	3	0
2	10/06/2011	1	1
3	01/23/2013	0	3
4 (not used)	09/05/2013	0	6
5	09/19/2013	2	4

TABLE II. DILUTION OF PRECISION DURING TRIALS

Flight No. #	**Table Column Head**			
	Max VDOP	***Min VDOP***	***Max HDOP***	***Min HDOP***
1	1.88	1.10	1.29	0.89
2	1.65	1.0	0.97	0.75
3	1.68	0.95	1.09	0.76
4	1.47	0.98	1.1	0.79
5	2.97	1.23	1.06	0.68

C. *Data reduction*

The results for ILS approaches were derived from the localizer and glideslope deviations that were recorded directly from the onboard ILS receiver in Differences in Depth of Modulation (DDM). These values were transformed to degrees with the formula given in [14]

$$\alpha_{lat,\, full\, scale} = \pm \tan^{-1}\left(\frac{Course\ Width\ at\ Threshold}{Dist\ Threshold\ to\ Azim.\ Ref.\ Point}\right) \quad (1)$$

and the assumption that a full scale deflection occurs at 0.155 DDM. Reference [14] describes the local area augmentation system, but, as the GLS approaches were designed to be equal to the ILS approach, the calculations yield comparable results. The deviations recorded from the ILS system represent the FTE during the ILS approaches. In the same manner the vertical FTE was transformed with:

$$\alpha_{vert,\, degrees} = \text{Vertical Deviation}_{DDM}\left(\frac{0.25\ x\ GPA}{0.175}\right) \quad (2))$$

The results for the GLS approaches presented in this work are based on the Septentrio receiver. This Septentrio receiver is not GBAS capable by itself, but the data gathered from this receiver was used together with the GBAS messages received by the MMR to calculate a GBAS solution after the flight. The software used to do so was the PEGASUS toolset provided by EUROCONTROL [16].

The raw deviation data from the MMR is based on the GBAS corrected position. Therefore the deviations represent the GLS FTE for the GLS approaches. These deviations were displayed to the pilot who conducted the GLS approaches. The deviations obtained by the post-processing with PEGASUS and the Septentrio data were nearly identical (same antenna) to the MMR deviations and were used instead, to achieve a higher data rate for presenting the results here.

To determine the true position of the aircraft, dual frequency carrier phase data from the Septentrio receiver was post-processed with RtkLib 4.2.2 [17] relative to the IGS reference site PTBB [18] located at the Physikalisch Technische Bundesanstalt (PTB) about 6km southwest of the airport. The reference solution was obtained using kinematic integer ambiguity resolution, which yields sub decimeter RMS accuracy [19].

This position reference was used to determine the deviations from the desired flight path according to [14]. This is equivalent to the way that deviations are calculated by the MMR and the Pegasus toolset. Additionally, the GLS approach is designed to be equal to the ILS approach and therefore all deviations are comparable. The deviations obtained by the calculations based on the reference position represent the TSE for each flight. For every flight the TSE and the FTE were obtained in post-processing. The NSE was calculated by subtraction of the FTE from the TSE. In summary the following data was used:

- TSE; deviations calculated based on the reference position according to [14], corrected by the different antenna positions
- FTE; deviations received by the onboard ILS and for GBAS obtained by the Pegasus toolset based on the calculated GBAS position of the Septentrio receiver
- NSE; TSE - FTE

All data were time synchronized. To compare the different approaches to each other, all data was presented in terms of distance to the runway threshold. The distance to the runway threshold was calculated based on the true reference position.

For the approaches, deviations were considered if the aircraft was established on the final approach path (laterally and vertically) and the system was operational. In addition, data was only considered until a go-around was initiated. As stated above, some of the GLS approaches had a curved leg at the beginning. Therefore, the final approach path was significantly shorter (approx. 5000m) than the ILS final approach. This can be seen in the results we present in this work.

Furthermore, for the determination of the vertical NSE (and therefore the TSE) all position data was corrected for the different locations of the antennas and sensors. All positions were transformed to the GNSS antenna position of the Septentrio and the MMR (as shown in Figure 3). Therefore, the glideslope signals and the signals from the barometric altimetry system had to be corrected taking the attitude of the aircraft into account.

With these corrected results, the vertical position accuracy of the different systems (GBAS and barometric altimeter) was compared. In this case data was considered throughout the flight if the respective system was operational (e.g. the aircraft was within GBAS coverage region).

III. RESULTS

The flight trial data were synchronized and transformed with regard to the distance to the runway threshold. This was done based on the reference position obtained in post-processing.

A. *Results for ILS*

Figure 4 shows the mean TSE over the distance to the runway threshold during all six investigated ILS approaches. The red line indicates the lateral TSE and the green line indicates the vertical TSE. The standard deviation for every mean value is shown as a vertical line.

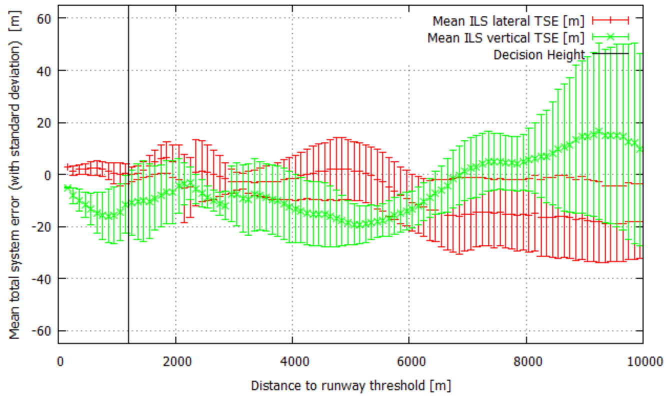

Figure 4: ILS Mean TSE

Figure 5 shows an example of the recorded ILS FTE during three approaches. The red crosses represent the localizer deviation in degrees over the distance to the runway threshold. The deviations are transformed from DDM to degrees by the formula given above. The green crosses indicate the glideslope deviations over the distance to the runway threshold. It can be seen that especially the localizer signal is distorted to a certain degree further away from the threshold. It has to be stated that the vertical deviation indication is more sensitive than the lateral deviation indication. Therefore, the same FTE value in degrees would yield a larger FTE in meter.

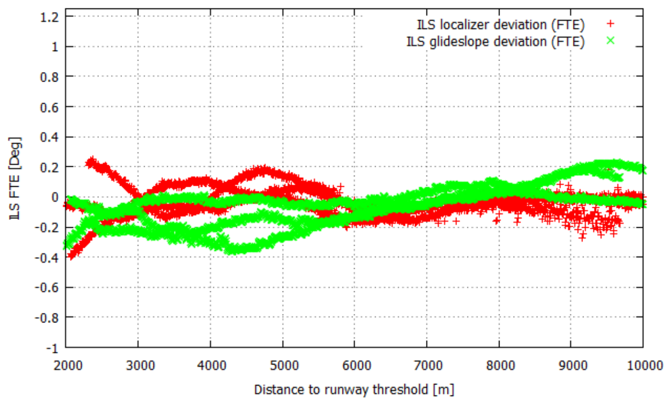

Figure 5: ILS Devs FTE example

B. Results for GLS

For the GLS approaches, data was only considered if the aircraft was on a straight final. In some of the flights curved approaches were investigated. As the curved part is not comparable to ILS, data gathered before the straight final segment of those approaches were disregarded. Figure 6 shows an example of the GLS FTE during three GLS approaches.

It can be seen that the deviations are a lot smoother and steadier than in the ILS case. The red crosses indicate the localizer deviation in degrees over the distance to the runway. The green crosses indicate the glideslope deviation. The magenta crosses indicate a curved approach during which the pilot was not able to intercept the straight final approach segment promptly. This approach was not considered in the analysis of the lateral errors. It can also be seen that the curved leg ended around 7000m away from the runway threshold. Therefore, only lateral deviations observed beyond that point were considered in the analysis.

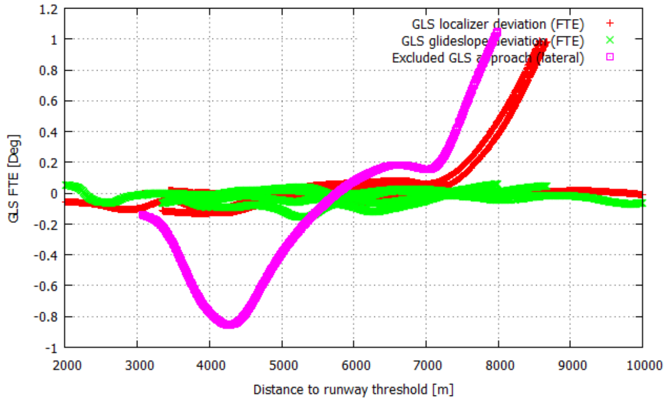

Figure 6: GLS Devs FTE example

Figure 7 shows the mean lateral TSE for seven considered GLS approaches. The vertical lines indicate the standard deviation for every mean value.

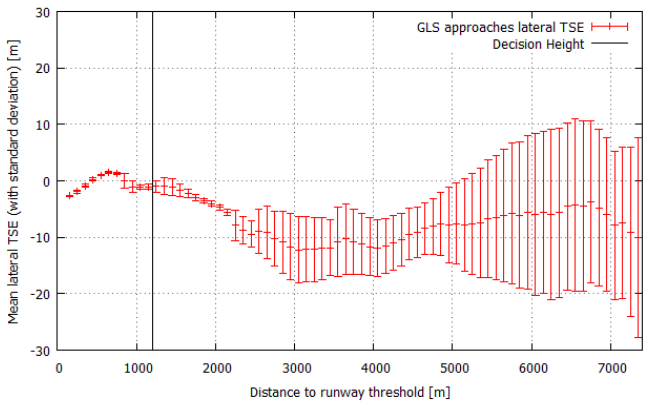

Figure 7: Mean lateral TSE during GLS approaches

Figure 8 shows the same data for the vertical TSE during GLS approaches. Here, all eight approaches were considered. In both figures the standard deviation decreases towards the runway threshold as fewer approaches were continued to perform a landing. Many of the approaches were discontinued by a go-around in order to conduct more approaches in a single flight.

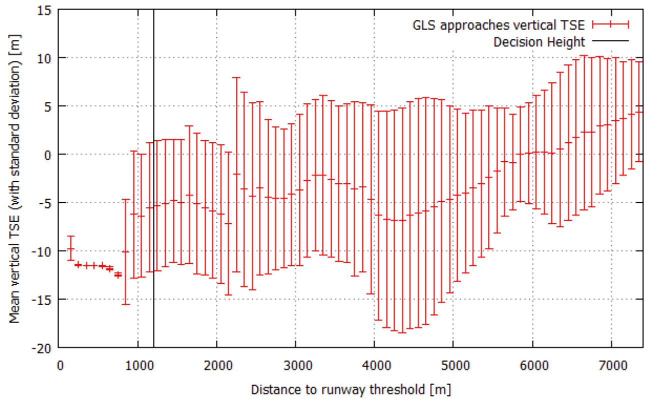

Figure 8: Mean vertical TSE during GLS approaches

As described above, one of the components of the TSE is the FTE. Figure 9 shows the mean lateral FTE of the seven approaches considered. Figure 10 shows the mean FTE for the vertical domain. All eight approaches are considered again. Comparing the TSE and the FTE it becomes evident that the FTE is the major component of the TSE during a GLS approach. It was found that the vertical TSE is increasing significantly after the decision height during the visual part of the approach (see Figure 10 at distances smaller than 1200m).

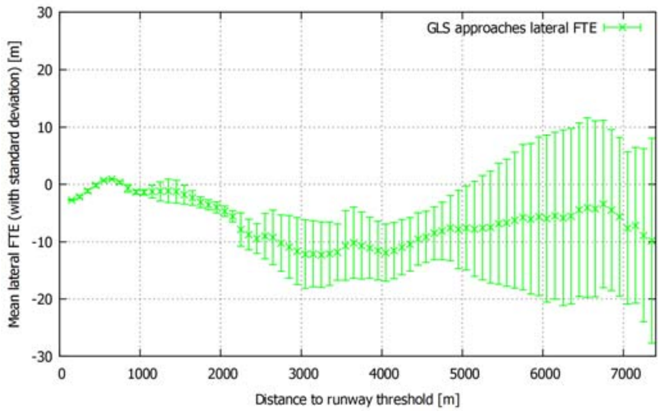

Figure 9: Mean lateral FTE during GLS approaches

Figure 10: Mean vertical FTE during GLS approaches

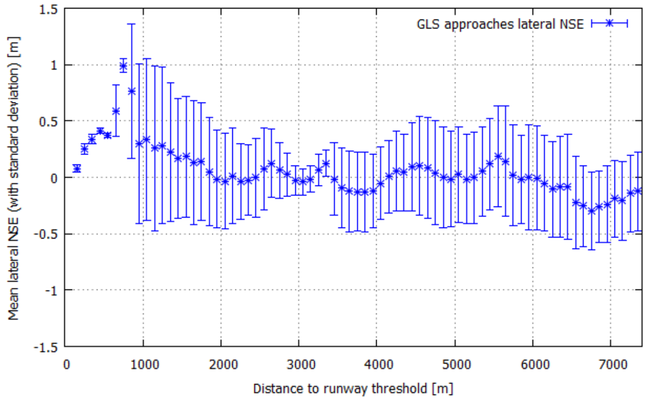

Figure 11: Mean lateral NSE during GLS approaches

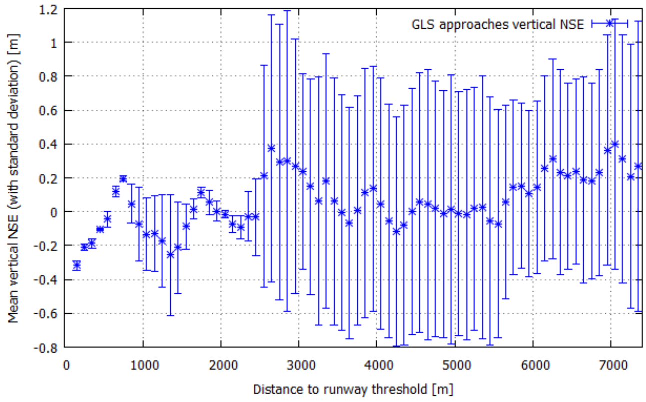

Figure 12: Mean vertical NSE during GLS approaches

The second investigated component of the TSE is the NSE. The NSE of GBAS was gathered by subtracting the observed FTE from the calculated TSE in order to account for the along-track error. Figure 11 shows the mean lateral NSE during the final straight segment of the seven considered GLS approaches. It can be seen that the error is generally small and distributed around zero.

Figure 12 shows the mean vertical NSE of the eight considered GLS approaches. The vertical NSE is as well generally small and distributed around zero.

In order to compare the vertical NSE performance from different sources during our GLS approaches, the error distribution over the approaches of a single flight is shown in Figure 13. The green histogram shows the NSE distribution for GBAS. The blue one shows the vertical NSE distribution of the barometric altimetry system.

As stated above, data was only taken into account if the aircraft was established on the localizer and the glide slope and before a go around was initiated and before the decision height. As multiple approaches were flown during one flight and only a single final landing was conducted, the usable data close to the runway threshold are sparse due to the small number of approaches. Therefore, care should be taken in analyzing the data statistically.

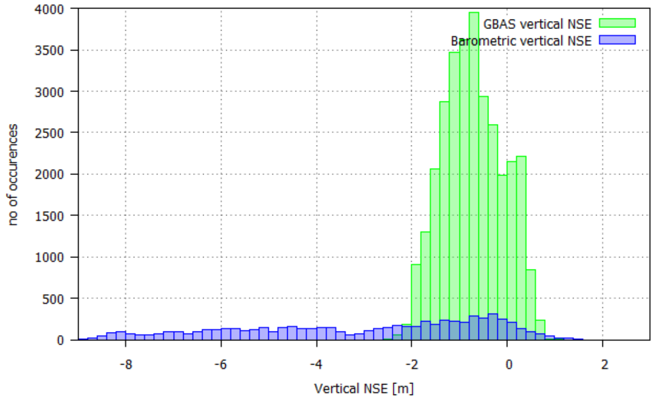

Figure 13: NSE distribution during the approaches of a single flight (GBAS, green and barometric altitude, blue)

IV. Discussion

For GLS approaches, it is evident that the lateral NSE is fairly small (the mean error remains generally smaller than 0.5m in the analyzed flight trials) compared to the FTE. It has to be stated, that some of the conducted GLS approaches had a curved leg. The capture of the straight final approach segment is therefore somewhat more difficult and it occurred slightly later than for standard straight-in approaches. This is visible in Figure 6 (magenta points) between approximately 3500m and 5000m away from the threshold. Especially during this approach the pilot was not able to intercept the localizer promptly after a curved leg. Therefore this approach was not considered in the analysis of the lateral error performance.

The vertical NSE for GLS approaches is also rather small and shown to be of similar magnitude as the lateral NSE. The observed TSE (both laterally and vertically) is well within the assumed reference values of the ILS collision risk model [20].

To be able to compare the ILS TSE and the GLS TSE, the analysis focused on the last part of the final approach in Figure 14. There, it is visible that the TSE of both types of approaches in this distance to the runway threshold (where ILS is the most accurate) is very similar and very small. This is especially notable when considering that the allowable lateral alert limit for the NSE of GLS approaches alone is approximately 40m for this distance to the threshold.

When comparing the vertical TSE (Figure 15), it can be seen that the observed error in the approaches is smaller during GLS approaches than during ILS approaches. As the curved approaches already had a glide path angle corresponding to the final segment, they do not have an influence on the vertical TSE in this case.

Looking at the distribution of the vertical NSE during a complete flight, it can be stated that in the GBAS case the error is normally distributed with a small mean and standard deviation (see Figure 13). When investigating the vertical NSE of the barometric altimeter, it can be seen that the setting of the barometric correction of the pilot has a direct influence. If the air pressure changes over time, the NSE will increase. This error will prevail until the pilot adapts the barometric correction setting. Therefore, the NSE is not normally distributed and usually greater than for GBAS.

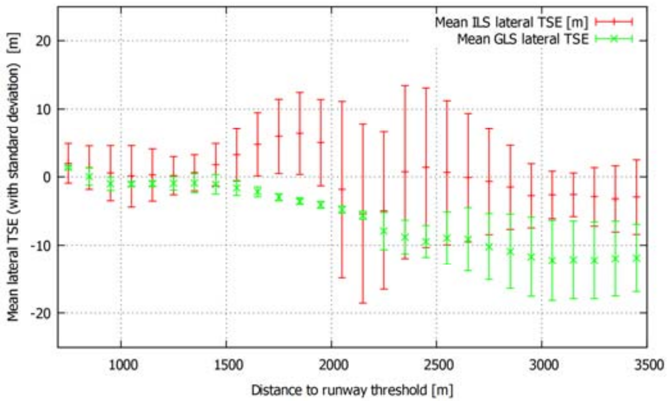

Figure 14: Comparison of mean lateral TSE during ILS (red) and GLS (green) approaches

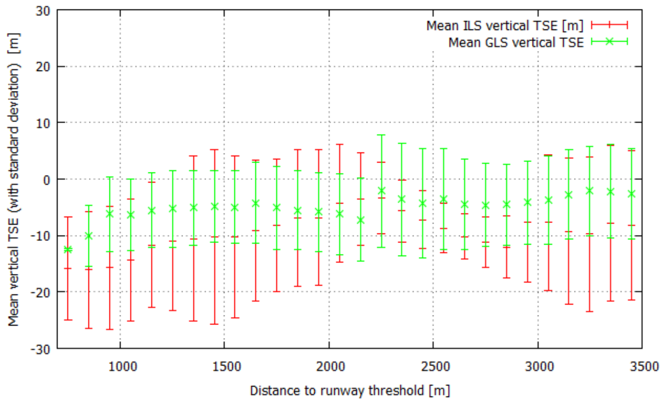

Figure 15: Comparison of mean vertical TSE during ILS (red) and GLS (green) approaches

V. CONCLUSION

In conclusion it can be stated that the GLS TSE performance is similar to the ILS TSE performance and would therefore allow simultaneous operations onto parallel runways as well. As the results presented here are based on a small number of approaches, the statistical analysis should be verified with additional data. The investigations in this work indicate however that the design concept of GLS being introduced as “ILS-look-alike” yields comparable behavior.

In addition, the vertical position accuracy for GBAS is higher and more reliable than the barometric vertical position accuracy and effort should be made to introduce augmented satellite systems as the main source of the vertical position information rather than barometric altimetry systems.

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