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Summary

It is important for safety, capacity, and environmental reasons, that aircraft follow the desired flight path as accurately as possible, especially in the vicinity of an airport, i.e. the terminal manoeuvring area (TMA). The ability of an aircraft to maintain its desired path depends on various factors of which the accuracy of the navigation system plays a major role. In this study, the lateral deviation from a nominal flight path depending on the positioning sensor in use is investigated by using actual radar measurements of the aircraft's position. A comparison is made between the performance with GPS as positioning sensor and with DME (Distance Measuring Equipment) as positioning sensor on a straight path. Analysis shows a significant decrease in the track dispersion when GPS is used as a primary sensor (about a factor 1.6) instead of DME. Additionally, the disabling of Selective Availability (SA) of the GPS signal decreased the track dispersion again with a factor of 1.8.

List of Abbreviations

ATC	Air Traffic Control
CDA	Continuous Descent Approach
CDU	Control and Display Unit
DME	Distance Measuring Equipment
FCS	Flight Control System
FMC	Flight Management Computer
FMS	Flight Management System
FTE	Flight Technical Error
GPS	Global Positioning System
IAF	Initial Approach Fix
ILS	Instrument Landing System
IRS	Inertial Reference System
NSE	Navigation System Error
RNP	Required Navigation Performance
SA	Selective Availability
SSR	Secondary Surveillance Radar
TMA	Terminal Manoeuvring Area
TSE	Total System Error
UTC	Universal Time Co-ordinated
VOR	Very High Frequency Omni-Directional (Radio) Range

Contents

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1 Introduction

The ability of aircraft to follow the desired flight path as accurately as possible is important for safety, capacity, and environmental reasons, particularly in the vicinity of an airport, i.e. the terminal manoeuvring area (TMA). Various factors contribute to the accuracy of which the accuracy of the navigation system plays a major role.

In this study, the lateral deviation from a nominal flight path, depending on the positioning sensor in use, is computed using actual radar measurements of the aircraft's position. Particularly the use of GPS (Global Positioning System) as the positioning sensor of an aircraft's navigation system is of interest since it provides the highest accuracy compared to conventional positioning sensors. Therefore, a comparison is made between the performance with GPS as positioning sensor and with DME (Distance Measuring Equipment) as positioning sensor.

A comparison between the positioning sensors is made on a straight segment during a continuous descent approach (CDA) operation at Schiphol airport. This approach procedure was chosen for several reasons. Firstly, this procedure contains a large straight downwind segment of approximately 14 NM, which excludes additional effects such as a turning manoeuvre. Secondly, since this procedure is flown during night hours the influence of other air traffic is minimised. Thirdly, pilots conduct this operation without intervention of Air Traffic Control (ATC). Finally, a large amount of radar data could be made available with relatively little effort. A more detailed description of this approach procedure is given in the next section.

On the straight segment, the flight track deviation from the published flight path is calculated for different types of aircraft. Since GPS may merely be used for horizontal navigation, only the lateral deviation from the nominal path is investigated. The aircraft types that are considered are Boeing 737-300/400, Boeing 737-800, and Boeing 747-400. These aircraft types each have different positioning sensors (i.e. GPS or DME) that provide input for the Flight Management System (FMS) to calculate navigation and steering commands.

2 Continuous Descent Approach

Since December 1996, a Continuous Descent Approach (CDA) procedure has been published for runway 06 at Schiphol airport. This approach procedure is a compulsory operation during night hours, because it reduces the noise exposure on the ground.

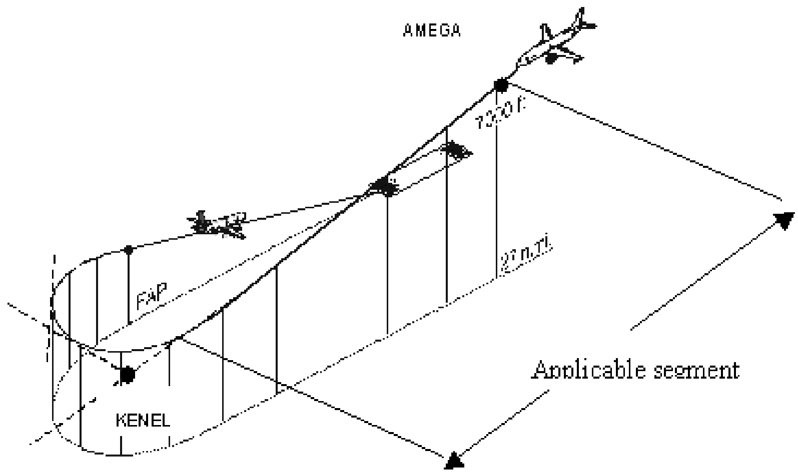

Figure 1: An illustration of the CDA from the Northeast (AMEGA) direction and the downwind segment under study.

After arriving over one of the three Initial Approach Fixes (IAF) of the Schiphol TMA (see Ref. [1]), the pilot will be cleared by ATC for a predefined approach route for runway 06. The CDA starts at one of the corresponding reporting point AMEGA, DETSI or NORBI. In this study, the CDA from the Northeast direction (i.e. AMEGA) is considered, which is depicted in Figure 1.

The AMEGA reporting point is situated at an along track distance of 27 NM from the runway threshold and is to be passed at or above FL070. The descent point – for an optimal path – to descend below FL070 is at the pilot's discretion and is conducted using (near) idle power setting, and without intervention of Air Traffic Control (ATC). The downwind segment under study is from reporting point AMEGA to turning point KENEL and is flown with LNAV mode of the autopilot. The baseleg turn towards the ILS intercept point at 2500 ft above mean sea level is initiated at KENEL.

3 The Navigation system

The Flight Management System (FMS) is a complex system and is capable of performing many functions such as navigation management, performance management, and fuel management. During this study the focus will be on the navigation management function.

Generally, the FMS consists of the Flight Management Computer (FMC), Flight Control System (FCS), Flight Deck Instruments, Control and Display Unit (CDU), and Sensor Systems. A simplified schematic is given in Figure 2. The precise implementation depends on the aircraft and the manufacturer (see Ref.[2] to [5]).

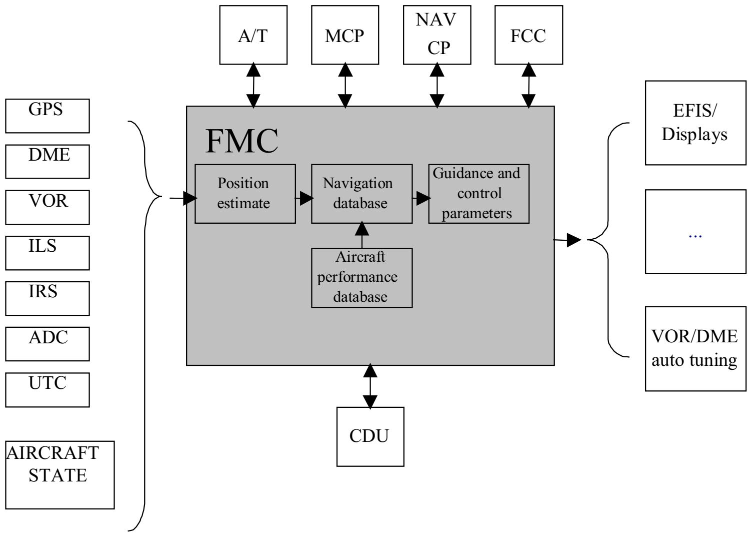

Figure 2: Simplified decomposition of the FMS in which the FMC is the core processing unit.

To obtain a position estimate, all available aircraft data is gathered in the FMS including positioning information from various sensors (e.g. DME, VOR, and GPS), and the air data computer (e.g. altitude, speed, heading, and attitude). The position estimate, the desired position (from the navigation database), the aircraft state (e.g. flap and gear settings etc.), and the aircraft performance parameters (from the aircraft performance database) are used to calculate the guidance and control signals. As already mentioned the FMS uses a combination of inputs from sources that originate from either ground based (DME, VOR/DME and ILS), airborne based (IRS), or space based systems (GPS). Next, a brief description of these sensors is given.

The IRS calculates its position based on dead reckoning using inertia data that is provided by accelerometers. The position based on IRS becomes inaccurate if the IRS is no longer updated by DME, VOR/DME or GPS. The IRS-drift for stabilised platforms is normally conservatively assumed to be 2T+2 (NM) with T the number of hours since IRS alignment.

The DME receiver calculates its position by measuring the slant ranges to at least two ground-based DME beacons. The DME range error will be less than 0.2 NM (95%) for systems installed after January 1st, 1989. For a DME/DME position, the position error is $\sigma^2=(\sigma^2_{DME1}+\sigma^2_{DME2})/\sin(\alpha)$ in which α is the angle between the two DME installations. A position based on a VOR/DME infrastructure is calculated by measuring the slant range and bearing to the VOR/DME. The bearing signal has an accuracy of at least 0.7 degrees (95%). In order to take into account the VOR/DME for the FMS, the facility has to be located within 25 NM of the aircraft, at this slant distance the maximum error would amount to 0.3 NM. For a co-located VOR/DME position, the position error is $\sigma^2=\sigma^2VOR+\sigma^2DME$. Note that in case of sufficient DME stations available, VOR/DME updating will not take place and the FMS defaults to DME/DME.

A GPS position in two dimensions can be calculated when the ranging signals of three GPS satellites and elevation provided by the aircraft's sensors are available. At least four satellites are required for three-dimensional positioning and the accuracy primarily depends on the number of received satellites that are geographical favourably located. The removal of Selective Availability (SA) increased the horizontal position accuracy from 100 m (95%) to approximately 33 m (95%). SA was the intentional degradation of the accuracy of GPS ranging signals by the US Department of Defence, which operates and maintains GPS. SA was turned off on May 2nd, 2000 at 04.00 hrs UTC. More details on GPS accuracy and measures can be found in Ref. [7].

In principle, the FMS updates the IRS position estimate with information received from GPS, DME, or VOR/DME depending on the availability and estimated accuracy of the sensors and the particular aircraft integration. The FMS periodically evaluates the most favourable combination of DME installations and tunes to the DME installations. The way the FMC combines the multi-sensor data to calculate a position estimate depends on the FMS manufacturer and commonly uses an algorithm known as a Kalman filter that estimates the position based on recursive data measurements.

The deviation of the aircraft's true position from its nominal (or desired) path is called the total system error (TSE) (see Ref. [8]). The TSE in the lateral dimension is a combination of:

1. Navigation System Error (NSE); and
2. Flight Technical Error (FTE).

The NSE consists of the error caused by the positioning sensor and the computation error by the navigation system. It can be assumed that the computation error is very small compared to the error caused by the positioning sensor. The FTE is the error induced by the pilot or system while controlling the aircraft and depends on the mode of flight, e.g. manual, flight director or autopilot. During the CDA the latter is used. Differentiation between the NSE and FTE is not possible, because radar measurements of the aircraft's true position are used to determine the deviation from the desired flight path, i.e. the TSE.

The TSE can be linked to an RNP (Required Navigation Performance) value. To establish that an aircraft can navigate according to a specified RNP value k means that the TSE in each dimension must not exceed k NM for 95% of the time for all aircraft. More details about the RNP concept can be found in the ICAO manual Ref. [8].

4 Flight Track Analysis

To analyse the flight track data, several steps have to be performed:
1. Track collection;
2. Track selection;
3. Transformation;
4. Cross-sections; and
5. Statistical analysis.

Next, each step is explained in more detail.

All flight tracks in the Schiphol TMA are constantly monitored and logged by the Civil Aviation Authorities Netherlands for noise and safety reasons. Raw data from the secondary surveillance radar (SSR) is updated every 4 seconds and is used by FANOMOS (Ref. [11]) to reconstruct the actual flight track of the aircraft. For each track, FANOMOS records with fixed intermediate times (4.0 sec) the position of the aircraft, the ground speeds and the total recorded length of the track. These numbers are then stored in a database.

For this study, flight tracks from KLM and Transavia that perform a CDA originating from the Northeast to the runway 06 in the period from November 1, 1998 until October 30, 2000 have been extracted from the database. Aircraft from KLM and Transavia use the same navigation equipment for each of the aircraft types. Additionally, a visual inspection of the vertical trajectories is made to assure that the aircraft followed a continuous descent. For different types of aircraft and primary sensor 240 tracks were randomly selected. For the aircraft equipped with a GPS sensor a distinction is made between before and after SA was removed. An overview of the different sets can be found in Table 1. Insufficient data was available for the Boeing 747-400 (GPS) aircraft even if data of 2001 would have been taken into account. Therefore, this aircraft has not been evaluated in this study.

After the selected tracks have been exported from the database, all tracks are transformed such that (the co-ordinates of) the tracks are relative to the nominal track.

Dataset	**Aircraft type**	**Period**	**Primary sensor**	**Airline (KLM/TRA)**
I	Boeing 737-300/400	Nov 1, 1998 - Oct 30, 2000	DME	TRA / KLM
II	Boeing 747-400	Nov 1, 1998 - Oct 30, 2000	DME	KLM
III	Boeing 737-800	Nov 1, 1998 - May 1, 2000	GPS (with SA)	TRA
IV	Boeing 737-800	May 2, 2000 - Oct 30, 2000	GPS (without SA)	TRA

Table 1: The four different sets of tracks of CDAs performed by KLM and Transavia with different types of aircraft and sensors for each data set 240 tracks were selected.

Next, for each set of tracks (I, II, III, IV), cross-sections are made by computing the (lateral) deviation from the nominal track at fixed longitudinal positions. These cross-sections start at the AMEGA point and are spaced 2 NM. The last cross-section is located at 3.5 NM before the turning point KENEL in order not to include aircraft manoeuvres due to initiation of turns. As a result, 6 cross-sections are made. An illustration of the position of these cross-sections is given in Figure 3.

Figure 3: An illustration of the CDA from Northeast on RWY06. This figure shows Schiphol airport, the nominal route (dashed line), the six cross-sections perpendicular to the nominal route. The stars indicate the AMEGA and KENEL waypoints, and the final approach point (FAP).

Summary statistics like the mean, the median, the standard deviation, the variance, the skewness, and the kurtosis, are computed for each data set to obtain an impression of the data. More details on these measures can be found e.g. Ref. [10].

To obtain a more complete description, the probability distribution function that corresponds to the measured data needs to be determined. The distribution fitting is done using the maximum likelihood method, and to verify if the data follow the given distribution the Kolmogorov-Smirnov goodness-of-fit test can be used (see Ref. [10]). Since it is often assumed that the lateral flight track deviation follow a normal (i.e. Gaussian) distribution, this distribution is fitted. In addition, the Generalised Laplace distribution (see e.g. Ref [9]) is fitted. This distribution is many way similar to the normal distribution: it is symmetric and can also have a clock-shape. However, the Generalised Laplace distribution has an additional parameter that makes it more flexible and more (or less) mass can be shifted towards the tails, making it more (or less) peaked. The Generalised Laplace distribution has the normal distribution as a subclass.

5 Analysis results

For each selection of tracks (I, II, III, VI) and each of the 6 longitudinal positions, a set containing the lateral deviation from the nominal track was obtained as described in the previous section. For each data set a top view of flight tracks and some statistical results are given.

Figure 4 shows a topview of the selected Boeing 737-300 and Boeing 737-400 performing a CDA with DME as primary sensor. From the set of 240 flights, 209 were made by Transavia aircraft and 31 by KLM aircraft. The data from the two airlines can be combined since KLM and Transavia use similar aircraft, FMS and sensor integration.

Figure 4: Topview of the selected CDAs performed by Boeing 737-300/400 using DME as primary sensor (data set I).

The majority of the approaches originate from the East. As a result, a few nautical miles after the AMEGA point, the aircraft are established on the nominal path. On the downwind segment, there are only a few tracks deviating from the nominal path. In the turn, only a few aircraft initiate the turn earlier, making a sharper turn.

Figure 5 shows a topview of the selected Boeing 747-400 performing a CDA with DME as primary sensor derived from 240 tracks flown by KLM aircraft. The majority of approaches originate from the Northeast and East. On the downwind segment several tracks deviate from the nominal path and are attributed to flying the procedure uncoupled to the autopilot or ATC have provided radar vectors. Six tracks south of the nominal path and one track north of the nominal path have been excluded from statistical calculations. A large dispersion in the baseleg turn can be observed with outliers reaching the city of Leiden.

Figure 5: Topview of the selected CDAs performed by Boeing 747-400 using DME as primary sensor (data set II).

Figure 6 shows the selection of 240 Boeing 737-800 aircraft performing a CDA with GPS as primary sensor when SA was enabled.
Figure 7 shows the selection of 240 when SA was disabled. The majority of all aircraft originate from the East. It is also observed that the aircraft are quickly established on the nominal path. On the downwind segment, the nominal path is followed quite precise in both cases. With SA disabled, the aircraft follow the nominal path more accurately then with SA enabled. In the baseleg turn, the sample with SA enabled shows a variety of turns some with outliers. Two distinct concentrations of tracks are seen. In case SA is enabled the dispersion is less pronounced. Analysis of the baseleg turn was not part of the study.

Figure 6: Topview of the selected CDAs performed by Boeing 737-800 using GPS as primary sensor with SA enabled (data set III).

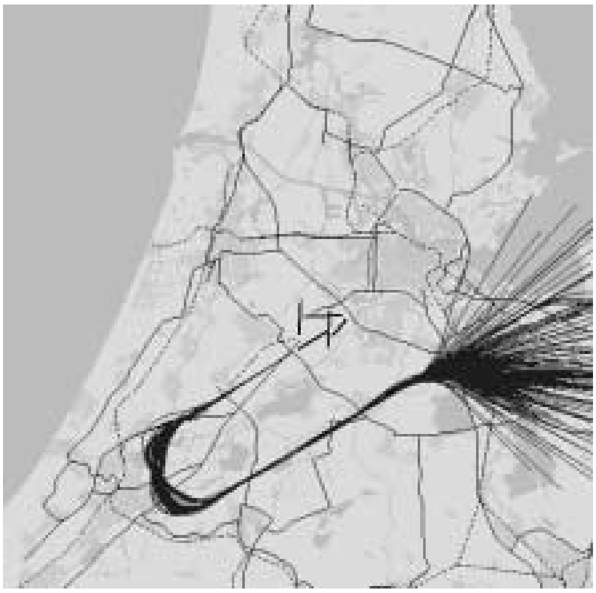

Figure 7: Topview of the selected CDAs performed by Boeing 737-800 using GPS as primary sensor with SA disabled (data set IV).

To compare the dispersion of the different flight tracks, the standard deviations of the lateral deviation from the nominal path have been computed. The results are plotted in Figure 8. The solid lines are the data sets with DME as primary sensor (squares are Boeing 737-300/400 and crosses are Boeing 747-400). The dashed lines are the data sets with GPS as primary sensor (diamonds indicate Boeing 737-800 with SA and triangles Boeing 737-800 without SA). From this figure the gradual decrease in the dispersion can be seen and that the aircraft thave established their nominal path at about 4 NM after passing the AMEGA waypoint.

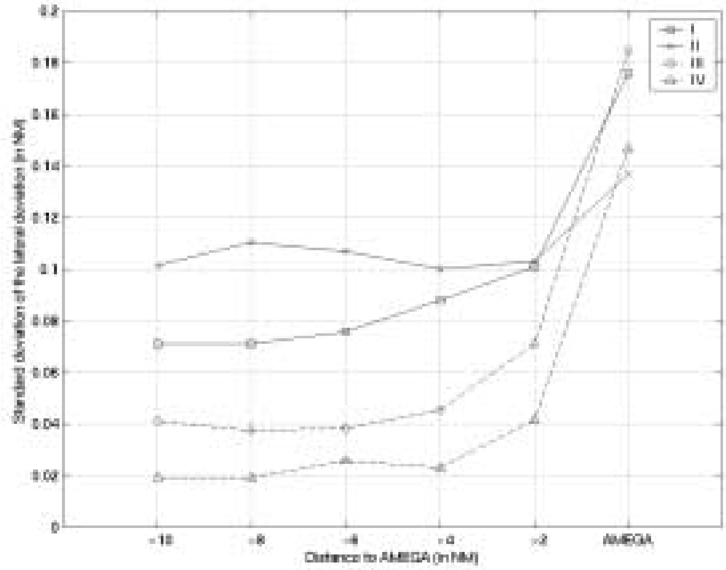

Figure 8: The standard deviations of the lateral deviation from the nominal flight path. The solid lines are the data sets with DME as primary sensor (squares are Boeing 737-300/400 and crosses are Boeing 747-400). The dashed lines are the data sets with GPS as primary sensor (diamonds indicate Boeing 737-800 with SA and triangles Boeing 737-800 without SA).

The probability distribution fitting procedure and the goodness-of-fit-test have shown that the lateral deviation from the nominal path on the downwind segment follow a generalised Laplace probability distribution for all data sets. The normal distribution does not fit adequately. Based on the generalised Laplace distribution, contourplots for all datasets have been made.
Figure 9 and Figure 10 show the contours of the 68.3%-, 95.5%- and 99.7%-containment areas (i.e. the interval in which e.g. 68.3% of all the samples are located) for the Boeing 737 using DME and using GPS with SA disabled (data sets I and IV respectively). In case a normal distribution would have been valid, these percentages correspond to the 1σ, 2σ and 3σ values respectively.

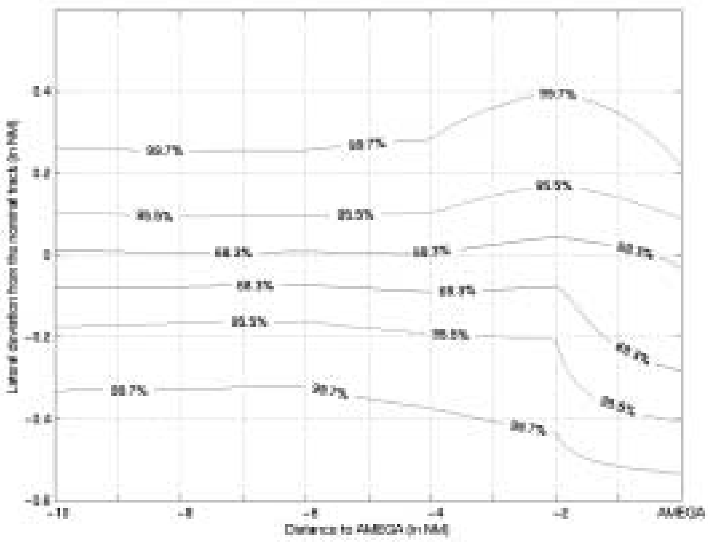

Figure 9: Contour plots of the lateral deviation from the nominal path for B 737-300/400 with DME as positioning sensor (data set I). The contours of the 68.3%, 95.5% and 99.7% containment areas are plotted based on the Generalised Laplace distribution.

The contourplots for the other two data sets have been omitted. The figures, however, show the gradual decrease in dispersion for the Boeing 747 DME, 737 DME, 737 GPS SA enabled, and 737 GPS SA disabled datasets.

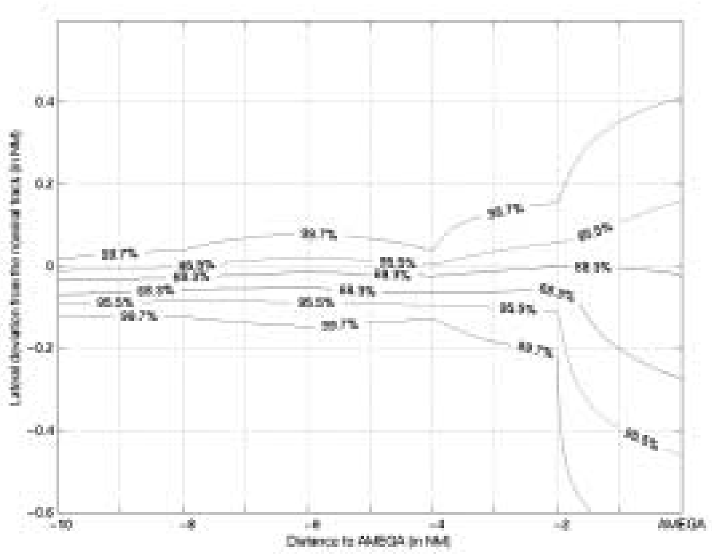

Figure 10: Contour plots of the lateral deviation from the nominal path for Boeing 737-800 with GPS as positioning sensor and SA disabled (data set IV). The contours of the 68.3%, 95.5% and 99.7% containment areas are plotted based on the Generalised Laplace distribution.

For indication purposes only, the RNP values provided by Boeing (Ref. [6]) are compared with the actual measurements of the deviation. The 95%-containment areas are computed using the fitted probability distribution. Table 1 shows the maximum value of the semi-width of the 95%-containment areas. The numbers have been computed for the flight phase from AMEGA - 4 NM to AMEGA - 10 NM. Comparison of the actual measurements with the performance figures provided by Boeing indicate that the figures for Boeing 737 GPS SA enabled (RNP 0.11), Boeing 737 DME (RNP 0.18), and 747 DME (RNP 0.19) correspond fairly well to the measurements. This comparison is just an indication since for a true comparison the accuracy of this measure has to be taken into account.

Dataset	**Type**	**Semi-width of 95%-area (NM)**
I	737 DME	0.14
II	747 DME	0.23
III	737 GPS SA	0.09
IV	737 GPS	0.05

Table 1: The maximum value of the semi-width of the 95%-containment area based on the generalised Laplace distribution.

6 Discussion and conclusions

This study evaluated the track dispersion for three different aircraft types with associated primary positioning sensor on the basis of 240 tracks for each aircraft type. Insufficient flight tracks were available for the Boeing 747-400 with GPS as primary sensor. Therefore a comparison of Boeing 747-400 GPS with the Boeing 747-400 DME could not be made. From the above-described results the following conclusions can be drawn:

- The dispersion of the tracks decreases significantly when GPS is used instead of DME as a primary positioning sensor for the Boeing 737 (about a factor 1.6).
- Although SA has been removed and is unlikely to be turned on again, the impact on the aircraft position is clearly visible. The track dispersion of Boeing 737 GPS with SA enabled shows decrease with a factor of 1.8 compared to Boeing 737 with SA disabled.
- The track dispersion of the Boeing 747 with DME is higher than for the Boeing 737 with DME.
- The largest track dispersion, i.e. Boeing 747 DME, is 4.6 times larger than the smallest track dispersion, i.e. Boeing 737 GPS SA disabled.

Note that the above conclusions are based on the assumption that the nominal flight path is defined in the FMS navigation database as published in AIP.

One needs to observe that calculated numbers for the track dispersion presented in this study are in fact an over-estimation of the true spread since they include the error caused by using FANOMOS and the SSR radar, which causes an additional spread. However, since all data sets contain this additional spread, comparisons between the data sets can be made assuming that the spread of the lateral deviation is (much) larger than the spread induced by FANOMOS and the SSR. It is recommended that the error induced by FANOMOS is investigated in more detail. For this purpose data logged by the FMS may be used. One needs to bear in mind that these data only estimate the aircraft’s true position since the data is obtained by using the positioning sensor. A more preferable technique would be to use differential GPS, which allows the aircraft’s position to be calculated to centimetre accuracy in post-processing. These positioning measurements can then be compared with FANOMOS measurements.

In order to obtain a more complete analysis of the navigation performance, other factors besides the navigation function of the FMS need to be investigated, such as the flight technical error contribution and the path definition error. Also results will vary in areas with mountainous terrain or with less DME coverage.

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