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GNSS Guidance for All Phases of Flight: Practical Results

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GNSS, or more specifically, Satellite Based Augmentation System (SBAS), guidance provides the prospect of a low-cost means for aircraft to become equipped to fly area navigation (RNAV) operations. The implementation of such RNAV operations within UK airspace offers potential benefits to both the airline operators and the Air Traffic Service Providers (ATSPs).

KEY WORDS

1. Air Navigation. 2. GNSS. 3. Nav Practice.

1. INTRODUCTION. Traditionally, air routes have been defined between fixed radio navigation beacons, such as VOR and NDB, located on the ground. Whilst this approach has served the aviation community well for many years it also acts as an inherent constraint in the Air Traffic system. All routes have to start and terminate at a limited set of fixed points. Air Traffic Service Providers are now seeking to be able to design air routes more flexibly without the constraint of the ground navigation infrastructure. The advent and subsequent development of aircraft Flight Man-

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agement Systems (FMS) have made possible the definition of an ATS route between any two waypoints – arbitrarily defined points in space, that exist only in the aircraft's navigation database. The concept for designing and using these routes is known as 'area navigation' (RNAV).

RNAV operations can be designed with greater environmental efficiency, they can offer fuel-efficient climb and descent profiles and, in the busy terminal areas within Scotland and London, they offer the prospect of reduced Air Traffic Control (ATC) workload due to a reduced need to provide radar vectors to aircraft. The National Air Traffic Service (NATS), as the UK's foremost ATSP, has a significant interest in the use of GNSS to support RNAV operations for all phases of flight. Therefore, NATS together with the Defence Evaluation and Research Agency, DERA, set out to investigate the technical capability of GNSS guidance to support fully automated en-route, terminal area, precision approach and curved precision approach flight operations.

2. AIMS OF THE PROJECT. DERA operate a BAC 1–11 aircraft, modified as a flying laboratory, which is used to research new concepts in avionics and air traffic management. Since September 1998, this aircraft has been used to demonstrate the use of SBAS positioning for manually flown precision approaches (Schuster-Bruce *et al*., 1998). More recently, the aims of these trials were to integrate the SBAS receiver with the existing aircraft guidance and control systems, using aircraft standard ARINC interfaces and demonstrate the ability to fly:

(a) autopilot-coupled SBAS precision approaches to the Category-I minima,
(b) using SBAS flight management system (FMS) guidance onto the extended runway centre-line with subsequent autopilot glide-slope capture,
(c) SBAS/FMS-coupled area navigation (RNAV) procedures from initial climb out, through the en-route part of flight and into the terminal area, including the ability to fly RNAV departure and approach procedures,
(d) SBAS-coupled curved approaches.

3. AIRBORNE EQUIPMENT. The airborne SBAS equipment consists of a modified NovAtel Millennium GPS receiver, connected to a PC running software written by Stanford Telecom (S-Tel) in accordance with RTCA/DO-229. This PC is known as the User Platform (UP). Since the SBAS broadcast is on the GPS L1 frequency, the Millennium receiver is connected to a standard L1/L2 GPS antenna. The receiver then passes GPS pseudoranges, GPS satellite ephemerides and the raw SBAS message to the UP software for processing and the determination of the aircraft's SBAS-corrected position. It also calculates protection limits, which indicate the expected accuracy of the position solution using integrity indicators incorporated into the SBAS broadcast data. These protection limits are compared with given limits dependent on the phase of flight, and an alarm is given if the protection limits are larger than the required accuracy. A database within the UP contains a description of the approach path to enable the calculation of guidance commands for 'straight in' precision approaches.

The SBAS signal-in-space used for the flight trials was provided by the EGNOS System Test Bed (ESTB) as described in ESA, Doc. E-TN-ITF-E31-0008-ESA (2000) and Secretan *et al*. (2000). The ESTB provides ranging (R-GEO), wide-area differential corrections (WAD) and GNSS integrity channel (GIC) broadcasts over

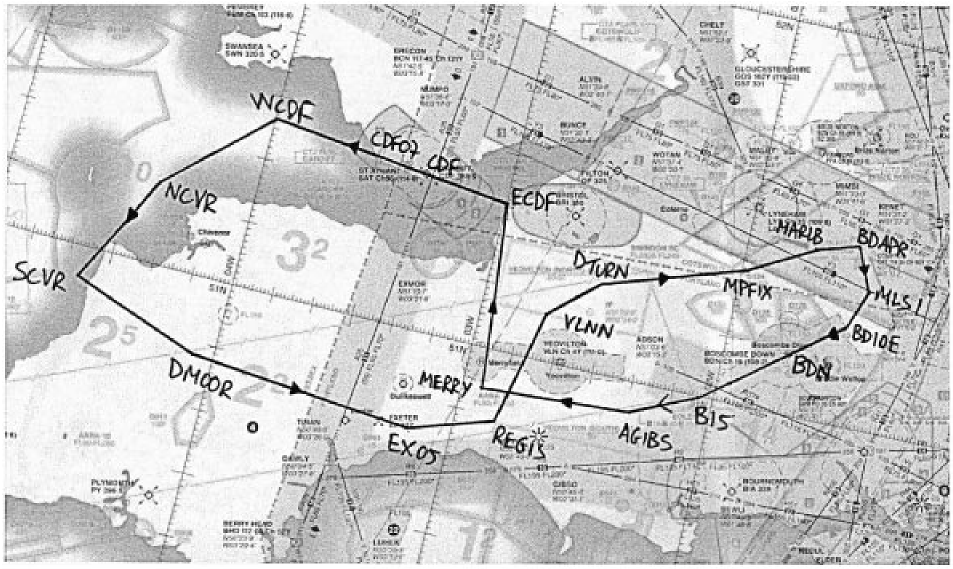

Figure 1. En-route flight path.

the Inmarsat Atlantic Ocean Region (East) Geostationary satellite. The message format broadcast by ESTB is compliant with Change 1 of RTCA/DO-229. The UP is connected to the existing electronic displays on the left-hand side of the cockpit on the BAC 1–11 in the same way as a standard Instrument Landing System (ILS) and, for manual flight, the pilot in the left-hand seat can fly the aircraft following the SBAS guidance. All the instruments on the right-hand side of the cockpit are conventional, certified units, including an analogue ILS, which are used by a safety pilot to crosscheck the experimental SBAS guidance. If a problem were to occur, the safety pilot could take control of the aircraft.

The digital autopilot installed on board the DERA BAC 1-11 was developed in-house in order to replace the standard analogue version, while the FMS is the Experimental Flight Management System (EFMS) that was developed under the leadership of Eurocontrol as part of the Programme for Harmonised ATM Research in Eurocontrol (Eurocontrol DOC 98-70-19, 1999). Although the EFMS was designed for use in a future air traffic management system, these trials relied on the lateral and vertical guidance functions (LNAV and VNAV) and in particular, the ability to guide around constant radius turns. DERA have software control over both the autopilot and EFMS and this aided integration of these systems with the UP.

3.1. *Integration.* The UP was connected such that ILS-like approach path guidance signals were supplied to the autopilot, and GNSS-derived position and velocity data to the EFMS was via the aircraft's ARINC 429 databus. The EFMS could then guide the aircraft laterally around a defined route eventually to intercept the extended runway centre-line, and subsequently the autopilot would be able to transition from EFMS guidance to direct UP guidance inputs. The EFMS could also handle vertical and time control via altitude, thrust and speed demands.

In manual operation, the autopilot monitored the localiser and glide-path deviation signals once the appropriate Prime Localiser and Prime Glide-path selections had been made by the pilot via the autopilot control panel. When these

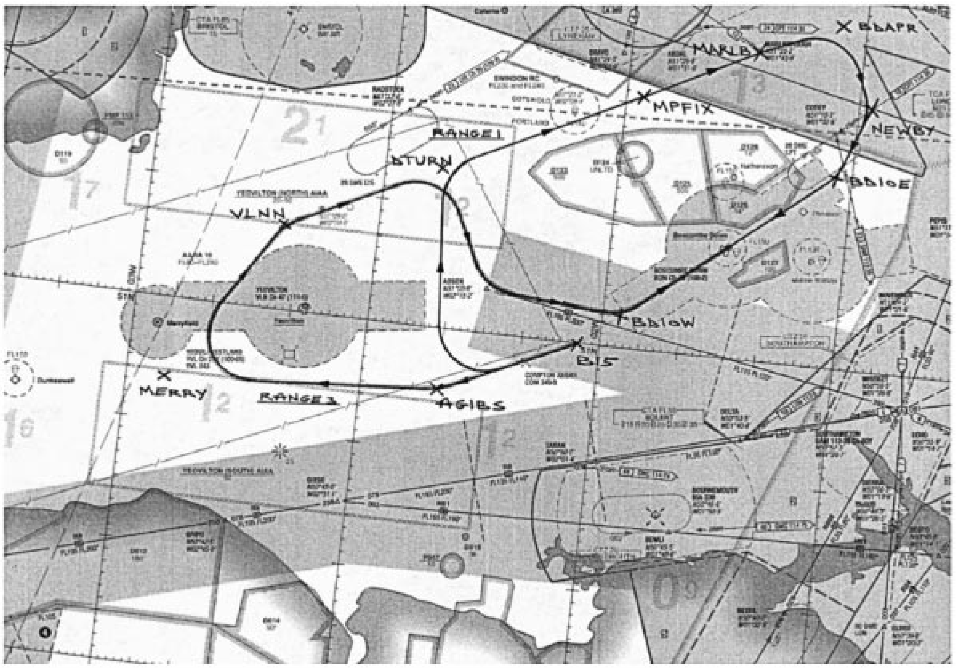

Figure 2. TMA routes.

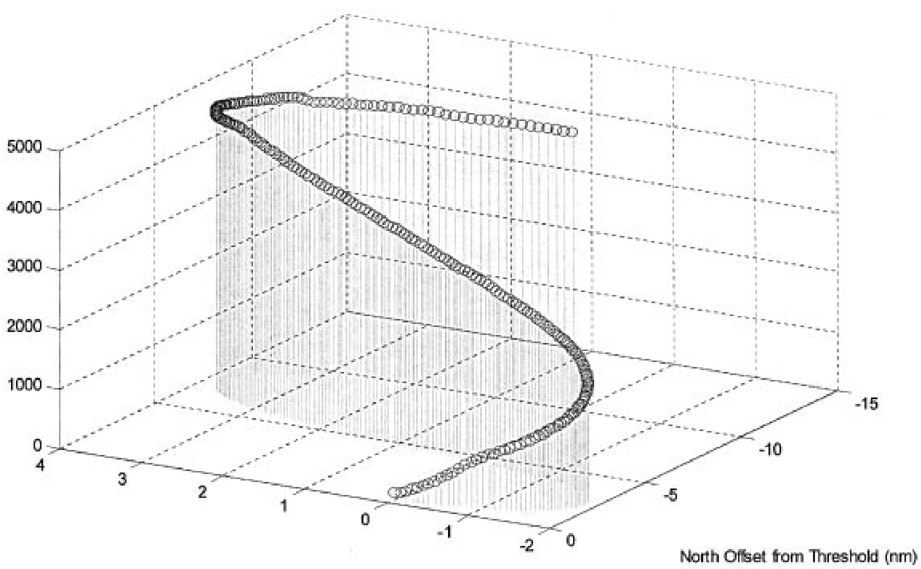

Figure 3. 3D view of curved approach to Runway 05.

deviation signals reached certain threshold values, the autopilot would then start using the appropriate signal to control the aircraft directly and capture the localiser centre-line or glide-path. An enhancement to the system was implemented that allowed the EFMS to trigger the Prime Localiser and Prime Glide-path modes of the autopilot automatically. This permitted a more complete system to be demonstrated,

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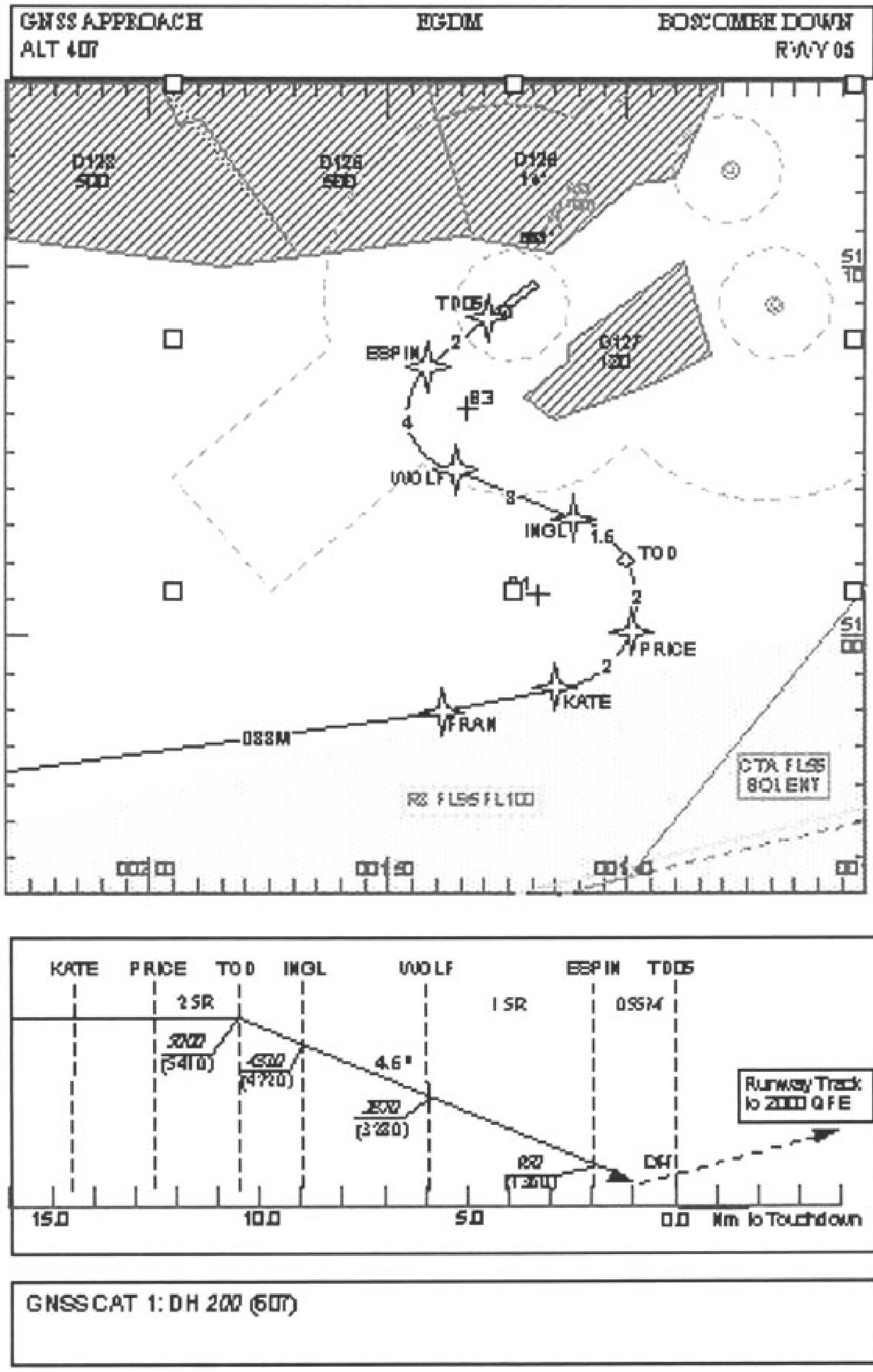

Figure 4. Experimental approach plate for curved approach to RWY 05.

whereby no direct pilot action was required to control the aircraft's lateral and vertical profiles from engaging LNAV and VNAV on the autopilot until reaching the decision height on the approach. This automatic system was also necessary for the curved approach procedures that were flown. A special mode was developed that allowed the autopilot to capture the glide-path before the localiser. To achieve this, the EFMS computed a pseudo-glide-path deviation signal based on the SBAS position solution. This was then transmitted to the autopilot and, under these conditions, the autopilot would use the EFMS data to fly the glide-path. Once the localiser had been captured at 2 nm from touchdown, the autopilot would start using the SBAS UP-derived glide-path deviation signal instead of the EFMS one. Speed control in the approach phase was left to the pilot, since the EFMS cannot currently sense the flap positions.

4. TRIAL ROUTES. The flight trials took place in February 2000 from DERA Boscombe Down. In all, six data-gathering sorties were conducted totalling about 15 hours of flying. These included 18 'straight in' approaches, six RNAV routes in the terminal manoeuvring area (TMA) and eight curved approaches. A series of routes were developed to check out the coupled SBAS system in all phases of flight. The en-route track took the aircraft around a figure-of-eight trajectory over SW England covering about 250 nm (up to altitudes of 24 000ft) as shown in Figure 1.

In order to assess the operation of the aircraft in the Terminal Manoeuvring Area, two feeder routes were devised (see Figure 2), which take the aircraft from the B15 waypoint round onto a 30° lateral intercept to acquire the approach path to either runway 23 or runway 05 at Boscombe Down. Although these feeder routes were not devised to look like operational departure or approach procedures (SIDs or STARs), they included manoeuvres that would be typical of RNAV operations in the TMA. These included constant radius turns, with radii varying from 5 to 3 nm.

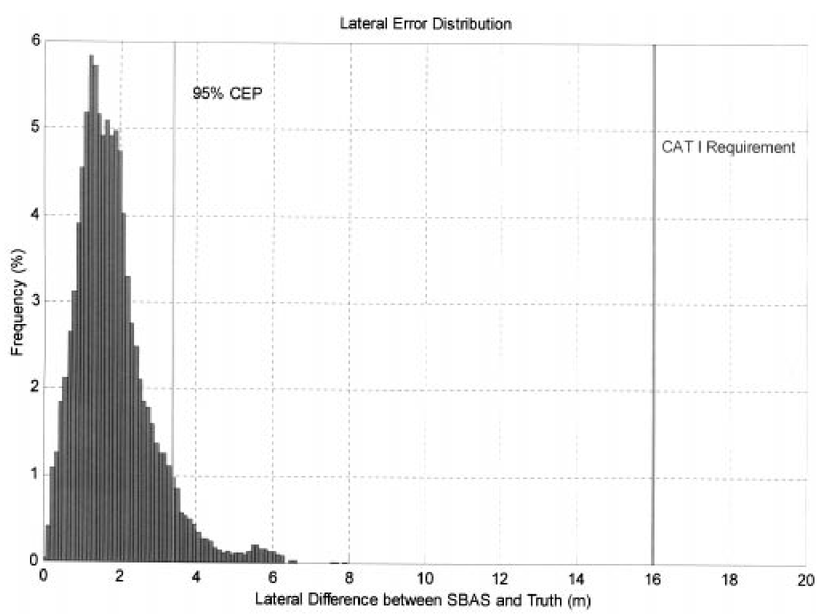

Figure 5. Distribution of lateral component of Navigation Sensor Error.

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Table 1. Navigational Sensor Error.

	Mean (m)	σ (m)	RMS (m)	Absolute max. (m)
North	−0·51	1·48	1·57	9·70
East	−0·56	1·27	1·39	5·48
Lateral	1·84	0·99	2·09	10·71
Vertical	1·86	2·13	2·83	11·62

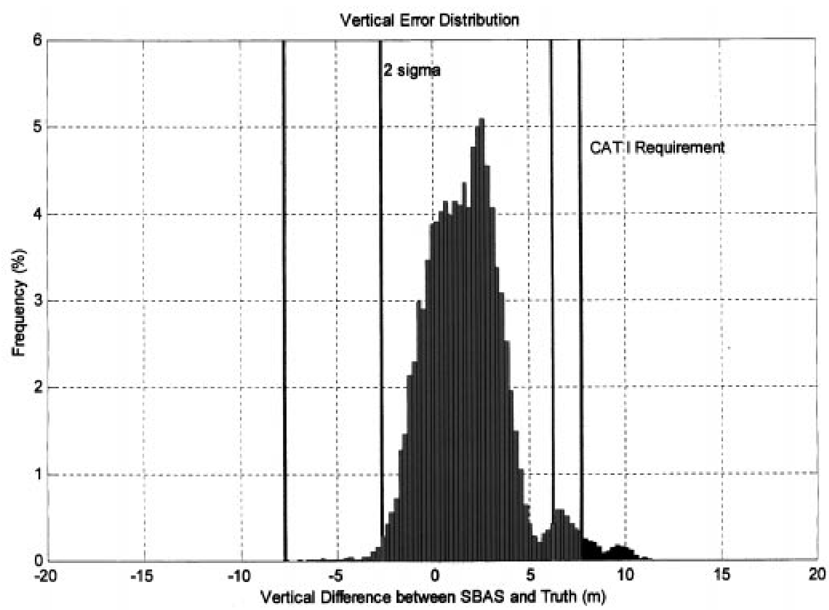

Figure 6. Distribution of vertical component of Navigation Sensor Error.

Finally, experimental approach plates were developed for curved approaches to both runway 23 and runway 05 at Boscombe Down. The approach to runway 05 is shown in Figures 3 and 4. These approaches involved constant radius turns and glide-slope angles of 4·5° and 6° under FMS control. The aircraft would then transition to direct autopilot guidance from the UP when the aircraft was positioned on the extended runway centre-line at a range of 2 nm from the threshold.

5. RESULTS.

5.1. *Navigation Performance*. In order to assess the accuracy of the SBAS position solutions, a post-processed dual frequency, carrier-phase GPS solution was used as a truth track. This relies on data from one receiver on the aircraft and from another placed at a surveyed site on the ground. All the data collected when the ESTB was transmitting wide area corrections was analysed with the exception of points where navigation alerts were flagged. It can be seen from Figure 5 and Table 1 that the 95% CEP value of 3·0 m is well within the CAT-I requirement of 16 m and, furthermore, the maximum value of the lateral error of 10·7 m is also within the lateral accuracy requirements.

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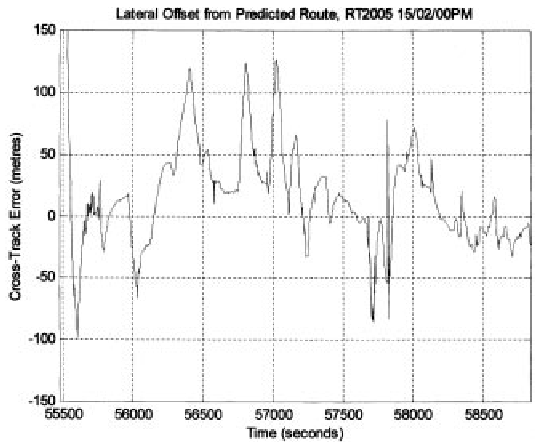

Figure 7. En-route Cross Track Error using SBAS navigation.

Table 2. Flight Technical Error in the TMA.

Date	Runway	UP Mode	Mean X-Track Error (m)	Standard Deviation (m)
27 Jan 00	05	Stand-alone	1·2	21·4
03 Feb 00	23	″	2·1	11·9
″	05	″	3·9	20·0
″	23	″	4·5	15·4
″	05	″	−5·6	21·6
10 Feb 00	23	SBAS	5·0	22·8
″	05	″	0·2	20·7

The distribution of the vertical NSE errors can be seen in Figure 6 and Table 1. Here it can be seen that 95% of the errors are within 6·3 m, satisfying the CAT-I accuracy requirement of 7·7 m. Furthermore only 2·1% of the data exceeded the CAT-I accuracy requirement, with a maximum observed value of 11·62 m. The data within the tail on the positive side of Figure 6 was all recorded during one flight and may be indicative of some minor teething problems within the ESTB that have now been corrected.

5.2. *Aircraft Guidance Performance.*

5.2.1. *En-route.* During the en-route flights, the EFMS lateral guidance performance was within 85 m (2-sigma). The route was flown twice, once using stand-alone GPS and the second time using SBAS corrected GPS. Figure 7 shows the cross-track errors obtained when using the SBAS position. The results showed that the improved navigation accuracy made very little difference to the aircraft flight technical error (FTE), which was well within the bounds for RNAV operations. For en-route operations, the principal advantage of SBAS is the improved integrity of the navigation solution.

5.2.2. *Terminal Manoeuvring Area.* Seven runs using the TMA feeder routes were flown, spread over three trial flights, two using stand-alone GPS and one using SBAS. The lateral performance achieved by the EFMS using the UP derived position solution is given in Table 2. This covers the period on each run from engaging LNAV

Table 3. Flight Technical Error during curved approaches.

Date	Rwy	Glide Path Angle	Mean X-Track Error (m)	Standard Deviation (m)
10 Feb 00	23	4·5°	−3·2	3·5
″	05	4·5°	7·8	3·1
15 Feb 00	23	4·5°	−2·3	3·6
″	23	4·5°	9·6	4·5
″	05	4·5°	56·8	9·1
″	05	4·5°	12·0	9·5
17 Feb 00	23	6·0°	7·3	2·1
″	05	6·0°	−2·5	3·6

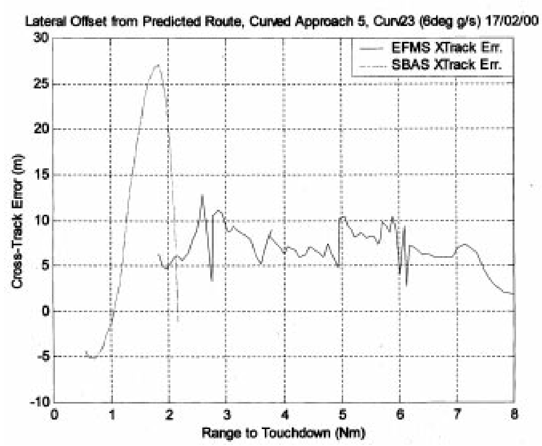

Figure 8. Cross Track Error during curved approach to Runway 23.

on the autopilot until the localiser is captured. As seen from the results for the en-route trials, the flight technical error for the lateral performance of the EFMS in the TMA is not affected by whether the GPS position source is stand-alone or SBAS-corrected. The EFMS was capable of guiding the aircraft to within about 30 metres of the defined route using either solution. The slightly lower values recorded, compared to the en-route phase, can almost entirely be attributed to the lower groundspeed in the TMA.

5.2.3. *Curved Approaches*. Two curved approach routes were flown, CURV23 to runway 23 and CURV05 to runway 05 at Boscombe Down. The EFMS was operated in a similar way to the flights involving the TMA feeder routes with the priming of the autopilot's localiser control mode at the very end of the final turn, about 2 nm from touch-down. Two glide-path angles were used namely, 4·5° to 6°. The aircraft was fully configured for the approach (undercarriage down, required flap set and approach speed selected) prior to capturing the glide-path, although in some cases the final speed change had not been completed before the glide-path intercept. There were no major problems flying these approaches, and the autopilot remained engaged throughout the runs until disconnected by the pilot around the decision height.

As previously mentioned, the EFMS provided lateral guidance to the autopilot, until it triggered localiser capture at the end of the final turn. The main focus, in terms

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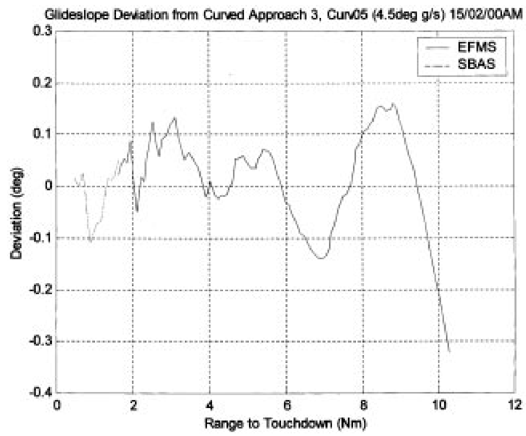

Figure 9. Glide-slope deviation during curved approach to Runway 23.

Table 4. Glide-path deviation during curved approaches.

Date	Rwy	G/P	Glide Path Deviation Mean	Glide Path Deviation Standard Deviation	Deviation in CAS Mean (kts)	Deviation in CAS Standard Deviation (kts)
10 Feb 00	23	4·5°	−0·00°	0·06°	0·6	1·0
″	05	4·5°	−0·01°	0·05°	0·4	0·9
15 Feb 00	23	4·5°	0·01°	0·16°	0·4	2·8
″	23	4·5°	0·01°	0·19	1·4	4·0
″	05	4·5°	0·02°	0·09°	1·4	2·3
″	05	4·5°	0·03°	0·15°	2·1	2·6
17 Feb 00	23	6·0°	−0·03°	0·12°	0·8	1·6
″	05	6·0°	0·01°	0·16°	1·4	2·1

of the lateral performance, was how well the EFMS could maintain the aircraft on the fixed route while it was descending on the glide-path. Table 3 gives the cross-track error values for the various curved approaches during the period between glide-path capture and localiser capture. The 4·5° glide-paths were captured just over 10 nm from touchdown, while the 6° glide-paths were captured at about 8 nm from touchdown.

The results show that the aircraft was kept fairly stable relative to the routes used for these curved approaches. The standard deviation values are all below 10 m, which emphasises that there was not a significant variation in the lateral deviation throughout each run. The most noticeable error value is for the first approach to RWY 05 on 15 February, where the mean cross-track error was about 57 metres. This is the result of an integrator having accumulated an offset value of approximately 90 metres within the EFMS lateral guidance algorithm when ATC delayed the aircraft close to the start of the curved approach route. The position of the aircraft, and the long time constant of this integrator, meant that the offset had not fully cleared by the end of approach. This is therefore not a representative value for an unhindered run.

The main effect that was seen from the lateral results for the curved approaches was that the lateral route computed within the EFMS did not exactly align with the localiser centre-line computed by the UP, as shown in Figure 8. At the end of the final

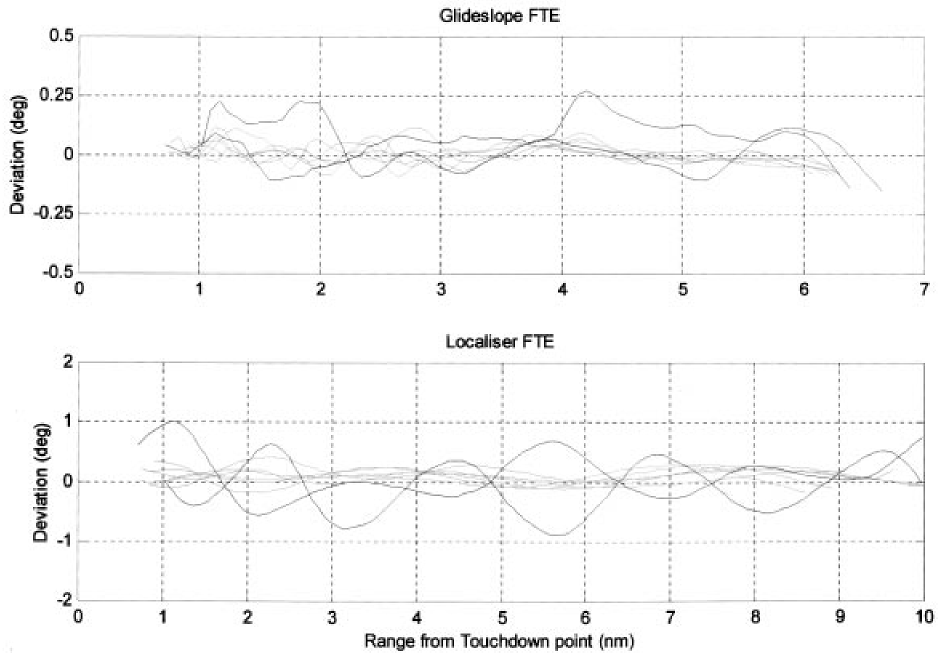

Figure 10. Comparison between Pilot and Autopilot controlled approaches for 3·0° glide-slopes.

turn, there was consequently a localiser deviation value to be corrected by the autopilot over the 2 nm before touch-down. This difference amounted to about 20 metres at the transition to localiser guidance for the approach to RWY 23 and to about 40 metres for the approach to RWY 05. The value of the turn radius can only be defined in the EFMS database to an accuracy of 0·01 nm, and this can partly explain the variation. What is required is a more accurate determination of the waypoint coordinates defining the start of the turns in order to improve the alignment between the EFMS route and the extended runway centre-line determined by the UP. Given the accuracy that the EFMS has demonstrated in tracking these turns, it should be possible to place the aircraft within 15 metres of the centre-line at the transition point.

Figure 9 and Table 4 show the vertical performance of the autopilot during the curved approaches between glide-path capture and localiser capture, i.e. while using the EFMS glide-path deviation signal. It is clear from the standard deviation values that when the autopilot is working harder to maintain the selected speed, it also deviates more from the glide-path. This can be partly attributed to the weather conditions. On 10 February, the air was fairly calm while on 15 February, the conditions were becoming more turbulent, causing greater fluctuations in the aircraft's speed and altitude.

The larger glide-path deviation values for 17 February are also related to the steeper glide-path angle. Additionally, the autopilot actually captured the glide-path slightly early because the steeper gradient produced a higher rate of change in the glide-path deviations as the aircraft approached it. The autopilot's control law is configured for capturing a standard 3° glide-path. Furthermore, the top of the glide-

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Table 5. FTE for Autopilot controlled straight approaches.

		Mean (°)	σ (°)	RMS (°)	Abs. Max. (°)
3° Glide-slope	Localiser	0·09	0·11	0·15	0·42
	Glide-slope	0·00	0·04	0·04	0·12
4·5° Glide-slope	Localiser	0·07	0·11	0·13	0·49
	Glide-slope	0·01	0·08	0·08	0·28

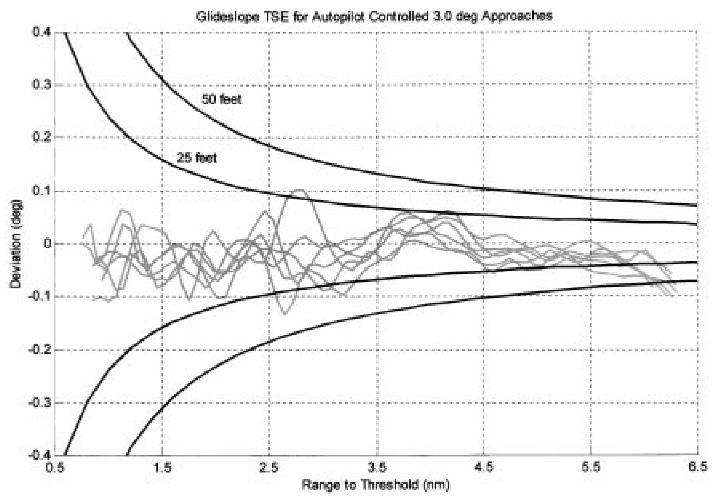

Figure 11. Glide-slope Total System Error for 3·0° Approaches.

path is also closer to touch-down for the 6° approach and the effect is that the same vertical offset on capturing the glide-path translates to a larger angular deviation.

The larger standard deviation in speed performance for the second approach to RWY 23 on 15 February was caused by the pilot requesting a change in speed at the same moment that the glide-path capture manoeuvre was started. The autopilot therefore had to contend simultaneously with both transitions, which affected the early part of the descent. When the autopilot switched to the glide-path deviation signal from the UP, the difference between the EFMS and UP values was typically less than 0·03° and was never more than 0·1° on the runs with the EFMS using the UP height data. This resulted in a smooth transition in the autopilot's vertical control mode.

5.2.4. *Straight-in Approaches*.

5.2.4.1. *Flight Technical Error*. The flight technical error for the autopilot controlled straight approaches was derived using the UP calculated guidance deviations that were passed to the autopilot for control purposes. As a comparison, equivalent approaches flown manually using the SBAS guidance are also shown. Figure 10 shows the deviations for two manual and six automatic approaches. It can be seen that the deviations for the manual approaches (shown as the two thinner lines) are greater than those for the autopilot-controlled approaches (shown as the six thicker lines). It was found that during the trials, the difference between the manual and autopilot approaches was smaller for the 4·5° glide-slope than for the 3° glide-slope. However, the reason for this may be that the 3° approaches were flown in much windier conditions than the 4·5° approaches, leading to the conclusion that the autopilot is better able to handle the windier conditions.

Table 5 gives a comparison between the autopilot performance during the 3° and 4·5° approaches. Although there was very little variation in the lateral guidance performance, the vertical deviations were much higher on the 4·5° approaches than the 3° approaches. This result is to be expected since the vertical velocity of the aircraft is much higher on the steeper approach ($\sim$ 900 ft/min as opposed to $\sim$ 600 ft/min at $\sim$ 120 kts) and is consequently more difficult for both the pilots and autopilot to control.

5.2.4.2. *Total System Error*. The total system error for the SBAS-guided autopilot-controlled straight approaches was derived by using the truth track to compute the deviations from the theoretical approach path using the same reference points and algorithms that were used within the SBAS UP. These deviations are shown in Figure 11 for a 3° glide-slope, together with two error envelopes for reference purposes. It can be seen that the aircraft remained within 25 feet of the expected glide-slope for almost the entire duration of the approaches.

6. CONCLUSIONS.

These trials have successfully demonstrated Satellite Based Augmentation of GPS for use in all phases of flight. It has been possible to couple the SBAS positioning and guidance with the existing aircraft autopilot and flight management system. This allows the aircraft to fly seamlessly from initial climb out, through the en-route phases into the terminal area and down to the precision approach decision height under automatic control, whilst relying on the same basic navigation system. Data has been collected showing the effectiveness of both the navigation and guidance systems. This integration has also made it possible to fly advanced RNAV procedures, such as curved approaches where the aircraft does not intercept the straight approach path until it is two nautical miles from the runway threshold.

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