Northern European Satellite Test Bed

Alan Schuster-Bruce

(*Racal Avionics*)

James Lawson

(*National Air Traffic Services*)

Michael Quinlan

(*Racal Research*)

Dr Andrew McGregor

(*Defence Evaluation Research Agency*)

Satellite Based Augmentation Systems are being developed in Europe (EGNOS), the USA (WAAS), and in Japan (MSAS). As part of their support to EGNOS, NATS and Racal have developed and deployed a prototype SBAS system called the Northern European Satellite Test Bed (NEST Bed). NEST Bed uses GPS L1/L2 reference stations at: Aberdeen, Rotterdam, Ankara, Cadiz, Keflavik, and Bronnoysund. Data is sent to the Master Control Centre at NATS Gatwick Services Management Centre for processing. The resulting 250 bits-per-second message is sent to Goonhilly for up-linking by BT to the Navigation Payload of either the Inmarsat AOR-E or F5 spare satellite. NEST Bed was deployed and commissioned during summer 1998, and flight tests were successfully demonstrated at the September 1998 Farnborough Air Show where approaches were flown to Boscombe Down on the DERA BAC1-11 aircraft. In October 1998, a NATS/FAA flight trial was held in Iceland involving NEST Bed and the FAA NSTB. NEST Bed is also being used for SARPS validation.

1. INTRODUCTION. The system concept known as Wide Area DGPS (WADGPS), is a method of augmenting navigation satellites (GPS and GLONASS) to provide high integrity and high accuracy positioning services, over a large area, while optimising the bandwidth of the broadcast channel and the density of the ground infrastructure. Such systems are currently of interest for safety-related transport applications, especially for airborne navigation. In the US, the FAA is developing the Wide Area Augmentation System (WAAS). Its European counterpart is EGNOS (European Geostationary Navigation Overlay Service), being developed by the European Space Agency (ESA), with the support of the European Commission, Eurocontrol and the European CAAs. In Japan, the MSAS is being developed. The ICAO name for these systems is Satellite Based Augmentation System (SBAS).

SBAS systems provide three main functions: an additional rangeing signal per overlay satellite; WADGPS; and integrity. The correction signal is broadcast from a geostationary satellite, and this signal, although generated from the ground and simply frequency translated by the satellite, is similar to a GPS signal. The signal is time-synchronised to GPS time and hence suitable receivers can use the signal as an additional GPS satellite. In fact, since the satellite is geostationary and 'always there', the satellite is worth two or three GPS satellites in terms of constellation availability

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away from the polar regions. SBAS systems must also provide an integrity function and hence warn, in a timely manner (six seconds), that there is a fault in the system.

The Wide Area Differential correction broadcast with the rangeing is decomposed into three components: the satellite clock error; the satellite ephemeris (or orbit) error; and the ionospheric error. The major component of the satellite clock error is due to the effects of selective availability and hence needs to be broadcast frequently. The satellite clock and satellite ephemeris corrections are broadcast on a 'per satellite basis'. The ionospheric error is user-position-dependent and a 'grid' sampling model of the ionosphere is broadcast.

It is noted that an important function of a SBAS system is to provide a high integrity service; to that end, GPS satellite monitoring is performed, and the quality of the corrections broadcast is also provided to the user.

The Wide Area Differential corrections message of 250 bits per second is FEC encoded, resulting in a 500 bits-per-second data rate broadcast from the Inmarsat satellite.

2. PURPOSE OF THE NEST BED. NEST Bed is being used for the following purposes:

(i) Conduct Category 1 landing approach analysis.
(ii) Collect data to help design SBAS operating procedures for both users and service providers.
(iii) Demonstrate an EGNOS prototype to the aviation community.
(iv) Validate ICAO SARPS and RTCA DO229 MOPS.
(v) Develop and refine clock and ionosphere algorithms for SBAS.

3. NEST BED GROUND ARCHITECTURE. NEST Bed has a number of Rangeing and Integrity Monitoring Stations (RIMS) which contain L1/L2 GPS receivers with a rubidium or caesium atomic frequency standards and a computer. The location of the RIMS is shown in Figure 1. Data is sent every second from the RIMS via X25 to the SkyFix control centre at Aberdeen and is then routed via a NATS circuit to the Master Control Centre (MCC) at the NATS Services Management Centre at Gatwick. The MCC processes the data, provides real-time displays and logs the data. The MCC is based on a number of Pentium PCs running Windows NT and linked by Ethernet. The MCC output is a 250 bits-per-second message that is sent via ISDN to Goonhilly. The BT Goonhilly Earth Station radiates to either the in-orbit spare F5 satellite at 20° E or to the AOR-E satellite at 15° E using Inmarsat RF signal generator equipment. Although the signal from Goonhilly is correctly time-synchronised, NEST Bed does not implement the GEO orbit function and no GEO orbit information is provided in the correction signal – hence NEST Bed does not currently provide the 'rangeing function'.

A static monitor station is also installed at Gatwick which provides a SBAS-corrected position. This provides a good measure in real time of the performance of NEST Bed.

4. ALGORITHMS. NEST Bed currently implements the following Wide Area Differential algorithms:

(i) Data Pre-processing.
(ii) Clock Correction Function.
(iii) Ionospheric Modelling Function.

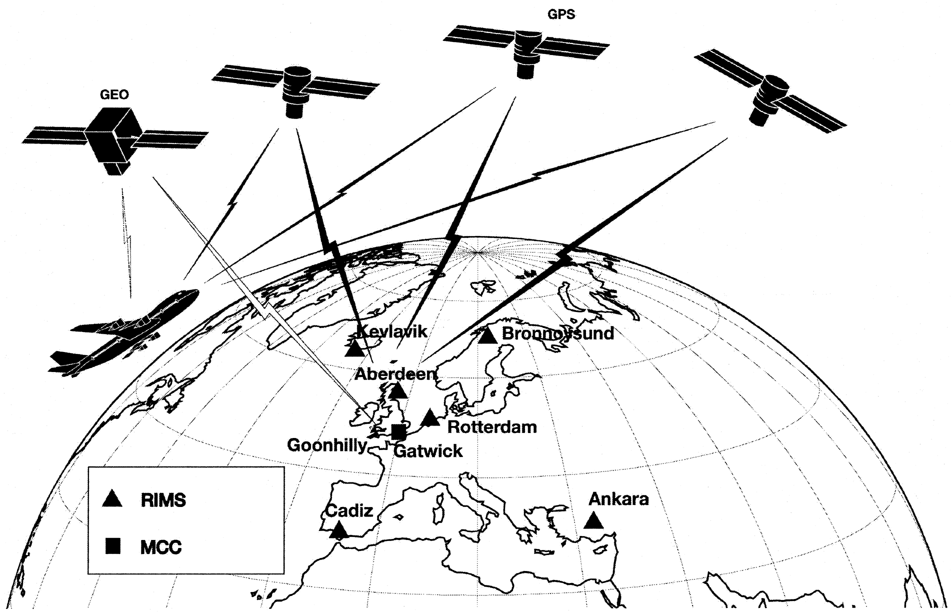

Figure 1. NEST Bed stations.

NEST Bed currently does not implement the orbit determination algorithm; all the results reproduced in this paper use the broadcast GPS orbit data. The orbit uploads to the GPS satellites from the DoD result in performance that is considerably better than the GPS specification and hence independent orbit corrections are not essential. The clock and ionospheric algorithms used in NEST Bed are advanced prototypes of algorithms that Racal Research will be providing for EGNOS. The NEST Bed message format is RTCA DO229 Change 1.

4.1. *Data Pre-processing*. Data pre-processing can be carried out at either the RIMS or the MCC to remove as many naturally occurring errors as is possible. NEST Bed pre-processes the data at the RIMS to maximise the use of processors available in the system, reducing the processing load at the MCC, and to minimise the required data communications bandwidth between the RIMS and MCC. The following pre-processing of range measurement data is performed:

(i) Tropospheric delay errors are removed using fixed mean parameters (but allowing for possible future use of local meteorological sensors).
(ii) Cycle slips are detected and, if possible, repaired.
(iii) Ionospheric delay errors are measured and removed using the differential L1/L2 frequency measurements.
(iv) The pseudorange and ionospheric delay estimates are carrier-phase filtered to reduce the measurement errors due to multipath and thermal noise.

4.2. *Clock Correction Function*. The pre-processed satellite range measurements from all RIMS in the system are combined at each 1-second epoch, and an optimal set of common-view double-difference measurements are generated. Processing of these measurements, combined with the actual satellite geometric range at the time of the measurements, allows individual clocks within the system to be observed. The clock correction function has several components that can be summarised as follows:

(i) Generate an estimate of 'Network Time' from an ensemble mean of all RIMS atomic clocks.
(ii) Generate an estimate of 'Satellite GPS Time' for each satellite using the broadcast GPS navigation message (that is, what a GPS user would understand by 'GPS time' for a satellite).
(iii) Generate an 'Average GPS Time' from individual satellite 'Satellite GPS Time' estimates.
(iv) Steer 'Network Time' to 'Average GPS Time' to ensure that all clock corrections estimated remain within the dynamic range of the correction message. If 'Network Time' and 'Average GPS Time' are allowed to diverge, this difference will appear as a component of the clock correction.
(v) Estimate the offset of each RIMS clock from 'Network Time' and correct all measurements for this offset. This is an essential synchronisation process.
(vi) Using the synchronised measurements, estimate the instantaneous error of each satellite clock with respect to 'Satellite GPS Time'.
(vii) For each satellite, generate a fast clock correction (predominantly SA effects) and a slow clock correction (drift effects) along with a quality estimate for the correction.
(viii) Provide the fast and slow corrections as range errors, with respect to 'Satellite GPS Time', for broadcast to the user.

Clock corrections are calculated every 1-second epoch, and the fast corrections are broadcast to the user at least once every six seconds.

4.3. *Ionosphere*. The ionospheric model function is required to allow the user to estimate the range errors due to ionospheric delay. The GPS satellite navigation message provides a rudimentary ionospheric model that can be used, but this is not sufficiently accurate for SBAS operation. The ionosphere is a complex system, and the range errors it introduces vary with time and location, complicated further by the effect of solar activity and localised disturbances.

The ionospheric model implemented treats the ionosphere as a solar-fixed thin shell rotating around the Earth. The shell is tessellated, and each tile represents a continuously variable delay estimate 'surface'. In a process that has similarities with finite element analysis, the delay estimate surface for each tile is continuously refined from dual frequency ionospheric delay measurements made by the RIMS. The estimation process is required because the number of measurements sampling the ionospheric delay 'shell' is small compared to the size of the surface being modelled.

The ionospheric corrections broadcast to the user consist of vertical ionospheric delay estimates for locations on a pre-defined grid covering an identified region of the Earth. (Ionospheric corrections are broadcast only for regions within the coverage area of the overlay satellite). The ionospheric correction broadcast also has a confidence measure for each vertical delay broadcast. The ionospheric correction function must interpolate between the rotating internal model and the static vertical delay grid-points in the broadcast model to generate the correction message. The user interpolates the received vertical delays in the region of the visible satellites, as projected onto the ionospheric shell, and establishes a line-of-sight (or slant) ionospheric delay estimate for each satellite.

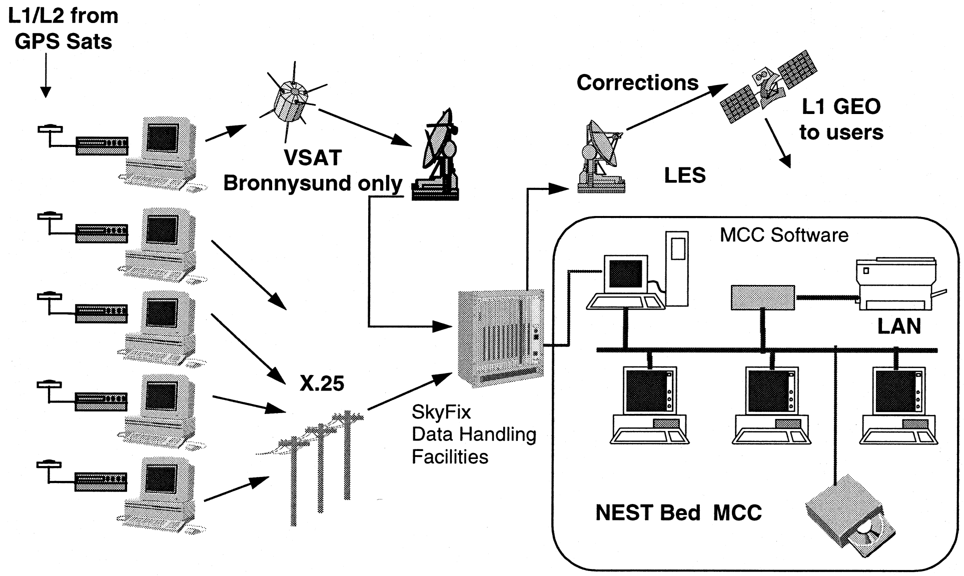

Figure 2. NEST Bed overview schematic.

5. NEST BED PREPARATION (Figure 2). The algorithms running on NEST Bed have been developed by Racal over many years and in particular during the European Commission-sponsored MAGNET project starting in January 1996. The MAGNET project had only sufficient funding to allow the fielding of the reference stations and their operation for two months. NATS and Racal agreed, in early 1998, jointly to fund a programme to field the MAGNET equipment initially for one year, and the resulting project is known as NEST Bed, with the initial aim of carrying out a flight demonstration of an SBAS system at the 1998 Farnborough Air Show. In addition to the RIMS and MCC, access to a navigation payload and uplink equipment to the payload was required. It had always been intended to use the Inmarsat AOR-E satellite and Euridis for this purpose, but unfortunately they were not available. Instead, Inmarsat offered both to provide access to the navigation transponder on the spare Inmarsat 3 satellite known as F5, and to provide RF uplink equipment that was developed to carry out the on-orbit check-out of the navigation payloads. BT offered to operate the equipment at Goonhilly.

The NEST Bed RIMS were fielded in June 1998 and the MCC was installed at Gatwick in July 1998, with the first signal radiated over the satellite at the end of July. As expected, there were a number of teething problems but by mid-August a signal was being radiated that provided a user with vertical accuracy of typically better than five metres, and this allowed the first flights to be carried out on board the DERA BAC1-11 aircraft operating from Boscombe Down.

6. AIRCRAFT EQUIPMENT. The BAC1-11 aircraft is a flying laboratory operated by the Defence Evaluation Research Agency (DERA). It has been used on previous GPS flight trials and so was the obvious choice for the NEST Bed flight test aircraft. The aircraft equipment consists of a NovAtel GPS/GEO Millennium receiver feeding L1 pseudorange and SBAS corrections to a Stel User Platform (UP). The UP generates ILS *look-a-like* signals in the form of analogue glideslope and

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localiser deviation signals, which are fed to the pilot's displays on the left hand side of the cockpit. The pilot in the left-hand experimental seat normally flies the aircraft, while a safety pilot uses conventional navigation equipment in the right-hand seat. If there are any problems, the safety pilot takes over. The aim of SBAS systems is to provide precision approach capability down to Cat 1 decision height – 200 feet. Hence the approaches were flown down to this height.

7. NEST BED DEMONSTRATIONS. During the Farnborough Air Show, the BAC1-11 flew on the Monday to Thursday evenings, taking off from Farnborough and making a number of approaches to Boscombe Down using NEST Bed before returning to Farnborough. The passengers included many key individuals from the European aerospace industry. The equipment worked correctly throughout all the flights. In addition, real-time displays of NEST Bed performance were shown on both the NATS and Racal Farnborough stands. The Farnborough flights were the first demonstration of an European-developed GNSS-like system being used to navigate a CAT 1 aircraft approach.

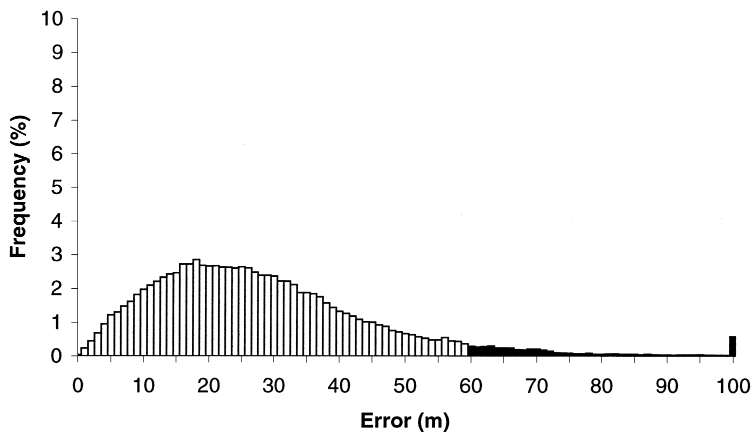

Figure 3. GPS horizontal error at Reading, 90 hours' continuous operation, 2nd–6th October 1998. ■, H error > = 95%; □, H error < 95%.

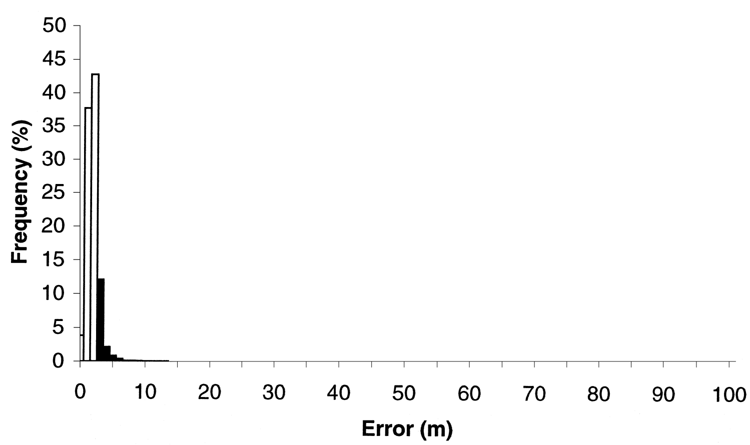

Figure 4. NEST Bed corrected horizontal error at Reading, 90 hours' continuous operation, 2nd–6th October 1998. ■, Corrected H error > = 95%; □, corrected H error < 95%.

In July 1998, NATS was invited by ESA and the FAA to take part in a National Satellite Test Bed (NSTB) trial in Iceland during October 1998. Iceland is outside the original coverage area of NEST Bed and hence it was decided to add a NEST Bed RIMS in Iceland. The Iceland trials involved SBAS signals being radiated from the NSTB on AOR-W and from NEST Bed on F5. Both the FAA 727 aircraft and DERA BAC1-11 flew a number of approaches utilising both signals. Both aircraft correctly received signals from both test beds, and the system performance of the two systems was comparable. It was discovered that it was not possible to use data simultaneously from both SBAS systems, and on investigation this was due to the receiver implementation in the aircraft. This problem will be addressed in the ICAO, RTCA and EUROCAE committees to determine if there is a need to give more detailed requirements in the receiver specifications. Detailed analysis of the data from Iceland is still being carried out.

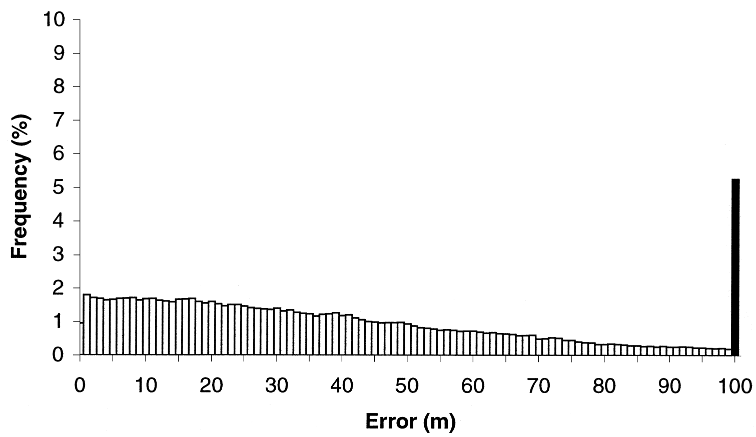

Figure 5. GPS vertical error at Reading, 90 hours' continuous operation, 2nd–6th October 1998. ■, V error > = 95%; □, V error < 95%.

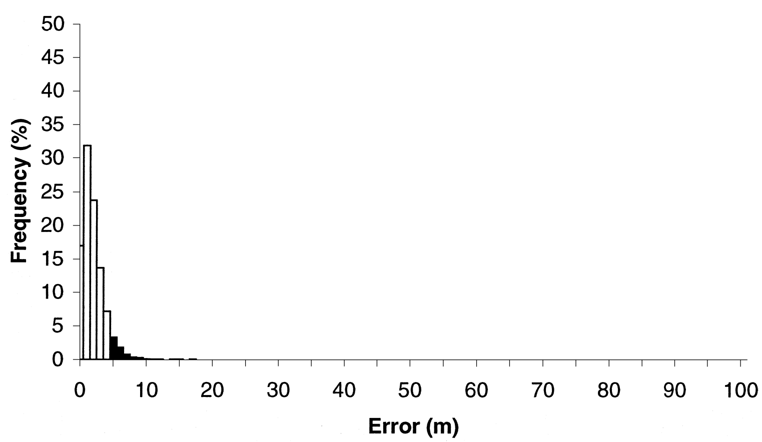

Figure 6. NEST Bed-corrected vertical error at Reading, 90 hours' continuous operation, 2nd–6th October 1998. ■, corrected V error > = 95%; □, corrected V error < 95%.

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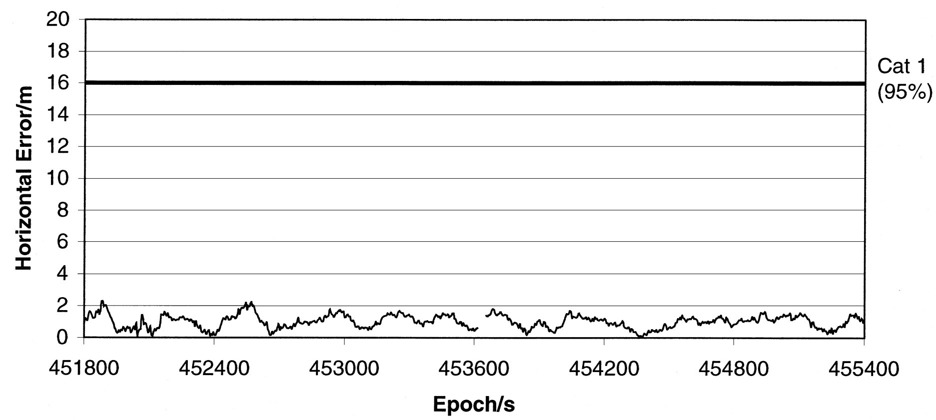

Figure 7. NEST Bed horizontal error at Gatwick, 0530 to 0630 20 November 1998.

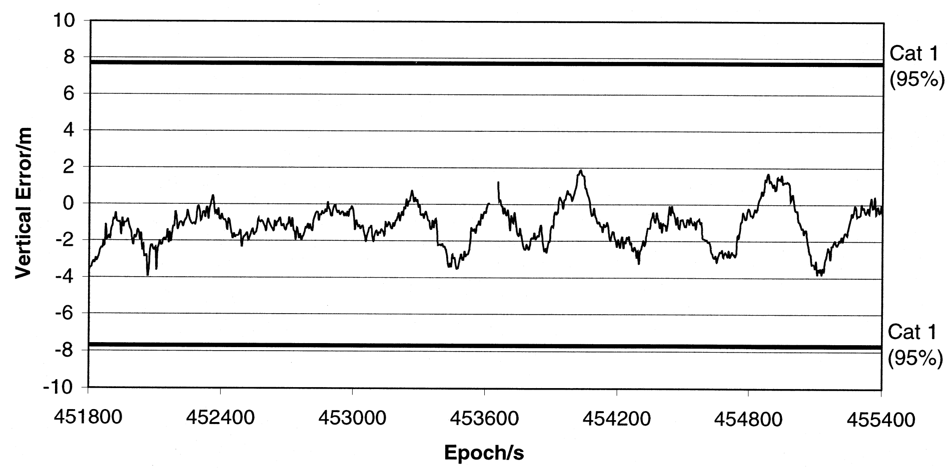

Figure 8. NEST Bed vertical error at Gatwick, 0530 to 0630 20 November 1998.

In November 1998 NEST Bed was used in the European Commission MAGNET demonstration of marine and rail receivers. Uplinking was from Goonhilly using the AOR-E satellite instead of F5.

8. TEST RESULTS. Figure 3 and Figure 4 compare the absolute horizontal position errors at a monitor in Reading (UK) obtained by stand-alone GPS and NEST Bed-corrected GPS over a continuous four-day period in October 1998 (during the joint trials between NEST Bed and the FAA NSTB). NEST Bed-corrected position errors are better than 2·5 metres, 95% of the time. Figures 5 and 6 show the same comparison for the vertical errors, with the NEST Bed-corrected position error better than 4·5 metres, 95% of the time.

Figures 7–10 show the error variation over a one and 12-hour period in November 1998 (during the MAGNET trials) for both vertical and horizontal errors, recorded at a monitor at Gatwick. For these plots, the accuracy limits (95%) for Category 1 landing are also shown.

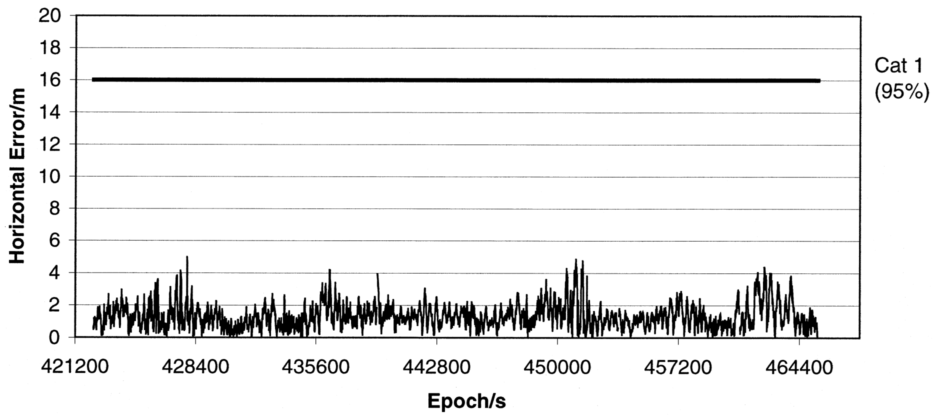

Figure 9. NEST Bed horizontal error at Gatwick, 2100 19 November to 1000 20 November 1998.

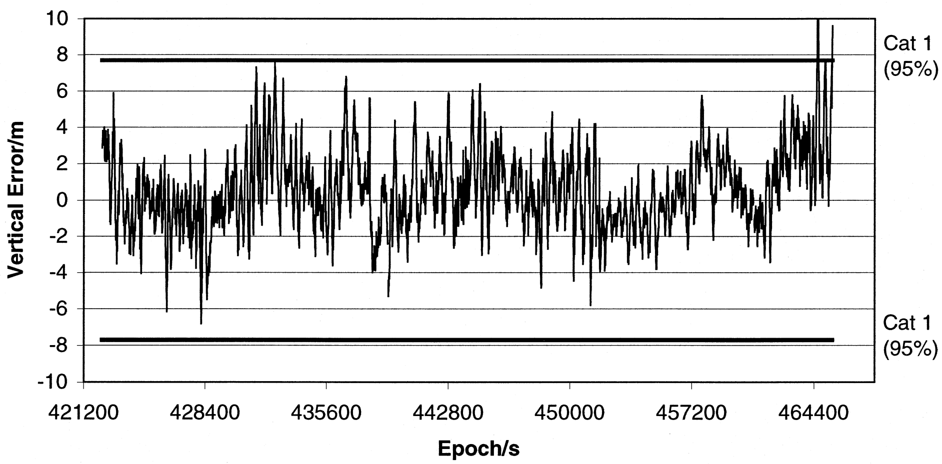

Figure 10. NEST Bed vertical error at Gatwick, 2100 19 November to 1000 20 November 1998.

Figures 11 and 12 show results on the aircraft from an approach during the demonstration at Farnborough. This approach was flown in true Category 1 meteorological conditions and hence the runway was not visible until the aircraft reached the 200 feet decision height. The accuracy shown is calculated as the difference between the NEST Bed solution and a post[2] processed GPS carrier phase truth track. The time duration of these plots is approximately five minutes.

Figures 13 and 14 show results from the same approach as Figures 11 and 12 and show a comparison of the NEST Bed[2] generated deviation signal and the ILS deviation signal. The flight technical error is clearly visible, as well as the good correlation between the two systems. It is noted that the NEST Bed signal is less noisy than the ILS signal. The mathematical conversion between deviation and metres is:

$$0{\cdot}1° \text{ at } 10 \text{ nm} \equiv 1° \text{ at } 1 \text{ nm} \equiv 29 \text{ metres}.$$

A large amount of data has been collected which is currently being analysed.

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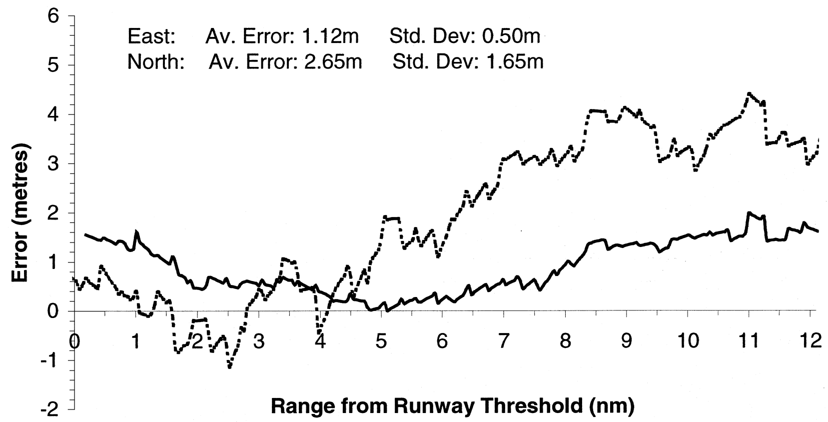

Figure 11. NEST Bed accuracy east and north axes. Approach 3: 9/9/98 Boscombe Down. ——, East; ---, North.

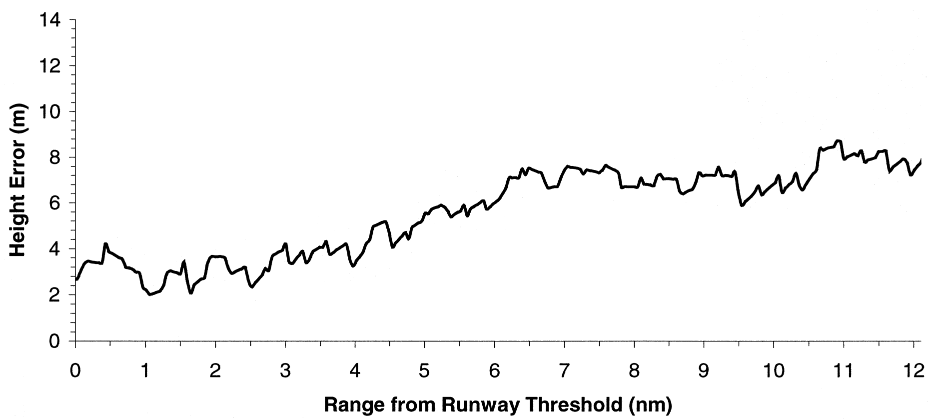

Figure 12. NEST Bed vertical accuracy. Approach 3: 9/9/98 Boscombe Down. Average error: 6·95 metres; standard deviation: 2·73 metres.

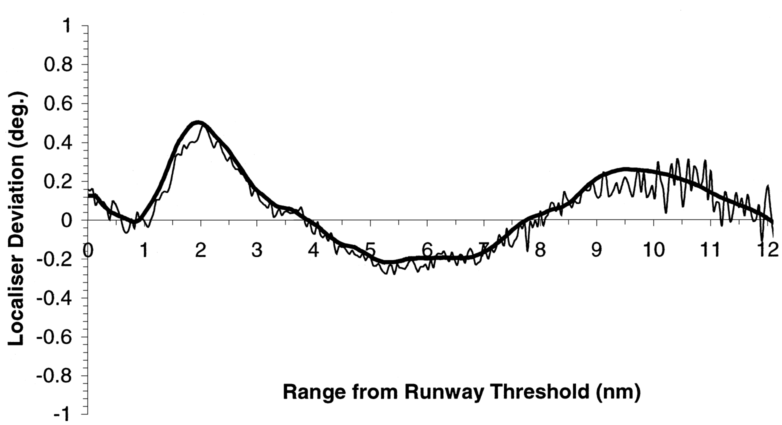

Figure 13. Comparison of NEST Bed and ILS Localiser Approach 3L 9/9/98 Boscombe Down. ——, ILS. ▬▬, NEST Bed.

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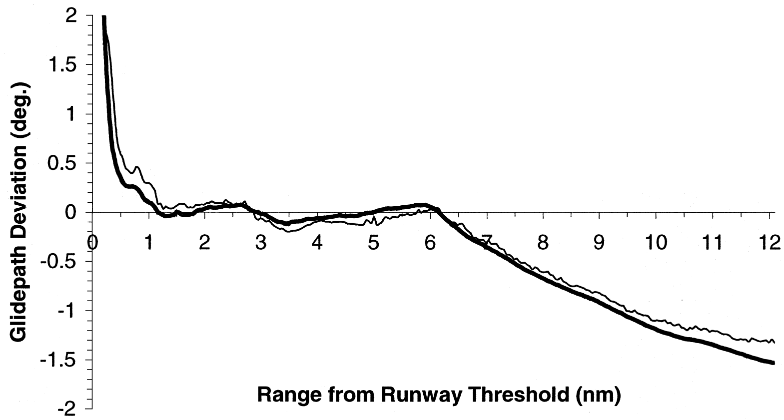

Figure 14. Comparison of NEST Bed and ILS Glidepath. Approach 3: 9/9/98 Boscombe Down. ——, ILS; ▬▬, NEST Bed.

9. FUTURE WORK. NATS and Racal are currently investigating future upgrades to NEST Bed including adding the orbit function, improvements to the user position monitor, ionospheric work, changes required due to DO-229A, and reducing the communication delays. In addition, NEST Bed will be used for all the activities described in section 2.

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KEY WORDS

1. Air. 2. GNSS. 3. Augmentation. 4. Trials.

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