A NORTH SEA TRIAL TO INVESTIGATE THE USE OF DIFFERENTIAL GPS FOR INSTRUMENT APPROACHES TO OFFSHORE PLATFORMS*

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Abstract

The UK CAA has undertaken a Flight Trials Programme in the North Sea to investigate the use of Differential GPS (DGPS) for instrument approaches to offshore platforms. The flight trials were conducted during 1996, using a chartered S76C helicopter equipped with a DGPS trials installation designed by Cranfield Aerospace Ltd. The airborne system included four GPS receivers, MF and UHF datalink receivers, and an acquisition and processing unit. The processing unit reformatted DGPS data for transmission to the helicopter's area navigation system (RNAV-2) and generated guidance information for display on the cockpit instruments. Two methods of providing differential corrections were adopted for the trials; existing shore-based differential corrections, transmitted by marine beacon, and platform-based differential corrections transmitted by a platform station purpose built for the trial. This enabled the advantages and disadvantages of each system to be assessed. The GPS "carrier phase" positioning technique, via post-processing, was adopted as the "truth" system against which the performance of the real-time DGPS equipment was compared. In total, seven test flights were conducted involving data gathering exercises at four offshore platforms, representing low, medium and high multipath environments. The current weather radar approach pattern was flown using DGPS guidance and alternative "DGPS approach" trajectories were also investigated. The paper gives an overview of the flight trials undertaken and describes the main findings with particular emphasis on the flyability and piloting issues.

1. Introduction

A specific need exists for an accurate and reliable instrument approach aid for use at offshore platforms. There are approximately 300 helidecks in the North Sea and up to 450 offshore helicopter movements per day from the UK. The meteorological conditions vary considerably throughout the year and also exhibit considerable local variations on any particular day. Currently, approach guidance to offshore platforms is provided by means of the aircraft's weather radar, which is far from ideal for the task. The concept of Differential GPS, however, offers the potential to fulfil the need for an offshore approach guidance system at relatively low cost.

Consequently, in 1994, the UK Civil Aviation Authority instigated a research project to investigate the use of Differential GPS for helicopter instrument approaches to offshore platforms. The aim of the project was to demonstrate the suitability of the technology for the task and to provide the knowledge and experience required to support its introduction.

Aware of the considerable amount of work being conducted elsewhere to address the wide ranging technical issues associated with the use of GPS technology, the CAA first commissioned a literature search and review. The purpose of this exercise was to identify, obtain and examine all existing literature that could be relevant to the use of DGPS for offshore helicopter approaches, in order to establish the extent and quality of work already undertaken and thus avoid duplication of effort. In the event it was discovered that very little had been reported on the application of DGPS to helicopter operations and nothing was identified that addressed the conditions that prevail at offshore platforms; in particular, the large number of reflectors which could give rise to additional errors caused by "multipath" reception.

The findings of the literature survey (Ref 1) enabled a Flight Trials Project Specification to be produced for a proof of concept trial designed to address the CAA's objectives. The specification addressed the general configurations of the ground and airborne systems, the nature of the flight testing to be performed, and the data collection and analysis required.

At present, the only airworthiness and operational requirements that exist in relation to offshore approaches are those written specifically for operations using airborne weather radar. These requirements are unsuitable for application to any other potential form of offshore approach guidance. Hence, a longer term objective of the research project was to use the information gathered from the flight trials programme to develop generic requirements for offshore approach guidance, together with the airworthiness

* Paper presented at the 23rd European Rotorcraft Forum, Dresden, Germany, September 1997

requirements specific to the various elements of a DGPS system.

Other objectives of the flight trials programme were:

- to quantify the performance of representative Differential GPS equipment installed in a helicopter, when operating in the vicinity of offshore structures, and
- to investigate flyability and piloting issues such as approach trajectories, and cockpit displays and indications.

Invitations to tender were issued in 1995 and a contract awarded to the College of Aeronautics, Cranfield University, as prime contractor. The flight trials were conducted during 1996, using a chartered Bond S76C helicopter equipped with a DGPS trials installation designed by Cranfield Aerospace Ltd (the commercial arm of the College of Aeronautics).

In total, seven test flights were conducted involving data gathering exercises at four offshore platforms, representing low, medium and high multipath environments. The current weather radar approach pattern was flown using DGPS guidance and alternative "DGPS approach" trajectories were also investigated.

The paper gives an overview of the flight trials undertaken. The airborne and ground based equipment is first described, followed by the flight trials programme. The main findings to date are reported, with the emphasis on the flyability and piloting issues. More detailed information on the technical performance of the DGPS equipment is reported separately, Ref 2. Additional work required before approval of the use of DGPS for offshore approaches can be considered, is also described.

2. Trials airframe

A Sikorsky S76C helicopter (G-SSSC), chartered from Bond Helicopters Ltd and based at Aberdeen airport, was employed as the trials airframe for the test flights.

The S76C's standard seating capacity is twelve passengers plus two crew members and the aircraft is representative of the small to medium-sized helicopters currently in passenger operation on the North Sea. In order that the results of the trials programme could be translated, with a reasonable level of confidence, to different helicopter types and equipment installations, ground trials were performed to quantify the effect of the airframe and rotors on GPS performance.

2.1. Existing avionics fit

In common with the majority of the UK offshore fleet at the time the trials were performed, the principal en-route navigation aid fitted to the aircraft was Decca Navigator which was accessed via a Racal Avionics area navigation system (RNAV-2). Due to the progressive withdrawal of some of the European Decca transmitters, the UK North Sea operators are currently in the process of installing GPS en-route equipment as a replacement.

Other sensors carried included a standard IFR equipment fit (VOR, ILS, DME and ADF), radio altimeter, and air data computer.

The Racal RNAV-2 comprised a navigation processor unit, which was interconnected with a number of the aircraft systems including Decca Navigator, VOR, air data computer, compass and IHUMS (health and usage monitoring); and a Control Display Unit mounted on the central cockpit pedestal. The RNAV-2 also provided a navigation data overlay facility on the weather radar display, which allowed the crew to correlate weather radar returns with the position of the waypoints in the current stored route.

Of particular significance to the trials programme was the fact that the RNAV-2 possessed a data input suitable for use with a GPS sensor. This allowed the GPS equipment, which was fitted on a temporary basis, to be readily integrated with the existing aircraft systems, and effectively allowed GPS to replace Decca Navigator as the principal en-route aid during the flight trials, whilst allowing the crew to continue to follow standard RNAV-2 based operating procedures.

The RNAV-2, although very flexible for normal en-route operations, only provided steering guidance in the horizontal plane and the unit was never intended to be used to provide an approach facility. To complement and extend the capabilities of the RNAV-2, the experimental GPS equipment included a dedicated approach guidance processor unit which could be selected to drive the cockpit instruments directly.

Navigational data was displayed to the pilots via standard Horizontal Situation Indicator (HSI) and Attitude Director Indicator (ADI) displays, the latter incorporating the facility to display both "raw data" deviations and flight director command bars. Cockpit switch selections allowed the information displayed to be derived from the standard IFR equipment, from the RNAV-2's horizontal steering output, or from the experimental DGPS equipment. The aircraft was also fitted with a digital four axis autopilot which could be coupled to any of these systems.

2.2. Experimental GPS installation

A series of modifications to the trials airframe were undertaken to allow it to accept an experimental DGPS installation. This was mounted on a removable equipment pallet designed and constructed at Cranfield, and installed in the aircraft's aft baggage bay. A schematic diagram of the airborne equipment installation is shown in Figure 1.

A single GPS patch antenna was installed on the top of the aircraft's tail fin, and was arranged to provide an RF signal input to four GPS receivers via a low-noise preamplifier and passive signal splitter.

Of the four GPS receivers carried on the trials pallet, three were configured to accept differential corrections in the industry standard RTCM-SC104 format and to output differentially corrected position solutions. The outputs from the receivers were available for use in real time to provide aircraft guidance, and were also recorded for subsequent analysis.

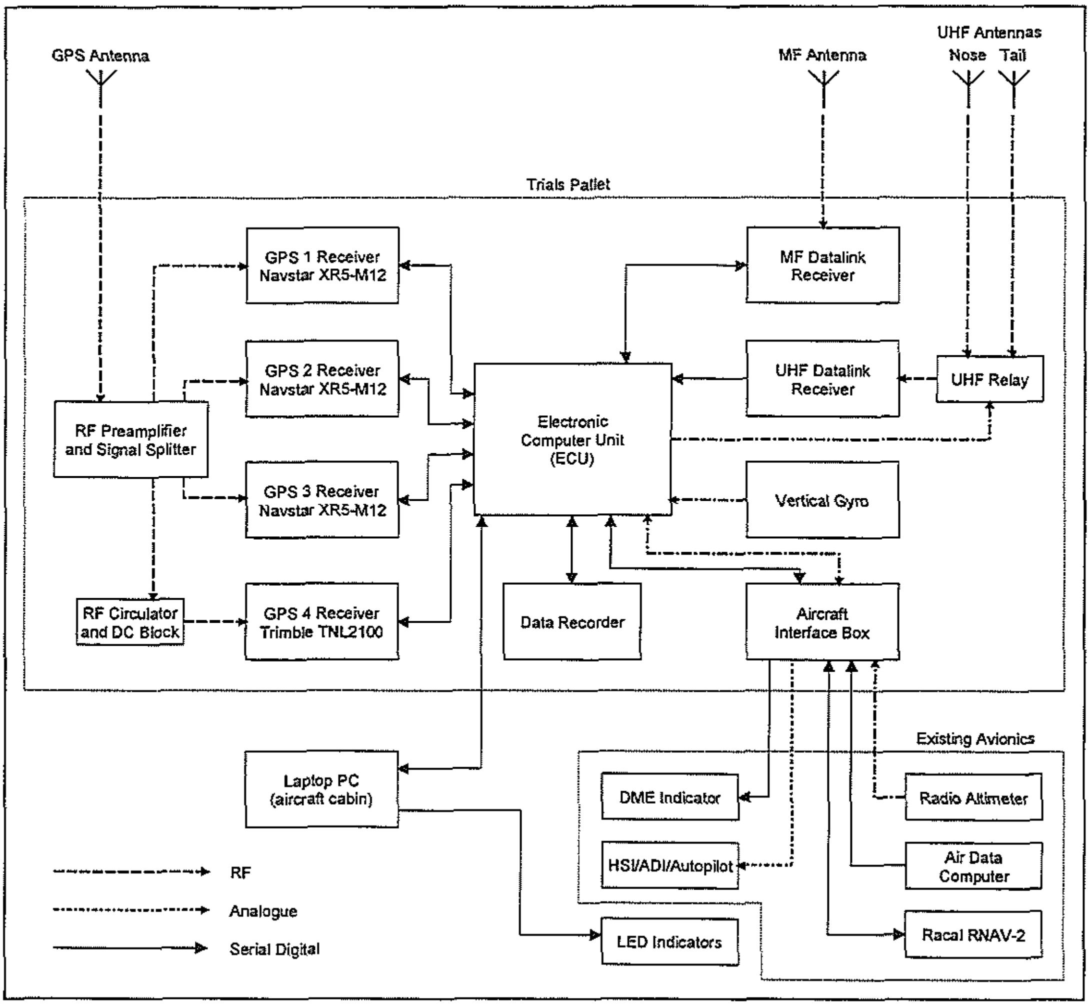

Figure 1. Trials aircraft DGPS installation

The aircraft installation incorporated the ability to receive differential corrections concurrently from two alternative sources. An MF receiver, capable of decoding corrections broadcast from marine radiobeacons in the frequency range 283 to 325 kHz, enabled correction data to be received from the General Lighthouse Authorities encrypted service in the British Isles, as well as from various freely available services in mainland Europe. A second source of differential corrections was provided in the form of a UHF datalink receiver, capable of receiving corrections transmitted by a private base station which was temporarily sited on the "target" offshore platform for the duration of each trial. The UK authorities assigned a dedicated UHF datalink frequency of 455.5 MHz specifically for the trials programme.

Additional antennas were installed on the aircraft for operation with the two differential datalink receivers: an H-field loop antenna in the case of the MF receiver, and a pair of quarter wave stub antennas on the aircraft nose and tail (either of which could be switched to the datalink receiver antenna input) for the UHF system.

Of the three real-time differentially corrected GPS receivers, two were twelve channel XR5-M12 units manufactured by Navstar Systems Ltd. One receiver was supplied with corrections from the MF receiver and the second with corrections from the UHF datalink. This enabled a direct comparison to be performed between the performance of identical receivers operating from the two correction sources.

A third differentially-corrected receiver was included in order to investigate the level of consistency between the Navstar GPS receiver and one from an alternative manufacturer. This unit was a six channel Trimble Navigation model TNL-2100 which was capable of operating in differential mode.

The remaining GPS receiver acted as the airborne "truth" reference and was configured to output a series of real-time satellite measurements for later processing. These measurements included both conventional pseudoranges and a satellite carrier phase observable, which were combined with similar measurements taken at fixed onshore and offshore locations during post-flight processing to yield a "truth" position history for the aircraft. No real-time differential corrections were supplied to the "truth" reference receiver (also supplied by Navstar) which accordingly operated throughout the trials in stand-alone GPS mode.

The outputs of the GPS receivers were connected to a central microprocessor-based computer unit which ran a custom embedded software program. GPS data was recorded onto miniature hard disc storage modules by means of a separate recorder unit.

Data from a number of other aircraft sources was also sampled and recorded in real time by means of analogue and

ARINC 429 databus interfaces. The parameters recorded included radio altitude, pressure altitude, true air speed, heading, and pitch/roll attitude (the latter being derived from a dedicated vertical gyro).

An ARINC 429 databus was used to transmit differentially-corrected GPS data to the Racal RNAV-2 processor, where it could be selected by the pilot as the principal en-route navigation source in place of Decca.

A series of analogue outputs from the trials installation, comprising horizontal and vertical deviations together with associated flag discretes and a "To/From" output, could be selected to drive the cockpit HSI and ADI indicators and the aircraft autopilot. Interface hardware was provided to ensure that the signal levels were identical to those output by the aircraft ILS receiver, allowing data to be presented to the pilot in ILS "look-alike" format. These analogue outputs were complemented by a digital connection to the central cockpit DME indicator, allowing range data derived from the trials equipment to be displayed to the pilot.

The embedded software in the processor unit translated the real-time DGPS data into a suitable format for display, using a set of user-defined parameters to specify the desired approach trajectory. These parameters were set up, and the operation of the recording equipment monitored, using a laptop PC located in the aircraft cabin.

The trials equipment was designed and approved solely for experimental purposes and there was never any intention for it to be used as an operational navigation system. This allowed changes to the system configuration to be incorporated during the trials programme without the need to recertificate the installation.

3. Fixed equipment

In addition to the aircraft systems, GPS receivers were also operated at two fixed sites. These were the offshore platform at which the trial was being undertaken and a surveyed onshore location. Differential corrections were also obtained from a number of onshore marine beacons.

3.1. Offshore GPS equipment

During each of the offshore trials, a self-contained GPS reference system was operated at a suitable location (normally the edge of the helideck) on the "target" platform.

The platform reference system served two purposes, each of which was undertaken by a separate GPS receiver: to provide a record of raw GPS satellite measurement data for use during the carrier-phase post-processing exercise, and to act as a differential base station for the generation and transmission of corrections to the aircraft via the UHF datalink.

Corrections were generated in RTCM-SC104 Type 1 and Type 2 format at a 1Hz update rate, and transmitted on the assigned UHF frequency of 455.5MHz by a 2W telemetry transmitter, which was estimated to provide a range in excess of 20nm. Data recording was performed using a processing unit and data recorder similar to the equipment used on board the aircraft.

3.2. Onshore GPS equipment

A third "truth" reference GPS receiver was located at a fixed onshore location, with its antenna mounted on an external metallic mast. The services of a specialist survey company were employed to obtain an accurate set of co-ordinates for this antenna location.

The onshore reference receiver was interfaced with a third set of processing and recording equipment, so that the data from all three locations was available in a common format.

3.3. Onshore differential stations

The differential corrections received on the trials aircraft via the MF receiver originated from a series of coastal marine beacons, each of which transmits a low rate DGPS data stream on a sub-carrier. In the British Isles, operation of the MF DGPS stations is undertaken by a commercial company (Differential Technology Ltd) on behalf of the General Lighthouse Authorities, and the signals are encrypted to enable a license fee to be charged to users. In much of mainland Europe and in other areas of the world (such as the USA), the correction data is provided as a public service with no encryption imposed.

During the course of the trials, MF differential corrections were obtained from the marine beacon stations at Girdle Ness (Aberdeen) and Sumburgh (Shetland Islands) in the UK, and from Utsira in Norway.

4. Offshore approach procedures

In advance of the flight trials, considerable effort was taken to determine the form of approach profile most suitable for use with the DGPS guidance, taking into consideration the likely limitations of the equipment and airframe and the various operational and safety constraints. This was achieved by utilising the present offshore procedures as a starting point.

4.1. Weather radar approach

Approach guidance to offshore locations is currently provided by the helicopter's weather radar, in combination with a platform NDB if one is present. The only other equipment provided by the platform operators to assist helicopter pilots is helideck and platform lighting, and a VHF radio channel which provides two-way communication with the platform radio operator and helicopter landing officer.

Offshore helicopter weather radars are essentially standard commercial units, but often incorporate a modification which provides a display more suitable for operation at very short ranges. Examination of weather radar returns during an approach, and correlation with the relative positions of the destination platform and other known obstacles, provides the pilot with confirmation of his position.

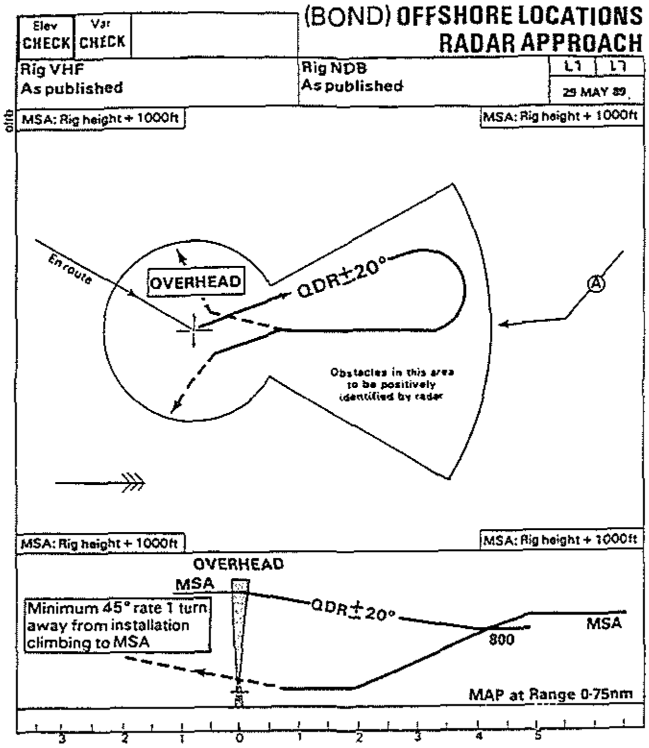

Figure 2. Bond Helicopters weather radar approach (courtesy of British Airways AERAD)

The helicopter operators have developed approach procedures which employ the weather radar as the primary means of ensuring separation between the aircraft, platform and other obstacles. Figure 2 depicts the radar procedure employed by Bond Helicopters Ltd.

This "Aerad" weather radar approach commences with an overflight of the platform to provide a positive indication that the correct destination has been located. This may be achieved visually, or by using the platform NDB, or by correlation between the area navigation system and the radar returns.

A downwind leg is then flown, offset by 20°, to allow an inbound turn to be undertaken at a range of around 4nm to bring the aircraft onto a direct into-wind course to the platform. At the same time the aircraft is able to descend below minimum safe altitude using the radar returns to confirm that the approach sector is free from obstacles.

Once established on the final approach track using a combination of weather radar and NDB, a further descent to a minimum descent height of (typically) 200ft is undertaken. To maintain separation from the platform in the event that visual contact cannot be established, the aircraft is required to turn away from the direct track at a range of 1.5nm, initially by 10° and then by 15°. The Missed Approach Point is defined as a range of 0.75nm from the platform: if visual contact has not been established by this point, the crew has the assurance of being able to perform a safe go-around manoeuvre which will remain clear of the platform.

4.2. DGPS approach

If real-time DGPS data were available, then an alternative form of approach track could be employed. A straight into-wind approach, without turns, arranged to be offset by a defined distance to one side or other of the platform was chosen (Figure 3).

The lateral offset required to maintain safe separation is dependent upon various factors, including the accuracy of the DGPS equipment, the extent to which flight path errors are tolerated, and the confidence with which the position of the platform and any temporary obstacles can be determined. It was anticipated that a viable lateral offset would be of the order of a few hundred metres, potentially offering a significant improvement over the weather radar minimum decision range of 0.75nm.

For the test flights, it was decided to employ the lowest value for the lateral offset that was envisaged to be viable for any future operational system. The approach track was arranged to be offset laterally, relative to the centre of the platform structure, by 200m at the smaller platforms and 250m at the larger installations. The aim was to ensure that a separation of approximately 180m was imposed between the point of closest approach and the nearest part of the platform structure. Approaches were performed with both left and right-hand offsets.

A defined point along the approach track was required to form the Missed Approach Point (MAP) by which the decision to commence a visual landing manoeuvre or to go around would need to be taken. The point of closest approach to the platform was unsuitable for this purpose since, even if visual contact were established, the aircraft would have already passed abeam the platform before commencing the landing manoeuvre. Instead, a decision was taken to define the MAP in terms of the platform bearing relative to the approach track. It was considered that a visual landing could only be safely undertaken if this bearing was no more than

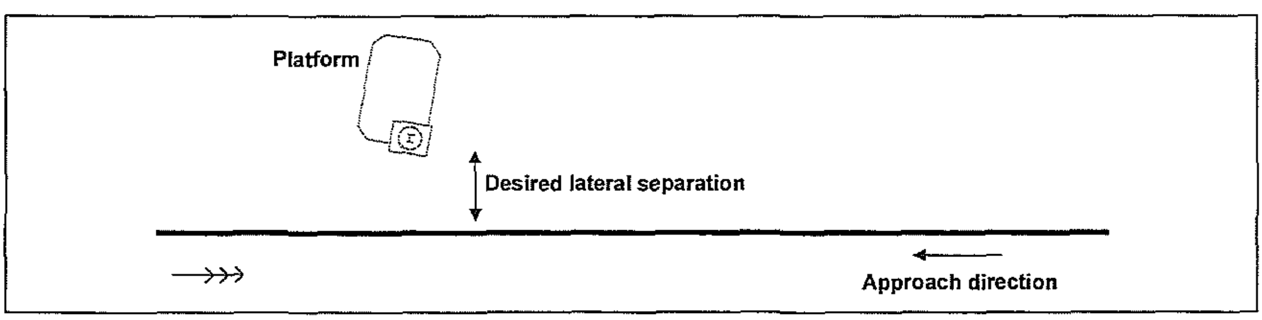

Figure 3. Laterally offset approach track (plan view)

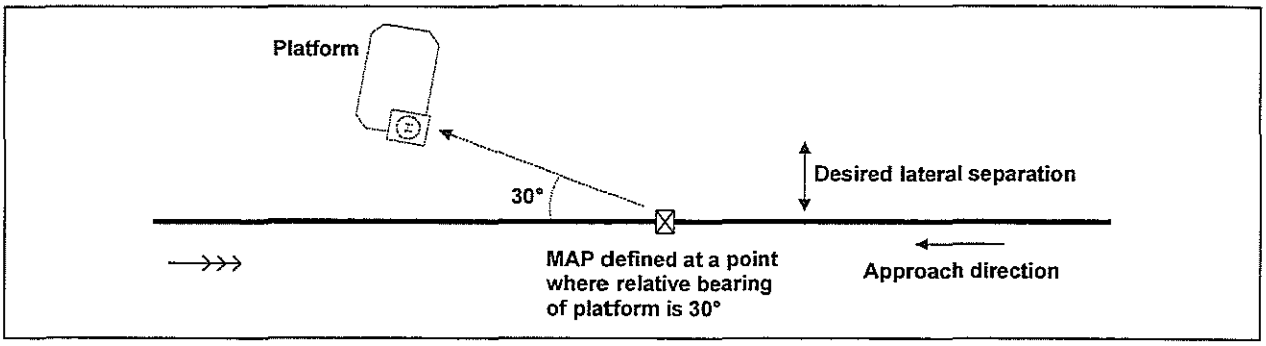

Figure 4. Missed Approach Point positioning (plan view)

around 30°: this not only maximised the probability of visual acquisition being achieved, but also ensured that the platform was reasonably positioned for a landing manoeuvre to be undertaken.

Accordingly, the MAP for the trials flights was defined as the point at which the relative bearing to the platform was equal to an angle of 30° (Figure 4). There is no certainty that a landing would necessarily be possible from a MAP in this position at all offshore locations, dependent upon the relative orientation of the platform structure, helideck and approach track. Considerable further work, beyond the scope of this trial, would be required to define the criteria for an appropriate MAP position in relation to approach direction and helideck orientation.

As with the weather radar approach, it was considered desirable for there to be no changes in altitude during the period when visual acquisition of the platform would be sought in marginal weather conditions. This led to the concept of a "level segment" flown at minimum descent height for a set distance before and after the MAP (Figure 5). The value initially selected for the length of the level segment was 1500m, which implied that at a nominal 80kt ground speed the aircraft would be flying level for around 35s. This was anticipated to be about the shortest operationally acceptable segment length for a 200ft MDH.

The availability of DGPS positioning data enabled a fixed approach path along which the aircraft could descend to minimum descent height to be defined. This "approach segment" consisted of a fixed angle approach, ending at the start of the level segment, which could be intercepted by the aircraft at a safe altitude in a similar manner to an ILS glide slope. The same concept was applied to the go-around or overshoot segment following the end of the level segment, to provide a missed approach manoeuvre consisting of a fixed climb angle back to a safe altitude. The approach angle was initially set to 3.5° as this is approximately the descent angle attained when flying the standard radar approach. For simplicity the overshoot angle was initially set identical to the approach angle.

To evaluate this form of DGPS approach, the aircraft data processor unit was arranged to generate cockpit guidance information which indicated the aircraft position relative to the desired trajectory. This was generated automatically by the software using a set of parameters entered by the user to define the approach profile in terms of the platform latitude and longitude; the desired approach track direction and offset; the length and height of the level segment; and the approach and overshoot angles.

The guidance information displayed in the cockpit consisted of the following elements:

- Localiser deviation, proportional to the DGPS cross-track displacement relative to the desired approach track.
- Glideslope deviation, proportional to the aircraft vertical displacement relative to the desired approach profile. This was derived by firstly using the horizontal DGPS solution to determine the desired approach height (which

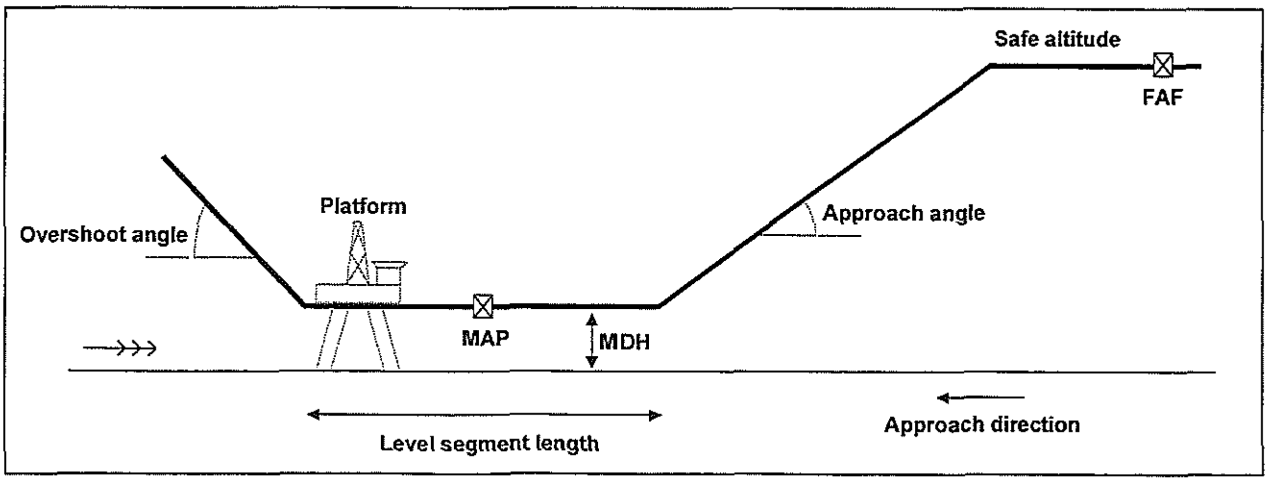

Figure 5. Vertical approach profile (side elevation)

is a function of the along-track distance to the MAP) for the current position, and then subtracting the desired height from the radio altimeter reading. Radio altitude was selected in preference to barometric or GPS altitude as it offered the most accurate measure of the true height above the sea.

- A range indication, displayed in digital form on a DME readout. This could be arranged to display either the along-track distance to the MAP, or the true slant range to the platform.

- An approach status display which provided, alongside the DME readout in abbreviated alphanumeric form, an indication as to the current approach segment (approach, level or overshoot) and whether the MAP was ahead of or behind the aircraft.

Any of the three differentially-corrected receivers could be selected to provide the DGPS input to the guidance algorithms. Because the receivers only generated new solutions at one second intervals, a linear extrapolation algorithm which combined position and velocity data was used to provide continuous guidance.

Various options were available regarding the form of scaling by which the cross-track and vertical displacements could be translated into horizontal and vertical deviations for display on the HSI and ADI. It was decided that a constant scaling would be appropriate throughout the level segment, but that a lesser degree of sensitivity would be required at greater ranges from the platform. Accordingly it was decided to employ three separate pairs of scaling values which defined the instrument scalings for the following points: the whole of the level segment; a point at 4nm range on the approach segment; and a corresponding 4nm point on the overshoot segment. The scaling for intermediate ranges on the approach and overshoot segments was arranged to vary linearly between the 4nm points and the ends of the level segment.

The localiser and glideslope sensitivities were initially set to provide full-scale instrument deflection in response to deviations of ±120m (localiser) and ±100ft (glideslope) during the level segment. The corresponding sensitivities during the approach and overshoot segments varied linearly with distance from the platform, with the sensitivities at 4nm range being approximately one quarter of the level segment values.

5. Flight trials programme

A series of seven flight trials were performed using the trials airframe and equipment over the spring, summer and autumn of 1996 at various onshore and offshore locations in the Aberdeen area.

5.1. Trials locations

It was anticipated that multipath propagation of the satellite signals, due to the proximity of the metallic structures, would present the greatest single contribution to the degradation of DGPS equipment performance at offshore locations. Multipath propagation was expected to affect not only the trials aircraft receivers, but also the base station mounted at a fixed location on the platform which would be providing one of the two available sources of differential corrections.

Multipath propagation effects were expected to vary significantly as a function of the relative geometry of the satellites, the GPS receiver, and the reflecting surfaces involved. Variations of this geometry with time would occur both at a comparatively slow rate, due to the orbital motion of the satellites, and also (in the case of the mobile receiver) at a much faster rate due to changes in aircraft position.

In view of the importance assigned to this aspect of the trials programme, four offshore structures anticipated to possess differing multipath characteristics were selected for investigation. The intention was that these would form a representative cross-section of the different types of platform commonly encountered in the North Sea.

Beatrice C is a small unmanned water injection platform on which the helideck forms the highest point of the structure. This form of construction is particularly common in the shallower waters of the southern North Sea and it was expected that the structure would provide a low multipath environment.

Piper B is a large oil and gas production platform typical of the structures found in the northern North Sea. In common with a number of other recently installed platforms, the accommodation module (including the helideck) is located as far as possible from the derricks and other production equipment for safety reasons. This structure was expected to provide a medium level multipath environment.

Tartan A is another large oil and gas production installation broadly similar to the Piper design but with less separation between the accommodation and production modules. The platform possesses a large, partially clad, derrick structure close to the helideck and was anticipated to provide a medium to high multipath environment.

Buchan A is a former drilling rig which has been converted for operation as a production platform. Unlike the other platforms visited, which are physically attached to the sea bed, the Buchan is of semi-submersible construction and is subject to oscillatory motion as a result of wind, wave and tidal effects. In common with mobile installations of similar design, the helideck is at a very low level relative to the remainder of the superstructure. The latter, in addition to providing a significant obstruction during takeoff and landing, was expected to provide a relatively high GPS multipath environment.

Each of the four platforms was the subject of a separate flight trial during which a standard series of flight manoeuvres were performed. The Beatrice C was the subject of two flight trials: the second of these, undertaken at the end of the trials programme, was performed to gather some additional GPS data and also provided the opportunity to demonstrate the operation of the approach guidance equipment to industry representatives.

The offshore flights were complemented by two onshore trials at the beginning of the programme which were undertaken to verify the operation of the onboard equipment, and to perform measurements of the performance of the DGPS equipment in a controlled environment. On each of these flights a small number of trial approaches were made at arbitrary locations in order to test the approach guidance software.

5.2. Aircraft crew

The aircraft was flown by a Bond Helicopters Ltd Senior Training Captain and a CAA Senior Test Pilot. Evaluation of offshore DGPS approaches was performed by both pilots, to obtain opinions on the suitability of the various approach profiles from both an operational and a flight test viewpoint.

A Flight Test Engineer from Cranfield University and a CAA Flight Test Observer made up the remainder of the trials crew. The FTE had particular responsibility for monitoring the operation of the airborne DGPS equipment, and for entering approach parameters via the laptop PC.

5.3. Flight trial profiles

A standard series of flight manoeuvres was undertaken at each of the four offshore platforms visited, to provide the project pilots with the opportunity to evaluate different approach guidance techniques, and to gather data relating to the performance of the DGPS equipment at each location.

"Modified Aerad" Approaches. A series of four approaches, which were DGPS variants of the "Aerad" weather radar procedure of Figure 2, were undertaken at each platform. For each of these approaches the platform overflight and downwind legs were identical to the Aerad procedure, but the inbound leg was undertaken using the horizontal and vertical DGPS profiles described in section 4.2 in place of the standard radar procedure. This allowed GPS data to be collected at much closer ranges to the platform (200m in place of 0.75nm) during the approach and go-around, as well as providing the opportunity to obtain pilot comments upon the new procedure. The four approaches (Figure 6) were performed using different inbound tracks at 90° intervals around the compass, so as to obtain DGPS data points for analysis which were relatively evenly spaced around and above the platform. Each approach commenced as the aircraft passed overhead the platform and ended with the execution of a missed approach procedure.

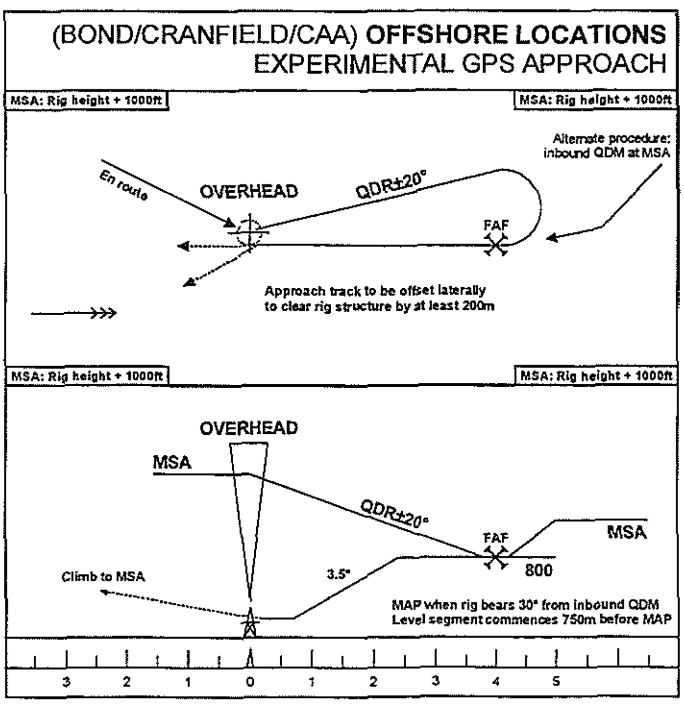

Figure 6. "Modified Aerad" DGPS approach procedure

Platform Orbits. A series of orbital manoeuvres at nominally constant ranges from the platform structure were performed to obtain a larger set of data regarding DGPS performance close to the platform.

One complete circumnavigation of each platform was performed at ranges of 2.0nm, 1.0nm, 0.5nm and 0.2nm, with a radalt height of 200ft throughout. When the wind conditions permitted, a series of additional manoeuvres was performed at extreme close ranges to the platform structure.

The orbital manoeuvres were flown by coupling the aircraft autopilot to the output of the RNAV-2, which (using GPS as its navigation source) was able to generate circular trajectories of the desired radii.

Experimental Approaches. A further series of approaches were performed in order to provide a more detailed evaluation of the DGPS guidance facility, as well as obtaining additional data for subsequent analysis.

For these approaches the platform overflight and downwind legs were omitted, each approach being commenced by positioning the aircraft manually to establish on the localiser at around 4nm finals. Between three and six of these approaches were performed at each of the platforms. On each flight, experimental approaches were performed using two or more alternative sets of approach parameters in order to allow the pilots to perform a comparison between the different forms of approach.

6. Flyability and piloting issues

In the course of the seven test flights a total of 61 DGPS approaches were flown, of which 46 were performed at offshore platforms. All approaches were undertaken in VMC.

Initial reactions to the DGPS approach profile, and guidance presentation, were very favourable. The approach guidance was generally easy to fly and provided smooth and consistent indications. Over the course of the test flights a number of modifications were investigated, partly in order to investigate the effect of varying some of the approach parameters, and also in response to observations and feedback from the pilots during and after each flight.

6.1. Transition to level segment

During the first offshore flight, both pilots noted a tendency to disregard the radio altimeter when following the HSI approach guidance during the latter stage of the approach because the attention required to follow the vertical guidance from the descent to the level segment, in order not to miss the transition, tended to dominate. Good cross checking of height is clearly important, and it was apparent that the excessive attention paid to the vertical guidance prior to the transition could be reduced by providing a "faired in" vertical profile to eliminate the sudden change in approach angle upon reaching the level segment. This was investigated on the subsequent test flight and was configured as a "smoothing" of the flight profile over the last 50ft of height above the level segment.

The vertical fairing worked well in smoothing the transition to the level segment. It significantly reduced the workload, allowing a better instrument scan, and resulted in improved flight path accuracy during the transition. The same fairing was applied to the transition to the overshoot segment but this was found to be unhelpful since the previous more positive indication to climb, from the HSI glideslope needle, was considered to be more attention-getting and therefore more appropriate. It was noted that in order to more adequately accommodate different glideslopes, it would be better to specify the vertical fairing over a constant horizontal distance, rather than a constant vertical height. This was assessed on the next test flight where the vertical fairing, this time specified over a constant horizontal distance of 500m, worked well in smoothing the transition to the level segment for both 3.5° and 6° glideslopes.

6.2. Approach angle

During the first offshore flight, approaches were flown with 6° and 9° glideslopes in addition to the 3.5° angle initially selected. The 6° approaches were flown both into and down wind without difficulty using ground speeds in the range 45 to 70kt, giving a rate of descent of 600 to 800ft/min. The transition between the descent and the level segment was quite abrupt without the vertical fairing subsequently introduced. The 9° approaches at 60 to 65kt ground speed resulted in a near autorotative state during the descent, with rates of descent up to 1400ft/min and a very abrupt transition at 200ft. This represented the limiting case for the S76C but might be more feasible for other aircraft types exhibiting greater drag, if the guidance were refined slightly. The primary advantage of steeper approaches is to provide improved clearance from any obstacles in the approach path.

6.3. Overshoot angle

A positive full fly up indication was obtained at the go-around point. However, the rate of climb with a 3.5° slope of approximately 450ft/min was considered to be too low. Consequently it was decided that a 6° overshoot angle would be more appropriate for the go-around, resulting in a rate of climb of approximately 750ft/min. This was evaluated and favoured by both pilots.

6.4. Range indication

It was immediately apparent that the range information on the central DME display was too remote from the HSI and could not be easily incorporated into the pilot's instrument scan. Although each HSI incorporated a digital distance indicator, this could not be driven directly from the DGPS equipment. It was noted, however, that the two decimal places available on the central DME display (which provided a display resolution of 0.01nm) allowed the pilot to obtain a much more useful range-rate indication than would have been possible using the single decimal place HSI indicators. This additional information would be important in defining closure to short range MAPs.

During the early flights, the DME display was arranged to indicate range as along-track distance to the MAP. On subsequent flights an assessment was made of the alternative presentation of range to the platform instead of to the MAP.

Distance to the platform was favoured over distance to the MAP since it was considered that all distances should emanate from the platform. Whilst the distance from the platform displayed at the MAP may vary according to the chosen decision range, it will always provide the true physical distance thereby enhancing situational awareness. This also mirrors the situation during onshore ILS approaches where DME indications provide distance to the threshold.

Since distance to the platform was determined with respect to the defined waypoint position, which was selected to be the centre of the platform structure, the actual platform clearance was dependent upon the particular orientation and direction of the helicopter approach track and the position of the MAP in relation to the platform. This issue becomes more critical as the decision range is reduced.

6.5. Mode change annunciation

In addition to providing range data, the centrally mounted DME display was configured to show the current approach phase in alphanumeric form.

It was soon apparent that range related mode change information is very useful and that clear Decision Range annunciation should be a requirement. For certification, such indications would need to be clear and well placed within the instrument scan. To assess this further a small panel approximately 75mm by 15mm, containing four LED indicators, was added. The panel was powered by a flying lead directly from the laptop computer in the cabin and could be attached beside the handling pilot's HSI using hook and loop fasteners.

The four lights were labelled as follows:

- APP (green) On approach
- LEV (amber) Level segment
- MAP (amber) Missed Approach Point
- G/A (red) Go-Around point

These four lights provided mode change annunciation within the instrument scan which greatly improved pilot awareness of approach modes, particularly in the latter stages of the approach. The comment was made, however, that there should be some appropriate indication of the commencement of the vertical fairing, to enable the pilot to anticipate the correct control inputs to satisfy the demanded flight path. This was achieved by configuring the amber "level segment" light to first flash at the start of the fairing to the level segment and then remain solidly illuminated once the level segment was attained. The flashing amber light provided a good cue of the start of the fairing and assisted the pilot in following the guidance from the descent to level phase of the approach.

6.6. Lateral guidance sensitivity

Changes to the lateral guidance sensitivity in the level segment were investigated to consider the effect of using ±90m and ±60m full scale in place of ±120m.

The increase in lateral sensitivity to ±60m full scale was considered to be too severe, but ±90m provided a useful increase in sensitivity that was never excessive for the flying task. Acceptable approaches were flown at 120kt, 80kt and 60kt IAS, corresponding to approximately 105kt, 65kt and 45kt ground speed, with 80kt IAS considered the most appropriate speed. The lateral sensitivity of ±90m full scale is comparable to the sensitivity of a normal ILS installation at a typical Category 1 decision height of 200ft (Ref 3).

The choice of lateral guidance sensitivity may have an impact upon the extent to which the approach track is offset from the platform, due to the need to maintain safe obstacle separation not only with the localiser needle centred, but also with, for example, a half-scale lateral deviation indication present. Lateral deviation warnings might be required as part of an operational system, dependent upon the proximity of the flight path to the platform structure.

6.7. Vertical guidance sensitivity

An increase in level segment vertical sensitivity from ±100ft to ±50ft full scale was investigated at approach speeds of 80kt and 40kt. At 40kt, the increased sensitivity made the task more difficult to fly. At 80kt, the flying task was still achievable, with control of height judged to be "tighter" but still acceptable. A vertical sensitivity of ±50ft full scale is comparable to the sensitivity of a normal ILS installation at a typical Category 1 decision height of 200ft.

Although both ±50ft and ±100ft full scale were considered acceptable, further investigation covering a range of glideslopes, airspeeds and ground speeds would be required to optimise the sensitivity.

6.8. Crosswind and reduced speed approaches

Reduced approach speeds were investigated on one of the test flights. Three approaches were flown at 50kt IAS (two crosswind and one downwind) and two crosswind approaches at 40kt IAS. The piloting task was difficult at these lower speeds, as airspeed control required considerable attention. In addition, the large drift angles during the crosswind approaches (up to 35°) made judgement of the heading corrections required to maintain the correct flight path very difficult, with the result that the flight path was never satisfactorily stabilised.

During an approach with, for example, a left-hand offset and a crosswind from the right, the aircraft was often pointing at, or to the right of, the destination platform. This visual effect was often disconcerting to the crew and could lead to problems carrying out a landing manoeuvre if the platform appeared to be to the wrong side on attaining visual contact with the platform, especially for shorter decision ranges. There could also be problems if the platform was sighted, apparently on the wrong side, during a go-around manoeuvre. Overall, slow speed approaches were difficult, and low speed crosswind approaches are probably not operationally viable.

6.9. Autocoupled approaches

A small number of approaches were flown fully autocoupled and it was noted that, in each case, the helicopter descended to around 150ft upon reaching the level segment before climbing back to the desired 200ft. Since no consideration had been given to optimising the autopilot gains for a coupled approach that incorporated a step change in approach angle, this was not particularly surprising.

However, an attempt was made to reduce the effect of this undershoot by extending the faired transition between the approach and level segments. An autocoupled approach was flown at 80kt, with a vertical fairing into the level segment over the increased horizontal distance of 1000m compared with the 500m used previously. The vertical fairing began at 300ft radalt and the helicopter descended to a minimum height of 165ft. Hence, the increased horizontal distance for the fairing into the level segment only resulted in a reduction in undershoot of approximately 15ft. Clearly the issue of coupling to the autopilot is a topic in itself that needs to be considered separately and is outside the scope of this trial.

6.10. Alternative go-around techniques

One reason for executing a go-around could be the loss of GPS data and consequently it would not be possible to use this information to provide guidance through the overshoot segment. With this in mind, the alternative facility provided by the aircraft autopilot go-around function was compared with the 6° GPS overshoot guidance. The autopilot go-around function holds the current heading and controls the speed to not less than 75kt, to give a 700ft/min rate of climb, and was selected by the pilot when the helicopter reached the end of the level segment. Although this worked satisfactorily, care would have to be taken when integrating this into the DGPS procedures. Since most helicopters do not possess an automatic go-around facility, the most likely option in the event of loss of GPS would be a manually flown missed approach.

On one of the latter test flights, investigations were made into the feasibility of incorporating a DGPS-commanded climbing turn into the overshoot segment. Initially, the system was configured to provide a 20° track change which was introduced over the first 500m of the overshoot segment (equating to a rate 0.5 turn at 80kt). For this approach, the pilot commented that the heading change demanded at go-around was not positive enough and so for the next approach the 500m distance was reduced to 100m which resulted in a rate 3 turn demand.

It was considered that the combination of the localiser needle moving to one side, the glideslope needle moving upwards and a flashing red go-around light provided a compelling overshoot cue. However, the possibility of loss of DGPS guidance means that the decision range should not be set such that the pilot is required to perform a turn during the go-around to ensure obstacle separation.

6.11. Curved approaches

Midway through the trials programme the capabilities of the DGPS guidance software were extended to enable the inbound turn of the "modified Aerad" approaches to be flown as an approximately Rate 1 turn using DGPS data fed to the HSI and Flight Director, rather than the RNAV-2 guidance previously used. For the first approach, using the raw data indications on the HSI, it was found to be very difficult to follow the guidance around the turn due to the problems experienced by the pilot in relating the displayed localiser indications to the desired flight profile. This was largely due to the fact that, unlike the case with the RNAV-2 turn guidance, the HSI course carriage setting was not automatically updated to reflect the desired course around the turn.

On some subsequent approaches, the turn was manually flown using the flight director guidance on the ADI. Although some success was achieved, the lack of HSI course indication proved to be a problem and on one approach the pilot was unable to follow the guidance correctly around the turn. This was a result of the pilot commencing the turn relatively late, and then manoeuvring too rapidly in an attempt to regain the desired track.

Since the turn could alternatively be flown using the RNAV-2 coupled to the autopilot, it was felt that there may be no real need to provide DGPS guidance prior to the Final Approach Fix (FAF). However, if guidance were to be provided all the way round the turn, then the course carriage needs to be driven by the guidance system.

6.12. Removal of the level segment

To investigate the effect of performing a direct descent at a constant approach angle, two approaches were flown which incorporated a descending approach directly to the MAP with the level segment removed. Both were performed with a significant crosswind and employed a MAP which was arranged to be offset 60m from the centre of the platform (or approximately 20m from the edge of the helideck). This also enabled investigation of any multipath effects when flying close to the platform at the end of the approach.

One approach was flown with a 3.5° glideslope to the MAP, followed immediately by a go-around consisting of a climbing turn to the left of 45°. The second approach was flown with a 6° glideslope followed by a landing on the helideck. On both approaches the vertical fairing at the bottom of the approach segment was retained and this proved to be beneficial, serving to arrest the descent with the MAP reached at the point of levelling out.

For the 6° approach the 80kt speed was considered to be too fast, requiring some rapid manoeuvring in order to land from the approach. The advantage of a direct approach to the deck is improved obstacle avoidance, but speeds would need to be reduced in the latter stages. Approach profiles of this nature will require further investigation.

6.13. Loss of differential corrections

The majority of the approaches were performed using DGPS position solutions derived from the MF-corrected Navstar receiver. The DGPS guidance algorithms could be arranged to immediately provide a warning to the pilot, in the form of flag indications, if the receiver reverted to non-differential positioning mode. This situation would normally result in a missed approach manoeuvre being performed. When this warning was manually disabled during the trials, the transition between differential and non-differential modes was found to result in sudden step changes in the displayed indications, most notably on the localiser deviation, which was considered unacceptable. It will clearly be important to reduce the likelihood of losing the differential position solution.

On the last two flight trials, severe difficulties occurred with the reception of differential corrections via the MF datalink, resulting in significant periods when the MF receiver was unable to obtain a satisfactory signal from any of the available marine beacons. These difficulties may have been due to the ambient weather conditions (precipitation is known to affect the MF reception) or to problems with the antenna installation, possibly due to static build-up which is known to affect other avionic equipment on the S76C. It is also significant that the aircraft was operating at an extended distance from the marine beacons, frequently in excess of the published range, although the reason for the absence of any difficulties during the earlier trials is not clear.

Initially an attempt was made to continue to provide pilot guidance using the MF-corrected data but it soon became apparent that it would be preferable to change to the UHF-corrected Navstar receiver which was operating normally.

The lateral guidance obtained from the UHF-corrected receiver, although not suffering from datalink problems, appeared to be more sensitive and "twitchy". Post-flight processing revealed that this appeared to be due to multipath from the rig structure affecting the GPS signals received at the platform reference station and hence the transmitted UHF corrections.

The instabilities on the localiser deviation were reduced by changing the lateral guidance sensitivity back to ±120m. This resulted in the lateral guidance, in particular that displayed on the ADI, becoming much more usable. However, comparison with an ILS approach undertaken on return to Aberdeen, revealed that the latter was easier to fly than the DGPS guidance. This was considered to be primarily due to the fact that the gains were more appropriate during the latter stages of the ILS approach.

6.14. Input of approach data

During the flight trials, approach parameters were input to the guidance algorithms by the FTE using a laptop PC. Whilst very flexible, this arrangement was never intended to be representative of the user interface which might be considered for an operational DGPS system. To minimise the probability of incorrect data entry, it is desirable to confine to a minimum the number of parameters input by the pilot to specify an approach: in the limit this would require only the entry of a destination identifier and approach direction, causing a pre-programmed approach profile to be automatically selected from a database.

Careful consideration must be given to the integrity of the database used to store the co-ordinates and any other fixed approach parameters for each platform. Although many of the issues relating to database integrity (such as the consistency of co-ordinate datums, the possibility of transcription error, and the detection of corrupted data) are similar to those being addressed by the onshore community, there is an additional problem relating to those offshore structures whose position periodically changes.

7. GPS receiver accuracy

Data recorded during the offshore flight trials from the "truth" reference receivers was post-processed using a commercially available carrier phase analysis package. The software combined the GPS satellite data recorded on the aircraft and at a fixed reference site (either the onshore or platform system), and computed the vector displacement between the two receivers. Provided that the position of the reference site was accurately known, this allowed the absolute position of the aircraft to be determined.

The availability of reference receiver data from two static sites (the onshore and platform systems) allowed two separate truth solutions to be determined, one for the vector between onshore system and aircraft, and another for the vector between platform system and aircraft. This provided two semi-independent sets of aircraft position solutions, with a comparison between the two providing a measure of confidence in the truthing system, which was found to converge to somewhere in the region of ±1m following the first 20 to 30 minutes of recorded data.

The recorded real-time position data from each of the onboard receivers was compared against the "truth" solution in order to determine the error in each receiver. A more comprehensive discussion of the results is presented in a separate paper (Ref 2) but a summary is shown in Table 1, which presents statistics of the horizontal position errors (in terms of mean, 95% confidence level, and maximum) during the manoeuvres at each of the offshore platforms. Since the DGPS height output was not used to provide aircraft guidance, the vertical position errors have not been included.

The UHF-corrected receiver was found to exhibit large maximum errors at two of the platforms. The fact that the mean error remained small, and that large maximum errors were not observed on the corresponding MF-corrected receiver data, suggests that these were temporary position error excursions resulting from the effect of multipath upon the platform reference station.

The consistently larger mean and 95% errors observed for the UHF-corrected data, relative to the MF corrected receiver, may also have been due to the slight uncertainty involved in the siting of the platform system. The platform base station was required to be initialised with an accurate estimate of its position, which in many cases proved difficult to determine owing to the limitations of the survey information held by the platform operators.

No clear evidence for the presence of multipath at the trials aircraft could be established from the data. It had been expected that the Tartan and Buchan platforms would offer the worst multipath environment, and that consequently the mean and 95% error figures for these platforms would be larger. The absence of this result leads to the conclusion either that multipath effects upon the aircraft will not be a

Table 1. Summary of DGPS receiver performance (horizontal error) at each platform

		Beatrice C	Piper B	Tartan A	Buchan A
MF corrected Navstar	Data points	3146	5792	10302	6418
	Mean error	3.5m	1.8m	2.7m	3.8m
	95% error	6.8m	4.3m	6.4m	9.6m
	Largest error	17.7m	10.6m	53.3m	17.1m
UHF corrected Navstar	Data points	4588	6544	10302	9107
	Mean error	9.6m	6.7m	6.7m	5.9m
	95% error	12.5m	15.4m	22.0m	13.0m
	Largest error	18.6m	125.1m	92.4m	22.3m
MF corrected Trimble	Data points	1306	Receiver not fitted	Receiver not fitted	6721
	Mean error	3.2m			4.5m
	95% error	6.8m			9.1m
	Largest error	9.2m			21.0m

significant factor, or alternatively that (owing to the limited data set) the aircraft never passed through a region where the relative geometry with the platform and satellites gave rise to multipath effects. Owing to the limited size of the data set, additional trials would need to be performed to provide a confirmation of one or the other hypothesis.

Comparison of the results from the MF-corrected Navstar receiver with those obtained from the Trimble receiver, which was supplied with identical correction data, revealed that there were no significant differences between the two receivers during the course of the flight trials. This suggests that there is unlikely to be a large performance differential between similar GPS receivers from different manufacturers.

8. Conclusions

1. Offshore approaches were successfully undertaken using a combination of DGPS and radio altimeter to provide horizontal and vertical guidance. The optimum instrument sensitivities were similar to those used for onshore ILS approaches.

2. A vertical approach profile with multiple segments was found to be feasible when anticipatory guidance for the transition to the level segment was included.

3. Approach angles of up to 6° were acceptable and this was also considered to be the optimum angle for a DGPS-guided overshoot manoeuvre. Consideration must be given to ensuring a safe go-around in the event of DGPS failure.

4. Clear range and mode annunciation, well placed within the instrument scan, was found to be essential.

5. Approaches with excessive angles of drift were considered not operationally viable.

6. Autocoupled approaches were completed using the DGPS guidance equipment, but there is a need to optimise the autopilot and/or instrumentation gain settings.

7. Direct approaches to a helideck (with no level segment) were performed, but approach profiles of this nature require further investigation.

8. DGPS offers the potential for a seamless transition between en-route and approach guidance, if unambiguous course and mode indications are provided.

9. Annunciation must be provided to the pilot to indicate GPS failures, such as reversion to non-differential mode.

10. It will be essential to ensure the integrity of the data used to perform the approach.

11. Multipath signal propagation does not appear to present a fundamental barrier to the use of DGPS at offshore platforms, but additional analysis and a larger data set will be needed to better understand the multipath environment.

9. Further Work

9.1. Offshore DGPS trials

The final report from Cranfield University on the offshore approach trials programme, containing preliminary conclusions and recommendations, will be published shortly in the form of a CAA paper. Consideration will then need to be given to "in-service" trials to obtain a larger data set and to permit a more wide-ranging evaluation of the capabilities and performance of DGPS approach guidance.

9.2. Simulation analysis

Nortel Technology Ltd have been developing a GNSS Receiver Performance Simulator (Ref 4) jointly funded by CAA's SRG and NATS. This PC-based software tool, capable of generating statistically significant data sets, was used to study satellite coverage and geometry in the North Sea region prior to the trial (Ref 5). The simulator will shortly include a "trials analysis" mode, allowing data gathered during the offshore flights to be used as the basis for subsequent analysis, for example to explore the effect that satellite failures would have had upon the accuracy and availability of the GPS solutions obtained during the trials.

9.3. CAA GNSS steering group

The CAA is addressing GPS certification issues through an inter-divisional body known as the SRG GNSS Steering Group. This group has recently been considering the use of GPS for North Sea en-route navigation and guidance to operators on this subject will shortly be published. Attention will then turn to the issues concerning offshore approaches and the results of the trials programme will provide supporting material for the group's discussions.

10. Acknowledgements

Several individuals provided invaluable assistance to the project team in the execution of the trials programme. Particular thanks are expressed to Captain N.D. Mortimer of Bond Helicopters and Mr. N. Talbot of the CAA who evaluated the DGPS approaches from the pilots' perspective; to Mr. S.M. Wedell and his colleagues from the engineering and operations staff of Bond Helicopters; to Mr. G. Ffoulkes-Jones of Navstar Systems; and to Mr. S.R. Gale and colleagues from Differential Technology. The authors also wish to acknowledge the contributions to the programme provided by Mr. D.A. Howson of the CAA, Dr. R. Johannessen of Lambourne Navigation, Mr. P. Crampton of Nortel Technology, and Mr. D.A. Williams of Cranfield University.

Abbreviations

ADF	Automatic Direction Finder
ADI	Attitude Director Indicator
ARINC	Aeronautical Radio, Inc.
CAA	Civil Aviation Authority
DC	Direct Current
DGPS	Differential Global Positioning System
DME	Distance Measuring Equipment

ECU	Electronic Computer Unit
FAF	Final Approach Fix
FTE	Flight Test Engineer
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
HSI	Horizontal Situation Indicator
IAS	Indicated Airspeed
ICAO	International Civil Aviation Organization
IFR	Instrument Flight Rules
IHUMS	Integrated Health and Usage Monitoring System
ILS	Instrument Landing System
LED	Light Emitting Diode
MAP	Missed Approach Point
MDH	Minimum Descent Height
MF	Medium Frequency
NATS	National Air Traffic Services
NDB	Non-Directional Beacon
PC	Personal Computer
RF	Radio Frequency
RNAV-2	Racal Avionics area navigation system
SRG	Safety Regulation Group
UHF	Ultra High Frequency
UK	United Kingdom
USA	United States of America
VHF	Very High Frequency
VMC	Visual Meteorological Conditions
VOR	VHF Omni Range

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