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DEVELOPMENT AND FLIGHT TEST OF AN X-BAND PRECISION APPROACH CONCEPT FOR REMOTE-AREA ROTORCRAFT OPERATIONS

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Abstract

A novel airborne radar-based precision approach concept was developed and flight tested as a part of NASA's Rotorcraft All-Weather Operations Research Program. A demonstration, transponder-based beacon landing system (BLS), incorporating state-of-the-art X-band radar technology and digital processing techniques, was built and flight tested to demonstrate the concept feasibility. The BLS airborne hardware consists of an add-on microprocessor, installed in conjunction with the aircraft weather/mapping radar, which analyzes the radar beacon receiver returns and determines range, localizer deviation, and glide slope deviation. The ground station is an inexpensive, portable unit which can be quickly deployed at a landing site. Results from the flight test program show that the BLS concept has a significant potential for providing rotorcraft with low-cost, precision, instrument approach capability in remote areas.

Introduction

Advanced airborne-radar approach (ARA) concepts are being developed and evaluated as a part of NASA's Rotorcraft All-Weather Operations Research Program. A self-contained navigation system that requires minimum ground-based equipment is of interest because it would make possible the full exploitation of the helicopter's unique capability of remote-site, off-airport landings. In pursuing this goal, NASA Ames Research Center is conducting cooperative research with the University of Nevada, Reno (UNR), to develop ARA concepts in which airborne weather/mapping radar is used as a primary navigational aid for helicopter approaches and landings in instrument flight rules (IFR) conditions. In the first phase of this effort, the detection of passive ground-based corner reflectors using a device called an echo processor was successfully demonstrated (1). Use of this passive-reflector detection scheme in the overland environment provides the pilot with a target on his radar display, and gives him the range and bearing information necessary for a nonprecision approach to the landing site.

Expanding on the echo processor technology, a second phase of the NASA/UNR research program was undertaken with the objective of developing and demonstrating the feasibility of a weather radar-based precision approach concept. The feasibility criteria for this concept included 1) minimal, passive or battery-powered ground-based equipment; 2) the same pilot technique for flying the approaches as for instrument landing system (ILS) approaches; and 3) airborne weather/mapping radar modifications that could be accomplished as inexpensive retrofits for current civil radar systems.

To meet these objectives, a concept was pursued whereby an array of specially designed directional passive reflectors oriented along the localizer track would provide the directional signals necessary to derive ILS-type guidance. Using an onboard digital microprocessor installed in conjunction with the airborne weather radar, glide slope and localizer guidance would be calculated and displayed to the pilot on his existing ILS course-deviation indicator (CDI). The reflector-based ground station would need no ground power, but would require 1.2 to 1.8 km (4,000 to 6,000 ft) of terrain for installation of the reflector array when used in conjunction with civil weather/mapping radar systems. Although this requirement would not be a problem for aircraft landing on conventional runways, it would be impractical for heliports.

An alternative to the radar reflector array, a radar transponder-based ground unit, has proven to be much more practical. An X-band transponder beacon with multiple-pulse reply capability was modified to reply through an array of directional antennas. The beacon-based ground station can be packaged in a small, inexpensive, battery-powered, portable unit.

This beacon landing system (BLS) concept has significant potential for a large number of applications. It differs from other portable landing system concepts in that the airborne radar is actively used to interrogate and receive ground station signals. Thus, distance to the landing site is inherently available onboard the aircraft. Also, the ground station power requirements are small, because of the pulse-type replies of the ground station instead of the continuous wave (CW) mode of operation used in other landing systems. This paper describes the BLS concept, the concept demonstration hardware, and the flight tests conducted to verify the design principles.

Concept Description

The BLS concept represents a combination of advanced digital signal processing techniques and X-band radar systems. Many of the same operating

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principles are used for a standard ILS, with important differences being in the carrier frequency and beam-discrimination methods. The following sections describe the operating theory and the concept demonstration hardware built to validate the feasibility of a weather radar-based precision approach system.

Landing System Concepts

The weather radar precision approach concept operates on the principle of four overlapping, narrow radar beams oriented left, right, above, and below the desired flightpath. The sketch in Fig. 1 depicts the two glide slope beams, oriented above and below the desired flightpath. With this beam orientation, as the aircraft deviates from the desired flightpath, one signal increases in amplitude and the other decreases. When all four signals are of equal intensity, the aircraft is on course. Glide slope deviation from the desired course is proportional to the difference in received signal strength of the up-down beams, and localizer deviation is similarly derived using the left-right beams.

A survey shows that two basic types of precision approach systems are used: fixed-beam systems and scanning-beam systems (2). Fixed-beam systems,

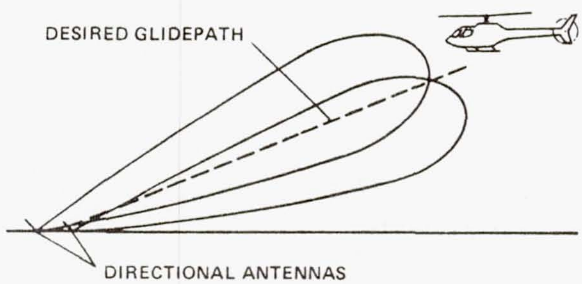

Fig. 1 Overlapping directional antenna beams provide course guidance.

including ILS and BLS, provide a single approach corridor, whereas scanning-beam systems, such as the microwave landing system (MLS), have the added flexibility of pilot-selectable approach paths (3). A summary of ILS, MLS, and BLS characteristics is shown in Table 1. Although ILS and BLS are both fixed-beam systems, there are important differences between the two. First, the carrier frequency for the ILS beams is two orders of magnitude lower than for the X-band BLS. Since antenna size to achieve a given beam width is inversely proportional to carrier frequency, the high frequency of the BLS makes it possible to use small antennas at the ground site. Second, the techniques for discriminating between the four beams are very different. For ILS, the ground signals are transmitted on a CW basis, and they are tone-modulated for purposes of discriminating between the beams. The BLS makes use of the multiple-reply capability of X-band ground transponder beacons, incorporating a high-speed switching circuit to transmit the time-sequenced replies through the four directional antennas. The onboard microprocessor installed in conjunction with the airborne weather/mapping radar can then discriminate between the four directional guidance beams based on the time sequencing of the pulses. Unlike other landing systems, the BLS is a transponder-based system, and range to the ground station is inherently available. Other landing systems require co-located DMEs or marker beacons to provide the pilot with range fixes.

Ground-Based System

The ground station (Fig. 2) consists of a modified X-band radar transponder beacon with multiple-reply capability. Normally, the first reply is used to identify position, and additional time-sequenced replies are used for identification. In a standard beacon, all replies are transmitted through an omnidirectional antenna. Power for the beacon is either 28 V dc or 50-60 Hz, 120 V ac. With the BLS

Table 1. Comparison of landing systems

System characteristics	ILS	MLS	BLS
Frequency	100 MHz - LOC 300 MHz - GS	5000 MHz	9400 MHz
Antenna size	Large	1.8 to 3.6 m (6 to 12 ft)	0.6 to 1.2 m (2 to 4 ft)
Guidance beams	Fixed: up, down, left, right	Scanning	Fixed: up, down, left, right
Signal characteristics	CW, tone-modulated	Interrupted, CW	Transponder using sequential pulses
Derivation of guidance	Beam amplitude comparison	Time between signal peaks	Beam amplitude comparison
Range data	Requires co-located DME or marker beacons	Requires co-located DME or marker beacons	Inherently available
Airborne equipment	Widely installed	Must be added	Minimum retrofit for radar-equipped aircraft

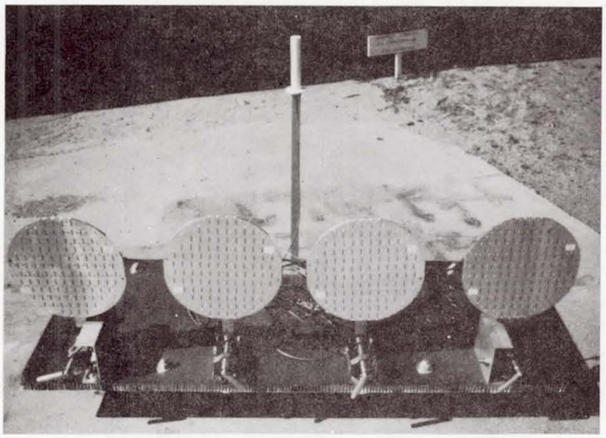

Fig. 2 Landing system ground station.

concept, the beacon is modified to the extent that a logic circuit is added into the normal beacon receiver video and modulator lines. This logic circuit is used to control both the beacon transmissions and a single-pole, five-position, solid-state microwave switch connected to the beacon transmitter. The switch allows sequential transmission of beacon reply pulses from five different antennas for each interrogation. The logic operates as follows. In the absence of an interrogating signal from an airborne weather radar, switch position 1 is selected, connecting the beacon to an omnidirectional antenna. Upon interrogation, the first reply pulse is transmitted through this omnidirectional antenna, providing a standard beacon-type 360° coverage reply for general landing site identification. After the first reply pulse, the logic circuit sequentially switches five beacon identification pulses, four to the four directional antennas, respectively, and one back to the omnidirectional antenna. The purpose of the last omnidirectional pulse is to provide a pulse spacing between it and the first pulse that positively identifies the station. The net result of this process is the radiation of six pulses, the first from the omnidirectional antenna followed by four directional pulses, followed by another omnidirectional pulse.

As seen in Fig. 2, the four directional antennas used for the demonstration BLS ground station are standard 30 cm (12 in.), weather radar flat-plate antennas. These antennas were chosen because of their low cost and availability, but testing has revealed some multipath problems associated with such small antennas. Currently, a trade-off study of antenna size versus system performance is being conducted, the initial results of which indicate that BLS antennas 60 to 120 cm (2 to 4 ft) in diameter would be best. Also, a single antenna with four appropriately oriented feed horns should replace the four separate directional antennas used for the concept demonstration ground station.

For test purposes, the BLS ground station pallet (Fig. 2) was placed on the ground and leveled laterally using an inclinometer. Localizer alignment was accomplished by sighting along the edge of the pallet, and glide slope alignment by tilting the pallet longitudinally using the inclinometer.

Airborne System

The weather/mapping radar used for the BLS demonstration flight tests is typical of radars installed for offshore operations. The radar is an X-band (9375 MHz), color radar, with an average pulse power of 8 kW and a pulse repetition rate of 121 pulses/sec. The radar can be operated in a primary mode, beacon mode, or a combined radar and beacon mode. For BLS testing, the normal 46 cm (18 in.) flat-plate antenna was replaced with a very small, non-scanned, wide-beam antenna. For a production system, an antenna switch would be provided to allow use of the normal 46 cm (18 in.) antenna for weather/mapping radar functions and the fixed wide-beam antenna for BLS approaches.

The BLS processor is designed to interface easily with the airborne weather/mapping radar, as shown in the installation diagram, Fig. 3. The processor is an 8086-based microprocessor with A/D (analog-to-digital) and D/A converters. Two signals, the beacon-receiver video and the modulator trigger, are input to the BLS processor from the radar receiver/transmitter (R/T) unit; and an automatic gain control (AGC) voltage is returned to the R/T. The BLS processor analyzes the beacon video signal to calculate range, localizer deviation, and glide slope deviation. Localizer and glide slope deviations are displayed to the pilot on an ILS-type CDI. Although the range information is available within the processor, it was not displayed during the flight test program.

System Operation

This section describes the concept demonstration BLS equipment in operation. Figure 4 shows a plot of the overlapping antenna beam patterns for the BLS ground station. The 30 cm (12 in.) ground station antennas have an 8° beamwidth and the beams are oriented ±3° from the desired course for localizer and glide slope. With this ±3° beam orientation, the minimum glide slope possible is about 4°. Lower glide slopes could be achieved using larger ground

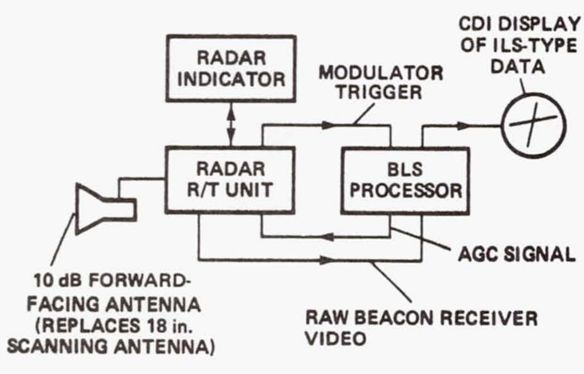

Fig. 3 Airborne system.

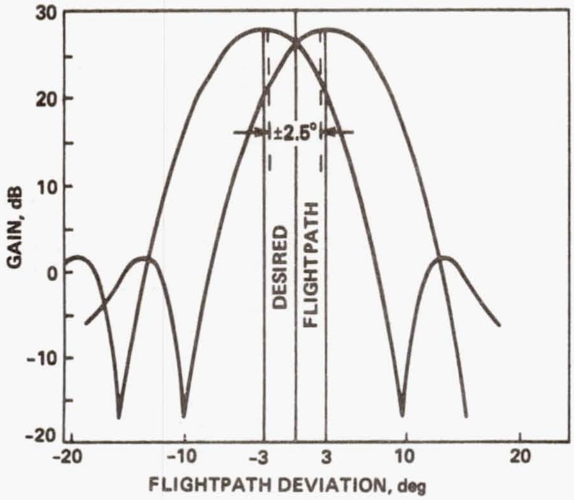

Fig. 4 Overlaid antenna patterns (±3° from course centerline).

station antennas and aligning the beams more closely with the desired course. Figure 5 shows an oscilloscope trace of the airborne beacon receiver video with the six BLS reply pulses spaced at 6 µsec intervals. The 8086 microprocessor is programmed to search this radar return for the two omnidirectional radar pulses 30 µsec apart. When consistent omnidirectional returns are received, the first is tracked and range gates are opened at each directional pulse location to measure signal strength. The first omnidirectional pulse is also used to adjust the AGC voltage, keeping the radar receiver in its linear range and ensuring that side lobes of the directional precision guidance antennas do not

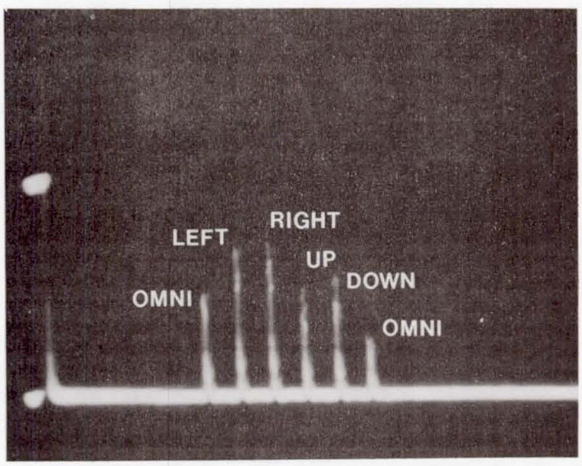

Fig. 5 Received beacon video signal onboard the test aircraft.

generate false courses. For each guidance signal pair, the signal amplitudes are differenced, scaled, and filtered for output to the CDI.

The filter in the BLS microprocessor is a recursive digital filter of the form

$$\bar{x}_t = \frac{50\ \bar{x}_{t-1} + x_t}{51}$$

where $\bar{x}$ = filtered localizer (or glide slope) deviation, and x = unfiltered deviation at time t. This filter has a time constant of 0.42 sec, given the radar pulse-repetition rate of 121 pulses/sec. Also, the ILS-type CDI indicator applies additional filtering to the BLS microprocessor output signals before displaying the course deviations to the pilot. The sensitivity of the BLS CDI is ±3.4° for the localizer and ±2.2° for glide slope.

Flight Test Program

The BLS flight test program had the following objectives: 1) to demonstrate the operational feasibility of flying precision helicopter approaches using the BLS, and 2) to measure the navigational performance achieved with the concept demonstration BLS hardware. The operational feasibility of the BLS was evaluated based on pilot comments and pilot tracking performance achieved during BLS approaches. Following system checkout and demonstration flights, five data flights were made, allowing three test pilots to evaluate the system. The flight test and test results are described below.

Aircraft

The test aircraft was an IFR-equipped Sikorsky SH-3G helicopter, the military equivalent of the S-61N. The SH-3G is a twin-turbine, five-bladed, single-rotor helicopter with emergency amphibious capabilities. The aircraft has a flying boat hull and two outrigger sponsons, into which the main landing wheels can retract. The rotor diameter is 19 m (62 ft), the gross weight is 8,660 kg (19,000 lb), and maximum airspeed is 120 knots. During flight testing, two pilots, the aircraft crew chief, and one to three experimenters were aboard. Experimental equipment and data acquisition system equipment were mounted on a rack in the cargo area.

Test Locations

The SH-3G helicopter was based at the NASA Ames Research Center, Moffett Field, California. System checkout and initial evaluation flights were made at Moffett Field, and quantitative data collection flights were made at the Crows Landing NALF, Patterson, California. The NASA Ames Flight Systems Research Facility at Crows Landing, equipped with radar tracking systems, a data telemetry receiver, and ground-based data monitoring and recording equipment, was used to record quantitative data to analyze BLS performance.

Approach Procedures

The approach procedures were similar to those used for standard ILS approaches. TACAN bearing and distance were used to position the aircraft for BLS intercept. Following acquisition of the BLS guidance, the warning flags on the BLS CDI would disappear, and the pilot intercepted and tracked inbound on the BLS course. On system checkout and demonstration flights at Moffett Field, the BLS ground station was located near the approach end of runway 32R, and approaches were made parallel to the runway 32 approach corridor. Glide slopes ranging from 4° to 9° were demonstrated. At Crows Landing, most of the approaches were made with the BLS ground station located 200 ft left of the runway 35 centerline and near the STOL runway threshold. This location allowed excellent tracking system coverage throughout the approaches.

Flight Test Results

The quantitative flight evaluation of the BLS was accomplished during a series of five flights. On three of the five flights (flown by three different pilots), each pilot flew under simulated instrument meteorological conditions (IMC) and was instructed to track the BLS localizer and glide slope CDI down to a decision height of 100 ft. Approaches made during these flights were used to obtain pilot comments on the system, as well as to obtain data on the overall tracking performance achievable with the BLS. The remaining two data flights were used to investigate the navigation accuracy of the BLS by flying a series of approaches with large excursions in both localizer and glide slope from the BLS approach path.

Figure 6 shows a typical view of the helicopter as it approaches the battery-powered BLS ground station on an approach. Note that during this flight test program, the omnidirectional ground station antenna was replaced with a directional antenna in order to match signal strengths at the airborne receiver. For a production system, the power radiated from the omni antenna would be about 25 dBm greater than that transmitted from the directional antennas. Testing to date has demonstrated BLS guidance intercept at ranges out to 17 n. mi. and glide slopes ranging from 4° to 9°. For quantitative evaluation, a 6.6° glide slope was used with localizer intercept 5-6 n. mi. out from the ground station.

Pilot Comments

Pilot comments on the BLS have been favorable and enthusiastic, confirming the operational feasibility of a BLS. Pilot workload and piloting techniques were like those of ILS approaches. Since localizer and glide slope intercepts and course tracking used standard ILS techniques, pilot acceptability of the BLS approaches was excellent, and pilot training on BLS approach procedures was minimal. One deficiency noted by the pilots was that the localizer needle became too sensitive during approximately the last mile of the approach. This was caused by the combined effect of a co-located localizer/glide slope ground transmitter and a localizer CDI presentation based on angular deviation, with full-scale needle deflection representing ±3.4° from course centerline. The pilots recommended use of a constant-width localizer algorithm instead of an angular deviation algorithm for the last part of the approach. Since range information is available within the BLS microprocessor, this type of algorithm can easily be implemented for future testing.

Pilot Tracking Performance

During the three data flights on which the pilots were flying under simulated IMC conditions, a total of 25 approaches were made. Composite plots showing the lateral and altitude tracks are shown in Figs. 7 and 8, respectively. Figure 9 shows the one-sigma standard deviations of localizer cross-track errors achieved during this BLS testing. Also shown are the comparable envelopes for 6° glide slope MLS approaches (Fig. 14 in Ref. 4) and ARA approaches to oil rigs both with and without automatic target-tracking equipment (5). The one-sigma standard deviations from glide slope for BLS and MLS approaches are shown in Fig. 10. (Note that since ARA approaches are nonprecision approaches, there is no glide slope tracking data for comparison.) These envelopes show that the tracking performance achieved with the concept demonstration BLS was excellent, far exceeding that previously achieved for civil ARAs and comparable to that achieved on MLS approaches.

BLS Navigation Accuracy

The second objective of the test program was to identify the navigation accuracy achieved with the demonstration BLS equipment. Although this equipment was not optimized for accuracy, studies of the system errors are proving useful for further development of the BLS concept. Navigation errors identified to date include bias errors, signal multipath effects, and time lag effects.

Bias errors, particularly in the localizer course, resulted from two sources: alignment of the directional antennas on the BLS ground station with respect to each other and alignment of the BLS ground station with respect to the desired approach course. For glide slope, use of the inclinometer for setting the ground station pallet at the desired glide slope was repeatable within ±0.1° over the five data flights. However, the alignment of the ground station glide slope antennas was 0.6° above the reference plane of the ground station pallet. Set up of the localizer course by siting along the edge of the ground station pallet was less accurate, and localizer course biases of up to ±2° occurred. For future systems, an improved localizer alignment siting method should be incorporated into the ground station.

Another problem, identified early in the test program, was with multipath, particularly in the glide slope signals. The glide slope exhibited some waviness which was worse at the lower glide slopes. Subsequent ground tests confirmed some nonlinearities in the approach course attributable to multipath phenomena. These multipath errors were reduced by installing a small radar fence, 4.6 m (15 ft) in front of the ground station. Currently, studies are

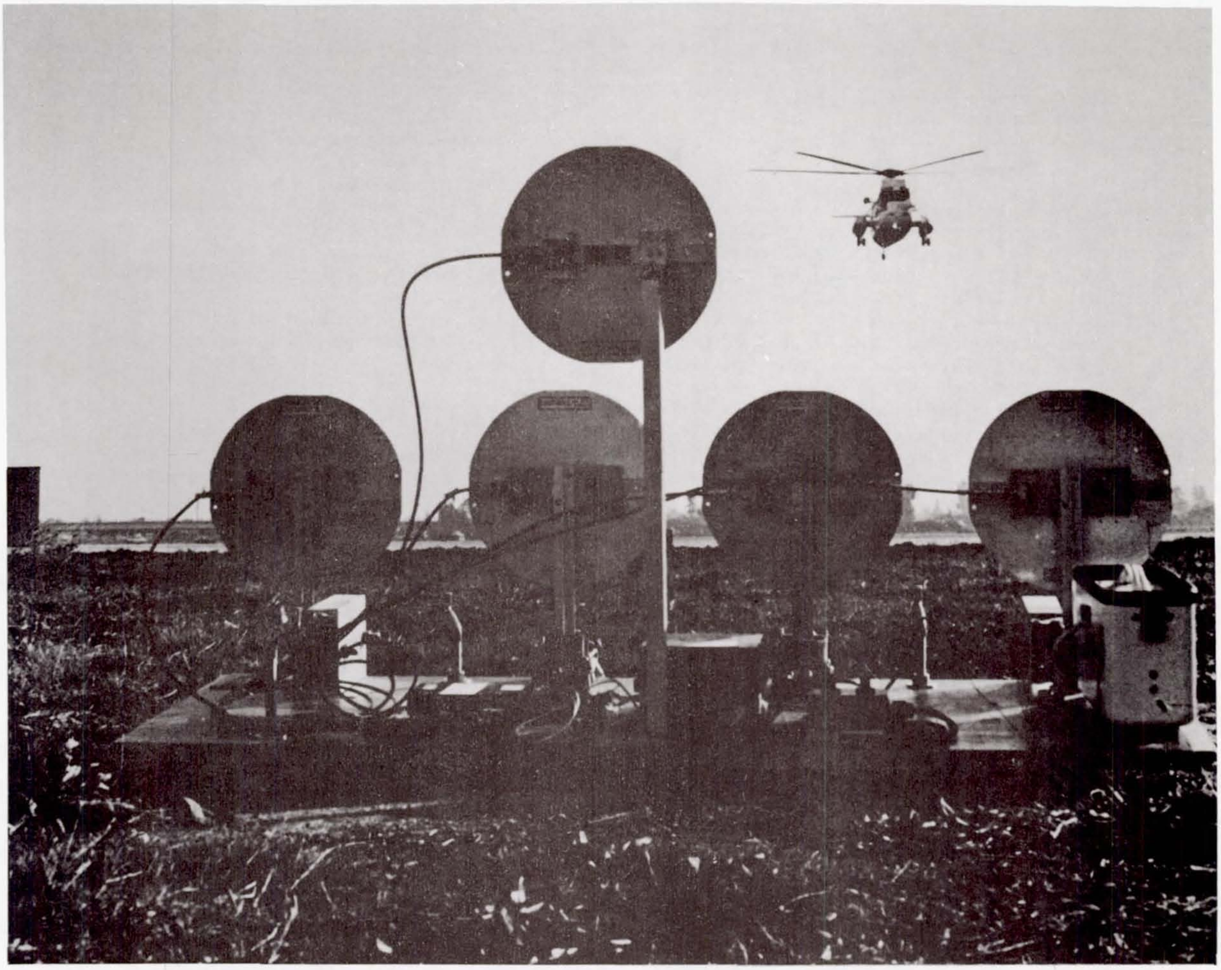

Fig. 6 BLS flight demonstration on short final approach path.

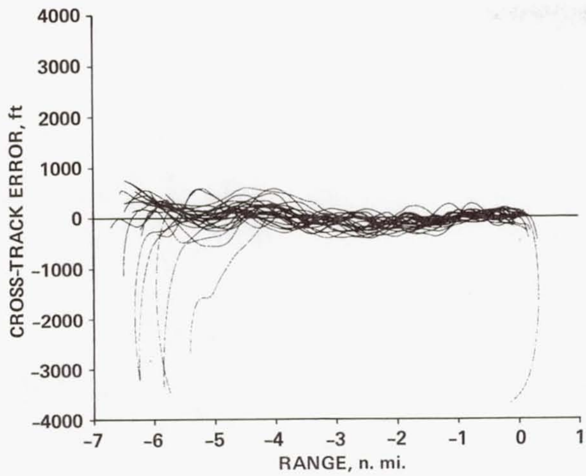

Fig. 7 Composite of x-y tracks on BLS approaches.

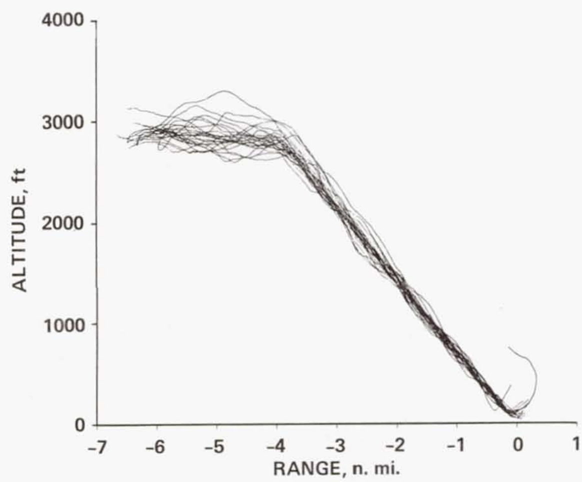

Fig. 8 Composite of altitude profiles on BLS approaches.

in progress to reduce the multipath errors by using larger ground station antennas — antenna diameters of 60-120 cm (2-4 ft) instead of the 30 cm (1 ft) antennas used in the concept demonstration BLS.

In analyzing the test data, it was noted that the BLS signals lagged the aircraft position by 2.0 sec, whereas the microprocessor filter on the BLS guidance signals should have resulted in a lag of about 0.4 sec. Subsequent checks of the airborne equipment revealed a software error in the filtering algorithm, resulting in a 2.0-sec time constant rather than the design time constant of 0.42 sec. Since the CDI time constant is about 2.5 sec, the additional filtering in the BLS microprocessor had no adverse impact.

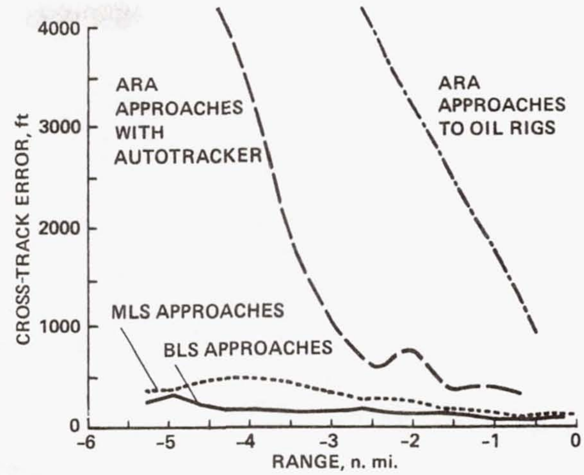

Fig. 9 Standard deviation of cross-track errors for various types of approaches.

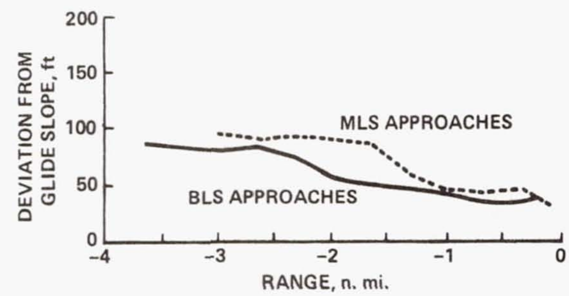

Fig. 10 Standard deviation of glide slope errors for BLS and MLS approaches.

Independent of the bias and lag BLS errors, the one-sigma navigation accuracy achieved with the concept demonstration BLS was ±0.22° in localizer and ±0.14° in glide slope. Figures 11 and 12 show composite data from the flight tests, comparing the localizer and glide slope positions calculated by the BLS with the actual localizer and glide slope deviations as determined using the tracking radar. These navigation accuracy data points were taken over a period of 3 weeks on four separate data flights.

Conclusions

A novel weather radar-based precision approach concept has been successfully developed and demonstrated in flight tests. This concept appears to have significant potential for both civil rotorcraft operations and certain military missions in which remote-site precision landing systems are required. The portability and low power consumption of the BLS ground station also make the concept attractive for emergency and rapid deployment missions that require

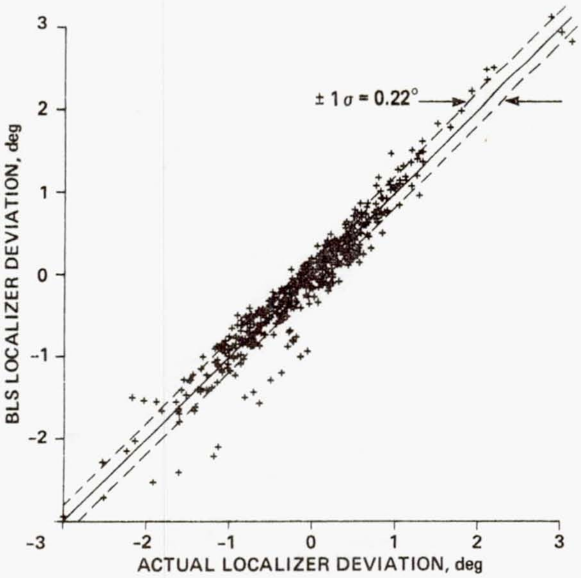

Fig. 11 Composite showing BLS localizer navigation accuracy.

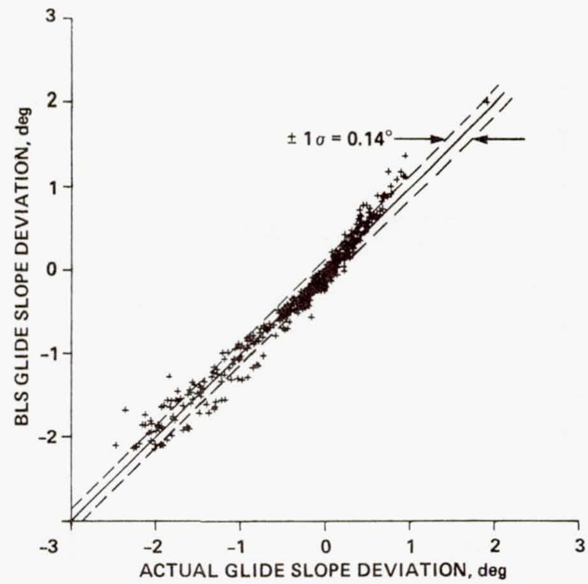

Fig. 12 Composite showing BLS glide slope navigation accuracy.

precision approach capability. Specific project conclusions are as follows:

1) The BLS X-band ground station is portable, compact, inexpensive, light weight, and battery powered.

2) Pilot workload and technique for BLS approaches are similar to those in conventional ILS approaches.

3) ILS-type guidance can be derived using a small microprocessor, easily interfaced with airborne weather/mapping radar.

4) Approach cross-track errors using the BLS are far smaller than those achieved previously for civil ARAs and comparable to those achieved on MLS approaches. Glide slope tracking errors using the BLS are also comparable to MLS.

5) One-sigma navigation accuracy achieved with the concept demonstration BLS equipment was ±0.22° in localizer and ±0.14° in glide slope with bias errors of less than ±2.0° for localizer and ±0.1° for glide slope.

6) Future development and testing should include ground stations using a single antenna with multiple feed horns; trade-off studies of ground station antenna sizes; and incorporation of constant-width localizer algorithms at close range in order to reduce the close-in localizer sensitivity.

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16. Abstract

A novel airborne radar-based precision approach concept was developed and flight tested as a part of NASA's Rotorcraft All-Weather Operations Research Program. A demonstration, transponder-based beacon landing system (BLS), incorporating state-of-the-art X-band radar technology and digital processing techniques, was built and flight tested to demonstrate the concept feasibility. The BLS airborne hardware consists of an add-on microprocessor, installed in conjunction with the aircraft weather/mapping radar, which analyzes the radar beacon receiver returns and determines range, localizer deviation, and glide slope deviation. The ground station is an inexpensive, portable unit which can be quickly deployed at a landing site. Results from the flight test program show that the BLS concept has a significant potential for providing rotorcraft with low-cost, precision, instrument approach capability in remote areas.

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