TECHNICAL DEVELOPMENT REPORT NO. 326

PRELIMINARY EVALUATION OF THE BELL AIRCRAFT AUTOMATIC LANDING SYSTEM

FOR LIMITED DISTRIBUTION

October 1957

CIVIL AERONAUTICS ADMINISTRATION
TECHNICAL DEVELOPMENT CENTER
INDIANAPOLIS, INDIANA

EQUIPMENT

General.

The Bell Aircraft automatic landing system is comprised of a servo loop containing a precision tracking radar, a flight path computer, and data link, all of which are installed on the ground. A data-link receiver, automatic approach coupler, and an automatic pilot are required in the aircraft. In operation, the radar detects and tracks the aircraft and furnishes position information to the computer. The computer compares this information with the desired flight path, and passes correction signals in the form of lateral and vertical commands to the data-link transmitter. The data-link system transmits these correction signals to the aircraft, and the aircraft receiver, in turn, feeds them to the automatic pilot through the approach-coupler system. The automatic pilot performs the necessary corrections in the aircraft position, thereby completing the servo loop. Figure 1 illustrates the principles of system operation.

Radar.

The radar operates at 36,000 Mc and employs a 4-foot parabolic reflector which produces a beam width of 0.5°. The pulse width is 0.2 microsecond at a rate of 2,000 pulses per second (pps). A conical scan at 50 cycles per second (cps) is employed for greater precision in tracking. The conical scan is produced by feeding energy from the transmitter through a circular waveguide which is contained in the shaft of the scan motor. At the end of the waveguide, and directed at the reflector, is an eccentric aperture from which the reflector is illuminated. The decentered lobe of radiation thus scans conically about the axis of the reflector. The radar transmitter uses a magnetron, and the local oscillator uses a klystron. Range, azimuth, and elevation tracking circuitry are essentially conventional. Primarily because of the high resolution of the system, it is desirable to install a small corner reflector (approximately 10 inches on a side is adequate) on the aircraft. This is done to provide a predominate reflection point on the aircraft. In the absence of such a point, the radar is prone to oscillate between two or more points of strong reflection; for example, between the several engines of a multiengine aircraft.

During the period of the tests there was no significant rainfall. It is reported by Bell engineers that the system operates satisfactorily in rainfall up to 10 millimeters per hour. To increase immunity to precipitation further, a new antenna, which optionally provides linear or circular polarization, is under development. One case of a completely successful landing to touchdown in a driving snowstorm was reported by Bell engineers.

Computer.

The computer receives aircraft position in three-dimensional polar coordinates from the radar with range information corrected from slant range to horizontal range. These dimensions are converted to rectangular form and corrected for radar offsets from the desired touchdown point in all three dimensions. An additional correction may be inserted to compensate for the height of the corner reflector above the ground at touchdown. Other functions performed by the computer include limiting the maximum command signals which can be transmitted, reducing this maximum limit at a preselected distance from the touchdown point, and providing increased sensitivity as the aircraft proceeds along the landing path toward touchdown. Basically, the computer, an analog type, compares the position of the aircraft with the desired track as determined by the above and other considerations, and sends correction signals of the proper type to the data-link transmitter.

Data Link.

The type of data link employed is not critical to system operation and any of several types of data links may be, and have been, employed. Obviously, if the system ultimately is to be universal, either a standard data link must be developed or there must be sufficient flexibility in ground data-link transmitting equipment to accommodate the data-link system installed in the aircraft. The data link employed in these tests made use of two transmitters on the ground, tuned to the glide slope and localizer frequencies, respectively. Radiation from these transmitters was essentially omnidirectional and each was modulated with the proper ratio of 90/150-cps control voltages as determined by the correction signals from the computer. In this manner any aircraft equipped with localizer and glide-slope receivers may be landed with the Bell landing system. If the aircraft is not equipped with an automatic pilot, the landing may be performed manually by visual reference to the crosspointer instrument. In addition, it is possible for a ground controller to "talk down" the pilot as in GCA or PAR operation. In this case, there is no data-link requirement other than the voice communication channel.

TEST RESULTS

Flight Tests.

A total of 29 approaches were made on the system, 20 of them with the Center's DC-3 aircraft N-181, 4 of them in a DC-3 aircraft owned by Safe Flight Instrument Corporation, and 5 in a Cessna Model 310 airplane. A number of approaches were started but not completed due to traffic wave-offs and other causes not involving malperformance of the landing system. Of the approaches completed, 16 of those performed in N-181 were successful to touchdown, 3 of those conducted in the Safe Flight aircraft were successful to touchdown, and 3 of those conducted in the Cessna 310 were successful to touchdown. The percentages of success are shown in Table I.

TABLE I

PERCENTAGE OF SUCCESSFUL APPROACHES

	Approaches Completed	Touchdown	No Touchdown	Percentage Successful
N-181	20	16	4	80
Safe Flight	4	3	1	75
Cessna 310	5	3	2	60
Total	29	22	7	75.8

There follows a chronological description of the different approaches based on the comments of an observer in the aircraft.

RECORD OF AUTOMATIC LANDINGS MADE ON BELL SYSTEM AT NIAGARA FALLS AND BUFFALO, NEW YORK AIRPORTS

The first flight was made August 19 in the Center's aircraft, N-181, with no corner reflector, using the ILS localizer frequency 109.3 Mc and glide-slope frequency 332.0 Mc as the data link. The first approach brought the airplane 75 feet to the right of the centerline of the runway, which indicated that possibly some of the controls were not set properly in the Bell trailer.

The second approach was made at 105 - 108 mph and a successful automatic landing was made to touchdown.

The third approach was made successfully to touchdown. The airspeed at contact was 90 mph.

During the fourth approach, the maximum deviation of the glide-slope indicator showed the aircraft to be 2 1/2 dots above the glide slope over a considerable portion of the approach. Airspeed over the runway was 96 mph. The automatic pilot was disengaged because the airplane was flared off approximately 5 feet above the runway, and then the control caused a dive which might have injured the landing gear.

On the fifth approach, the maximum deviation of the aircraft was 2 dots above the glide slope, approximately 3 miles from touchdown, corresponding to 20 feet above the glide slope at that point. The maximum deflection of the localizer pointer was one-half dot to the right, corresponding to 30 feet to the right of the runway. A landing was made 37 feet to the right of the centerline of the runway.

The sixth approach was made by deliberately intercepting the gate 600 feet to the right of the runway. The aircraft consistently flew 2 to 3 dots above the glide slope. By visual observation, the aircraft appeared to be approximately 0.3° to the right of the centerline of the runway. The aircraft landed approximately 30 feet on the right-hand side of the centerline of the runway, and a successful landing was accomplished.

Low amplitude but rapid oscillation of the radar antenna was noted on the ground. The antenna centers on the strongest radar target return which varied in random fashion between the two engines and the nose of the airplane. On the evening of August 19, a corner reflector, approximately 10 inches on a side, was installed in front of the airspeed indicator support. The corner reflector eliminated all of the oscillation on later flights.

On August 20, the seventh approach was made. An oscillation of 1 1/2 dots was observed on the glide slope. The localizer pointer gave a satisfactory indication. There was no flare in the glide slope and the aircraft was landed short with a hard landing, approximately 1.6 g.

The eighth approach was made with a plus- or minus-1 dot oscillation of the glide-slope pointer. The aircraft landed 15 feet to the right of the centerline of the runway, and a very smooth automatic landing was accomplished.

On the ninth approach, the aircraft was one-half dot under the glide slope at contact. An excellent landing was made with the localizer indicator centered; however, the landing was made 20 feet to the right of the centerline of the runway. The glide slope was smooth with no oscillation.

On the tenth approach, the aircraft landed 17 feet to the right of the centerline of the runway and the maximum glide-slope deviation observed was 1 1/2 dots, corresponding to 15 feet above the glide slope. The localizer indicator was centered during the entire approach. A successful landing was made even though the airspeed over the edge of the field was 130 mph.

On the eleventh approach, touchdown was accomplished 100 feet in front of the trailer after leveling off high and dropping down at the last minute. This was a successful approach.

On the twelfth approach, a successful landing was made; however, the aircraft landed 50 feet to the right of the centerline of the runway.

The thirteenth approach was made by disengaging the automatic pilot and making the approach entirely by manual control with the information fed to the localizer and glide-slope indicators. The approach on the localizer was good, however, the glide-slope flare caused ballooning. A successful landing was made.

The fourteenth approach also was made manually. The glide-slope indications were satisfactory, the localizer alignment was good, and a very smooth landing was made.

Next, flights were made in the Safe Flight aircraft, which was equipped with a Bendix PB-10 automatic pilot and a Safe Flight attitude automatic throttle control. On the fifteenth approach, the aircraft was "locked on" 400 feet to the left of the centerline of the runway at 109 mph. This average speed was maintained to contact; however, considerable oscillation was observed. Excessive aileron control occurred after passing over the edge of the field. A satisfactory landing was made.

On the sixteenth approach, the following observations were made in order to determine the effectiveness of the automatic throttle which was controlled by the aircraft attitude. The speed of both engines was maintained at 2,300 rpm. The information in Table II was recorded periodically.

TABLE II

AUTOMATIC THROTTLE CONTROL APPROACH DATA

Position on Approach	Airspeed (knots)	Manifold Pressure (inches water)
Approaching middle marker	-	26
Middle marker	105	16
	104	22
	102	25
	105	17
	100	13
	95	21
Inner marker	100	16

The aircraft let down to an altitude of 2 feet above the runway when aligned 30 feet to the right of the centerline of the runway. As a cautionary measure, a landing was not made. The temperature recorded at 1,300 feet MSL was 21° C.

The seventeenth approach was made entering the gate at 4 1/2 miles, 1,500 feet to the right of the centerline of the runway at 115 mph. The aircraft immediately banked to the left and picked up a heading which caused it to bracket the centerline of the runway. On the approach, the maximum deviation of the glide-slope command signals was 3 dots, indicating the aircraft was 30 feet above the glide slope. Excessive banking occurred over the runway, however, a satisfactory landing was made.

The eighteenth approach was made by decreasing the amplitude of correction signals transmitted to the aircraft by a factor of 2 to 1. This resulted in a much smoother approach, with less oscillation and banking. A very smooth landing was made.

The next approaches were made in the Cessna N-310W.

The nineteenth approach was made intercepting the gate at 112 mph with 18.2 inches manifold pressure and 2,300 rpm. The glide was maintained at 100 mph with 13.8 inches manifold pressure and 2,300 rpm. The aircraft descended approximately one dot under the glide slope, with the localizer indications aligned with the centerline of the runway. A good automatic landing was made with flare on the centerline of the runway.

The twentieth approach was made entering the gate at 110 mph with 17.5 inches manifold pressure and 2,300 rpm. The descent down the glide slope was at 102 mph and with 13.5 inches manifold pressure and 2,300 rpm. The aircraft landed successfully on the centerline of the runway at 90 mph; however, the aircraft touched down rather hard.

The twenty-first approach was made entering the gate 2,100 feet to the right side of the centerline of the runway. The localizer course was bracketed without oscillation. The automatic pilot was extremely tight in its control, and aileron action was extremely fast. This was noted mostly between two and five miles from the airport. The control was much smoother from two miles to contact. A very smooth landing was made at 90 mph on the centerline of the runway.

Approaches 22 and 23 were abandoned due to extremely violent operation of the equipment, apparently caused by radar or servo failure in the ground equipment. This concluded the tests on August 20.

On August 21, the equipment was moved from the Niagara Falls Airport to the Buffalo Airport where tests could be conducted in conjunction with the standard ILS system.

The twenty-fourth approach was made manually on the ILS. The localizer alignment and glide slope were found to be good.

The twenty-fifth approach was made using the automatic approach coupler on the ILS from a distance of six miles to four miles. This automatically placed the aircraft in the center of the gate four miles from the end of the runway. The ILS receiver was changed from the localizer frequency 110.3-Mc channel to the data-link channel 109.3 Mc at the gate. When this change was made, the command signal showed two dots down, indicating that the aircraft was 20 feet above the Bell glide slope. This command pitched the aircraft downward suddenly; however, the aircraft bracketed the new localizer course and glide slope smoothly to make a successful smooth landing.

On the twenty-sixth approach, the same general procedure was followed; that is, the automatic pilot was engaged on the ILS six miles from the airport and flown to a point approximately three miles from touchdown. At three miles the Bell automatic landing equipment was engaged and a sudden down command of approximately four dots was given. The glide slope and localizer were bracketed and the flare was made; however, the flare was too high and the aircraft tended to pitch downward excessively at the end of the flare. No contact was made on this approach.

On the twenty-seventh approach, the automatic approach equipment was engaged with the ILS six miles from the airport. When the gate was entered at four miles, the Bell system was engaged, the aircraft pitched downward, bracketed the localizer course and the glide slope, and successfully landed itself on the centerline of the runway.

The twenty-eighth approach was made entering the gate at approximately four miles, locking on the Bell system. A very smooth landing was made on the centerline of the runway. At contact the command signal showed that the aircraft was receiving a 1 1/2 dot up command. This caused the nose to be in a nose-high attitude, which accounted for the very smooth landing somewhat short of the calculated touchdown point.

On the twenty-ninth approach, the maximum deviation of the aircraft was 1 1/2 dots above the glide slope after bracketing the glide slope and localizer course. No touchdown was made during this approach because the aircraft leveled off approximately 10 feet above the runway and was at this altitude when passing the trailer 40 feet to the left of the centerline of the runway. A very definite flare was observed; however, the aircraft seemed to fly approximately parallel with the surface of the runway for a long time while passing the Bell trailer.

The thirtieth approach was made but no touchdown was accomplished because left commands were being received when the airplane was approaching the runway, which would have caused one wheel to land off the runway.

Approaches were then made in the Cessna at Buffalo, but none of these was completed due to a defective radar unit in the Bell equipment. This concluded the flight tests at Niagara Falls and Buffalo.

DISCUSSION

General.

The ground equipment, with the exception of the basic radar and antenna, was housed in a trailer which also contained excellent provisions for recording continuously the performance of various system components and the actual position of the aircraft along the landing path in three coordinates. In addition, an X-Y recorder was used to provide a plot of distance versus altitude. Recordings produced by these devices exhibited close correlation with the observations of personnel in the aircraft with respect to both roughness and displacements. Command signals fed to the data-link transmitters also were recorded on the ground in terms of dots up or down and right or left. The commands as received in the aircraft were recorded simultaneously, and on one series of flights, range marks were superimposed on the ground and aircraft recordings simultaneously by means of voice communications. Using the range marks for correlation, the transmitted command signals were plotted on the same graph as the received command signals to determine the over-all faithfulness of the data link. Figures 2 and 3 are graphs of this type for localizer and glide slope, respectively, for a representative flight.

Acquisition.

During the tests described in this report, initial acquisition of the aircraft was accomplished manually. The system has more than adequate sensitivity to detect and track aircraft at ranges up to four miles and the acquisition gate can be set anywhere between this distance and distances as little as one mile. The procedure followed during these tests was as follows:

1. The pilot was instructed to fly to a point approximately 4 miles from touchdown at an altitude of 800 plus or minus 100 feet and requested to be within plus or minus 1,000 feet of the extended runway centerline.

2. As the aircraft proceeded at 800 feet altitude along the approach path, an observer on the ground, using an A-type display connected to the radar receiver output, positioned the antenna in both azimuth and elevation through use of calibrated control knobs adjacent to the display. Superimposed on the display was a range gate. When the aircraft target return was maximized and the target was at the leading edge of this gate, he would operate a "lock on" switch.

3. From this moment on, the radar antenna automatically tracked the aircraft, adjusting itself in both azimuth and elevation as the aircraft became decentered from the axial intersection of the conical scan. When the aircraft was "locked on" the pilot would be so advised by voice communication and requested to engage the automatic pilot. It is not recessary, of course, that the automatic pilot be engaged in order to provide continuous track information on the aircraft at the ground station; however, the servo loop is not completed until the automatic pilot has been engaged.

Obviously, a second landing aircraft cannot be handled until the preceding aircraft either has landed or executed a missed approach. This problem can be solved by the installation of a second radar and provision for an additional data-link channel. With an entry gate at four miles, approximately two minutes are required from the time the aircraft is engaged until it is released at touchdown. If a higher landing rate is desired, either a second system must be provided or the entry gate must be moved closer to the runway. In actual practice, an aircraft can be "locked on" successfully and brought to a satisfactory touchdown if its lateral position at the entry gate is considerably more than 1,000 feet off the extended centerline of the runway. The amount of offset which can be tolerated depends upon the distance of the entry gate and the characteristics of the airplane, a finite time being required to make gross corrections without excessive overshoot. Since the acceptable airspace limits of the entry gate are not large, it follows that a reasonably accurate guidance system must be provided to insure passage through the gate prior to the time that the landing system takes over. The CAA ILS is more than adequate for this purpose, and in most cases, it is believed that the current standard short-range navigation systems also are adequate.

Flare.

A particularly desirable feature of the Bell landing system is the provision for a flared landing. By appropriate adjustment of the flight path computer, substantial variations in glide-slope angles can be effected. During all flights conducted during the period of the tests covered by this report, the following glide-slope configuration was employed:

1. Three degrees from "lock on" to a distance of 2,500 feet from touchdown. This corresponds to an altitude of 48 feet.

2. One and three-quarters degrees from 48 feet altitude to 16 feet altitude.

3. Three-quarters degree from 16 feet altitude to touchdown.

Figure 4 illustrates the specific geometry of the glide slope from a distance of approximately 4,000 feet to touchdown.

During the flights at Buffalo where CAA ILS equipment also was available, automatic approaches prior to arrival at the entry gate were made on the ILS; and when the pilot was advised by the ground controller that the aircraft was "locked on", frequencies of the glide-slope and localizer receivers were changed to those employed by the Bell system data-link transmitter. In every instance, a strong down command was received at this transition point. This was to be expected, inasmuch as the initial glide slope of the Bell system was at the same angle as the ILS glide slope, and both systems were set up to employ the same touchdown point. Hence, incorporation of the final flare in the Bell system made it necessary that the 3° portion of the Bell glide slope fall lower in altitude than the ILS glide slope, as illustrated in Fig. 5A. If coincident glide slopes are operationally desirable up to the point of the initial flare, it would be necessary to move the touchdown point of the Bell system further down the runway as shown in Fig. 5B. An alternative method of providing coincidence of glide slopes at the transition point from one system to another would be to employ a slightly steeper glide slope on the Bell system and make the transition at the point of intersection of the two glide slopes as shown in Fig. 5C. In all flights at Buffalo Airport, the localizer transition was very smooth.

Fail-Safeness.

Considering the functions performed by the landing system and its flexibility and precision, the system is relatively simple, a fact which should contribute to over-all reliability. However, a number of observations made during this series of tests pointed up the need for some form of monitoring and introduction of fail-safe circuits where possible. Specifically, on one occasion the servo loop used for tracking the radar antenna in azimuth and elevation exhibited some sort of malperformance. This was during an approach being attempted in the Cessna 310 aircraft. This malperformance was manifested on the ground by circular oscillation of the radar dish, and in the aircraft by very violent up and down commands in rapid succession. It was reported by an observer in the aircraft that the aircraft attitude changed from -10° to +20° almost instantaneously and resulted in a stall-warning indication.

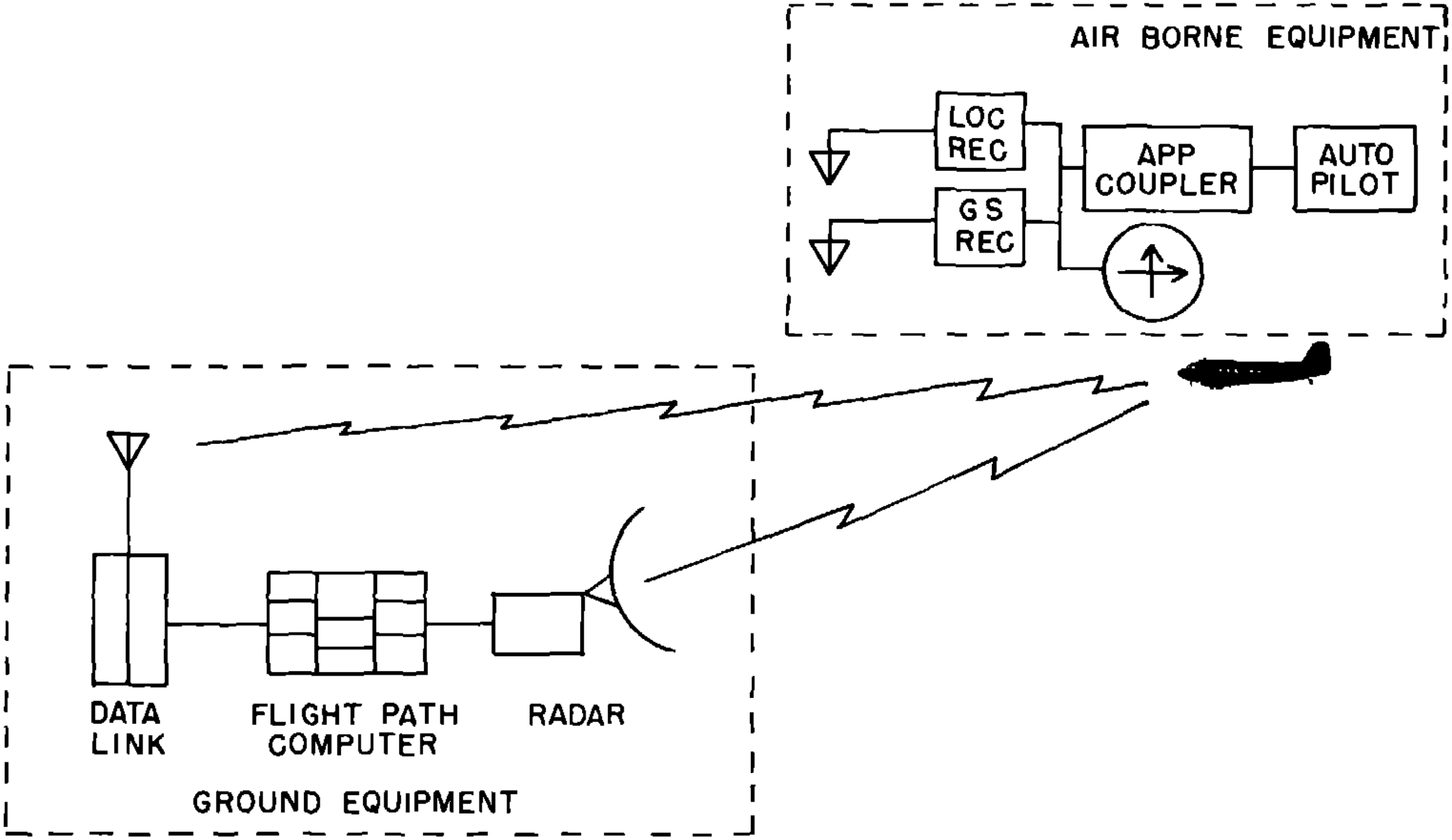
Fortunately, the aircraft was several hundred feet above the ground at this time. On another occasion, the pilot of N-181 was advised that he was "locked on" by the radar when in reality a second aircraft had been detected and "locked on" by the radar. Almost immediately it was apparent to both the ground controller and the pilot that a mistake had been made, however, circumstances can be imagined where such a mistake might go unnoticed.

CONCLUSIONS AND RECOMMENDATIONS

It is not possible at this time to arrive at other than the most tentative conclusions; however, on the basis of the tests herein described, the Bell landing system appears to possess an inherent precision superior to that provided by commonly used landing systems today. Among questions as yet not answered is the practicability of retaining this precision throughout the complete servo loop, particularly in the approach coupler and automatic pilot in the aircraft. Obviously, any new landing system intended for use within the Common System should be applicable to many types of aircraft. In general terms, the Bell landing system may be described as a system requiring minimum aircraft equipment. This is true only if the majority of already installed approach couplers and automatic pilots can control the aircraft position to the precision required, assuming valid command signals are supplied. If the differences in existing automatic pilots and differences in adjustment of the same model automatic pilots in different aircraft place a requirement for significant compensating adjustments on the ground on an individual aircraft basis, widespread acceptance of the system by aircraft operators is not likely. However, if the majority of automatic pilots and coupler units can be adjusted to a fixed set of standards compatible with the system, this technique appears to be practical as an automatic landing system.

On the basis of two manual approaches conducted to touchdown, the system is equal to existing systems in flyability during the earlier part of the approach path and better at altitudes below approximately 200 feet. Implementation as a manual system, although not requiring an automatic pilot, would require a data-link channel in the aircraft. It appears that this device could be relatively simple, perhaps operating on a communication channel through existing airborne receivers, with a small translator box at the output of the receiver for converting command signals to a form suitable for operating a crosspointer instrument. In aircraft already equipped with ILS, it is possible that one of the present ILS channels could be utilized as a data link similar to the manner employed in these tests.

Before firm recommendations can be made with regard to civil use of the Bell landing system, more exhaustive tests must be performed and studies must be conducted to determine the degree to which the service provided meets operational requirements and represents a substantial and progressive step in the solution of the over-all air traffic control problem. Particular emphasis should be placed on determining the susceptibility to precipitation, the practicability of introducing adequate monitoring and fail-safe features, and the problems associated with standardization of approach couplers. It is recommended that these tests and studies be conducted.



CAA TECHNICAL
DEVELOPMENT CENTER
INDIANAPOLIS INDIANA

FIG. I BLOCK DIAGRAM, BELL LANDING SYSTEM

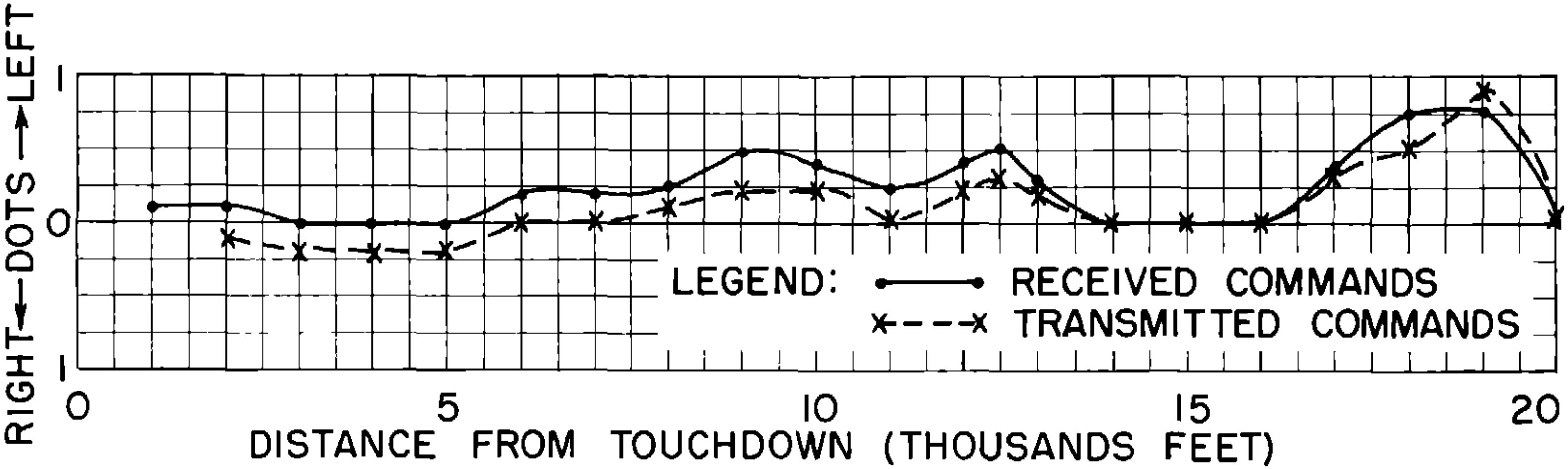
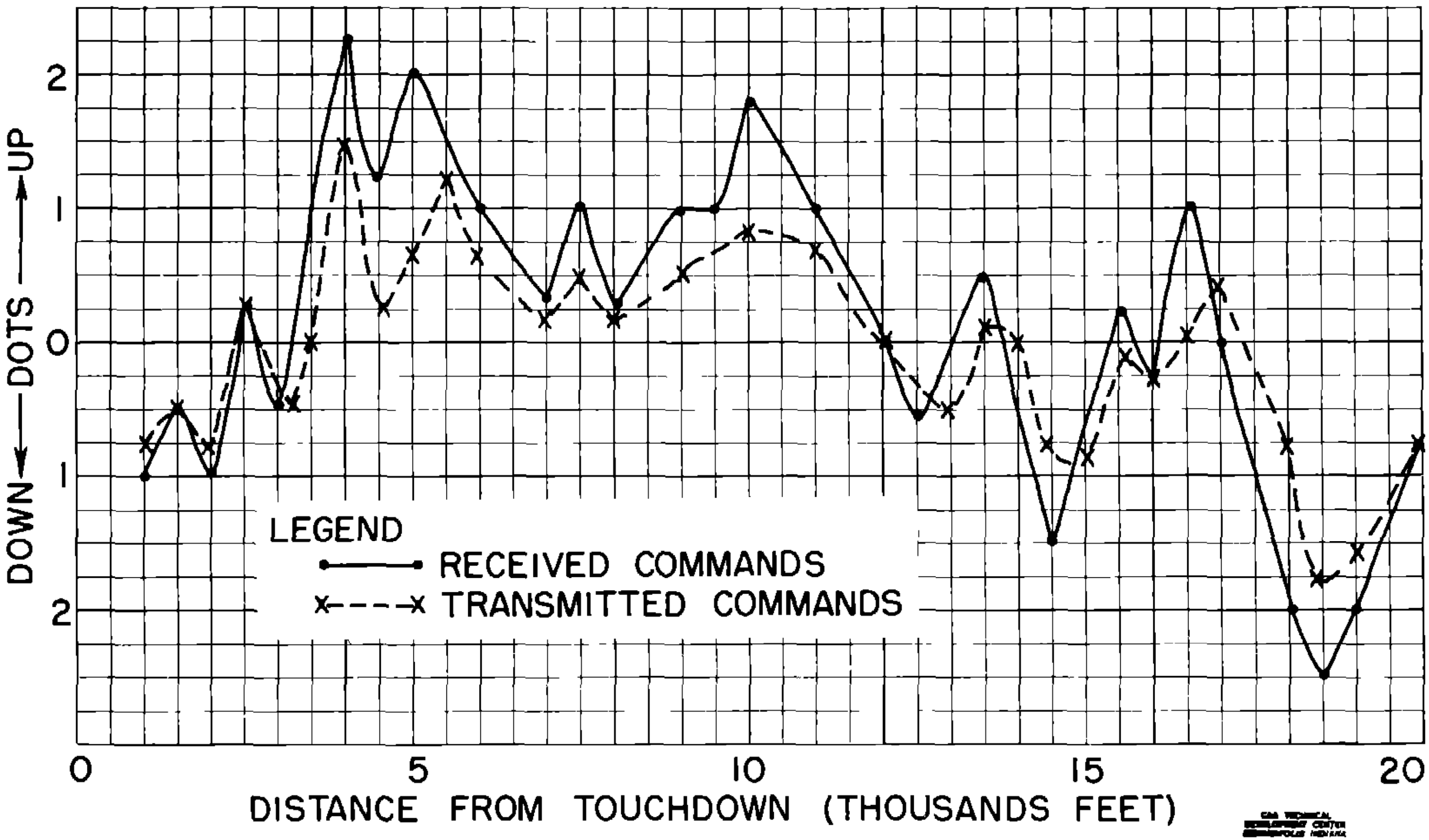


FIG 2 COMPARISON OF LOCALIZER COMMANDS TRANSMITTED AND COMMANDS RECEIVED



CAA TECHNICAL
DEVELOPMENT CENTER
INDIANAPOLIS INDIANA

FIG. 3 COMPARISON OF GLIDE SLOPE COMMANDS TRANSMITTED AND COMMANDS RECEIVED.

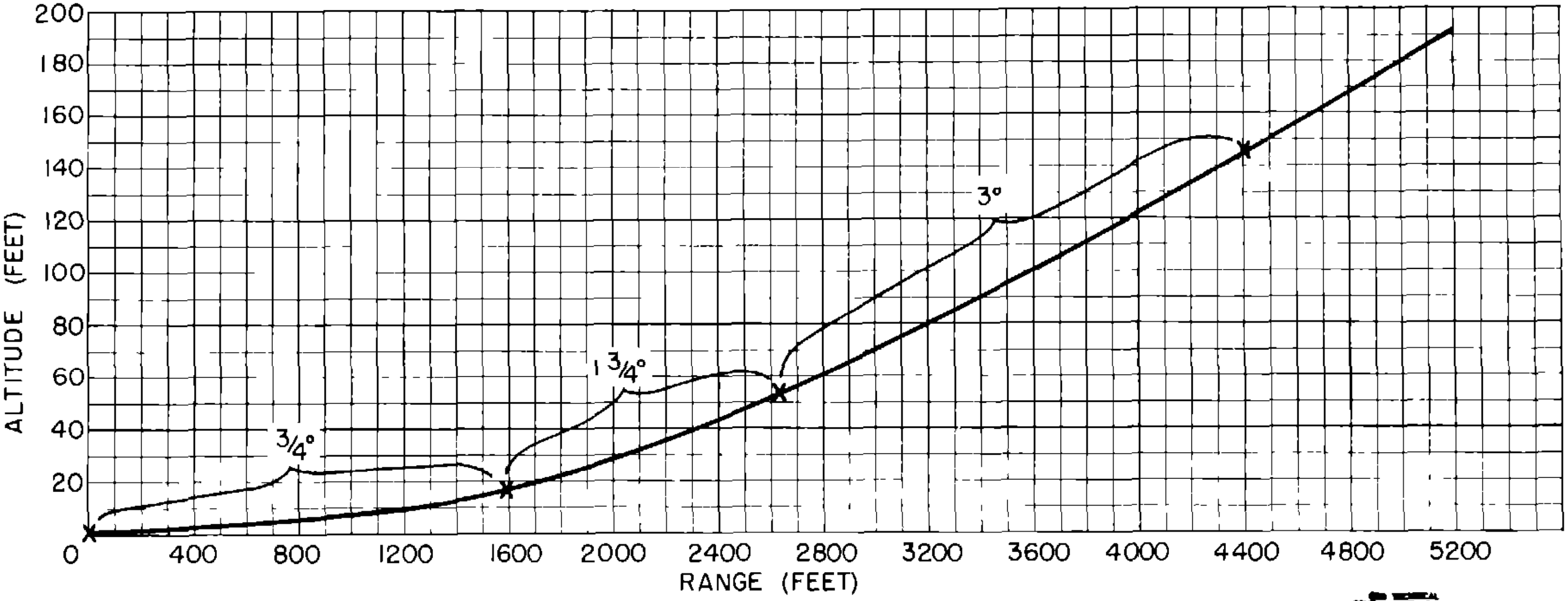
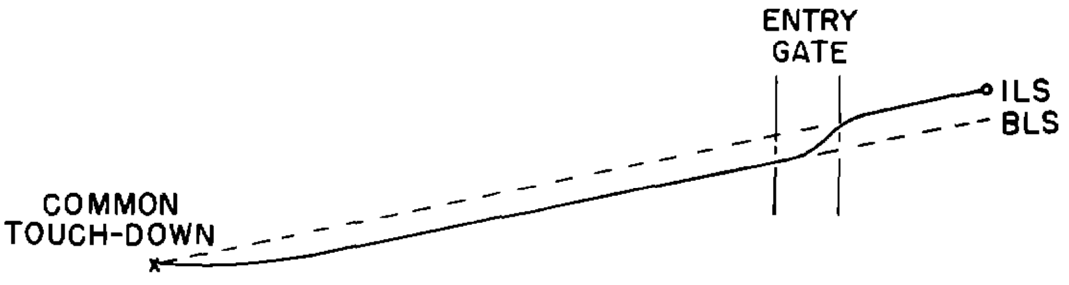
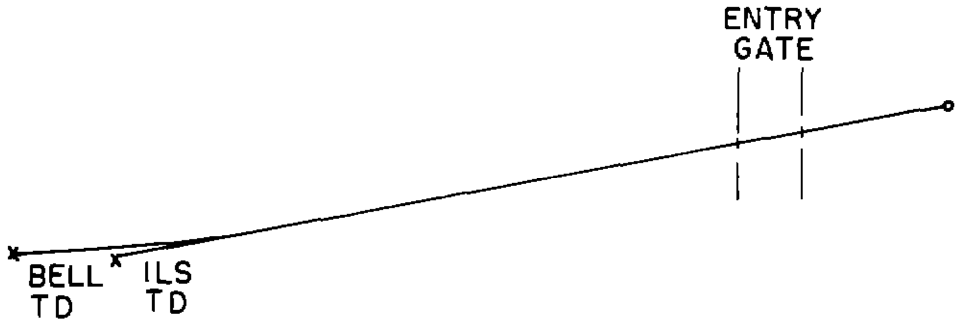


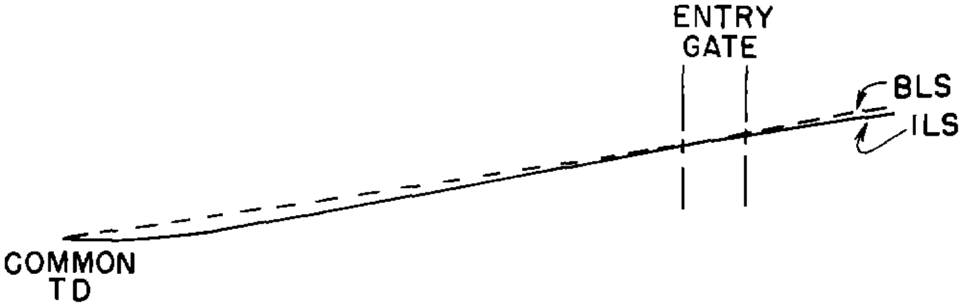
FIG 4 BELL LANDING SYSTEM GLIDE SLOPE



(A) ILS AND BLS GLIDE SLOPES AS USED IN CAA TESTS



(B) ONE METHOD FOR PROVIDING COINCIDENT GS AT ENTRY GATE



(C) 2ND METHOD FOR PROVIDING COINCIDENT GS AT ENTRY GATE

FIG 5 TRANSITION FROM CAA ILS TO BLS GLIDE SLOPE