SIMULATOR EVALUATION OF MANUALLY FLOWN CURVED INSTRUMENT APPROACHES

Dennis Sager

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DENNIS SAGER

SUBMITTED TO THE DEPARTMENT OF AERONAUTICS AND ASTRONAUTICS ON JANUARY 4, 1973 IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE.

ABSTRACT

Pilot performance in flying horizontally curved instrument approaches was analyzed by having nine test subjects fly curved approaches in a fixed-base simulator. Approaches were flown without an autopilot and without a flight director. Evaluations were based on deviation measurements made at a number of points along the curved approach path and on subject questionnaires. Results indicate that pilots can fly curved approaches, though less accurately than straight-in approaches; that a moderate wind does not affect curve flying performance; and that there is no performance difference between 60^{o} and 90^{o} turns. A tradeoff of curved path parameters and a paper analysis of wind compensation were also made.

Thesis Supervisor: Robert W. Simpson
Title: Professor of Aeronautics and Astronautics

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There is a large number of people without whose aid this project could not have been completed. Foremost among them is my thesis supervisor, Professor Robert Simpson. Many of the ideas for the curved approach experimental program are his.

I wish to thank Mark Connelly and David Melanson for their aid with the aircraft simulator and Robert Fitch for programming the simulation computer. Professors Renwick Curry and Amedeo Odoni provided valuable aid in experimental setup and statistical analysis. Giselle Mazarredo and Sue Casterlin provided typing assistance.

The management and pilots of Eastern Air Lines, and especially Captain Steve Stiles, provided invaluable assistance to the curved approach test program. Of course, the program itself could never have been conducted without the voluntary contribution of time and ideas by the test subjects listed below:

Captain Richard Dion	Eastern Air Lines
Steve Dodge	M.I.T.
Captain Charles Hodgson	Eastern Air Lines
Professor Walter Hollister	M.I.T.
Jack Howell	Eastern Air Lines
William Kelly	Eastern Air Lines
Captain R.P. Kliegle	Eastern Air Lines
Captain Ed Schweitzer	American Airlines
Joseph Tymczyszyn	M.I.T.

Finally, thanks must go out to the National Aeronautics and Space Administration and to my wife Jeanni, the former for supporting the research through NASA Grant NGL 22-009-640, "Joint University Research Program for Air Transportation Needs", and the latter for supporting me.

TABLE OF CONTENTS

ACRONYMS

CI	Course Indicator
CRT	Cathode Ray Tube
deg	degrees
DME	Distance Measuring Equipment
FAA	Federal Aviation Administration
ft	feet
HSI	Horizontal Situation Indicator
ILS	Instrument Landing System
km	kilometers
LGS	Landing Guidance System
m	meters
min	minutes
MIT	Massachusetts Institute of Technology
MLS	Microwave Landing System
RTCA	Radio Technical Commission for Aeronautics
s	seconds

1. Introduction

The introduction of the Microwave Landing System (MLS) (also known as the Landing Guidance System (LGS)) around 1980 will add new dimensions to aircraft instrument approaches. The precise position information provided by the MLS will enable aircraft to perform both vertically and horizontally curved approaches in instrument meteorological conditions. It is anticipated that most of these "more sophisticated" curved approaches will be flown using an autopilot or a flight director. However, in the cases of malfunctioning equipment or aircraft equipped with neither an autopilot, nor a flight director, there is a question as to whether the pilot will be able to manually fly a curved MLS approach. This is especially true in the presence of a wind shear. This report presents an evaluation of pilot capability to manually fly a horizontally curved MLS approach, with and without a wind shear, and a brief look at providing wind compensation in the curved approach path.

1.1 Description of the MLS

The Microwave Landing System is in the development stage. Precise details of its operations are not yet determined. However, the Radio Technical Commission for Aeronautics (RTCA) in its Special Committee 117 report (Reference 1) does provide a fairly detailed specification. Though a doppler system has not been ruled out, the MLS will likely be composed of three parts: a scanning beam in azimuth, a scanning beam in elevation, and a precision Distance Measuring Equipment (DME). Because the MLS will operate at microwave frequencies and because of the scanning nature of the signal, the azimuth and elevation information will be more precise than that provided by the current Instrument Landing System (ILS). Using azimuth, elevation, and DME information, a precise determination of an aircraft's position with respect to the touchdown point can be made. This gives the MLS the capability to provide guidance for an infinite variety of approach paths, the paths themselves being generated on board the aircraft. The MLS coverage zone as presently planned is a wedge extending from the touchdown point outward 60° either side of the extended runway center line. Any curved path within this 120° region (and within the MLS range of 60 kilometers (km)) can be synthesized on board the aircraft.

More detailed descriptions of MLS hardware may be found in the RTCA report (Reference 1) and in References 2 and 3. A description of some possible uses of the MLS is provided in Reference 4.

It is anticipated that the MLS will be operational in the late 1970's. The Federal Aviation Administration (FAA), as described in Reference 5, envisions that 300 U.S. airports will be MLS equipped by 1982.

1.2 Test Objectives

This series of simulated curved MLS approaches was conducted to determine how easily horizontally curved approaches could be manually flown. (The vertical path corresponded to a constant descent rate.) More specifically, a comparison was made between flying straight-in and curved instrument approaches. This comparison was made with a no wind condition simulated. Curved approaches were flown using the same simulated Collins FD-109 instrument package (without flight director) as might be used on a conventional ILS approach. Minor modifications were made, but the basic concept was the same - needles to indicate elevation (glide slope) and azimuth (localizer) errors.

Additional measurements were made comparing curved approaches with and without a wind shear, providing an indication of the deleterious effect of wind on curved approaches. And a concept of compensating the curved ground path for wind was examined but not experimentally tested. Pilots, in theory, would need only fly a constant air velocity (constant air speed and descent rate) to properly complete the wind compensated approach. The nominal path in wind compensated approaches would be biased so that the wind would blow the aircraft to the proper position at the proper heading for landing.

This experimentation assumed that, operationally, there would be some flexibility in the ground tracks for MLS approach paths for a given runway to permit path adjustments for approach speed and bank angle.

2. Description of Simulation

Data for this curved approach study was obtained by measuring the performance of pilots in flying curved paths in a fixed-base simulator. This section provides a description of the simulator, the pilot subjects, and the test cases.

2.1 The Simulator

A Boeing 707 was simulated using a motionless cockpit shell donated by Boeing, an Adage AGT-30 digital computer, and interfacing electronics and displays assembled by the Massachusetts Institute of Technology (MIT) Electronic Systems Laboratory. The simulator utilized is the same simulator used for Traffic Situation Display experimentation described in References 6 and 7.

Test cases containing the simulated aircraft's initial position and the nominal approach path were loaded into the Adage computer. The computer used the initial conditions and and pilot control inputs to propagate the aircraft's attitude, velocity, and position. This position information was in turn utilized by the computer to drive aircraft displays and to make position error measurements used in the curved approach evaluation.

Most 707 instruments were represented by "paste-ons", but the basic flight instruments were actively simulated by the computer through a masked Cathode Ray Tube (CRT) display. The CRT display represented a Collins FD-109 package (normally not found on a 707) consisting of altimeter, vertical velocity indicator, attitude director indicator, airspeed indicator, radio-magnetic indicator, and horizontal situation indicator (HSI). Additionally, there was a set of marker lights controlled by the computer and a set of engine pressure ratio gages.

No flight director displays were provided.

Pilot input devices included landing gear lever, heading memory knob, throttles, rudder petals, and a "Control Wheel Steering" control wheel. Control Wheel Steering is an option on some transport aircraft which uses onboard electronics to hold the attitude input by the pilot (rate command/attitude hold). Turns made using Control Wheel Steering are coordinated and do not require rudder input.

A modification to the "normal" FD-109 package was made for curved approach testing. The course set arrow and window were automatically controlled by the computer to correspond to the current aircraft position along the nominal approach path.

The specific dynamics of the simulator correspond to a Boeing 707-123B with a mass of about 75,000 kilograms.

The simulator was programmed in Adage assembly language by Robert Fitch of MIT. The Adage computer has a 16384 word, 30 bit memory and a machine cycle time of 2 microseconds.

2.2 Pilot Subjects

Six airline pilots and three general aviation pilots served as test subjects in the curved approach evaluation. All subjects volunteered their time to participate in this experimental program. A listing of the subject names and companies is given in the Acknowledgements.

The ages of the subjects ranged from 25 to 45. The experience level ranged from 1400 hours to 20000 hours. No attempt was made to statistically correlate performance with age or experience. However, Figures 2-1 and 2-2 show a comparison of mean crosstrack errors for each subject over all test cases. These figures show the error measured at 122 meters (m) (400 feet(ft))

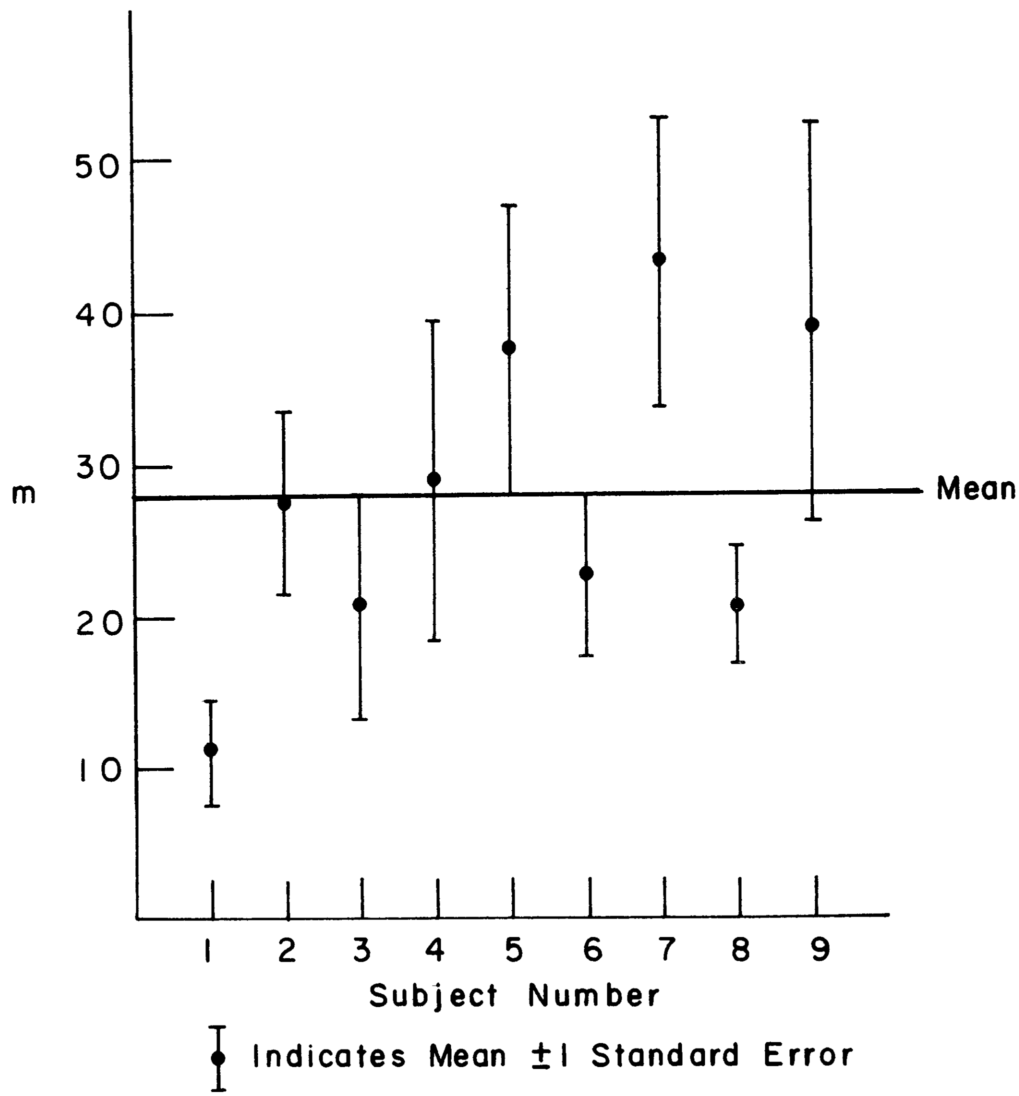


Figure 2-1 Mean Magnitude of Crosstrack Error at 122 m Altitude (End of Turn) over All Cases for Each Subject

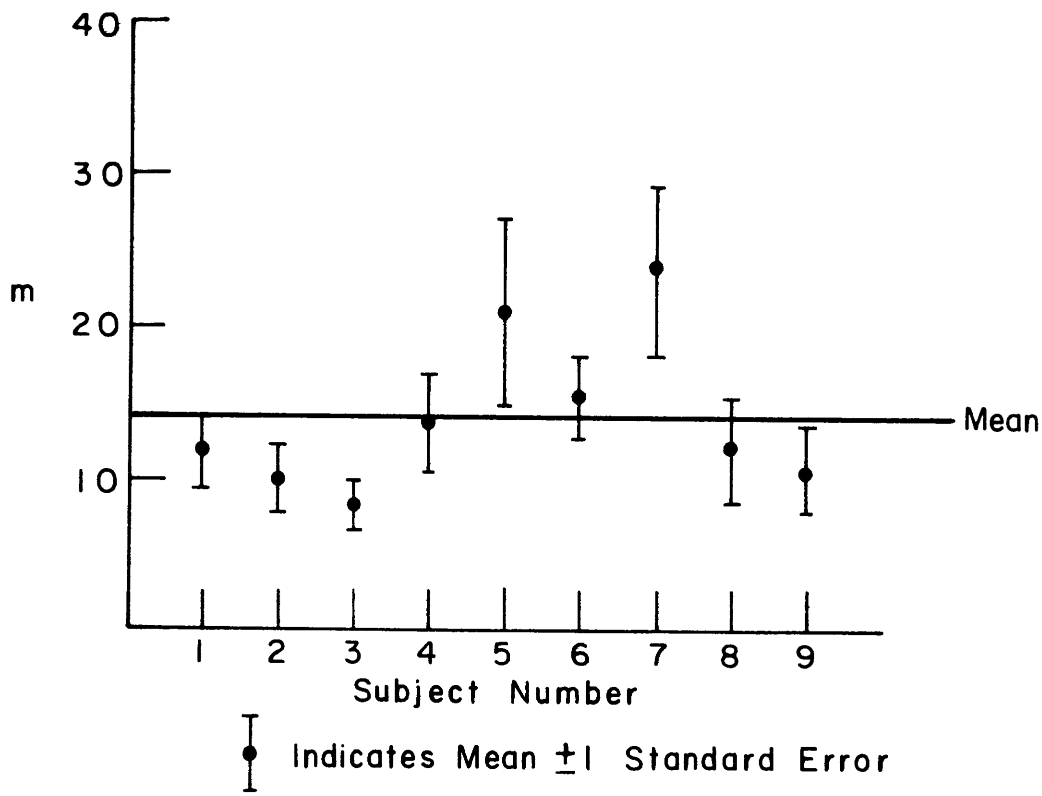


Figure 2-2 Mean Magnitude of Crosstrack Error at 30.5 m Altitude over All Cases for Each Subject

and at 30.5 m (100 ft). Subjects 1 through 6 were airline pilots while subjects 7 through 9 were general aviation pilots. A brief description of the background of each subject follows:

Subject	Age	Hours	Position or Rating
1	mid 40's	15000	airline captain
2	about 30	3000	airline second officer
3	about 30	1500	airline second officer
4	mid 40's	20000	airline captain
5	about 40	7000	airline captain
6	about 40	14000	airline captain
7	about 40	3000	commercial/instrument
8	mid 20's	2000	air transport rating
9	mid 20's	1400	commercial/instrument

Note that the subject numbers do not correspond to the alphabetical listing of subjects in the Acknowledgements.

2.3 Test Cases

The test cases used to evaluate curved approaches were all initiated with the aircraft 1 minute from nominal intersection of the curved approach path. For the 60 degree turn and no turn cases, the no wind flight time from path intersection to touchdown was a nominal 3 minutes, making a total case time of 4 minutes. Because of MLS coverage geometry considerations, the time from path intersection to touchdown for 90 degree (deg) turn cases was 2 minutes 28 seconds, making a total case time of about 3½ minutes.

Cases were constructed with both left and righ turns, with no turns, and with and without wind. Turn amounts were 60° and 90°. When wind was incorporated, the wind was a linear shear in direction and speed. The wind at 0 m was from 050° at

5m/second (s) (10 knots). At 600 m (1969 ft) the wind was from 020^{o} at 10 m/s (19 knots). A more detailed description of the approach paths is given in Section 3. Curved approach evaluations were based on how closely pilots conformed to the nominal curved paths. A further discussion of data analysis is presented in Section 4.

All test cases were initiated with full flaps and landing gear down and with the aircraft at its final approach speed of 67 m/s (130 knots). In addition, all aircraft were on a heading such that they would intersect the nominal approach path at an angle of 15 degrees.

The blue Outer Marker light flashed to signal the point of descent initiation (Descent Marker) and was flashed again to signal the point of turn initiation (Turn Marker). After limited pre-test experimentation, it was decided to flash the Descent and Turn Marker lights (blue marker light) for a total of 6 seconds, commencing 4 seconds before the actual point of desired descent or turn initiation. The orange Middle Marker and the white Inner Marker lights operated as in normal approaches. All marker light flashing was based on actual aircraft position rather than on the nominal time parameters.

All testing was performed with a single pilot only and with no simulation of air traffic control conversations or commands. No additional pilot workload in the form of a landing checklist was added.

3. Curved Approach Paths

This section describes the curved approach paths that were flown. Presented are the basic geometry of the approach path, the concept of wind compensation, MLS coverage, curve parameter tradeoffs, and the constancy of the time of turn initiation. These paths were generated by using a PL/I computer program on an International Business Machines 370 to propagate an approaching aircraft's trajectory backwards from touchdown, taking into consideration approach speed, descent rate, turning rate, and wind shear. Figure 3-1 shows an example of this computer output.

3.1 Path Geometry

The curved approach paths consisted of a straight line pre-turn segment, a curved segment, and a straight line final segment. Figures 3-2 and 3-3 show the approach geometry. Figure 3-4 shows the paths for a 60° and a 90° turn.

Vertically, an approaching aircraft maintained a constant no wind descent rate. In the case of non-wind compensated approaches, this corresponded to a constant glide slope. The descent rate used in testing was 4 m/s (787 ft/minute (min)) which corresponded to a glide slope of 3.42°.

The horizontal path was constructed from touchdown backwards. The final approach segment length was determined by the distance required for the aircraft to descend from the end of turn altitude to touchdown at the specified descent rate. As will be discussed later in this section, the altitude at the end of the approach turn was a tradeoff parameter. A value of 122 m (400 ft) was chosen for this testing. This yielded a final approach segment length of 2039 m, this segment beginning about 30 seconds before touchdown.

Figure 3-1 Sample Curved Approach Path Generation Output

CURVED LGS APPROACH

PAGE 3

DESECENT RATE = 4.00 M/S (787 FT/MIN) APPROACH SPEED = 67.0 M/S (130 KNOTS)

BANK ANGLE = 10.0 DEG APPROACH TURN = 90 DEG RIGHT

NO WIND TURN RADIUS = 2596 M (1.40 N MI)

DISTANCE FROM TOUCHDOWN TO LOCALIZER = 3500 M (11483 FT)

WIND SHEAR:
0 M (0 FT) - 50 DEG AT 5.0 M/S (10 KNOTS)
600 M (1969 FT) - 20 DEG AT 10.0 M/S (19 KNOTS)

TIME FROM TD (MIN)	(SEC)	POINT	X (M)	X (N MI)	Y (M)	Y (N MI)	PATH DIST. FROM LOC. (M)	(N MI)	STRAIGHT LINE DIST. FROM TD (M)	(N MI)	AZIMUTH FROM TD (DEG)	HDG (DEG)	ALTITUDE (M)	(FT)	WIND (DEG)	(M/S)	(KNOTS)
0	29		17360	9.4	10643	5.7	5440	2.9	1940	1.0	0.0	35	116	381	44	6.0	12
0	30		17322	9.4	10588	5.7	5506	3.0	2006	1.1	0.0	35	120	394	44	6.0	12
0	30	ENDTURN	17303	9.3	10561	5.7	5539	3.0	2039	1.1	0.0	35	122	400	44	6.0	12
0	31		17286	9.3	10535	5.7	5570	3.0	2070	1.1	0.0	34	124	407	44	6.0	12
0	32		17253	9.3	10484	5.7	5631	3.0	2131	1.2	0.1 L	33	128	420	44	6.1	12
0	33		17222	9.3	10431	5.6	5692	3.1	2192	1.2	0.2 L	31	132	433	43	6.1	12
0	34		17192	9.3	10378	5.6	5753	3.1	2253	1.2	0.4 L	30	136	446	43	6.1	12
0	35		17164	9.3	10324	5.6	5814	3.1	2313	1.2	0.5 L	28	140	459	43	6.2	12
0	36		17137	9.3	10270	5.5	5875	3.2	2373	1.3	0.7 L	27	144	472	43	6.2	12
0	37		17112	9.2	10214	5.5	5936	3.2	2433	1.3	1.0 L	25	148	486	43	6.2	12
0	38		17088	9.2	10158	5.5	5997	3.2	2493	1.3	1.3 L	24	152	499	42	6.3	12
0	39		17066	9.2	10101	5.5	6058	3.3	2553	1.4	1.6 L	22	156	512	42	6.3	12
0	40		17045	9.2	10044	5.4	6119	3.3	2612	1.4	1.9 L	21	160	525	42	6.3	12
0	41		17026	9.2	9986	5.4	6180	3.3	2671	1.4	2.2 L	19	164	538	42	6.4	12
0	42		17009	9.2	9927	5.4	6241	3.4	2730	1.5	2.6 L	18	168	551	42	6.4	12

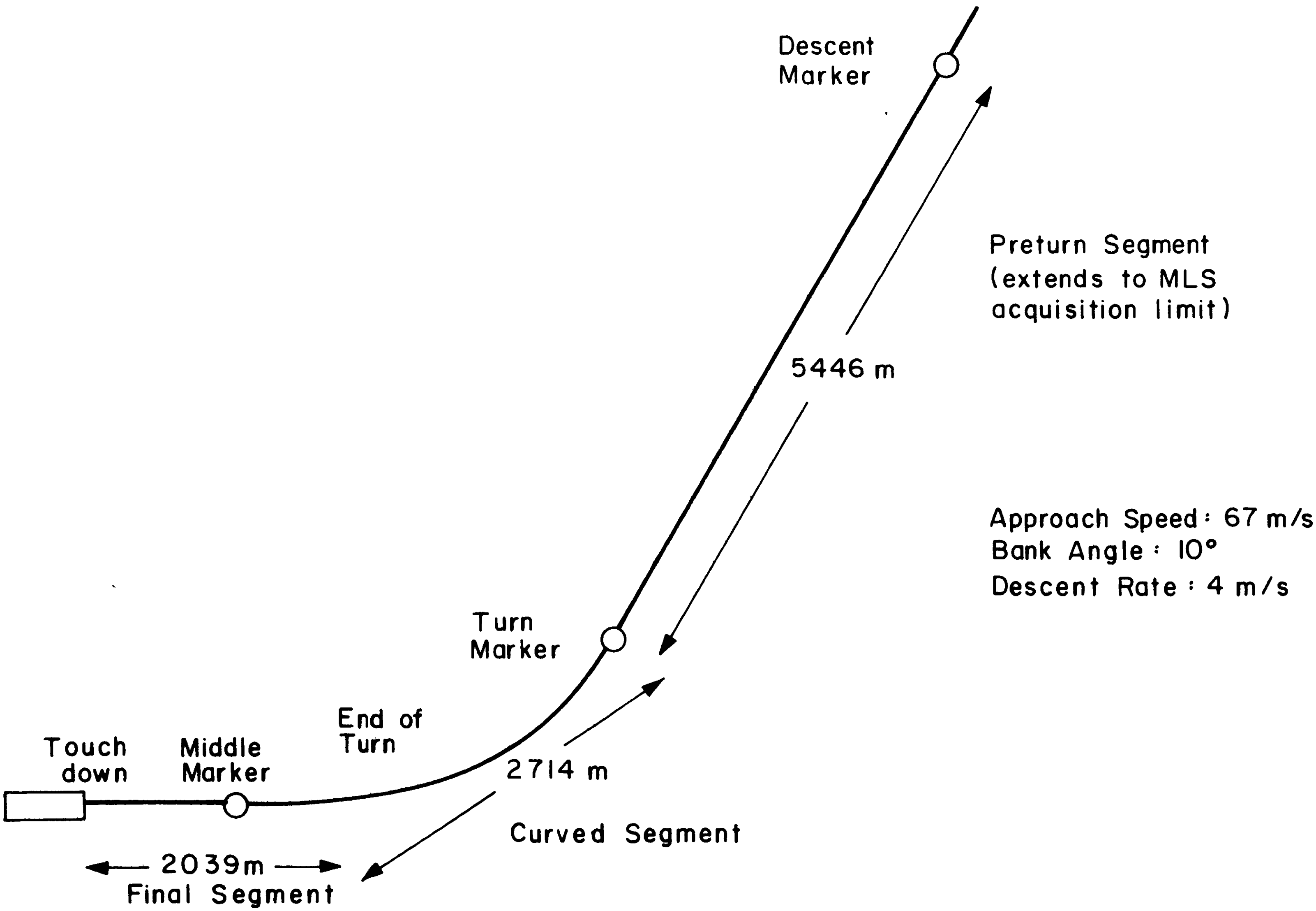


Figure 3-2 Curved Path Geometry – Horizontal (60° Turn)

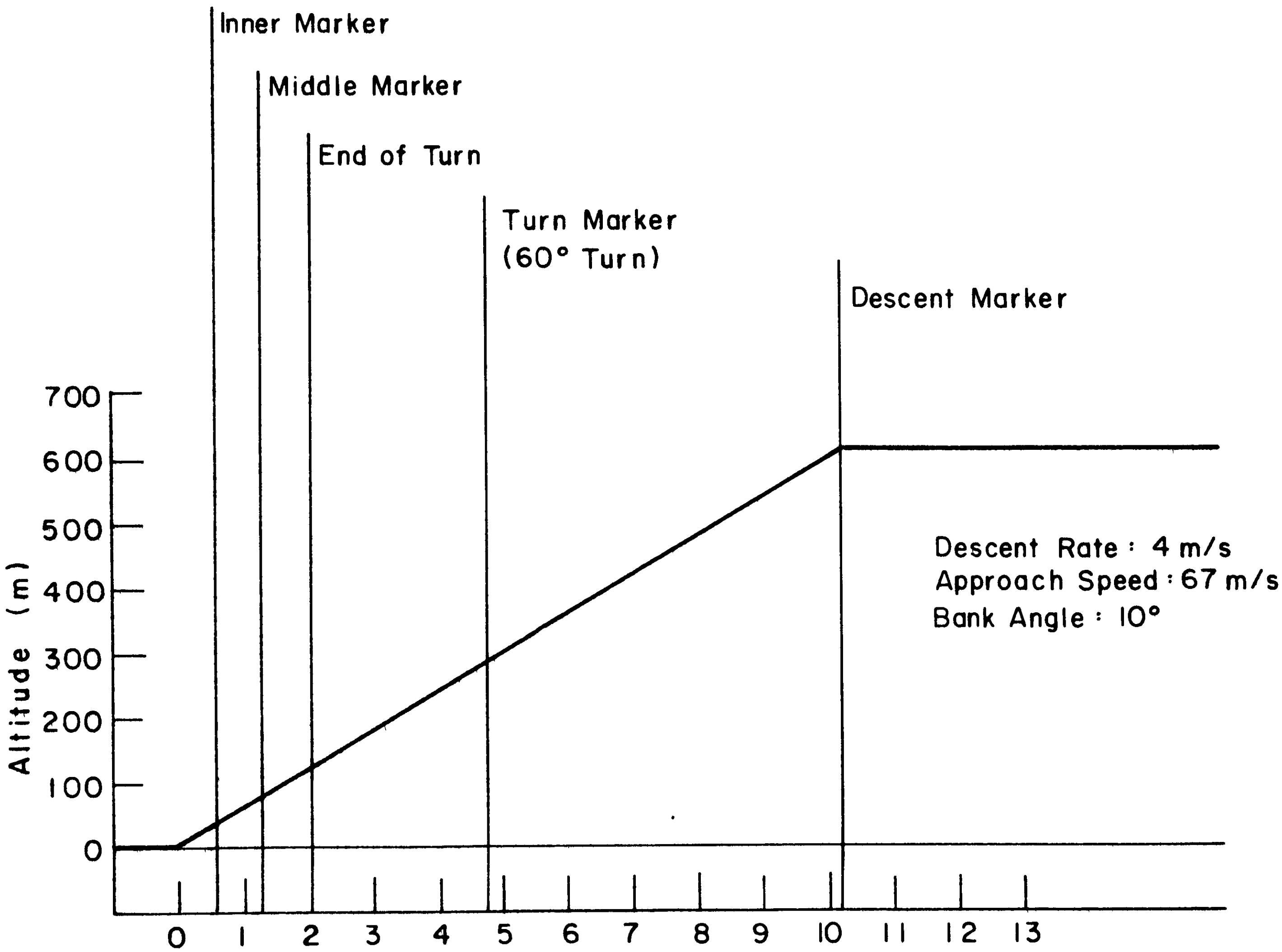


Figure 3-3 Curved Path Geometry – Vertical

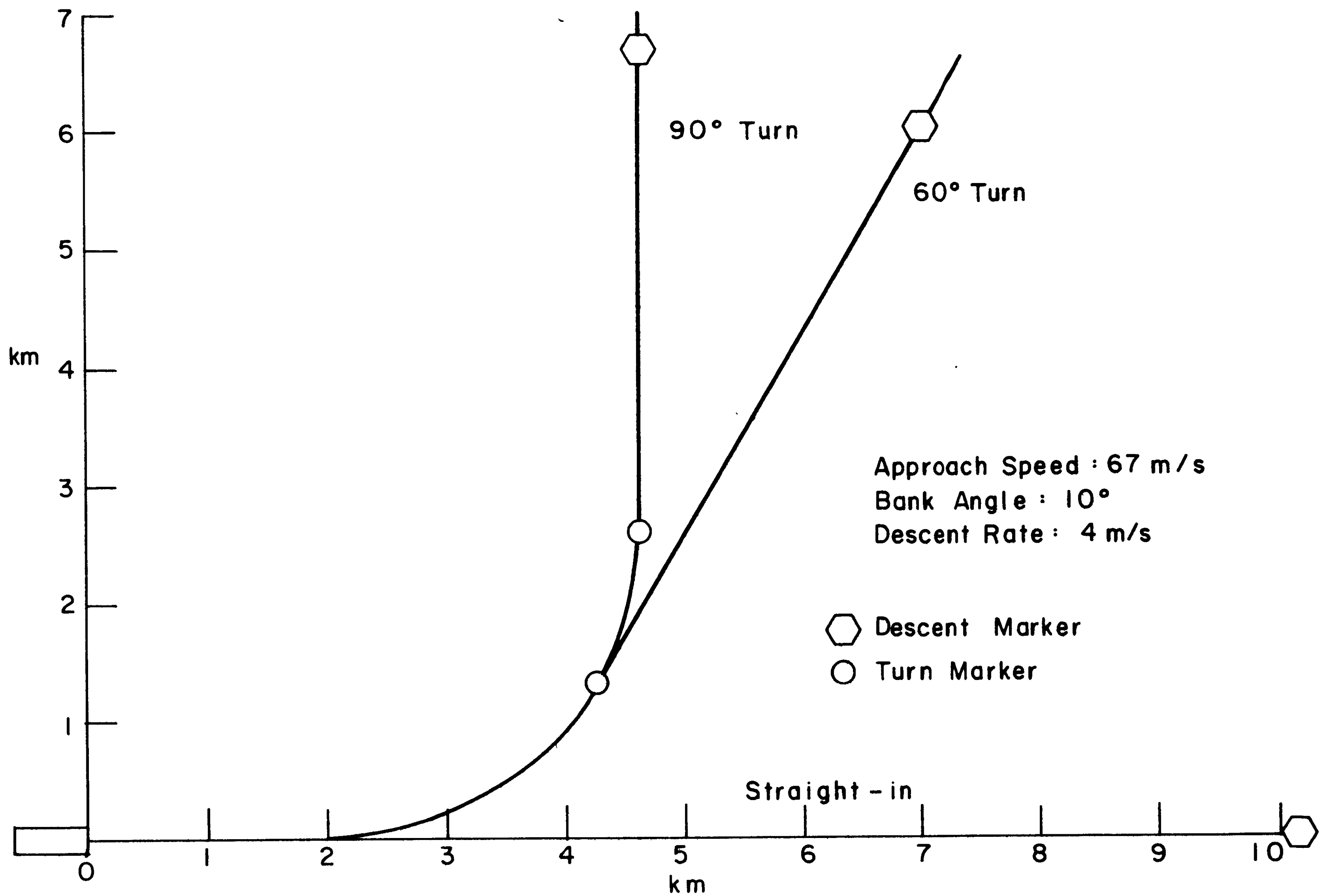


Figure 3-4 Straight -in, 60°, and 90° Turn Approaches

The curved segment was constructed to end at the end of turn point and to begin at a point determined by the selected bank angle, approach speed, and turn heading change. With the approach speed of 67 m/s and a bank angle of 10^{o}, a 60^{o} heading change (with no wind) took 41 seconds and covered a curved path distance of 2714 m. A 90^{o} heading change required 61 seconds over a curved path distance of 4070 m.

These curved segments were generated assuming an instantaneous transition to and from a 10^{o} bank angle. Actually, aircraft dynamics can introduce a delay on the order of a second in achieving the proper centrifugal acceleration. Pilot response lag and passenger comfort considerations can introduce additional delays. Reference 8 looks at this problem in detail. However, with the Turn Marker flashing 4 seconds before the time for an instantaneous turn, pilots were able to compensate for the aircraft dynamics by beginning their turn early. Similarly, simply by looking at their deviation and desired (runway) heading, pilots were able to roll out of the curved segment with no problem.

The preturn segment was simply a straight line from the point of turn initiation to the MLS acquisition limit. The heading of this segment differed from the runway heading by the desired heading change. The Descent Marker was located on this segment. Until reaching the Descent Marker, the glide slope needle remained centered with the aircraft in level flight at the nominal altitude for initiation of the approach. For testing, 610 m (2001 ft) was selected as the initial altitude for straight-in and 60^{o} turn approaches. For 90^{o} turn approaches 580 m (1903 ft) was chosen.

3.2 Wind Compensation

A method for compensating for wind shear was investigated on paper but was not tested. In this "paper" investigation, approach paths were biased such that a pilot would need only fly a constant heading, airspeed, and descent rate to remain on the desired approach path. The geometrical shape of the path was distorted so that a pilot flying constant air derived quantities (airspeed, heading, descent rate) would be blown to the proper geographic points. Thus the curved segment in a wind compensated approach was not an arc of a circle, but was a distorted curve. The initial approach segment was a straight line to the Descent Marker at which point a slight distortion from wind was introduced. The final approach segment (from 122 m altitude to touchdown) was not wind compensated. This segment required that the pilot himself compensate for crosswind. For all wind studies a wind shear with two points and linear interpolation was used. The wind used was from 050° at 5 m/s (10 knots) at 0 m and from 020° at 10 m/s (19 knots) at 600 m (1969 ft). Figures 3-5 and 3-6 show 60° and 90° right turns with and without wind compensation. The approaches shown are to a runway with a heading of 035°. In the 60° turn case, for example, both initial approach segments have the aircraft heading at 335°. However, the wind compensated path is moved such that an aircraft on that path maintaining a heading of 335° will be blown to the same point that an aircraft on the no-wind path will reach in the absence of wind by maintaining that same heading of 335°. It must be noted that accurate wind compensation assumes precise knowledge of the wind shear.

Again, it must be emphasized that no wind compensated cases were actually flown. The generation of the wind

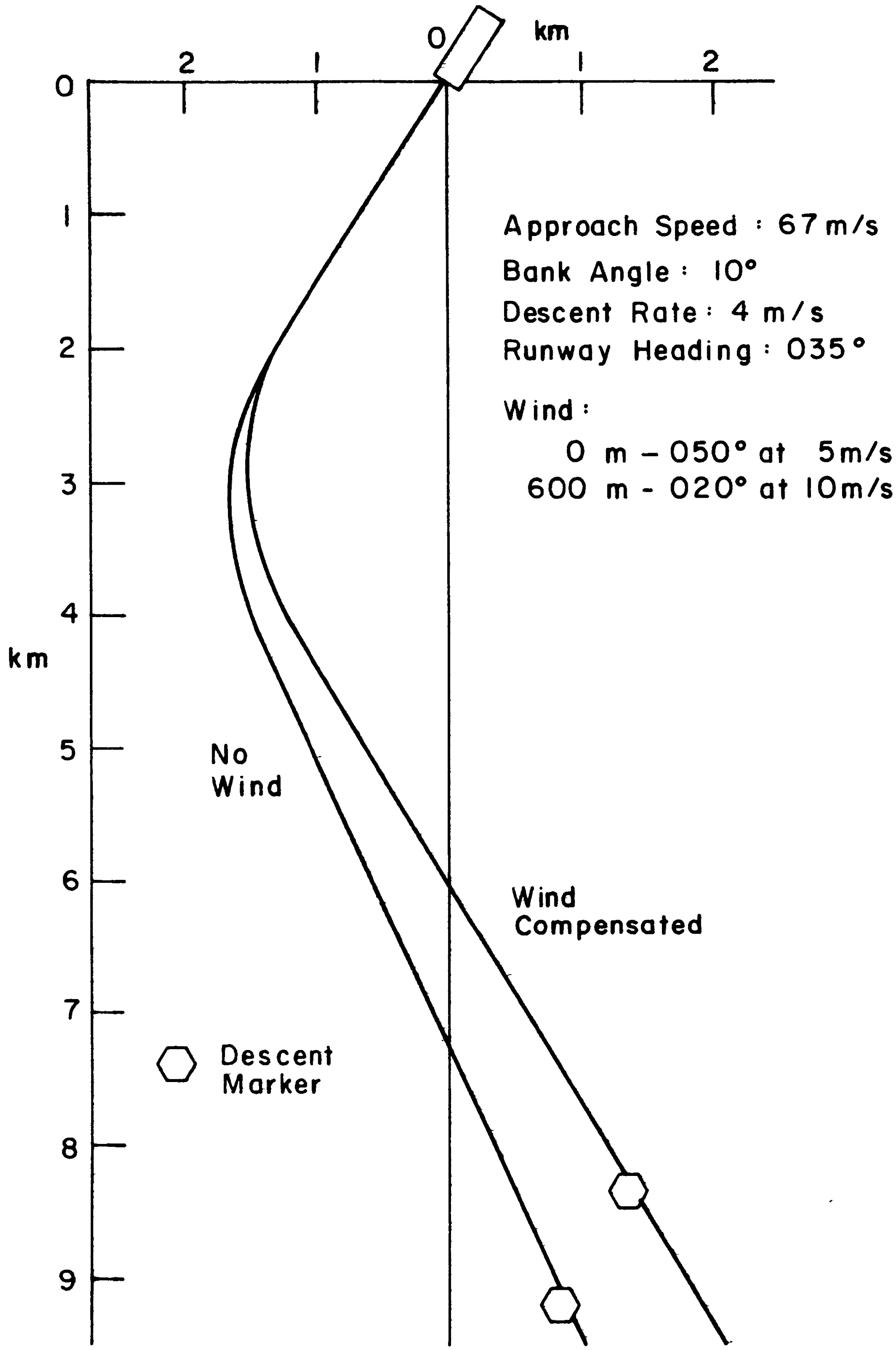


Figure 3-5 60° No Wind and Wind Compensated Approaches

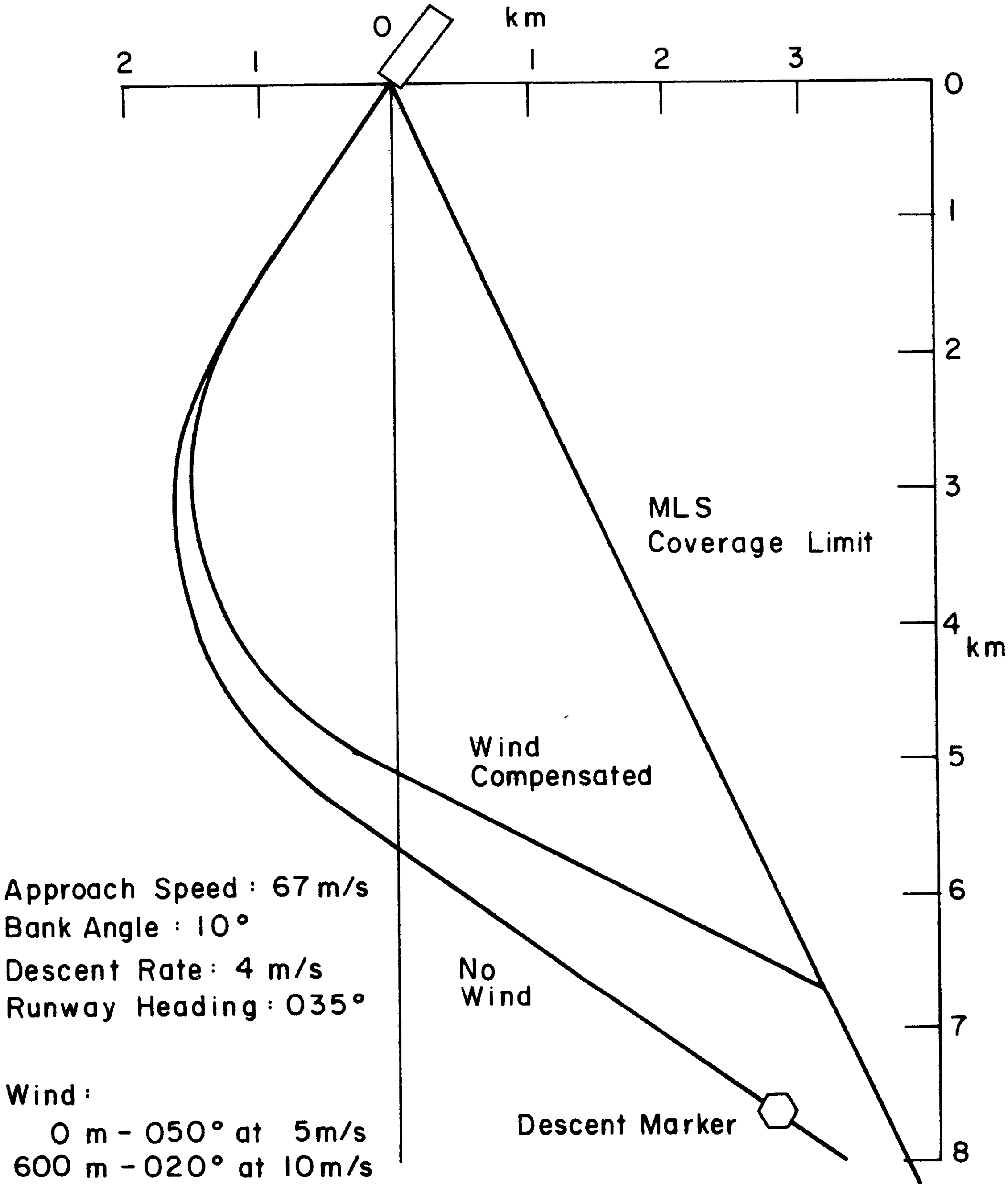


Figure 3-6 90° No Wind and Wind Compensated Approaches compensated paths, however, did demonstrate two points. First, with the moderate wind shear used, the geographic position difference between no wind and wind compensated paths is small. Thus, a wind compensated path would be no less useful than a no wind path for noise reduction or aircraft merging purposes. Second, in cases where the aircraft is landing into the wind (the usual case), wind compensation aggravates the problem of having part of the approach path outside of the MLS coverage limit. The question of MLS coverage is further discussed in Section 3.3.

The effects of the headwind and crosswind components are shown in Figures 3-7 and 3-8 which show the effect of wind direction on wind compensated 60^o and 90^o turns. Figure 3-8 shows the effect especially well. The wind compensated path for a landing headwind begins closer to the touchdown point than the no-wind path. The crosswind and no-wind paths have a similar preturn segment. However the wind compensated path for a crosswind that is a preturn tail wind is on the inside of the no-wind path. When the crosswind is a preturn headwind, the wind compensated path is on the outside of the no-wind path.

3.3 MLS Coverage

References 1, 2, and 3 describe a number of planned MLS configurations. For the curved approach testing, a maximum capability system was assumed, providing a range of 60 km. There are several possible MLS equipment location configurations. For the testing, it was assumed that the azimuth scanning beam was located beyond the end of the runway at the location of today's ILS localizer (3500 m from touchdown). The elevation scanning beam and the DME were assumed to be located at the touchdown point. Localizer needle sensitivity was the same as

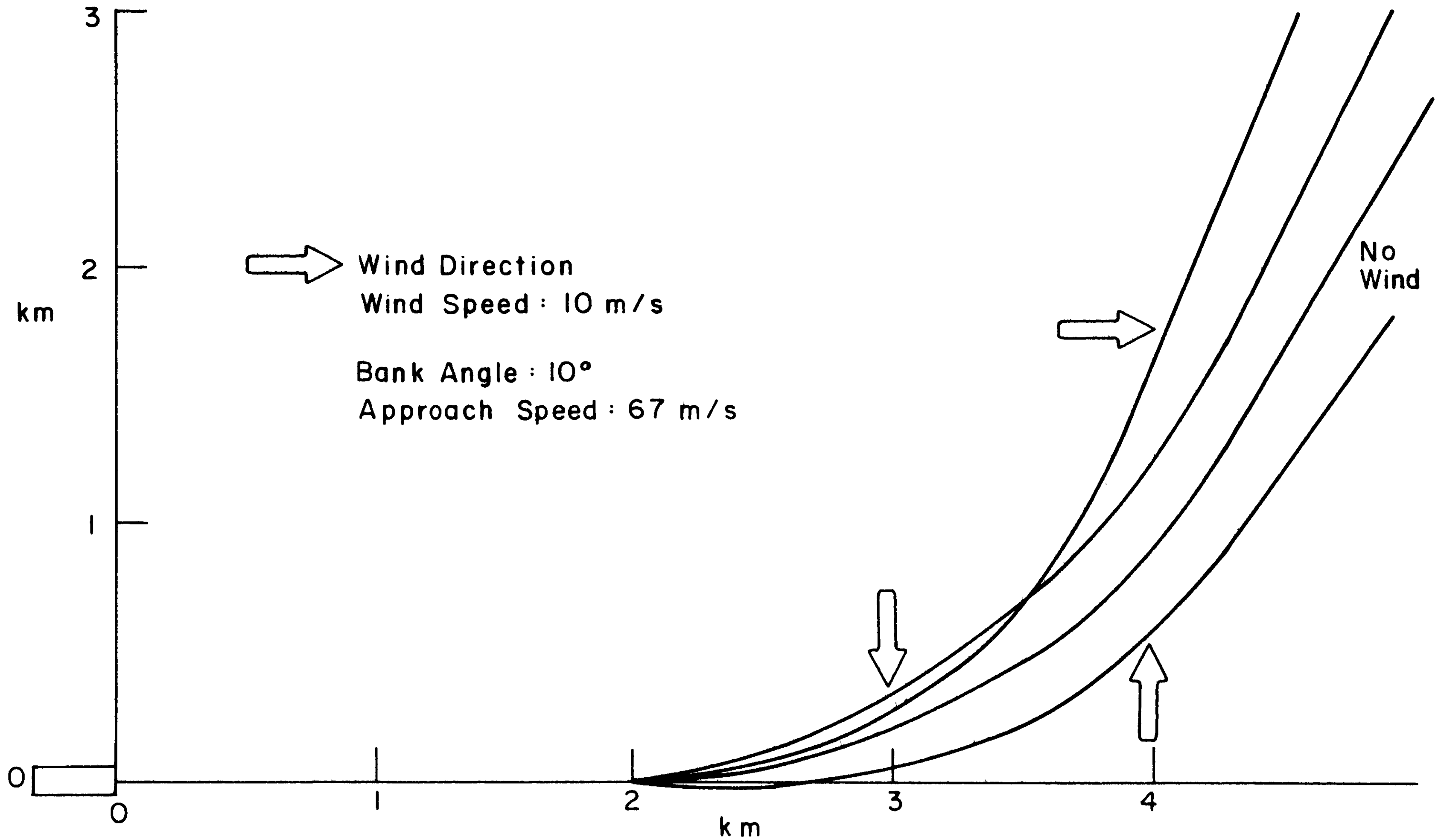


Figure 3-7 Variation in Wind Compensated Paths with Wind Direction – 60° Turn

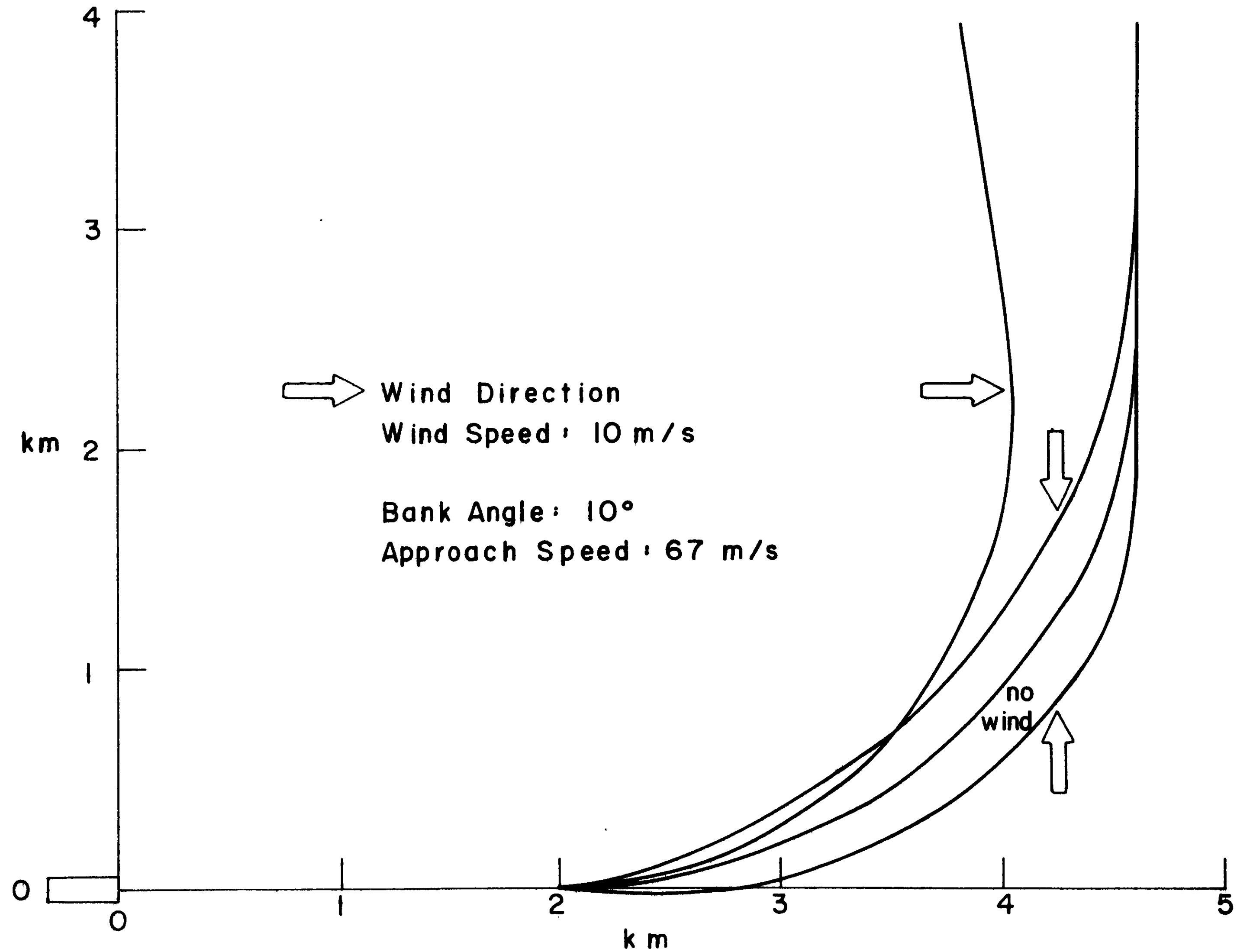


Figure 3-8 Variation in Wind Compensated Paths with Wind Direction - 90° Turn

if the curved path were straightened out along the runway centerline. Full scale deflection represented an angular displacement of 2.5° as measured from the azimuth scanning beam, 3500 m beyond the touchdown point. The glide slope needle functioned in the same manner. Full scale displacement represented a 0.7° displacement from touchdown measured along the arc of the curve. For displacements exceeding full scale but within the MLS coverage region, full scale deflection was indicated. Thus, the localizer and glide slope functioned with the same sensitivity as today's ILS.

Although the azimuth scanning beam was located beyond the end of the runway, the 120° arc of coverage was measured from the touchdown point in conformance to the specifications in Reference 1. This limited the MLS coverage area and forced the altitude of approach initiation to be 580 m instead of 610 m for 90° heading changes so that the point of descent initiation would be within the MLS coverage envelope. This is discussed more fully in Section 3.4. The MLS equipment configuration used in this study is shown in Figure 3-9.

3.4 Curve Parameter Tradeoff

There are a number of parameters affecting the ease of flying and the geometry of curved approaches. Some of these parameters are approach speed, bank angle, amount of turn, altitude at the end of the turn, initial altitude, and descent rate. The significance of the interrelated parameters is discussed below.

3.4.1 Approach Speed

Obviously, approach speed is not a parameter that can be varied to alter curved approach paths. However, approach speed does affect the curved path. It interacts with descent rate to

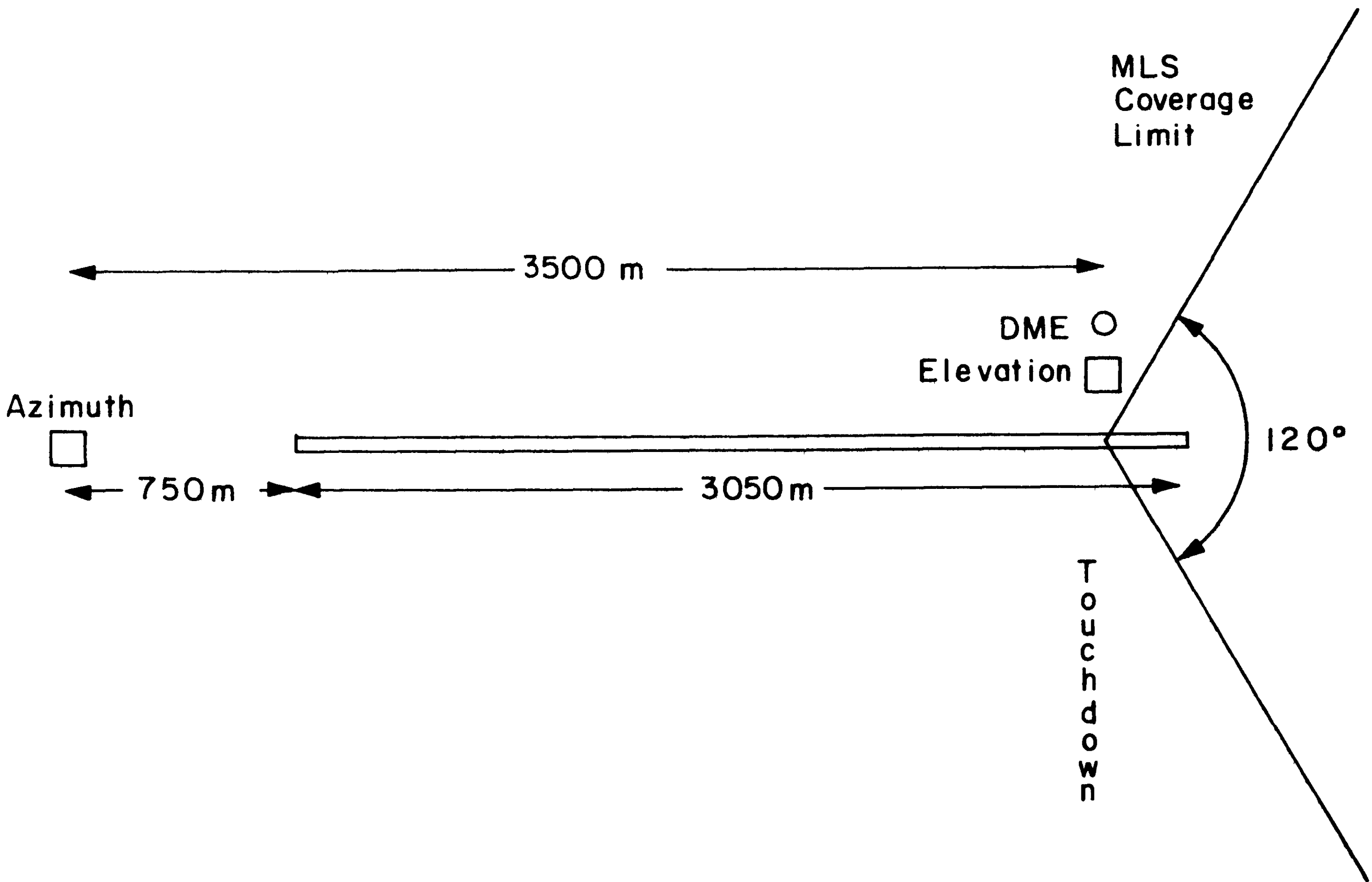


Figure 3-9 MLS Equipment Configuration

determine the effective descent angle of the path and it determines the length of time required to complete the segments of the approach. These points are obvious. The approach speed also is involved in the determination of the radius of curvature of the curved segment. The radius of curvature is given by the formula

$$r = \frac{v^2}{g \ \mathrm{TAN}\phi} \qquad (3\text{-}1)$$

where

r = radius of curvature

v = approach speed

ϕ = bank angle

g = local acceleration of gravity

Note that the radius of curvature depends on the square of the approach speed. As the approach speed increases, the path length of the curved segment increases rapidly. Or, looking at it in another way, attempting to fly a path designed for an approach speed of 67 m/s (130 knots) and 10° bank at a slightly high approach speed of 72 m/s (140 knots) would require a bank angle of 11.5°.

Approach paths for 50 m/s (97 knots) and 67 m/s (130 knots) are contrasted for 60° and 90° turns in Figures 3-10 and 3-11, respectively. It can be seen from Figure 3-11 that the slower approach speeds can aggravate problems with MLS coverage. In the example shown, the Descent Marker for the 50 m/s case is outside of the MLS $\pm 60^{\circ}$ coverage limit.

3.4.2 Bank Angle

As pointed out in Section 3.4.1, the bank angle is a factor in the determination of the curved approach path. The nominal bank angle for an approach can be varied within limits. However, too steep a bank angle and the aircraft may stall.

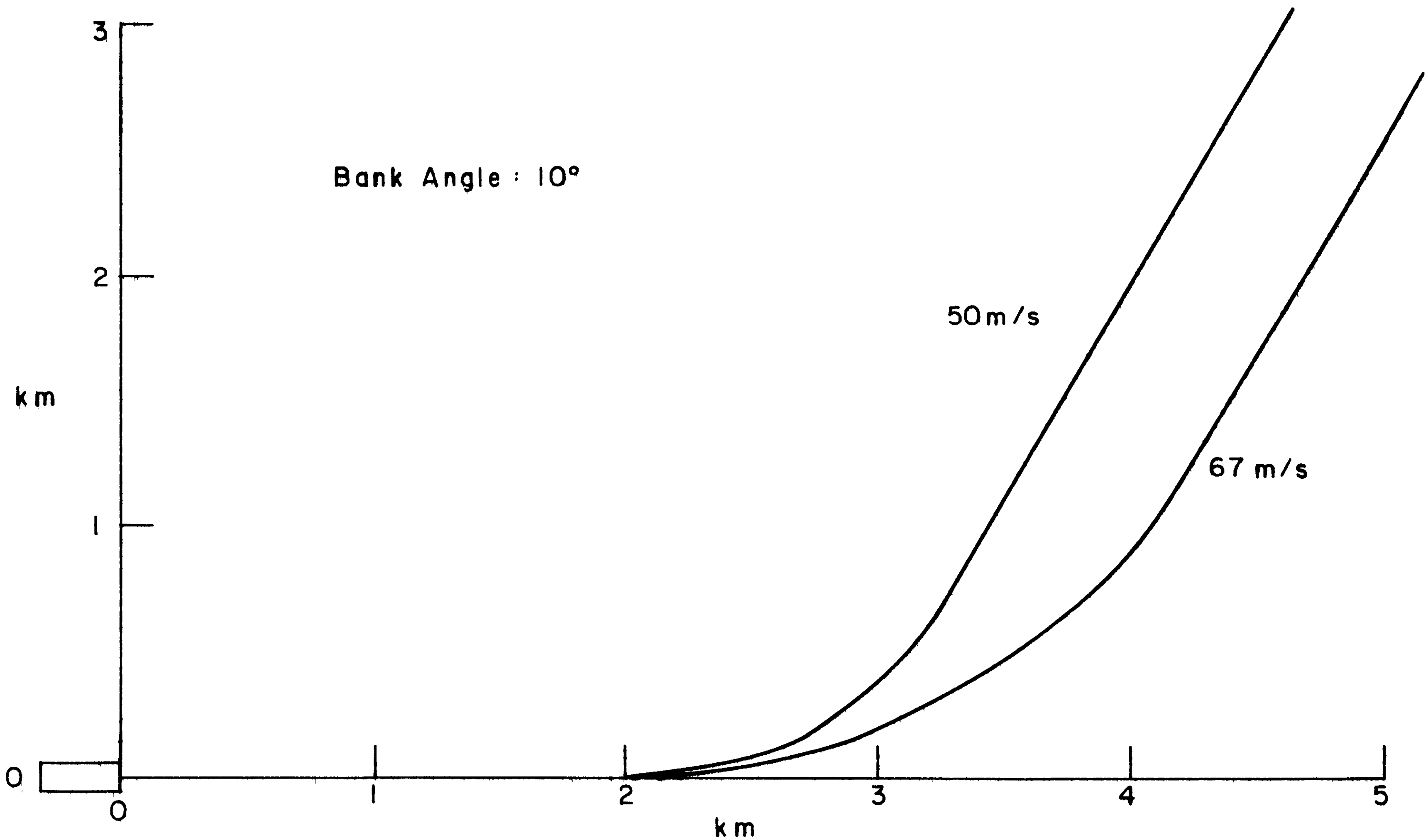


Figure 3-10 Variation in Approach Path with Approach Speed – 60° Turn

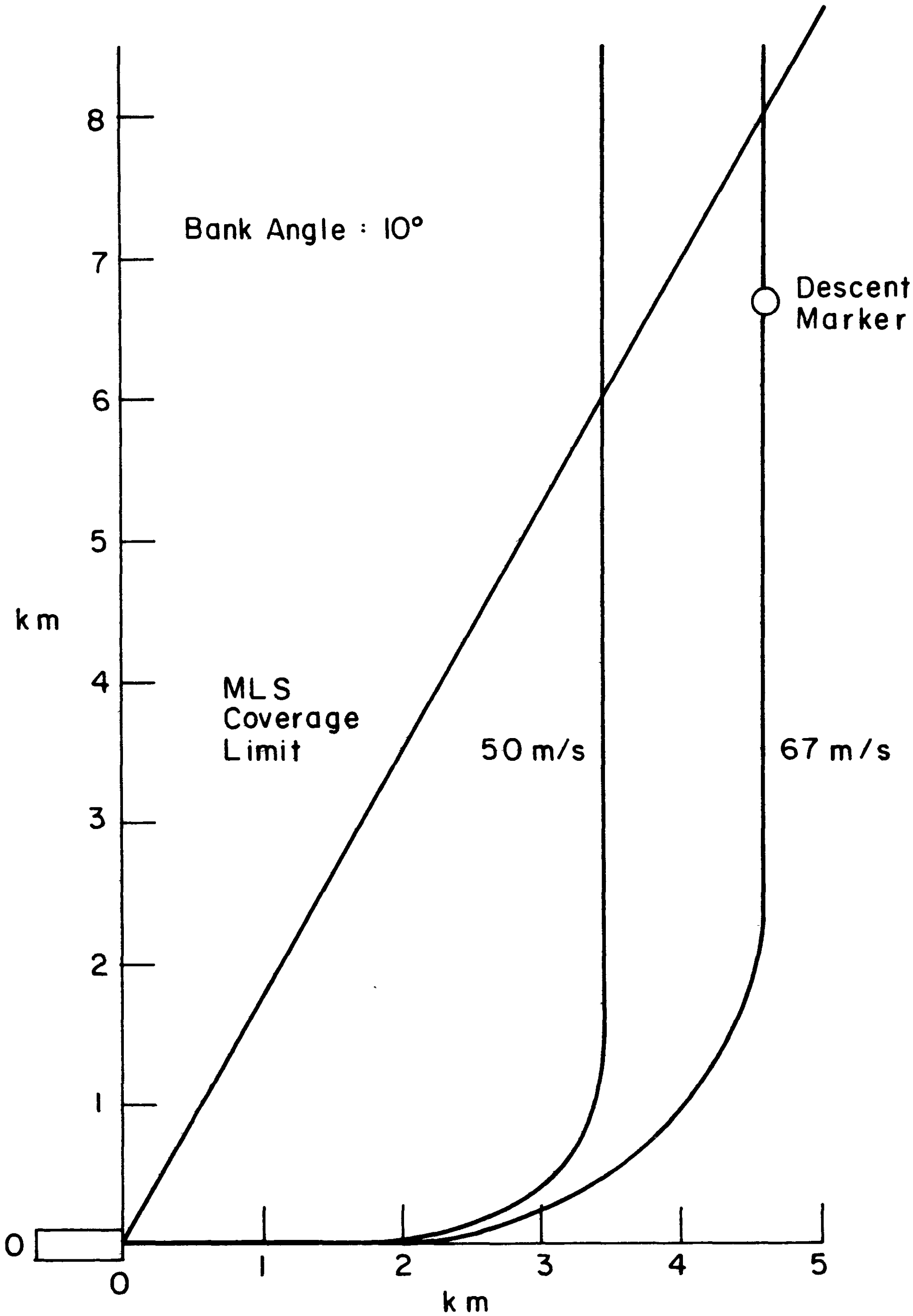


Figure 3-11 Variation in Approach Path with Approach Speed -90° Turn

Too shallow a bank, and curved approach flexibility is lost because the approach doesn't "curve" enough. Figure 3-12 shows approach paths for 5^{o}, 10^{o}, 15^{o}, and 20^{o} of bank.

A bank angle of 10^{o} was selected to generate paths for curved approach testing. This selection of 10^{o} bank appears to be an optimum choice. As can be seen from Figure 3-12, 10^{o} bank does generate a sufficient path curve to provide the benefits of a curved approach. On the other hand, 10^{o} is not too steep. When flying 10^{o} curves in testing, pilots at times had to double their nominal 10^{o} bank angle to 20^{o} to make course corrections. This temporary bank of 20^{o} is acceptable. However, if a nominal bank angle of 20^{o}, for example, were to be flown, a similar temporary doubling of nominal bank angle to 40^{o} for course corrections would be unacceptable. At approach speed, and low altitude, a 40^{o} bank angle would not be acceptable from the standpoint of safety and passenger acceptability.

In addition, the curve tightening effect of large bank angles can cause problems with MLS coverage.

3.4.3 Amount of Turn

The amount of turn is a factor in both curved approach flexibility and MLS coverage considerations. The greater the amount of turn that is possible, the more useful is the curved approach concept. On the other hand, as has been previously demonstrated, turns in excess of 60^{o} exit the MLS coverage wedge. There is also the obvious consideration that the greater the amount of curve, the greater the curved path distance that the pilot must fly. Testing was conducted on 60^{o} and 90^{o} turns.

3.4.4 Altitude at the End of Turn

An end of turn altitude of 122 m (400 ft) was selected for testing. This may not have been an optimum choice (as will be discussed in later sections). The lower the end of turn alti-

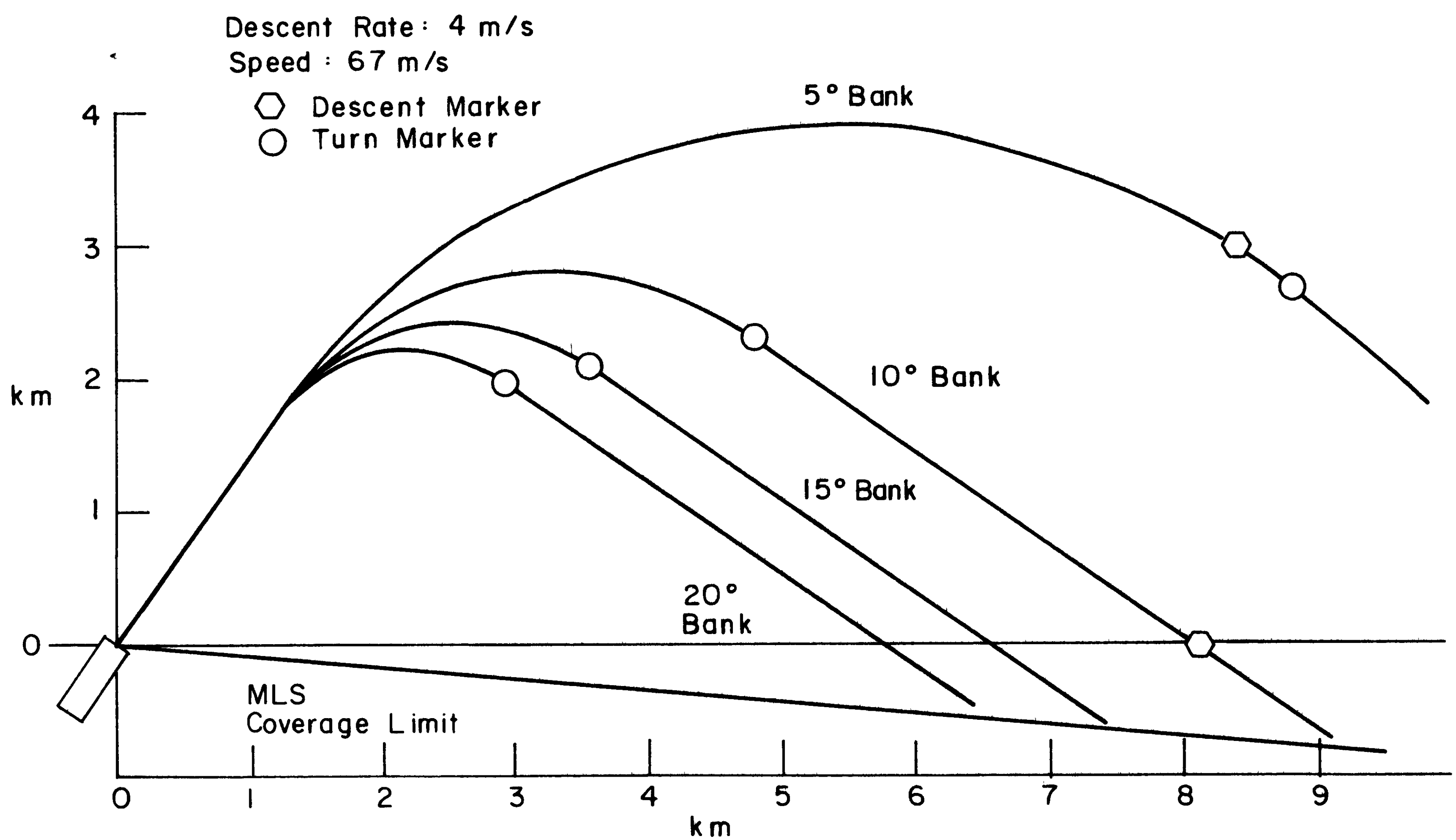


Figure 3-12 Effect of Bank Angle on Approach Path

tude, the greater the effect of the curved approach. Obviously, if the end of turn altitude were, for example, raised to 600 m, the approach would not be unlike a conventional ILS approach. However, as the end of turn altitude is lowered, three problems can occur. First, by lowering the end of turn, the length of the straight final segment is reduced. This aggravates MLS 60° coverage limit problems. This is illustrated in Figure 3-13. Second, a lower end of turn means the pilot has less time to determine the optimum crab angle for landing. And finally, safety considerations preclude flying with steep bank angles and trying to roll out of a turn on the runway heading at too low an altitude, especially in instrument meteorological conditions.

3.4.5 Initial Altitude and Descent Rate

The lower the initial altitude and the greater the descent rate, the shorter is the path distance from the Descent Marker to touchdown. This reduction in path distance can permit turns greater than 60° by allowing the Descent Marker to be within the MLS 60° coverage limit. However, the descent rate and initial altitude are usually set or at least constrained by basic approach standards and by local conditions. Generally these parameters cannot be modified greatly to permit increased flexibility in curved path generation. It must also be noted that pushing descent initiation too close to touchdown may deteriorate curved path flying performance by not leaving enough time between the Descent Marker and the Turn Marker for the pilot to stabilize his descent rate.

In testing, a descent rate of 4 m/s (787 ft/min) was used. At 67 m/s approach speed, this corresponded to a glide slope angle of 3.42°, slightly steeper than today's ILS. An initial

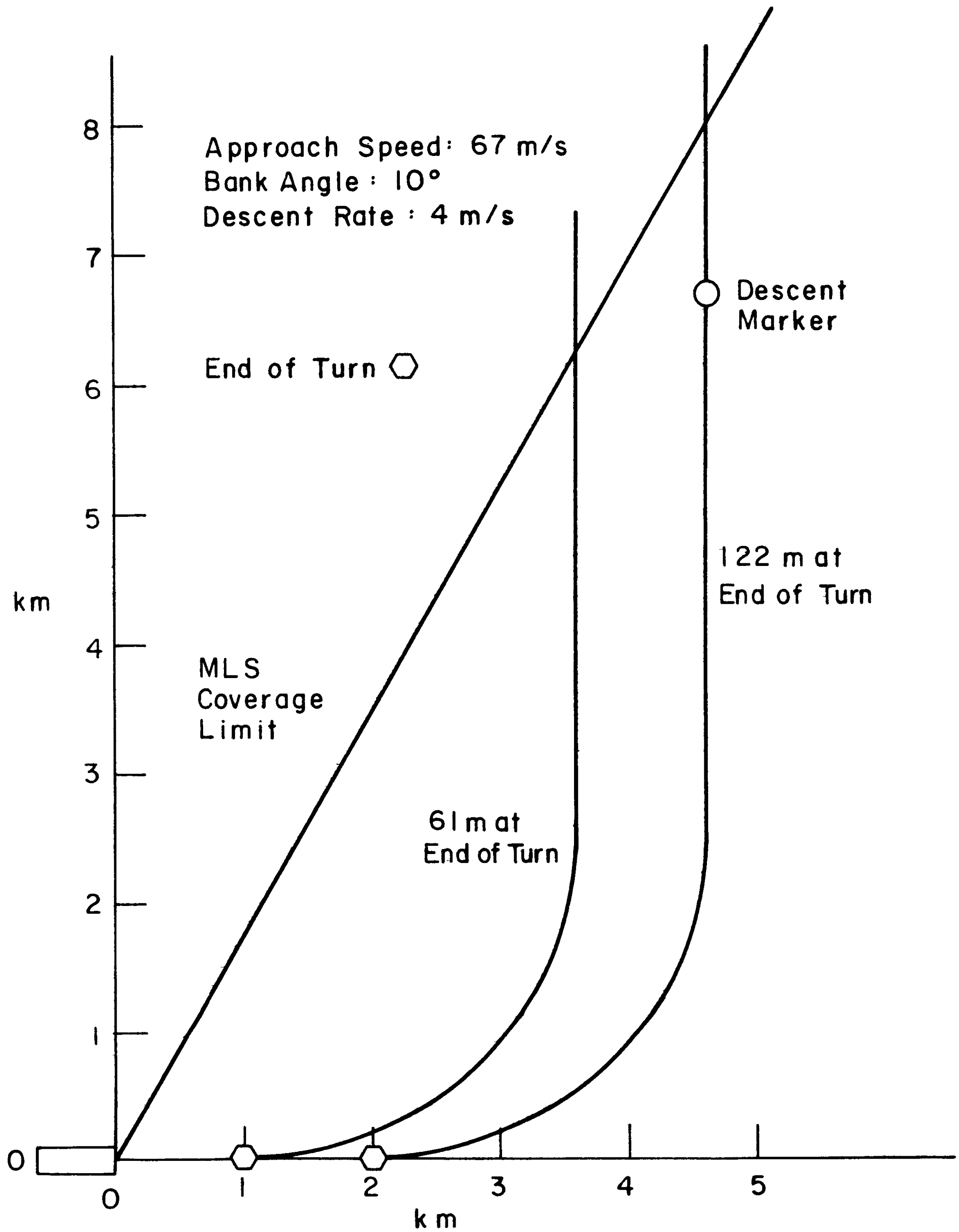


Figure 3-13 Variation in Approach Path with Altitude at End of Turn - 90° Turn

altitude of 610 m (2001 ft) was used for 60^{o} turns and comparison straight-in approaches. An initial altitude of 580 m (1903 ft) was selected for 90^{o} turns, the lower altitude alleviating MLS 60^{o} coverage limit problems.

3.5 Time of Turn Initiation

For a given turn amount, bank angle, and altitude of the end of turn, the time from turn initiation to touchdown does not vary significantly with approach speed. For example, the time from the Turn Marker to touchdown for a 45^{o} turn at 10^{o} bank with an end of turn altitude of 122 m is 1:04 at 50 m/s (97 knots) and 1:06 at 101 m/s (196 knots). This phenomenon is illustrated by Table 3-1. The increase in turn radius of higher speed paths is counteracted by the faster travel along the paths at the higher approach speeds. This phenomenon, while having little effect on manually flying curved approaches, might be useful in the development of an algorithm for sequencing arriving aircraft with different approach speeds, flying curved approach paths.

Table 3-1

Time from Turn Initiation to Touchdown
(in seconds)

Bank Angle (deg)	Distance from End of Turn to Touchdown (m)	Amount of Turn (deg)	Approach Speed (m/s)				
			33	50	67	84	101
10	1020	60	51	51	56	63	71
10	2039	45	77	64	61	62	66
10	2039	60	82	71	71	75	81
10	2039	90	92	86	91	101	112
15	2039	60	75	61	57	58	60

4. Experimental Program

Data for the analysis of curved approaches was collected in an experimental program utilizing nine pilots as simulator test subjects. The pilots were trained in one session and performance data was collected in a second session. The subjects then completed a questionnaire after the second session. Section 4 describes the subject training, the administration of the test cases, and special curve flying techniques.

4.1 Training

Subject pilots were trained to fly the simulator and to fly curved approaches in a three hour training session. The session began with a briefing from a checklist. The briefing provided a general description of the MLS. Briefing topics also included simulator flying technique and instrument presentation, detailed curved approach case descriptions, and specific curved approach flying techniques.

A non-curved approach training case was then run. The subject pilots flew the simulator through a takeoff and landing. Flying around the pattern and performing a conventional approach gave the subjects a feel for the simulator and for the aircraft dynamics. After completing the simulator training run, all pilots flew all ten curved approach test cases (including two straight-in approaches) in a fixed order for training. Coaching and suggestions were given during the training runs. Printed results were discussed after each training case. This completed the training session.

Before data was collected in the second (data collection) session, two curved approach cases were repeated by the pilot as refresher training for the simulator and for flying curves. The same two refresher training cases were flown by each pilot, and the cases provided a sample of most conditions found in the test cases (e.g., wind, no wind, left and right turns).

It must be emphasized that the amount of training was dictated by practicality, and not by a demonstration that additional training would yield little additional proficiency. The results of the comparison between straight-in and curved approaches must be considered in light of this fact. Data on curved approaches was collected after each pilot had flown only ten curved instrument approaches. This is an obvious unfair comparison with straight-in approaches, of which each pilot has flown hundreds or even thousands. However, since neither the time, nor the resources, nor the pilot volunteers were available for an extensive, prolonged curved approach training program, the comparison must be made based on insufficient curved approach training. While subject pilots did feel that they improved their curved approach flying skills even as data collection progressed, they all seemed to have had an understanding of the basic techniques before any data acquisition runs were made. Figures 4-1 and 4-2 illustrate the training effect. These graphs show the crosstrack error at the end of turn (122 m) for given cases (60° no wind and 90° with wind) as a function of the case sequence in the data collection program. The training effect is variable, with the training being more prominent for the 60° turns. Figures 4-1 and 4-2 include a least square curve fit of this possible training effect. These figures, while indicative of a training effect, cannot be considered conclusive.

4.2 Test Case Conduct

Data collection cases were run in the second session after the two refresher training runs cited in Section 4.1.

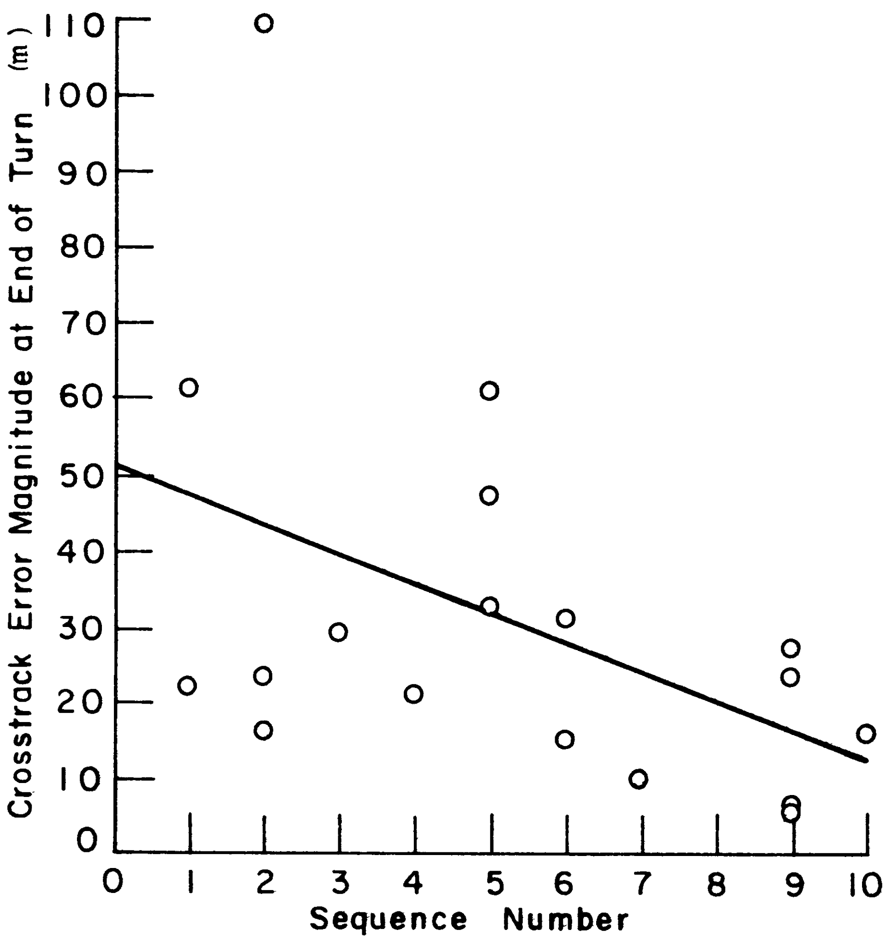


Figure 4-1 Training Effect for 60° No Wind Turns

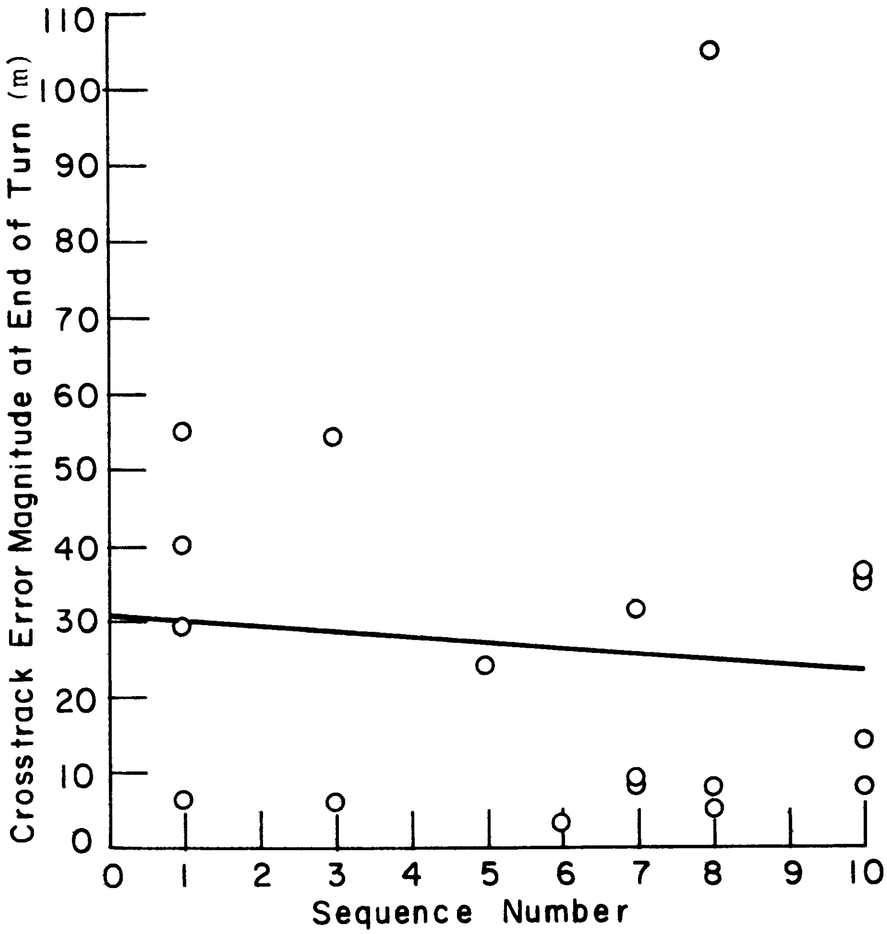


Figure 4-2 Training Effect for 90° Turns with Wind

All subjects flew all ten test cases. The ten cases were as follows:

STRTN-N	straight-in, no wind
STRTN-W	straight-in, wind
C60RN-N	60° right turn, no wind
C60RN-W	60° right turn, wind
C60LN-N	60° left turn, no wind
C60LN-W	60° left turn, wind
C90RN-N	90° right turn, no wind
C90RN-W	90° right turn, wind
C90LN-N	90° left turn, no wind
C90LN-W	90° left turn, wind

Data collection experimental programs were prepared in which the ten cases were ordered using a random number table. These randomly ordered experimental programs were assigned to subjects, again by a random number table. Pilot subjects flew the data collection cases alone and without assistance. Before each case was run, the subject received an oral briefing noting such items as the turn direction and amount and the wind. A case rundown, as shown in Figure 4-3, was also provided. A modified Jeppesen Approach Chart showing the appropriate curved approach path was given to the pilot. This chart was available throughout the run. The case initial position was noted on the chart by an "X". An example chart for a 60° left turn is shown in Figure 4-4.

At the termination of each case, a printout was made of 31 error measurements. A sample printout is shown in Figure 4-5. This printout shows crosstrack and altitude errors at the end of turn (122 m), at 30.5 m (100 ft), along the segment from the Descent Marker to the end of turn, and along the

CASE C60LN-N

TURN:

Direction Left

Amount 60^{o}

Wind Compensated? N/A

Nominal Turn Bank Angle 10^{o}

Altitude at Turn Marker 933 feet

Altitude at End of Turn 400 feet

WIND:

X None

0 ft. : 050^{o} at 10 knots

2000 ft. : 020^{o} at 20 knots

APPROACH PARAMETERS:

Approach Speed 130 knots

Descent Rate 787 fpm

Runway Heading 035^{o}

Descent Marker Altitude 2000 feet

INITIAL CONDITIONS:

Gear Down

Flaps Full

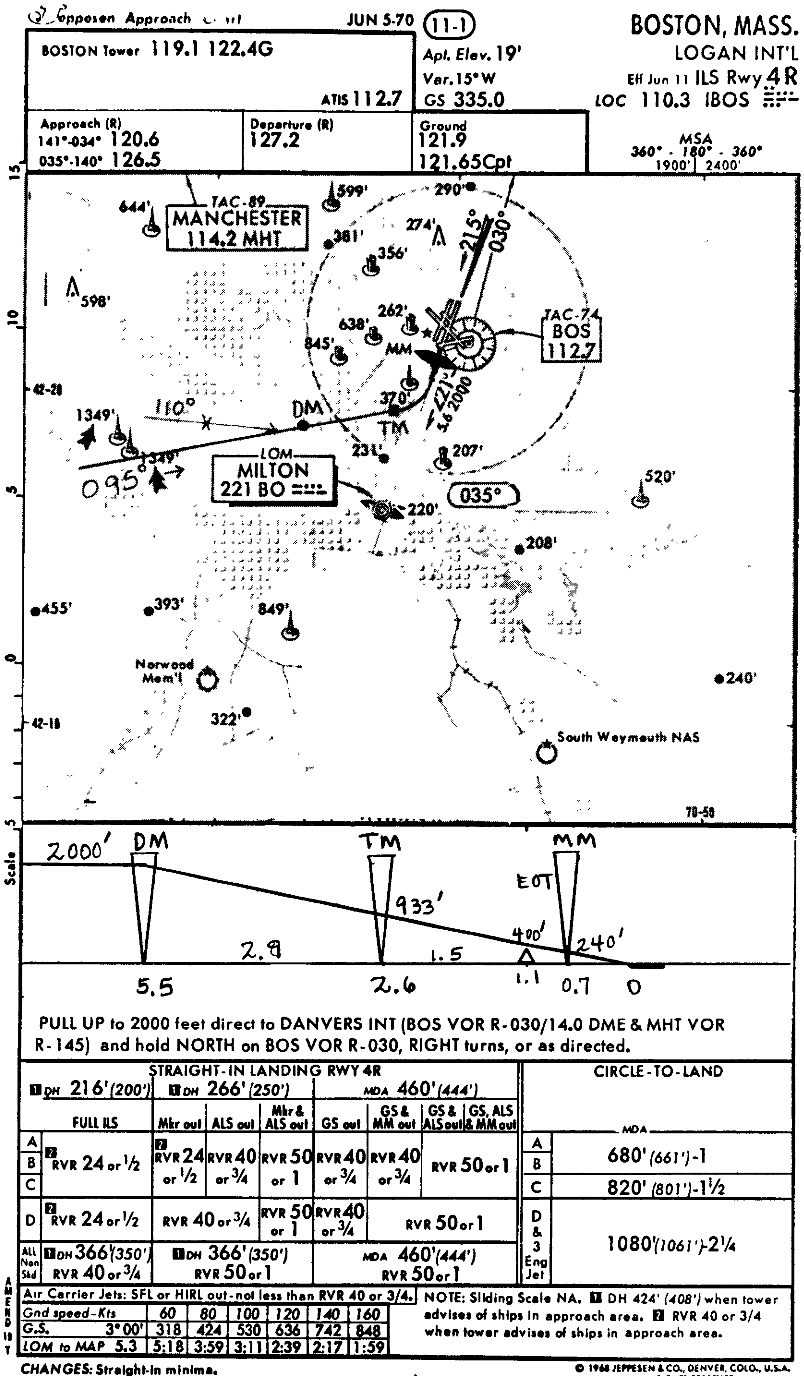
Speed 130 knots

Altitude 2000 feet

Initial Approach Heading 095^{o}

Intercept (current) Heading 110^{o}

Figure 4-3 Sample Case Briefing Sheet



130 knots: 787 ft/min

NOT TO BE USED FOR NAVIGATIONAL PURPOSES

Figure 4-4 Approach Chart for 60° Left Turn

(modification and use with permission of Jeppesen & Co.)

Figure 4-5 Example Computer Output from Curved Approach Test Case

CROSSTRACK ERROR

	MEAN (M)	MEAN (DEG)	MEAN MAG. (M)	MEAN MAG. (DEG)	STD. DEV. (M)	STD. DEV. (DEG)
DESCENT MARKER TO END TURN	-0004	-00.00	0011	00.06	0013	00.06
END TURN (POINT)	-0002	-00.01				
END TURN TO 100 FEET	-0016	-00.18	0016	00.18	0006	00.06
100 FEET (POINT)	0000	00.00				

ALTITUDE ERROR

	MEAN (M)	MEAN (DEG)	MEAN MAG. (M)	MEAN MAG. (DEG)	STD. DEV. (M)	STD. DEV. (DEG)
DESCENT MARKER TO END TURN	-0000	-00.00	0003	00.03	0003	00.00
END TURN (POINT)	-0000	-00.00				
END TURN TO 100 FEET	0004	00.28	0004		0002	00.25
100 FEET (POINT)	0002	00.32				

segment from the end of turn to 30.5 m. Error measurements are shown in both degrees (angular deviation from nominal along path) and meters (absolute off path error). This data was punched onto cards and later processed by computer, as will be described in Section 5.

4.3 Curved Approach Flying Technique

Subject pilots flew curved instrument approaches using conventional ILS type deviation displays. No flight director was provided. The HSI was modified, however, to have the Course Indicator (CI) needle point in the direction of the current nominal heading along the curved path. Thus pilots had to be taught how to use this deviation and nominal heading information to fly a curved path. This section presents the suggested technique.

On flying a conventional straight-in approach, the pilot assumes a heading and corrects deviations by working in heading increments off of his nominal heading. Flying curved approaches is a two step procedure. The CI indicates the current nominal (as opposed to flight director command) heading for that point of the curve corresponding to the aircraft's position. The pilot assumes a nominal 10^{o} bank angle and corrects differences between current and nominal heading by working in bank angle increments about the 10^{o} nominal. Further, the pilot must correct crosstrack deviations by purposefully maintaining a heading difference (lead or lag) until the deviation is reduced.

If $\Delta\psi$ is the difference between the actual heading and the nominal heading and $\Delta\phi$ is the difference between the actual bank angle and the nominal bank angle, then

$$\dot{\Delta\psi} = \frac{g}{v} \text{TAN}(\Delta\phi) \qquad (4\text{-}1)$$

or

$$\Delta\psi = \int \frac{g}{v} \text{TAN}(\Delta\phi)\ dt \qquad (4\text{-}2)$$

Similarly, the crosstrack error Δx can be related to $\Delta\psi$ by

$$\dot{\Delta x} = v\ \text{SIN}(\Delta\psi) \qquad (4\text{-}3)$$

Since $\Delta\psi$ is generally fairly small (less than 10°), equation 4-3 can be written as

$$\dot{\Delta x} = v\ \Delta\psi \qquad (4\text{-}4)$$

or

$$\Delta x = \int v\ \Delta\psi\ dt \qquad (4\text{-}5)$$

Combining equations 4-2 and 4-5, the crosstrack error is related to bank angle by

$$\Delta x = \int v\ (\int \frac{g}{v} \text{TAN}(\Delta\phi)\ dt)\ dt \qquad (4\text{-}6)$$

or, assuming g and v constant,

$$\Delta x = g \iint \text{TAN}(\Delta\phi)\ dt \qquad (4\text{-}7)$$

Putting this in more practical terms, the pilots were told 1) not to let the difference between their actual and the nominal headings to become too large, and 2) to remember that, because of the double integration effect, the deviation needle would seem to correct itself very slowly when a bank angle increment was applied, but that the needle would seem to all of a sudden rapidly swing across the HSI. In conjunction with point 2, pilots were reminded that a bank angle increment would not begin to produce a deviation correction, no matter how large the bank angle increment, until the current heading lead had changed to a lag or vice versa. Wind creates a special flying problem on curved approaches since the wind generally blows parallel to the runway. On a 90° turn a pilot faces a strong crosswind at the beginning of the turn, but ends the turn with practically no crosswind. At the beginning of the turn, the pilot may have a significant crab angle which causes his current heading to lead the nominal heading. The pilot needs this lead at the beginning of the turn, even if there is no deviation. However, by the end of the turn, the pilot does not require a lead or crab angle, as the wind is then effectively a headwind. Thus, the pilot must develop the capability of gradually dumping his initial crab angle during the turn.

5. Results

Curved approach performance and acceptability were analyzed in two ways. Pilot opinion was collected by questionnaires and discussions for a subjective analysis. More objective results were obtained by computer statistical processing of individual test case error printouts. This section briefly describes the analysis of this data and presents the results. Conclusions are presented in Section 6.

5.1 Subjective Results

Subjective results are based on discussions with pilots and on questionnaires completed at the end of the data collection session. The questionnaire is shown in Appendix A. The subjective results reflect pilot opinion of the desirability and safety of this type of curved approach implementation. The pilot opinions were based on safety, operational, and ease of flying considerations. The following are some of the questionnaire and discussion results.

1. Curved versus conventional approaches:

	Curved much harder	Curved little harder	About the same
Total	2	6	1
Airline	1	5	0
General Aviation	1	1	1

One airline pilot, who felt that flying curves was a little harder in simulation, felt that in actual flight curved approaches would be no harder.

2. Effect of wind on curves:

	Much harder with wind	Little harder with wind	No difference
Total	2	6	1
Airline	2	3	1
General Aviation	0	3	0

The same airline pilot referenced in 1. felt that wind would have no effect in an actual flight.

3. Difference of wind effect on curved and straight-in approaches:

	Affect curved more	About the same
Total	5	4
Airline	3	3
General Aviation	2	1

4. Need for End of Turn marker light:

	Yes	No	Don't know
Total	7	1	1
Airline	5	1	0
General Aviation	2	0	1

5. 60° versus 90° turns:

	60° easier	The same
Total	5	4
Airline	2	4
General Aviation	3	0

6. Willingness to fly curved approaches in instrument meteorological conditions:

	Yes	No	Don't know	Conditional
Total	5	0	1	3
Airline	3	0	0	3
General Aviation	2	0	1	0

Conditions given included changes in procedures and mandatory flight director.

7. Desired change in altitude of end of turn from 122m (400 ft):

	Yes	No	Conditional
Total	2	6	1
Airline	2	3	1
General Aviation	0	3	0

Suggested changes included raising the end of turn altitude to 183 m (600 ft) and using the MLS to funnel traffic to the Outer Marker for a conventional approach. The conditional suggestion was to base the end of turn altitude on aircraft size and type.

8. Desired change in bank angle from 10°:

	Yes	No
Total	0	9
Airline	0	6
General Aviation	0	3

9. Willingness to fly curves with modifications suggested by pilot:

	Yes	No	Don't know	No answer
Total	7	0	1	1
Airline	5	0	0	1
General Aviation	2	0	1	0

10. Willingness to fly curves if runway visible before end of turn:

	Yes	No	Don't know
Total	7	0	2
Airline	5	0	1
General Aviation	2	0	1

Additional questions were raised concerning possible safety hazards from vertigo or operation of aircraft at moderately large bank angles at low altitude.

5.2 Numerical Results

Numerical results of curved approach testing were compiled by the computer analysis of test case error printouts. Two analysis routines were employed. One tabulated the mean, standard deviation, and maximum and minimum magnitudes of the 31 case output quantities for specified subjects and cases. It is important to distinguish the difference between the mean and standard deviation of data from various subjects and the measurement of the mean and standard deviation of errors along a path segment in a given run. The former are statistical measures of a collection of data points from a number of runs. The latter are single quantities output at the end of each test run in printouts such as Figure 4-5. Thus, for example, there can be a measure of the mean of the standard deviations of the crosstrack error from the Descent Marker to the end of turn.

Appendix B contains the mean and standard deviations for the collection of all subjects for each individual case. The case names found in the printout are defined in Section 4.2. The signs on the computer printout results indicate the following:

CROSSTRACK ERROR

+ left deviation (fly right)
- right deviation (fly left)

ALTITUDE ERROR

+ low deviation (fly up)
- high deviation (fly down)

The second program performed a Student's test to compute the level of significance of differences in the means of two sets of test cases. The output level indicates the probability that the two groups of cases shown in the printout are different. Thus a level of 0.99 indicates a high probability that the two groups are different. A level near 0.00 indicates a high probability that the two groups are the same.

The remainder of Section 5.2 will present statistical data from curved approach testing.

5.2.1 Curved versus Straight-in Approaches

Pilots were able to fly curved approaches, though not as accurately as they could fly straight-in approaches. Figures 5-1 through 5-4 show crosstrack and altitude errors for straight-in and curved approaches. Note that 18 straight-in and 72 curved cases are compared. Errors for the straight-in approaches are lower. Table 5-1 compares mean magnitude of crosstrack errors between straight-in and curved approaches. (The standard error is the standard deviation divided by the square root of the number of cases.) It must be emphasized that the "95% level" numbers (95% probability of the magnitude being less than or equal to that number) in Table 5-1 are raw estimates based on a limited number of data points. The error distributions at 122 m and 30.5 m altitudes for curved and straight-in approaches are shown in histograms in Figures 5-5 through 5-12.

Figure 5-1 Crosstrack Errors for Straight-in Approaches

PAGE 1

18 POINTS PER ITEM / DATA ACQUISITION

2 CASES:

STRTN-N STRTN-W

9 SUBJECTS:

1 2 3 4 5 6 7 8 9

	METERS				DEGREES			
	MEAN	STD DEV	MAX MAG	MIN MAG	MEAN	STD DEV	MAX MAG	MIN MAG
CROSSTRACK ERROR								
DESCENT MARKER TO END TURN								
SEGMENT MEAN	-10.4	17.4	44	0	-0.043	0.082	0.21	0.00
SEGMENT MEAN MAGNITUDE	20.8	9.6	44	8	0.092	0.052	0.21	0.03
SEGMENT STANDARD DEVIATION	18.0	5.7	26	8	0.095	0.039	0.18	0.03
END OF TURN	-2.7	15.4	42	0	-0.032	0.149	0.42	0.00
END OF TURN (MAGNITUDE)	10.6	11.4	42	0	0.099	0.116	0.42	0.00
END TURN TO 30.5M								
SEGMENT MEAN	-4.7	11.1	24	1	-0.046	0.119	0.28	0.00
SEGMENT MEAN MAGNITUDE	10.6	6.6	24	2	0.106	0.079	0.28	0.00
SEGMENT STANDARD DEVIATION	6.1	3.5	17	1	0.078	0.046	0.21	0.00
30.5M	-0.8	13.2	32	0	-0.010	0.183	0.45	0.00
30.5M (MAGNITUDE)	9.1	9.6	32	0	0.124	0.135	0.45	0.00

Figure 5-2 Altitude Errors for Straight-in Approaches

PAGE 2

18 POINTS PER ITEM / DATA ACQUISITION

2 CASES:

STRTN-N STRTN-W

9 SUBJECTS:

1 2 3 4 5 6 7 8 9

	METERS				DEGREES			
	MEAN	STD DEV	MAX MAG	MIN MAG	MEAN	STD DEV	MAX MAG	MIN MAG
ALTITUDE ERROR								
DESCENT MARKER TO END TURN								
SEGMENT MEAN	1.3	6.4	18	0	0.007	0.042	0.12	0.00
SEGMENT MEAN MAGNITUDE	6.7	3.9	18	2	0.038	0.030	0.12	0.00
SEGMENT STANDARD DEVIATION	7.9	8.1	39	1	0.017	0.023	0.09	0.00
END OF TURN	-1.1	2.5	6	0	-0.029	0.072	0.17	0.00
END OF TURN (MAGNITUDE)	1.8	2.0	6	0	0.059	0.050	0.17	0.00
END TURN TO 30.5M								
SEGMENT MEAN	-0.6	2.0	6	0	-0.016	0.101	0.31	0.00
SEGMENT MEAN MAGNITUDE	1.3	1.9	6	0				
SEGMENT STANDARD DEVIATION	0.7	1.0	4	0	0.047	0.073	0.28	0.00
30.5M	-0.3	1.5	5	0	-0.041	0.208	0.67	0.00
30.5M (MAGNITUDE)	0.7	1.3	5	0	0.128	0.169	0.67	0.00

Figure 5-3 Crosstrack Errors for Curved Approaches

PAGE 1

72 POINTS PER ITEM / DATA ACQUISITION

8 CASES:

C60RN-N C60LN-N C60LN-W C60RN-W C90LN-N C90RN-N C90LN-W C90RN-W

9 SUBJECTS:

1 2 3 4 5 6 7 8 9

	METERS				DEGREES			
	MEAN	STD DEV	MAX MAG	MIN MAG	MEAN	STD DEV	MAX MAG	MIN MAG
CROSSTRACK ERROR								
DESCENT MARKER TO END TURN								
SEGMENT MEAN	-3.7	37.2	158	0	-0.017	0.201	0.87	0.00
SEGMENT MEAN MAGNITUDE	40.3	25.8	172	9	0.225	0.147	0.96	0.03
SEGMENT STANDARD DEVIATION	35.6	16.8	76	9	0.243	0.142	0.71	0.06
END OF TURN	5.8	42.8	150	0	0.064	0.460	1.70	0.00
END OF TURN (MAGNITUDE)	32.1	29.0	150	0	0.339	0.318	1.70	0.00
END TURN TO 30.5M								
SEGMENT MEAN	3.2	24.5	95	0	0.038	0.286	1.18	0.00
SEGMENT MEAN MAGNITUDE	21.2	16.8	95	4	0.237	0.206	1.18	0.03
SEGMENT STANDARD DEVIATION	11.8	10.0	49	2	0.141	0.112	0.56	0.03
30.5M	-2.2	19.7	71	0	-0.030	0.276	1.00	0.00
30.5M (MAGNITUDE)	15.1	12.8	71	0	0.209	0.183	1.00	0.00

Figure 5-4 Altitude Errors for Curved Approaches

PAGE 2

72 POINTS PER ITEM / DATA ACQUISITION

8 CASES:

C60RN-N C60LN-N C60LN-W C60RN-W C90LN-N C90RN-N C90LN-W C90RN-W

9 SUBJECTS:

1 2 3 4 5 6 7 8 9

	METERS				DEGREES			
	MEAN	STD DEV	MAX MAG	MIN MAG	MEAN	STD DEV	MAX MAG	MIN MAG
ALTITUDE ERROR								
DESCENT MARKER TO END TURN								
SEGMENT MEAN	-1.8	4.6	15	0	-0.015	0.040	0.12	0.00
SEGMENT MEAN MAGNITUDE	6.0	3.0	15	1	0.047	0.035	0.15	0.00
SEGMENT STANDARD DEVIATION	5.8	3.0	16	1	0.015	0.024	0.09	0.00
END OF TURN	-1.2	5.0	20	0	-0.036	0.166	0.68	0.00
END OF TURN (MAGNITUDE)	3.2	4.1	20	0	0.111	0.129	0.68	0.00
END TURN TO 30.5M								
SEGMENT MEAN	-0.4	3.3	14	0	-0.022	0.181	0.87	0.00
SEGMENT MEAN MAGNITUDE	1.8	2.8	14	0				
SEGMENT STANDARD DEVIATION	1.0	1.2	6	0	0.080	0.148	0.84	0.00
30.5M	-0.5	2.1	11	0	-0.076	0.282	1.31	0.00
30.5M (MAGNITUDE)	0.9	2.0	11	0	0.163	0.242	1.31	0.00

Table 5-1

Straight-in versus Curved Comparison
Mean Magnitude of Crosstrack Error-in Meters

point or segment	mean magnitude	standard error	maximum error*	95% level*	ratio of mean magnitudes	ratio of 95% levels*	% greater than ½ dot*
Descent Marker to End of Turn							
all curved cases	40.3	3.0	-	-	1.9	-	-
all straight-in cases	20.8	2.3	-	-			-
End of Turn (122 m)							
all curved cases	32.1	3.4	150	76	3.0	2.4	15%
all straight-in cases	10.6	2.7	42	32			0%
30.5 m Altitude							
all curved cases	15.1	1.5	71	33	1.7	1.2	3%
all straight-in cases	9.1	2.3	32	27			0%

*Based on limited testing involving only 18 straight-in and 72 curved approaches.

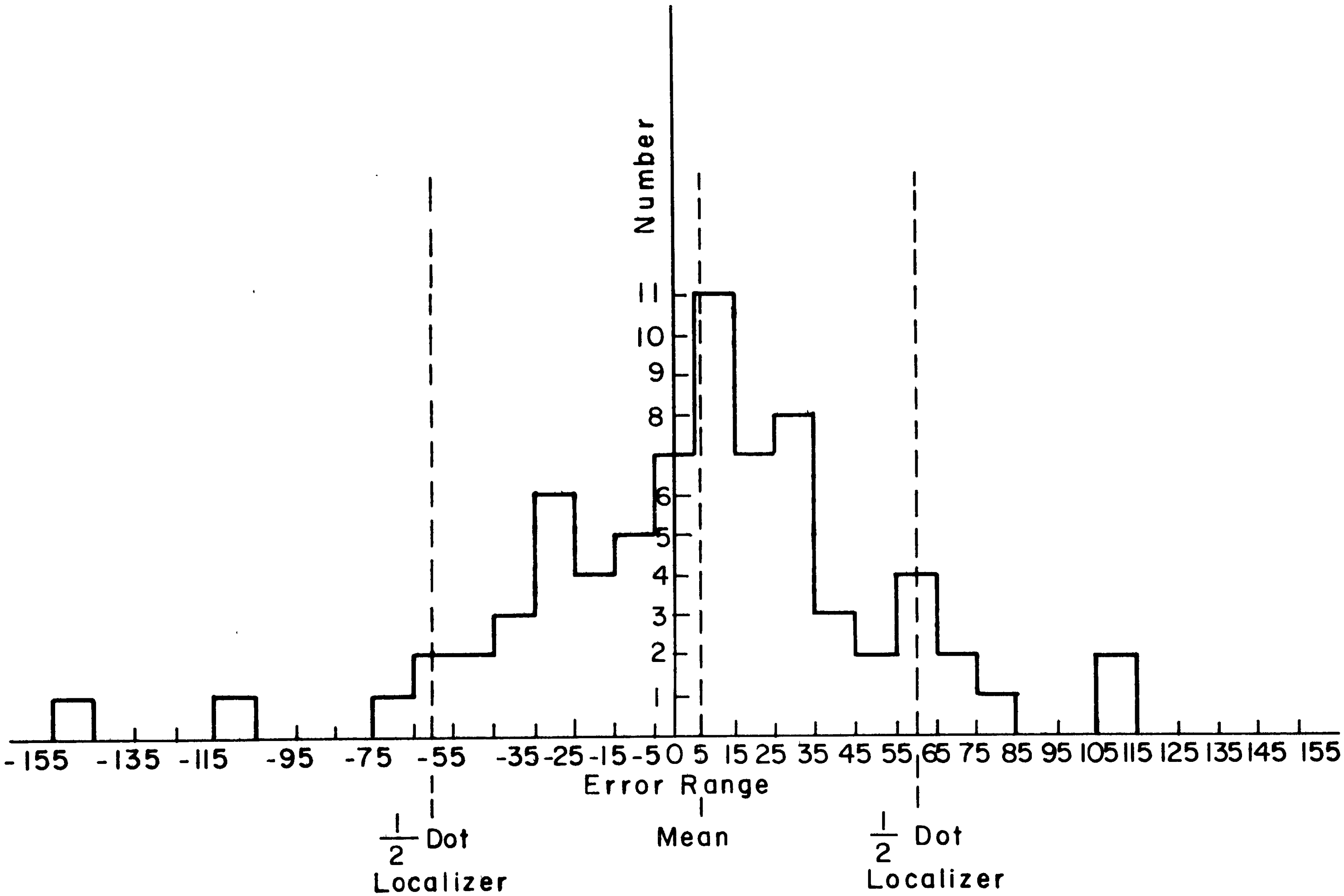


Figure 5-5 Histogram of Crosstrack Errors at End of Turn for All Curves — in Meters

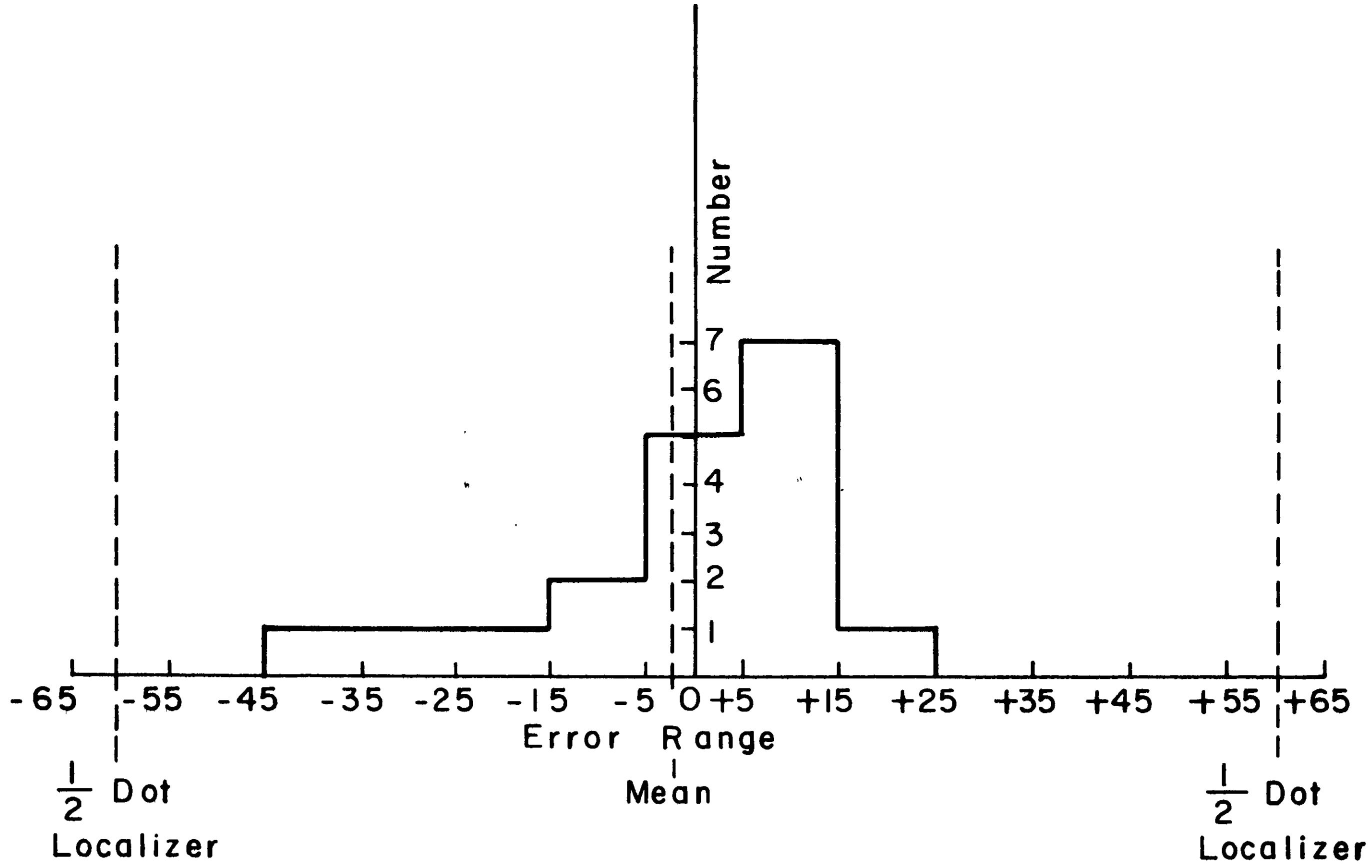


Figure 5-6 Histogram of Crosstrack Errors at 122 m Altitude for All Straight-ins – in Meters

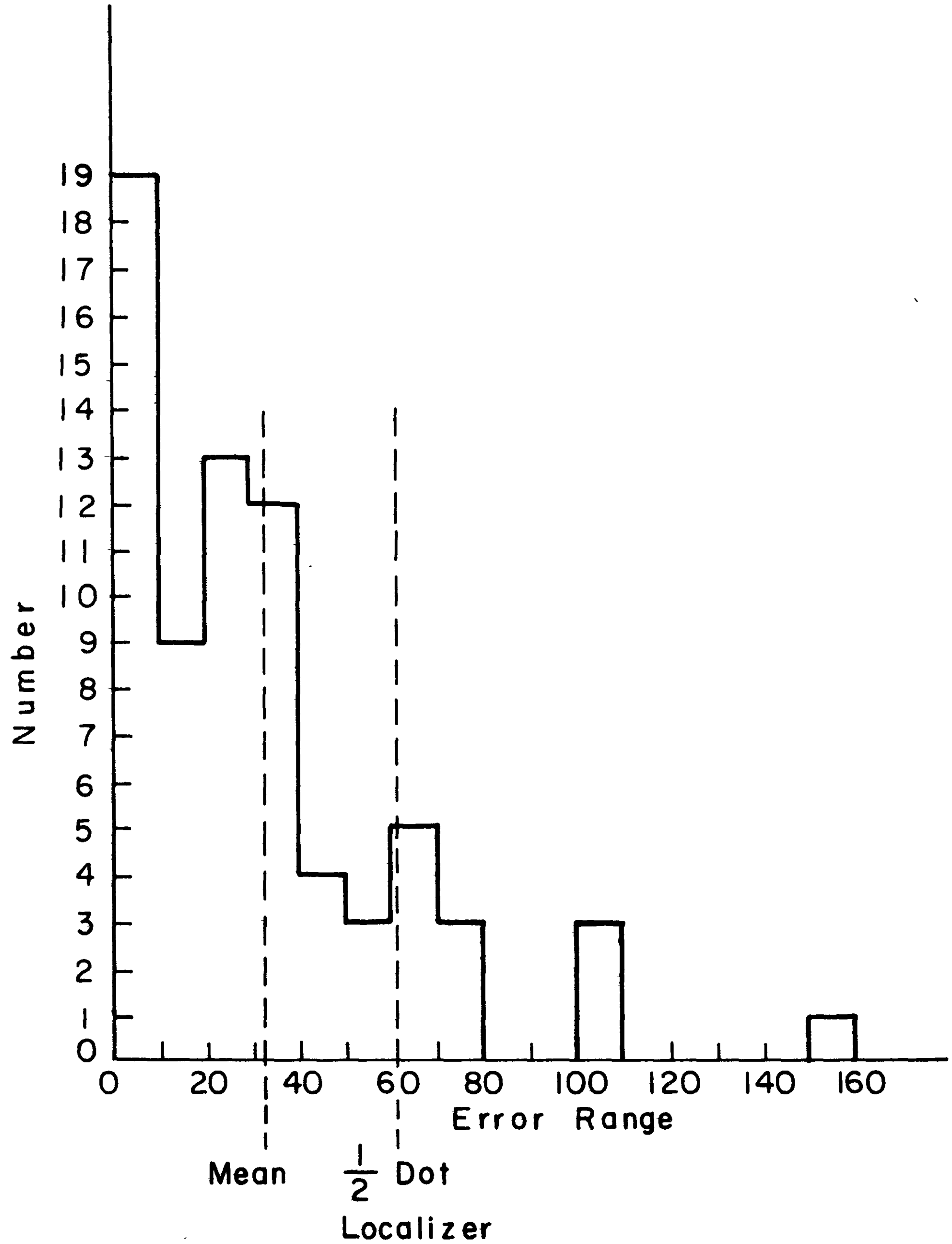


Figure 5-7 Histogram of Magnitudes of Crosstrack Error at End of Turn for All Curves - in Meters

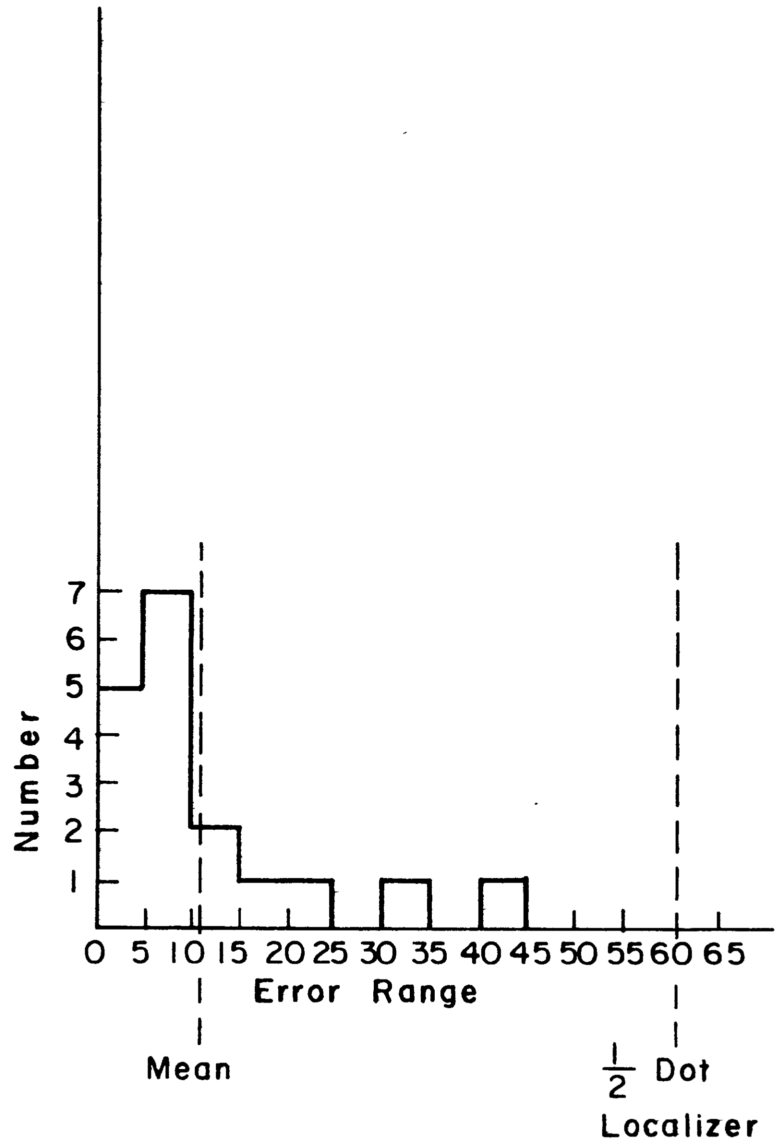


Figure 5-8 Histogram of Magnitudes of Crosstrack Error at 122m Altitude for All Straight-ins - in Meters

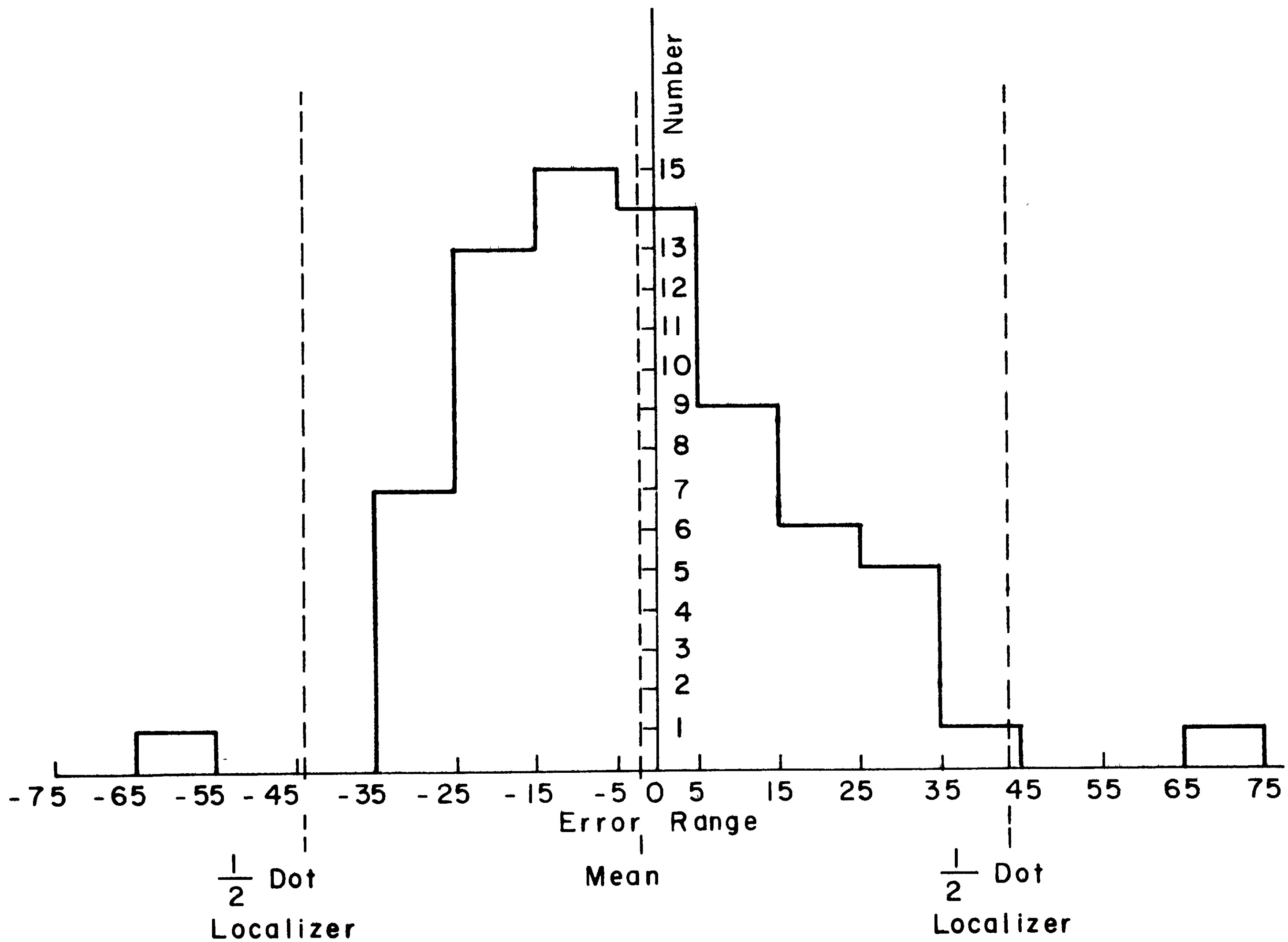


Figure 5-9 Histogram of Crosstrack Errors at 30.5 m Altitude for All Curves – in Meters

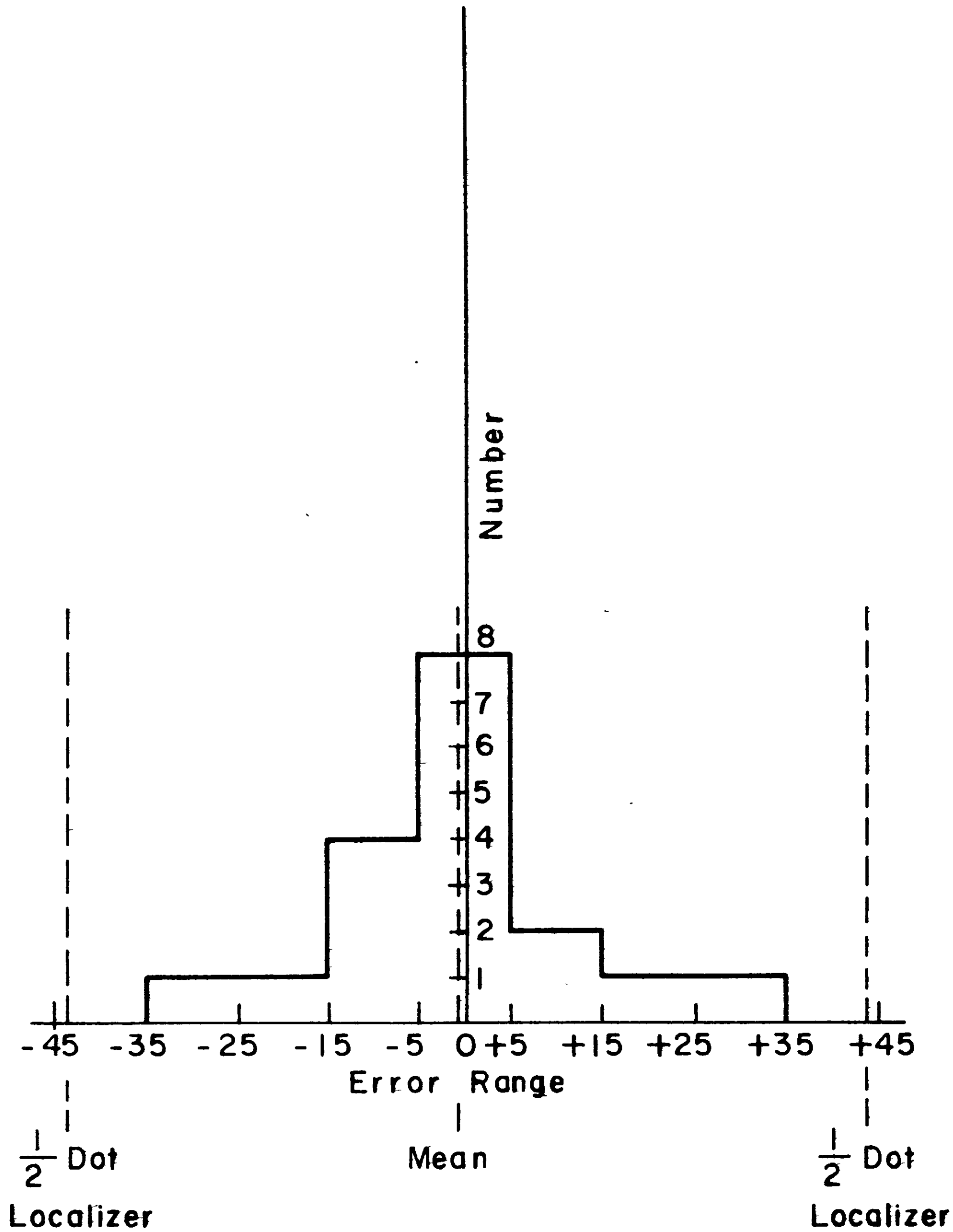


Figure 5-10 Histogram of Crosstrack Errors at 30.5m Altitude for All Straight-ins - in Meters

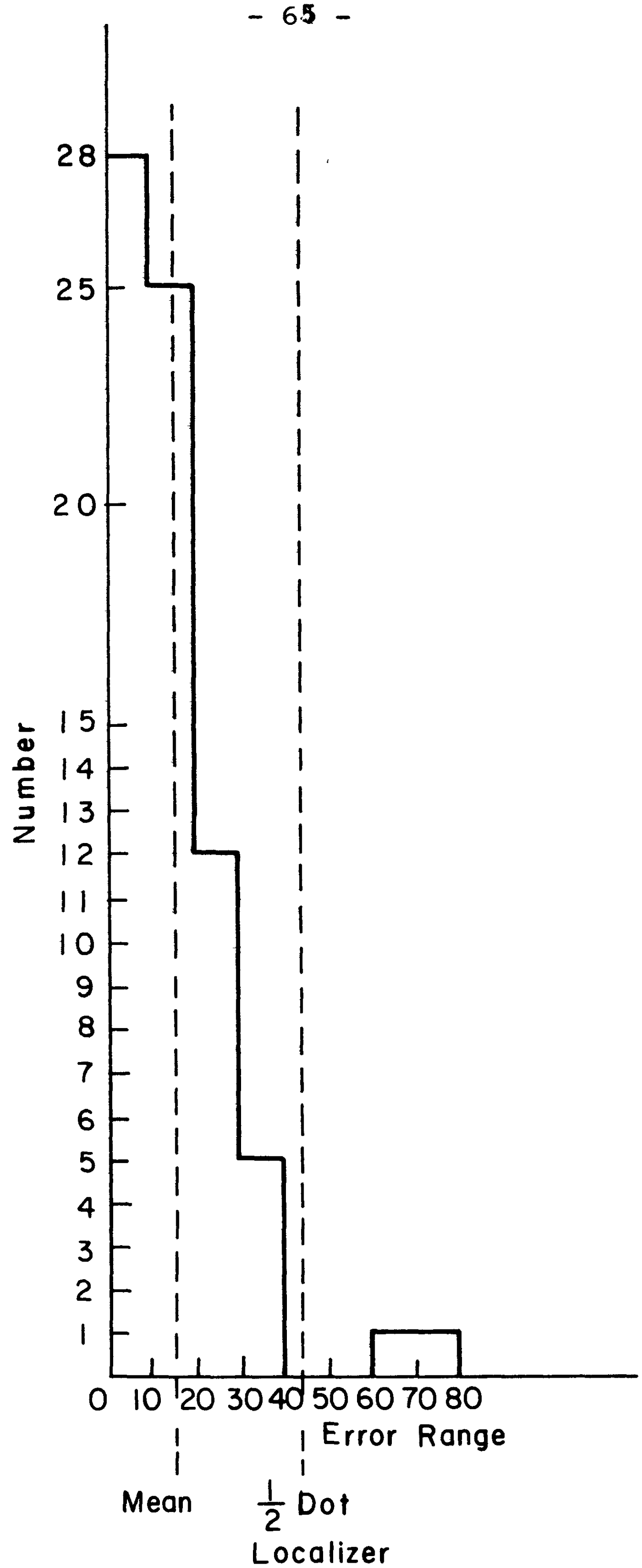


Figure 5-11 Histogram of Magnitudes of Crosstrack Error at 30.5 m Altitude for All Curves - in Meters

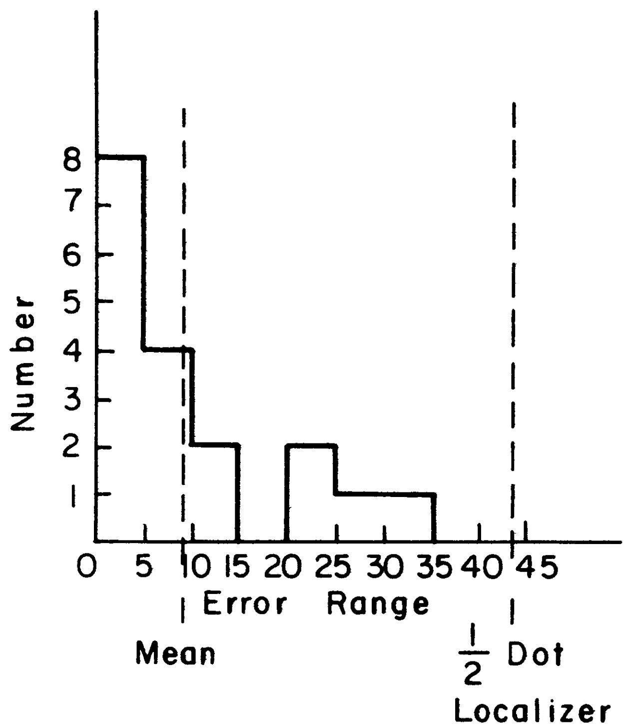


Figure 5-12 Histogram of Magnitudes of Crosstrack Error at 30.5 m Altitude for All Straight-ins-in Meters

Comparing the curved and straight-in numbers shows a definite difference in performance from the Descent Marker to the End of Turn and at the End of Turn (122 m altitude) point. The difference at the 30.5 m altitude is questionable. The mean of the mean magnitudes from the Descent Marker to the End of Turn is nearly twice as large for the curved approaches as for the straight-ins. At the end of turn point this ratio of means is increased to 3.0. By 30.5 m, however, the ratio is only 1.7. Snedecor's F tests show probabilities of difference in the standard deviations of the means of crosstrack error of the curved and straight-in distributions exceeding 99.9% from the Descent Marker to the End of Turn and at the End of Turn point. However, the F test difference at the 30.5 m altitude point shows a probability of difference between 90% and 95%, not quite large enough to statistically verify a difference.

5.2.2 The Effect of Wind

Wind does not have a significant effect on pilot performance in flying curved approaches. Wind cases do have a larger mean magnitude and standard deviation of crosstrack error from the Descent Marker to the End of Turn. However, by the End of Turn point this difference disappears. In fact, the mean magnitudes of crosstrack error at the End of Turn and at 30.5 m altitude are slightly less for wind cases than for no wind cases. While not proving statistically that there is no difference between wind and no wind cases, the t test results in Figure 5-13 and the means in Figures 5-14 through 5-17 indicate this. The key points of this comparison are shown in Table 5-2.

The significance of the differences in the means of the segment mean magnitude and standard deviation of crosstrack error from the Descent Marker to the End of Turn do show that before

Figure 5-13 t Test Comparision of Wind and No Wind Curves

36 POINTS PER ITEM / 35 DEGREES OF FREEDOM / DATA ACQUISITION

9 SUBJECTS:

1 2 3 4 5 6 7 8 9

4 CASES PER GROUP:

GROUP 1	GROUP 2
C60LN-N	C60LN-W
C60RN-N	C60RN-W
C90LN-N	C90LN-W
C90RN-N	C90RN-W

	CROSSTRACK ERROR				ALTITUDE ERROR			
	METERS		DEGREES		METERS		DEGREES	
	T STAT	LEVEL	T STAT	LEVEL	T STAT	LEVEL	T STAT	LEVEL
DESCENT MARKER TO END TURN								
SEGMENT MEAN	0.319	0.248	0.571	0.428	3.505	0.999	2.614	0.987
SEGMENT MEAN MAGNITUDE	2.627	0.987	2.143	0.961	0.642	0.475	0.625	0.464
SEGMENT STANDARD DEVIATION	2.348	0.975	1.840	0.926	0.420	0.323	0.197	0.155
END OF TURN	1.535	0.866	1.565	0.873	1.413	0.833	1.211	0.766
END OF TURN (MAGNITUDE)	-0.667	0.491	-0.716	0.521	-0.434	0.333	-0.180	0.142
END TURN TO 30.5M								
SEGMENT MEAN	0.943	0.648	0.940	0.646	0.879	0.615	0.824	0.584
SEGMENT MEAN MAGNITUDE	-0.706	0.515	-0.726	0.527	-1.221	0.770		
SEGMENT STANDARD DEVIATION	-0.671	0.493	-0.178	0.140	-1.208	0.765	-1.060	0.704
30.5M	1.430	0.838	1.486	0.854	1.354	0.815	1.712	0.904
30.5M (MAGNITUDE)	-0.421	0.324	-0.414	0.318	-1.171	0.750	-1.110	0.725

Figure 5-14 Crosstrack Errors for Curves with No Wind

PAGE 1

36 POINTS PER ITEM / DATA ACQUISITION

4 CASES:

C60LN-N C60RN-N C90LN-N C90RN-N

9 SUBJECTS:

1 2 3 4 5 6 7 8 9

	METERS				DEGREES			
	MEAN	STD DEV	MAX MAG	MIN MAG	MEAN	STD DEV	MAX MAG	MIN MAG
CROSSTRACK ERROR								
DESCENT MARKER TO END TURN								
SEGMENT MEAN	-4.8	23.9	57	2	-0.028	0.151	0.43	0.00
SEGMENT MEAN MAGNITUDE	33.4	13.1	61	9	0.194	0.098	0.43	0.03
SEGMENT STANDARD DEVIATION	31.7	14.9	73	11	0.215	0.125	0.56	0.06
END OF TURN	-0.9	47.2	150	0	-0.009	0.512	1.70	0.00
END OF TURN (MAGNITUDE)	34.2	32.6	150	0	0.363	0.362	1.70	0.00
END TURN TO 30.5M								
SEGMENT MEAN	0.8	26.7	95	0	0.009	0.317	1.18	0.00
SEGMENT MEAN MAGNITUDE	22.6	19.1	95	4	0.254	0.237	1.18	0.03
SEGMENT STANDARD DEVIATION	12.6	11.8	49	2	0.144	0.133	0.56	0.03
30.5M	-5.3	21.4	71	0	-0.075	0.299	1.00	0.00
30.5M (MAGNITUDE)	15.8	15.4	71	0	0.217	0.219	1.00	0.00

Figure 5-15 Altitude Errors for Curves with No Wind

PAGE 2

36 POINTS PER ITEM / DATA ACQUISITION

4 CASES:

C60LN-N C60RN-N C90LN-N C90RN-N

9 SUBJECTS:

1 2 3 4 5 6 7 8 9

	METERS				DEGREES			
	MEAN	STD DEV	MAX MAG	MIN MAG	MEAN	STD DEV	MAX MAG	MIN MAG
ALTITUDE ERROR								
DESCENT MARKER TO END TURN								
SEGMENT MEAN	-3.2	4.0	15	0	-0.023	0.035	0.12	0.00
SEGMENT MEAN MAGNITUDE	5.9	3.2	15	1	0.045	0.033	0.12	0.00
SEGMENT STANDARD DEVIATION	5.7	2.9	12	1	0.014	0.023	0.09	0.00
END OF TURN	-2.0	5.1	20	0	-0.059	0.159	0.57	0.01
END OF TURN (MAGNITUDE)	3.4	4.3	20	0	0.114	0.125	0.57	0.01
END TURN TO 30.5M								
SEGMENT MEAN	-0.8	3.7	12	0	-0.039	0.193	0.59	0.00
SEGMENT MEAN MAGNITUDE	2.2	3.1	12	0				
SEGMENT STANDARD DEVIATION	1.2	1.4	6	0	0.098	0.151	0.56	0.00
30.5M	-0.9	2.3	10	0	-0.132	0.303	1.31	0.00
30.5M (MAGNITUDE)	1.2	2.1	10	0	0.196	0.266	1.31	0.00

Figure 5-16 Crosstrack Errors for Curves with Wind

PAGE 1

36 POINTS PER ITEM / DATA ACQUISITION

4 CASES:

C60LN-W C60RN-W C90LN-W C90RN-W

9 SUBJECTS:

1 2 3 4 5 6 7 8 9

	METERS				DEGREES			
	MEAN	STD DEV	MAX MAG	MIN MAG	MEAN	STD DEV	MAX MAG	MIN MAG
CROSSTRACK ERROR								
DESCENT MARKER TO END TURN								
SEGMENT MEAN	-2.5	46.9	158	0	-0.007	0.240	0.87	0.00
SEGMENT MEAN MAGNITUDE	47.2	32.6	172	14	0.256	0.179	0.96	0.06
SEGMENT STANDARD DEVIATION	39.5	17.7	76	9	0.270	0.153	0.71	0.09
END OF TURN	12.5	36.8	105	3	0.136	0.388	1.18	0.03
END OF TURN (MAGNITUDE)	30.0	24.7	105	3	0.314	0.266	1.18	0.03
END TURN TO 30.5M								
SEGMENT MEAN	5.7	21.7	68	0	0.067	0.248	0.81	0.00
SEGMENT MEAN MAGNITUDE	19.8	14.0	68	4	0.219	0.167	0.81	0.03
SEGMENT STANDARD DEVIATION	11.0	7.7	41	3	0.139	0.085	0.46	0.03
30.5M	0.8	17.3	35	1	0.015	0.242	0.50	0.00
30.5M (MAGNITUDE)	14.5	9.5	35	1	0.200	0.138	0.50	0.00

Figure 5-17 Altitude Errors for Curves with Wind

PAGE 2

36 POINTS PER ITEM / DATA ACQUISITION

4 CASES:

C60LN-W C60RN-W C90LN-W C90RN-W

9 SUBJECTS:

1 2 3 4 5 6 7 8 9

	METERS				DEGREES			
	MEAN	STD DEV	MAX MAG	MIN MAG	MEAN	STD DEV	MAX MAG	MIN MAG
ALTITUDE ERROR								
DESCENT MARKER TO END TURN								
SEGMENT MEAN	-0.5	4.8	12	0	-0.006	0.043	0.12	0.00
SEGMENT MEAN MAGNITUDE	6.2	2.9	14	2	0.049	0.036	0.15	0.00
SEGMENT STANDARD DEVIATION	5.9	3.1	16	1	0.015	0.025	0.09	0.00
END OF TURN	-0.4	4.8	17	0	-0.013	0.170	0.68	0.00
END OF TURN (MAGNITUDE)	2.9	3.8	17	0	0.108	0.132	0.68	0.00
END TURN TO 30.5M								
SEGMENT MEAN	-0.1	2.7	14	0	-0.005	0.167	0.87	0.00
SEGMENT MEAN MAGNITUDE	1.4	2.4	14	0				
SEGMENT STANDARD DEVIATION	0.9	1.0	4	0	0.061	0.142	0.84	0.00
30.5M	-0.2	1.9	11	0	-0.019	0.246	1.28	0.00
30.5M (MAGNITUDE)	0.6	1.8	11	0	0.130	0.209	1.28	0.00

Table 5-2

Wind/No Wind Comparison
Crosstrack Error for Curves - in Meters

point or segment	mean	standard error	ratio of means	t test significance
magnitude from Descent Marker to End of Turn				
no wind cases	33.4	2.2	1.4	99%
wind cases	47.2	5.4		
standard deviation from Descent Marker to End of Turn				
no wind cases	31.7	2.5	1.2	98%
wind cases	39.5	3.0		
magnitude at end of turn				
no wind cases	34.2	5.4	0.9	49%
wind cases	30.0	4.1		
magnitude at 30.5 m				
no wind cases	15.8	2.6	0.9	32%
wind cases	14.5	1.6		

the End of Turn point, the size of the error is likely to be larger with wind and the variation in error size is also likely to be larger in each wind approach as compared to no wind approaches.

5.2.3 Comparison between 60° and 90° Turns

The only effect in increasing the turn amount from 60° to 90° was to increase the mean of the segment mean magnitude and standard deviation from the Descent Marker to the End of Turn. It was statistically demonstrated that there was no difference between 60° and 90° turns at the End of Turn point. The results also fail to prove a difference at 30.5 m. The t test results are given in Figure 5-18. Mean printouts are shown in Figures 5-19 through 5-22. The 60° versus 90° comparison is summarized in Table 5-3.

5.2.4 Left and Right Turn Comparison

A surprising and difficult to explain difference between left and right turn performance was found. This difference is of little physical significance and shows up only at the 30.5 m level where the mean magnitude of crosstrack error for left turns is less than that for right turns. No difference in turn performance could be found during the turn or at the End of Turn point, other than the fact that the mean of the segment standard deviations from the Descent Marker to the End of Turn was slightly, but statistically significantly, higher for left turns. These results are summarized in Table 5-4.

This difference between left and right turns at 30.5 m is probably a fluke, or results, perhaps, from some simulator bias. It is not a wind effect. The crosswind component on landing is only 1.3 m/s. Further, this effect is demonstrated for both wind and no wind cases. Figures 5-23 through 5-25 show t test

Figure 5-18 t Test Comparision of 60° and 90° Curves

36 POINTS PER ITEM / 35 DEGREES OF FREEDOM / DATA ACQUISITION

9 SUBJECTS:

1 2 3 4 5 6 7 8 9

4 CASES PER GROUP:

GROUP 1	GROUP 2
C60LN-N	C90LN-N
C60RN-N	C90RN-N
C60LN-W	C90LN-W
C60RN-W	C90RN-W

	CROSSTRACK ERROR				ALTITUDE ERROR			
	METERS		DEGREES		METERS		DEGREES	
	T STAT	LEVEL	T STAT	LEVEL	T STAT	LEVEL	T STAT	LEVEL
DESCENT MARKER TO END TURN								
SEGMENT MEAN	0.915	0.633	0.771	0.554	-0.697	0.510	0.114	0.090
SEGMENT MEAN MAGNITUDE	2.932	0.994	3.505	0.999	2.503	0.983	3.714	0.999
SEGMENT STANDARD DEVIATION	4.987	1.000	4.235	1.000	2.533	0.984	0.144	0.114
END OF TURN	0.686	0.502	0.756	0.546	1.608	0.883	1.301	0.798
END OF TURN (MAGNITUDE)	-0.041	0.033	0.414	0.319	-0.882	0.616	0.235	0.184
END TURN TO 30.5M								
SEGMENT MEAN	0.982	0.667	0.929	0.641	1.049	0.699	0.758	0.547
SEGMENT MEAN MAGNITUDE	0.091	0.072	0.414	0.318	-0.301	0.235		
SEGMENT STANDARD DEVIATION	-1.825	0.923	-1.558	0.872	-1.379	0.823	0.616	0.458
30.5M	1.734	0.917	1.758	0.912	1.455	0.845	1.790	0.918
30.5M (MAGNITUDE)	0.955	0.654	1.007	0.679	-0.826	0.585	-1.172	0.751

Figure 5-19 Crosstrack Errors for 60° Curves

PAGE 1

36 POINTS PER ITEM / DATA ACQUISITION

4 CASES:

C60LN-N C60LN-W C60RN-N C60RN-W

9 SUBJECTS:

1 2 3 4 5 6 7 8 9

	METERS				DEGREES			
	MEAN	STD DEV	MAX MAG	MIN MAG	MEAN	STD DEV	MAX MAG	MIN MAG
CROSSTRACK ERROR								
DESCENT MARKER TO END TURN								
SEGMENT MEAN	-7.3	24.2	59	2	-0.035	0.119	0.28	0.00
SEGMENT MEAN MAGNITUDE	32.2	12.9	72	9	0.171	0.073	0.40	0.03
SEGMENT STANDARD DEVIATION	28.3	12.7	64	9	0.184	0.093	0.46	0.06
END OF TURN	2.6	40.2	109	4	0.026	0.405	1.10	0.03
END OF TURN (MAGNITUDE)	32.2	24.1	109	4	0.322	0.247	1.10	0.03
END TURN TO 30.5M								
SEGMENT MEAN	0.5	19.7	55	0	0.008	0.217	0.65	0.00
SEGMENT MEAN MAGNITUDE	21.0	12.9	55	5	0.227	0.153	0.65	0.03
SEGMENT STANDARD DEVIATION	14.0	11.9	49	2	0.162	0.133	0.56	0.03
30.5M	-6.1	17.1	64	1	-0.083	0.239	0.90	0.00
30.5M (MAGNITUDE)	13.8	11.8	64	1	0.189	0.168	0.90	0.00

Figure 5-20 Altitude Errors for 60° Curves

PAGE 2

36 POINTS PEP ITEM / DATA ACQUISITION

4 CASES:

C60LN-N C60LN-W C60RN-N C60RN-W

9 SUBJECTS:

1 2 3 4 5 6 7 8 9

	METERS				DEGREES			
	MEAN	STD DEV	MAX MAG	MIN MAG	MEAN	STD DEV	MAX MAG	MIN MAG
ALTITUDE ERROR								
DESCENT MARKER TO END TURN								
SEGMENT MEAN	-1.5	4.6	15	0	-0.015	0.036	0.12	0.00
SEGMENT MEAN MAGNITUDE	5.2	2.9	15	1	0.033	0.028	0.12	0.00
SEGMENT STANDARD DEVIATION	4.9	2.4	10	1	0.014	0.022	0.09	0.00
END OF TURN	-2.2	5.4	20	0	-0.063	0.155	0.57	0.00
END OF TURN (MAGNITUDE)	3.6	4.6	20	0	0.107	0.129	0.57	0.00
END TURN TO 30.5M								
SEGMENT MEAN	-0.8	3.3	12	0	-0.039	0.157	0.59	0.00
SEGMENT MEAN MAGNITUDE	1.9	2.9	12	0				
SEGMENT STANDARD DEVIATION	1.3	1.3	6	0	0.068	0.130	0.56	0.00
30.5M	-0.9	2.2	10	0	-0.136	0.299	1.31	0.00
30.5M (MAGNITUDE)	1.1	2.1	10	0	0.198	0.262	1.31	0.00

Figure 5-21 Crosstrack Errors for 90° Curves

PAGE 1

36 POINTS PER ITEM / DATA ACQUISITION

4 CASES:

C90LN-N C90LN-W C90RN-N C90RN-W

9 SUBJECTS:

1 2 3 4 5 6 7 8 9

	METERS				DEGREES			
	MEAN	STD DEV	MAX MAG	MIN MAG	MEAN	STD DEV	MAX MAG	MIN MAG
CROSSTRACK ERROR								
DESCENT MARKER TO END TURN								
SEGMENT MEAN	-0.1	46.5	158	0	-0.000	0.257	0.87	0.00
SEGMENT MEAN MAGNITUDE	48.4	32.2	172	14	0.279	0.179	0.96	0.06
SEGMENT STANDARD DEVIATION	42.9	17.2	76	14	0.302	0.158	0.71	0.09
END OF TURN	9.0	45.2	150	0	0.102	0.507	1.70	0.00
END OF TURN (MAGNITUDE)	31.9	33.2	150	0	0.355	0.376	1.70	0.00
END TURN TO 30.5M								
SEGMENT MEAN	5.9	28.2	95	0	0.068	0.339	1.18	0.00
SEGMENT MEAN MAGNITUDE	21.4	20.0	95	4	0.247	0.248	1.18	0.03
SEGMENT STANDARD DEVIATION	9.6	7.0	38	3	0.120	0.079	0.43	0.03
30.5M	1.6	21.3	71	0	0.024	0.299	1.00	0.00
30.5M (MAGNITUDE)	16.4	13.6	71	0	0.229	0.194	1.00	0.00

Figure 5-22 Altitude Errors for 90° Curves

PAGE 2

36 POINTS PER ITEM / DATA ACQUISITION

4 CASES:

C90LN-N C90LN-W C90RN-N C90RN-W

9 SUBJECTS:

1 2 3 4 5 6 7 8 9

	METERS				DEGREES			
	MEAN	STD DEV	MAX MAG	MIN MAG	MEAN	STD DEV	MAX MAG	MIN MAG
ALTITUDE ERROR								
DESCENT MARKER TO END TURN								
SEGMENT MEAN	-2.2	4.5	12	0	-0.014	0.043	0.12	0.00
SEGMENT MEAN MAGNITUDE	6.9	3.0	14	2	0.061	0.035	0.15	0.00
SEGMENT STANDARD DEVIATION	6.7	3.2	16	1	0.015	0.026	0.09	0.00
END OF TURN	-0.3	4.3	17	0	-0.009	0.172	0.68	0.00
END OF TURN (MAGNITUDE)	2.7	3.4	17	0	0.115	0.129	0.68	0.00
END TURN TO 30.5M								
SEGMENT MEAN	0.0	3.2	14	0	-0.006	0.201	0.87	0.00
SEGMENT MEAN MAGNITUDE	1.7	2.8	14	0				
SEGMENT STANDARD DEVIATION	0.8	1.0	5	0	0.091	0.163	0.84	0.00
30.5M	-0.2	2.0	11	0	-0.016	0.249	1.28	0.00
30.5M (MAGNITUDE)	0.7	1.9	11	0	0.128	0.214	1.28	0.00

Table 5-3

60° versus 90° Turn Comparison
Crosstrack Errors - in Meters

point or segment	mean	standard error	ratio of means	t test significance
magnitude from Descent Marker to End of Turn				
60° turns	32.2	2.2	1.5	99%
90° turns	48.4	5.4		
standard deviation from Descent Marker to End of Turn				
60° turns	28.3	2.1	1.5	100%
90° turns	42.9	2.9		
magnitude at End of Turn				
60° turns	32.2	4.0	1.0	3%
90° turns	31.9	5.5		
magnitude at 30.5m				
60° turns	13.8	2.0	1.2	65%
90° turns	16.4	2.3		

Table 5-4

Left versus Right Turn Comparison
Crosstrack Error - in Meters

point or segment	mean	standard error	ratio of means	t test significance
magnitude from Descent Marker to End of Turn				
left turns	40.0	4.2	1.0	17%
right turns	40.6	4.4		
standard deviation from Descent Marker to End of Turn				
left turns	39.6	3.0	0.8	99%
right turns	31.7	2.5		
magnitude at End of Turn				
left turns	32.4	5.2	1.0	10%
right turns	31.7	4.5		
magnitude at 30.5m				
left turns	12.0	1.6	1.5	97%
right turns	18.3	2.5		

Figure 5-23 t Test Comparision of All Left and Right Turns

36 POINTS PER ITEM / 35 DEGREES OF FREEDOM / DATA ACQUISITION

9 SUBJECTS:

1 2 3 4 5 6 7 8 9

4 CASES PER GROUP:

GROUP 1	GROUP 2
C60LN-N	C60RN-N
C60LN-W	C60RN-W
C90LN-N	C90RN-N
C90LN-W	C90RN-W

	CROSSTRACK ERROR				ALTITUDE ERROR			
	METERS		DEGREES		METERS		DEGREES	
	T STAT	LEVEL	T STAT	LEVEL	T STAT	LEVEL	T STAT	LEVEL
DESCENT MARKER TO END TURN								
SEGMENT MEAN	2.889	0.993	2.734	0.990	1.134	0.735	1.076	0.711
SEGMENT MEAN MAGNITUDE	0.213	0.168	0.058	0.046	-1.352	0.815	-1.624	0.887
SEGMENT STANDARD DEVIATION	-2.915	0.994	-1.405	0.831	-0.977	0.665	-1.190	0.758
END OF TURN	1.846	0.926	1.873	0.930	0.129	0.102	0.470	0.359
END OF TURN (MAGNITUDE)	-0.131	0.104	-0.166	0.131	0.151	0.119	-0.132	0.104
END TURN TO 30.5M								
SEGMENT MEAN	0.443	0.339	0.334	0.260	0.146	0.115	0.552	0.415
SEGMENT MEAN MAGNITUDE	0.107	0.085	0.089	0.070	0.416	0.320		
SEGMENT STANDARD DEVIATION	1.303	0.799	1.172	0.751	0.380	0.294	0.340	0.264
30.5M	-1.347	0.813	-1.331	0.808	0.066	0.052	-0.410	0.316
30.5M (MAGNITUDE)	2.248	0.969	2.281	0.971	-0.334	0.259	-0.439	0.336

Figure 5-24 t Test Comparision of Left and Right Turns with No Wind

18 POINTS PER ITEM / 17 DEGREES OF FREEDOM / DATA ACQUISITION

9 SUBJECTS:

1 2 3 4 5 6 7 8 9

2 CASES PER GROUP:

GROUP 1	GROUP 2
C60LN-N	C60RN-N
C90LN-N	C90RN-N

	CROSSTRACK ERROR				ALTITUDE ERROR			
	METERS		DEGREES		METERS		DEGREES	
	T STAT	LEVEL	T STAT	LEVEL	T STAT	LEVEL	T STAT	LEVEL
DESCENT MARKER TO END TURN								
SEGMENT MEAN	1.270	0.779	1.919	0.928	0.000	0.000	-0.000	0.000
SEGMENT MEAN MAGNITUDE	0.762	0.544	0.451	0.342	-1.082	0.706	-1.065	0.698
SEGMENT STANDARD DEVIATION	-1.871	0.921	-0.983	0.660	-0.801	0.566	-0.615	0.453
END OF TURN	2.634	0.983	2.554	0.979	-0.455	0.345	-0.252	0.196
END OF TURN (MAGNITUDE)	0.000	0.000	-0.041	0.033	1.073	0.702	1.141	0.730
END TURN TO 30.5M								
SEGMENT MEAN	1.064	0.698	0.920	0.630	-0.545	0.407	-0.257	0.200
SEGMENT MEAN MAGNITUDE	0.604	0.446	0.551	0.411	1.075	0.703		
SEGMENT STANDARD DEVIATION	0.773	0.550	0.770	0.548	0.591	0.438	1.142	0.731
30.5M	-0.685	0.497	-0.673	0.490	-0.636	0.467	-0.793	0.561
30.5M (MAGNITUDE)	2.033	0.942	2.054	0.944	1.320	0.796	1.139	0.730

Figure 5-25 t Test Comparision of Left and Right Turns with Wind

18 POINTS PER ITEM / 17 DEGREES OF FREEDOM / DATA ACQUISITION

9 SUBJECTS:

1 2 3 4 5 6 7 8 9

2 CASES PER GROUP:

GROUP 1	GROUP 2
C60LN-W	C60RN-W
C90LN-W	C90RN-W

	CROSSTRACK ERROR				ALTITUDE ERROR			
	METERS		DEGREES		METERS		DEGREES	
	T STAT	LEVEL	T STAT	LEVEL	T STAT	LEVEL	T STAT	LEVEL
DESCENT MARKER TO END TURN								
SEGMENT MEAN	2.722	0.986	2.089	0.948	1.693	0.891	1.508	0.850
SEGMENT MEAN MAGNITUDE	-0.454	0.344	-0.439	0.334	-0.797	0.564	-1.197	0.752
SEGMENT STANDARD DEVIATION	-2.190	0.957	-1.037	0.686	-0.569	0.423	-1.166	0.740
END OF TURN	-0.052	0.041	-0.027	0.021	0.677	0.492	0.852	0.594
END OF TURN (MAGNITUDE)	-0.226	0.176	-0.222	0.173	-1.351	0.806	-1.639	0.880
END TURN TO 30.5M								
SEGMENT MEAN	-0.812	0.572	-0.875	0.606	0.807	0.569	0.975	0.657
SEGMENT MEAN MAGNITUDE	-0.431	0.328	-0.404	0.308	-0.814	0.573		
SEGMENT STANDARD DEVIATION	1.280	0.782	1.021	0.679	-0.156	0.122	-0.798	0.564
30.5M	-1.384	0.816	-1.375	0.813	0.587	0.435	0.111	0.087
30.5M (MAGNITUDE)	1.013	0.675	1.042	0.688	-1.528	0.855	-1.753	0.902

results for all left versus right turns and for left versus right turns without and with wind. Figures 5-26 through 5-29 show the means for all left and right turns.

5.2.5 Inside versus Outside of Curve

When flying curved approaches, subjects tended to have deviations which were on the outside of the curved path rather than on the inside. Referring back to Figures 5-26 and 5-28, it can be seen that the average of the mean signed crosstrack deviations for the segment from the Descent Marker to the End of Turn is -18.1 m for left turns and +10.7 m for right turns. In both cases, the sign of the deviation indicates that the subjects were on the outside of the curve. Combining these two figures, an average value of 14.4 m outside the curve can be computed for the mean deviation along the segment from the Descent Marker to the End of Turn. The t test result in Figure 5-23 shows a 99% likelihood of difference between the signed means along this segment for left and right turns, again illustrating the tendency to be on the outside of the turn. Wind could be a contributing factor to this tendency. The wind has a significant component blowing from the inside to the outside of the curve. Figures 5-24 and 5-25 show t test results which are statistically conclusive (99% level) for wind cases, but are not (78% level) for no wind cases.

5.2.6 Altitude Performance

Although the computer printouts in Section 5 contain statistical data on altitude errors in flying curved approaches, these errors were not discussed in the previous portions of Section 5. Flying horizontally curved paths did not have a physically significant effect on the vertical profile performance. For example, the mean magnitude of altitude error at

Figure 5-26 Crosstrack Errors for Left Turns

PAGE 1

36 POINTS PER ITEM / DATA ACQUISITION

4 CASES:

C60LN-N C60LN-W C90LN-N C90LN-W

9 SUBJECTS:

1 2 3 4 5 6 7 8 9

	METERS				DEGREES			
	MEAN	STD DEV	MAX MAG	MIN MAG	MEAN	STD DEV	MAX MAG	MIN MAG
CROSSTRACK ERROR								
DESCENT MARKER TO END TURN								
SEGMENT MEAN	-18.1	31.5	152	2	-0.091	0.170	0.75	0.00
SEGMENT MEAN MAGNITUDE	40.0	25.4	152	9	0.225	0.143	0.75	0.03
SEGMENT STANDARD DEVIATION	39.6	17.7	75	11	0.257	0.143	0.71	0.06
END OF TURN	-4.2	44.7	150	3	-0.046	0.481	1.70	0.03
END OF TURN (MAGNITUDE)	32.4	31.1	150	3	0.343	0.339	1.70	0.03
END TURN TO 30.5M								
SEGMENT MEAN	1.8	25.1	72	3	0.025	0.289	0.87	0.03
SEGMENT MEAN MAGNITUDE	21.0	15.5	72	4	0.235	0.187	0.87	0.03
SEGMENT STANDARD DEVIATION	10.2	8.4	42	2	0.125	0.093	0.46	0.03
30.5M	1.1	15.3	34	0	0.017	0.212	0.48	0.00
30.5M (MAGNITUDE)	12.0	9.5	34	0	0.164	0.136	0.48	0.00

Figure 5-27 Altitude Errors for Left Turns

PAGE 2

36 POINTS PER ITEM / DATA ACQUISITION

4 CASES:

C60LN-N C60LN-W C90LN-N C90LN-W

9 SUBJECTS:

1 2 3 4 5 6 7 8 9

	METERS				DEGREES			
	MEAN	STD DEV	MAX MAG	MIN MAG	MEAN	STD DEV	MAX MAG	MIN MAG
ALTITUDE ERROR								
DESCENT MARKER TO END TURN								
SEGMENT MEAN	-2.4	4.8	15	0	-0.019	0.041	0.12	0.00
SEGMENT MEAN MAGNITUDE	6.4	3.1	15	2	0.052	0.032	0.15	0.00
SEGMENT STANDARD DEVIATION	6.1	3.0	12	1	0.017	0.026	0.09	0.00
END OF TURN	-1.3	4.8	17	0	-0.045	0.169	0.68	0.01
END OF TURN (MAGNITUDE)	3.1	3.9	17	0	0.113	0.133	0.68	0.01
END TURN TO 30.5M								
SEGMENT MEAN	-0.5	3.4	14	0	-0.034	0.188	0.87	0.00
SEGMENT MEAN MAGNITUDE	1.6	3.0	14	0				
SEGMENT STANDARD DEVIATION	1.0	1.0	3	0	0.074	0.162	0.84	0.00
30.5M	-0.6	2.3	11	0	-0.064	0.298	1.28	0.00
30.5M (MAGNITUDE)	0.9	2.1	11	0	0.174	0.250	1.28	0.00

Figure 5-28 Crosstrack Errors for Right Turns

PAGE 1

36 POINTS PER ITEM / DATA ACQUISITION

4 CASES:

C60RN-N C60RN-W C90RN-N C90RN-W

9 SUBJECTS:

1 2 3 4 5 6 7 8 9

	METERS				DEGREES			
	MEAN	STD DEV	MAX MAG	MIN MAG	MEAN	STD DEV	MAX MAG	MIN MAG
CROSSTRACK ERROR								
DESCENT MARKER TO END TURN								
SEGMENT MEAN	10.7	37.0	158	0	0.056	0.202	0.87	0.00
SEGMENT MEAN MAGNITUDE	40.6	26.2	172	19	0.226	0.151	0.96	0.09
SEGMENT STANDARD DEVIATION	31.7	14.8	76	9	0.229	0.141	0.68	0.09
END OF TURN	15.8	38.4	107	0	0.173	0.411	1.20	0.00
END OF TURN (MAGNITUDE)	31.7	26.8	107	0	0.334	0.296	1.20	0.00
END TURN TO 30.5M								
SEGMENT MEAN	4.7	23.7	95	0	0.051	0.282	1.18	0.00
SEGMENT MEAN MAGNITUDE	21.4	18.0	95	4	0.239	0.223	1.18	0.03
SEGMENT STANDARD DEVIATION	13.4	11.1	49	3	0.157	0.126	0.56	0.03
30.5M	-5.6	22.8	71	1	-0.077	0.321	1.00	0.00
30.5M (MAGNITUDE)	18.3	14.8	71	1	0.254	0.210	1.00	0.00

Figure 5-29 Altitude Errors for Right Turns

PAGE 2

36 POINTS PER ITEM / DATA ACQUISITION

4 CASES:

C60RN-N C60RN-W C90RN-N C90RN-W

9 SUBJECTS:

1 2 3 4 5 6 7 8 9

	METERS				DEGREES			
	MEAN	STD DEV	MAX MAG	MIN MAG	MEAN	STD DEV	MAX MAG	MIN MAG
ALTITUDE ERROR								
DESCENT MARKER TO END TURN								
SEGMENT MEAN	-1.3	4.3	12	0	-0.010	0.038	0.12	0.00
SEGMENT MEAN MAGNITUDE	5.6	2.9	14	1	0.042	0.036	0.15	0.00
SEGMENT STANDARD DEVIATION	5.5	2.9	16	2	0.012	0.022	0.09	0.00
END OF TURN	-1.2	5.2	20	0	-0.027	0.163	0.57	0.00
END OF TURN (MAGNITUDE)	3.2	4.2	20	0	0.109	0.124	0.57	0.00
END TURN TO 30.5M								
SEGMENT MEAN	-0.4	3.2	12	0	-0.011	0.173	0.56	0.00
SEGMENT MEAN MAGNITUDE	1.9	2.6	12	0				
SEGMENT STANDARD DEVIATION	1.1	1.4	6	0	0.085	0.132	0.53	0.00
30.5M	-0.5	2.0	10	0	-0.087	0.264	1.31	0.00
30.5M (MAGNITUDE)	0.8	1.9	10	0	0.152	0.233	1.31	0.00

30.5 m was 0.7 m (with standard error of 0.3 m) for straight-in cases and 0.9 m (with standard error of 0.2 m) for curved cases. At other points the differences were as large as a couple of meters, but, in the practical physical sense, altitude flying differences were not significant in the various comparisons.

6. Conclusions

This section summarizes the key findings in Section 5 and presents conclusions and recommendations on flying curved approaches. These conclusions must be evaluated in light of the limited experimental program. Before curved approach procedures are standardized, a more extensive experimental program involving more subjects and actual flight testing will obviously be required. The following are the conclusions and recommendations from this limited curved approach test program:

1. Pilots can fly curved instrument approaches with a conventional ILS display modified to show the current nominal heading on the curve. However, crosstrack errors are increased. These errors are on the order of twice or three times as large at the end of the turn as the errors at the same altitude for a straight-in approach. After the end of the turn, the difference in crosstrack errors between curved and straight-in approaches diminishes.

2. Vertical profile (altitude) performance is not deteriorated to any physically significant extent when flying horizontally curved approaches.

3. Pilot acceptance of curved approaches may not correspond with acceptable pilot performance in flying curved paths. Some pilots who flew the simulator well expressed reservations about flying curves in real aircraft. While no pilot expressed an outright unwillingness to fly actual curved approaches, some said they would fly curved approaches only when

certain conditions were met. It should be noted that other pilots expressed no reservations at all about flying curved approaches.

4. Pilot performance will improve with more extensive training. Not only will mean errors be decreased, but the "tails" of the error distribution will be notably decreased. A number of the large errors resulted when pilots, because of their lack of experience in flying curved approaches, initially reacted to a building deviation with the wrong control action. These momentary "wrong way" reactions will disappear as pilots "get the feel" of flying curved approaches.

5. Wind, at least at a moderate velocity, does not adversely affect performance in flying curved approaches. The wind compensation described in Section 3.2 is apparently not required. Most test subjects felt that wind made flying curves more difficult, and errors in the turn were higher with wind. However, the errors at the end of the turn were no different with and without wind.

6. There was no major difference in performance between 60^{o} and 90^{o} turns. As with the wind/no wind comparison, differences which occurred in the turn disappeared by the end of the turn. This is especially significant in light of the MLS acquisition delays with 90^{o} turns encountered in the test cases. Apparently,

moderate "disturbances" at the initiation of the approach can be overcome. About half of the pilots felt 60° turns were easier.

7. When pilots have a crosstrack deviation in a turn, the deviation is more likely to be on the outside of the curved path than the inside.

8. There is probably no difference between performances on the left and right turns. The statistical difference at 30.5 m altitude noted in Section 5 is probably just chance. However, in future testing, the possibility of difference, though remote, should be considered.

9. A flight director would probably enhance curved approach performance and would increase pilot confidence. Though conventional ILS displays seem adequate, alternate presentations should be investigated.

10. Curved path parameters as presented in these test cases seem acceptable. There is universal acceptance of the 10° nominal bank angle, though this could possibly be increased to 15°. Increasing the 122 m (400 ft) end of turn altitude to 152 m (500 ft) or even 183 m (600 ft) would increase the likelihood of pilot acceptance and might enhance safety.

11. Operational and safety aspects of flying curved

approaches, such as a low altitude engine failure in a steep bank, must be investigated in addition to pilot performance.

APPENDIX A

SUBJECT QUESTIONNAIRE

SUBJECT NUMBER__________________ DATE________________

LGS Curved Approach Questionnaire

Please answer the following questions. Feel free to add any comments or explanations when desired and to inquire about any question whose meaning is unclear. Thank you.

1. How do you compare curved approaches with conventional ILS approaches?

___________ Curved much harder

___________ Curved a little harder

___________ About the same

___________ Curved easier

2. How does a wind shear affect the ease of flying a curved approach?

__________ Much harder with wind than with no wind

__________ A little harder with wind

__________ About the same with or without wind

3. How do you compare the disturbing effect of wind on a curved approach with the disturbing effect of wind on a straight-in approach?

__________Wind affects curved more

__________About the same

__________Wind affects straight-in more

4. After training, do you feel that pilots will require a marker light to emphasize the end of turn?

__________Yes

__________No

__________Don't know

5. Do you find a difference in ease of flying between a 60° turn and a 90° turn?

__________60° easier

__________About the same

__________90° easier

6. With more training, do you think that you would be willing to fly curved approaches (as simulated in this testing) in instrument meteorological conditions?

__________Yes

__________No

__________Don't know

7. Would you like to see a change (from 400 feet) in the altitude at the end of the turn?

__________Yes (If so, to what?_______)

__________No

8. Would you like to see a change in the nominal turn bank angle from 10°?

__________Yes (If so, to what?________)

__________No

9. With these changes would you be willing to fly curved approaches in instrument meteorological conditions?

__________Yes

__________No

__________Don't know

10. Would you be willing to fly curved approaches if the weather conditions were such that the runway would be visible before the end of turn?

__________Yes

__________No

__________Don't know

APPENDIX B

RESULTS FOR EACH CASE OVER ALL SUBJECTS

(Case name mnemonics are defined in Section 4.2)

PAGE 1

9 POINTS PER ITEM / DATA ACQUISITION

1 CASES:

STRTN-N

9 SUBJECTS:

1 2 3 4 5 6 7 8 9

	METERS				DEGREES			
	MEAN	STD DEV	MAX MAG	MIN MAG	MEAN	STD DEV	MAX MAG	MIN MAG
CROSSTRACK ERROR								
DESCENT MARKER TO END TURN								
SEGMENT MEAN	-8.8	19.8	44	0	-0.037	0.091	0.21	0.00
SEGMENT MEAN MAGNITUDE	21.4	10.7	44	9	0.097	0.060	0.21	0.03
SEGMENT STANDARD DEVIATION	17.3	5.3	25	8	0.097	0.046	0.18	0.03
END OF TURN	-6.0	15.9	42	0	-0.062	0.156	0.42	0.00
END OF TURN (MAGNITUDE)	10.9	13.0	42	0	0.102	0.133	0.42	0.00
END TURN TO 30.5M								
SEGMENT MEAN	-8.7	6.7	22	3	-0.087	0.065	0.21	0.03
SEGMENT MEAN MAGNITUDE	10.2	5.5	24	5	0.101	0.063	0.25	0.03
SEGMENT STANDARD DEVIATION	6.7	4.1	17	3	0.083	0.046	0.21	0.06
30.5M	-5.3	13.2	32	0	-0.074	0.182	0.45	0.00
30.5M (MAGNITUDE)	10.2	9.9	32	0	0.139	0.139	0.45	0.00

PAGE 2

9 POINTS PER ITEM / DATA ACQUISITION

1 CASES:

STRTN-N

9 SUBJECTS:

1 2 3 4 5 6 7 8 9

	METERS				DEGREES			
	MEAN	STD DEV	MAX MAG	MIN MAG	MEAN	STD DEV	MAX MAG	MIN MAG
ALTITUDE ERROR								
DESCENT MARKER TO END TURN								
SEGMENT MEAN	-3.0	3.5	9	0	-0.020	0.024	0.06	0.00
SEGMENT MEAN MAGNITUDE	5.7	2.6	9	2	0.030	0.020	0.06	0.00
SEGMENT STANDARD DEVIATION	9.1	10.9	39	1	0.013	0.015	0.03	0.00
END OF TURN	-1.1	2.2	6	0	-0.030	0.066	0.17	0.01
END OF TURN (MAGNITUDE)	1.3	2.1	6	0	0.048	0.054	0.17	0.01
END TURN TO 30.5M								
SEGMENT MEAN	-0.9	2.6	6	0	-0.041	0.125	0.31	0.00
SEGMENT MEAN MAGNITUDE	1.7	2.5	6	0				
SEGMENT STANDARD DEVIATION	0.7	1.3	4	0	0.064	0.096	0.28	0.00
30.5M	-0.7	1.6	5	0	-0.091	0.214	0.67	0.00
30.5M (MAGNITUDE)	0.7	1.6	5	0	0.107	0.206	0.67	0.00

PAGE 1

9 POINTS PER ITEM / DATA ACQUISITION

1 CASES:

STRTN-W

9 SUBJECTS:

1 2 3 4 5 6 7 8 9

	METERS				DEGREES			
	MEAN	STD DEV	MAX MAG	MIN MAG	MEAN	STD DEV	MAX MAG	MIN MAG
CROSSTRACK ERROR								
DESCENT MARKER TO END TURN								
SEGMENT MEAN	-12.0	14.5	37	2	-0.050	0.071	0.18	0.00
SEGMENT MEAN MAGNITUDE	20.2	8.4	37	8	0.087	0.043	0.18	0.03
SEGMENT STANDARD DEVIATION	18.7	6.0	26	9	0.093	0.030	0.12	0.03
END OF TURN	0.6	14.1	32	0	-0.002	0.136	0.32	0.00
END OF TURN (MAGNITUDE)	10.3	9.6	32	0	0.096	0.097	0.32	0.00
END TURN TO 30.5M								
SEGMENT MEAN	-0.8	13.0	24	1	-0.006	0.144	0.28	0.00
SEGMENT MEAN MAGNITUDE	10.9	7.5	24	2	0.111	0.093	0.28	0.00
SEGMENT STANDARD DEVIATION	5.6	2.8	9	1	0.073	0.045	0.12	0.00
30.5M	3.8	11.7	27	0	0.054	0.160	0.37	0.00
30.5M (MAGNITUDE)	8.0	9.3	27	0	0.110	0.129	0.37	0.00

9 POINTS PER ITEM / DATA ACQUISITION

1 CASES:

STRTN-W

9 SUBJECTS:

1 2 3 4 5 6 7 8 9

	METERS				DEGREES			
	MEAN	STD DEV	MAX MAG	MIN MAG	MEAN	STD DEV	MAX MAG	MIN MAG
ALTITUDE ERROR								
DESCENT MARKER TO END TURN								
SEGMENT MEAN	5.6	5.7	18	0	0.033	0.039	0.12	0.00
SEGMENT MEAN MAGNITUDE	7.8	4.6	18	2	0.047	0.035	0.12	0.00
SEGMENT STANDARD DEVIATION	6.7	3.0	12	1	0.020	0.028	0.09	0.00
END OF TURN	-1.0	2.7	5	0	-0.029	0.078	0.15	0.00
END OF TURN (MAGNITUDE)	2.3	1.7	5	0	0.071	0.042	0.15	0.00
END TURN TO 30.5M								
SEGMENT MEAN	-0.3	1.1	3	0	0.010	0.060	0.12	0.00
SEGMENT MEAN MAGNITUDE	1.0	0.9	3	0				
SEGMENT STANDARD DEVIATION	0.8	0.6	2	0	0.030	0.028	0.09	0.00
30.5M	0.1	1.3	3	0	0.009	0.189	0.39	0.01
30.5M (MAGNITUDE)	0.8	1.0	3	0	0.149	0.117	0.39	0.01

PAGE 1

9 POINTS PER ITEM / DATA ACQUISITION

1 CASES:

C60RN-N

9 SUBJECTS:

1 2 3 4 5 6 7 8 9

	METERS				DEGREES			
	MEAN	STD DEV	MAX MAG	MIN MAG	MEAN	STD DEV	MAX MAG	MIN MAG
CROSSTRACK ERROR								
DESCENT MARKER TO END TURN								
SEGMENT MEAN	-6.8	27.4	42	6	-0.027	0.135	0.21	0.03
SEGMENT MEAN MAGNITUDE	33.1	8.0	47	22	0.174	0.039	0.25	0.12
SEGMENT STANDARD DEVIATION	24.4	9.0	43	14	0.150	0.045	0.21	0.09
END OF TURN	11.6	35.7	61	15	0.113	0.359	0.62	0.14
END OF TURN (MAGNITUDE)	33.6	16.9	61	15	0.333	0.174	0.62	0.14
END TURN TO 30.5M								
SEGMENT MEAN	2.7	15.7	29	0	0.013	0.170	0.31	0.03
SEGMENT MEAN MAGNITUDE	24.1	11.8	46	7	0.263	0.142	0.53	0.06
SEGMENT STANDARD DEVIATION	20.1	15.0	49	6	0.226	0.174	0.56	0.06
30.5M	-17.3	19.1	64	4	-0.246	0.269	0.90	0.06
30.5M (MAGNITUDE)	18.9	17.5	64	4	0.266	0.249	0.90	0.06

PAGE 2

9 POINTS PER ITEM / DATA ACQUISITION

1 CASES:

C60RN-N

9 SUBJECTS:

1 2 3 4 5 6 7 8 9

	METERS				DEGREES			
	MEAN	STD DEV	MAX MAG	MIN MAG	MEAN	STD DEV	MAX MAG	MIN MAG
ALTITUDE ERROR								
DESCENT MARKER TO END TURN								
SEGMENT MEAN	-3.2	2.9	8	0	-0.027	0.030	0.09	0.00
SEGMENT MEAN MAGNITUDE	4.3	2.5	8	1	0.027	0.030	0.09	0.00
SEGMENT STANDARD DEVIATION	4.3	2.2	8	2	0.013	0.021	0.06	0.00
END OF TURN	-4.6	6.5	20	0	-0.126	0.186	0.57	0.01
END OF TURN (MAGNITUDE)	5.2	6.0	20	0	0.150	0.167	0.57	0.01
END TURN TO 30.5M								
SEGMENT MEAN	-2.7	3.9	12	0	-0.123	0.183	0.56	0.00
SEGMENT MEAN MAGNITUDE	3.0	3.7	12	0				
SEGMENT STANDARD DEVIATION	1.6	1.8	6	0	0.113	0.169	0.53	0.00
30.5M	-2.2	3.2	10	0	-0.324	0.397	1.31	0.01
30.5M (MAGNITUDE)	2.2	3.2	10	0	0.324	0.397	1.31	0.01

PAGE 1

9 POINTS PER ITEM / DATA ACQUISITION

1 CASES:

C6ORN-W

9 SUBJECTS:

1 2 3 4 5 6 7 8 9

	METERS				DEGREES			
	MEAN	STD DEV	MAX MAG	MIN MAG	MEAN	STD DEV	MAX MAG	MIN MAG
CROSSTRACK ERROR								
DESCENT MARKER TO END TURN								
SEGMENT MEAN	8.0	23.8	40	5	0.027	0.114	0.21	0.00
SEGMENT MEAN MAGNITUDE	32.2	15.7	72	19	0.171	0.091	0.40	0.09
SEGMENT STANDARD DEVIATION	22.6	7.6	35	9	0.174	0.100	0.43	0.09
END OF TURN	6.1	37.9	71	4	0.061	0.382	0.73	0.03
END OF TURN (MAGNITUDE)	30.8	22.9	71	4	0.306	0.237	0.73	0.03
END TURN TO 30.5M								
SEGMENT MEAN	-4.0	9.0	19	0	-0.050	0.091	0.21	0.00
SEGMENT MEAN MAGNITUDE	16.4	9.6	38	6	0.176	0.111	0.43	0.06
SEGMENT STANDARD DEVIATION	14.4	11.9	41	3	0.166	0.133	0.46	0.06
30.5M	-6.9	15.3	33	6	-0.091	0.212	0.46	0.07
30.5M (MAGNITUDE)	14.2	8.9	33	6	0.193	0.126	0.46	0.07

PAGE 2

9 POINTS PER ITEM / DATA ACQUISITION

1 CASES:

C6ORN-W

9 SUBJECTS:

1 2 3 4 5 6 7 8 9

	METERS				DEGREES			
	MEAN	STD DEV	MAX MAG	MIN MAG	MEAN	STD DEV	MAX MAG	MIN MAG
ALTITUDE ERROR								
DESCENT MARKER TO END TURN								
SEGMENT MEAN	1.7	2.7	6	0	0.007	0.024	0.06	0.00
SEGMENT MEAN MAGNITUDE	4.2	1.3	6	2	0.020	0.020	0.06	0.00
SEGMENT STANDARD DEVIATION	4.2	1.6	8	2	0.007	0.012	0.03	0.00
END OF TURN	-1.1	5.1	15	0	-0.031	0.143	0.42	0.00
END OF TURN (MAGNITUDE)	2.9	4.4	15	0	0.082	0.122	0.42	0.00
END TURN TO 30.5M								
SEGMENT MEAN	-0.1	1.5	4	0	0.007	0.060	0.12	0.00
SEGMENT MEAN MAGNITUDE	0.9	1.3	4	0				
SEGMENT STANDARD DEVIATION	0.8	1.2	4	0	0.030	0.032	0.09	0.00
30.5M	0.0	0.0	0	0	-0.010	0.070	0.12	0.00
30.5M (MAGNITUDE)	0.0	0.0	0	0	0.059	0.040	0.12	0.00

PAGE 1

9 POINTS PER ITEM / DATA ACQUISITION

1 CASES:

C60LN-N

9 SUBJECTS:

1 2 3 4 5 6 7 8 9

	METERS				DEGREES			
	MEAN	STD DEV	MAX MAG	MIN MAG	MEAN	STD DEV	MAX MAG	MIN MAG
CROSSTRACK ERROR								
DESCENT MARKER TO END TURN								
SEGMENT MEAN	-11.6	8.4	21	2	-0.070	0.047	0.12	0.00
SEGMENT MEAN MAGNITUDE	24.0	9.3	42	9	0.131	0.069	0.28	0.03
SEGMENT STANDARD DEVIATION	27.7	15.4	64	11	0.182	0.118	0.46	0.06
END OF TURN	-16.0	38.1	109	6	-0.160	0.384	1.10	0.06
END OF TURN (MAGNITUDE)	28.2	30.1	109	6	0.282	0.305	1.10	0.06
END TURN TO 30.5M								
SEGMENT MEAN	-1.8	18.3	35	3	-0.002	0.201	0.40	0.03
SEGMENT MEAN MAGNITUDE	18.6	11.4	35	5	0.198	0.131	0.40	0.03
SEGMENT STANDARD DEVIATION	10.9	11.3	42	2	0.124	0.123	0.46	0.03
30.5M	-2.1	13.2	26	1	-0.028	0.177	0.35	0.01
30.5M (MAGNITUDE)	10.6	8.2	26	1	0.141	0.110	0.35	0.01

9 POINTS PER ITEM / DATA ACQUISITION

1 CASES:

C60LN-N

9 SUBJECTS:

1 2 3 4 5 6 7 8 9

	METERS				DEGREES			
	MEAN	STD DEV	MAX MAG	MIN MAG	MEAN	STD DEV	MAX MAG	MIN MAG
ALTITUDE ERROR								
DESCENT MARKER TO END TURN								
SEGMENT MEAN	-3.8	4.6	15	0	-0.030	0.037	0.12	0.00
SEGMENT MEAN MAGNITUDE	6.0	3.9	15	2	0.040	0.035	0.12	0.00
SEGMENT STANDARD DEVIATION	6.1	2.8	10	2	0.017	0.029	0.09	0.00
END OF TURN	-2.7	5.4	16	1	-0.077	0.155	0.46	0.03
END OF TURN (MAGNITUDE)	3.8	4.7	16	1	0.112	0.132	0.46	0.03
END TURN TO 30.5M								
SEGMENT MEAN	-0.9	4.5	12	0	-0.054	0.214	0.59	0.00
SEGMENT MEAN MAGNITUDE	2.8	3.7	12	0				
SEGMENT STANDARD DEVIATION	1.6	1.2	3	0	0.109	0.171	0.56	0.00
30.5M	-1.6	2.1	6	0	-0.220	0.296	0.82	0.04
30.5M (MAGNITUDE)	1.6	2.1	6	0	0.260	0.261	0.82	0.04

PAGE 1

9 POINTS PER ITEM / DATA ACQUISITION

1 CASES:

C60LN-W

9 SUBJECTS:

1 2 3 4 5 6 7 8 9

	METERS				DEGREES			
	MEAN	STD DEV	MAX MAG	MIN MAG	MEAN	STD DEV	MAX MAG	MIN MAG
CROSSTRACK ERROR								
DESCENT MARKER TO END TURN								
SEGMENT MEAN	-18.8	23.7	59	2	-0.069	0.131	0.28	0.00
SEGMENT MEAN MAGNITUDE	39.6	12.1	60	18	0.208	0.060	0.28	0.09
SEGMENT STANDARD DEVIATION	38.4	10.9	54	20	0.229	0.075	0.34	0.09
END OF TURN	8.8	42.6	76	6	0.089	0.432	0.78	0.06
END OF TURN (MAGNITUDE)	36.3	23.9	76	6	0.367	0.245	0.78	0.06
END TURN TO 30.5M								
SEGMENT MEAN	5.2	29.0	55	4	0.071	0.321	0.65	0.03
SEGMENT MEAN MAGNITUDE	24.9	16.0	55	8	0.270	0.193	0.65	0.06
SEGMENT STANDARD DEVIATION	10.6	3.5	17	6	0.133	0.040	0.21	0.09
30.5M	2.0	13.9	30	1	0.031	0.193	0.43	0.00
30.5M (MAGNITUDE)	11.6	8.0	30	1	0.156	0.118	0.43	0.00

PAGE 2

9 POINTS PER ITEM / DATA ACQUISITION

1 CASES:

C60LN-W

9 SUBJECTS:

1 2 3 4 5 6 7 8 9

	METERS				DEGREES			
	MEAN	STD DEV	MAX MAG	MIN MAG	MEAN	STD DEV	MAX MAG	MIN MAG
ALTITUDE ERROR								
DESCENT MARKER TO END TURN								
SEGMENT MEAN	-0.8	5.5	11	0	-0.010	0.040	0.06	0.00
SEGMENT MEAN MAGNITUDE	6.3	2.4	11	3	0.047	0.015	0.06	0.03
SEGMENT STANDARD DEVIATION	4.8	2.3	9	1	0.020	0.020	0.06	0.00
END OF TURN	-0.6	3.3	8	0	-0.019	0.098	0.21	0.03
END OF TURN (MAGNITUDE)	2.6	2.2	8	0	0.083	0.055	0.21	0.03
END TURN TO 30.5M								
SEGMENT MEAN	0.3	0.9	2	0	0.017	0.053	0.12	0.00
SEGMENT MEAN MAGNITUDE	0.9	1.1	3	0				
SEGMENT STANDARD DEVIATION	1.1	0.7	3	0	0.020	0.032	0.09	0.00
30.5M	0.1	0.9	2	0	0.011	0.167	0.25	0.00
30.5M (MAGNITUDE)	0.6	0.7	2	0	0.149	0.077	0.25	0.00

PAGE 1

9 POINTS PER ITEM / DATA ACQUISITION

1 CASES:

C90RN-N

9 SUBJECTS:

1 2 3 4 5 6 7 8 9

	METERS				DEGREES			
	MEAN	STD DEV	MAX MAG	MIN MAG	MEAN	STD DEV	MAX MAG	MIN MAG
CROSSTRACK ERROR								
DESCENT MARKER TO END TURN								
SEGMENT MEAN	7.1	25.9	40	5	0.064	0.167	0.31	0.03
SEGMENT MEAN MAGNITUDE	37.0	12.1	61	19	0.228	0.099	0.43	0.09
SEGMENT STANDARD DEVIATION	32.2	11.7	52	17	0.247	0.131	0.53	0.09
END OF TURN	27.4	38.4	107	0	0.311	0.429	1.20	0.00
END OF TURN (MAGNITUDE)	34.8	31.9	107	0	0.389	0.360	1.20	0.00
END TURN TO 30.5M								
SEGMENT MEAN	10.4	33.8	95	0	0.128	0.413	1.18	0.00
SEGMENT MEAN MAGNITUDE	23.9	26.6	95	4	0.277	0.337	1.18	0.03
SEGMENT STANDARD DEVIATION	8.3	3.8	15	4	0.100	0.040	0.15	0.03
30.5M	0.9	29.1	71	1	0.016	0.405	1.00	0.00
30.5M (MAGNITUDE)	22.4	18.5	71	1	0.309	0.263	1.00	0.00

PAGE 2

9 POINTS PER ITEM / DATA ACQUISITION

1 CASES:

C90RN-N

9 SUBJECTS:

1 2 3 4 5 6 7 8 9

	METERS				DEGREES			
	MEAN	STD DEV	MAX MAG	MIN MAG	MEAN	STD DEV	MAX MAG	MIN MAG
ALTITUDE ERROR								
DESCENT MARKER TO END TURN								
SEGMENT MEAN	-3.1	3.6	10	0	-0.020	0.032	0.09	0.00
SEGMENT MEAN MAGNITUDE	6.4	2.5	10	2	0.053	0.027	0.09	0.00
SEGMENT STANDARD DEVIATION	6.3	2.4	9	3	0.010	0.020	0.06	0.00
END OF TURN	-0.2	4.2	8	0	-0.006	0.167	0.31	0.01
END OF TURN (MAGNITUDE)	3.1	2.9	8	0	0.128	0.107	0.31	0.01
END TURN TO 30.5M								
SEGMENT MEAN	0.6	3.8	9	0	0.030	0.231	0.53	0.00
SEGMENT MEAN MAGNITUDE	2.6	2.8	9	0				
SEGMENT STANDARD DEVIATION	1.1	1.5	5	0	0.140	0.159	0.50	0.00
30.5M	0.1	1.2	2	0	0.003	0.174	0.31	0.03
30.5M (MAGNITUDE)	0.8	0.9	2	0	0.141	0.101	0.31	0.03

PAGE 1

9 POINTS PER ITEM / DATA ACQUISITION

1 CASES:

C90RN-W

9 SUBJECTS:

1 2 3 4 5 6 7 8 9

	METERS				DEGREES			
	MEAN	STD DEV	MAX MAG	MIN MAG	MEAN	STD DEV	MAX MAG	MIN MAG
CROSSTRACK ERROR								
DESCENT MARKER TO END TURN								
SEGMENT MEAN	34.6	50.9	158	0	0.158	0.295	0.87	0.00
SEGMENT MEAN MAGNITUDE	60.2	41.9	172	32	0.330	0.236	0.96	0.18
SEGMENT STANDARD DEVIATION	47.4	14.6	76	30	0.343	0.165	0.68	0.18
END OF TURN	18.2	38.1	105	3	0.208	0.425	1.18	0.03
END OF TURN (MAGNITUDE)	27.8	31.8	105	3	0.308	0.360	1.18	0.03
END TURN TO 30.5M								
SEGMENT MEAN	9.6	25.4	68	0	0.113	0.299	0.81	0.00
SEGMENT MEAN MAGNITUDE	21.0	18.1	68	4	0.239	0.219	0.81	0.03
SEGMENT STANDARD DEVIATION	10.6	6.0	21	4	0.139	0.075	0.28	0.03
30.5M	0.9	20.4	35	4	0.014	0.290	0.50	0.04
30.5M (MAGNITUDE)	17.6	10.4	35	4	0.248	0.151	0.50	0.04

PAGE 2

9 POINTS PER ITEM / DATA ACQUISITION

1 CASES:

C9ORN-W

9 SUBJECTS:

1 2 3 4 5 6 7 8 9

	METERS				DEGREES			
	MEAN	STD DEV	MAX MAG	MIN MAG	MEAN	STD DEV	MAX MAG	MIN MAG
ALTITUDE ERROR								
DESCENT MARKER TO END TURN								
SEGMENT MEAN	-0.7	5.4	12	0	0.000	0.051	0.12	0.00
SEGMENT MEAN MAGNITUDE	7.6	3.4	14	3	0.067	0.042	0.15	0.03
SEGMENT STANDARD DEVIATION	7.1	3.9	16	3	0.017	0.029	0.09	0.00
END OF TURN	1.2	1.9	4	0	0.053	0.079	0.17	0.00
END OF TURN (MAGNITUDE)	1.7	1.6	4	0	0.076	0.058	0.17	0.00
END TURN TO 30.5M								
SEGMENT MEAN	0.8	1.5	4	0	0.044	0.111	0.28	0.00
SEGMENT MEAN MAGNITUDE	1.2	1.3	4	0				
SEGMENT STANDARD DEVIATION	0.9	0.9	3	0	0.058	0.082	0.25	0.00
30.5M	0.0	0.5	1	0	-0.019	0.107	0.21	0.01
30.5M (MAGNITUDE)	0.2	0.4	1	0	0.086	0.067	0.21	0.01

PAGE 1

9 POINTS PER ITEM / DATA ACQUISITION

1 CASES:

C90LN-N

9 SUBJECTS:

1 2 3 4 5 6 7 8 9

	METERS				DEGREES			
	MEAN	STD DEV	MAX MAG	MIN MAG	MEAN	STD DEV	MAX MAG	MIN MAG
CROSSTRACK ERROR								
DESCENT MARKER TO END TURN								
SEGMENT MEAN	-8.1	24.4	57	4	-0.079	0.174	0.43	0.03
SEGMENT MEAN MAGNITUDE	39.7	15.9	61	21	0.244	0.119	0.43	0.12
SEGMENT STANDARD DEVIATION	42.4	15.8	73	26	0.282	0.137	0.56	0.18
END OF TURN	-26.6	53.7	150	3	-0.299	0.605	1.70	0.03
END OF TURN (MAGNITUDE)	40.1	44.4	150	3	0.448	0.505	1.70	0.03
END TURN TO 30.5M								
SEGMENT MEAN	-8.3	30.7	72	3	-0.101	0.368	0.87	0.03
SEGMENT MEAN MAGNITUDE	23.8	21.5	72	4	0.280	0.265	0.87	0.03
SEGMENT STANDARD DEVIATION	10.9	10.5	38	3	0.124	0.120	0.43	0.03
30.5M	-2.7	15.7	34	0	-0.041	0.222	0.48	0.00
30.5M (MAGNITUDE)	11.1	11.4	34	0	0.154	0.164	0.48	0.00

PAGE 2

9 POINTS PER ITEM / DATA ACQUISITION

1 CASES:

C90LN-N

9 SUBJECTS:

1 2 3 4 5 6 7 8 9

	METERS				DEGREES			
	MEAN	STD DEV	MAX MAG	MIN MAG	MEAN	STD DEV	MAX MAG	MIN MAG
ALTITUDE ERROR								
DESCENT MARKER TO END TURN								
SEGMENT MEAN	-2.6	4.4	8	0	-0.017	0.038	0.06	0.00
SEGMENT MEAN MAGNITUDE	6.7	2.9	11	2	0.060	0.028	0.12	0.03
SEGMENT STANDARD DEVIATION	5.9	3.4	12	1	0.017	0.021	0.06	0.00
END OF TURN	-0.7	1.8	5	0	-0.029	0.074	0.18	0.01
END OF TURN (MAGNITUDE)	1.3	1.4	5	0	0.064	0.046	0.18	0.01
END TURN TO 30.5M								
SEGMENT MEAN	0.0	0.7	1	0	-0.010	0.053	0.09	0.00
SEGMENT MEAN MAGNITUDE	0.4	0.5	1	0				
SEGMENT STANDARD DEVIATION	0.6	0.5	1	0	0.030	0.028	0.06	0.00
30.5M	0.1	0.3	1	0	0.012	0.093	0.25	0.00
30.5M (MAGNITUDE)	0.1	0.3	1	0	0.059	0.072	0.25	0.00

PAGE 1

9 POINTS PER ITEM / DATA ACQUISITION

1 CASES:

C90LN-W

9 SUBJECTS:

1 2 3 4 5 6 7 8 9

	METERS				DEGREES			
	MEAN	STD DEV	MAX MAG	MIN MAG	MEAN	STD DEV	MAX MAG	MIN MAG
CROSSTRACK ERROR								
DESCENT MARKER TO END TURN								
SEGMENT MEAN	-33.8	48.4	152	5	-0.144	0.249	0.75	0.03
SEGMENT MEAN MAGNITUDE	56.8	39.5	152	14	0.316	0.203	0.75	0.06
SEGMENT STANDARD DEVIATION	49.7	20.1	75	14	0.334	0.174	0.71	0.09
END OF TURN	17.0	24.4	54	6	0.188	0.272	0.60	0.06
END OF TURN (MAGNITUDE)	25.0	16.2	54	6	0.277	0.181	0.60	0.06
END TURN TO 30.5M								
SEGMENT MEAN	11.9	13.3	34	6	0.132	0.156	0.40	0.06
SEGMENT MEAN MAGNITUDE	16.8	8.0	34	6	0.192	0.095	0.40	0.06
SEGMENT STANDARD DEVIATION	8.6	5.3	22	4	0.118	0.055	0.25	0.06
30.5M	7.3	16.0	31	3	0.106	0.222	0.43	0.04
30.5M (MAGNITUDE)	14.7	9.7	31	3	0.203	0.138	0.43	0.04

PAGE 2

9 POINTS PER ITEM / DATA ACQUISITION

1 CASES:

C90LN-W

9 SUBJECTS:

1 2 3 4 5 6 7 8 9

	METERS				DEGREES			
	MEAN	STD DEV	MAX MAG	MIN MAG	MEAN	STD DEV	MAX MAG	MIN MAG
ALTITUDE ERROR								
DESCENT MARKER TO END TURN								
SEGMENT MEAN	-2.3	3.9	11	0	-0.020	0.047	0.12	0.00
SEGMENT MEAN MAGNITUDE	6.8	2.8	11	3	0.063	0.039	0.15	0.03
SEGMENT STANDARD DEVIATION	7.6	2.7	12	4	0.017	0.032	0.09	0.00
END OF TURN	-1.3	6.8	17	0	-0.056	0.270	0.68	0.03
END OF TURN (MAGNITUDE)	4.7	5.1	17	0	0.191	0.198	0.68	0.03
END TURN TO 30.5M								
SEGMENT MEAN	-1.3	4.7	14	0	-0.087	0.289	0.87	0.00
SEGMENT MEAN MAGNITUDE	2.4	4.2	14	0				
SEGMENT STANDARD DEVIATION	0.7	0.9	3	0	0.137	0.253	0.84	0.00
30.5M	-0.9	3.6	11	0	-0.060	0.441	1.28	0.00
30.5M (MAGNITUDE)	1.6	3.4	11	0	0.227	0.383	1.28	0.00

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