NASA Technical Memorandum 85873

A Flight-Test and Simulation Evaluation of the Longitudinal Final Approach and Landing Performance of an Automatic System for a Light Wing Loading STOL Aircraft Equipped With Wing Spoilers

Stuart C. Brown, Gordon H. Hardy,
and William S. Hindson

SEPTEMBER 1984

NASA

NASA Technical Memorandum 85873

A Flight-Test and Simulation Evaluation of the Longitudinal Final Approach and Landing Performance of an Automatic System for a Light Wing Loading STOL Aircraft Equipped With Wing Spoilers

Stuart C. Brown, Gordon H. Hardy,
and William S. Hindson

Ames Research Center
Moffett Field, California

NASA

National Aeronautics
and Space Administration

Scientific and Technical Information Branch

1984

TABLE OF CONTENTS

NOMENCLATURE

a_z — aircraft acceleration in vertical body axis direction, g

CTOL — conventional takeoff and landing

DLC — direct lift control

DME — distance measuring equipment

g — acceleration due to gravity, m/sec^2

GPIP — glidepath intercept point

h_{rw} — aircraft altitude relative to main wheels, measured by radio altimeter, m

IC_o — initial condition on dynamic element in flare guidance system at flare initiation

LWL — light wing loading

MLS — microwave landing system

N — number of samples in a group

P.C. — MLS antenna electronic phase center

P_e — probability of exceedance of a value of a random variable

q — pitch body angular rate, rad/sec

$\bar{q}$ — dynamic pressure, N/m^2 (psf)

R — MLS range (DME), m

STOL — short takeoff and landing

s — Laplace operator, sec^{-1}

TACAN — tactical air navigation system providing bearing and distance information

V_c — calibrated airspeed, knots

V_G — filtered ground speed, knots

x,y,z — rectangular coordinate system oriented with respect to runway; x origin is at the MLS elevation P.C.

δ_e — elevator position, deg

δ_{sp} — spoiler position, deg

θ — pitch attitude angle, deg

θ_{eng} — pitch attitude angle when servo actuators engaged

μ — mean value of a random variable for a set of approaches (see appendix B)

σ — standard deviation of a random variable for a set of approaches (see appendix B)

σ_a — average value of standard deviations obtained along the final-approach path from a set of approaches

$2\sigma_p$ — symmetrical increment of a random variable about a nominal for which the $P_e \leqslant 4.5\%$

σ_t — root mean square of standard deviations of total (unfiltered) MLS noise obtained along the final-approach path from all approaches

$(\hat{\ })$ — filtered value

Subscripts

0 — condition at flare initiation

td — touchdown

cg — aircraft center of gravity

SUMMARY

As part of a comprehensive flight-test investigation of short takeoff and landing (STOL) operating systems for the terminal area, an automatic landing system has been developed and evaluated for a light wing loading turboprop-powered aircraft. An advanced digital avionics system performed display, navigation, guidance, and control functions for the test aircraft. Control signals were generated in order to command powered actuators for all conventional controls and for a set of symmetrically driven wing spoilers. This report describes effects of the spoiler control on longitudinal autoland (automatic landing) performance.

Flight-test results, with and without spoiler control, are presented and compared with available (basically, conventional takeoff and landing) performance criteria. These comparisons are augmented by results from a comprehensive simulation of the controlled aircraft that included representations of the microwave landing system navigation errors that were encountered in flight as well as expected variations in atmospheric turbulence and wind shear.

Flight-test results show that the addition of spoiler control improves the touchdown performance of the automatic landing system. Spoilers improve longitudinal touchdown and landing pitch-attitude performance, particularly in tail-wind conditions. Furthermore, simulation results indicate that performance would probably be satisfactory for a wider range of atmospheric disturbances than those encountered in flight.

Flight results also indicate that the addition of spoiler control during the final approach does not result in any measurable change in glidepath track performance, and results in a very small deterioration in airspeed tracking. This difference contrasts with simulation results, which indicate some improvement in glidepath tracking and no appreciable change in airspeed tracking. The modeling problem in the simulation that contributed to this discrepancy was not resolved.

INTRODUCTION

The development of short takeoff and landing (STOL) aircraft capable of linking metropolitan centers and smaller communities has been in progress for a number of years. These aircraft require a high lift capability to perform steep, curved approach paths into small STOLports (airports with short takeoff and landing strips). One method for achieving this capability is through the use of relatively light wing loading (LWL) and an extensive mechanical flap system. Some background information, including flight-demonstration programs, was provided in reference 1 for the LWL Twin Otter aircraft.

One problem associated with LWL aircraft is its sensitivity to atmospheric disturbances. This sensitivity results in a deterioration in ride comfort and an increased difficulty in tracking the final-approach path. The difficulty in using an elevator for path tracking is that there is a delay between the elevator command to rotate the airplane in pitch and the subsequent path response of the airplane. A way to overcome the sluggish pitch-attitude path response is to use a direct lift control (DLC) device. Examples of DLC devices are fast-acting flaps, and symmetrically deflected ailerons or wing spoiler surfaces. DLC spoilers have been used for some time to achieve faster vertical path response for heavy jet transports (refs. 2 and 3). Specifically, operational spoilers were incorporated into the manual and autoland (automatic landing) systems for the Lockheed L-1011 aircraft (refs. 4 and 5).

Spoilers were also investigated for smaller LWL aircraft with the initial purpose of improving ride comfort in the presence of atmospheric disturbances (e.g., ref. 6). In the design study described in reference 6, a supplementary automatic control for the vertical axis used portions of the ailerons deflected symmetrically and the elevator to provide gust alleviation for cruise flight. Spoilers supplemented the symmetrical aileron segments and the elevator for the final approach. The remaining portions of the conventional control surfaces were available for normal operation. This study showed that significant reductions in vertical acceleration could be achieved during cruise conditions in which only vertical turbulence was considered.

Spoiler control for improving manual-approach-path tracking and landing performance for light aircraft has also been investigated. For light aircraft, landing-approach-path control can be accomplished primarily with either the throttle or the elevator. Airspeed is maintained with the control that is not being used for path tracking. In a flight investigation reported in reference 7, the primary path control mode studied coupled upper-surface spoilers and lower-surface speed brakes with the throttle control. In a simulation study of a light aircraft reported in reference 8, several variations of a manually applied spoiler control were investigated as a primary approach path control.

The NASA Ames Research Center has conducted a research program to determine the requirements for STOL operating systems. One portion of this program was concerned with the determination, development, and testing of requirements for an automatic approach and landing system for LWL STOL aircraft. An airborne system, known as STOLAND and described in reference 9, was installed on a Twin Otter aircraft. The system consisted of a digital computer, electronic displays, and the interface equipment needed to interconnect the computer with the displays and the aircraft controls and sensors. Servo actuators were provided for all of the automatic-system controls. Longitudinal final-approach and touchdown results for the aircraft using conventional surface and throttle controls are reported in reference 1.

The Twin Otter aircraft used for the autoland work was also equipped with a set of lift/drag and lateral-control wing spoilers to determine the benefits of spoilers for both manual and automatic operating modes. Information regarding the design and expected aerodynamic performance of the spoiler installation is provided in reference 10. The spoilers were designed to improve longitudinal and lateral control.

The evaluation of lift/drag spoilers on an LWL aircraft for improving autoland performance began with the design study reported in reference 11. This study made use of a fast-time simulation to generate both the control-system design and a statistical estimate of expected performance. The results of this study showed that the spoiler control system improved tracking performance on the final approach and at touchdown. The study reported in reference 11 provided a design basis for the spoiler control laws used in the flight tests. The control laws were programmed in the airborne digital computer and validated using a real-time simulation facility at the Ames Research Center. This facility incorporated a comprehensive model of the airplane, the controls, and the wind and navaid disturbances, along with duplicates of the computer and displays installed in the airplane.

This report describes an evaluation of the effects of spoiler control on the longitudinal performance of an automatically controlled aircraft during the final approach and at touchdown. Flight-test results are supplemented by results obtained in the real-time simulation facility. These results illustrate the effects of the spoilers for a wider range of disturbances than those encountered in flight. Glidepath tracking and touchdown performance were also compared with the STOL design goals given in reference 1. The autoland accuracy goals were obtained from criteria developed for CTOL jet transport systems. Final-approach tracking requirements were obtained from reference 12, whereas touchdown criteria, modified for STOL runway geometry, were adapted from reference 13. The ride comfort goal used in this study was the vertical acceleration limit obtained from the analysis presented in reference 14.

This report first describes the incorporation of the spoiler control into the conventionally controlled system reported in reference 1. Second, the atmospheric conditions encountered during the flight tests are described. Finally, the spoiler-control flight-test results and simulation results are presented for the final approach and touchdown, and compared with applicable criteria.

DESCRIPTIONS

Detailed descriptions of the aircraft, the avionics systems, and associated flight- and simulation-test facilities were provided in reference 1. The discussion in this report will be confined to a brief description of the aircraft, the spoiler installation, the flight-test facilities, and the modifications in the glidepath track and flare control laws resulting from the addition of the spoiler control.

The Aircraft

The flight tests were conducted with a turboprop-powered de Havilland DHC-6, Series 100 Twin Otter aircraft (figs. 1 and 2). A major wing modification was made to add the spoiler installation shown in the figures. (A description of the overall spoiler design was given in reference 10.) Three deflected panels are shown on the upper and lower surface of each wing. The outer panels were intended only for lateral control, whereas the remaining panels were intended for lift/drag control. For the automatic system, only a minimum number of panels were considered necessary to assist with the longitudinal-path control. Preliminary flight-test results indicated that the innermost panels produced excessive buffeting of the horizontal tail. Of the remaining outer lift/drag panels, the upper panels were the most effective for lift changes, and thus only these were activated for the autoland tests. Powered servos were provided for the throttle and for the conventional and spoiler aerodynamic control surfaces to implement the automatic control.

Runway Geometry, Navigation, and Radar Tracking Systems

Flight tests were conducted using facilities at the Navy's Crows Landing auxiliary landing field. A simulated 514-m STOL runway was painted on the larger runway surface using guidelines from reference 15. The terminal-area navigation aids available at the site were a basic narrow microwave landing system (MLS) with a horizontal coverage of ±40° and a conventional tactical air navigation system (TACAN). Two tracking radar systems provided independent measurements of aircraft position. The STOL runway setting and the navigation and radar sites are shown in figure 3. The location of the MLS elevation-antenna phase-center (P.C.) results in a glidepath intercept point (GPIP) of 71.5 m from the runway threshold for a 6.0° approach. Information on the MLS specifications is given in reference 16. Estimates of radar-tracking and TACAN accuracy at the Crows Landing installation are presented in reference 17.

Control Laws

Laws relating to the spoiler control are discussed in this section. Spoiler control was added to provide faster acting vertical-path control than can be achieved by rotating the aircraft with the conventional elevator system. General descriptions of the navigation, guidance, and control laws (using conventional control) that are pertinent to the longitudinal final-approach and touchdown systems are given in reference 1; these include the guidance and control laws for glidepath track, airspeed, and flare, and the generation of the filtered navigation signals used for these laws. The incorporation of the spoiler control into the glidepath track and flare laws will be described in this report. General descriptions are provided in this section and additional details are given in appendix A. No further description of the airspeed control or navigation filtering will be given, since these items were not affected by the addition of the spoilers.

Final-approach tracking– A nominal approach speed 30% above the power-off stall speed was selected so that the airplane was trimmed on the front side of the power-required-versus-speed curve. Final-approach tracking was achieved by conventional use of the elevator and throttle controls supplemented with spoilers to quicken the path response. Power changes controlled airspeed. Complementary filtered glidepath error signals provided commands to the elevator-controlled pitch-attitude inner loop and to the spoilers.

The main objective of the spoiler-control design was to improve the precision of vertical-path tracking on final approach, with a secondary consideration to improve ride comfort. Hence, gains were adjusted as high as was feasible within the limits imposed by the stability margins and control activity observed in flight. The glidepath error signals used for spoiler control were washed out at lower frequencies (pitch-attitude control range) and accelerometer signals were used to complement the glidepath error signals at the higher frequencies.

The addition of spoiler control required a small modification to the basic pitch command. Flight-test results indicated that the addition of spoilers reduced the stability margin for the aircraft short-period mode. The margin was restored by reducing the pitch-command glidepath-error-rate gain. No change was needed for airspeed control.

Flare– The flare-control design without spoilers is described in reference 1. Conventional techniques were employed using pitch to control the path and using an open-loop throttle reduction to reduce airspeed. This section will describe the modifications to the pitch control and the addition of the spoiler control.

Linear combinations of filtered altitude and altitude rate signals obtained from the radio altimeter were used to determine the flare initiation altitude. The pitch flare-path control consisted of a feedback command signal to the pitch-attitude inner loop and was based on deviations from the nominal flare trajectory. This trajectory was a modified exponential function that provided a smooth transition from the flare-initiation conditions to the basic exponential flare path. Vertical acceleration feedback was also used. The pitch-attitude command was augmented by feed-forward (predictive) signals. This pitch-flare/path-control configuration was not changed by the addition of the spoilers. Modifications in the constants are noted in appendix A.

The feedback signals used for the spoiler control were the same as those for the pitch command, i.e., the path error signal and vertical acceleration. No washout for the spoiler signal was incorporated in the flare, to allow full spoiler response even for the lower frequency path errors which otherwise would be controlled by the pitch command. This was necessary in order to use the faster spoiler response during the short (5-6 sec) flare time interval. There was no change, with spoilers added, in the open-loop constant-retard rate command to the throttle in the flare.

ATMOSPHERIC DISTURBANCES

Estimates of the wind and turbulence encountered in flight during approaches with and without spoiler control are given in this section. A knowledge of the disturbances encountered is important in the assessment of the system performance because of the susceptibility of the LWL aircraft to these disturbances. The data-analysis technique for obtaining estimates of wind variations along the glidepath and the resulting mean winds and turbulence was described in reference 1.

Typical variations with distance along the glidepath representing the range of onboard-measured disturbances encountered during the spoiler-control flight-test period are shown in figure 4. Head winds, tail winds, and low winds are shown as a function of radar-measured horizontal distance from the MLS elevation antenna P.C., and the data are terminated at touchdown. The approaches with head winds show the largest amount of turbulence and some decreasing longitudinal wind shear near touchdown.

Statistical averages of the horizontal wind variations were obtained for the 152.4- to 30.5-m altitude range. On the 6.0° glide slope, these values correspond to the 1427- to 267-m horizontal-range parameter in figure 4. As a first step in the procedure (summarized in appendix B), a mean, representing the average wind, and a standard deviation, representing the turbulence level, were calculated for each approach. Some caution should be exercised in using the following turbulence results, since the flight instrumentation was not designed for this more exacting dynamic requirement. Moreover, while wind averages for altitudes below 30.5 m, including the flare, would certainly be pertinent, instrumentation problems precluded reliable estimates in this region. The mean values of horizontal wind for each approach analyzed are shown in figure 5. As was the case for approaches without spoiler control (ref. 1), the figure indicates that the longitudinal component of the winds can be partitioned into three groups – head, low, and tail winds. Statistical averages of wind and turbulence for the three groups of approaches with and without spoiler control are shown in table 1. The average value of the wind for a specific wind group, μ, is the average of the mean values which were calculated from the set of approaches in the group. The standard deviation of these mean wind values from the group is designated σ in the table. The procedure for computing the values of μ and σ is given by equations (B1) and (B2) in appendix B. The average turbulence for a specific wind group, σ_a, is the root mean square of the standard deviations which were calculated from the set of approaches in the group. The wind standard deviation, σ, is a quantitative measure of the variations shown within each wind group in figure 5. Note that the higher turbulence levels are generally associated with the higher wind magnitudes.

In subsequent presentations of aircraft performance, statistically averaged aircraft-response data will be separated into the head-, low-, and tail-wind groups. An examination of the number of approaches in each group (table 1) indicates that a larger number of head-wind samples without spoilers and head- and tail-wind samples with spoilers would have been desirable for determining statistical averages more accurately.

The data to be presented subsequently will also be combined by adjusting the results to a standard wind. The adjustments are based on a wind distribution model which will be described subsequently. Overall averages obtained using the model were calculated from equations (B3) and (B4) in appendix B and will be called combined averages. The combined averages for the longitudinal atmospheric disturbances are included in the bottom row of table 1.

To help substantiate the onboard wind measurement obtained during the final approach, the wind speed was also determined from a source located on a mast near the touchdown zone at an altitude of 4.7 m above the runway (table 2). The values were compiled as the aircraft passed that altitude just before touchdown. A comparison of wind results from tables 1 and 2 shows that the lower altitude ground-measured winds were of reduced magnitude and thus suggests the well-known atmospheric boundary-layer shape. A comparison of the averages with and without spoiler control shows that the atmospheric conditions were very similar for the two cases, although the turbulence level was slightly higher for the spoiler approaches. Hence, the averages indicate a reasonable basis for comparing effects of spoilers on aircraft performance.

Simulation results using steady wind, wind shear, and turbulence disturbances were used to further delineate effects of atmospheric disturbances on aircraft performance. The forms of the simulated disturbances are described in reference 1 and are summarized in appendix B. Simulated effects of atmospheric disturbances, comparing performance with and without spoiler control, are presented as follows: For the final approach, statistical averages of aircraft response to turbulence over the 152.4- to 30.5-m altitude range were given. Selection of this range allowed comparisons with flight measurements and with performance criteria. Responses to winds were not given, since the nominal wind variations considered did not produce any significant effects over this altitude range. At touchdown, where the wind effects are significant, deterministic results for a range of winds and wind shears are presented. While the response at touchdown to turbulence is also significant, the real-time operation of the simulation precluded generating the ensemble results needed for the statistical averages.

An atmospheric wind and turbulence model based on a range of disturbances similar to those that would be encountered by an operational aircraft is described in reference 1 and is summarized in appendix B. The model is used (1) to adjust statistically averaged aircraft responses to reflect a more typical distribution of wind than that actually encountered during flight testing and (2) to select realistic magnitudes of wind and turbulence for the simulation. The model is based on FAA recommendations for evaluating CTOL aircraft performance (ref. 13).

SYSTEM PERFORMANCE

Flight-test results are presented to show the effects of spoiler control on glidepath track and touchdown performance. The effects of atmospheric disturbances are included to the extent feasible because of the sensitivity of the LWL aircraft to them. In addition, consideration is given to the influence of navigation errors. Comparisons are made with criteria developed from CTOL evaluations described in reference 1. The results are also intended to provide part of a data base needed to facilitate the subsequent establishment of similar STOL criteria.

Simulation results with and without spoiler control are presented to enhance the flight evaluation of spoiler performance. The spoiler aerodynamic characteristics for the simulation were estimated with flight-test results obtained from aircraft responses to pilot-applied spoiler inputs. The transient responses were analyzed by means of the method described in reference 18. Results from the analysis indicated that the spoilers had a lift/drag ratio of about 10 and produced a small pitch-up moment when deflected. The values of the spoiler aerodynamic derivatives are given in appendix A. Simulation results were also used to augment the flight results for comparison with criteria, since the criteria are generally based on aircraft responses to a wider range of flight conditions than those encountered during flight testing. The atmospheric conditions simulated were described in the previous section. In addition, effects of MLS noise on aircraft performance were shown through the use of the simulation. The MLS noise, based on flight measurements during the final approach, was represented by a first-order random-noise model described in reference 1. The parameters are repeated in table 3. Only MLS-noise responses were obtained from the simulation; responses to bias could be determined largely through geometric or other considerations. Effects of spoiler control will be emphasized in the following discussion, since the flight and simulation results without spoilers and comparisons with criteria were presented in reference 1.

Summarized results from flight tests with spoiler control will be compared with those without spoilers from reference 1. Touchdown results were obtained for approximately 70 approaches with spoiler control and 80 approaches without spoiler control. However, only about one half of the approaches with spoilers were suitable for the evaluation of glidepath performance because the final spoiler control law for glidepath track was not obtained until late in the flight-test period, after the higher priority flare law was developed. The glidepath track control law, initially designed using the simulation, required further refinement in flight because the control mode associated with the aircraft short-period mode was more lightly damped than was estimated from the simulation. In order to be assured of obtaining touchdown results, which were of primary interest during this final phase of the flight-test period, a number of shortened landing approaches were flown with an interim low-spoiler-gain glidepath track control. These approaches allowed the aircraft and its controls to be properly positioned for flare entry and subsequent touchdown using full spoiler control.

Final Approach

Generally, nominal approach paths with the final glidepath tracking system were planned so that the low-frequency aircraft modes were damped and the aircraft was stabilized on the 6.0° glide slope when an altitude of 152 m was reached. For various reasons, only about 60% of the approaches allowed this condition to be met. Because of the limited number of final-approach results with spoilers, summary averages of aircraft response along the path were obtained rather than ensemble averages at a particular point on the path.

With spoiler control active, a final-approach speed of 74 knots was selected when the aircraft was at the maximum gross landing weight of 4,990 kg (11,000 lb). This selection provided a speed margin of about 30% above the stall speed with the spoilers deflected to their nominal position. A lower final-approach speed of 71 knots was used with the spoilers retracted. These stall speed margins were maintained as fuel was expended by reducing the approach speed. The margin resulted in the aircraft being trimmed to fly on the conventional front side of the power-required-versus-airspeed curve. The maximum gross weight provided a wing loading of 1250 N/m^2 (26 lb/ft^2).

The spoilers were operated over a range of 0 to 40° during glidepath track because preliminary flight-test results indicated that excessive buffeting would occur for larger deflections. When the spoilers were activated, they were set at a nominal value of 20° in order to allow a symmetrical ±20° variation. This deflection range resulted in an estimated spoiler lift effectiveness of ±0.13 g for typical final-approach conditions.

The flight results for the final approach are shown as typical variations with distance along the glidepath, histograms at the flare initiation point, and statistical averages of both of these forms. Only results with spoiler control are shown for the glidepath variations, since examples without spoilers were given in reference 1 and differences due to the spoilers are difficult to distinguish in this form. However, comparisons with and without spoiler control are summarized by including results without spoilers in the histograms and tables of statistical averages. The typical variations along the glidepath with spoiler control are shown over a shorter distance (1500 m) than that used in reference 1 (3000 m). Longer tracking distances with stabilized spoiler control were not generated, because the spoilers were not integrated into the glidepath capture law and therefore were not deployed until after the capture. Allowing for the subsequent transients after deployment, the aircraft low-frequency modes generally were not stabilized any closer than 1500 m. Furthermore, since the aircraft was not stabilized for a number of approaches until it was even closer, sufficient amounts of data to form a histogram were only available for the minimum approach altitude (flare initiation).

All results are grouped according to the winds encountered. The final-approach results are limited to head- and low-wind groups; the final glidepath track control configuration for spoilers had not been developed at the time of the flight in which tail winds were encountered. While the effect of steady wind was not significant for aircraft-motion variables on the final approach, the turbulence associated with each wind group did allow further delineation of atmospheric effects.

Glidepath system performance– A description is given in this section of glidepath tracking performance with and without spoiler control. The results evaluated are glidepath tracking error relative to the onboard-measured path, control activity, and ride comfort.

Glidepath tracking performance. The performance measure used for evaluating glidepath tracking performance was the complementary filtered glidepath error signal. This signal was employed for outer-loop path control and also was related to the vertical tracking variable designated for the glide slope error criterion (ref. 12). Typical variations along the glidepath with spoiler control during the previously described low- and head-wind conditions are shown in figure 6. Histograms of glidepath error at flare initiation for all approaches with final spoiler control are compared with the results without spoilers (fig. 7). No histograms are shown for higher altitudes because of the limited number of spoiler approaches with the aircraft stabilized at those altitudes. The data for the flare height are grouped into the two separate wind conditions. The means and standard deviations with spoiler control at flare initiation and averages over the 152.4- to 30.5-m altitude range are given in table 4. As previously mentioned, the latter averages were taken over the more limited number of approaches for which the aircraft was stabilized on the glidepath in this altitude range. Also shown are results without the spoiler control. For all cases presented, the performance with and without spoiler control is about the same.

The flight results, with and without spoiler control and averaged over the 152.4- to 30.5-m altitude range, are compared with simulation results and the CTOL criterion in table 5. The values, $2\sigma_p$, are the symmetrical increments of path error relative to zero for which $P_e = 4.5\%$. For the flight results, they were calculated from values of μ and σ (table 4) with the assumption of a gaussian distribution. Separate simulation results for turbulence (based on the atmospheric-disturbance model) and the MLS-noise model are shown in table 5 to assess the effects of each disturbance. The results for summed MLS noise and turbulence from the simulation are also shown. Because of the previously mentioned problems with the estimation of turbulence levels from flight results, a direct comparison of flight with simulation results cannot be made.

Simulation results (table 5) show that the spoiler control reduced the onboard-measured path error in the presence of turbulence and even reduced the error slightly with MLS noise. This improvement, due to spoiler control and predicted by simulation results, contrasts with the lack of measurable improvement shown in flight. The difference between simulation and flight results occurs for other aircraft-motion variables on the final approach that will be subsequently presented. A related discrepancy between flight and simulation results was previously mentioned. With spoiler control present, the control mode associated with the aircraft short-period mode was more lightly damped in flight than was predicted by the simulation. These discrepancies would need to be resolved in order to identify corresponding control modifications for improving flight performance. Possible causes for the discrepancies are (1) an inaccuracy in modeling the spoiler aerodynamics such as a nonlinearity; (2) a low-level turbulent flow disturbance induced by the deflected spoilers; (3) differences in the particular atmospheric disturbances encountered in flight for the sets of approaches with and without spoilers as contrasted with the more controlled conditions in the simulation; and (4) differences in the character of the atmospheric disturbances encountered in flight from those used in the simulation. Simulation results did show that the horizontal component of turbulence had a significant effect on vertical tracking. Although not shown in table 5, the 1-σ vertical error resulting from the horizontal component of turbulence was almost equal to that resulting from the vertical component. (The ratio of vertical- to horizontal-turbulence magnitudes simulated in this altitude range was 0.52 to 1.) During the limited spoiler flight-test period, the emphasis placed on touchdown performance precluded resolving this glidepath track problem. In any case, both flight and simulation results show errors much less than the CTOL limit (table 5).

Control activity. Example time histories of pitch attitude, elevator position, and spoiler position are shown in figure 8. Effects of spoiler control on statistical averages of these quantities over the 152.4- to 30.5-m altitude range are compared in table 6. Pitch attitude is included with the control variables because of its use as a path command control. The flight results shown are grouped as functions of the winds encountered. Figure 8 indicates that the spoilers exhibit higher frequency control activity than does pitch attitude. The mean values in table 6 represent trim conditions resulting from the average winds for flight and no wind for the simulation. An indication of the accuracy of the simulated spoiler aerodynamic representation for steady-state conditions can be obtained by an examination of the trim values. A comparison of trim from flight results for approach conditions with and without spoilers deflected shows that pitch attitude was not changed, but that a more positive increment of elevator deflection was required with the spoilers deflected. The simulation results provide good agreement with the low-wind flight results for the incremental effect of spoilers on both of these variables. However, the average value of the elevator deflections is somewhat less than in flight. Even though these trim differences have been affected by the airspeed change as well as the spoiler aerodynamics, the comparison shows a reasonable representation of the spoiler aerodynamics in the simulation.

Average control activity for each wind condition is indicated by σ_a in table 6. This value was obtained from the rms of the deviations for the approaches in each wind group. The most control activity occurs during the head winds and is a result of the larger turbulence level encountered. However, this highest control activity level is still considered to be relatively small. The addition of spoiler control has no appreciable effect on pitch or elevator activity.

Ride comfort. Vertical acceleration is the principal aircraft motion factor for longitudinal ride comfort. Typical variations of vertical acceleration during the final approach with spoiler control are shown in figure 9. Again, the approaches with maximum excursions occurred for the head-wind conditions associated with higher turbulence levels. The average acceleration level for each wind condition, with and without spoiler control, is given in table 7. Also included in the table are simulation results and the ride comfort limit based on a study of commercial passengers' level of acceptance of aircraft motion. This limit was calculated in reference 1 from the analysis given in reference 14 for the average approach condition encountered. Flight results do not show any significant difference in the acceleration level with spoiler control. However, the simulation results do show a small improvement with spoiler control. This difference in the effect of spoiler control between flight and simulation results is similar to that observed for glidepath track error. Although all acceleration levels are less than the neutral acceptance limit, the level with spoilers for head-wind conditions approaches the limit.

Airspeed control performance– Performance of the speed control system is compared in this section with and without the presence of the spoiler control. The flight results presented consist of the airspeed error and engine activity. Airspeed results from flight measurements are augmented with simulation results to facilitate the evaluation of spoiler control and the comparison with the CTOL criterion.

Airspeed tracking. Airspeed tracking accuracies are shown for the last part of the final approach below the 152.4-m altitude in the same manner as for glidepath error. The flight results, with and without spoiler control, are presented and compared with the CTOL criterion and then simulation results appropriate to disturbances specified by the criterion are shown. The controlled variable is an inertially complemented airspeed (ref. 1). Example velocity variations along the glidepath with spoiler control present are shown in figure 10. Histograms at flare initiation with and without spoilers are also shown (fig. 11). Summary averages along the glidepath and at flare initiation, with and without spoiler control, are given in table 8. As was done for glidepath error, all approaches for which the aircraft velocity was not quite stabilized at the 152.4-m altitude were omitted from the 152.4- to 30.5-m altitude-range averages. Comparisons from the table and the histograms show that velocity variations are slightly higher with the spoiler control active.

The flight results, with and without spoiler control and averaged along the glide slope over the 152.4- to 30.5-m altitude range, are further compared with simulation results and the CTOL criterion in table 9. The results from MLS noise and turbulence are shown separately to indicate the effects of these disturbances. As previously mentioned, the simulation and flight results cannot be compared directly because of accuracy problems encountered with the estimation of turbulence from flight. When contrasted with flight data, the simulation results do not indicate any measurable effect of spoiler control on the velocity error. In any case, the velocity variations from the flight and the simulation results are seen to be much less than the CTOL criterion.

Control activity. Examples of engine torque variations along the glidepath with spoiler control present are shown in figure 12. In addition, statistical averages, determined from approaches with and without spoiler control, are shown for the 152.4- to 30.5-m altitude range in table 10. The simulation results are given for the no-wind condition, and this accounts for the smaller average values for the simulation data. Engine torque was chosen to reflect control and engine activity levels associated with the airspeed control. Small changes in the variable are approximately proportional to changes in engine power, even though small changes in rpm occur with the low-power settings on the approach. For this power range, throttle activity can be estimated from the torque variations by the ratio, 0.043% of full-throttle travel per newton meter.

An indication of the accuracy of the spoiler drag representation in the simulation can be obtained by an examination of the trim values for engine torque. The simulation results show good agreement with flight for the increase in torque resulting from change in approach conditions with and without spoilers deployed. Although not shown, simulation results indicated that about one-half of this torque increase was due to the spoiler drag, whereas the remainder was due to the different trim condition.

Results from table 10 indicate a small increase in engine activity (σ_a) with spoiler control present. For this variable, the simulation and flight results show the same trend. The variations are still relatively small in comparison with the nominal take-off torque of about 1900 N•m.

Touchdown

The effect of spoilers on touchdown performance is assessed in this section first from flight results, and then from simulation results. Comparisons are also made with applicable criteria and design goals. The basic touchdown performance variables from flight, radar-measured longitudinal distribution, sink rate, pitch attitude, and airspeed, are presented in the form of histograms (fig. 13) and statistically averaged results (table 11). The more complete flight wind distribution experienced for the touchdown system allowed determination of the combined wind results (table 11) comparable with the no-spoiler results from reference 1. The combined results used for the histograms and the table were calculated from the corresponding separate wind results through the use of weighting factors from the previously discussed atmospheric model. The boundaries for measured 2-σ probability in the combined histograms are 0.023 P_e values obtained directly from the histogram distributions. The touchdown design goals shown in figure 13 were discussed in reference 1 and the associated longitudinal geometry is repeated for convenience in figure 14. The 0.023 P_e design goals and measurements from the distograms are labeled 2-σ values because of their relation to the gaussian distribution. For this distribution, the values of plus or minus 2 σ have, respectively, a probability of being or not being exceeded of 0.023. Comparisons of performance from the combined wind histograms, with and without spoiler control, with the touchdown design goals are summarized in table 12. Note that the 2-σ flight values in table 12, obtained from the combined histograms, differ slightly from those that would be calculated from the μ and σ combined values given in table 11. These differences are due to nongaussian distribution and round-off effects.

The aircraft performance at touchdown was improved by the addition of the spoiler control (see fig. 13 and table 11). Without spoilers, the aircraft tended to land shorter, harder, and with a higher pitch attitude as the wind increased in the head-wind direction. The addition of spoiler control resulted in more rapid path corrective action and reduced these trends. The spoiler control also reduced longitudinal position and pitch-attitude dispersions for a particular wind condition. This improvement was most apparent for tail winds. A contributing factor may have been that the increased drag of the deflected spoilers reduced the tendency of the aircraft to float during tail winds. The increase in average touchdown velocity with the spoiler control (table 11) reflected an increase in the touchdown speed goal from 60 to 64 knots. Wind variations caused no appreciable trend in touchdown velocity.

The reduction in dispersions due to the spoiler control is summarized by the combined wind results. Note that for pitch attitude, the spoiler control reduced the 1-σ dispersion even though the combined mean was the same. The reduction reflects the fact that the spoilers improve flare path tracking and thus reduce the need to make path corrections with pitch control.

All of the touchdown design goals were well within the required limits with spoiler control; however, without the spoilers, two of them, sink rate and pitch attitude, were only marginally achieved (table 12). The longitudinal dispersion was within the goal for both cases.

Further insight into the trends with wind can be obtained from the comparison of flight and simulation results with and without spoiler control shown in figure 15. To estimate the sensitivity of touchdown results to wind structure, simulation results were generated for the same sets of winds used in reference 1: (1) a runway-aligned wind without a cross-wind component or wind shear; (2) a runway-aligned wind with a cross-wind component obtained by interpolation of the flight-measured cross winds; and (3) a runway-aligned wind plus the same cross-wind component plus the log-linear wind-shear profile described in reference 1 and summarized in appendix B. In order to be comparable with flight results, the simulated wind-shear results in this figure were referenced to an average value over the same 152.4- to 30.5-m altitude range that was used for the flight winds.

An examination of flight and simulation results from figure 15 shows that the use of spoilers reduced the effects of wind on the touchdown variables. In addition, the simulation results indicate that the addition of spoiler control reduced the sensitivity to wind shear and cross wind. However, the flight-test longitudinal touchdown dispersions tend to be shorter than those predicted from the simulation. This difference is greatest for head winds. Even with spoiler control available, the longitudinal touchdown is somewhat shorter than desired after considering that even larger head-wind magnitudes must be anticipated for operational flight.

Simulation results for the entire wind range of interest, including effects of the two wind-shear variations described in reference 1, are shown in figure 16. The spoiler reduces the more extreme effects of mean wind variation and wind shear on the touchdown variables.

The simulation (fig. 16) and flight (table 12) results show that the addition of spoiler control should allow achievement of the touchdown goals (table 12), even when wind conditions more extreme than those encountered in flight are considered. The goals would be difficult to meet for the system tested without the spoilers.

CONCLUDING REMARKS

A series of flight tests was conducted to evaluate the effects of wing spoiler control on a digital autoland system for an LWL aircraft capable of flying steep (6.0°) approaches onto a STOL runway. Results describing longitudinal performance on the final approach and touchdown and comparisons with pertinent criteria are given. The flight-test results were augmented through the use of a simulation incorporating controlled aircraft dynamics, pertinent atmospheric disturbances, and navigational aids. The conclusions presented here focus on the effects of the spoiler control; more general conclusions for the aircraft without spoilers were given in reference 1.

The addition of spoiler control improved the touchdown performance of the automatic system. For the flight conditions encountered, the system performance with spoilers was well within all design goals, whereas without spoilers sink rate and pitch attitude were marginally close to these goals. The addition of spoilers showed particular improvement in longitudinal-range dispersion and pitch attitude for tail-wind conditions. In addition, simulation results showed that spoiler control would improve performance in the presence of more extreme wind and associated wind-shear conditions than were encountered in flight.

On final approach, the limited amount of flight results obtained with spoilers did not show any measurable improvement in performance over the results obtained without spoilers. The vertical tracking and ride comfort response remained about the same, but there was a slight deterioration in velocity tracking and a small increase in engine activity. However, performance still remained well within all desired goals. The effect of spoiler control on performance from simulation results contrasted somewhat with the flight results. The simulation results, which of course used more consistent reference conditions and disturbances than were encountered in flight, showed that spoiler control produced about 25% improvement in vertical tracking. No measurable change occurred in velocity tracking performance. The cause of the discrepancy between the flight and simulation results could not be resolved within the flight-test period available for the spoiler tests.

Ames Research Center
National Aeronautics and Space Administration
Moffett Field, California, January 24, 1984

APPENDIX A

CONTROL LAWS FOR AND SIMULATION OF SPOILERS

A general description of the navigation, guidance, and control laws pertinent to glidepath tracking and flare using conventional elevator and throttle controls was provided in reference 1. Therefore, only the spoiler control laws for glidepath tracking and flare, and their incorporation into the conventional pitch control laws are given in this report. Estimates of the spoiler aerodynamic characteristics that were incorporated into the simulation are also presented.

FINAL APPROACH TRACKING

Conventional control for final-approach tracking consisted of elevator control which rotated the aircraft to correct for path errors, and throttle control to correct for airspeed errors. The spoiler control was added primarily to provide a faster acting and therefore a more accurate means to control path tracking. A secondary consideration was to improve ride comfort. A simplified block diagram of the glidepath track law with spoiler control is given in figure A1. The system feedback functions and constants are shown in table A1. The higher frequency content of the feedback error signal to the spoiler command, δ_{spc}, in comparison with the pitch command, θ_c, can be seen by comparing the feedback functions, $F_{gs}(s)$ and $F_g(s)$ (table A1), and by noting the spoiler low-frequency washout filter T_g. The spoiler feedback function, $F_{gs}(s)$, contains higher derivative feedback content. The addition of the spoilers required a reduction in the glidepath track error gain, K_{dh}, for the pitch command. This gain was reduced in order to offset a deterioration in the damping of the controlled aircraft short-period mode with spoiler control present, which was observed in flight. All gains were maintained down to the flare-initiation altitude, since the MLS-derived glide slope error signal was accurate to this altitude.

The control gains shown in table A1 were used during the last portion of the final approach and were the maximum feasible for achieving good tracking performance. These maximum values were limited by stability considerations and control activity observed during preliminary flight tests. To accommodate approaches starting farther from the runway, pitch outer-loop and spoiler gain reductions as a function of distance from the runway should be used. For these greater distances, a reduction would allow decreased aircraft-motion activity at the expense of lower path-tracking accuracy. This tradeoff is acceptable, since accurate tracking is needed only during the last portion of the approach.

FLARE

The flare laws with conventional elevator and throttle controls were described in reference 1. Pitch attitude, controlled by the elevator, was used to adjust the aircraft path to the nominal flare trajectory, and an open-loop throttle retard was used to reduce airspeed. The addition of the spoiler control will be described in this section, along with related portions of the pitch path control. An overview of the pitch control and the spoiler control is shown in figure A2. (The nonlinear predictive functions, θ_p and δ_{ep}, shown in the diagram were described in ref. 1.) After flare was initiated, an outer-loop feedback path control generated a command signal, θ_c, to a conventional pitch-attitude control inner loop. The latter was formed by feeding back the attitude signals, θ and $\dot{\theta}$, to the elevator. The outer-loop control was based on an error signal that was calculated relative to a reference flare trajectory. This reference path was basically an exponential function of altitude, modified to provide a smooth transition from the flare initiation point to the exponential path. The pitch-attitude command was augmented by feed-forward signals, θ_p and δ_{ep}, because of the large pitch-attitude change (typically 9°) required during the short flare time interval. Several nonlinear functions were added to refine the command and feed-forward signals (ref. 1). No changes were made to the basic flare control configuration with the addition of spoilers.

The additions and minor changes to the basic flare control resulting from the spoilers can be seen in the block diagram shown in figure A2 and the pertinent constants listed in table A2. The only change to the basic control was a small modification in the nominal flare trajectory, which generated the closed-loop path error, θ_c. The gain, K_{hdf}, and the transition time constant, T_c, were modified. The signals forming the spoiler command, δ_{spc}, are shown in the lower portion of the figure. The overall gain to the spoilers ($K_{1s}(t)$, defined in fig. A2) was gradually increased, starting at flare initiation, in the same manner as the gain to the pitch command ($K_1(t, \theta_c')$ defined in ref. 1). The path feedback signals to the spoiler command, δ_{spc}, were basically the same as those to the pitch command, θ_c. The same feedback signals, θ_c' and a_z, were used with approximately the same gain ratio and with no differences in filtering. As stated in the body of this report, the fast-acting spoiler control was needed to assist in correcting the low-frequency path errors normally controlled through the pitch command because of the short time period available for the flare. Total spoiler effectiveness was also increased by raising the maximum spoiler limit 10° from that used during glidepath tracking. At flare initiation, the first-order term, T_{S2}, gradually decreased the residual incremental spoiler signal, which was present because of the glide slope track control.

SPOILER AERODYNAMIC SIMULATION

As stated in the body of this report, the spoiler aerodynamic characteristics implemented in the simulation were estimated from flight-test results. Pilot-applied spoiler inputs were used to induce aircraft transient responses. The spoiler-linearized characteristics were then estimated with the method described in reference 18. The resulting aerodynamic coefficients obtained are as follows:

$$C_{L_{\delta_{sp}}} = -0.50/\text{rad}$$

$$C_{D_{\delta_{sp}}} = 0.047/\text{rad}$$

$$C_{M_{\delta_{sp}}} = 0.095/\text{rad}$$

These derivative terms were added to the appropriate force and moment equations in the aircraft portion of the simulation.

REPRESENTATION OF ATMOSPHERIC DISTURBANCES

Descriptions of the estimation and use of wind and turbulence values in the flight and simulation results were presented in reference 1. The descriptions included the method for estimating wind from flight-test measurements, an atmospheric model for interpreting flight and simulation results, equations used for simulating wind and turbulence, and pertinent equations needed for the statistical analysis of the flight data. The atmospheric model, its application for interpreting flight data, and equations used for the simulation are summarized for more convenient reference in this section.

ATMOSPHERIC DISTURBANCE MODEL

The atmospheric model presented prescribes a probability distribution of wind and turbulence magnitudes that the aircraft would expect to encounter in operational use. The model was employed to (1) adjust statistically averaged flight-test results to reflect the more typical wind conditions represented by the model, and (2) select the wind range and turbulence magnitude used in the simulation. The model satisfies guidelines given in reference 13 for the range of atmospheric disturbances to be considered in determining the compliance of aircraft-system touchdown performance with FAA criteria. To evaluate longitudinal aircraft response results, only longitudinal components are needed. The wind distribution for the model is given as a cumulative probability distribution at a 7.6-m altitude (fig. B1). Details for determining the model are given in reference 1. As described in the reference, the magnitude of horizontal turbulence for the model was approximately represented by a gaussian distribution with a 2-σ level of 2.9 knots.

The wind model was employed to determine weighting factors for summarizing statistical aircraft-response results from the flight measurements. These measurements were grouped according to the separate winds encountered and then combined using the weighting factors, so that the summarized aircraft-response results could be adjusted to the wind probability distribution given by the model.

The equations for obtaining statistically averaged flight performance based on the wind distribution model (provided in appendix C of ref. 1) are summarized here. As stated in the body of this report, statistical averages for each separate wind group were obtained by the following equations:

$$\mu_{xj} = \frac{1}{N_j} \sum_{i=1}^{N_j} x_{ij} \tag{B1}$$

$$\sigma_{xj}^2 = \frac{1}{N_j} \sum_{i=1}^{N_j} (x_{ij} - \mu_{xj})^2 \tag{B2}$$

where

x_{ij} an aircraft response value for the ith approach occurring with the jth wind group

N_j number of approaches in the jth wind group

These equations were used to compute means and standard deviations for aircraft responses at a particular altitude on the approach or at touchdown. Statistical averages summarizing aircraft response along the 152.4- to 30.5-m altitude segment of the final approach path were obtained in a similar manner.

Equations for the combined wind statistical averages, μ_x and σ_x^2, can be expressed in terms of the separate wind averages by the following equations:

$$\mu_x = \sum_{j=1}^{N_w} W_j \mu_{xj} \tag{B3}$$

$$\sigma_x^2 = \sum_{j=1}^{N_w} \left\{ W_j \left[\sigma_{xj}^2 + (\mu_{xj} - \mu_x)^2 \right] \right\} \tag{B4}$$

where

W_j weighting factor for the jth wind group

N_w number of wind groups

As explained in reference 1, the weighting factors were obtained through use of the wind averages determined from flight and the wind distribution model. For the three groups of winds encountered during the spoiler approaches (table 1), the weighting factors are as follows:

	Head	Low	Tail
Wind, knots			
(h = 152.4 to 30.5 m)	-14	-2	9
Weighting factor, W_j	0.275	0.562	0.163

These values are slightly different from those for the approaches without spoiler control (ref. 1) because of the slight differences in average winds encountered.

SIMULATION OF ATMOSPHERIC DISTURBANCES

The equations for representing wind shear and turbulence in the simulation were described in reference 1 and are repeated for convenience in this section.

Two wind-shear shapes are simulated. A constant gradient wind shear (called the FAA wind shear (ref. 13)), is given by the following equation.

$$\left.\begin{array}{l} \text{For } h_{cg} > 61 \text{ m,} \\ \qquad V_w = 1.7\, V_r \\ \text{For } h_{cg} \leqslant 61 \text{ m,} \\ \qquad V_w = V_r\, [1 + 0.01312\,(h_{cg} - h_{ref})] \end{array}\right\} \qquad \text{(B5)}$$

The log-linear wind shear, given in a British Air Registration Board document (ref. 19), is defined by the equation

$$V_w = V_r\, [0.4512 \operatorname{Log}_{10} (h_{cg}) + 0.602] \qquad \text{(B6)}$$

Altitude of the aircraft cg, h_{cg}, in the equations is expressed in meters above the runway with the wind reference velocity, V_r, defined at h_{ref} = 7.6 m (25 ft). The gradient for the log-linear wind shear is progressively steeper at lower altitudes (a boundary-layer shape) and, for the same reference velocity, exceeds that of the FAA wind shear at altitudes below 15 m.

The Dryden turbulence representation described in reference 20 was used for the simulation. This three-axis model includes rotational and translational turbulence with the magnitude and frequency parameters functions of altitude. The horizontal turbulence magnitude is constant below a 30.5 m altitude, and decreases at higher altitudes. Simulation results with turbulence were used in this report to obtain statistical averages on the final approach over the same (152.4- to 30.5-m) altitude range used for flight data. The previously described atmospheric model defined the magnitude of the horizontal turbulence at a 7.6-m altitude. For the 152.4- to 30.5-m altitude range, average values of horizontal (h) and vertical (w) components of pertinent turbulence parameters from the equations used in the simulation are:

Magnitude:

$$\sigma_h = 1.42 \text{ knots}$$

$$\sigma_w = 0.74 \text{ knots}$$

Scale length:

$$L_h = 278 \text{ m}$$

$$L_w = 91 \text{ m}$$

REFERENCES

1. Brown, Stuart C.; Hardy, Gordon H.; and Hindson, William S.: A Flight-Test and Simulation Evaluation of the Longitudinal Final Approach and Landing Performance of an Automatic System for a Light Wing Loading STOL Aircraft. NASA TM-84270, 1982.

2. Lorengetti, R. C.: Direct Lift Control for Approach and Landing. AGARD-CP-59-70, 1970.

3. Smith, M. R.: Direct Lift Control Applications to Transport Aircraft – A U.K. Viewpoint. AGARD-CP-160, 1974.

4. Lykken, Lowell O.; and Shaw, Naren M.: Direct Lift Control for Improved Automatic Landing and Performance of Transport Aircraft. AIAA Journal of Aircraft, vol. 9, no. 5, May 1972.

5. Shah, N. M.; Gevaert, G.; and Lykken, L. O.: The Effect of Aircraft Environment on Category III Autoland Performance and Safety. AIAA 4th Aircraft Design, Flight Test, and Operations Meeting, Aug. 1972.

6. Gordon, C. K.; and Dodson, R. O.: STOL Ride Control Feasibility Study. NASA CR-2276, 1973.

7. Olcott, J. W.; Seckel, E.; and Ellis, D. R.: Analysis and Flight Evaluation of a Small, Fixed Wing Aircraft Equipped with Hinged-Plate Spoilers. NASA CR-166247, 1981.

8. Kohlman, David L.; and Brainerd, Carl H.: Evaluation of Spoilers for Light Aircraft Flight Path Control. AIAA Journal of Aircraft, vol. 11, no. 8, Aug. 1974.

9. Neuman, Frank; Watson, Delamar M.; and Bradbury, Peter: Operational Description of an Experimental Digital Avionics System for STOL Airplanes. NASA TM X-62448, 1975.

10. Anon: Evaluation of the Application of Spoilers as a Means of Raising Operational Levels of Safety of STOL Transports. Phase I. Analysis and Working Drawings. Aeronautical Research Associates of Princeton, Final Report, NASA Contract NAS2-7663, 1974.

11. Feinreich, B.; Degani, O.; and Gevaert, G.: Development and Evaluation of Automatic Landing Control Laws for Light Wing Loading STOL Aircraft. NASA CR-166160, 1981.

12. Anon: Criteria for Approval of Category IIIa Landing Weather Minima. FAA Advisory Circular 120-28B, 1977.

13. Anon: Automatic Landing Systems. FAA Advisory Circular 20-57A, 1971.

14. Jacobson, Ira D.; Kuhlthau, A. Robert; and Richards, Larry G.: Passenger Ride Quality in Transport Aircraft. AIAA Journal of Aircraft, vol. 15, no. 11, Nov. 1978.

15. Anon: Planning and Design Criteria for Metropolitan STOL Ports. FAA Advisory Circular 150/5300-8, 1965.

16. Burrous, C. N.; and Narimatsu, R.: Site Preparation and Installation of the Prototype Texas Instruments Basic Narrow Configuration Microwave Landing System. NASA TM-78588, 1979.

17. Warner, David N., Jr.; and Moran, Francis J.: Flight-Test Evaluation Errors in the MODILS and TACAN Navigation Aids at NALF Crows Landing. NASA TM-78584, 1979.

18. Bach, Ralph E., Jr.: A User's Manual for a Parameter Estimation Program. Northeastern University, Final Report, NASA Contract NAS2-7397, June 1974.

19. Anon: Air Registration Requirements, Paper no. 367, Issue 3, June 1970.

20. Chalk, C. R.; Neal, T. P.; Harris, T. M.; Prichard, F. E.; and Woodcock, R. J.: Background Information and User Guide for MIL-F-8785B (ASG), Military Specification – Flying Qualities of Piloted Airplanes. AFFDL TR-69-72, 1969.

TABLE 1.– ONBOARD-MEASURED WINDS DURING APPROACHES WITH AND WITHOUT SPOILER CONTROL FOR THE 152.4- TO 30.5-m ALTITUDE RANGE

Wind group	Number of approaches	Wind component, knots					
		Longitudinal			Lateral		
		Wind		Turbulence	Wind		Turbulence
		μ	σ	σ_a	μ	σ	σ_a
Spoilers							
Head	12	-14	1.7	1.6	16	2.4	1.6
Low	48	-2	3.4	.9	3	2.2	1.0
Tail	11	9	2.2	1.3	-7	1.4	1.2
Combined	---	-3.3	7.9	1.2	---	---	---
No spoilers							
Head	14	-13	1.2	1.5	14	1.8	1.5
Low	39	-1	3.5	.8	2	2.2	.9
Tail	29	10	1.7	1.1	-4	3.8	1.3
Combined	---	-2.7	7.9	1.1	---	---	---

TABLE 2.– GROUND-MEASURED WINDS FOR APPROACHES WITH AND WITHOUT SPOILER CONTROL AT 4.7-m ALTITUDE

Wind group	Spoilers					No spoilers				
	Number of approaches	Wind component, knots				Number of approaches	Wind component, knots			
		Longitudinal		Lateral			Longitudinal		Lateral	
		μ	σ	μ	σ		μ	σ	μ	σ
Head	12	-11	2.5	8	2.7	14	-9	1.6	7	1.8
Low	48	-4	2.0	0	2.2	39	-3	2.1	0	1.4
Tail	11	4	1.5	-7	1.7	29	6	2.9	-4	2.8

TABLE 3.– PARAMETERS FOR FIRST-ORDER MODEL OF MLS RANDOM NOISE (ref. 1)

Errors	Flight results	
	σ_t	Time constant, sec
Elevation	0.03 deg	3.0
DME	2.1 m	.4

TABLE 4.– EFFECT OF SPOILERS ON GLIDEPATH TRACK ERRORS FROM FLIGHT RESULTS

Configuration	Wind	Glidepath track error, m			
		152.4- to 30.5-m altitude		Flare initiation	
		μ	2σ	μ	2σ
Spoilers	Head	0.0	2.0	0.3	1.9
	Low	.2	1.6	-.4	.9
No spoilers	Head	.1	1.6	-.5	1.8
	Low	0.0	1.5	.2	1.3

TABLE 5.– COMPARISON OF FLIGHT AND SIMULATION RESULTS WITH AND WITHOUT SPOILERS, AND PERFORMANCE CRITERION; 152.4- TO 30.5-m ALTITUDE RANGE

Data source	Glidepath track error ($2\sigma_p$)	
CTOL performance criterion (ref. 12)	3.7	
	Spoilers	No spoilers
Flight		
Head wind	2.0	1.6
Low wind	1.6	1.5
Simulation		
Turbulence model	1.2	1.6
MLS noise	.6	.8
Turbulence and MLS noise	1.3	1.8

TABLE 6.– EFFECT OF SPOILERS ON GLIDEPATH TRACK CONTROL ACTIVITY; 152.4- TO 30.5-m ALTITUDE RANGE

Data source	Pitch attitude, deg				Elevator position, deg				Average spoiler position, deg	
	Spoilers		No spoilers		Spoilers		No spoilers			
	μ	σ_a	μ	σ_a	μ	σ_a	μ	σ_a	μ	σ_a
Flight										
Head wind	-7.9	0.8	-8.0	0.8	7.9	0.5	7.4	0.6	20.2	6.2
Low wind	-8.6	.6	-8.6	.5	8.2	.4	7.3	.3	20.1	3.5
Simulation										
MLS noise	-8.7	.2	-8.4	0.3	5.8	.2	5.1	.2	20.0	2.0

TABLE 7.– COMPARISON OF VERTICAL ACCELERATION FROM FLIGHT AND SIMULATION RESULTS WITH AND WITHOUT SPOILERS, AND THE RIDE COMFORT LIMIT; 152.4- TO 30.5-m ALTITUDE RANGE

Data source	Vertical acceleration (σ_a), g	
Vertical portion of acceptable ride comfort limit (ref. 14)	0.06	
	Spoilers	No spoilers
Flight		
Head wind	0.054	0.049
Low wind	.037	.030
Simulation		
MLS noise	.018	.019
Turbulence model	.025	.029

TABLE 8.– EFFECT OF SPOILERS ON CALIBRATED AIRSPEED ERRORS FROM FLIGHT RESULTS

Configuration	Wind	Airspeed error, knots			
		152.4- to 30.5-m altitude		Flare initiation	
		μ	2σ	μ	2σ
Spoilers	Head	-0.3	2.5	-1.4	2.0
	Low	-.4	2.0	.3	1.9
No spoilers	Head	.3	1.8	.8	3.0
	Low	.3	1.4	-.1	1.6

TABLE 9.– COMPARISON OF AIRSPEED ERRORS FROM FLIGHT AND SIMULATION WITH AND WITHOUT SPOILERS, AND PERFORMANCE CRITERION; 152.4- TO 30.5-m ALTITUDE RANGE

Data source	Airspeed error ($2\sigma_p$), knots	
CTOL performance criterion (ref. 12)	5.0	
	Spoilers	No spoilers
Flight		
Head wind	2.5	1.9
Low wind	2.0	1.5
Simulation		
Turbulence	2.1	2.1
MLS noise	.2	.2
Turbulence and MLS noise	2.2	2.2

TABLE 10.– EFFECT OF SPOILERS ON ENGINE TORQUE ACTIVITY; 152.4- TO 30.5-m ALTITUDE RANGE, N·m

Data source	Spoilers		No spoilers	
	μ	σ_a	μ	σ_a
Flight				
Head wind	526	105	375	69
Low wind	425	70	283	51
Simulation				
MLS noise	340	8	196	4
Turbulence model	340	137	196	83

TABLE 11.– EFFECT OF SPOILERS ON STATISTICAL AVERAGES OF FLIGHT RESULTS AT TOUCHDOWN

Parameter	Wind	Spoilers		No spoilers	
		μ	σ	μ	σ
Radar-measured longitudinal position, m	Head	27	15	13	18
	Low	59	11	66	16
	Tail	54	12	87	23
	Combined	49	18	53	33
Sink rate, mps	Head	-1.2	.3	-1.4	.3
	Low	-1.1	.2	-1.0	.2
	Tail	-1.2	.2	-.9	.2
	Combined	-1.2	.2	-1.1	.3
Pitch attitude, deg	Head	1.6	.5	3.1	1.0
	Low	1.1	.5	.5	.7
	Tail	1.4	.5	.6	.8
	Combined	1.3	.6	1.3	1.4
Calibrated airspeed, knots	Head	65.1	1.2	62.1	1.3
	Low	64.9	1.3	61.9	1.3
	Tail	66.5	1.4	62.8	1.6
	Combined	65.2	1.4	62.1	1.4

TABLE 12.– COMPARISON OF FLIGHT RESULTS WITH AND WITHOUT SPOILERS WITH TOUCHDOWN CRITERIA

Design goals (2σ) (ref. 1)	Flight (combined wind histogram)	
	Spoilers	No spoilers
$(x_{td_{long}} - x_{td_{short}}) \leqslant 152$ m	68	131
$\dot{h}_{td} \geqslant -1.8$ mps	-1.6	-1.8
$\theta_{td} \geqslant -0.5°$	.2	-.7

TABLE A1.– CONSTANTS FOR GLIDEPATH TRACK CONTROL LAW WITH SPOILERS

Path error pitch command:

$$F_g(s) = (K_{ih}/s + K_h)\Delta\hat{h} + K_{dh}\Delta\dot{\hat{h}}$$

where

K_{ih} = -0.0912 deg/m-sec, -0.0278 deg/ft-sec

K_h = -1.093 deg/m, -0.333 deg/ft

K_{dh} = { -1.348 deg/mps, -0.411 deg/fps, with spoilers; -3.645 deg/mps, -1.111 deg/fps, without spoilers }

Path error spoiler command:

$$F_{gs}(s) = K_{hs}\Delta\hat{h} + K_{dhs}\Delta\dot{\hat{h}} + K_{azs}a_z$$

where

K_{hs} = 12.02 deg/m, 3.66 deg/ft

K_{dhs} = 22.05 deg/mps, 6.72 deg/fps

K_{azs} = -10.83 deg/mps², -3.30 deg/fps²

Spoiler control filter time constants:

T_g = 3 sec

T_{s1} = 0.5 sec

Spoiler limits:

Position	0 and 40 deg
Rate	±60 deg/sec
$\delta_{sp_{nom}}$	20 deg

Pitch stability augmentation:

K_θ = 1.2 deg/deg

K_q = 0.9 deg/deg/sec

q_{ref} = 1532 N/m², 32.0 psf

TABLE A2.– FLARE SYSTEM CONSTANTS WITH SPOILER CONTROL

Closed loop path guidance:

$\dot{h}_{td}$ = -0.686 mps, -2.25 fps

K_{h_f} = 3.28 deg/m, 1.0 deg/ft

K_{hdf} = { 7.94 deg/mps, 2.42 deg/fps, with spoilers; 9.91 deg/mps, 3.02 deg/fps, without spoilers }

$T_{c\ell}$ = { 1.33 sec, with spoilers; 0.65 sec, without spoilers }

K_{a_z} = 0.623 deg/mps², 0.19 deg/fps²

Spoiler control:

$K_{sf\ell}$ = 4.0 deg/deg

K_{azs} = 1.312 deg/mps², 0.40 deg/fps²

T_{s1} = 0.5 sec

T_{s2} = 2.5 sec

T_{s3} = 1.0 sec

Spoiler limits:

Position	0 and 50 deg
Rate	±60 deg/sec
$\delta_{sp_{nom}}$	20 deg

Pitch stability augmentation system:

K_{θ_f} = 2.4 deg/deg

K_{q_f} = 2.3 deg/deg/sec

Figure 1.– Twin Otter test aircraft with spoiler control.

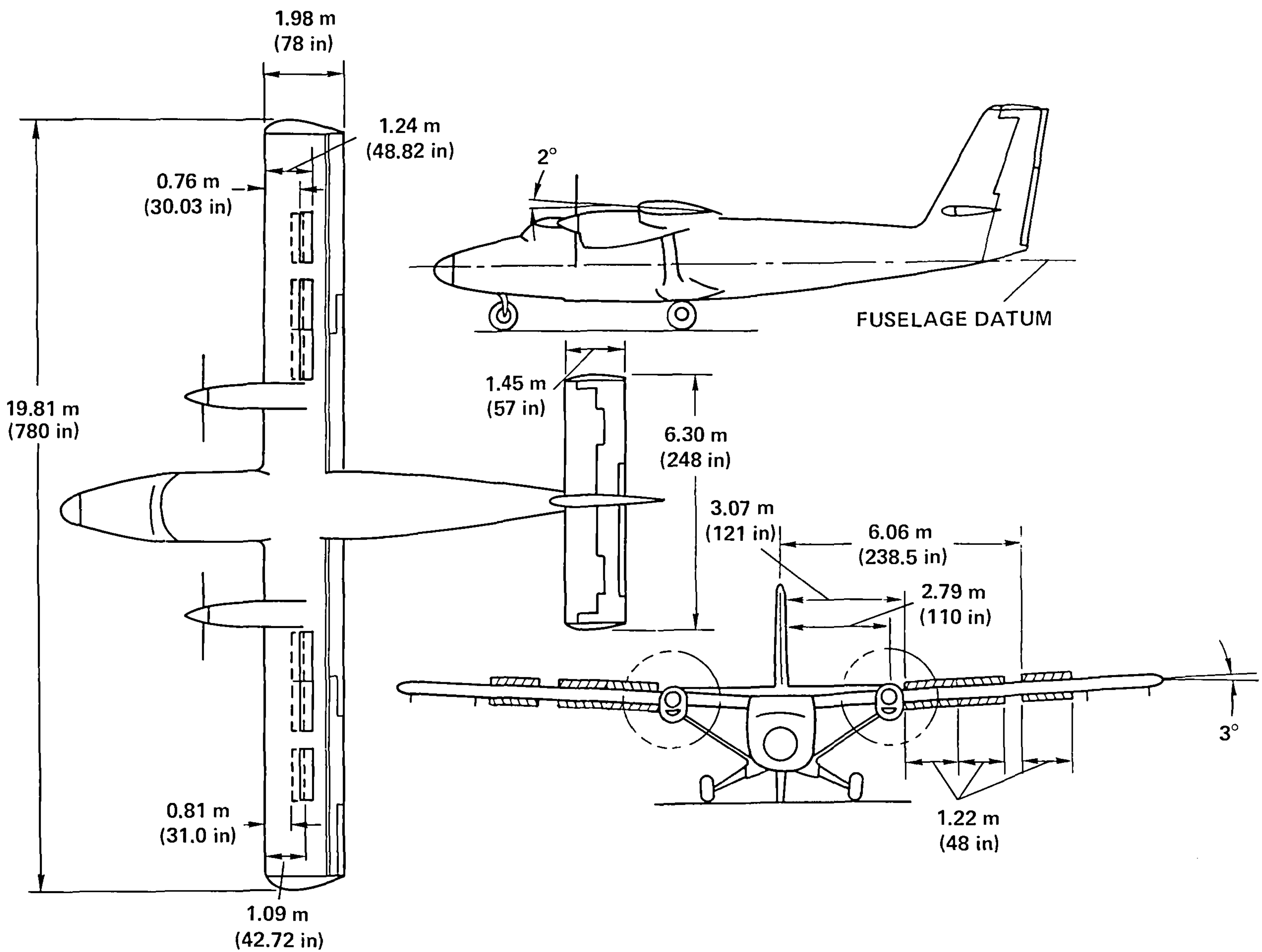


Figure 2.– Three-view drawing of test aircraft.

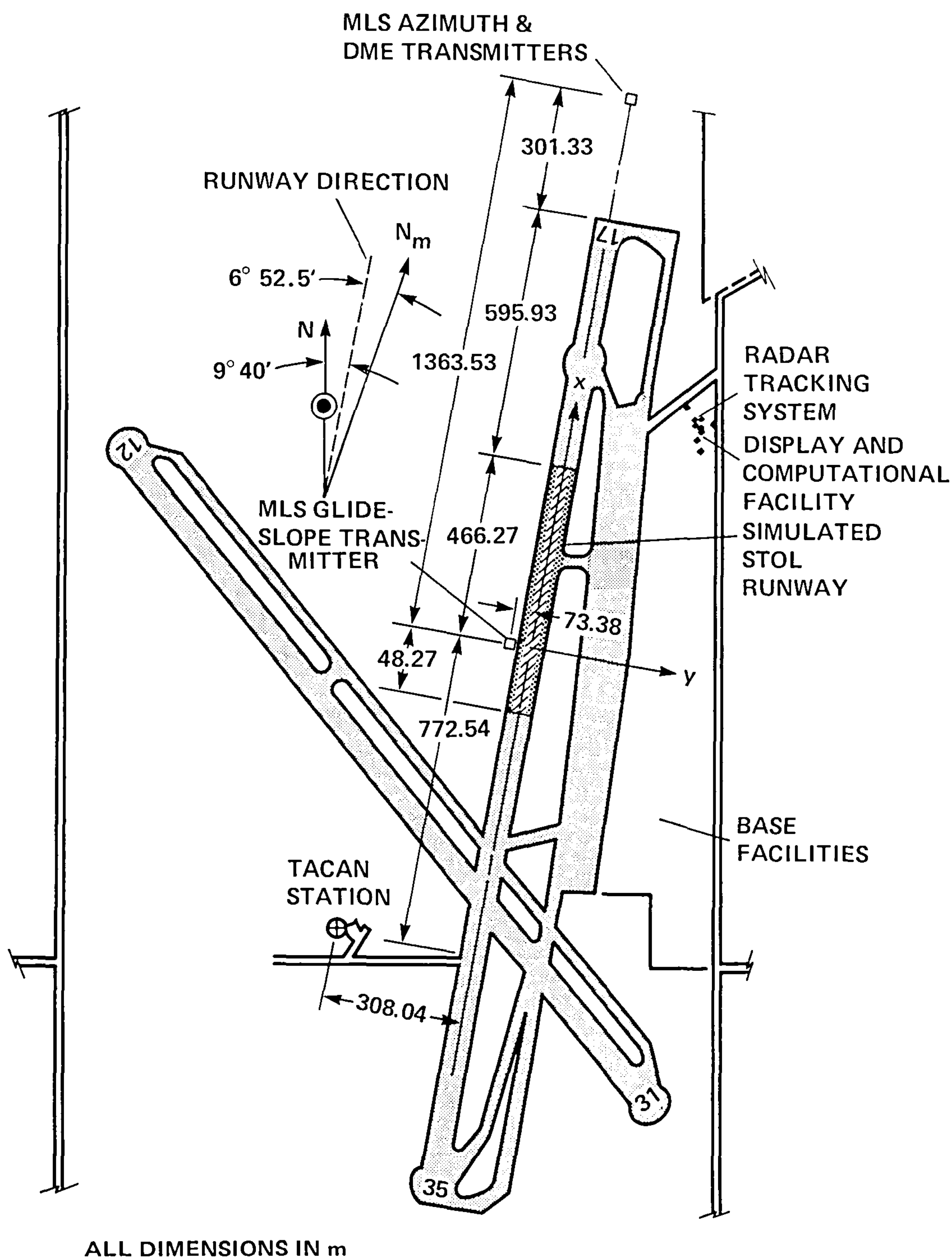


Figure 3.– Ground-support equipment deployment at Crows Landing.

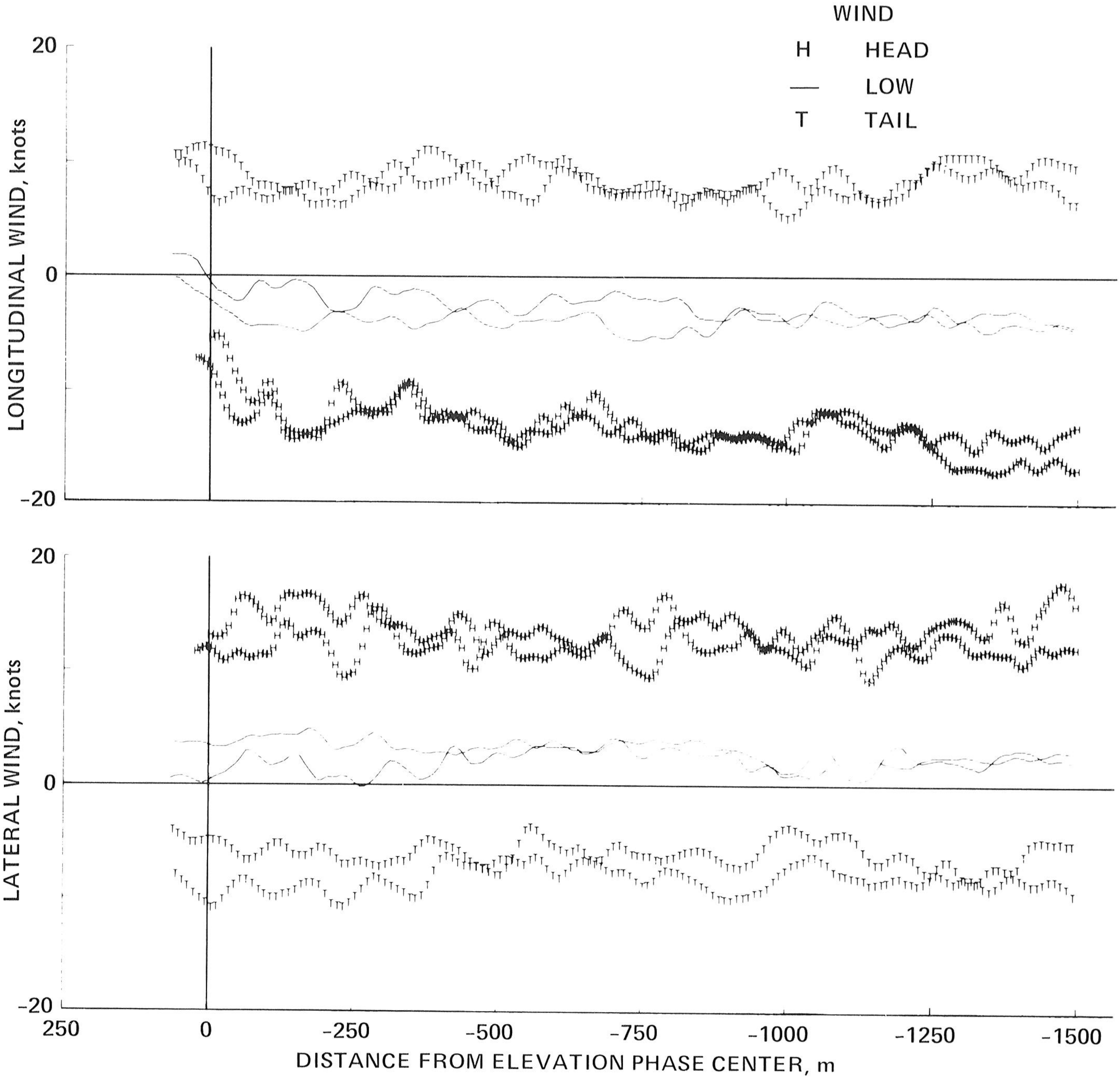


Figure 4.– Typical wind variations during approaches with spoiler control.

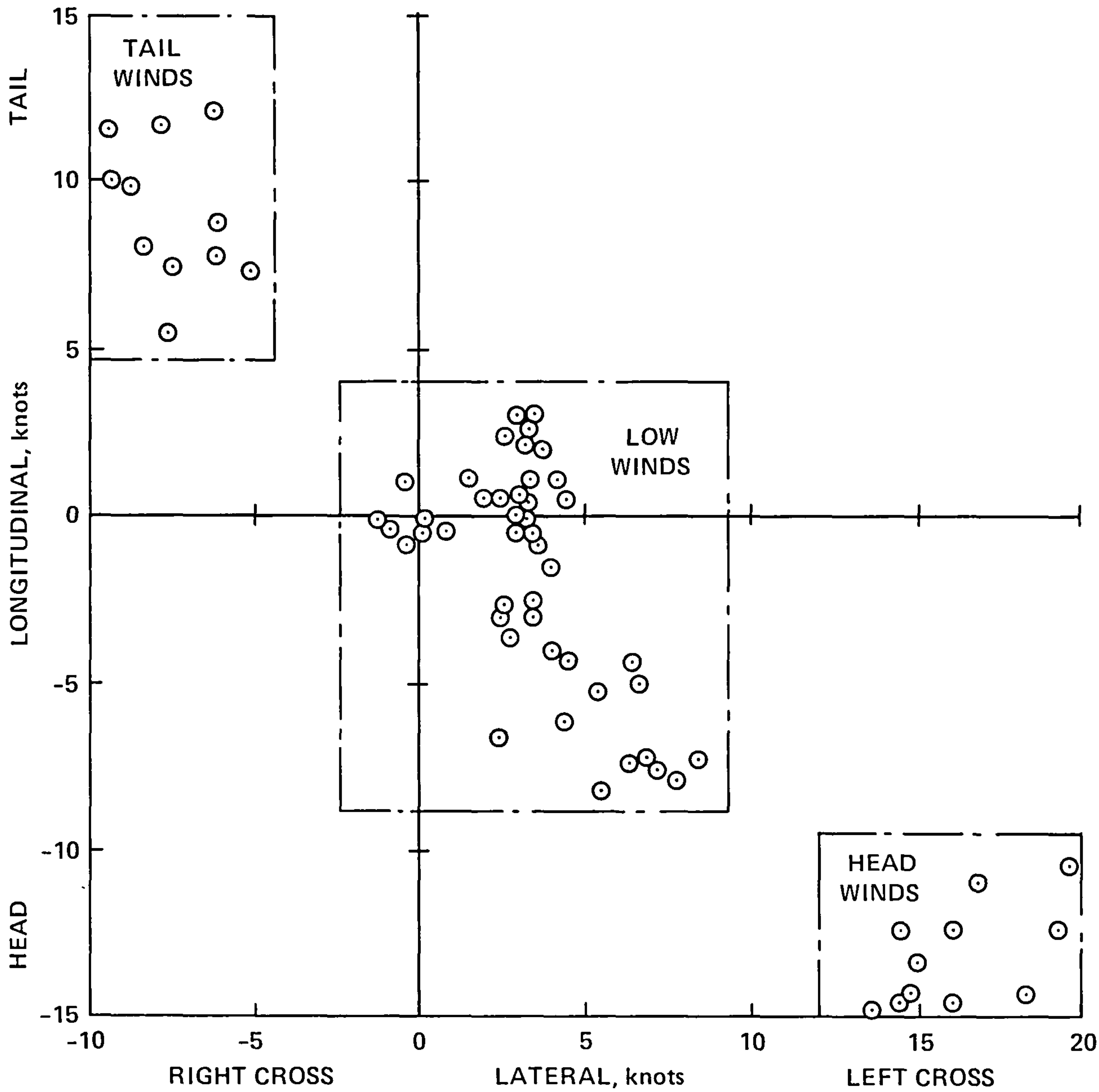


Figure 5.– Onboard-measured wind over the 152.4- to 30.5-m altitude range for the approaches with spoiler control.

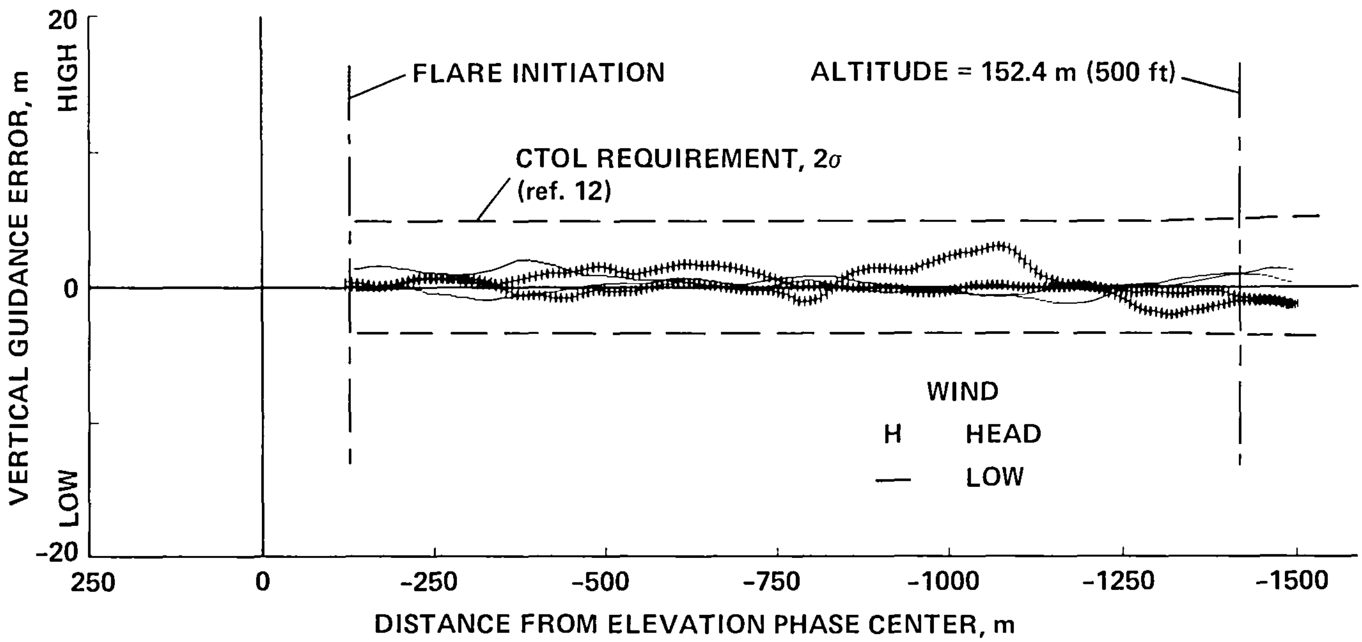


Figure 6.– Typical variations in glidepath track errors for approaches with spoiler control.

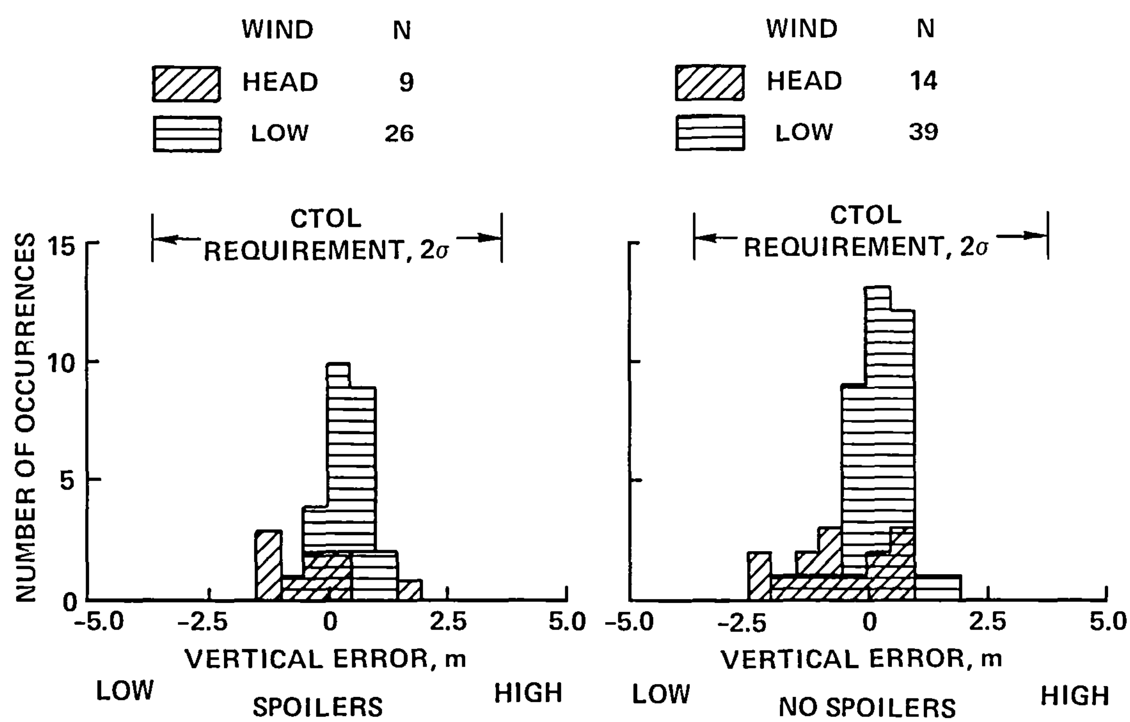


Figure 7.– Distributions of glidepath track errors at flare initiation.

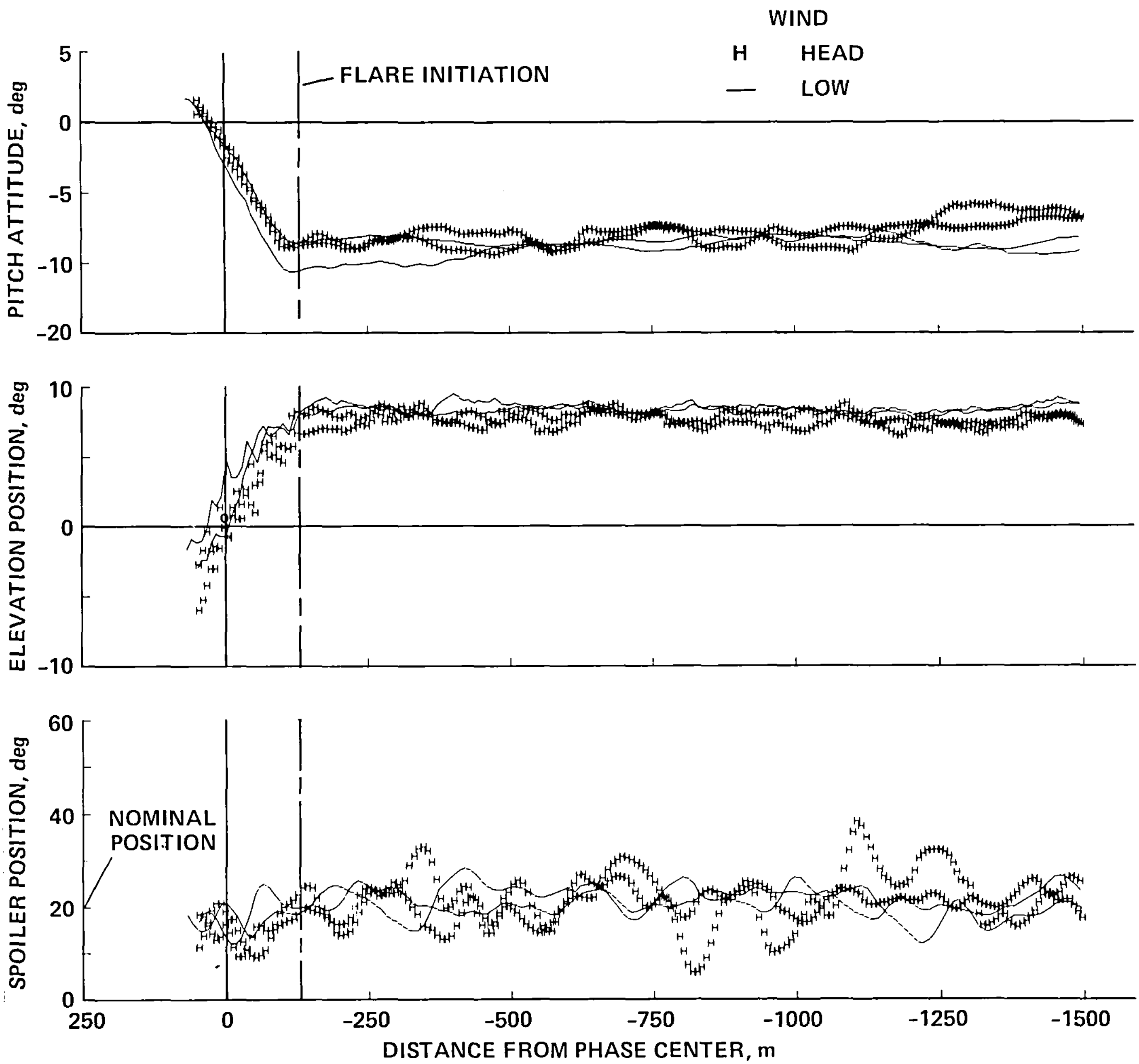


Figure 8.– Typical variations in glidepath track control variables for approaches with spoilers active.

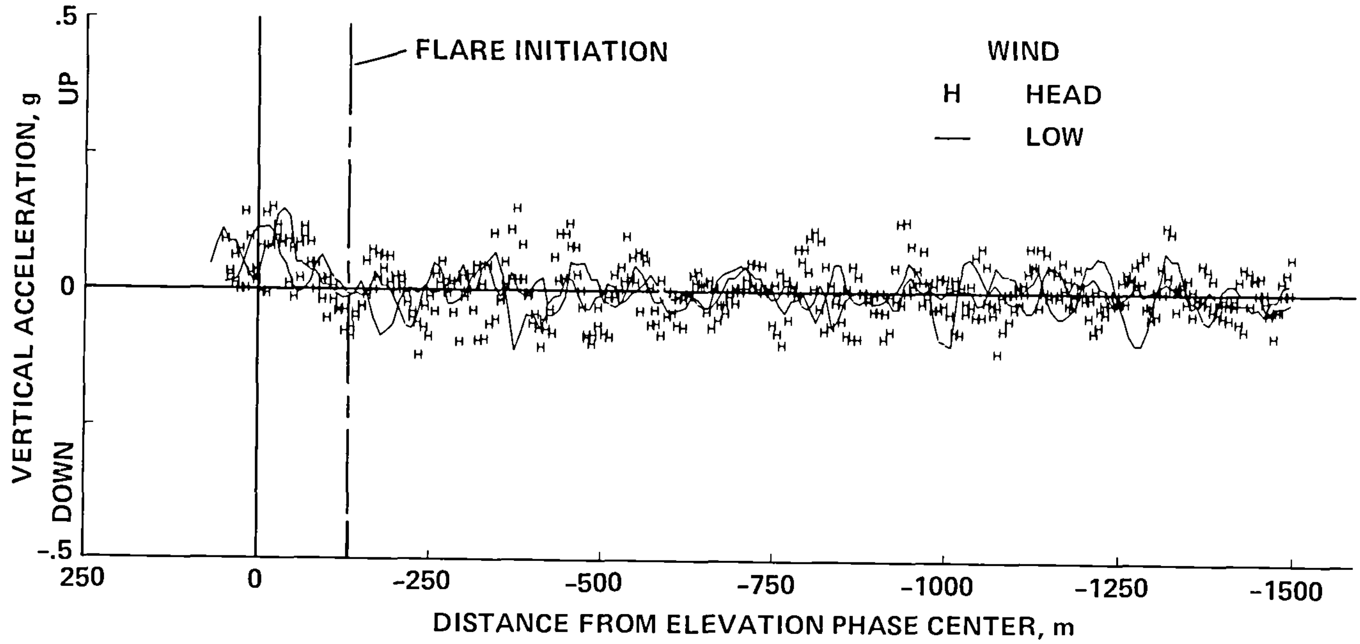


Figure 9.– Typical variations in vertical acceleration for approaches with spoiler control.

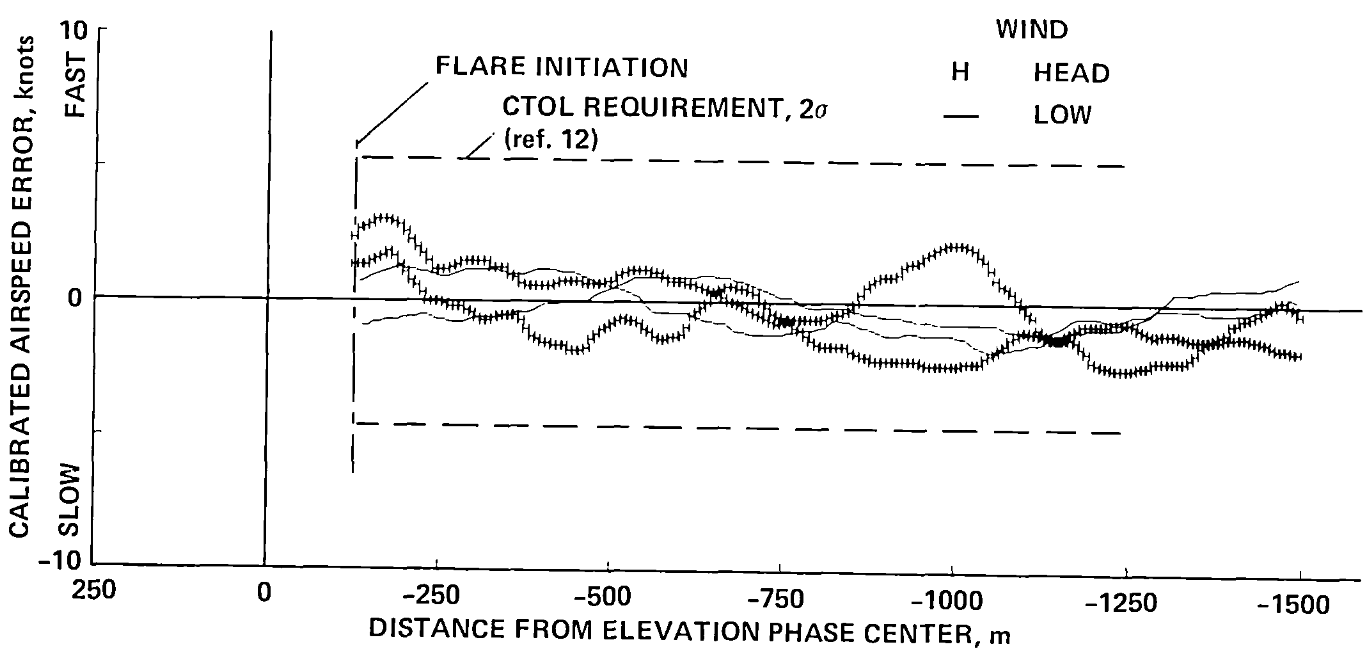


Figure 10.– Typical variations in calibrated airspeed errors for approaches with spoiler control.

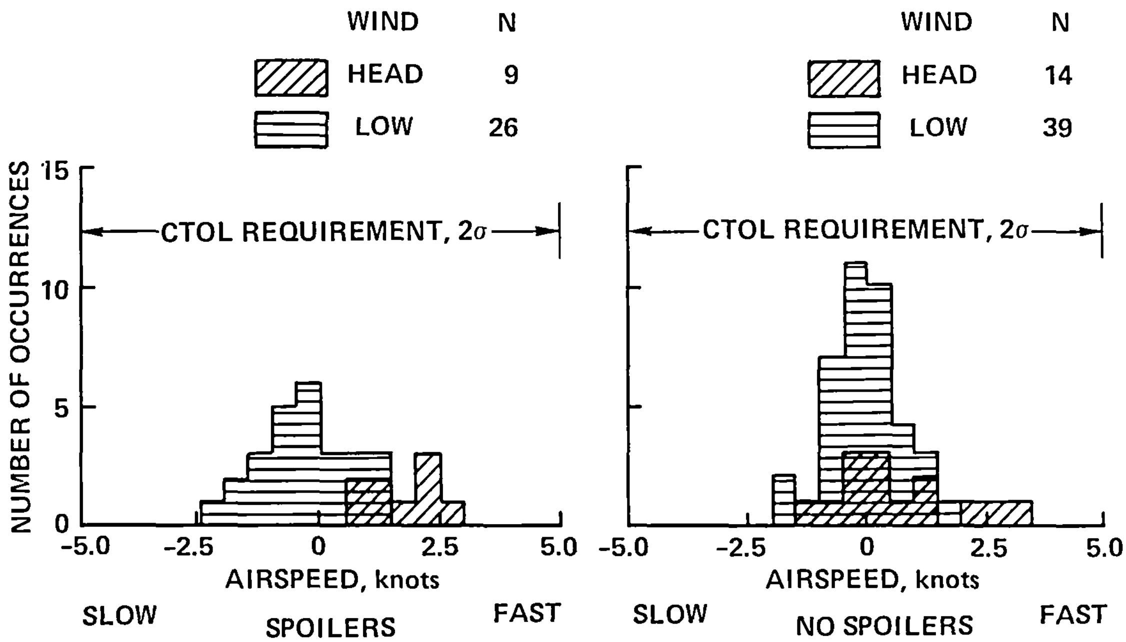


Figure 11.– Distributions of calibrated airspeed errors at flare initiation.

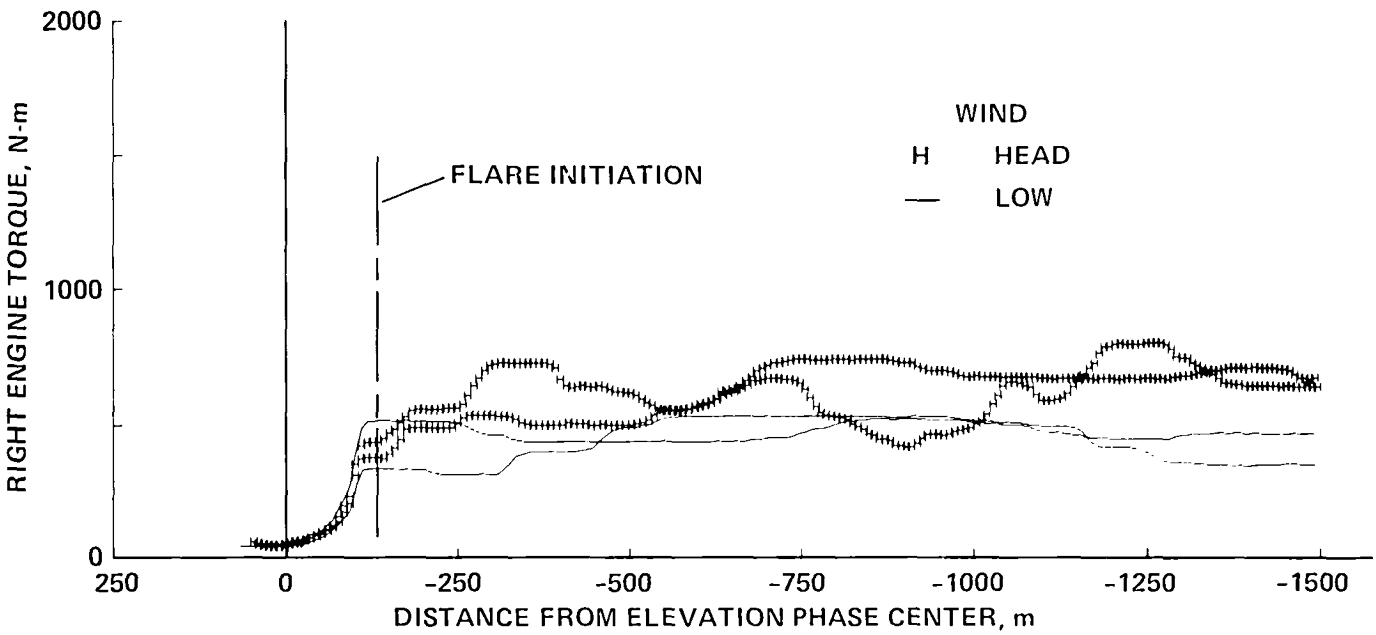
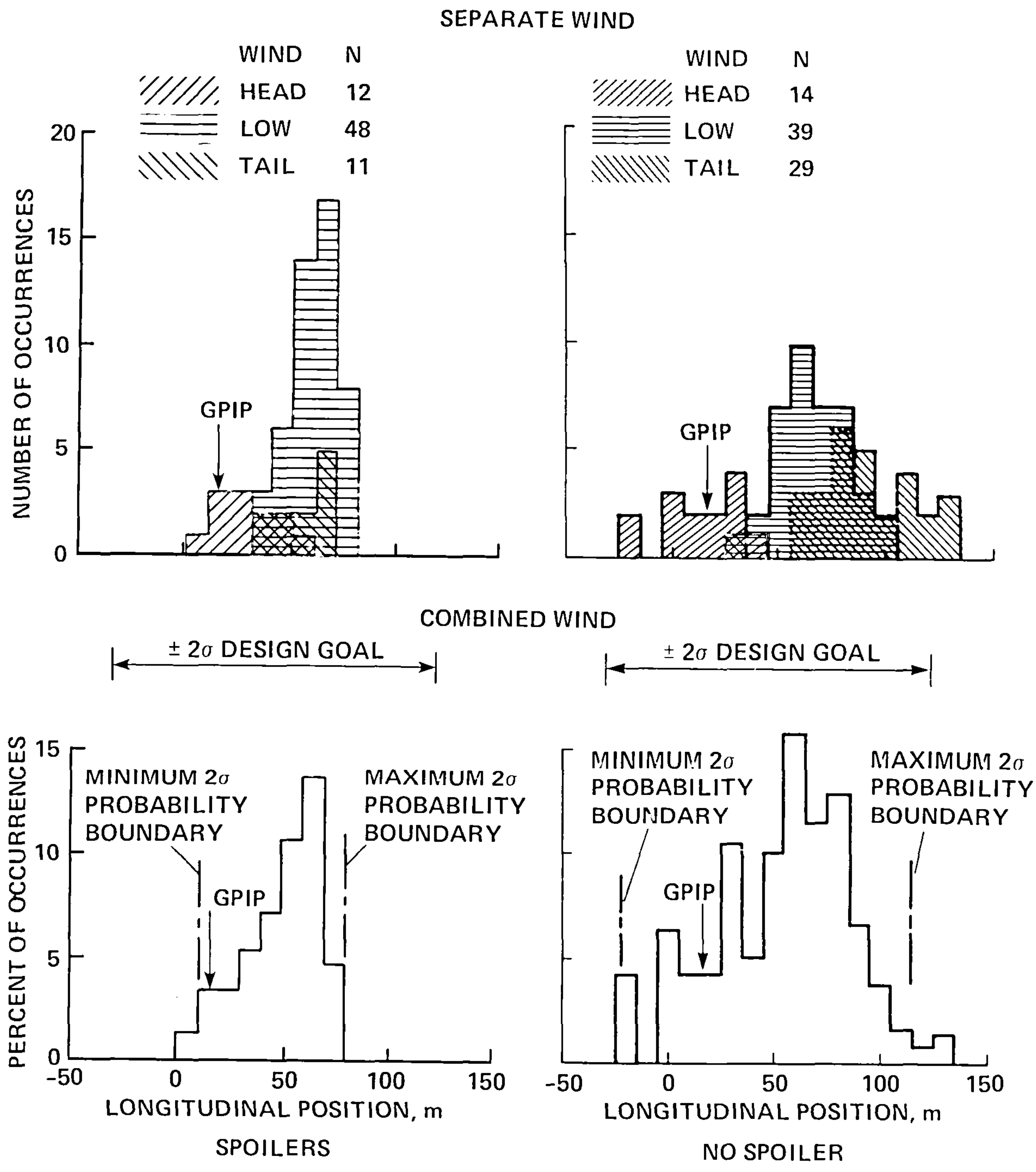
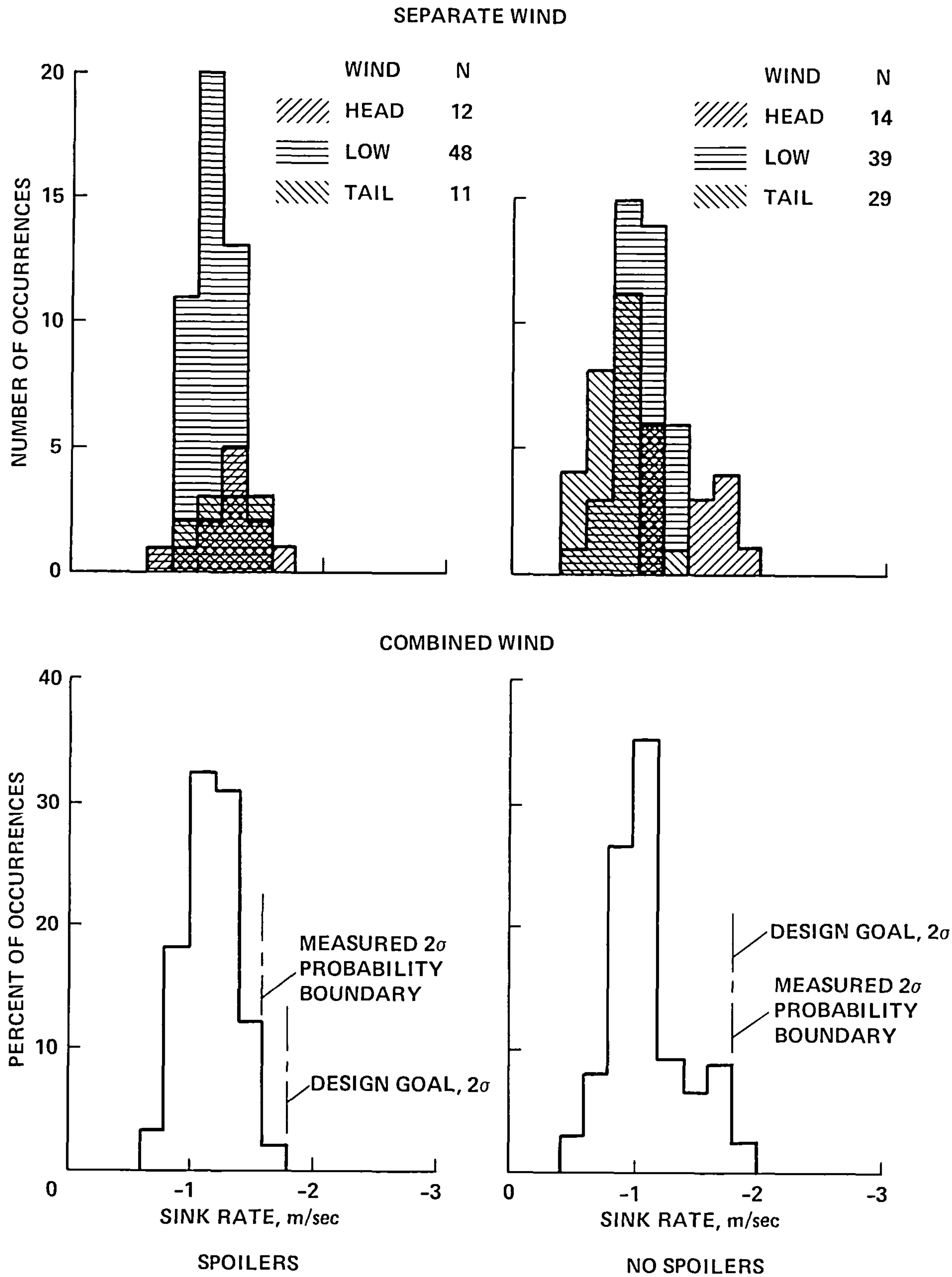


Figure 12.– Typical variations in engine torque for approaches with spoiler control.



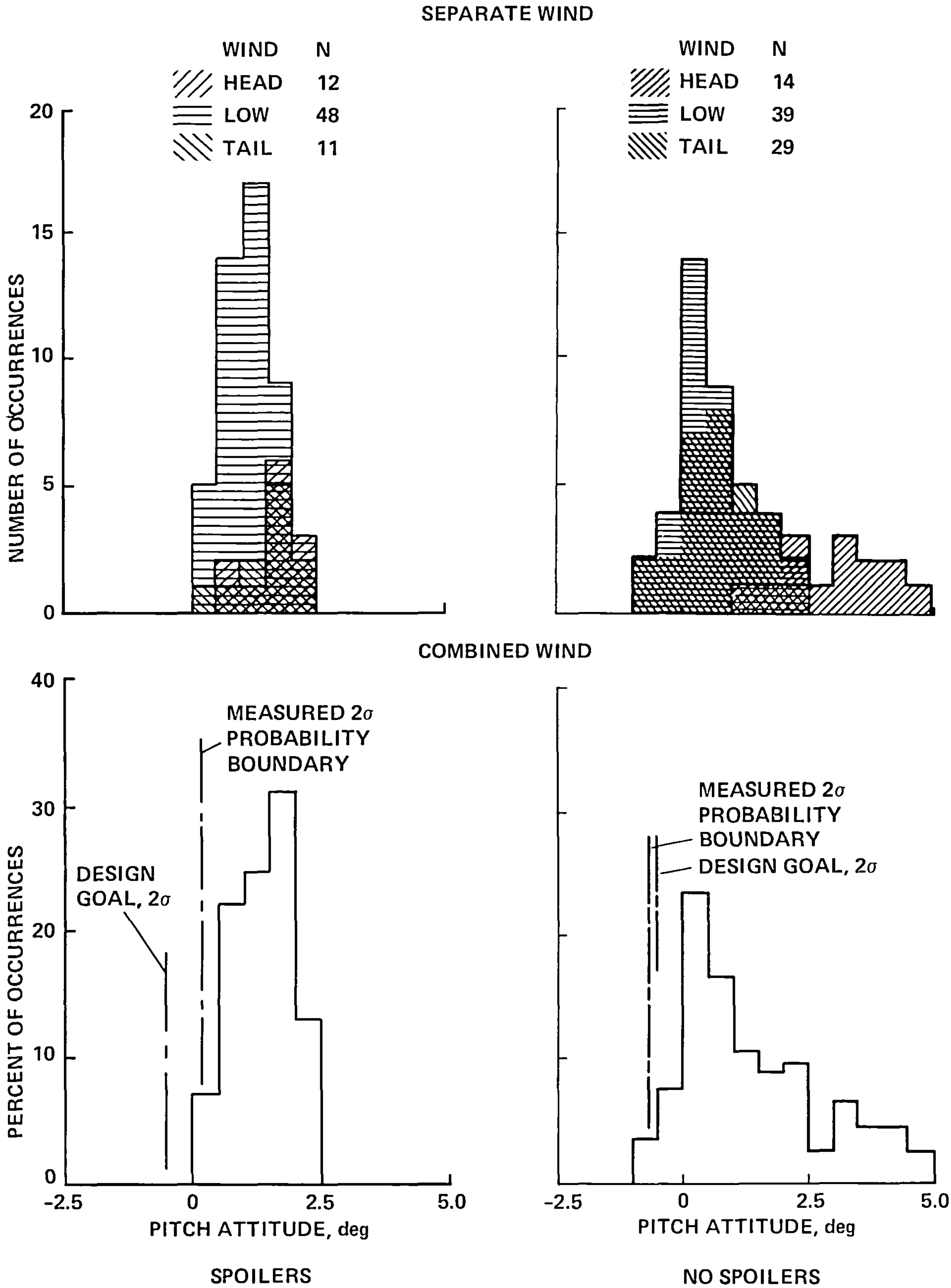
(a) Radar-measured longitudinal position from elevation P.C.

Figure 13.– Effect of spoilers on touchdown distributions determined from flight measurements.



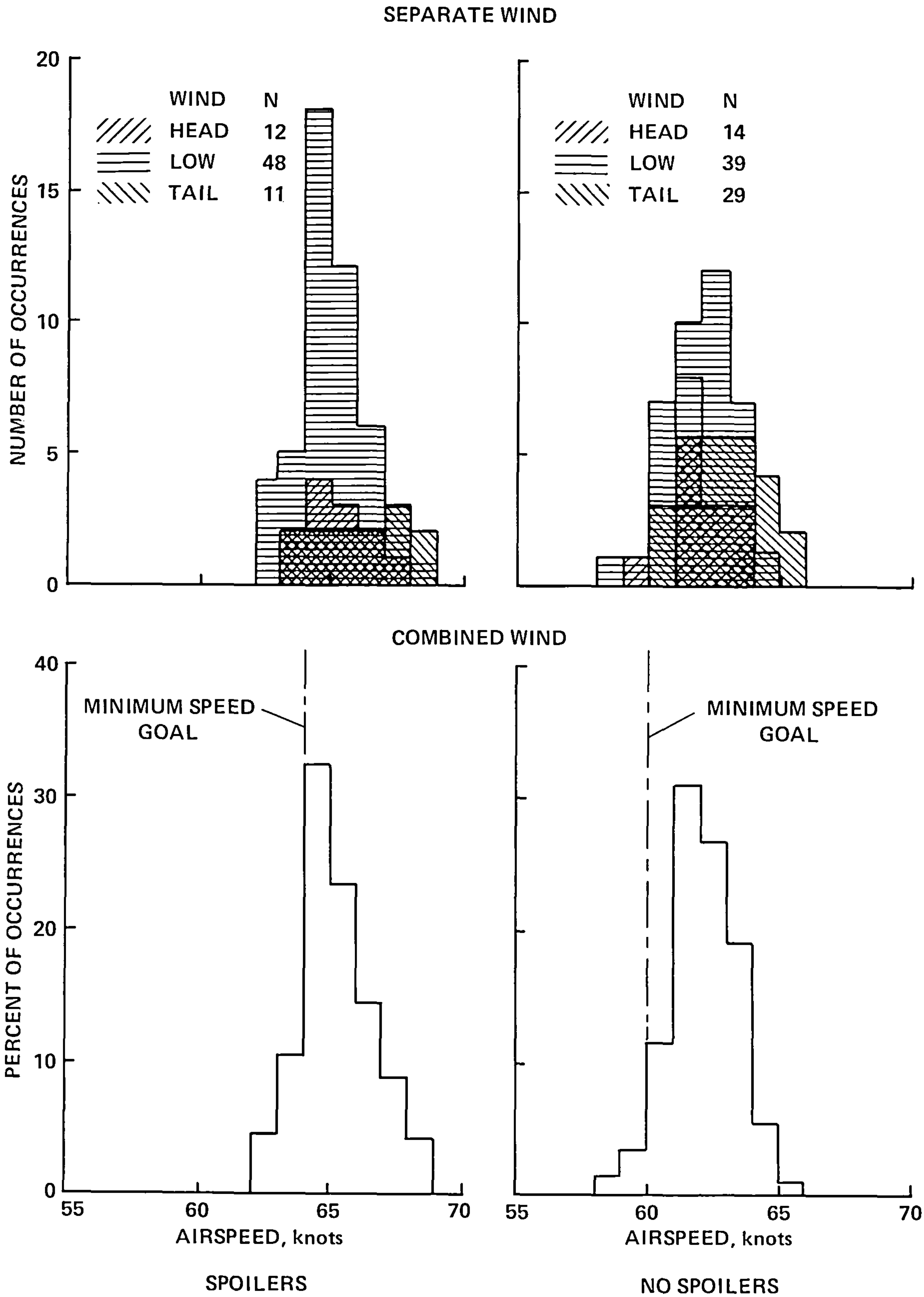
(b) Onboard-measured sink rate.

Figure 13.– Continued.



(c) Pitch Attitude.

Figure 13.– Continued.



(d) Calibrated airspeed.

Figure 13.– Concluded.

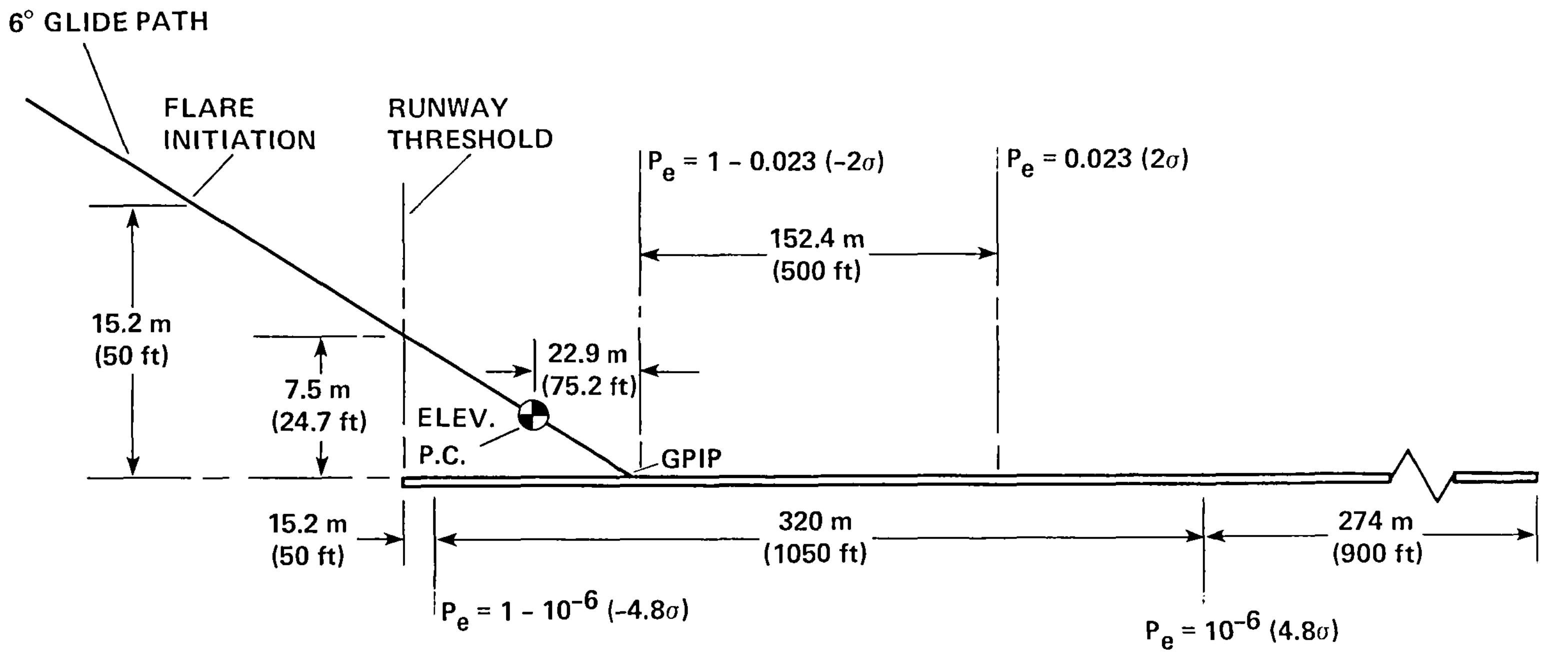
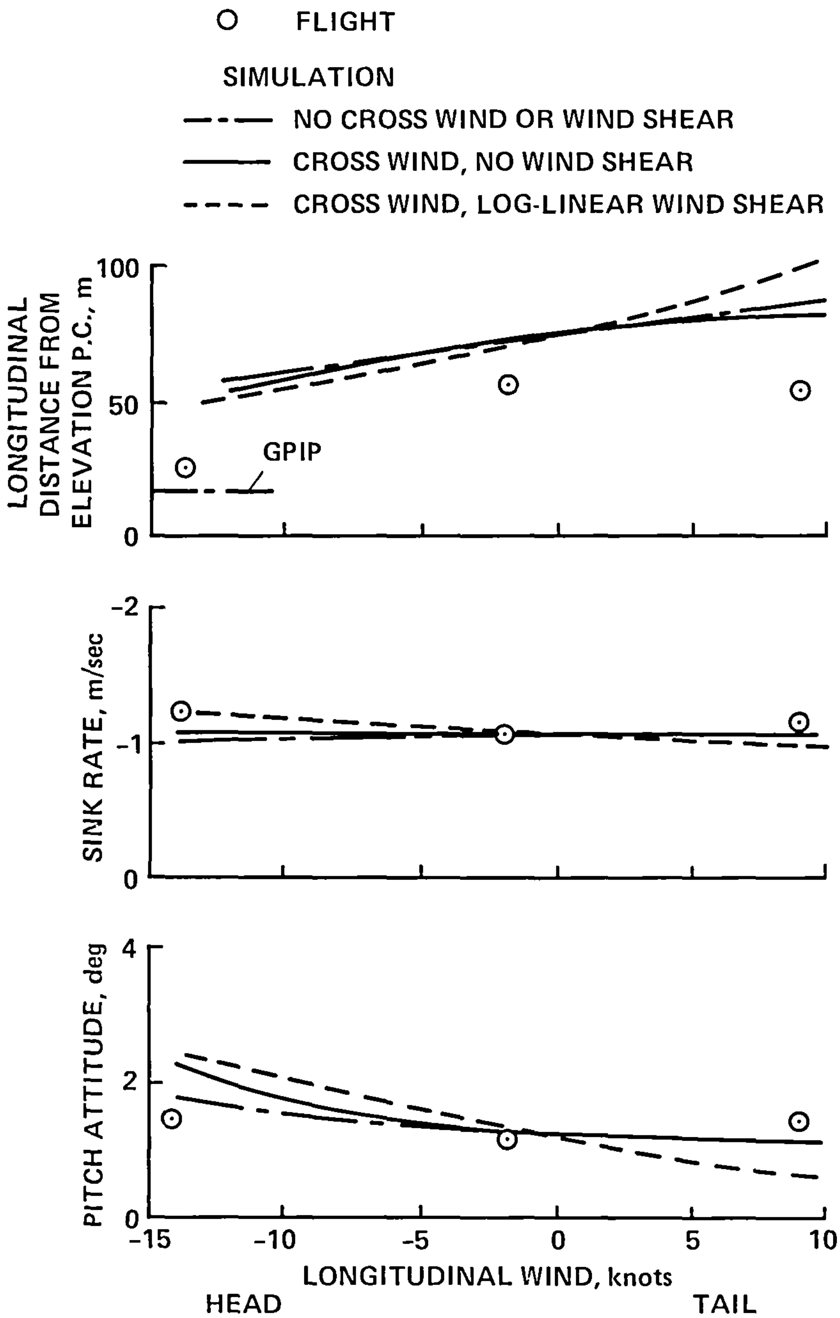
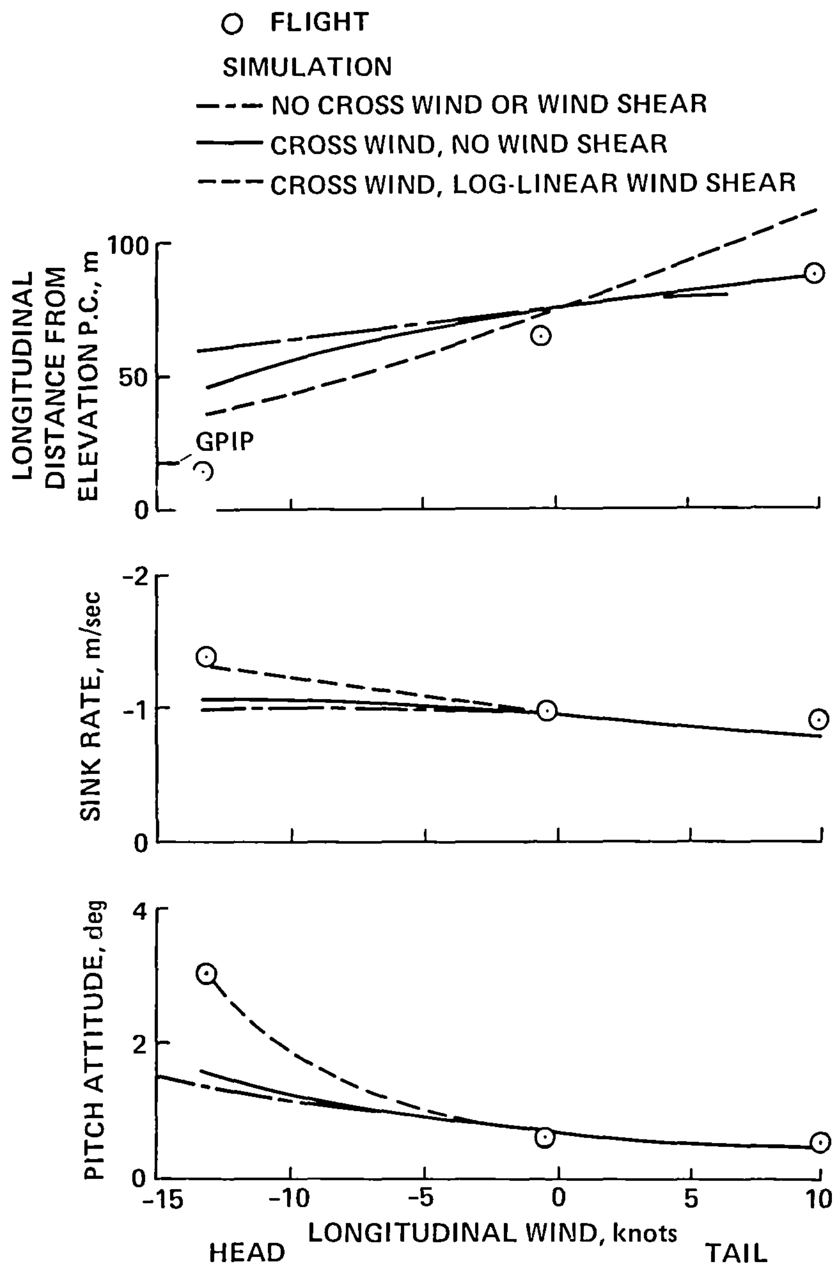


Figure 14.– Touchdown geometry and longitudinal dispersion criteria for STOLports.



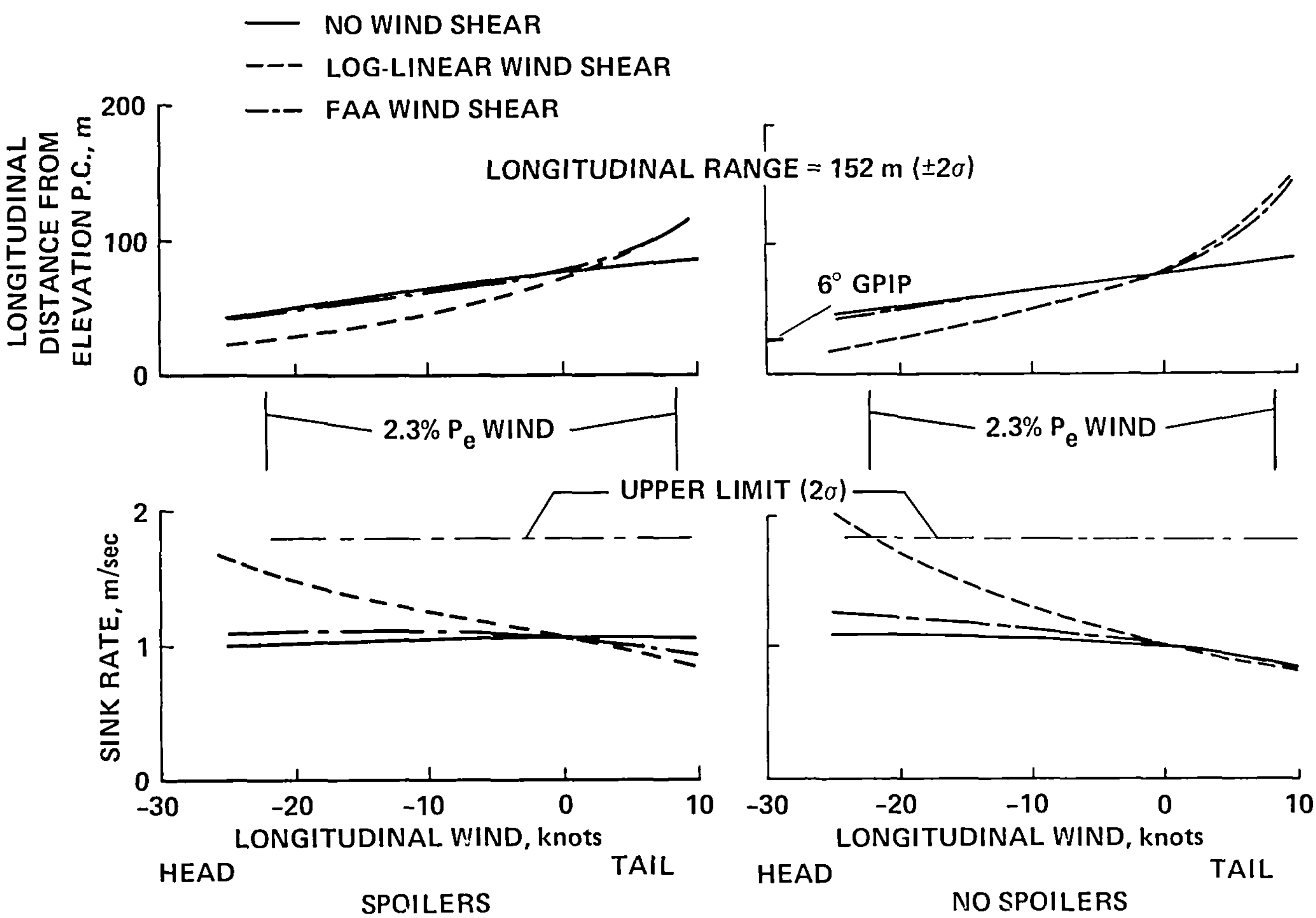
(a) Spoilers.

Figure 15.– Effect of wind on touchdown results from flight and simulation (longitudinal wind averaged over the 152.4- to 30.5-m altitude range).



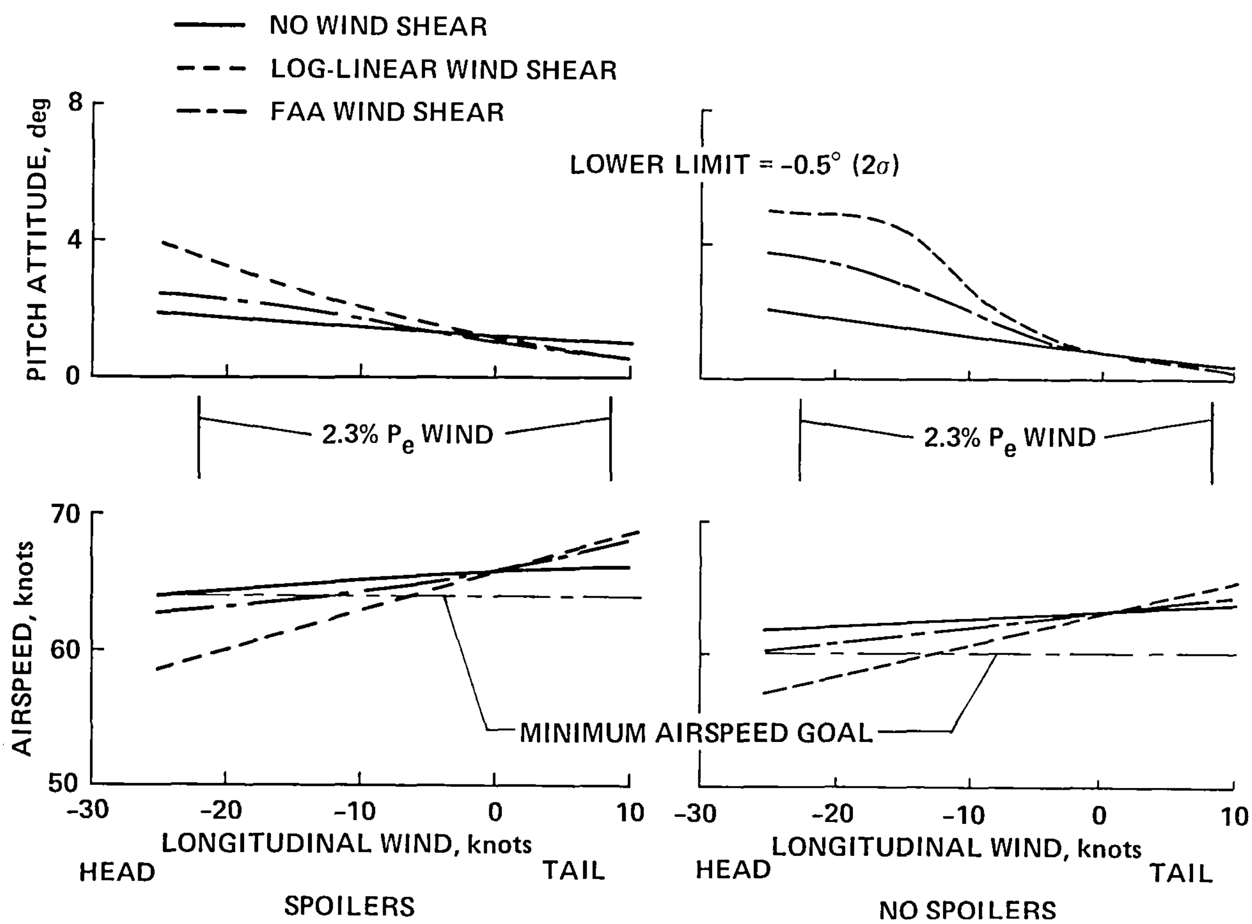
(b) No spoilers.

Figure 15.– Concluded.



(a) Longitudinal position and sink rate.

Figure 16.– Effect of wind on touchdown results from simulation (longitudinal wind at 7.6-m altitude above runway).



(b) Pitch attitude and airspeed.

Figure 16.– Concluded.

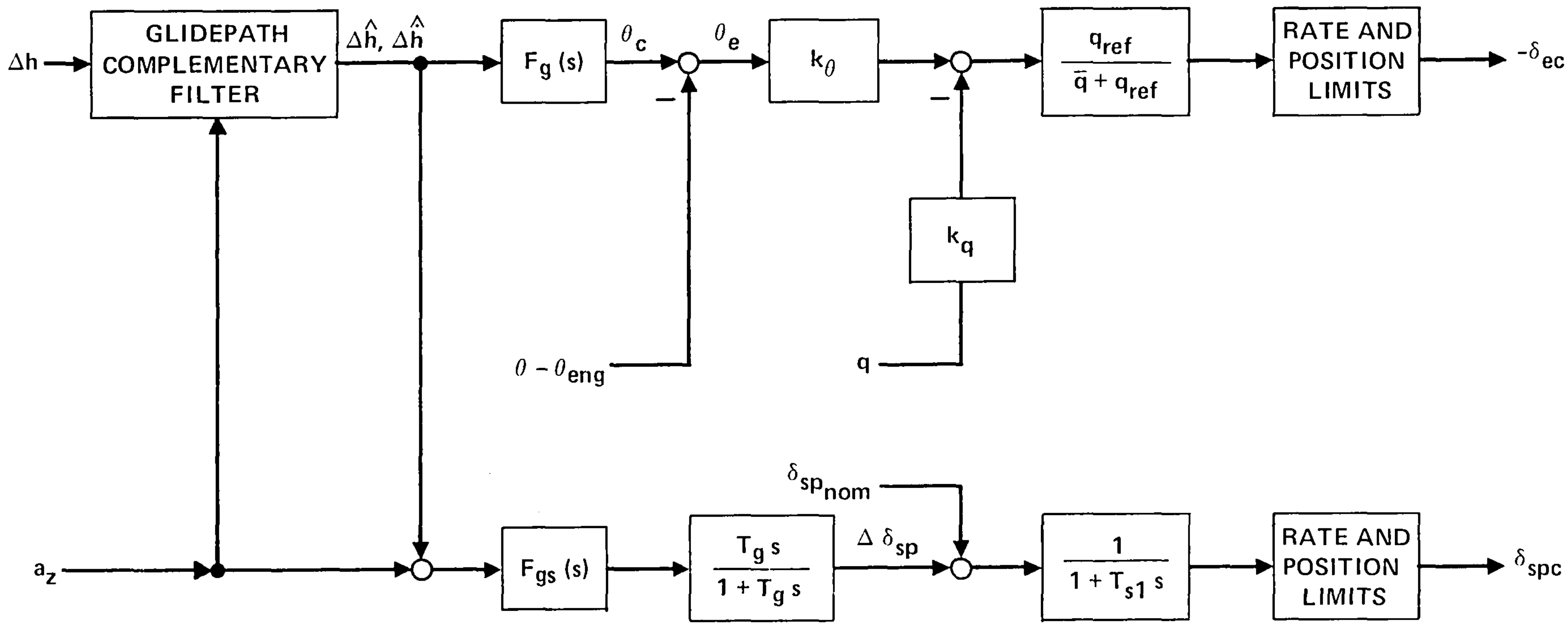


Figure A1.– Glidepath control law with spoilers.

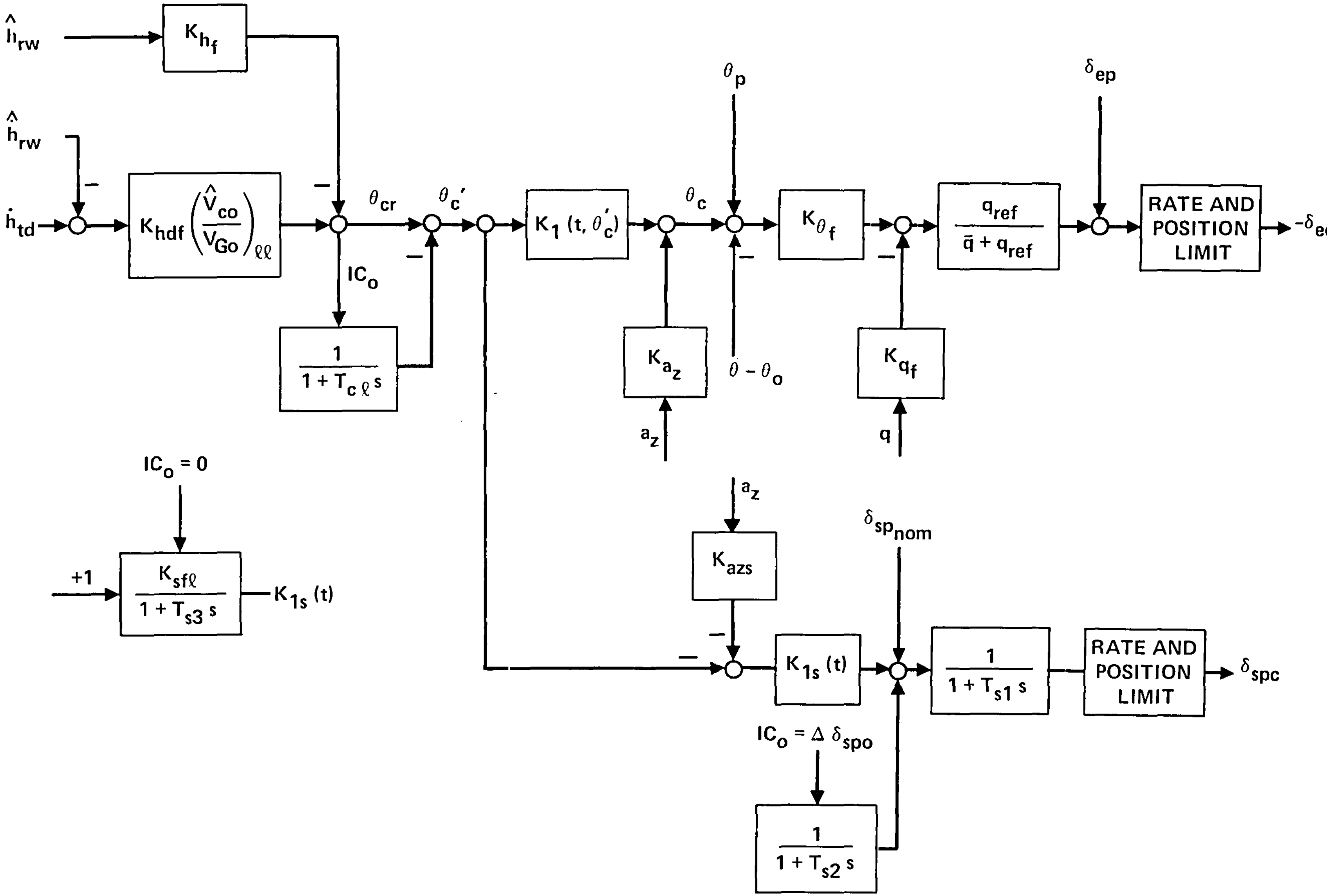


Figure A2.– Flare control law with spoilers.

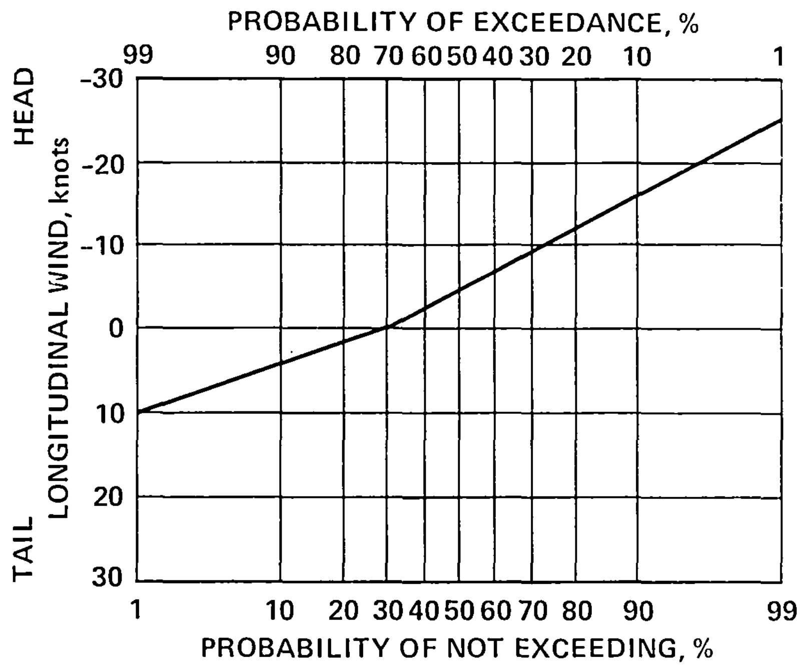


Figure B1.– Wind distribution model.

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA TM-85873		

4. Title and Subtitle	5. Report Date
A FLIGHT-TEST AND SIMULATION EVALUATION OF THE LONGITUDINAL FINAL APPROACH AND LANDING PERFORMANCE OF AN AUTOMATIC SYSTEM FOR A LIGHT WING LOADING STOL AIRCRAFT EQUIPPED WITH WING SPOILERS	September 1984
	6. Performing Organization Code

7. Author(s)	8. Performing Organization Report No.
Stuart C. Brown, Gordon H. Hardy, and William S. Hindson	A-9222

9. Performing Organization Name and Address	10. Work Unit No.
NASA Ames Research Center Moffett Field, Calif. 94035	T-6971
	11. Contract or Grant No.
12. Sponsoring Agency Name and Address	13. Type of Report and Period Covered
National Aeronautics and Space Administration Washington, D.C. 20546	Technical Memorandum
	14. Sponsoring Agency Code
	505-34-11

15. Supplementary Notes

Point of contact: Gordon H. Hardy, Ames Research Center, MS 211-3, Moffett Field, Calif. 94035
(415) 965-5278 or FTS 448-5278

16. Abstract

As part of a comprehensive flight-test investigation of short takeoff and landing (STOL) operating systems for the terminal area, an automatic landing system has been developed and evaluated for a light wing-loading turboprop-powered aircraft. An advanced digital avionics system performed display, navigation, guidance, and control functions for the test aircraft. Control signals were generated in order to command powered actuators for all conventional controls and for a set of symmetrically driven wing spoilers. This report describes effects of the spoiler control on longitudinal autoland (automatic landing) performance.

Flight-test results, with and without spoiler control, are presented and compared with available (basically, conventional takeoff and landing) performance criteria. These comparisons are augmented by results from a comprehensive simulation of the controlled aircraft that included representations of the microwave landing system navigation errors that were encountered in flight as well as expected variations in atmospheric turbulence and wind shear.

Flight-test results show that the addition of spoiler control improves the touchdown performance of the automatic landing system. Spoilers improve longitudinal touchdown and landing pitch-attitude performance, particularly in tailwind conditions. Furthermore, simulation results indicate that performance would probably be satisfactory for a wider range of atmospheric disturbances than those encountered in flight.

Flight results also indicate that the addition of spoiler control during the final approach does not result in any measurable change in glidepath track performance, and results in a very small deterioration in airspeed tracking. This difference contrasts with simulation results, which indicate some improvement in glidepath tracking and no appreciable change in airspeed tracking. The modeling problem in the simulation that contributed to this discrepancy with flight was not resolved.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Light wing loading STOL aircraft Automatic digital flight control Automatic landing system Spoiler control	Unclassified - Unlimited Subject Category: 08

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified	47	A03

*For sale by the National Technical Information Service, Springfield, Virginia 22161

NASA-Langley, 1984

National Aeronautics and
Space Administration

Washington, D.C.
20546

Official Business

Penalty for Private Use, $300

THIRD-CLASS BULK RATE

Postage and Fees Paid
National Aeronautics and
Space Administration
NASA-451

U.S.MAIL

NASA

POSTMASTER: If Undeliverable (Section 158 Postal Manual) Do Not Return