

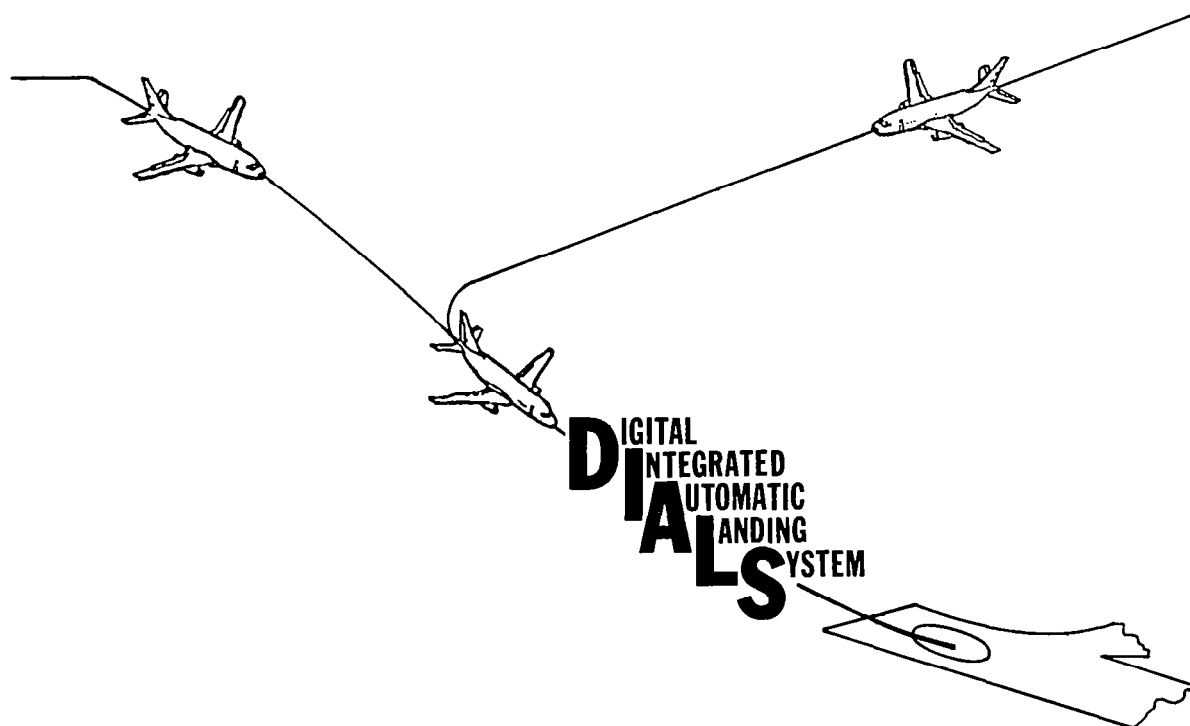
FLIGHT TEST RESULTS FOR THE DIGITAL
INTEGRATED AUTOMATIC LANDING SYSTEM (DIALS) -
A MODERN CONTROL FULL-STATE FEEDBACK DESIGN

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DIALS INTRODUCTION

A goal of the Advanced Transport Operating Systems (ATOPS) Program at Langley Research Center is to increase airport capacity. One on-going effort contributing to this goal is the development of advanced autoland systems which can capture the localizer and glideslope with low overshoot and safely do so for short finals (1.5 to 2.0 nautical miles). Another capability being developed is the ability to fly selectable and steeper glideslopes with the potential for noise reduction and wake vortex avoidance. Systems with improved performance in turbulence and shear wind encounters are also desired. One autoland system designed to have these capabilities and flight tested within the ATOPS program is called the Digital Integrated Automatic Landing System (DIALS). The DIALS is a modern control theory design performing all the maneuver modes associated with current autoland systems: localizer capture and track, glideslope capture and track, decrab, and flare. The DIALS is an integrated full-state feedback system which was designed using direct-digital methods. The DIALS uses standard aircraft sensors and the digital Microwave Landing System (MLS) signals as measurements. It consists of separately designed longitudinal and lateral channels although some cross-coupling variables are fed between channels for improved state estimates and trajectory commands. The DIALS was implemented within the 16-bit fixed-point flight computers of the ATOPS research aircraft, a small twin jet commercial transport outfitted with a second research cockpit and a fly-by-wire system. The DIALS became the first modern control theory design to be successfully flight tested on a commercial-type aircraft. Flight tests were conducted in late 1981 using a wide coverage MLS on Runway 22 at Wallops Flight Center. All the modes were exercised including the capture and track of steep glideslopes up to 5 degrees.



ATOPS TRANSPORTATION SYSTEM RESEARCH VEHICLE (TSRV)

The figure below shows a picture of the ATOPS research aircraft referred to as the TSRV which was used to flight test the DIALS. Flight test data of sensors and selected computer outputs were recorded on magnetic tape for postflight processing. In addition, on-line strip chart recorders provide real-time readouts of software selectable variables for in-flight system analysis and performance evaluation.

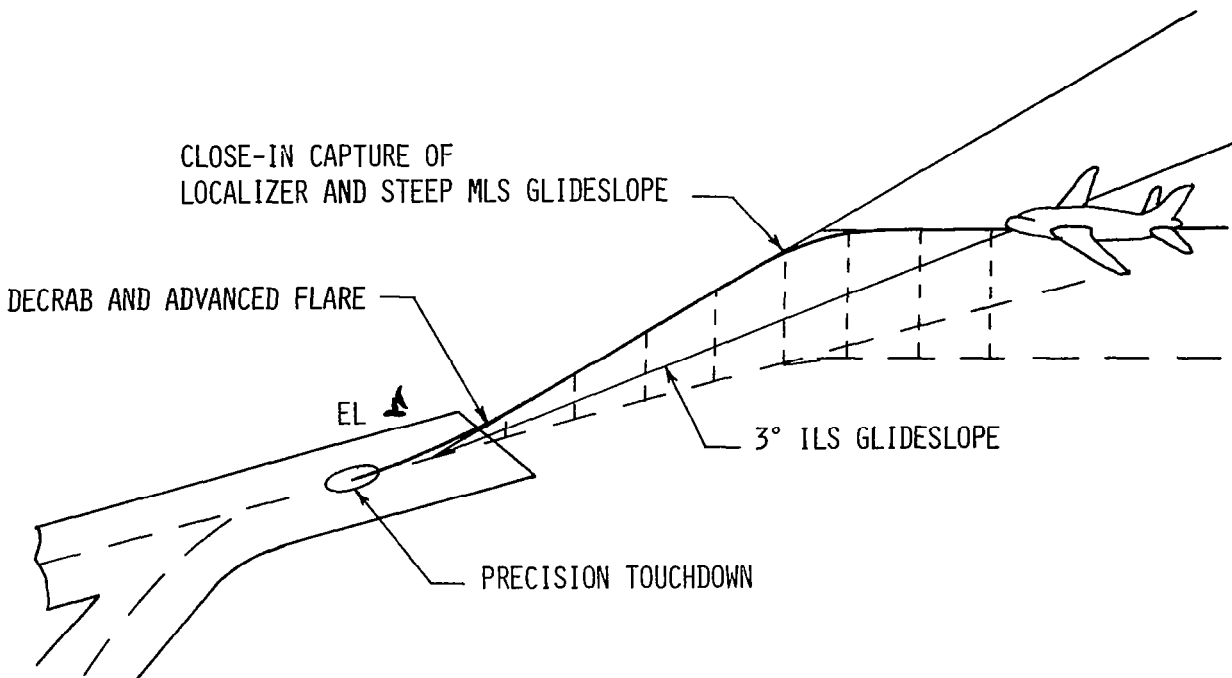
ADVANCED TRANSPORT OPERATING SYSTEMS (ATOPS)
TRANSPORTATION SYSTEMS RESEARCH VEHICLE (TSRV)

LANGLEY RESEARCH CENTER



DIALS AUTOMATIC OPERATIONS

The pictorial illustrates the automatic operations performed by DIALS. Prior to beginning the DIALS operations, the pilot selects the desired glideslope and desired reference airspeed. Then the aircraft is flown towards the runway centerline at a desired heading or ground track angle up to $\pm 60^\circ$ from the runway heading. The DIALS will then automatically initiate the capture maneuver when the capture criteria, which consider aircraft parameters, desired trajectory, and wind conditions, are satisfied. Localizer and glideslope capture can occur independently, in any order, or simultaneously. Upon completing the capture mode, the localizer and glideslope track modes are engaged to maintain the aircraft along runway centerline and the selected glideslope. At an altitude of 250 feet, the decrab maneuver is engaged. The control law commands the aircraft into a sideslip maneuver, a maneuver that pilots often use, while maintaining the track along runway centerline. In an altitude range of 80 to 150 feet, the flare maneuver is engaged. The exact engagement altitude is a function of the glideslope angle, the vertical velocity, and other aircraft parameters. During the flare maneuver, the aircraft is commanded to follow a fixed trajectory in space to a prespecified touchdown point on the runway. The fixed trajectory was chosen as a means to enable precision or low dispersion touchdown. With a precision touchdown capability, an aircraft can reliably decelerate and exit the runway at its earliest convenience and reduce occupancy time.



THE DIALS DESIGN AND SYSTEM DESCRIPTION

The DIALS was designed using stochastic modern control theory and direct-digital design methods. The system equations were linearized about a nominal glideslope, and a set of constant gains was determined according to a quadratic cost function. The gains were then used in one basic control law which accommodated all the autoland modes. The control law generates control commands at 10 Hz, which is one half that used in the digital baseline system on the research aircraft.

The sensors used for the DIALS flight tests were the digital MLS signals (azimuth, elevation, and range), pitch, roll, and yaw rate from standard rate gyros, body-mounted accelerometers, vertical velocity determined from MLS processing, calibrated airspeed, engine-pressure-ratio, throttle position, stabilizer position, barometric altitude, and radar altitude during flare. Pitch, roll, and yaw from an inertial platform were used although the design was intended to use standard vertical and directional gyros. However, these gyros were not available on the test vehicle.

DIALS has a full-state constant gain Kalman filter which estimates the states of the aircraft and steady, gust, and shear winds. The wind estimates are fed directly into the control law to provide improved performance to changing wind conditions.

The longitudinal and lateral control laws were each designed independently of one another. Each design was a multi-input multi-output problem resulting in integrated or coordinated controls. The controls coordinated in the longitudinal channel were throttle, elevator, and stabilizer while those coordinated in the lateral were the aileron and rudder.

- FULL-STATE DIRECT-DIGITAL DESIGN USING MODERN CONTROL THEORY
 - One Basic Control Law For All Modes
 - 10-Hz Sampling Rate
- SENSORS
 - Digital MLS Signals (Az, EL, R)
 - Attitudes & Attitude Rates
 - Body-Mounted Accelerometers
 - h_{MLS} & Calibrated Airspeed
 - EPR's, Throttle Position, & Stabilizer Position
 - Barometric Altitude & Radar Altimeter During Flare
- FULL-STATE KALMAN FILTER (CONSTANT GAINS) WITH WIND ESTIMATES THAT ARE USED DIRECTLY IN CONTROL LAW.
- LONGITUDINAL CONTROL LAW HAS INTEGRATED THROTTLE, ELEVATOR, & STABILIZER AND LATERAL LAW HAS INTEGRATED AILERON & RUDDER.

MODIFICATIONS TO DIALS NOMINAL DESIGN

One basic control law structure was used for the DIALS but some modifications were made to the nominal design as a result of evaluation in a nonlinear simulation to achieve desired performance for the various control modes.

For the glideslope capture mode, at the instant of engagement, the desired vertical velocity along the glideslope was commanded to the desired value through an easy-on rather than letting the command to the control law be a step command.

In the glideslope mode, the vertical position error is integrated and used in the control law when this mode is engaged. Also the gains on vertical position and vertical velocity are increased by means of an easy-on for tighter tracking.

Some similar changes were made for the localizer track mode. At track mode, engagement gains on the lateral position are increased through an easy-on, and the lateral position and roll errors each are integrated to eliminate position standoff and to drive roll attitude to wing level. The roll integrator insures that the control law will achieve the desired crab angle and zero sideslip in steady-state wind conditions.

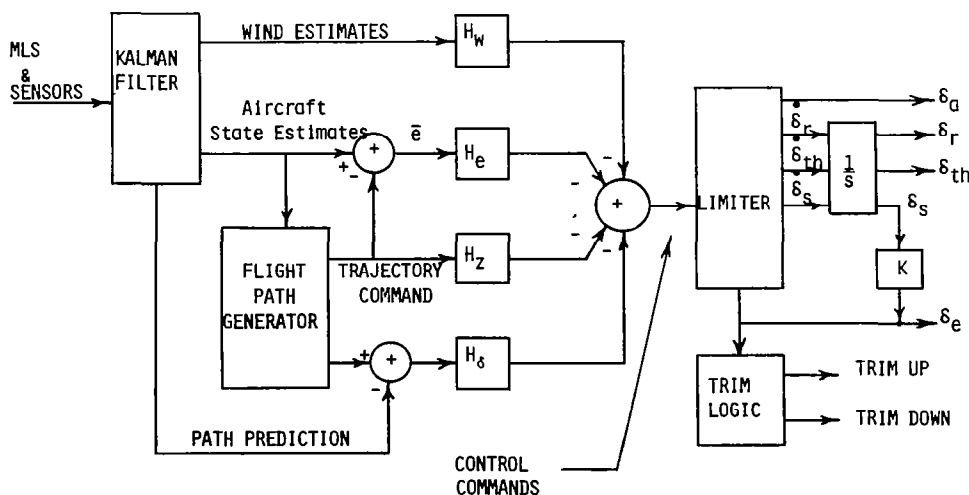
During the decrab mode, the aircraft heading is commanded to align with the runway through trajectory commands. To insure a sideslip condition, the gain on the roll integrator used during localizer tracking was ramped to zero, and the heading error was integrated and fed back to the control commands.

To insure close tracking of the flare trajectory, the gains on altitude, altitude rate, and pitch rate were increased by means of an easy-on at the initiation of the flare mode.

- G/S CAPTURE MODE
 - COMMANDED VERTICAL VELOCITY AT ENGAGEMENT WITH EASY-ON
- G/S TRACK
 - ADD INTEGRATOR ON VERTICAL POSITION ERROR
 - INCREASE GAINS (WITH EASY-ON ON VERTICAL POSITION & VELOCITY ERRORS)
- LOC TRACK
 - ADD INTEGRATORS FOR LATERAL POSITION & ROLL ERRORS
 - INCREASE GAIN (WITH EASY-ON) ON LATERAL POSITION ERROR
- DECRAB
 - ADD INTEGRATOR TO HEADING ERROR
 - REMOVE FEEDBACK OF ROLL INTEGRATOR WITH EASY-OFF
- FLARE
 - INCREASE GAINS (WITH EASY-ON) ON VERTICAL POS & VEL & PITCH RATE

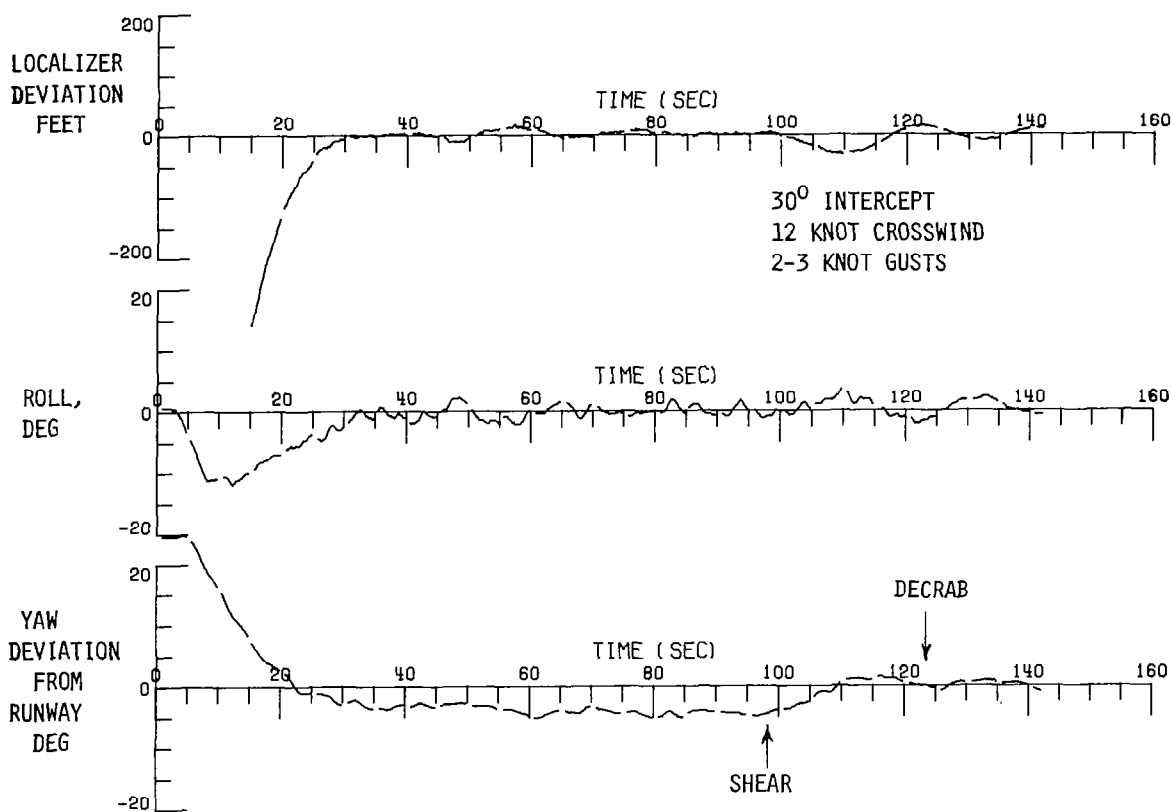
BLOCK DIAGRAM OF FEEDBACK LOOP

The block diagram shows the feedback loops associated with the DIALS longitudinal and lateral control laws. The Kalman filter processes the MLS and aircraft sensor data to determine estimates of the aircraft states and winds. There are 16 aircraft and wind states for the longitudinal channel and 13 for the lateral channel. The Kalman filter makes path predictions of the aircraft at the next iteration. These predictions are differenced with the flight path generator path, and the result is fed back to the controls to provide path lead information. The aircraft state estimates are differenced with desired trajectory from the flight path generator to form trajectory error signals. The desired trajectory signals are also fed back to the control law to provide the control law information about trajectory deviations from the nominal glideslope. Using the wind estimates and the above described signals, the control commands are generated ten times a second. The commands generated for the longitudinal controls are elevator position δ_e , throttle rate δ_{th} , and stabilizer rate δ_s . By choosing throttle rate as a command, it was possible to achieve satisfactory throttle rate activity by appropriate weighting of it in the quadratic cost function. Stabilizer rate was weighted in the cost so that this command acted primarily as a trimming function. By using rate commands, no penalty is incurred in the cost function for position deviations from the nominal values for the stabilizer and throttle. However, for the elevator, the desire is to keep it nominally near the neutral position so that maximum authority is always available. The commands from the lateral control law are aileron position δ_a and rudder rate δ_r . The three rate commands were integrated at a 20-Hz rate to provide smoother position commands to the aircraft servos. The stabilizer position is added to the elevator command. In the design, the stabilizer rate was intended to control the trim logic in such a manner as to turn the stabilizer trim motor on and off on the test vehicle; however, due to built-in restrictions on the direction of stabilizer movement as a function of elevator position, the stabilizer trimming was achieved by logic driven by the elevator deflection (logic that existed on the baseline test vehicle).



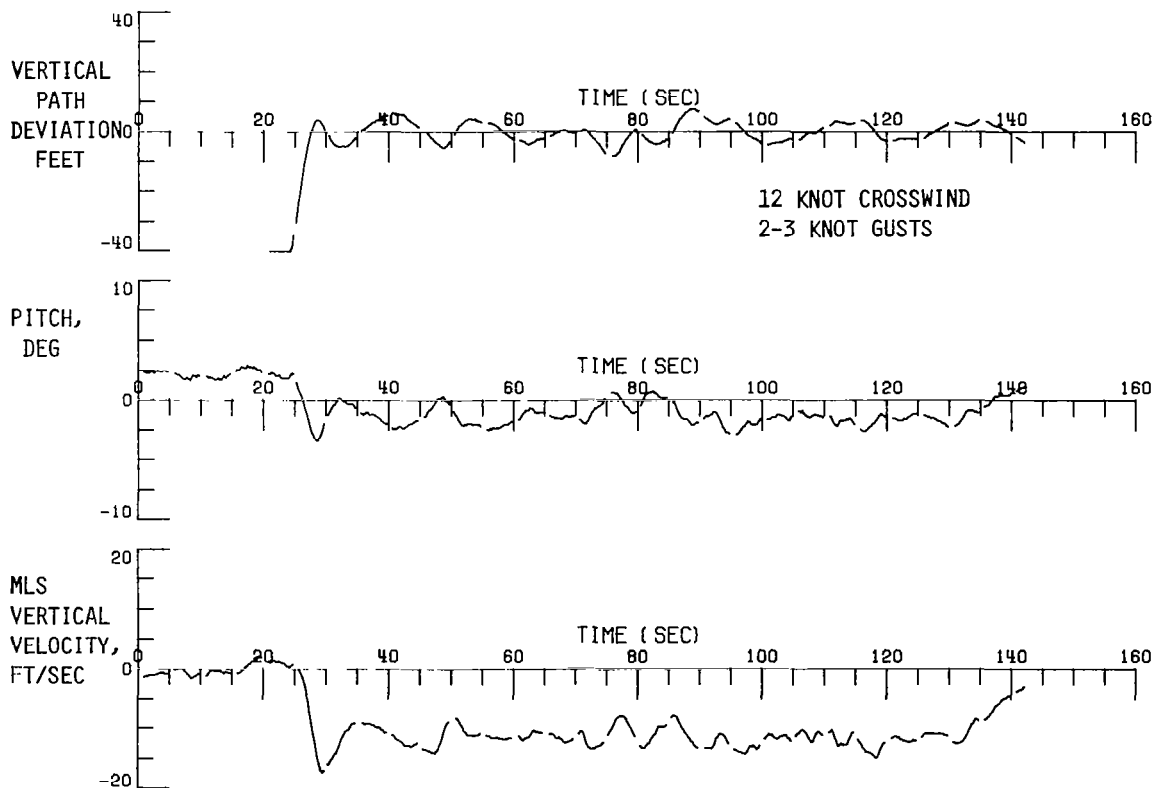
DIALS LOCALIZER CAPTURE - FLT 361, RUN 7

The capture of the localizer using a 30-degree intercept angle is shown below. This flight was conducted in 12 knot crosswinds with 2 to 3 knot gust variations. The top graph is a plot of the deviation of the aircraft from the runway centerline, the middle plot is the aircraft roll attitude, and the bottom graph is the aircraft yaw or true heading with respect to runway centerline. The capture maneuver was initiated at 5 seconds on the plots. The aircraft captures the localizer with no overshoot and was settled on runway centerline by 35 seconds. The aircraft heading smoothly achieves the crab angle with no oscillation indicating that the estimate of crosswind used by the control law is accurate. At 97 seconds into the flight, a lateral wind shear of 8 knots/100 feet was encountered. Incidentally, this magnitude of wind shear is that specified in the FAA Advisory Circular No. 20-57a for certification of autoland systems. The aircraft heading again smoothly changed to the runway heading as the wind diminished. The aircraft deviated approximately 25 feet from the runway centerline during the shear but corrected back to centerline within 10 seconds after the shear stopped.



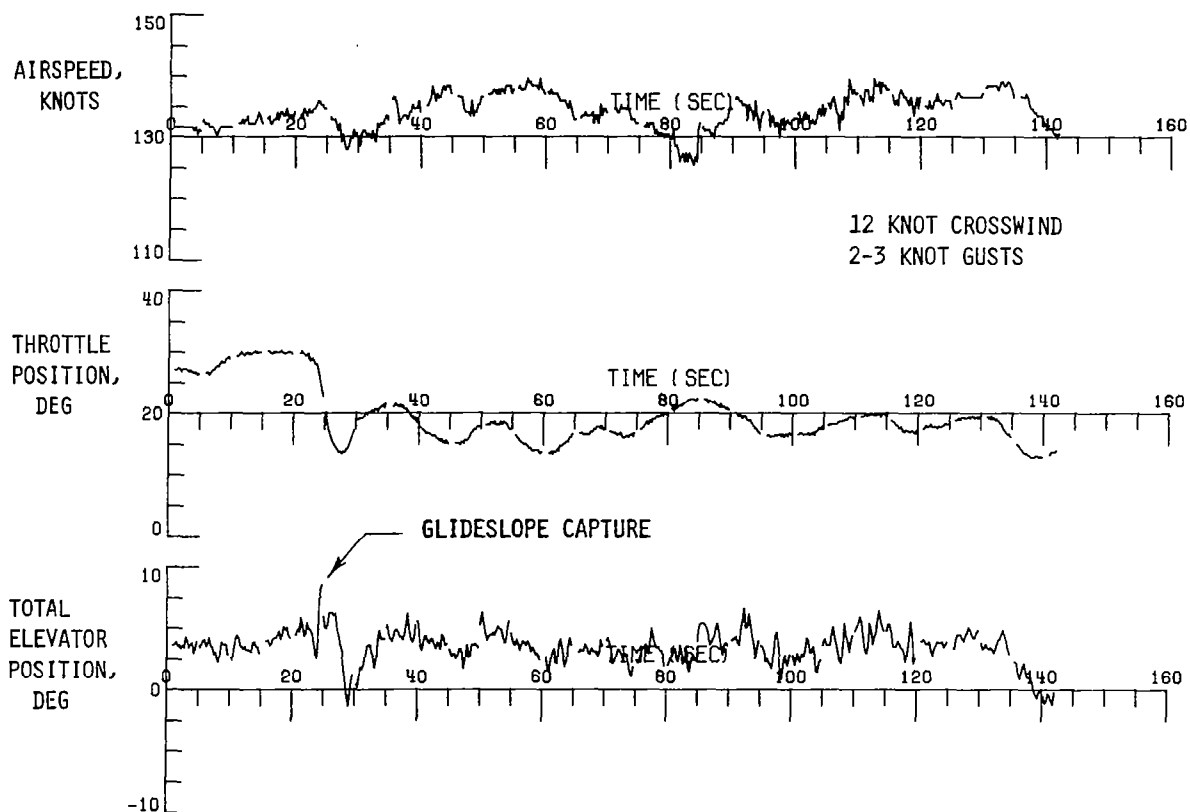
DIALS 3-DEGREE GLIDESLOPE CAPTURE AND TRACK - FLT 361, RUN 7

The graphs below show the capture of the 3-degree glideslope which begin at 24 seconds during the time the localizer capture was being completed. The top plot shows the aircraft deviation from the desired glideslope during the glideslope capture and track mode, and during the flare mode, it shows the deviation from the flare trajectory. The middle graph is a plot of the aircraft pitch attitude, and the bottom graph shows the vertical velocity from MLS processing. The glideslope is captured with no position overshoot although some overshoot does occur in the desired glideslope vertical velocity. This velocity overshoot is not present in the steeper glideslope captures and was not shown in the developmental simulation runs suggesting that an error was present in the glideslope capture criteria flight software. The shortness of time for the capture when compared to simulation times and the capture times for the steeper glideslope captures, to be discussed in subsequent figures, suggest that the capture maneuver was initiated too late or too close to the glideslope. The flare maneuver is initiated at 130 seconds into the flight. The pitch attitude reaches about 2 degrees for good nose wheel clearance, and the vertical velocity is smoothly reduced to an acceptable touchdown sink rate.



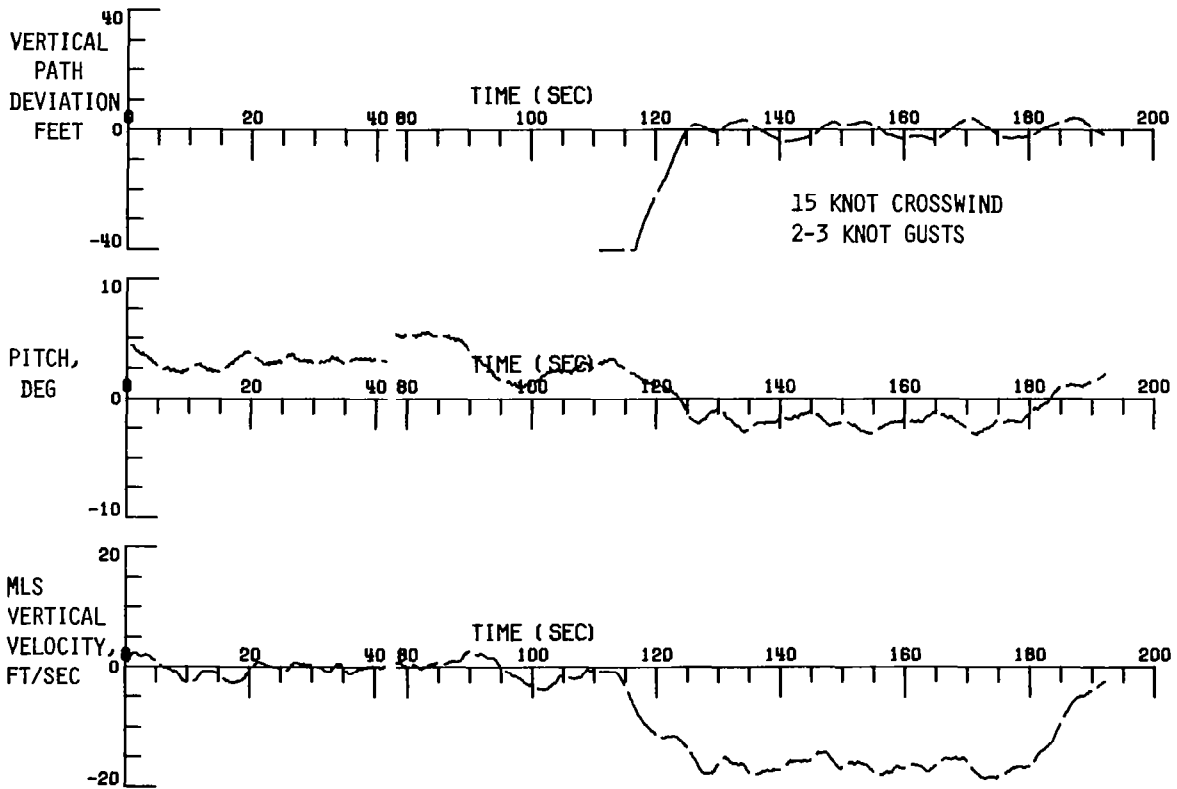
DIALS FLIGHT DATA - FLT 361, RUN 7

The flight data shown below are plots of calibrated airspeed (top graph), throttle position (middle graph), and total elevator position (bottom graph) which includes the mechanical downrigging of the elevator due to stabilizer trim position. This is companion data for the test run discussed in the previous two figures. The reference airspeed for this run was set to 130 knots. The data shows that the measured airspeed was somewhat higher than the selected reference by 5 to 8 knots. DIALS had a tendency to control the airspeed about 3 to 5 knots higher than the selected reference. The tendency may be related to the way the desired airspeed is achieved by DIALS. The current airspeed is estimated in DIALS by adding its estimate of ground speed and wind along the longitudinal axis. If this estimate is low, the DIALS will advance the throttle to increase inertial speed and thus airspeed. The slightly higher airspeed may be due to a bias in the measurement or a low estimate of airspeed. Coordination of the throttle and elevator is shown in the plots. At glideslope capture (24 seconds), the elevator goes positive (trailing edge down) to pitch the aircraft down while the throttle is immediately reduced towards glideslope thrust. Although the glideslope pitch is achieved at 30 seconds, the elevator continues to adjust to counteract the pitching moment due to thrust changes. During flare, the elevator moves to pitch the aircraft up while the throttle decreases to satisfy a commanded reduction in airspeed. Note that the throttle is not driven to idle but to a position to achieve the commanded airspeed.



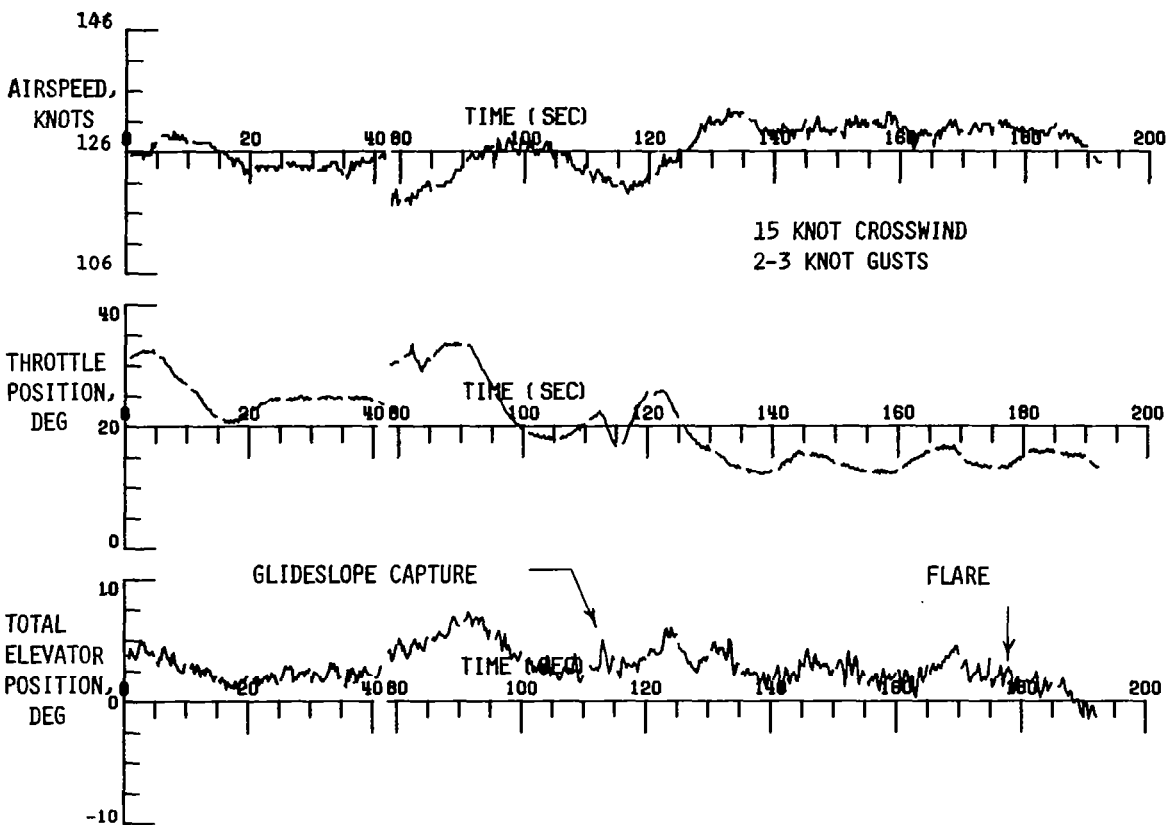
DIALS 4.5-DEGREE GLIDESLOPE CAPTURE AND TRACK - FLT 361, RUN 8

The variables plotted below are the same as those plotted two figures earlier. These plots show the glideslope capture and track and flare for a 4.5-degree glideslope. This flight test encountered 15 knot crosswinds and 2 to 3 knot gusts. The 40- to 80-second time period, which included portions of the localizer capture and track, has been omitted. The glideslope capture begins at 113 seconds and is completed at 126 seconds with no overshoot in position or vertical velocity. The flare maneuver begins at 177 seconds and touchdown occurs at 192 seconds for a 15-second flare duration. The flare maneuver was initiated at 134 feet above the touchdown point. The flare is automatically initiated at higher altitudes for the steeper glideslopes to reduce the sink rate to reasonable levels before the lower altitudes are reached for safety purposes. The pitch attitude at touchdown was 2.5 degrees, and the touchdown sink rate was 2 feet/second.



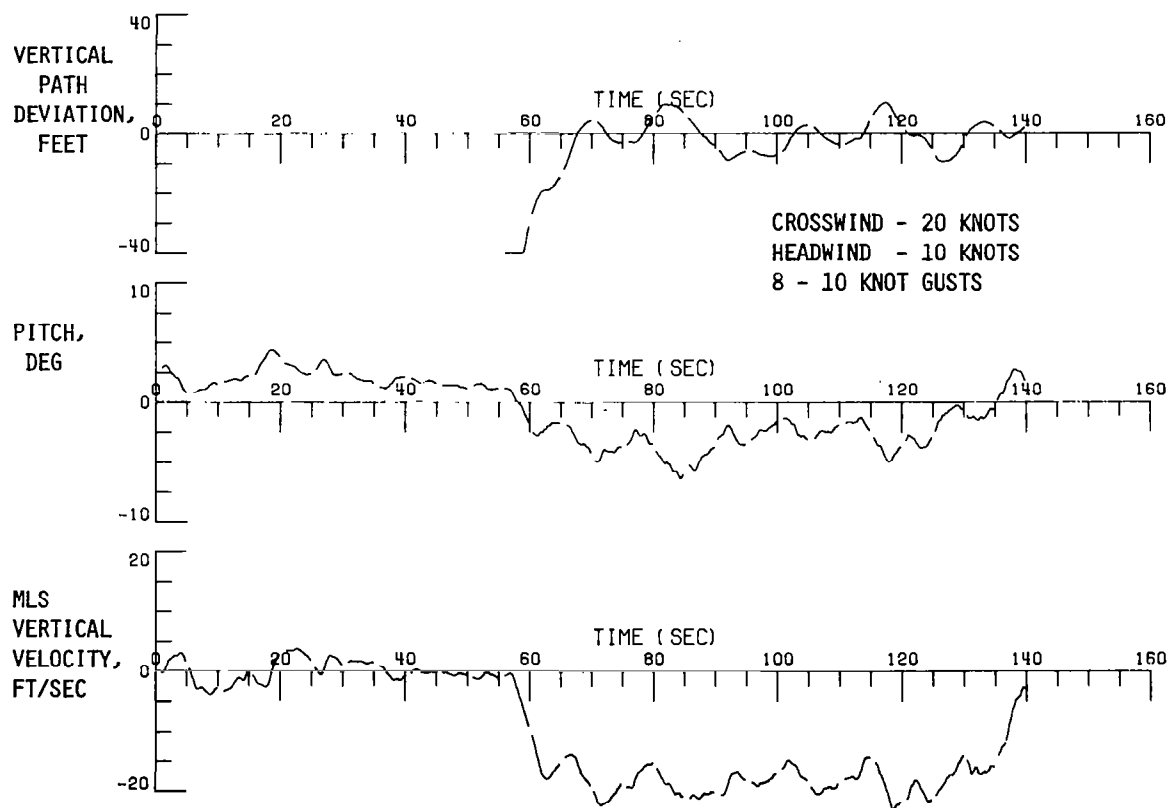
DIALS FLIGHT DATA - FLT 361, RUN 8

The graphs below are plots of additional variables for the same run discussed in the previous figure. The reference airspeed selected for this flight was 126 knots. The control of the baseline autothrottle on the test vehicle can be seen prior to glideslope capture which occurred at 113 seconds. The DIALS again controls the airspeed above the selected reference similar in magnitude to that discussed for the previous Run 7 of Flight 361. However, the variations in airspeed are much smaller than variations of the baseline control. A small positive elevator pulse is seen at 113 seconds along with a throttle reduction to initiate the glideslope capture. However, DIALS "sees" an airspeed error and immediately advances the throttle. The estimated thrust is fed back to the elevator control, and it moves positive to counteract the thrust increase and to push the nose of the aircraft down. At flare, the elevator goes negative to pitch the nose of the aircraft up while very little change is seen in throttle. The thrust must be maintained to add energy to the system to achieve the reduction in sink rate. The airspeed is being reduced to the commanded value without throttle change by the pitch-up maneuver.



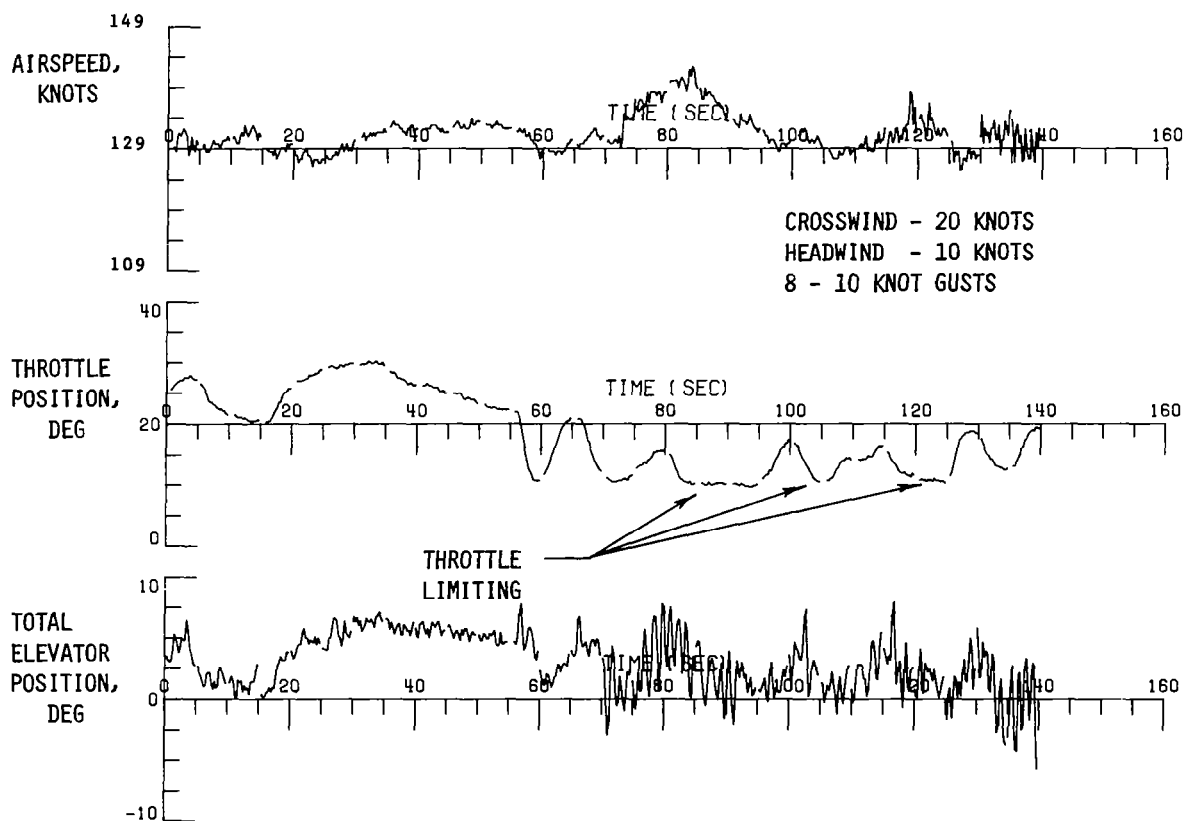
DIALS 5-DEGREE GLIDESLOPE CAPTURE AND TRACK - FLT 364, RUN 7

The graphs below show flight data for the steepest glideslope capture and track flight tested with DIALS, a 5-degree glideslope. This run was flown in strong wind conditions. The crosswind component was 20 knots and the headwind component was 10 knots with gust variations of 8 to 10 knots. The variables plotted are the same as those plotted in earlier figures. The glideslope capture occurs at 57 seconds and is completed by 70 seconds. The capture was achieved with essentially no overshoot in the glideslope or desired vertical velocity. The flare maneuver was initiated at 124 seconds, and a positive pitch attitude of 3 degrees was obtained. However, the touchdown was not completed due to lateral position drift during decrab. The drift was caused by rudder limiting built into the servos for safety purposes during these flight tests. The rudder limit was encountered due to the 20-knot crosswinds.



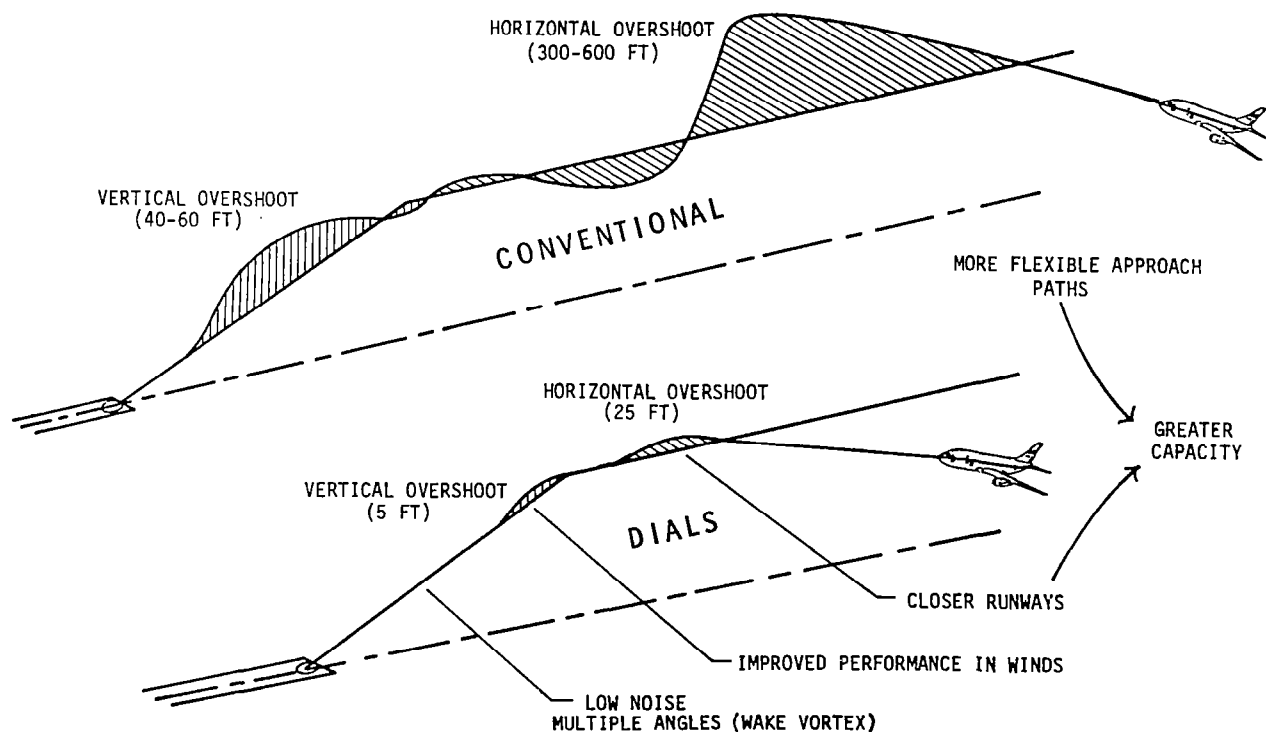
DIALS FLIGHT TEST DATA - FLT 364, RUN 7

The variables plotted below are additional data for the flight just discussed in the prior figure, and the variables are the same as those plotted in earlier figures. The reference airspeed for this flight was selected at 129 knots. Again, airspeed errors are biased to the positive side although the errors are closer to the selected airspeed than in runs discussed earlier. The throttle position plot shows that throttle limiting occurred at 10 degrees during the periods of 82 to 95 seconds, 104 to 106 seconds, and 121 to 125 seconds. The lower throttle limit is set to 10 degrees when the system is not in the flare mode to keep the engine spooled up. In flare, the throttle is allowed to go to idle, zero degrees. In spite of this limiting, the integrated control maintains stability and track of the glideslope. At flare (124 seconds), the throttle increases rather than decreases as was the case for the 3-degree glideslope because more energy must be added to the system to reduce the high sink rate that occurs along the 5-degree glideslope. Even at the point of near touchdown, the throttle is increasing while airspeed was decreasing.



DIALS FLIGHT TEST PERFORMANCE - LOCALIZER AND GLIDESLOPE

Below is a pictorial to illustrate the performance improvement of DIALS compared to conventional ILS systems. The improved performance was attributable both to the use of the MLS (the MLS signals have more accuracy and expanded coverage over ILS) and the advanced control law design. It shows that overshoot performance is better by an order of magnitude. DIALS achieved the improved glideslope overshoot with the additional capability to fly selected and steep glideslopes. The time required from localizer capture initiation to engagement of the track mode was a factor of 3 less than the conventional system time. The time to capture the glideslope (for the 3-degree glideslopes since conventional autolands for steeper glideslopes do not exist) was a factor of 4 less for DIALS. The reduced time to capture the localizer and glideslope provides the capability to fly shorter final approach paths and, in general, more path flexibility. The low overshoot during localizer capture will allow closer spacing of parallel runways. The capability to fly steeper glideslopes reduces the noise level on the ground and also provides a means for trailing aircraft to avoid wake vortices by selecting a glideslope steeper than that of the aircraft in front of it. The use of parallel runways spaced closer and the capability to fly short approach paths should result in greater terminal area capacity.



DIALS FLIGHT TEST RESULTS

The figure below summarizes the number and types of captures and automatic landings that were achieved during the DIALS flight tests. **Three-, four-and-one-half-, and five-degree** glideslopes were successfully captured. For 21 captures, the mean overshoot of the glideslopes was 4.6 feet with a standard deviation of 2.3 feet. The numbers in parentheses at the right represent a conventional system. The localizer captures were initiated from ground track angles of 20, 30, 40, and 50 degrees. The statistics of 41 captures resulted in a mean overshoot of 24.2 feet with a standard deviation of 25.7 feet. Typical overshoot distances for a conventional system are shown in parentheses at the right. The decrab maneuver was successfully performed in crosswinds up to 12 knots. Successful decrabs in higher crosswinds were prevented due to rudder limiting in the experimental system of the test vehicle. Ten completely automatic (hands-off) landings were achieved from both the **3- and 4.5-degree glideslopes**. In addition, seven additional landings were made in which the pilots had only a slight column input and did not disengage the automatics. The statistics for the ten hands-off landings were a mean touchdown vertical velocity of -2.4 feet/second with a standard deviation of 0.7 feet/second. The numbers to the right are, respectively, the mean and standard deviation for an advanced flare designed by classical methods and previously flight tested on the same aircraft using MLS signals.

- HAVE SUCCESSFULLY CAPTURED AND TRACKED 3, 4.5, AND 5° GLIDESLOPES

MEAN OVERSHOOT = 4.6 FT	}	21 CAPTURES	(40-60)
σ = 2.3 FT			

- HAVE SUCCESSFULLY CAPTURED RUNWAY CENTERLINE (LOCALIZED) AT 20°, 30°, 40° AND 50° INTERCEPT ANGLES

MEAN OVERSHOOT = 24.2 FT	}	41 CAPTURES	(300-1000)
σ = 25.7 FT			

- HAVE PERFORMED SUCCESSFULLY DECRAB MANEUVERS IN CROSSWINDS UP TO 12 KNOTS
- PERFORMED TEN COMPLETELY AUTOMATIC (HANDS-OFF) LANDINGS FROM BOTH 3° AND 4.5° GLIDESLOPES, PLUS SEVEN ADDITIONAL WITH SLIGHT COLUMN INPUT

MEAN \dot{h}_{td} = -2.4 FT/SEC	}	10 LANDINGS	(-2.34)
σ = .7 FT/SEC			

DIALS PLANS

A goal of the advanced control law research has been to develop methods and techniques whereby modern control theory can be applied readily to practical applications. While excellent experimental results were obtained from the DIALS flight test, the full-state design with its accompanying Kalman filter can be rather cumbersome resulting in large software memory requirements. Also certain practical considerations, such as the dynamics of existing sensor filters and stability augmentation systems, are difficult to incorporate in full-state designs. These practical considerations tend to make full-state designs less practical for direct commercial applications. Thus, the plans are to use the DIALS results as a bench mark and to continue development of modern control theory methods for more direct solutions to practical problems. With the recent development of a digital computer algorithm that efficiently and reliably solves the output feedback problem, the design of control systems with modern control theory becomes more practical. Successful 3-D guidance and control designs were recently achieved using this algorithm. Thus, the design and the development of an autoland system using output feedback techniques have begun. For this design, a third-order complementary filter along with MLS processing is being used to provide estimates of velocity and position rather than a Kalman filter. The existing SAS (yaw damper) on the test vehicle will be used rather than providing this damping in the design as was done with DIALS. The output feedback design allows inclusion of SAS dynamics and filter dynamics in the model without having to feed back these states as is necessary in full-state design. This system will be designed as a Type 1 system whereas DIALS was designed as a Type 0 system with integrators added to the various modes during development to achieve Type 1 properties. The new design will use the integrated control surfaces like DIALS as listed in the figure below. In addition, more attention will be given to methods to account for computational delays than was done in DIALS. Full nonlinear simulation development is planned along with flight tests in late 1984 or early 1985.

- NEW MORE PRACTICAL DESIGN USING LSF TECHNIQUES
 - Direct Digital Design
 - Use Third-Order Complementary Filter (Developed for ICAO MLS Processing) Rather Than Steady-State Kalman Filter
 - Use Existing SAS (Yaw Damper)
 - Design as Type 1 System (Path Integrators)
 - Integrated/Coordinated Controls For Elevator, Throttle And Stabilizer For Long. Axis And Aileron And Rudder For Lateral Axis
 - Design To Account For Transport Delays (Computational)

- DEVELOP BY MEANS OF FULL NONLINEAR SIMULATION INCLUDING SENSORS NOISES AND WINDS.

- PREPARE S/W REQUIREMENTS FOR FLIGHT TESTS IN CY 84.

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