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EVALUATION OF DISPLAY AND CONTROL CONCEPTS FOR A TERMINAL CONFIGURED VEHICLE IN FINAL APPROACH IN A WINDSHEAR ENVIRONMENT*

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ABSTRACT

The effects of display and control parameters on approach performance of a simulated Terminal Configured Vehicle (TCV) were explored experimentally in a manned simulation study and analytically using a state-of-the-art pilot/vehicle model. A revised treatment of nonrandom inputs was incorporated in the model. Response behavior was observed for two display configurations (a pictorial EADI presentation and a flight-director configuration requiring use of a panel-mounted airspeed indicator), two control configurations (attitude and velocity control wheel steering), and two shear environments, each of which contained a head-to-tail shear and a vertical component.

In general, performance trends predicted by the model were confirmed experimentally. Experimental and analytical results both indicated superiority of the EADI display with respect to regulation of height and airspeed errors. Velocity steering allowed tighter regulation of height errors, but control parameters had little influence on airspeed regulation. Model analysis indicated that display-related differences could be ascribed to differences in the quality of speed-related information provided by the two displays.

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INTRODUCTION

Windshear constitutes one of the major threats to flight safety in approach and landing operations. This threat is enhanced not only by the potential severity of the shear (defined as a wind whose velocity changes with altitude), but also by the tendency of the shear profile to change rapidly over time. This lack of predictability has led to the need for control and display aids to help pilots better cope with the presence of windshears.

This paper summarizes the second phase of a program to analyze display-control configurations for the Terminal Configured Vehicle (TCV). This work was performed for NASA Langley Research Center and was intended to augment a simulation study conducted there.

The first phase of this study explored the effects of certain control and display configurations on approach performance in a zero-mean, random turbulence environment. The LRC simulation was augmented by an analytic study performed at Bolt Beranek and Newman Inc. using the "optimal-control" pilot/vehicle model to explore both performance and workload differences among control/display configurations of interest. The reader is assumed to be familiar with the features of this model, which has been well documented in the literature. Frequent reference is made below to the report by Levison and Baron [1] which documents the results of the first study phase and which demonstrates application of the pilot model to analysis of TCV approach performance.

Approach performance of a TCV in windshear environments was studied in the second study phase, with control and display configuration (along with windshear profile) the major variables of interest. The existing pilot/vehicle model was modified to allow a revised treatment of nonrandom inputs; because the longitudinal and vertical components of the shear have greatest impact on path and airspeed regulation, only longitudinal-axis performance was explored in the analytic study. The results of the windshear study are documented in [2].

PROBLEM DEFINITION

Description of the Flight Task

The flight task of interest was the standard straight-in (3 degree) approach of a simulated TCV. The simulated atmospheric environment contained low-level zero-mean gusts plus a wind shear consisting of a rotating horizontal component and a brief interlude of either an updraft or a downdraft.

Speed and flight path were controlled manually. Flight-path control was aided by one of the following control augmentation schemes: "Attitude Control Wheel Steering (ACWS) or "Velocity Control Wheel Steering" (VCWS). Basically, these modes provide attitude-rate stabilization and allow the pilot, in effect, to command either attitude (ACWS) or path angle (VCWS). A more detailed description of control wheel steering is given in Levison and Baron [1]. In order to use the existing man-machine model, the track-hold feature of the CWS was approximated by continuous linear feedback law as shown in Figure 1.

Displays

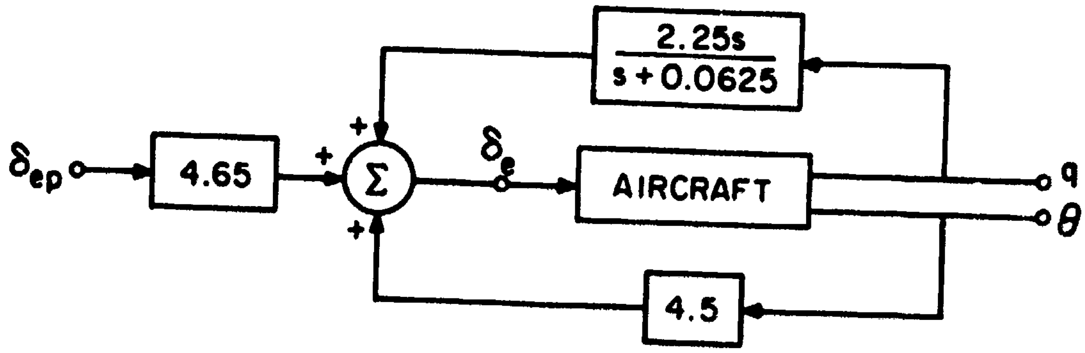
Flight control information was provided primarily by an electronic attitude/director indicator (EADI). Two display configurations were considered: (1) "advanced" display, which presented information in an integrated (pictorial) format, and (2) the flight director display, which provided director information based on path, path angle, and attitude errors.

The advanced display provided the following flight-control information (as diagrammed in Figure 2): (a) an aircraft symbol to serve as x-axis airframe reference, (b) an artificial horizon and pitch attitude scale, (c) a roll attitude scale and pointer, (d) a pair of so-called "gamma wedges" to indicate path angle, (e) a dashed line to indicate a point 3 degrees below the horizon, (f) a perspective runway symbol, (g) an extended runway center line to aid in lineup regulation, (h) a symbol to indicate track angle, (i) a glideslope indicator, (j) a localizer indicator, and (k) a so-called "potential gamma" symbol to provide information pertaining to speed management.

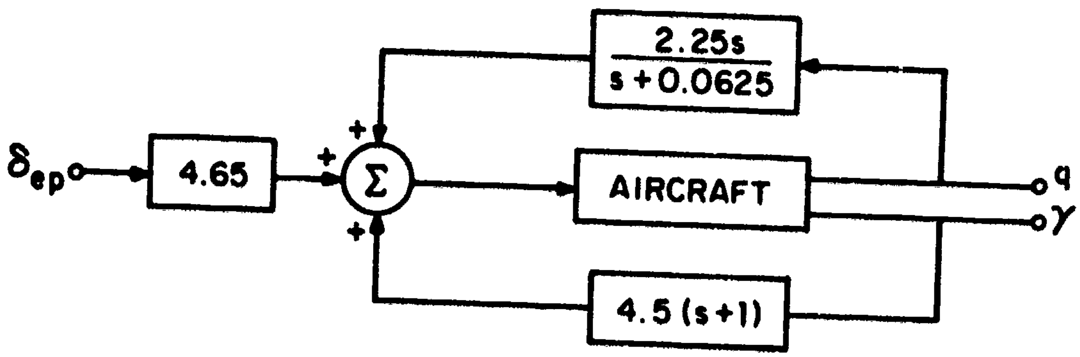
Except for the potential gamma symbol, this display was indentical to the advanced display described in [1], to which the reader is referred for additional details on the structure and use of this display. A weighted sum of airspeed error and rate of change of vehicle velocity was used to drive the potential gamma symbol, relative to the gamma wedge, in the vertical dimension.

The "flight director display" consisted of a raw status display plus director information. The EADI provided attitude information, glideslope and localizer errors in symbolic format, and director information. Airspeed and rate-of-climb were displayed by conventional panel meters. Perspective runway, gamma wedges, and potential gamma were omitted from the EADI in this display configuration.

Director information was provided with a pair of crossbars



(a) ATTITUDE CWS



(b) VELOCITY CWS

Figure 1. Linear Approximation to Control Wheel Steering

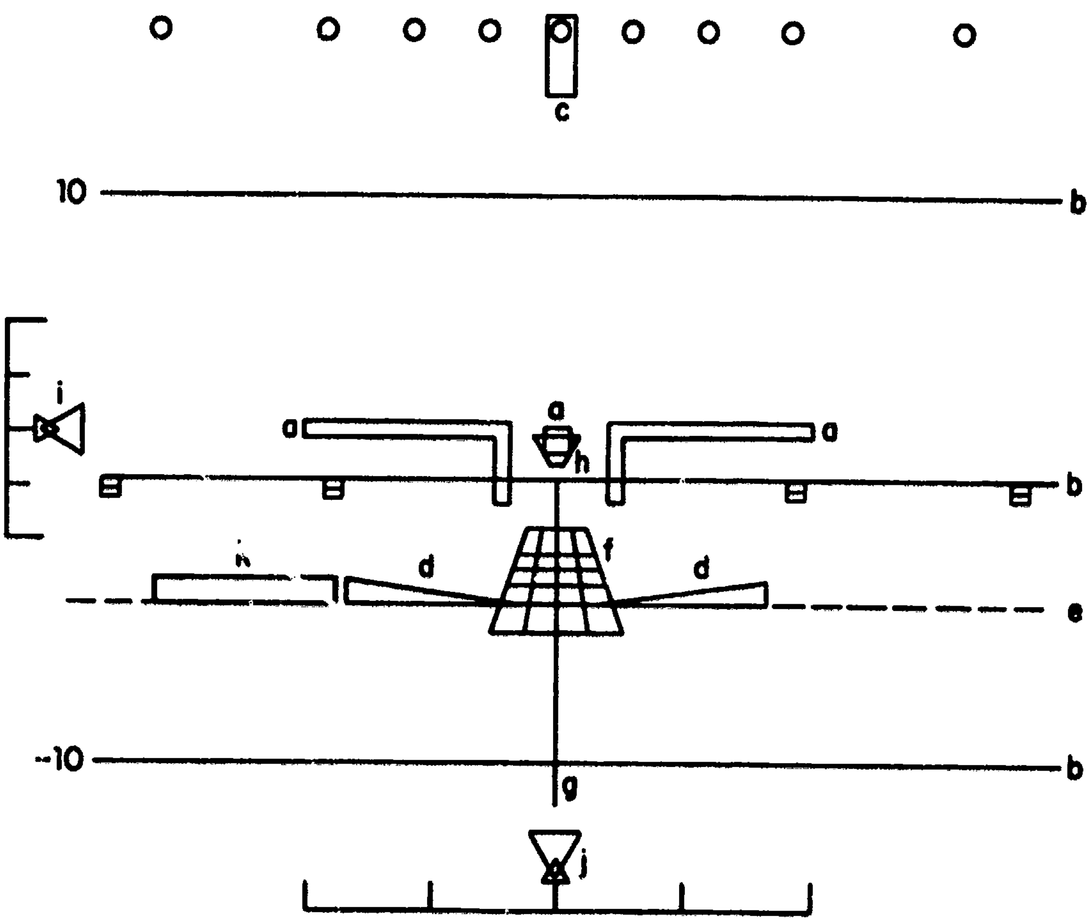


Figure 2. Sketch of the EADI Display
(Display elements defined in the text)

that deviated from the x-axis reference symbol in a "fly-to" mode. The director indicator was driven by a weighted sum of height, path angle, and pitch-rate errors as described in [2].

Wind Environment

Wind shears as well as zero-mean random gusts were simulated in the NASA-LRC experiments. In order to simplify problem formulation and reduce computational requirements, the effects of these simulated gusts were approximated in the bulk of the model analysis by including wide-band disturbances added in parallel with the control deflections. Preliminary model analysis was conducted to select disturbance levels that would give nearly the same predicted path and airspeed errors as would be obtained from a more faithful representation of the simulated gust inputs [2].

Each of the simulated windshears used in the experimental and analytical study contained a rotating horizontal component plus a brief vertical component. Figure 3 shows the relationship between wind speed and range for points along the nominal 3 degree glide path for two of these shears.* (Note that the horizontal and vertical wind components have been scaled differently in this figure.)

METHODS

Model Analysis

The model employed in this study was basically the so-called "optimal-control model" described extensively in the literature, modified to treat non-zero-mean (i.e., deterministic) inputs. As the treatment of the deterministic input (i.e., the windshear) was different from that used in previous studies (3-5), a brief discussion of this treatment is given below. A more detailed exposition of this aspect of the pilot model is given in the appendix to [2].

Modeling the pilot's response to a deterministic input involves two basic considerations: (1) the degree to which the

*Since windspeed is an explicit function of altitude, rather than range, deviation of the aircraft from the desired glide path would modify somewhat the range dependency shown in Figure 3.

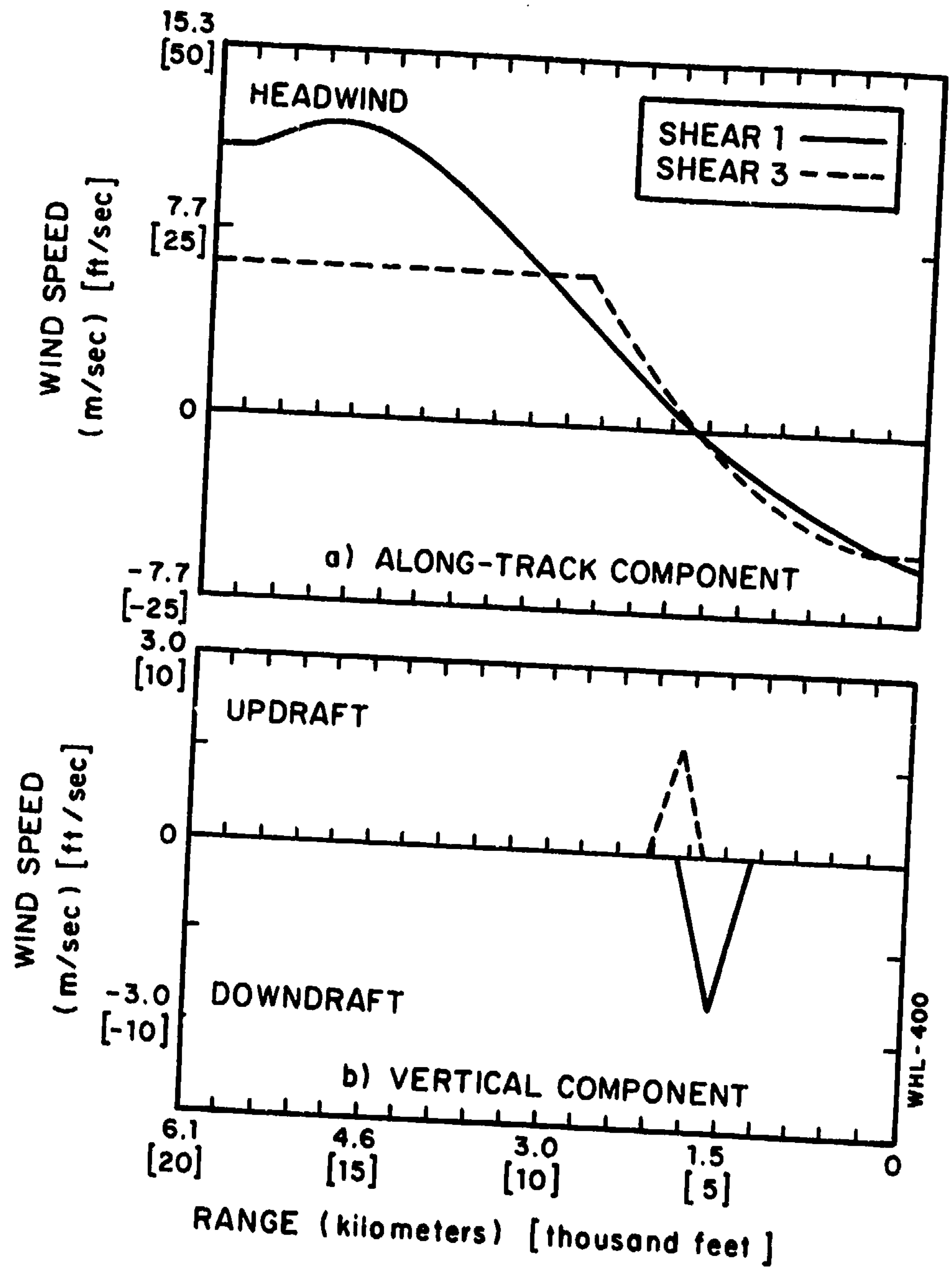


Figure 3. Windshear Profile

pilot understands the nature of the input (i.e., his "internal model"), and (2) the way in which the pilot detects and responds to the input. A simple representation of the pilot's knowledge of the windshear was adopted for the study; basically, we assumed no specific knowledge of the shear, only the knowledge that a non-zero-mean wind might exist. We assumed that the pilot would not gry to anticipate changes in the wind, but would, at best, attempt to estimate the current wind vector. This level of pilot knowledge was modeled by simply implementing a stepwise-constant representation of the wind. Since the wind varied relatively slowly with time, an integration time step of 1 second was sufficiently fine to allow an adequate representation of the continuously-varying wind speed.

The pilot/vehicle model was modified to reflect the following assumptions concerning pilot behavior in a non-zero-mean input environment:

a. The pilot continuously anticipates the behavior of the display variables he is utilizing, given his current estimates of system states and his internal model of system parameters.

b. The pilot performs a short-term average on the difference between expected and actual behavior of each display variable.

c. If average prediction error is sufficiently large with respect to the variability of this error, the pilot becomes additionally uncertain about his estimates of system state variables, and he attempts to upgrade these estimates.

Implementing this set of assumptions led to the following additional pilot-related model parameters: (1) the short-term averaging time, (2) the magnitude of the prediction error considered large enough to warrant special action, and (3) specific state variables to which the pilot attributes his uncertainty. In addition, an algorithm had to be formulated for relating prediction errors to increased uncertainty.

Model predictions were obtained with the assumptions that (1) prediction errors were averaged over about two seconds, (2) an average deviation of two standard deviations from the expected value warranted special consideration by the pilot, and (3) uncertainty could be associated with any of the principal state variables, including the state variables representing the horizontal and vertical shear components.

To obtain a model solution it was necessary to describe the task environment in a suitable mathematical format and to assign values to model parameters related to pilot limitations. System dynamics were modeled as described in [1], with the modification indicated in Figure 1 of this paper to account for control wheel steering augmentation.

The pilot was assumed to adopt a control strategy that minimizes a weighted sum of mean-squared response variables. In this study, the "cost function" included height error, sinkrate error, airspeed error, angle-of-attack error, control deflection, and rate-of-change of control deflection. Because the results of the previous study suggested that pilots tended to regulate height error in terms of an angular, rather than a linear, criterion, weightings associated with height and sinkrate errors were varied inversely with range. Weightings for other variables were kept fixed throughout the "flight" as documented in [2].

When tracking with the advanced display, the pilot was assumed to perceive height error, sinkrate error, pitch and pitch rate, flight path angle and path angle rate, and potential gamma. Because movement of the perspective runway with respect to the nominal glideslope was proportional to error in angular terms, the thresholds for height and sinkrate errors (in terms of feet and ft/sec) varied linearly with range. The height error threshold was based on an "indifference threshold" of 1.4 meters at the 30 meter decision height as determined from previous analysis. Other threshold values were based on considerations of visual resolution as described in Levison and Baron. The noise/signal ratio of -17 dB associated with use of the advanced display reflects a moderate-to-high level of workload with no interference among display elements (i.e., we assume integration of the displayed information).

When tracking with the director display, the pilot was assumed to rely primarily on the director symbol and the airspeed indicator for continuous flight-control information, with a negligible amount of time spent scanning the status information for monitoring purposes only. The threshold of 1.0 m/sec. on airspeed was based on the assumption that the pilot was indifferent to airspeed errors smaller than the calibration increments of the airspeed indicator (2 kts); threshold values for perception of director displacement and rate were based on visual resolution limitations. The noise/signal level of -14 dB reflects the same overall level of attention to the task as before, with the requirement to share attention between the director and airspeed indicators. For simplicity, equal sharing of attention between the two displays was assumed, and loss of visual inputs associated with eye movements was neglected.

Experimental Procedures

The experimental task was to track a 3° ILS beam to touchdown. Each experimental trial began at a simulated range of 6700 m from the runway threshold at an altitude of approximately 366 m. The aircraft was initially trimmed on the desired glide path for a 3° path angle in its approach configuration: 120-knot airspeed laps, gear down. Rudder was automatically controlled.

Zero-mean random gusts and wind shears were both simulated during each experimental trial. Three shear environments were explored, including those designated as "Shear 1" and "Shear 3", profiles of which are given in Figure 3.

Gust disturbances having an rms variation of 0.3m/sec were simulated for all three translational axes. Gust spectral characteristics were varied with altitude according to the wind models suggested by Chalk et al. [6].

Data were obtained from three NASA test pilots. Practice trials were provided using shears other than those specified for data collection. Each pilot "flew" two sessions of 18 approaches each for data collection; each session consisted of two replications of 3 control/display configurations and 3 shear environments presented in a balanced order. Thus, four replications per experimental condition per pilot were obtained.

Ensemble statistics were computed for selected response variables for each experimental condition. First, within-subject replications were analyzed to provide trajectories of mean response and of the standard deviation of the response. These measures were processed further to provide across-subject averages of the mean and standard-deviation response trajectories. Mathematical definitions of these statistical variables are given in Levison and Baron.

For purposes of data presentation, statistical analysis was performed for height and airspeed errors, sampled at 305 meter intervals beginning at a range of 4572 m from the ILS origin.

SUMMARY OF RESULTS

Considerations of space preclude an extensive presentation of either theoretical or experimental results. A sampling of results is presented to demonstrate three applications of the pilot/vehicle model in the context of this study: (1) prediction, (2) diagnosis, and (3) extrapolation. Additional results are documented in [2].

Prediction

The following four figures compare display and control trends for predicted and experimental mean response trajectories for the "Shear 1" environment.* Because the experiment was not full factorial, display differences are shown for the Attitude CWS configuration only, and control differences are compared for the advanced display configuration.

Effects of display on mean height error and mean airspeed error are shown, respectively, in Figures 4 and 5. In general, the trends predicted by the model are confirmed, but the differences observed experimentally are smaller than predicted. Model and experimental correlation is generally better for height than for speed response.

As predicted, experimental height error is generally more negative for the director than for the advanced display. The data also confirm the prediction that the director display leads to a larger swing in error over the course of the approach. There was also a tendency (not predicted) for the pilots to fly above the nominal glide path.

Figure 5 shows that the test pilots flew the director display with less negative (or more positive) airspeed errors than achieved for the advanced display--a trend the reverse of which was predicted by the model. Given the reported tendency of pilots to fly approach speeds greater than nominal when windshears are anticipated [7], we suspect that the test subjects attempted to compensate for the lack of good airspeed information from the director configuration by intentionally carrying excess airspeed. Experimental results confirm the prediction of greater swings in error with the director display, although the magnitudes of the display-related differences are less than predicted.

Figures 6 and 7 confirm the major trends predicted for control effects; namely, tighter regulation of height error was observed for velocity CWS, whereas control configuration had little effect on regulation of speed error.

Results for the Shear 3 environment, documented in [2], showed similar types of correlation between predicted and measured mean error trajectories.

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*Model results shown in these figures are true predictions in the sense that they were obtained before the experimental data were analyzed. Pilot-related model parameters were not adjusted to provide a best match to the data.

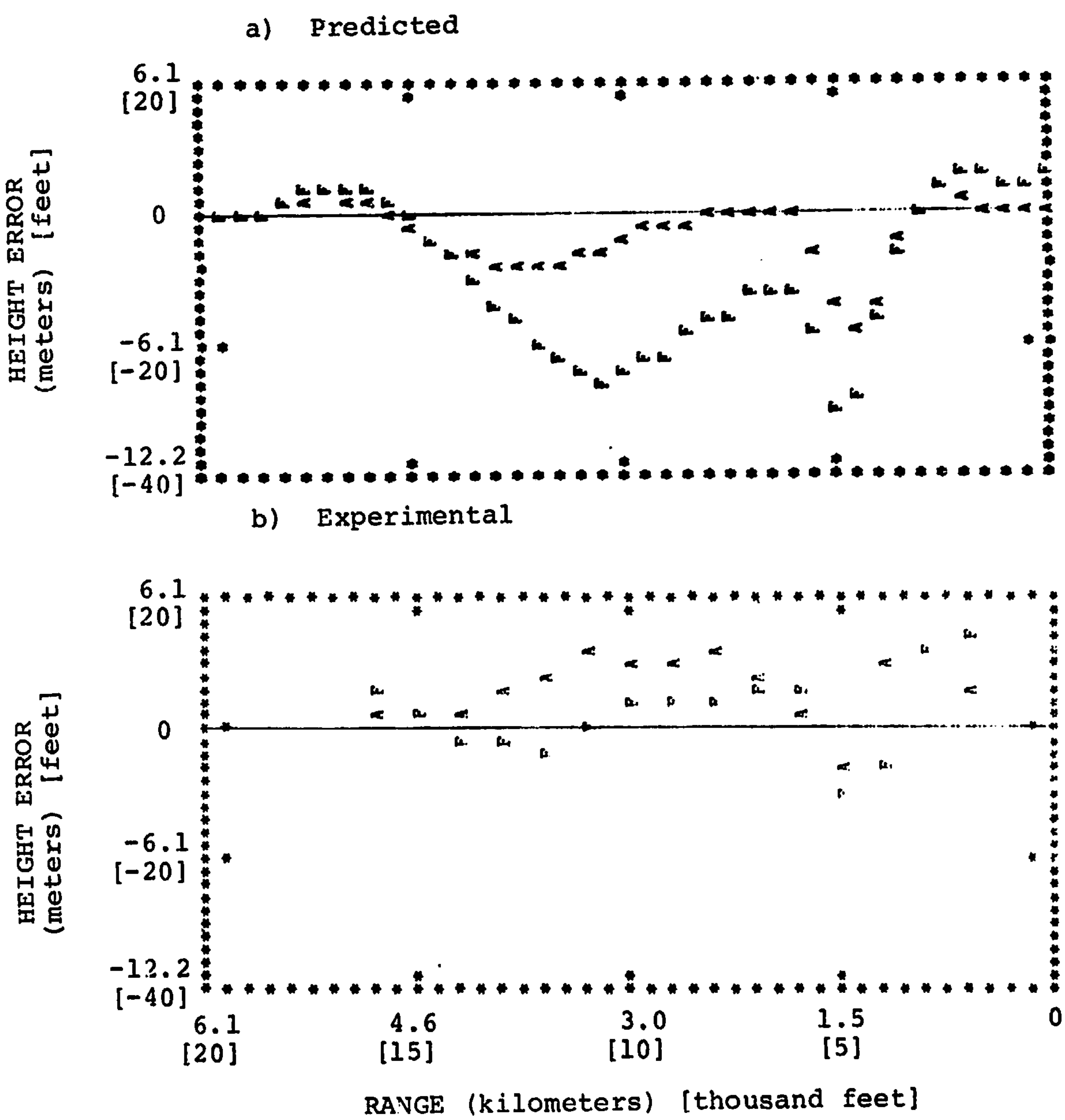

Figure 4. Effect of Display on Mean Height Error, Shear 1 Attitude CWS.
A = advanced display, F = flight director

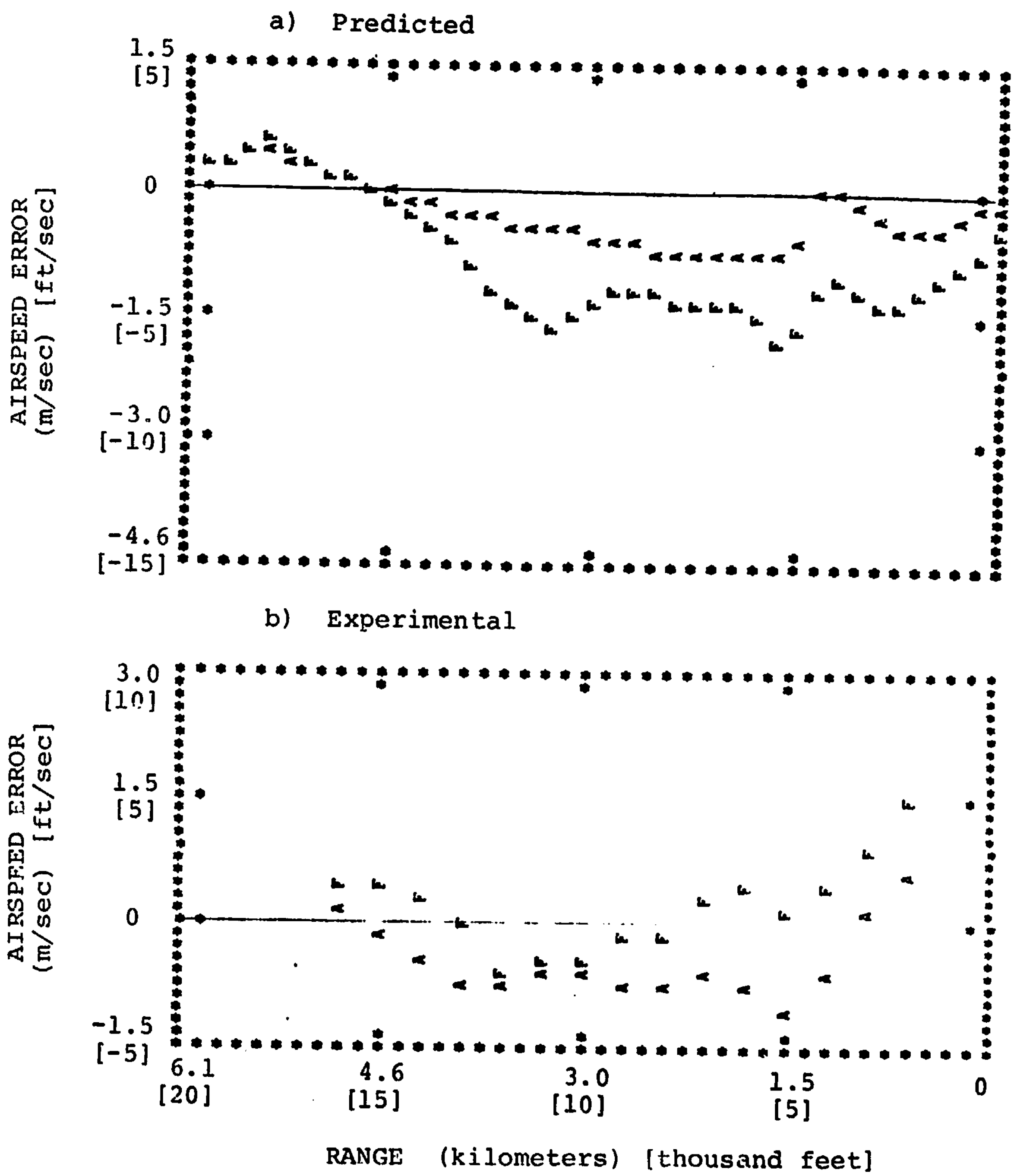

Figure 5. Effect of Display on Mean Airspeed Error, Shear 1

Attitude CWS.
A = advanced display, F = flight director

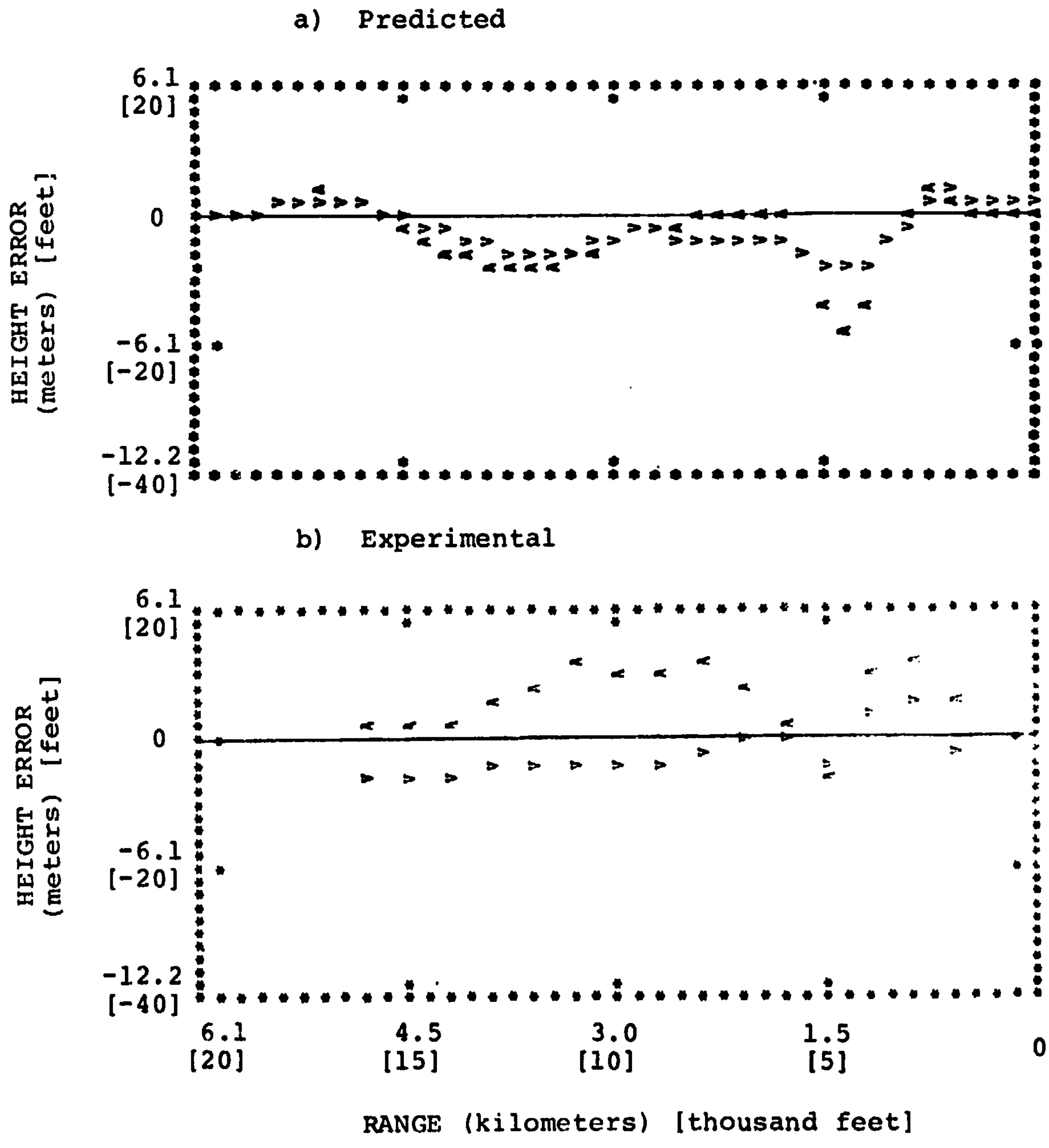

Figure 6. Effect of CWS on Mean Height Error, Shear 1

Advanced Display.
A = attitude CWS, V = velocity CWS.

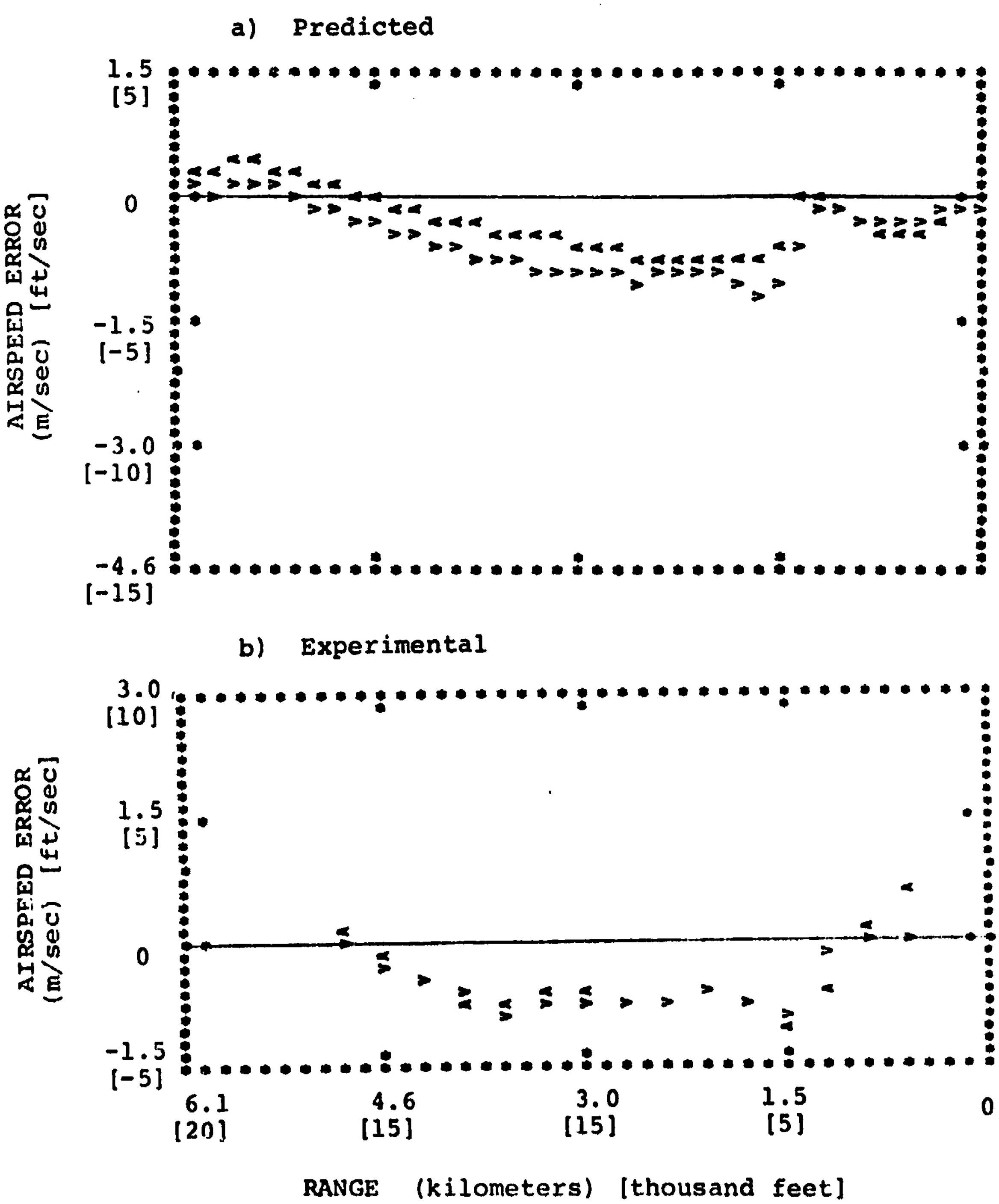

Figure 7. Effect of CWS on Mean Airspeed Error, Shear 1
Advanced display.
A = attitude CWS V = velocity CWS

Diagnosis

In order to ascertain the cause of the performance differences observed for the two display configurations, the director display configuration was reanalyzed with the threshold of 0.024 m/sec (as opposed to 1.0 m/sec assumed previously). This reduced threshhold was equivalent to that which would be associated with the potential gamma indicator of the advanced display if potential gamma were driven solely by airspeed error. Director laws and scaling were unchanged, and, as before, the pilot was assumed to share attention equally between the director and speed indicators.

Figure 8 shows that predicted performance with the director display, given improved airspeed resolution, is comparable to that achievable with the advanced display for the Shear 1 environment. Thus, reducing the perceptual threshold on airspeed should substantially improve performance with the flight director.*

Extrapolation

A reliable pilot/vehicle model provides a convenient tool for answering various "what if" questions that may not be readily explored experimentally. In this study we used the model to explore the consequences of providing the pilot with better knowledge of the wind environment. Specifically, the "advanced" display was considered with additional, direct, displays of horizontal and vertical wind assumed. Thresholds relating to perception of wind velocities were neglected, and an integrated display was assumed (i.e., noise/signal ratios remained at -17 dB for all display quantities). The intent here was not to simulate a physically realizable display, but to determine the performance potential associated with improved estimation of the wind environment.

Figure 9 shows that predicted performance with the two displays is nearly identical over most of the approach. Thus, it would appear that little overall improvement in performance can be expected from a display which provides the pilot with improved estimates of the instantaneous wind environment.

This latest result is contingent on the assumption that the pilot does not attempt to estimate the altitude- (hence, time-) varying nature of the shear but attempts only to estimate the current wind vector. It is possible that performance could be improved if the pilot were to attempt to extrapolate the wind--

*As of the writing of this paper, this prediction has not been tested experimentally.

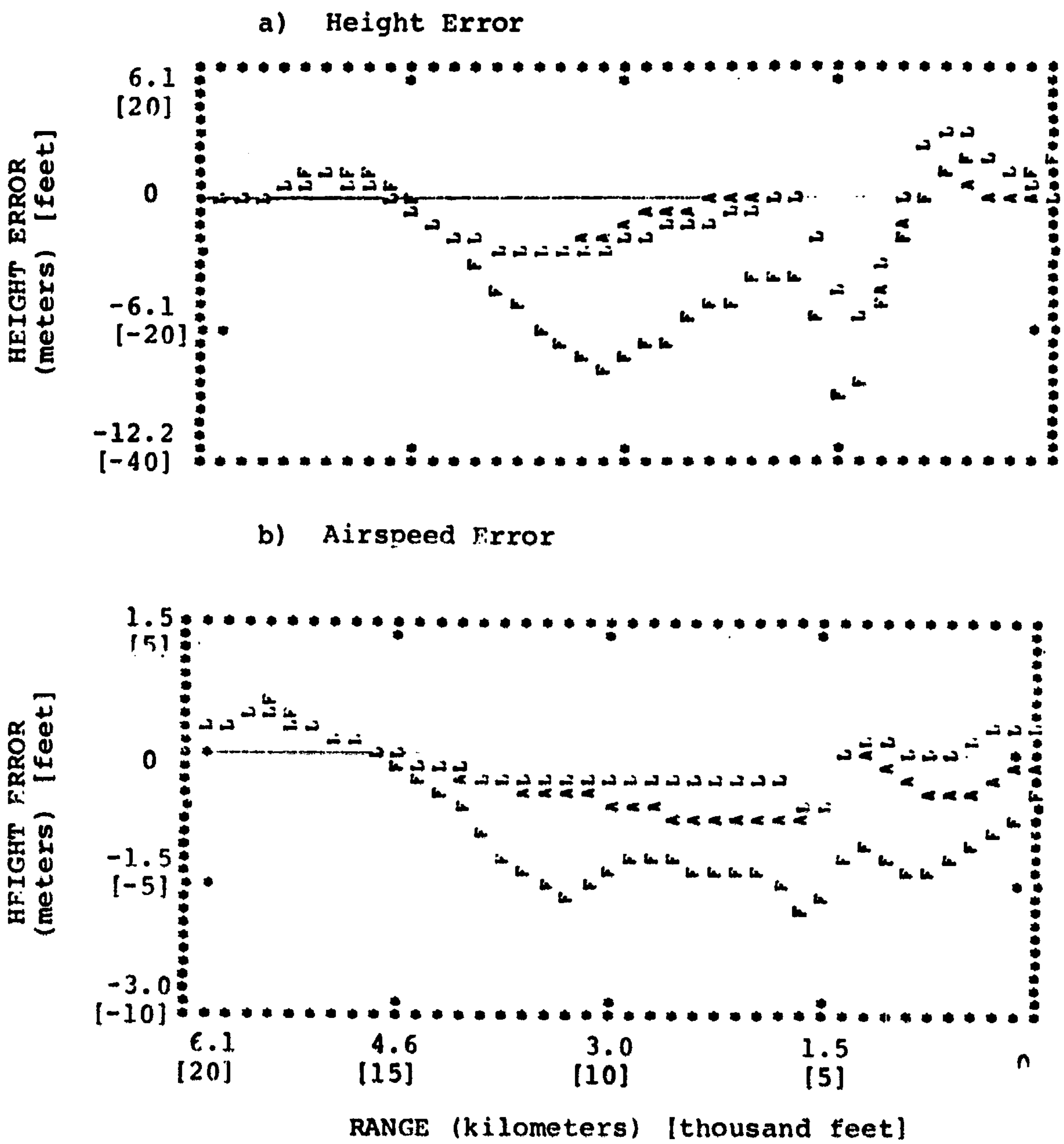

Figure 8. Effect of Reduced Threshold for Perception of Airspeed Error

Shear 1, attitude CWS
A = advanced display, F = flight director,
L = director with lowered perceptual threshold.

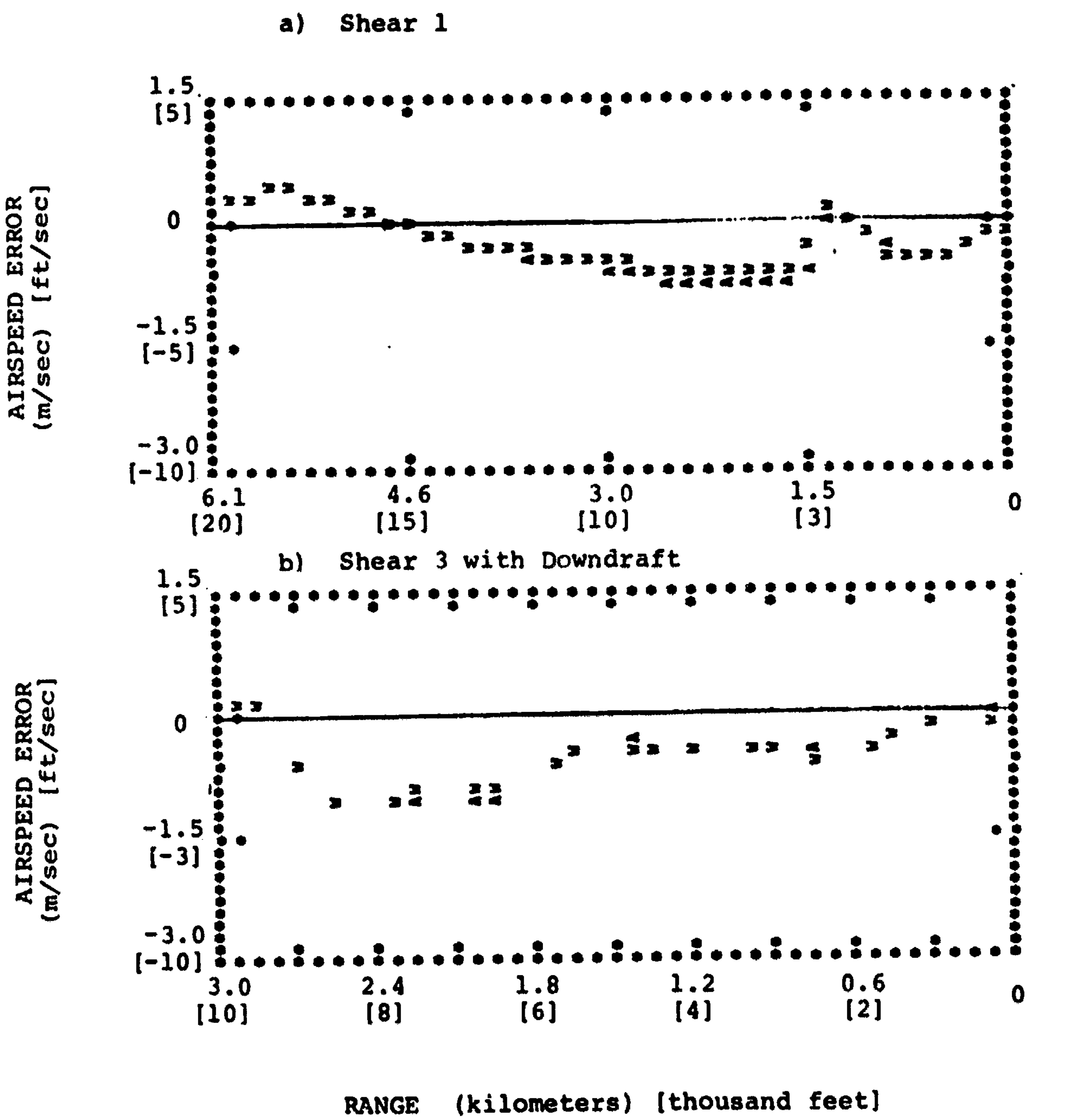

Figure 9. Effect of Explicit Display of Wind on Predicted Mean Height Error

Attitude CWS
A = advanced display, W = additional wind display

especially if the display were augmented to provide such predictive information. The potential for predictive capabilities of both pilot and display is a relevant area for future study.

DISCUSSION

In general, performance trends predicted by the model were confirmed experimentally. Experimental and analytical results both indicated superiority of the "advanced" display with respect to regulation of height and airspeed errors. Velocity steering allowed tighter regulation of height errors, but control parameters had little influence on airspeed regulation. Model analysis indicated that display-related differences could be ascribed to differences in the quality of speed-related information provided by the two displays.

Predictions were most accurate with regard to display-and control-related differences in the total swing of the mean error over the course of the approach, and least accurate with regard to response variability and absolute levels of mean error. Experimental run-to-run variability was from 2 to 3 times as great as predicted for both height and speed errors, [2], and mean errors tended to be less negative (or more positive) than predicted. The relatively large experimental variability may have been, in part, a result of keeping the data base small to prevent the pilot's learning of the shear profile. In addition, there appeared to be a tendency for the pilots to fly high and/or fast on some trials and not on others, a factor that could contribute to predictive inaccuracies.

With regard to future application of the pilot/vehicle model to the study of approach performance in windshears, one might profitably address questions relating both the pilot's conception of the behavior of the wind as well as to the wind information explicitly displayed. For example, one can assume that the pilot knows that the wind will change with altitude (and thus with time) in a smooth manner, and one can explore the consequences of displaying (a) the same variables displayed in this study, (b) additional variables relating to the current wind state, and (c) additional variables relating to the rate-of-change of wind. Furthermore, one can explore the interaction of these factors with the type and severity of shear. Additional factors that can be explored are the relation between performance and workload for candidate controls and displays, as well as the utility of motion cues in detection of windshears.

In conclusion, the model employed in this study has been validated with regard to its ability to predict important performance trends related to contro's and displays in windshear environments. Because of the operational necessity of understanding performance in windshears, we suggest that the pilot/vehicle model be applied further to aid in the design of simulation experiments and to explore a variety of factors that cannot be readily studied in the laboratory. While we cannot guarantee accurate predictions of absolute performance levels at this stage of model development, the model should provide reliable indications of the nature of performance and workload improvements that can be achieved with candidate controls and displays in a variety of windshear environments.

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