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FLIGHT INVESTIGATION OF A VERTICAL-VELOCITY COMMAND SYSTEM FOR VTOL AIRCRAFT

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16. Abstract

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The scope of the investigation included a determination of acceptable system parameters, a visual flight evaluation, and an instrument flight evaluation which employed a 10°, decelerating, simulated instrument approach task. The results indicated that the VVCS, which decouples the pitch and vertical degrees of freedom, provides more accurate glide-path tracking and a lower pilot workload than does the unaugmented system.

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SUMMARY

A flight investigation was undertaken to assess the potential benefits afforded by a vertical-velocity command system (VVCS) for VTOL (vertical takeoff and landing) aircraft. This augmentation system was conceived primarily as a means of lowering pilot workload during decelerating approaches to a hover and/or landing under category III instrument meteorological conditions.

The scope of the investigation included a determination of acceptable system parameters, a visual flight evaluation, and an instrument flight evaluation which employed a 10°, decelerating, simulated instrument approach task. The results indicated that the VVCS, which decouples the pitch and vertical degrees of freedom, provides more accurate glide-path tracking and a lower pilot workload than does the unaugmented system.

INTRODUCTION

Beginning in 1968, Langley Research Center has been studying control and display requirements for steep, decelerating approach and landings of VTOL aircraft under category III instrument meteorological conditions (IMC). These studies employed a research helicopter that was equipped with an experimental high-gain control augmentation concept in the pitch, roll, and yaw degrees of freedom and with an experimental three-cue VTOL flight-director display. Over 400 simulated IMC (hooded) decelerating approaches have been flown with this control-display combination, during which the navigation, guidance, control augmentation, and flight-director control laws were varied and refined to the point where successful approaches became a matter of course. Even with the best overall system, however, the pilot workload during the final stages of the deceleration was found to be disproportionately high when compared to all of the other phases of the task. The problem is illustrated in figure 1, which shows relative pilot workload as a function of the approach phase.

The peak workload was found to be directly related to the tracking situation at the beginning of the deceleration and to the wind conditions during the approach. For example, if the winds were light and the aircraft was on the glide path and center line at the beginning of the deceleration, then the relative workload would tend to follow the lower boundary of the region indicated in figure 1. On the other hand, if there was a strong crosswind, or the aircraft was diverging from the glide path and center line at the beginning of the deceleration, then pilot workload generally rose to an unacceptable level and remained there until a stabilized hover was established.

A primary cause for the higher level of workload was the rapid change in the power-required characteristic of the helicopter during the transition-to-hover maneuver. The power requirement manifests itself to the pilot as a trim-position change of the collective pitch lever of approximately 5.1 cm (2 in.) of upward movement over a time period of 15 sec. Unless the pilot was able to make the collective pitch input precisely, the aircraft would diverge from the glide path and the result would be a substantial increase in workload prior to establishing a stabilized hover.

In order to reduce this trim-change requirement, and hence the pilot workload, the vertical degree of freedom was augmented by using a concept referred to as a vertical-velocity command system (VVCS). The VVCS provided a vertical rate (rate of change of altitude) proportional to height-control-lever inputs. In order to eliminate the apparent power-required characteristics and to compensate for attitude effects, the concept was implemented by the use of a high-gain model-following technique. A series of visual flight tests were conducted to determine acceptable system parameters. Simulated IMC decelerating approaches were then flown both with and without the VVCS to compare tracking performance and pilot workload. This report describes the implementation and evaluation of the vertical-velocity command system.

SYMBOLS

Values are given in both the International System of Units (SI) and U.S. Customary Units. The measurements and calculations were made in U.S. Customary Units.

a_n	normal acceleration, m/sec^2 (ft/sec^2)
g	gravity constant, 9.8 m/sec^2 (32.2 ft/sec^2)
$K_{\dot{z}}/m$	vertical velocity damping, 1/sec
K_1,K_2,K_3	system gains
m	helicopter mass, kg (slugs)
s	Laplacian variable
T_δ/m	height control sensitivity, m/sec^2/cm (ft/sec^2/in.) or g/cm (g/in.)
$\dot{z}$	vertical (altitude) rate, m/sec (ft/sec)
$\ddot{z}$	vertical acceleration, m/sec^2 (ft/sec^2)
δ	height control position, cm (in.)
δ_{db}	height-control dead band, cm (in.)

δ^*	height control position outside dead band, cm (in.)
θ	pitch attitude, deg
τ	time constant, sec
τ_1	complementary filter time constant, sec
ϕ	roll attitude, deg

Subscripts:

c	commanded parameter
e	error
f	complementary filter output
m	model parameter

Abbreviations:

ADI	attitude director indicator
IMC	instrument meteorological conditions
IVSI	instantaneous vertical speed indicator
VVCI	vertical-velocity command indicator
VVCS	vertical-velocity command system

DESCRIPTION OF EQUIPMENT

Test Helicopter

The vertical-velocity command system was implemented on the helicopter shown in figure 2. This vehicle was equipped with onboard analog and digital computing systems which, when used in conjunction with the aircraft's electronic control system and appropriate sensors, could be programed to investigate various control augmentation concepts. In the present investigation, the pitch, roll, and yaw control augmentation systems were programed on the analog computer, and the VVCS was implemented on the digital computer.

Electronic control system.- The control system of the test helicopter has been modified by removing the mechanical linkages that connect the right-hand set of controls (evaluation pilot's center stick, pedals, and collective pitch lever) to the basic-ship system. The position of each control is sensed electrically and routed to the onboard computers for processing. The computer outputs drive the control surfaces through full-authority electrohydraulic actuators installed in each controlled degree of freedom (pitch, roll, yaw, and vertical).

The actuators are installed in parallel with the safety pilot's controls (the left-hand set of controls) which have not been altered and, as such, follow the control-surface motions resulting from computer inputs.

Cockpit controls.- The evaluation pilot's controls consist of a center stick for pitch and roll, pedals for yaw, and a height control lever (collective pitch lever) for vertical control. The center stick and pedals are equipped with a trimmable spring centering system which produces linear force gradients of 1.7 N/cm (1 lb/in.) in pitch and roll and 8.7 N/cm (5 lb/in.) in yaw. The breakout and friction forces of the center stick and pedals were negligible.

The height control lever was equipped with an adjustable friction device, had a full throw of ±7.6 cm (±3 in.), and had a force detent at midtravel (the center position). With the friction device adjusted to its lowest value, the sliding friction was between 4.4 N and 8.8 N (1 lb and 2 lb). An additional force of approximately 4.4 N (1 lb), applied at the grip, was required to move the control out of the detent.

Pitch, roll, and yaw control augmentation.- A high-gain attitude command system was provided in pitch and roll which yielded a second-order attitude response to pilot control inputs. For yaw control, a high-gain approach was also taken to implement turn-following and heading-hold modes. The turn-following mode provided automatic coordination for roll-initiated (pedal-fixed) turns. In this mode, the pedals could be utilized to produce intentional sideslips. The heading-hold mode forced the aircraft to maintain a fixed magnetic heading. In this mode, pedal inputs could be used to change the reference heading. A ±0.63 cm (±1/4 in.) dead band was employed in the heading-hold mode to prevent inadvertent pedal inputs.

The control augmentation was implemented such that the control response characteristics were essentially constant throughout the flight regime, and the angular response of the vehicle to external disturbances and trim changes was heavily suppressed.

The response characteristics in pitch, roll, and yaw are given in table I and were the same as those used during an earlier investigation reported in reference 1.

Instrument panel.- The evaluation pilot's instrument panel is shown in figure 3. The panel included an attitude director indicator (ADI), horizontal-situation (moving-map) display, airspeed indicator, radar altimeter, barometric altimeter, instantaneous vertical speed indicator (IVSI), vertical-velocity command indicator (VVCI), clock, and engine and rotor instruments. This panel is the same as the one described in reference 1, except that the VVCI has been installed in place of the power control position indicator.

The ADI shown in figure 4 presented three flight-director commands (described in a subsequent section), pitch and roll attitude, altitude error, cross-range error, and altitude (on a rising runway symbol). The moving-map display shown in figure 5 presented a plan view of the approach corridor in a heading-up orientation. Range and cross-range deviation were indicated by the position of the map relative to the fixed triangular aircraft symbol. Heading was obtained from a compass rose.

The VVCI (fig. 3) indicated the steady-state vertical rate being commanded. A nonlinear scale was employed to enhance the readability near zero and at the same time to provide coverage between ±10.2 m/sec (±2000 ft/min). A solid index was included about the zero point to assist the pilot in positioning the height control lever within the dead band.

Navigation and Guidance System

The navigation and guidance system described in reference 1 was utilized for the steep, decelerating instrument approach and landing task employed in the investigation. The system is composed of a ground-based tracking radar, a ground-to-air data link, and onboard analog computers for deriving navigation and guidance signals.

The system operates as follows: The ground-based tracking radar measures the position of the aircraft relative to the desired touchdown point. This information is telemetered to the aircraft and processed in the computers, as described in reference 2, to derive estimates of position and rate of change of position. These estimates, in conjunction with the control laws given in reference 1, are used to generate three flight-director commands, a pitch command for speed (range-rate) control, a roll command for cross-range control, and a height control command for altitude control. These commands, along with appropriate deviation information, are displayed on the ADI.

Modifications to the height-control-command control law were not required by the addition of the VVCS since the concept of commanding vertical rate had been used in formulating the control law for the unaugmented system.

Data System

An onboard magnetic-tape recording system was used to record selected parameters. Aircraft position, rate of change of position, and body accelerations were recorded continuously. Control positions, angular rates, body attitudes, flight-director commands, and the IVSI output were recorded at 20 samples per second.

VERTICAL-VELOCITY COMMAND SYSTEM

Response Characteristics

The height-control-augmentation concept was designed to provide a vertical rate (i.e., rate of change of altitude) response according to the following equation:

$$\ddot{z} = \frac{T_{\delta}}{m}(\delta^{*}) + \frac{K_{\dot{z}}}{m}\dot{z}$$

where $\delta^* = 0$ for $|\delta| \leqq |\delta_{db}|$ and $\delta^* = \delta - \delta_{db}$ for $|\delta| > |\delta_{db}|$ where the sign of δ_{db} is the same as that of δ. This equation describes a first-order vertical-rate response for a step input wherein the initial vertical acceleration is given by $(T_\delta/m)(\delta^*)$, the steady-state vertical rate is given by $(T_\delta/m)(\delta^*)/(-K_{\dot{z}}/m)$, and the time constant - which defines the time required to achieve 63 percent of the steady-state vertical rate - is given by $1/(-K_{\dot{z}}/m)$. The control sensitivity term T_δ/m is often expressed in g/cm (g/in.). These units are used in the remainder of this report.

It should be emphasized that the response is referenced to an inertial frame (as opposed to a body-axis frame of reference) and, as such, the vertical rate is independent of the vehicle's attitude, airspeed, etc. Furthermore, the concept implicitly provides an altitude-hold capability whenever the pilot's control is within the dead band δ_{db}, that is, when the pilot is commanding zero vertical rate.

Implementation

The VVCS was implemented on a general-purpose digital computer which was interfaced with onboard analog sensors and an analog electronic control system, as shown in figure 6. The desired vehicle response was achieved by using the model-following technique. In this technique, the desired vehicle response characteristics are formulated as a set of model equations and are programed on an airborne computer. The computer receives the pilot-control input and computes the model response (i.e., the desired response) in real time. Standard control techniques, involving the use of lead and feedback compensation, are employed to force the aircraft into following the desired response.

Figure 7 is a simplified functional block diagram of the computer program employed. The pilot's control position δ was processed through the dead-band network, and the resulting output δ^* was sent to a first-order lag circuit. The outputs of the model were a feed-forward term $\ddot{z}_m$ and the commanded vertical rate $\dot{z}_m$. The commanded rate was compared with the vehicle's "actual" vertical rate $\dot{z}_f$ to form a vertical-rate error signal. The error signal drove the control surfaces through proportional plus integral gains; this caused the helicopter to respond so as to drive the error signal to zero. A destabilizing signal derived from $\dot{z}_f$ was employed to counteract the inherent normal velocity damping of the basic vehicle. This term permits higher gains to be used in the error loop and also permits $\ddot{z}_m$ to be used as a lead term without additional shaping.

The vertical rate $\dot{z}_f$ of the vehicle was estimated by using a complementary filtering technique to combine high-frequency rate information derived from a body-mounted normal accelerometer, with low-frequency rate information derived from the instantaneous vertical speed system. Since the normal accelerometer processing involves integration and high-pass filtering, the two operations can be combined and accomplished by an equivalent low-pass filter. In the present implementation, the low-pass filtering was performed prior to digitizing the signal; thus, problems associated with digitizing a high-frequency input were minimized. Low-pass filtering of the instantaneous vertical-speed input, however, was performed by the digital computer program. A simple gravity correction term was incorporated to account for pitch and roll effects on the body-mounted normal accelerometer.

The digital implementation was compared (flown back-to-back) with an equivalent analog version for a series of VFR tasks, including approaches and hovering flight, and the pilot could not discern any differences between the two implementations.

TEST CONDITIONS AND PROCEDURES

System Variables

Software provisions were made to vary the height control sensitivity T_δ/m (acceleration per unit control input), the time constant of the response τ, and the size of the height-control dead band δ_{db}.

Dead-Band Tests

The initial part of the flight investigation was directed toward estabishing an acceptable dead-band size for subsequent testing. In order to limit the number of test conditions, the control dead-band tests were conducted for only one combination of control sensitivity and time constant; namely, T_δ/m = 0.079 g/cm (0.2 g/in.) and τ = 2.0 sec. Four sizes of discrete dead band were evaluated in the following predetermined sequence: ±0.63 cm (±1/4 in.), ±2.54 cm (±1 in.), ±0.32 cm (±1/8 in.), and ±1.27 cm (±1/2 in.). This sequence was selected to avoid a progression from small-to-large or large-to-small dead bands and also to provide large changes (factors of four or more) between test points.

The flight evaluation involved a variety of visual flight maneuvers, including precision hovering, quick starts and stops, hovering take-offs, climbs, descents, and approaches to a hover. The tests covered a speed range from hover to an indicated airspeed of 70 knots and covered altitudes from near 0 to 304.8 m (1000 ft).

Control-Sensitivity—Time-Constant Tests

The next phase of the flight investigation was to determine a satisfactory control-sensitivity—time-constant combination which would permit a valid evaluation of the potential afforded by the vertical-velocity-command concept. A set of six combinations of control-sensitivity—time-constant, which was indicated from experience to encompass a satisfactory combination, were selected for the initial evaluation. The combinations are shown in table II. Each combination was evaluated by using the same set of visual flight maneuvers described in the previous section on dead-band tests.

Visual Flight Evaluation

This visual-flight-evaluation phase of the investigation was directed at determining the advantages and disadvantages of the vertical-velocity command system for transport-type visual-flight helicopter operations. The tasks used were the same as those used for the preceding tests (i.e., dead-band tests and sensitivity—time-constant tests).

IMC Evaluation

The instrument flight task used to evaluate the height control system consisted of a 10°, decelerating, simulated instrument approach to a 15.3-m (50-ft) hover, as illustrated in figure 8. Instrument flight conditions were simulated by means of a conventional helmet-mounted hood and by covering the lower window areas in the cockpit with curtains. The evaluation pilot was given control of the aircraft on the downwind leg at about 228-m (750-ft) altitude, 65-knots indicated airspeed, and about 4570-m (15 000-ft) range. Using situation information only (i.e., no flight-director commands), the pilot had to execute an inbound turn to capture the approach center line; shortly before center-line capture, the pitch and roll flight-director commands were activated. Glide-path intercept was accomplished by using the height control command which was activated shortly before glide-path intercept. From this point on, the flight director provided continuous commands to guide the aircraft down to a 15.3-m (50-ft) hover. The task terminated when the pilot indicated he had obtained a stabilized hover.

RESULTS AND DISCUSSION

Response Characteristics

Dead band.- The results of the dead-band evaluation were entirely qualitative; performance data were not obtained during this phase of the investigation. The pilots agreed that the ±1.27-cm (±1/2-in.) and ±2.54-cm (±1-in.) dead bands were too large. On the other hand, they indicated that both the ±0.63-cm (±1/4-in.) and ±0.32-cm (±1/8-in.) dead bands were acceptable and that there were no apparent differences between either case. In light of these results, an additional series of flight tests were made with no dead band. The pilots commented that this case was unacceptable because it resulted in continuous control activity. The primary problem was that the pilots could not readily establish the zero rate-of-climb trim position. As a result of these tests, a dead band of ±0.32 cm (±1/8 in.) was selected for use in the remainder of the evaluation.

Sensitivity—time-constant tests.- The results of the sensitivity—time-constant tests are shown in figure 9. The figure indicates the primary reason the pilots downrated a given combination relative to the best combination tested. Vertical velocity damping, the reciprocal of the time constant, was used for the ordinate in figure 9 so as to facilitate the cross plotting of the constant-vertical-rate boundaries. As seen from the figure, the two combinations referred to as "sluggish" resulted in steady-state rates per unit control input of less than 0.8 m/sec/cm (400 ft/min/in.). According to the pilots, the two test points at 0.12 g/cm (0.3 g/in.) resulted in some overcontrolling. The combination of 0.079 g/cm (0.2 g/in.) and 0.25 1/sec was referred to as "too sensitive." In this case, sensitivity was used to indicate that the steady-state rate per unit control input, greater than 3 m/sec/cm (1500 ft/min/in.), was excessive. The results therefore clearly established the best combination tested.

As a matter of interest, the selected combination was compared to existing specifications (refs. 3 and 4). The comparison shown in figure 10 indicates that the best combination determined during these tests is well within the acceptable regions specified by existing requirements.

Visual Flight Evaluation

The results of the VFR evaluation identified specific advantages and disadvantages of the concept. In regard to advantages, the pilots commented that the aircraft could be controlled more precisely, even at a somewhat lower workload, with the VVCS than with the unaugmented (basic-helicopter) control system. It should be emphasized that the overall workload associated with the unaugmented vertical control system was low from the beginning since the pitch, roll, and yaw degrees of freedom were already highly augmented and the pilots were performing relatively easy VFR tasks. As such, even the slight reduction in workload was considered to be significant. The pilots commented that the principal benefit of the VVCS concept for VFR applications was the inherent decoupling between the vertical degree of freedom and pitch and the vertical degree of freedom and roll. Hovering take-offs were accomplished by simply pitching the aircraft nosedown to accelerate into forward flight and by setting the height-control-lever position for the desired rate of climb using the VVCI. From this point on, the pilot could execute climbing turns by means of lateral control inputs alone. Once the desired altitude was reached, the pilot would simply set the height control lever to the zero-vertical-rate command position (using the VVCI and/or the centering detent), and altitude hold was obtained. (It should be noted that the height-control-lever position corresponding to the zero trim point did not change with speed, gross weight, temperature, or other such factors because of the implementation method used.) The pilots commented that the centering device reduced the time required for scanning the VVCI; however, they all commented that the detent force cue was too light and should be increased.

The flight investigation uncovered two negative aspects of the concept. The first problem was that the pilots experienced difficulty in adapting to the absence of a flare when decelerating to a hover with the VVCS. This, of course, stems from their previous experience with conventional collective control systems wherein the vehicle's normal velocity damping is used to arrest the descent rate at the bottom of an approach. With the VVCS, the descent rate is independent of pitch attitude; hence, the conventional approach technique does not apply. The second disadvantage uncovered during these tests stemmed from the fact that engine power variations would occur even though the evaluation pilots' height control lever was not being moved. Here again, this characteristic was not in line with the pilots' previous experiences. Although the pilots were able to adapt to this characteristic, they remained apprehensive about exceeding torque limits of the drive system. They indicated that an operational system should incorporate some method of power limiting in order to preclude overtorqueing the drive system.

IMC Evaluation

Tracking performance for nine approaches performed during the same flight is shown in figure 11. Four approach tracks using the unaugmented (basic-helicopter) vertical degree-of-freedom control system are presented in figure 11(a); five approach tracks using the VVCS are presented in figure 11(b). Figure 11 indicates that the range-rate tracking performance is essentially the same with both the VVCS and the unaugmented control system. Also, the cross-range tracking performance is essentially the same with both systems. On the other hand, glide-path control performance with the VVCS shows a definite improvement over the performance obtained with the unaugmented control system. Furthermore, according to the pilots, this performance improvement was obtained for a lower overall workload. The pilots noted that glide-path capture was much easier with the VVCS than with the unaugmented system. In addition, once on the glide path, there were noticeably fewer height control command variations with the VVCS and, hence, less control activity. This result was anticipated since the VVCS concept decoupled the pitch and vertical degrees of freedom of the aircraft; coupling between the pitch and vertical degrees of freedom was known to be a major source of the glide-path deviations (and, hence, height-control-command activity) from previous investigations. Based on the pilots' comments, the decoupling characteristic of the VVCS was the principal benefit when performing IMC decelerating approaches to a hover.

CONCLUSIONS

A flight investigation was conducted to evaluate the potential benefits afforded by a VVCS (vertical-velocity command system) concept for VFR transport-type operations and IMC (instrument meteorological conditions) decelerating approaches to a hover. Based on the results obtained, the following conclusions are drawn:

1. The principal benefit of the VVCS for both visual flight and instrument flight applications is that it decouples the pitch and vertical degrees of freedom. For IMC approach applications, this results in more accurate glide-path tracking and a lower pilot workload than approaches flown with a conventional (unaugmented) system which does not suppress coupling.

2. For the parameters tested, the best combination of parameters was found to be: a sensitivity of 0.079 g/cm (0.2 g/in.), a time constant of 2 sec, and a dead band of ±0.32 cm (±1/8 in.).

3. The centering device on the height control lever enhanced the benefits associated with the VVCS concept by reducing the time spent looking at the VVCI (vertical-velocity command indicator).

4. Pilots trained on conventional (unaugmented) height control systems had difficulty in adapting to the VVCS concept because of the absence of a flare when performing VFR decelerating approaches to a hover.

5. The pilots indicated that an operational system should incorporate some method of power limiting in order to preclude overtorqueing the drive system.

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May 19, 1977

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TABLE I.- CONTROL-SYSTEM CHARACTERISTICS

Pitch and roll:	
Control power, rad/sec^2	1
Control sensitivity, rad/sec^2/cm (rad/sec^2/in.)	0.08 (0.2)
Damping ratio	0.75
Undamped natural frequency, rad/sec	1.43
Attitude sensitivity, rad/cm (rad/in.)	0.04 (0.10)
Yaw:	
Heading-hold mode:	
Undamped natural frequency, rad/sec	2.0
Damping ratio	0.7
Maximum heading-rate capability,[a] rad/sec	0.8
Heading-rate control sensitivity,[a] rad/sec/cm (rad/sec/in.)	0.14 (0.35)
Turn-following mode:	
Control power, rad/sec^2	0.25
Control sensitivity, rad/sec^2/cm (rad/sec^2/in.)	0.08 (0.2)
Directional stability, rad/sec^2/m/sec (rad/sec^2/ft/sec)	0.013 (0.004)
Damping-to-inertia ratio, 1/sec	0.7
Yaw due to roll angle, rad/sec^2/rad	0.30

[a] Outside a ±0.63-cm (±1/4-in.) dead band.

TABLE II.- CONTROL-SENSITIVITY—TIME-CONSTANT COMBINATIONS TESTED

Control sensitivity, T_δ/m		Time constant, τ, sec		
g/cm	g/in.	1	2	4
0.039	0.1		x	
.079	.2	x	x	x
.118	.3	x	x	

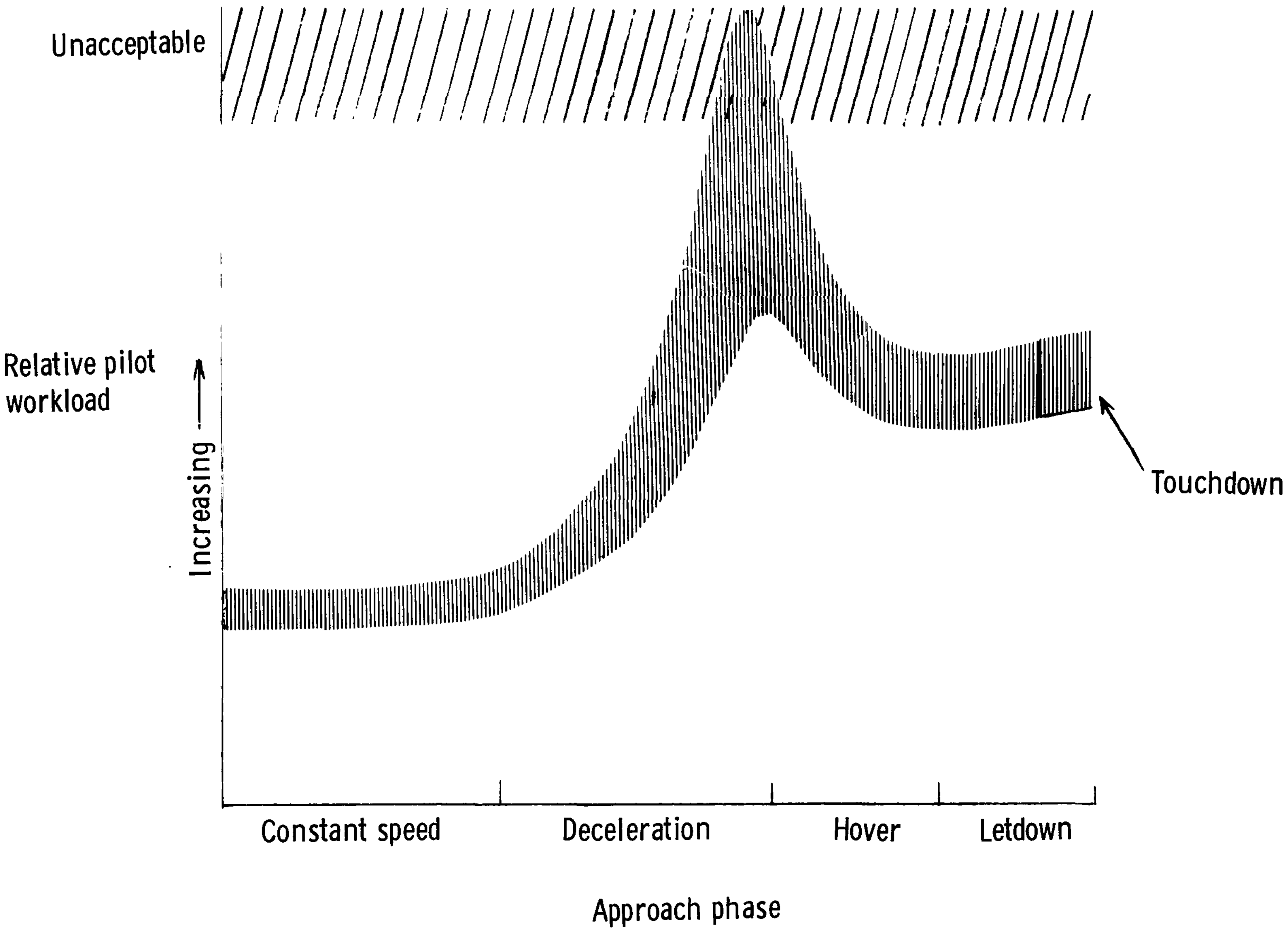

Figure 1.- Relative pilot workload as function of approach phase.

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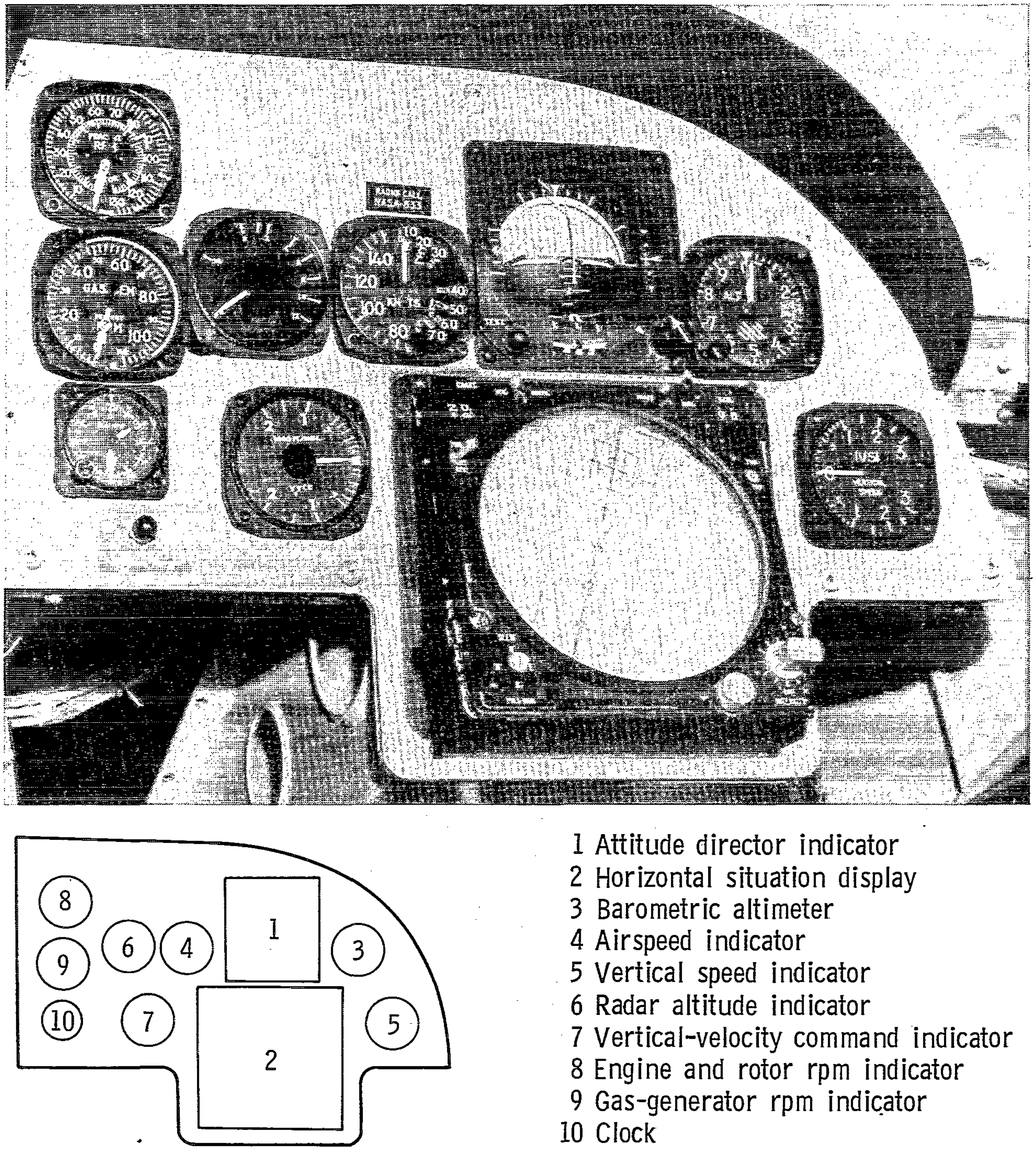
Figure 2.- Research helicopter.



1 Attitude director indicator
2 Horizontal situation display
3 Barometric altimeter
4 Airspeed indicator
5 Vertical speed indicator
6 Radar altitude indicator
7 Vertical-velocity command indicator
8 Engine and rotor rpm indicator
9 Gas-generator rpm indicator
10 Clock

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Figure 3.- Evaluation pilot's instrument panel.

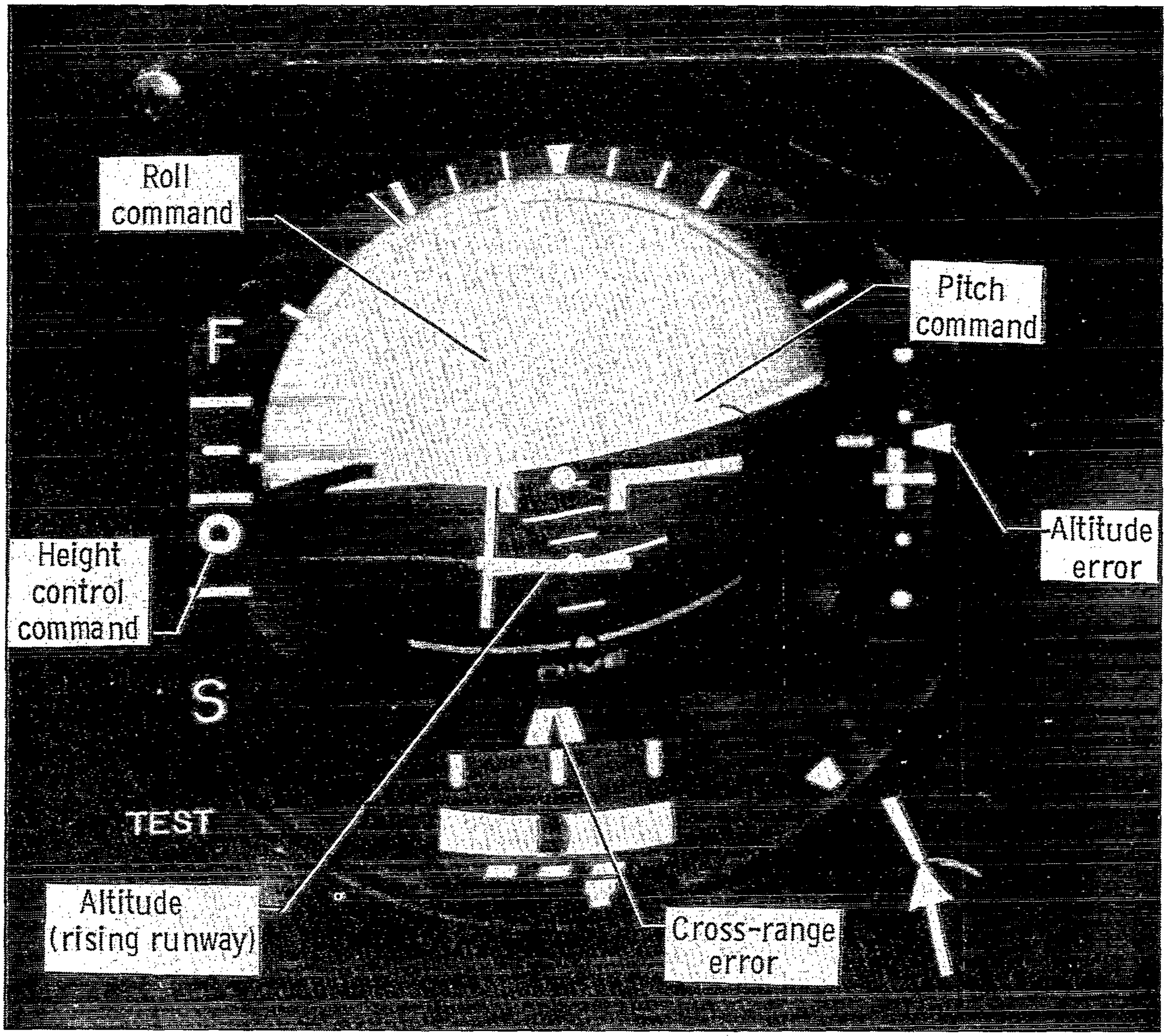

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Figure 4.- Attitude director indicator.

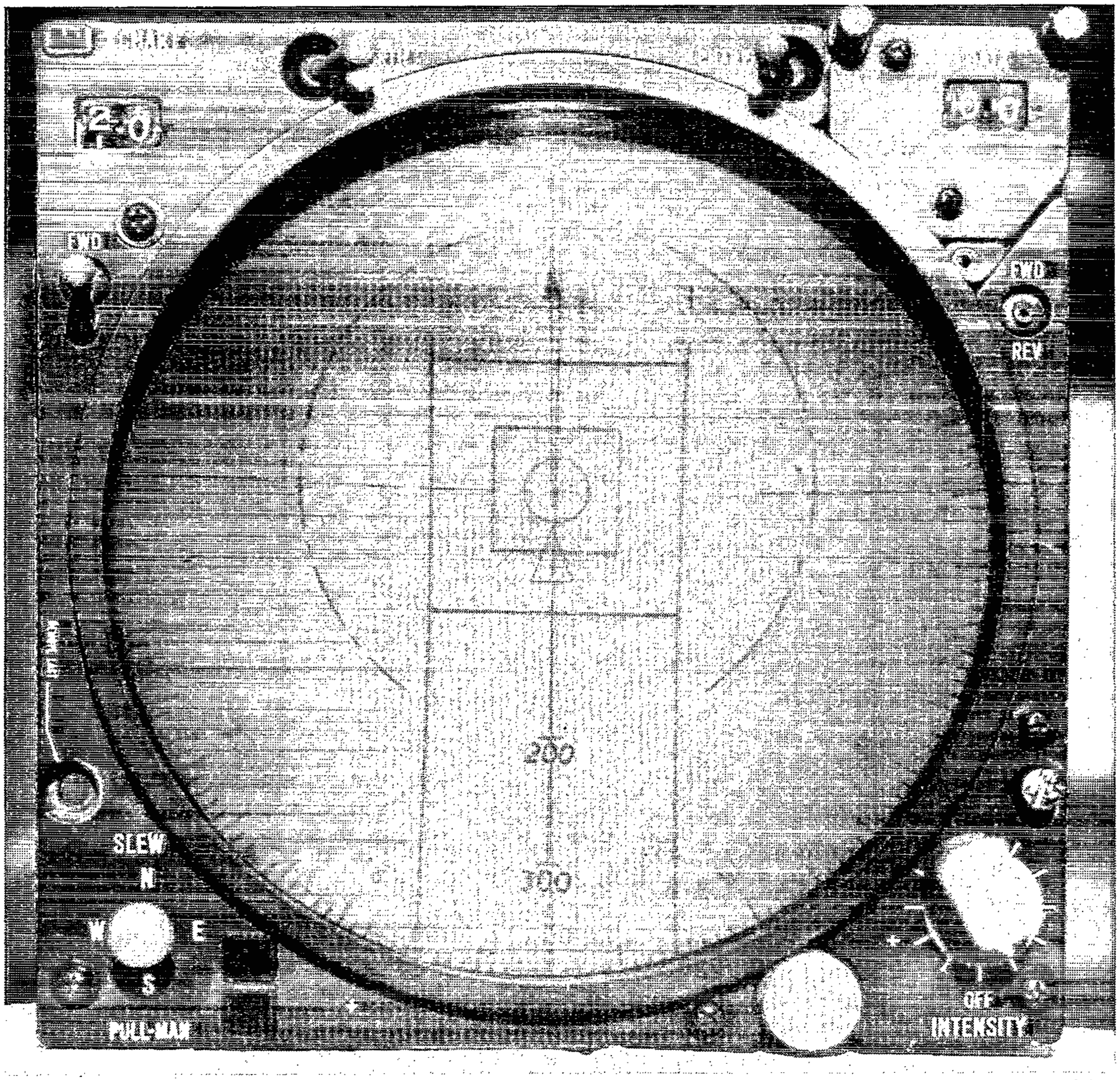

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Figure 5.- Horizontal-situation (moving-map) display.

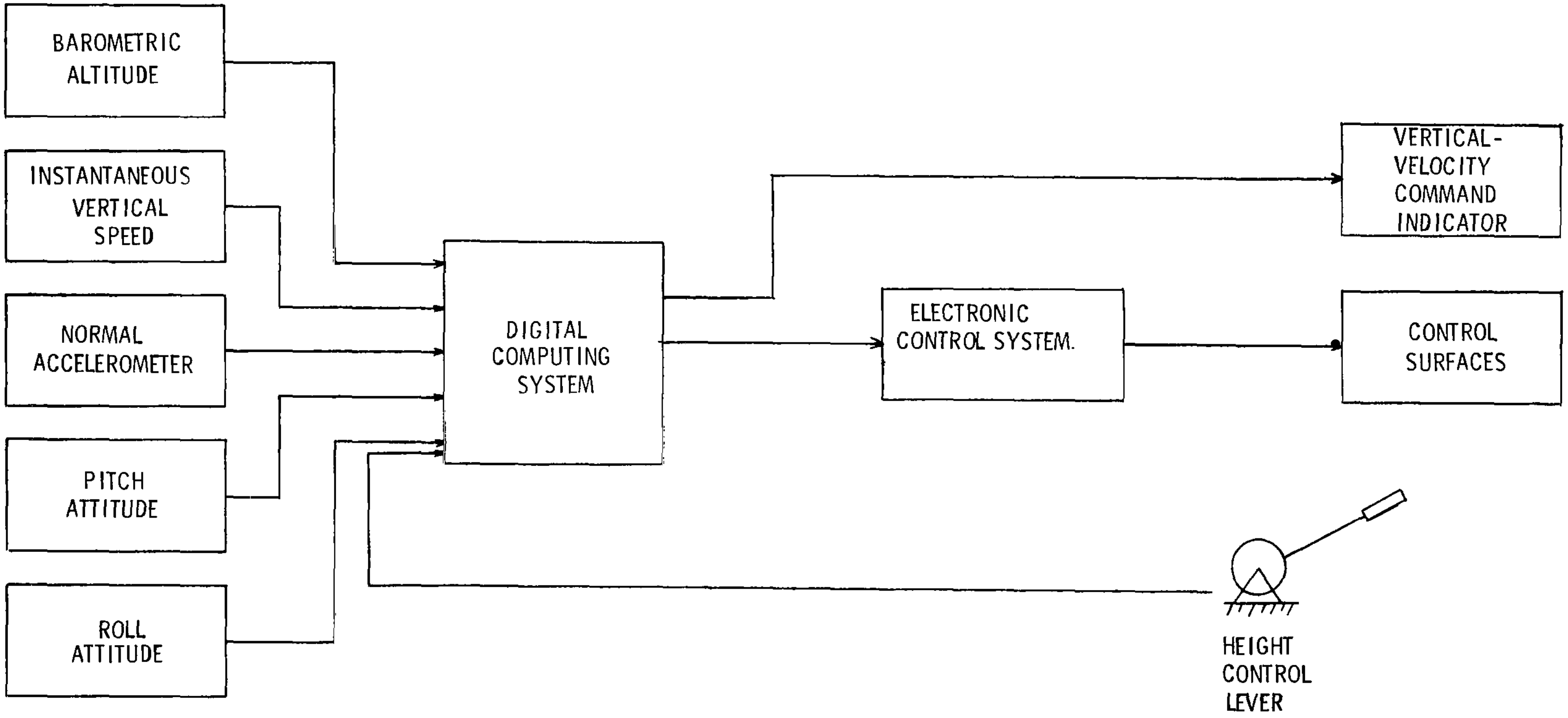


Figure 6.- Elements of vertical-velocity command system.

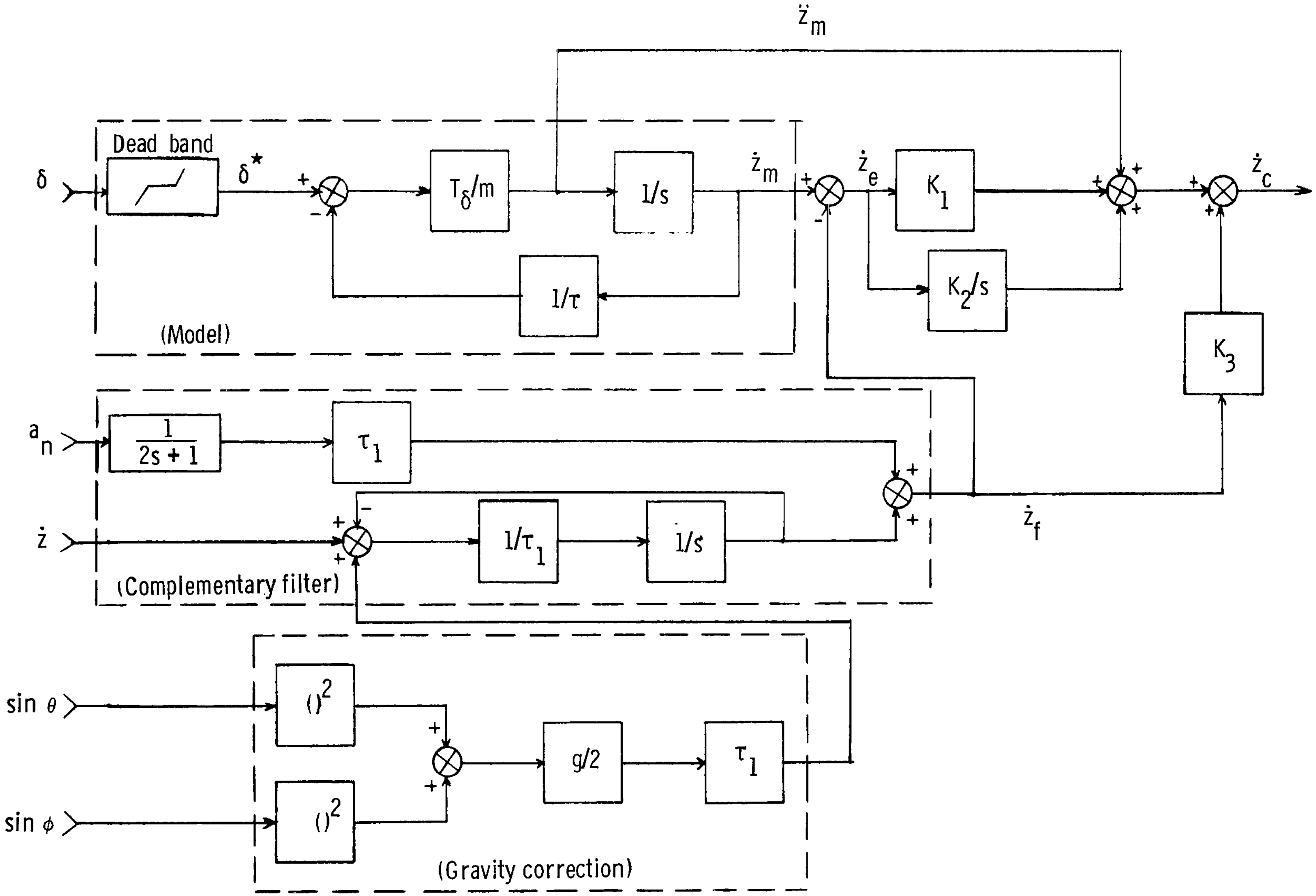


Figure 7.- Model-following implementation.

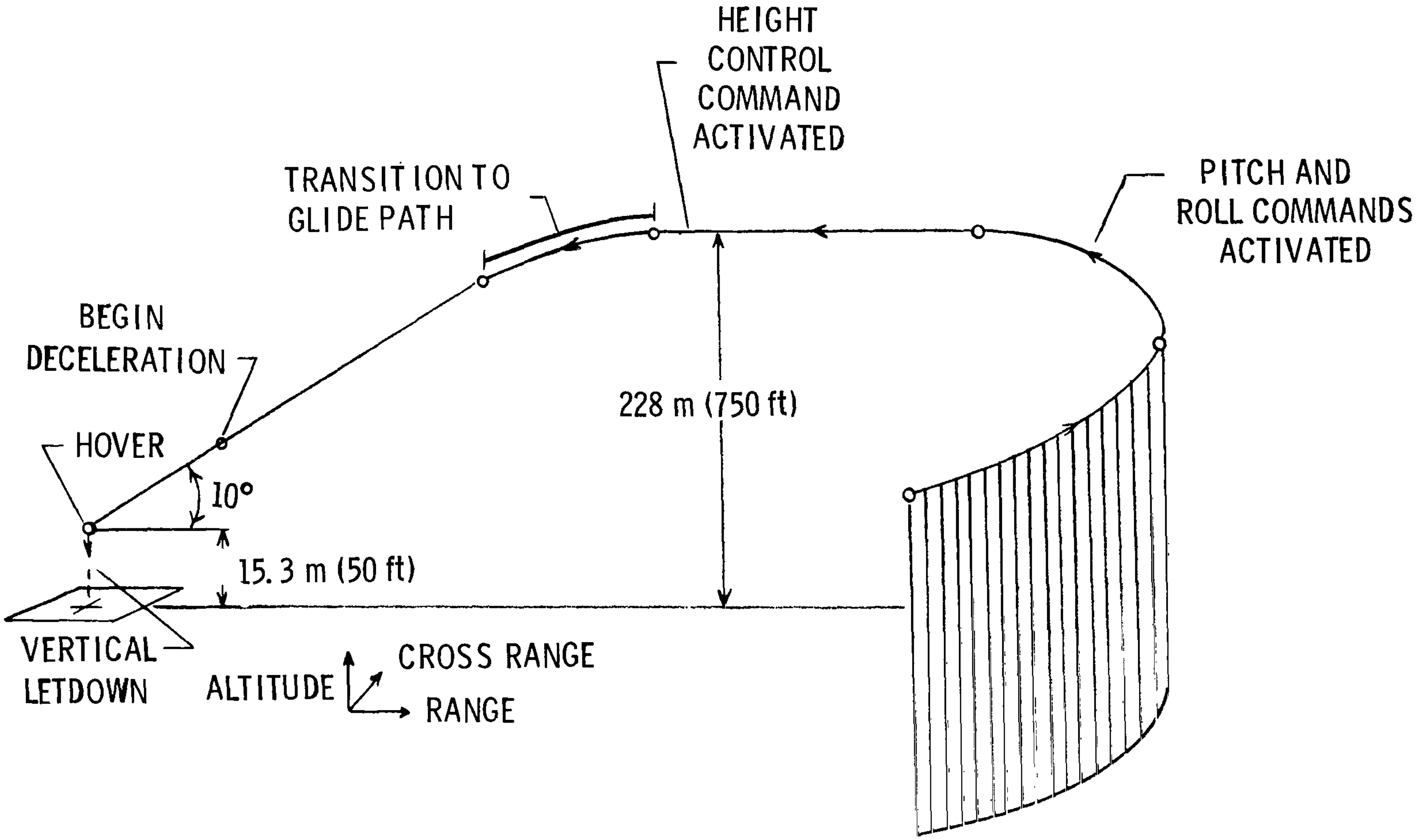


Figure 8.- Instrument flight task.

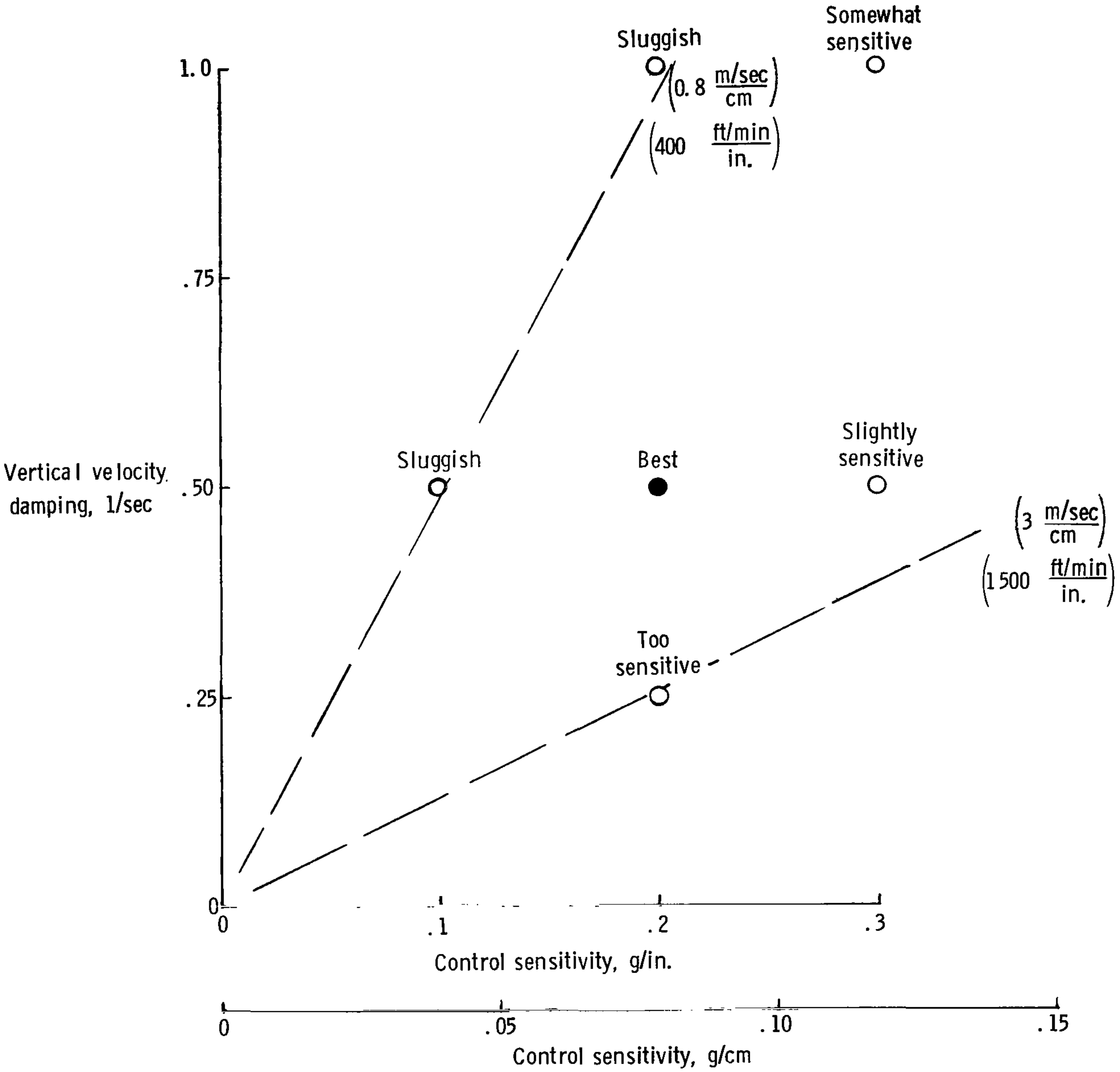


Figure 9.- Prime factor for downrating various control-sensitivity—time-constant combinations.

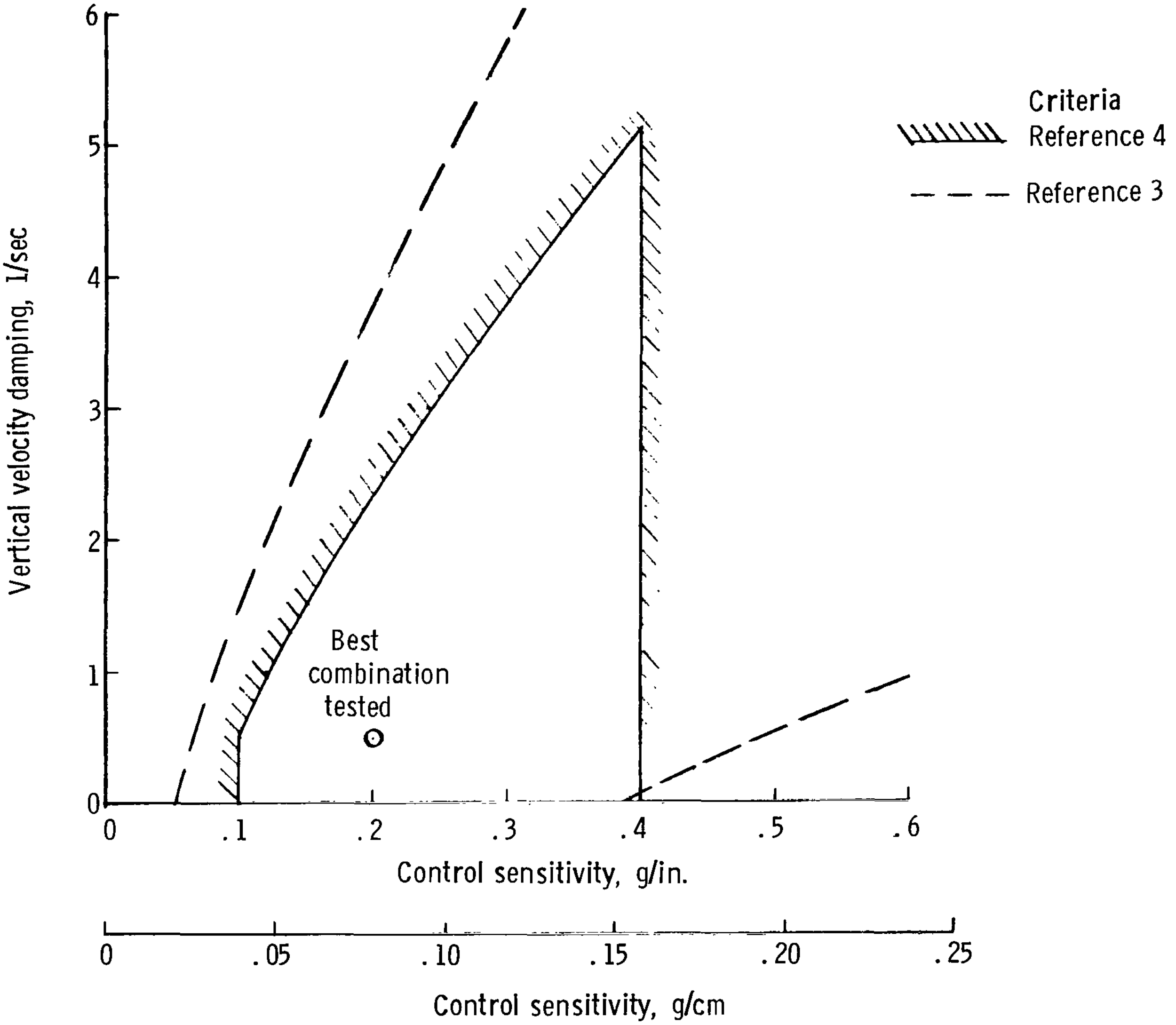
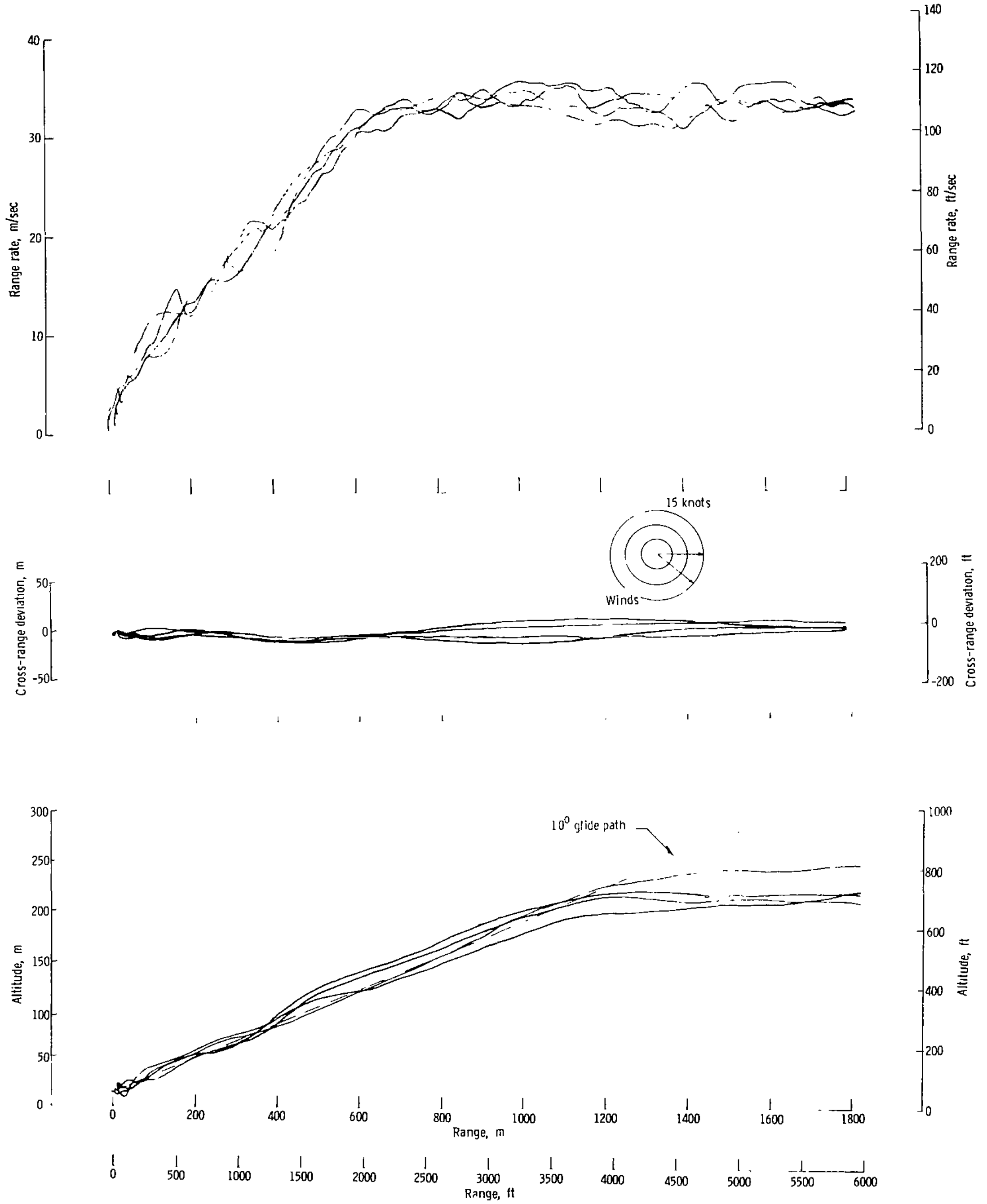
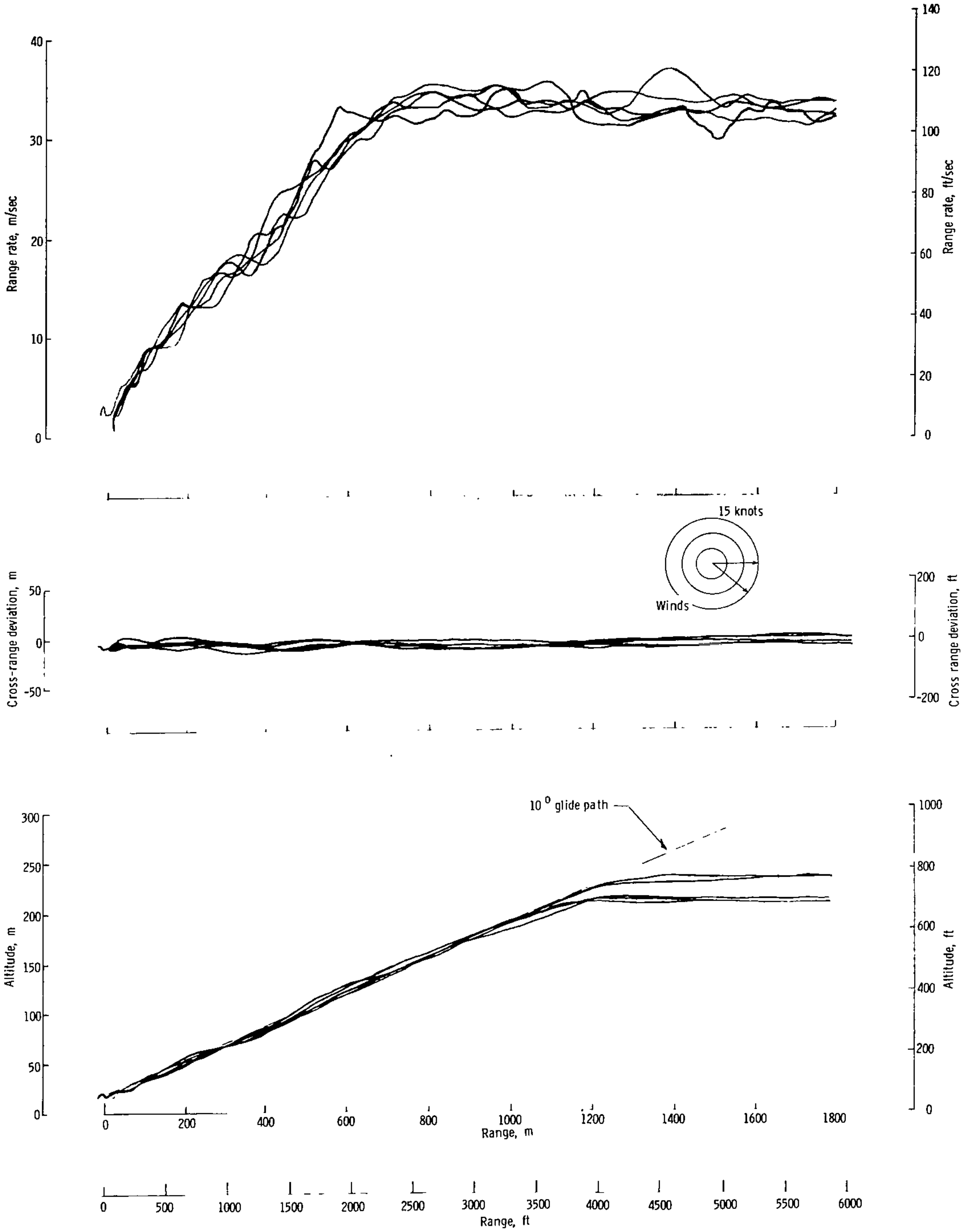


Figure 10.- Comparison of best combination tested to existing criteria.



(a) Unaugmented vertical control system.

Figure 11.- Tracking performance at 10° decelerating approach.



(b) Vertical-velocity command system.

Figure 11.- Concluded.

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