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by Bernard R. Kibort and Fred J. Drinkwater III

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SUMMARY

A quantitative evaluation was made of a large number of landings in a transport airplane. Data were collected during landings with normal pilot vision, with restricted peripheral vision, and with televised view forward. Various lens focal lengths were used and camera position was changed between nose and tail locations. Data were measured in the form of ground contact g and location of touchdown point.

The results indicated that with any of the TV displays the landing quality was inferior to that with either restricted peripheral vision or normal vision; there was greater mean error in ground contact point, but little difference in ground contact g. In general, however, it was concluded that, with practice, consistently good landings can be made with this airplane when forward vision is limited to a closed-circuit TV picture if more use is made of other cockpit instrument readings than is needed for the direct forward vision landings.

INTRODUCTION

The inability to land in all weather conditions creates one of the most serious limitations to the efficient use of civil and military aircraft. Rapid advances in the state of the art of autopilot systems have made automatic landings of aircraft possible in an experimental environment; however, for normal operation the pilot must be provided with a display which will allow him to monitor the landing and possibly to control manually failed or unsatisfactory modes of automatic operation. The requirements of such a display formed the basis of this study to determine whether a pilot could assume full manual control over the final phase of the landing if he were given a contact analog display, such as the one developed in the ANIP program (ref. 1).

Although simulator studies have used projected real world landing displays (ref. 2) and some flight tests have used a television picture (ref. 3) for landing guidance, the degree of degradation in landing performance in terms of contact g and touchdown point under actual flight conditions was still unclear. Therefore, comparative landing tests were made to determine the change in pilot performance between visual landing and contact analog display landings. A closed-circuit television system was installed in a transport aircraft to provide a simple, real world display without color, peripheral vision, or angular parallax cues and with greatly attenuated terrain details. Varying the lens focal length (which produced a selection of magnification ratios) and TV camera location created a range of display parameters to be investigated and compared with landings made with both the pilot's normal vision and peripheral vision reduced by an aperture corresponding to the effective size of the TV display. In addition to providing information for flight display application, the data were expected to provide required information for two-dimensional displays for several all-weather landing simulator studies.

A film is available as an addendum to the report. It indicates the quality of the TV, the presentation to the pilot, and the method of test operation.

EQUIPMENT

An R4D (DC-3) aircraft was used as the test vehicle for this experiment. The two-dimensional displays were produced by the use of a closed circuit TV system with turret-type TV cameras. One camera installed forward of the windscreen (see fig. 1) had three lenses with focal lengths of 12 mm, 25 mm, and 50 mm. These lenses produced wide angle (48.4°), normal (23.2°), and telephoto (10.9°) fields of view, respectively, which resulted in horizontal angular magnifications of 0.34, 0.73, and 1.55 (see fig. 2). Another TV camera with a 12 mm lens was mounted forward of the tail wheel (fig. 3). A TV monitor with a reversed yoke (to correct the picture from right to left) was viewed through a mirror located 10 to 12 inches from the pilot's eye (fig. 4), depending on the position of the pilot's head during approach. The optical distance of the pilot's eye to the 17-inch TV monitor (width of screen 14 in.) was between 46 and 48 inches. This resulted in a visual angle of 16.6° to 17.2°. All other outside visual cues (peripheral) were blanked out by heavy cardboard. The horizontal angle subtended by the display was the maximum possible because of the dimensions of the cockpit and available equipment. In light of previous investigations (refs. 4 and 5), it was felt that there would be little justification for the acquisition of specialized equipment to increase this angle.

The 4-inch square aperture was cut from an aluminum plate which replaced the mirror. The pilot's outside vision was again restricted to only that which could be seen through the opening - a reduced forward horizontal monocular field (fig. 5) ranging from 18.5° to 21.9°. However, if binocular vision is considered, the total horizontal visual angle subtended by the 4-inch width due to the spacing of the eyes varied between 31.6° and 37.6°, while the angle of binocular vision varied between 15.2° and 18.2°.

Landing performance was measured with a Fairchild Flight Analyzer camera and a 16-mm movie camera. An example of the type of picture taken with the flight analyzer camera is shown in figure 6. The touchdown point was determined by a flash bulb which was fired when the oleo strut was compressed 1/8 inch. An accelerometer at the aircraft center of gravity recorded the vertical acceleration at ground contact. This vertical acceleration cannot be readily transformed into vertical speed because of the cushioning effects by both the tires and oleo struts. However, since the quality of landings was compared to those with normal vision this conversion was not felt vital.

In retrospect, a third measure of landing quality would have been desired in the form of a horizontally oriented accelerometer for the purpose of measuring side loads at the time of ground contact. This measurement would indicate how well the pilot was able to: (1) aline his aircraft with the runway, and (2) cancel his drift component.

The touchdown target was a taxiway intersection located 2080 feet from the runway threshold. The flight analyzer and 16-mm movie cameras were located at a point 1992 feet from the runway threshold and 716 feet to the left of the runway center line. The flight analyzer camera covered a possible touchdown distance of ±600 feet from its position while the 16-mm camera covered a distance of ±2500 feet. The combination of camera sequence speed, flash-bulb ignition, distance from the runway, and landing speed produced an accuracy in determining the aircraft ground contact point of ±15 feet at the touchdown target.

TESTS AND PROCEDURES

A series of at least 40 landings were programed for each of the six displays (240 total) including the normal visual landing which was used as the reference (control) display. The test program was flown only when the visibility was greater than 5 miles and the cloud cover was higher than the traffic pattern altitude (at least 1500 feet). Wind conditions varied between 0 - 15K during test flights. The number of landings performed by each pilot is tabulated in table I.

Each flight was conducted in the following manner: The safety pilot made the first landing under normal visual conditions while the subject pilot observed the display. The subject pilot then made five landings using the display being evaluated. The pilots then exchanged positions and the entire procedure was repeated for six more landings. However, when data were gathered for the 4-inch aperture, the pilots felt so at ease with the display, that all five landings were made by the subject pilot without the need for the usual first observation pass to accustom themselves with the new display.

The safety pilot flew the aircraft until it was alined with the runway on a 3° glide path (using the visual mirror glide path system) 2 to 3 miles from the runway threshold. Control was then given to the subject pilot who continued the landing approach through the touchdown phase and rollout.

All approaches were made at 90 knots IAS with flaps up. This was necessary to provide the minimum nose down attitude (and consequently, provide the maximum forward view) when the tail camera was used. The average gross weight during the tests was approximately 25,700 pounds.

Pilots were instructed to attempt to land as close to the target touchdown point as possible, but not to sacrifice smooth contact with the runway for a small error in touchdown distance.

Although an 8-inch aperture (an 8-inch viewing port similar to the 4 inch) was also used in the initial stages of the study, the pilots were unanimous in their opinion that the difference between the 8-inch opening and normal vision during final approach and landing was negligible. For this reason, landings with the 8-inch aperture were discontinued.

RESULTS AND DISCUSSION

Performance Data

The problem of finding the field and starting the final approach was not studied since the electronic navigation equipment in use today is capable of satisfactorily positioning an aircraft on a low angle (approximately 3°) approach path to within 300 feet of the ground, and since azimuth guidance, in some cases, is satisfactory to ground contact. Therefore the task only included the final approach and landing, starting from a point 2 to 3 miles from the runway.

Pilot performance was based on two criteria - ground contact g and the distance of the actual ground contact point from the desired touchdown point. Since these appear to be independent variables, any assessment of landing quality requires that both criteria be considered. For example, if a landing were made essentially at the desired contact point, but the g load was significantly high, the over-all quality would be judged poorer than another landing in which the contact point was the same but the g level was lower. Performance with each display is shown in table II and figure 7. The mean values for touchdown error and contact g as well as the values for standard deviation for touchdown error and contact g are shown for each display. These were then compared to the normal visual case. With the exception of the 4-inch aperture, all of the values for standard deviation of touchdown error were significant within a confidence level of 2 percent ("F" test).[1] However, none of the standard deviation values for touchdown g show significant difference to a confidence level of 10 percent. Analysis of the mean touchdown error ("T" test)[1] indicated a significant difference between all the TV type landings and the normal visual approach. However, using the 4-inch aperture or normal vision made no significant difference in the mean touchdown error.

The average absolute touchdown error is just the average miss distance regardless of sign. The number of landings completed with each display is also shown. The "go-arounds" were not classified as landings and are therefore indicated under a separate column. Only nine go-arounds were required. These occurred with either the wide-angle or normal lens used on the nose camera or with the wide-angle lens on the tail camera. The results shown in Table II substantiate previous studies (refs. 7 and 8) which indicate that

[1]Reference 6 or any standard text in statistics

there is little difference between the landing performance under normal visual conditions and with restricted peripheral vision, provided the task begins on final approach. These data further expand the conclusions reached in reference 7 to include not only satisfactory touchdown error, but contact g as well. It should further be noted that the display in this study differed from that of reference 7 in that not only was color removed but clarity was reduced,[2] and still landing performance was satisfactory. An additional interesting observation is that there is no indication of the gradual deterioration of pilot performance due to fatigue while landing with restricted peripheral vision. This appears to be in conflict with the findings of reference 8. However, this might be explained by the fact that the pilots never made over six landings each on any one flight. Also, the maximum number of flights in one day was limited to two. Therefore, it is possible that the level of pilot fatigue referred to in reference 8 was never reached.

The general statement which can be made concerning table II and figure 7 is that the average error in touchdown point, when camera is in the nose position, varies directly with the focal length of the lens. Both the standard deviation and the mean of the touchdown distance increase as the focal length of the lens increases. However, if contact g as well as touchdown error is included in the assessment, one must consider that the average contact g was less with the telephoto lens than with normal vision. Only the tail camera produced a lower mean contact g. It should also be noted that the telephoto lens display produced the most consistent contact g of all the displays evaluated which supports the pilot comments in a later section regarding precise height-rate control.

Figures 8(a) through 8(f) are a plot of touchdown points from the touchdown target in the long (positive) and short (negative) directions versus contact g for each display. Touchdown points greater or less than 1600 feet were plotted at the +1600 and -1600 feet points, respectively. However, actual values for these points were used in the statistical computations. The figures indicate a lack of correlation between the two variables used as criteria for touchdown quality.

The two variables were then plotted separately versus consecutive landings to determine whether the pilots were learning between displays (figs. 9(a) through 9(d)). In general, they did not.

Figures 10(a) through 10(f) indicate individual pilot performance in terms of the two criteria for each display. The landings are plotted consecutively for each pilot. A general narrowing of the band of points would indicate a slight amount of learning between displays for individual pilots. The normal landings by pilot B, for example (fig. 9(b)), apparently indicate a slight learning tendency insofar as touchdown miss distance is concerned. The lack of a rise in the contact g during this time indicates there was no attempt to "spike" the aircraft on the ground at the desired touchdown point, and therefore a general increase in over-all touchdown quality exists. All other pilots demonstrated a rather constant quality during their normal visual approaches.

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[2]A supplementary 16-mm movie with portions recorded from the TV screen during actual approaches is available for more information.

The data in figure 10(b) seem to indicate a slight learning tendency for all pilots while using the 4-inch aperture. This is indicated by the decreasing touchdown miss distance while simultaneously lowering or holding constant the contact g. (Pilot A's contribution to this series was negligible.) Three "go-arounds" occurred early in the program. During the first three landing attempts by each pilot two out of the four pilots found it necessary to abort the landing approach at least once. The widest standard deviation of the touchdown points, as well as the largest mean miss distance (which was approximately 2-1/2 times greater than the mean miss distance for the normal visual landing), was recorded when the tail camera was used. However, the lowest mean contact g during the study was obtained from the data recorded with this display.

Pilot Comments

The pilot comments are grouped as follows: (1) approach phase, and (2) flare and touchdown phase. Pertinent pilot comments are discussed concerning all five displays during both phases.

Approach (2 miles to 1/4 mile from threshold).- With all TV displays, because of the lack of height and height-rate information, an attempt was made to hold power, airspeed, and rate-of-sink constant. This required a cross check between the TV display, the altimeter, rate-of-climb, and airspeed instruments. In contrast to this procedure, only the airspeed and rate-of-climb instruments were used in addition to the 4-inch aperture, and only the airspeed instrument was used while making a normal visual approach.

Telephoto lens: Because of its effect of increasing the scale of the display, the telephoto lens was rated as the most effective display for runway line-up and precise attitude control. It makes the apparent point of runway contact quite obvious and accentuates lateral displacement and angular rates, resulting in a tighter control of the aircraft position and attitude. However, the telephoto lens also increases the apparent height above the ground causing an initial tendency to fly a very flat approach but this tendency was alleviated by learning.

Normal and wide angle lens: These lenses initially caused the pilots to fly a steeper approach path. Because of the small scale factors, large deviations occurred in both lateral position and attitude before they became apparent to the pilot. Consequently, large corrections were necessary in heading and these caused a more oscillatory flight path than any of the other test displays. This was true when the wide angle lens was used at both the nose and tail positions. The absence of height and height rate information was most apparent at altitudes above 100 feet. It was felt that there was little difference between the wide angle lens and the normal lens and the pilot comments, in general, grouped these two lenses together.

Tail camera: The tail camera position was only marginally satisfactory on glide path because the attitude of the aircraft limited the forward view.

During the approach on a 3° glide path, the horizon was obscured by the fuselage and wing. If the airspeed increased above 95 knots, the attitude obscured the runway threshold. This, however, did provide the pilot with an effective airspeed control cue. When a combination of sun position and cloud cover were such that the shadow of the aircraft could be seen while on final approach, the camera could be used to track an extension of the runway center line quite effectively. Another method of maintaining lateral position was to use a reference point (antenna loop housing) on the forward part of the fuselage underside as a "forward sighting point." This method of tracking made it possible to detect heading changes of $1/2^{\circ}$ or less in smooth air.[3]

Four-inch aperture: There was little difference between the ability to control the aircraft during a normal visual approach and while vision was restricted to the 4-inch aperture. However, during the initial part of the study the reduced peripheral field caused the pilots to judge their height as being greater than it actually was.

Flare and touchdown.- Compared to the normal visual case, landings made with all the TV displays impaired the pilots ability to judge height during the initial portion of the flare maneuver. Between flare and touchdown, the pilots felt that there was little difference between the lenses as far as their ability to perform the landing task was concerned. Of interest was pilot D's ability to detect an audio cue (a change in propeller noise) the instant before touchdown.

Telephoto lens: Because of the relatively good rate information (height rate, attitude rate, etc.) provided by this lens, smooth flares and touchdowns were readily achieved. The foreshortening and magnification distorted the height information; however, the general consensus was that this problem was largely overcome as the pilots gained experience with the display. Additionally, cross winds sometimes required a "crab" which was large enough to cause the camera to "lose sight" of the runway.

Normal and wide angle lens: During the flare and touchdown there was very little difference between the picture obtained with the normal and wide angle lenses and that obtained with the telephoto lens.

Tail camera: Judging the height and height rate information is greatly facilitated if the shadow of the aircraft or wheels are visible on the ground (less than 10-feet altitude). However, at this point in the flight path, changes in pitch sometimes caused a conflict between the kinesthetic senses and the visual display. This can be attributed to the pilot and camera being located at opposite sides of the aircraft center of gravity which causes an initial disparity between the display motion and pitch control motion. There was also a tendency to overcontrol while using the tail camera, since the sink rate, when viewed from the tail, tends to remain constant or increase when "up elevator" is applied and conversely to remain constant or decrease when "down elevator" is applied.

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[3]Nine mils (0.82 inch on the pilot's monitor)

Four-inch aperture: Flare, flare height judgment, and cross-wind control were approximately the same as with the full view windscreen. In general, it was felt that this display provided essentially the same information as the normal full vision case.

CONCLUSIONS

A landing study was performed to evaluate pilot performance while landing with a closed circuit TV system and to compare it with his performance while landing under normal visual conditions. A comparison was also made with his performance when landing with restricted peripheral vision. It was concluded that:

1. It is possible to perform the landing task in an R4D using a two-dimensional display within the limits for touchdown error and contact g generally accepted by pilots as being safe for a normal visual landing. In fact, there was no significant difference in mean contact g between any of the displays.

2. The effect of scaling and foreshortening, produced by changing the focal length of the TV camera lens, appeared to be one of the most important factors controlling the basic cues used by the pilot during the landing task. The longer focal length lens enabled the pilot to control the aircraft more precisely during approach and roundout due to the effect of increased "gain" (optical magnification) of aircraft response, even at the expense of a decreased angle of view.

3. Pilot comments indicate that the elements of the display should respond in such a manner so as not to cause a conflict between the kinesthetic and the normal visual senses. This is brought out in the case of the tail camera, which produced opposite changes in the height indication on the display whenever aircraft pitch changes were performed close to the ground.

4. The restriction of peripheral vision to that within the limits of the 4-inch aperture had very little effect on performance once the runway was in sight and the approach was initiated.

5. Pilot comments indicated that a contact analog display of the size and clarity of the type used in this experiment required additional quantitative information for height and height rate before it would be acceptable for an all-weather landing instrument. This is brought out by the needs for continuous use of the altimeter and rate-of-climb instrument during the approach and flare phase of the task.

6. The data and pilot comments suggest a possible idealized display as having an acceptance angle of at least 45° with height, height rate, and displacement information superimposed and having a gain similar to that obtained with the telephoto lens (1.55 magnification ratio).

Ames Research Center
National Aeronautics and Space Administration
Moffett Field, Calif., Jan. 21, 1964

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TABLE I.- INDIVIDUAL PILOT PARTICIPATION

Display	Pilot				Total landings
	A	B	C	D	
Normal	9	9	15	10	43
4 inch	2	7	20	13	42
Nose 12 mm	15	14	14	0	43
Nose 25 mm	5	3	13	20	41
Nose 50 mm	9	9	9	10	37
Tail 12 mm	10	5	13	10	38
Total	50	47	84	63	244

TABLE II.- STATISTICAL DATA BY DISPLAY

Display	Standard deviation touchdown error, ft	Average touchdown error, ft	Absolute touchdown error, ft	Standard deviation contact g	Mean contact g	Number of landings	Aborted landings
Normal	373	-90	270	0.159	0.339	43	0
4 inch aperture	426	-132	284	.141	.341	42	0
Nose 12 mm	479	159	395	.175	.378	43	2
Nose 25 mm	652	59	518	.205	.396	41	4
Nose 50 mm	726	-126	542	.130	.326	37	0
Tail 12 mm	764	270	607	.159	.321	38	3

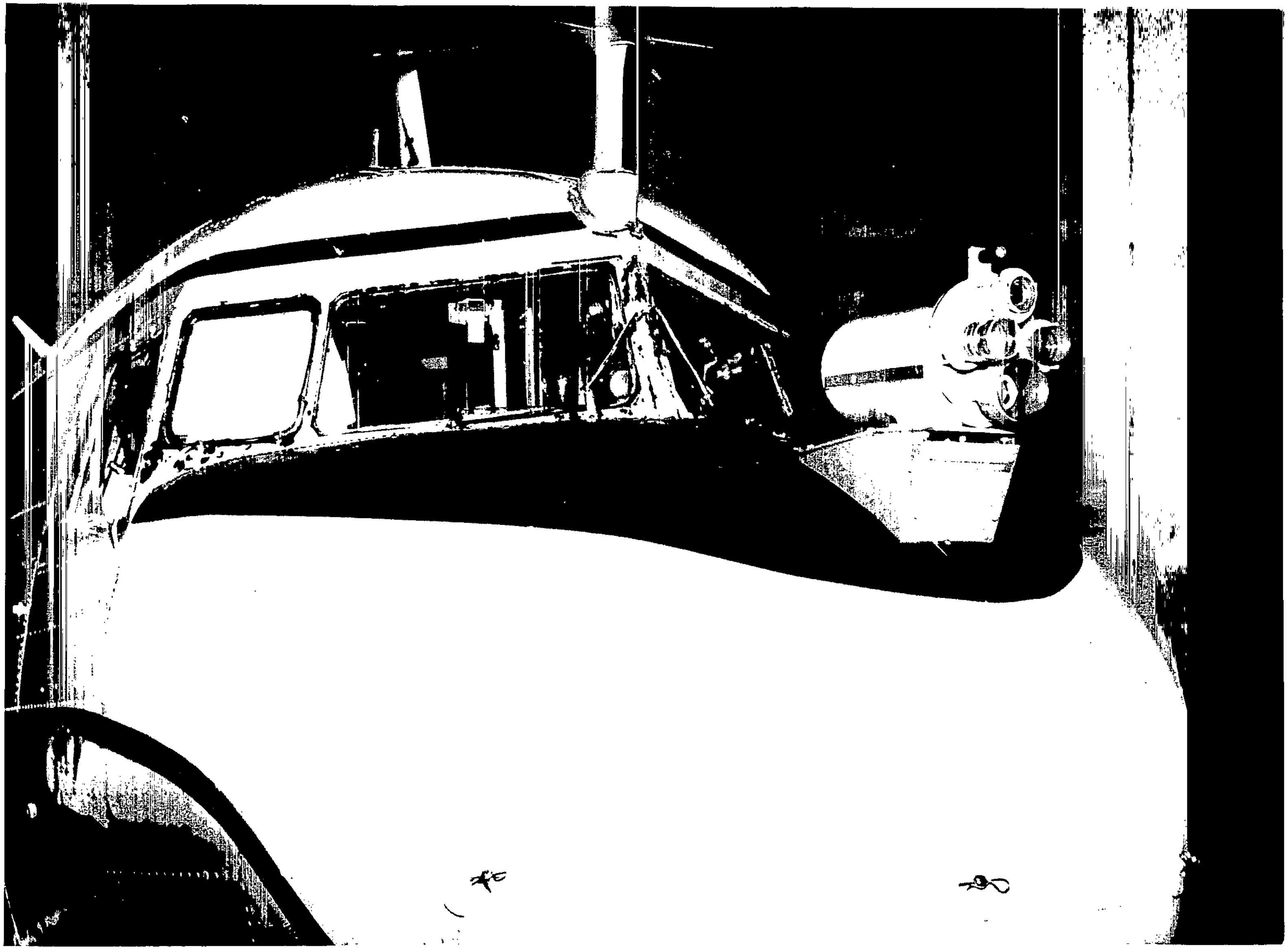

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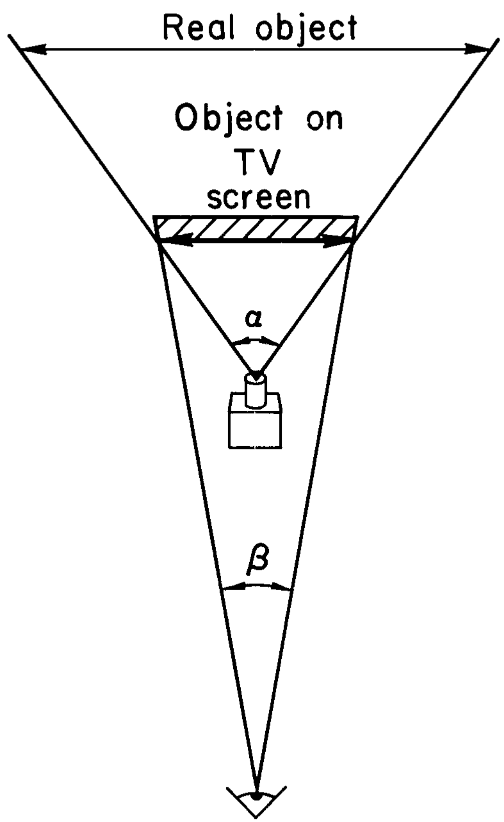
Figure 1.- Location of forward TV camera on test aircraft.



Angular magnification $\equiv (\beta/\alpha)$

Where: α = Horizontal angle subtended by real object at camera lens

β = Horizontal angle subtended by object image (appearing on TV screen) at viewers eye

Lens	Angle	Angular magnification (β/α)
12 mm	48.4°	0.34
25 mm	23.2°	0.73
50 mm	10.9°	1.55

Figure 2.- Schematic illustration of TV magnification ratios.

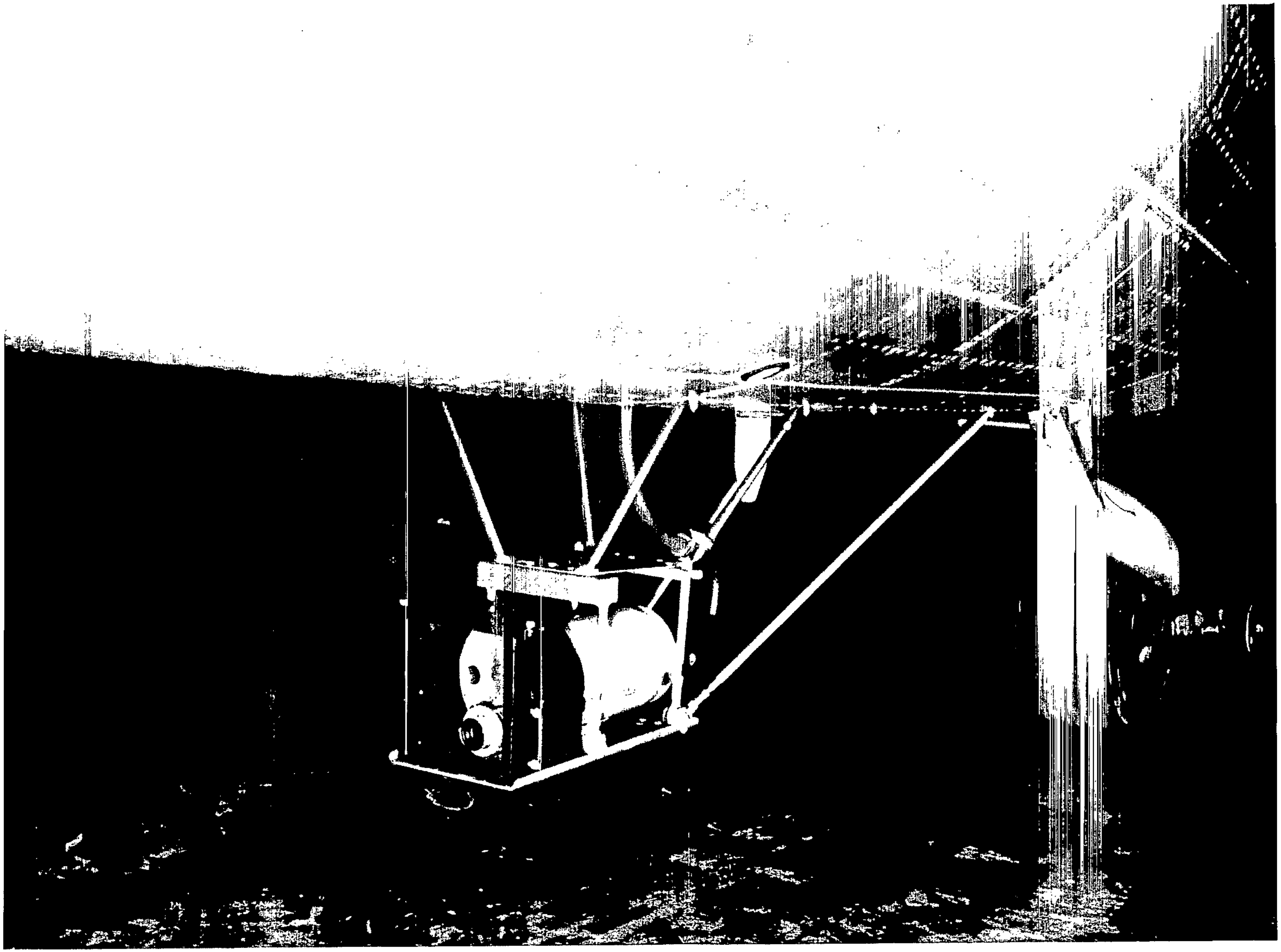


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Figure 3.- Location of tail TV camera.

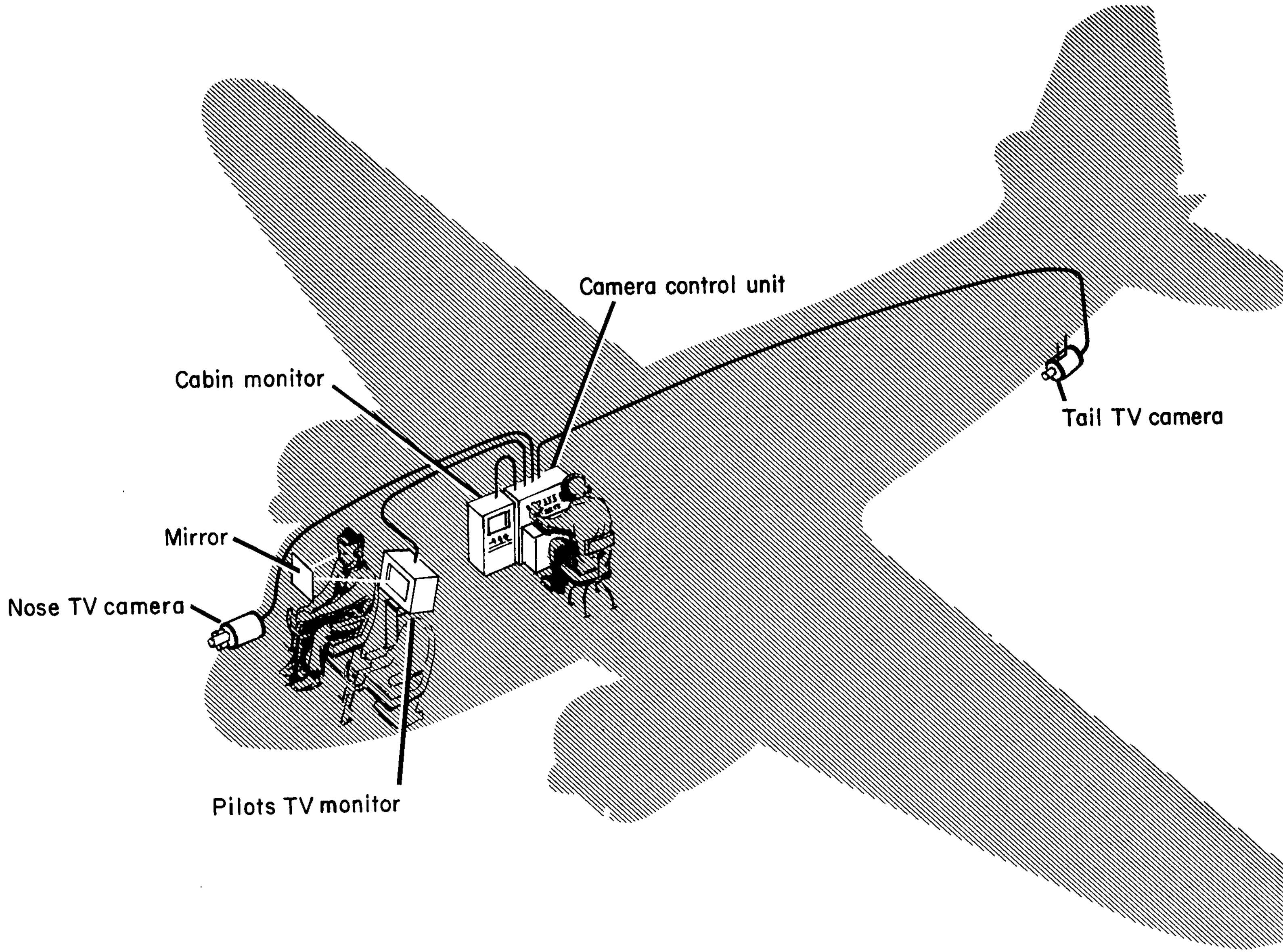


Figure 4.- Diagram of test equipment location.

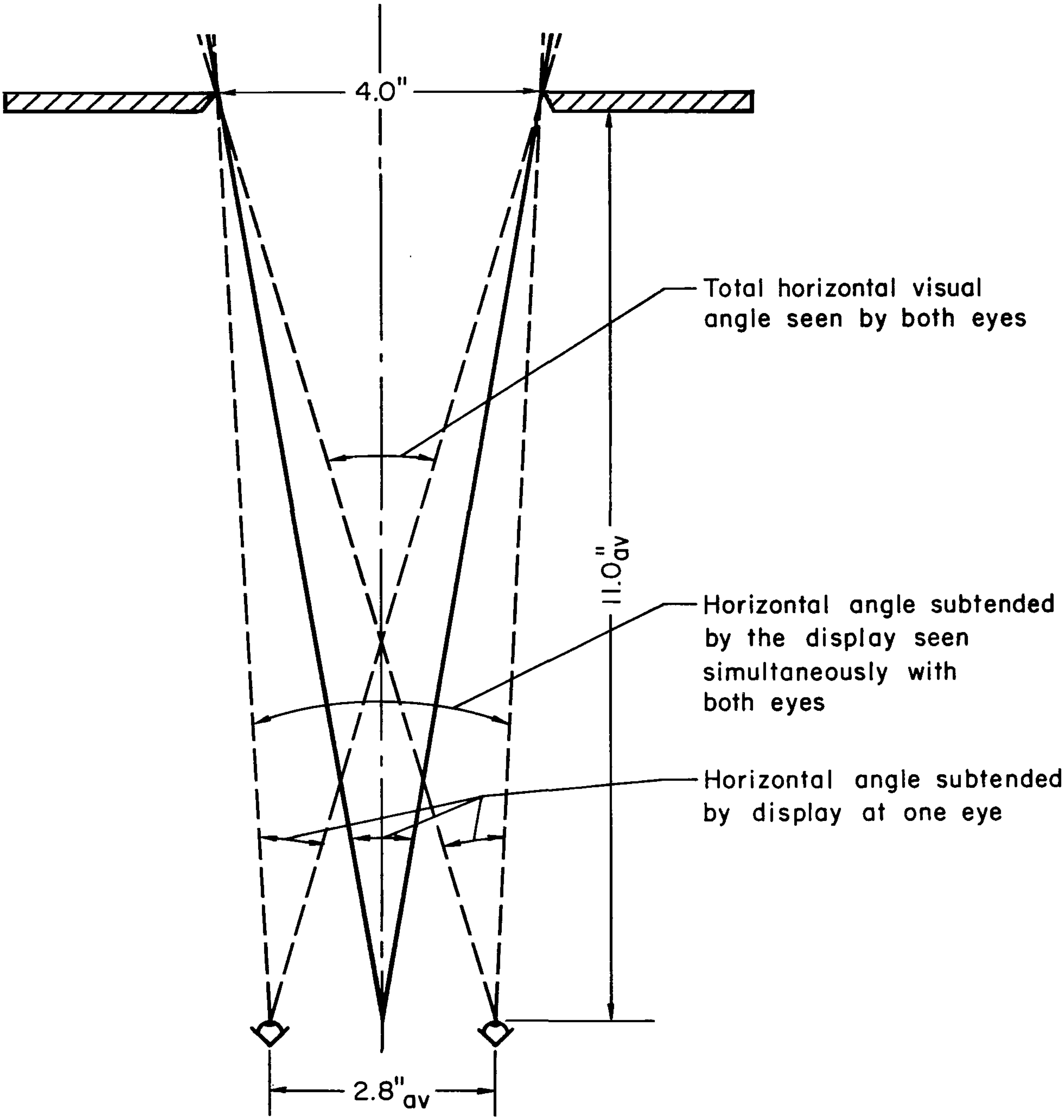


Figure 5.- Diagram of visual angles subtended by 4-inch aperture.

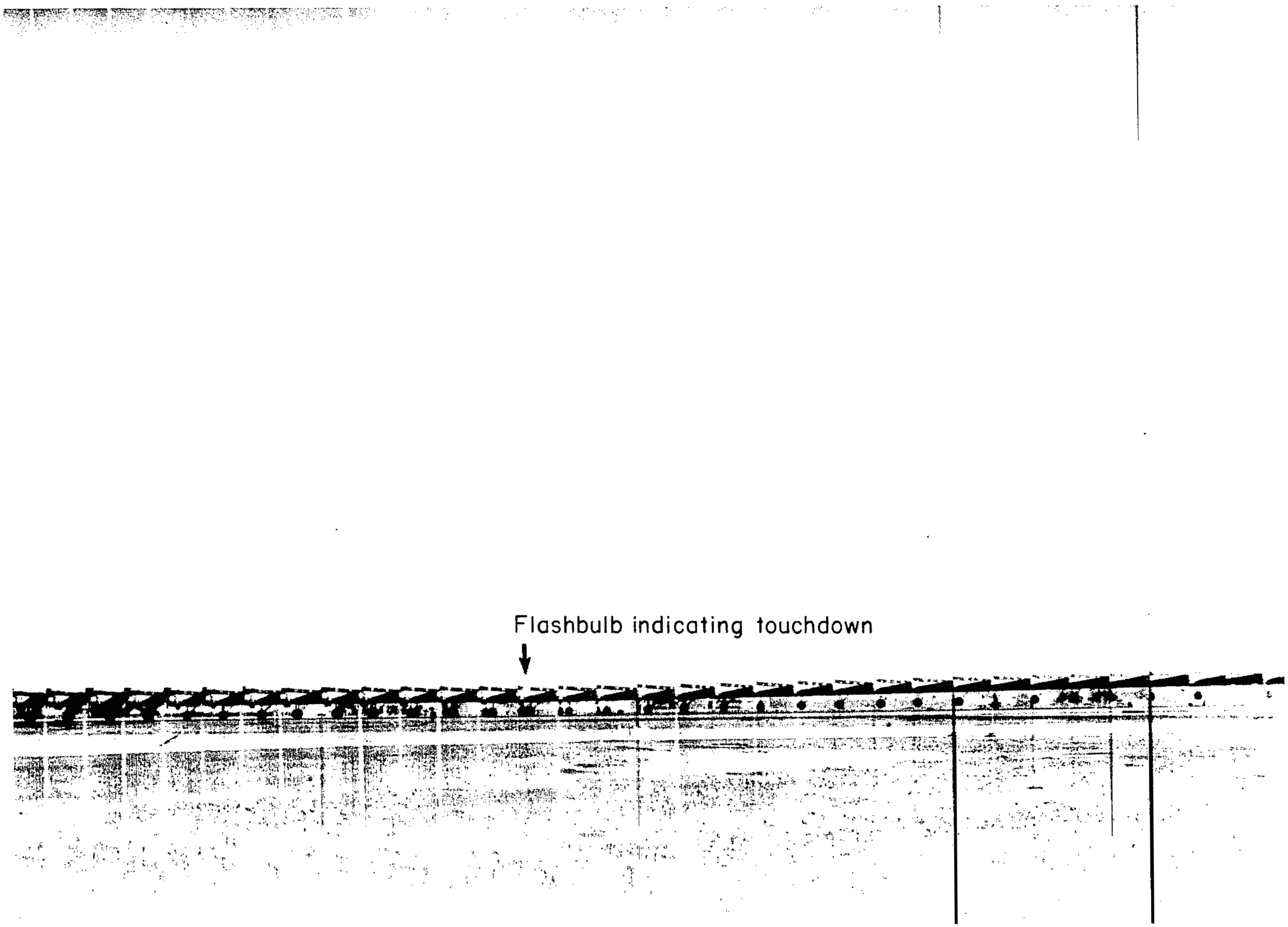


Figure 6.- Example of flight analyzer picture.

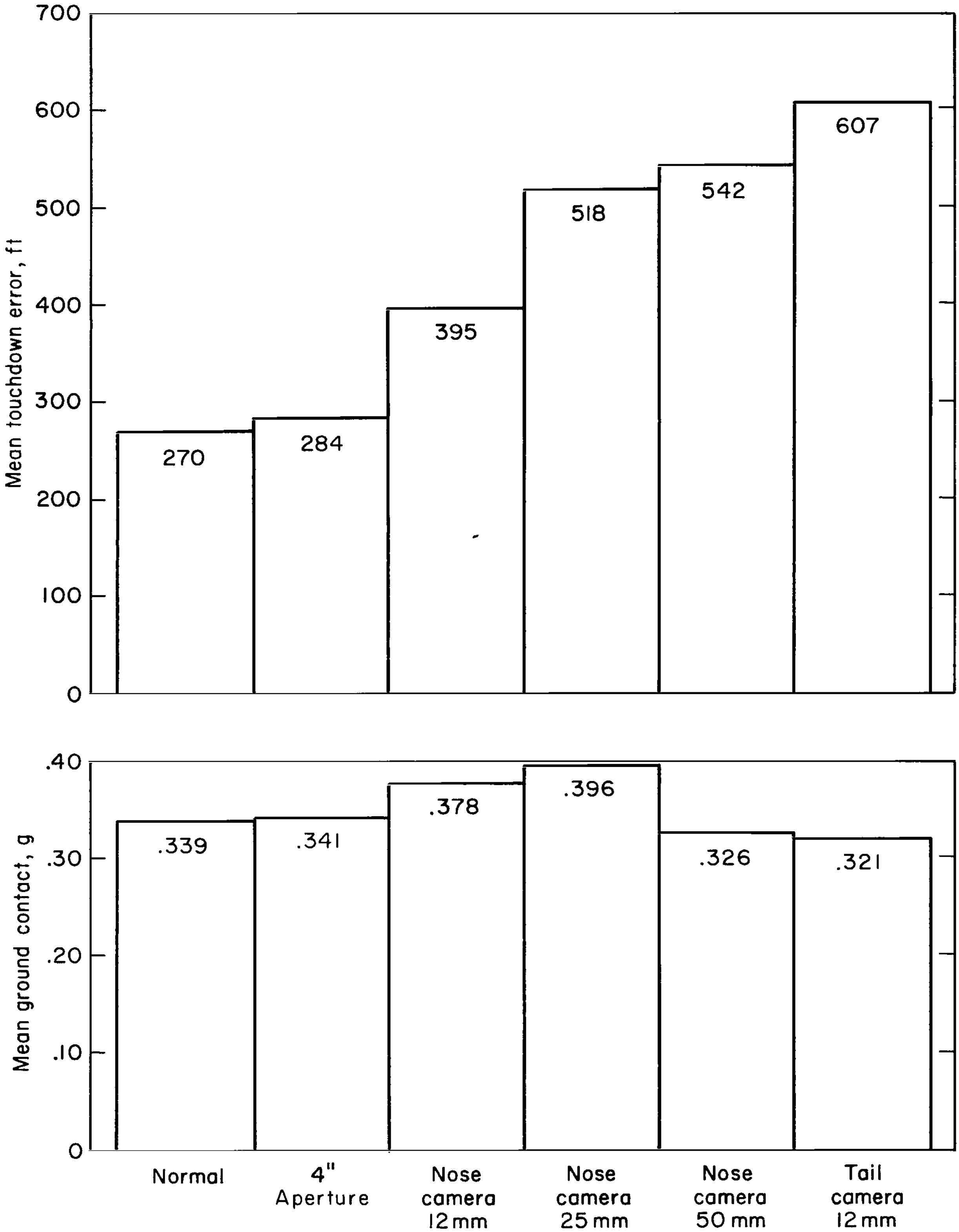
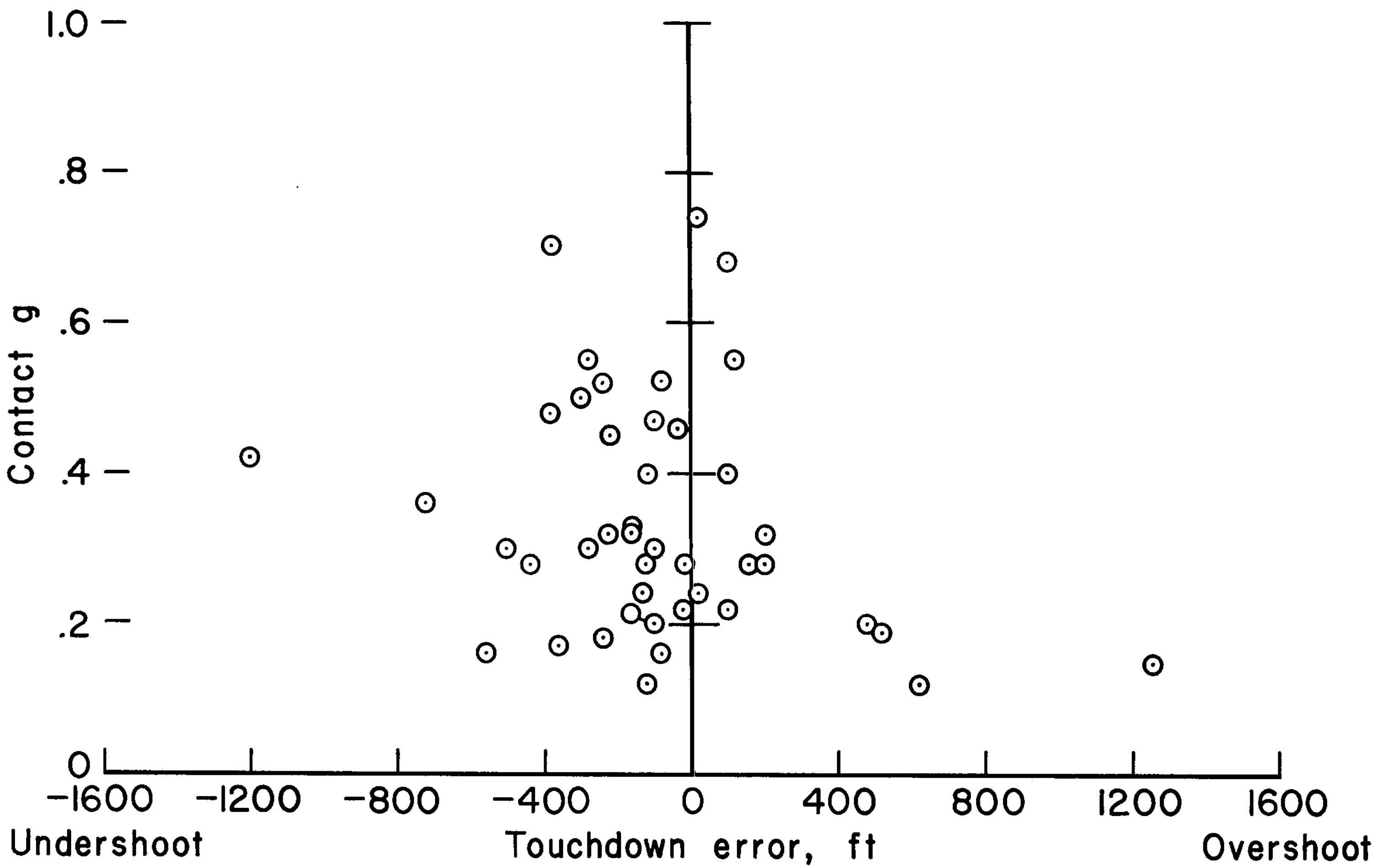
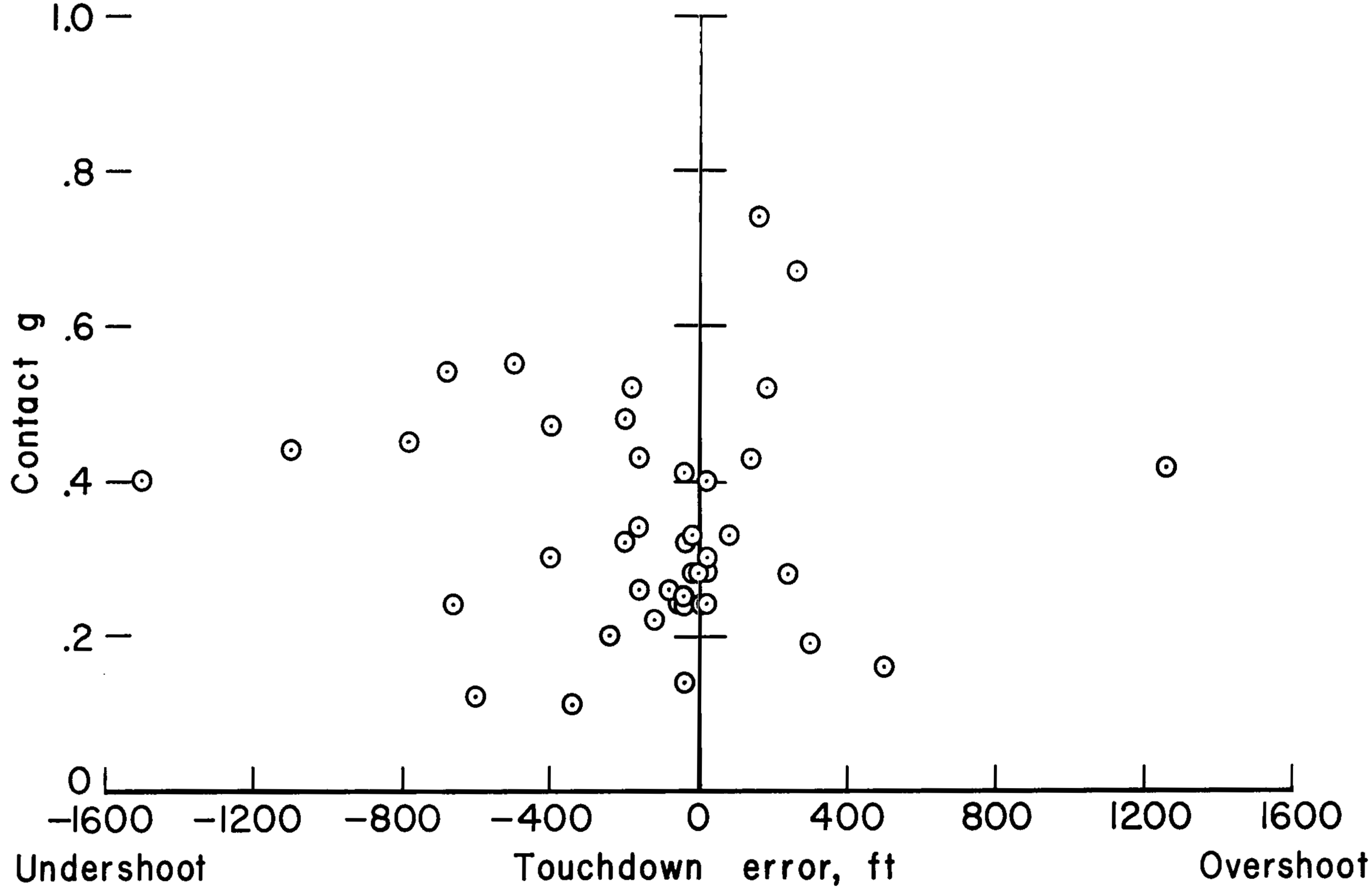


Figure 7.- Comparative mean values for touchdown error and contact g.



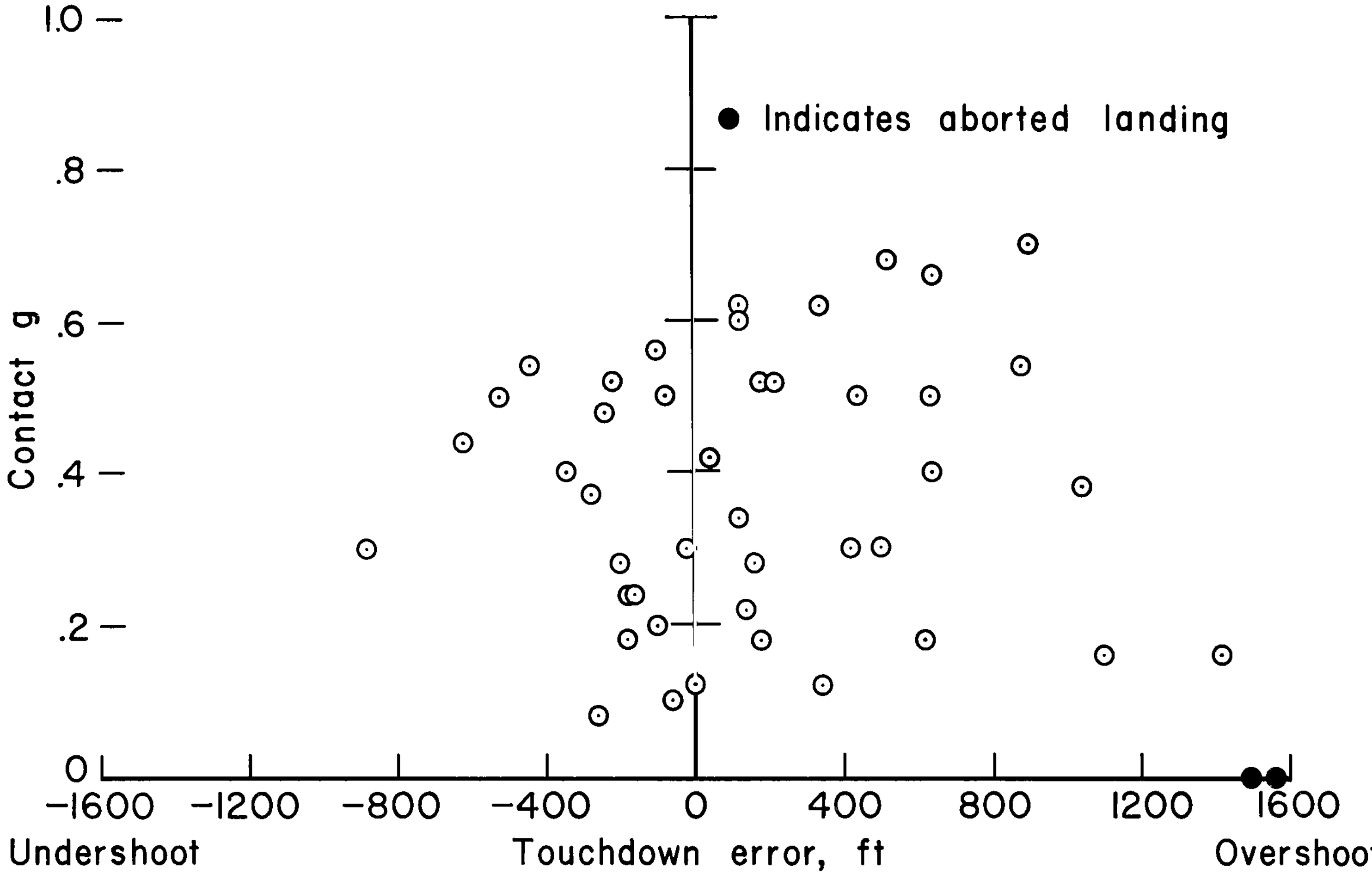
(a) Normal visual landings.

Figure 8.- Comparison of contact g with touchdown error.



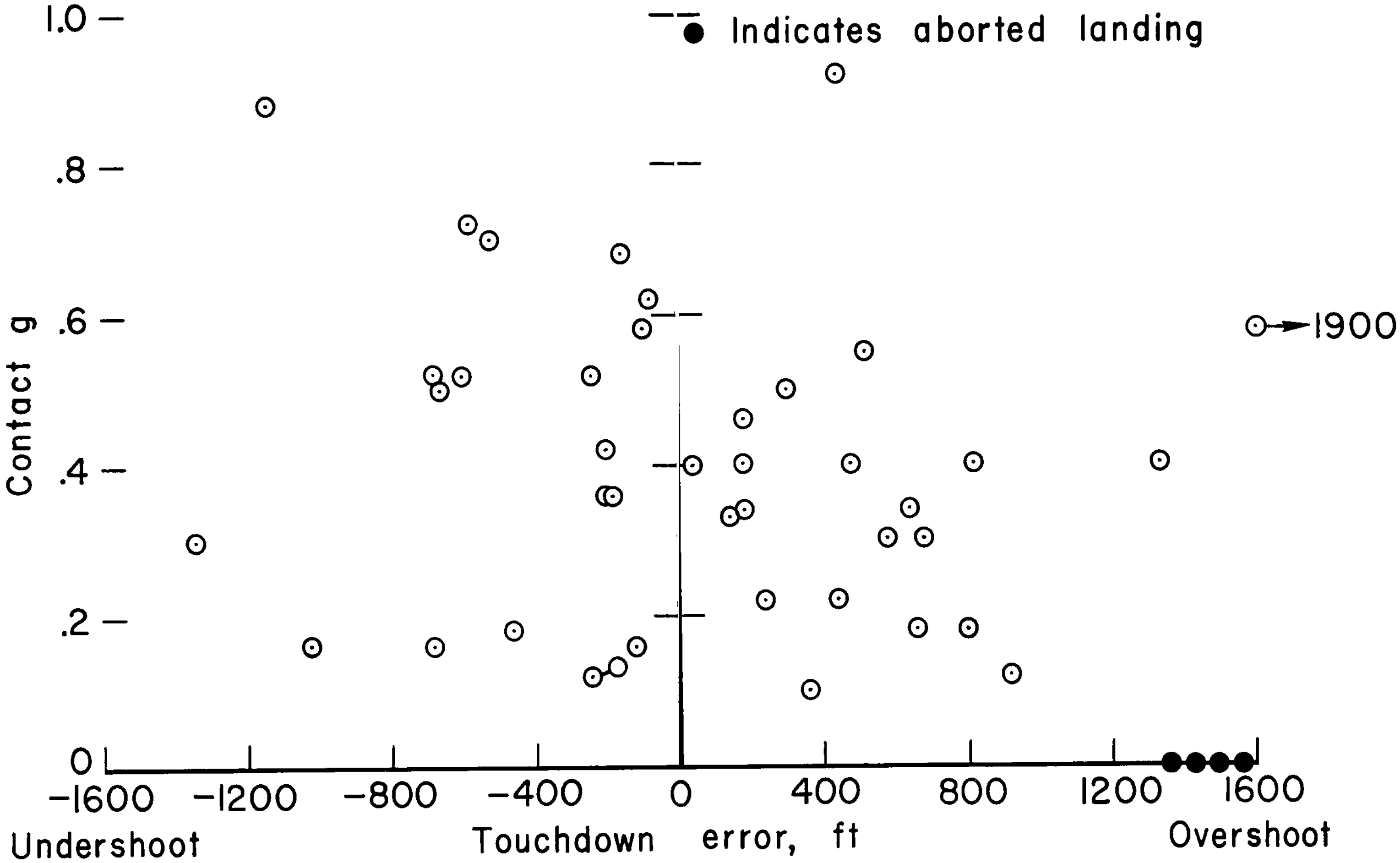
(b) 4-inch aperture landings.

Figure 8.- Continued.



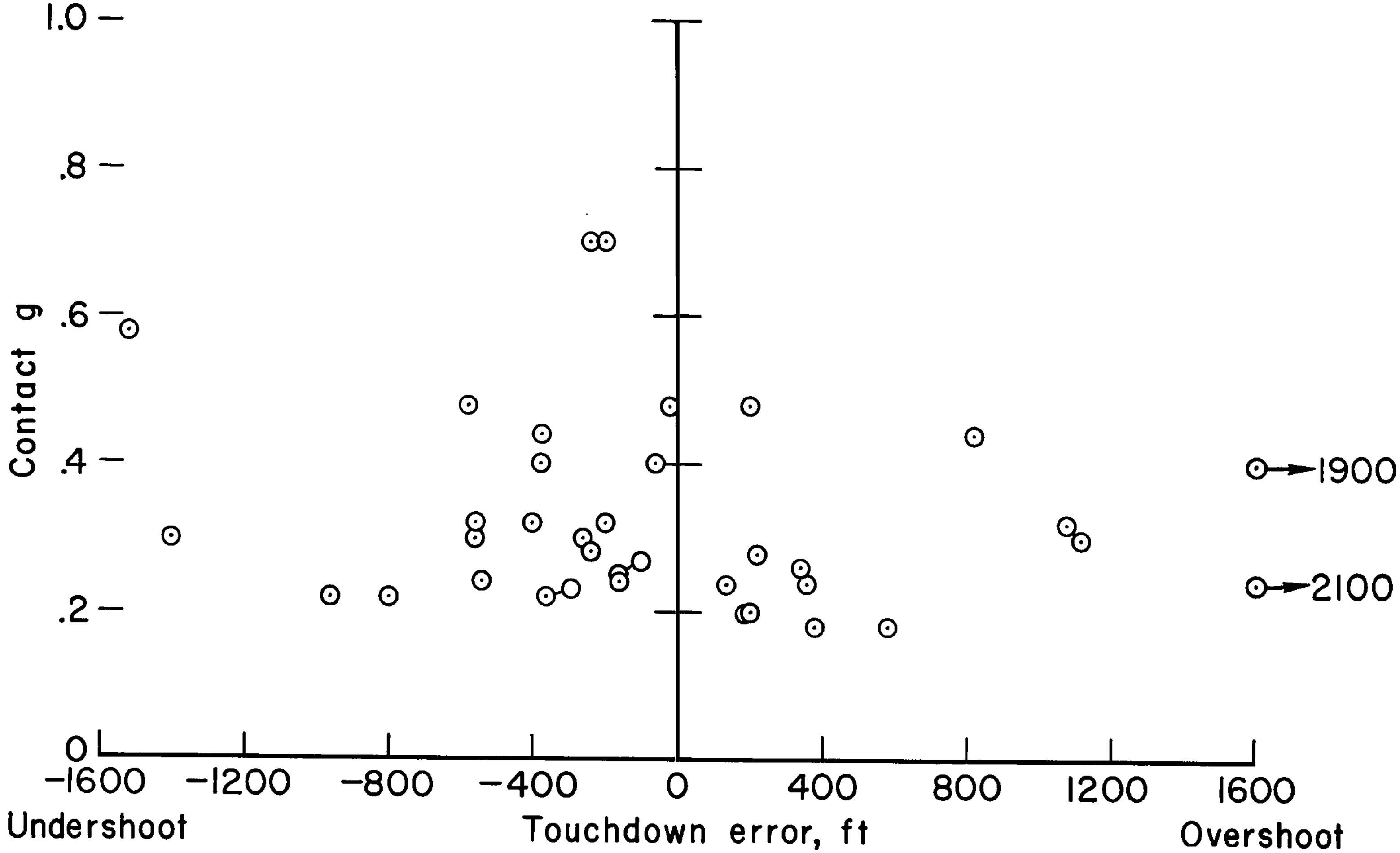
(c) Nose camera (12 mm lens) 48° visual angle.

Figure 8.- Continued.



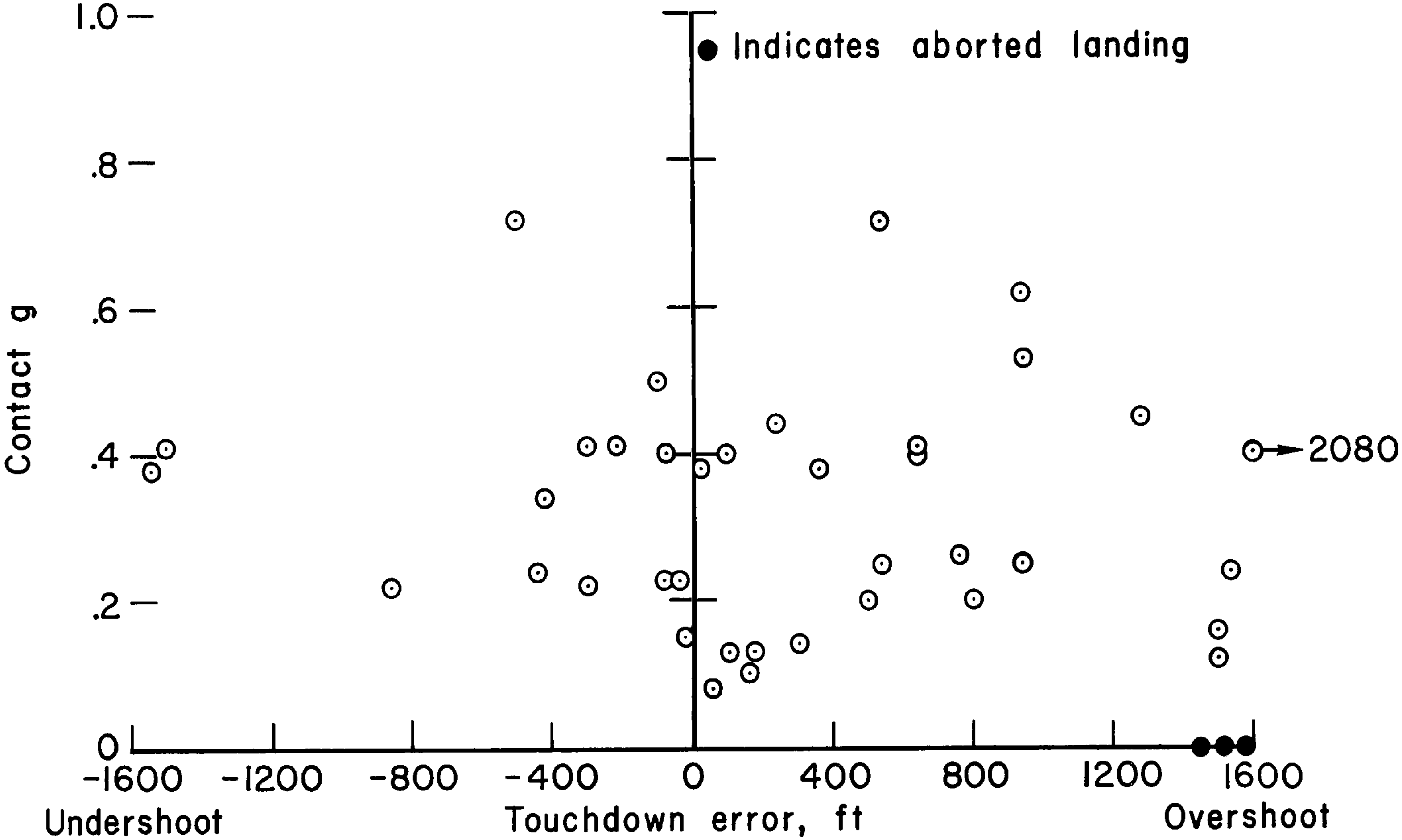
(d) Nose camera (25 mm lens) 23° visual angle.

Figure 8.- Continued.



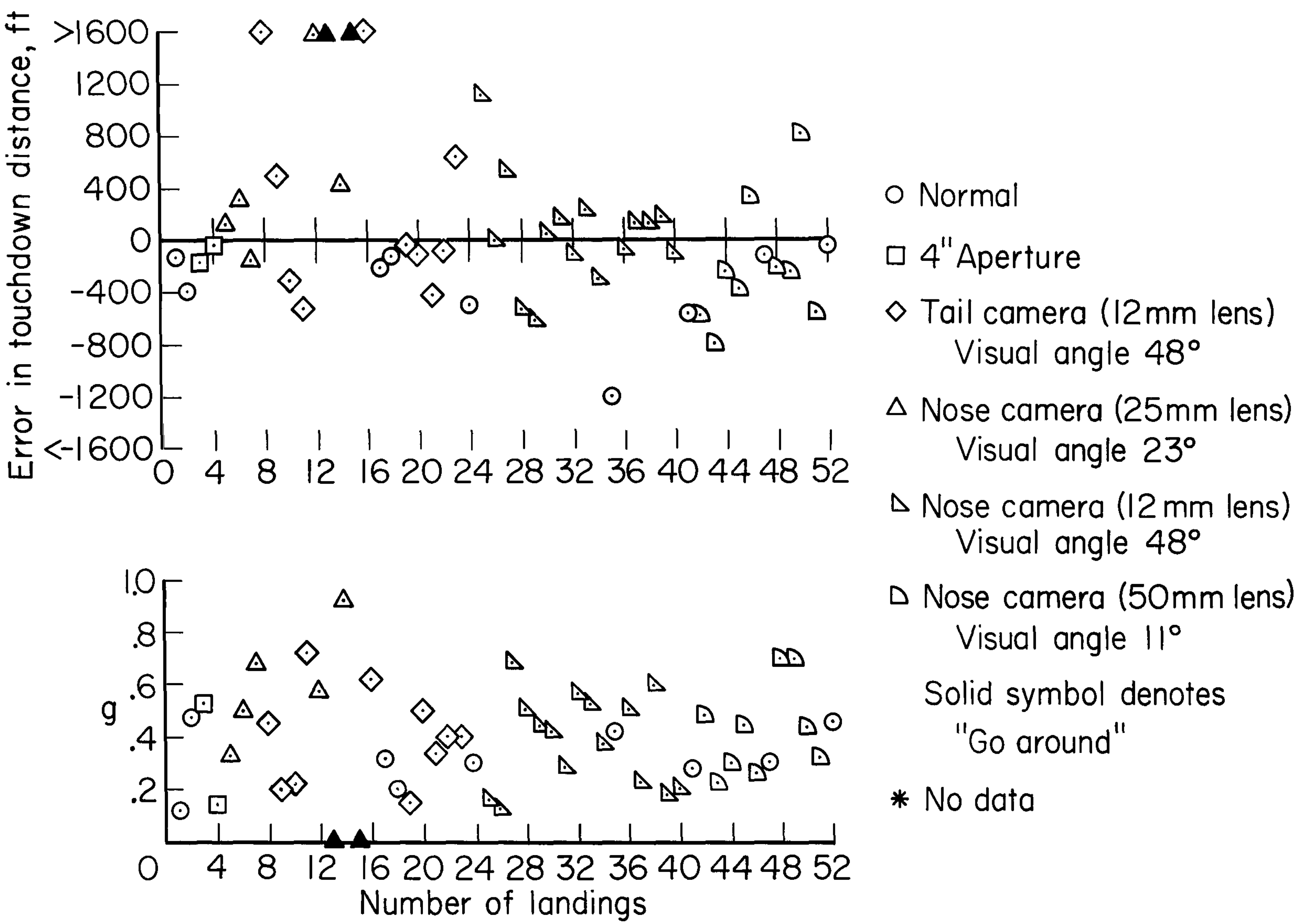
(e) Nose camera (50 mm lens) 11° visual angle.

Figure 8.- Continued.



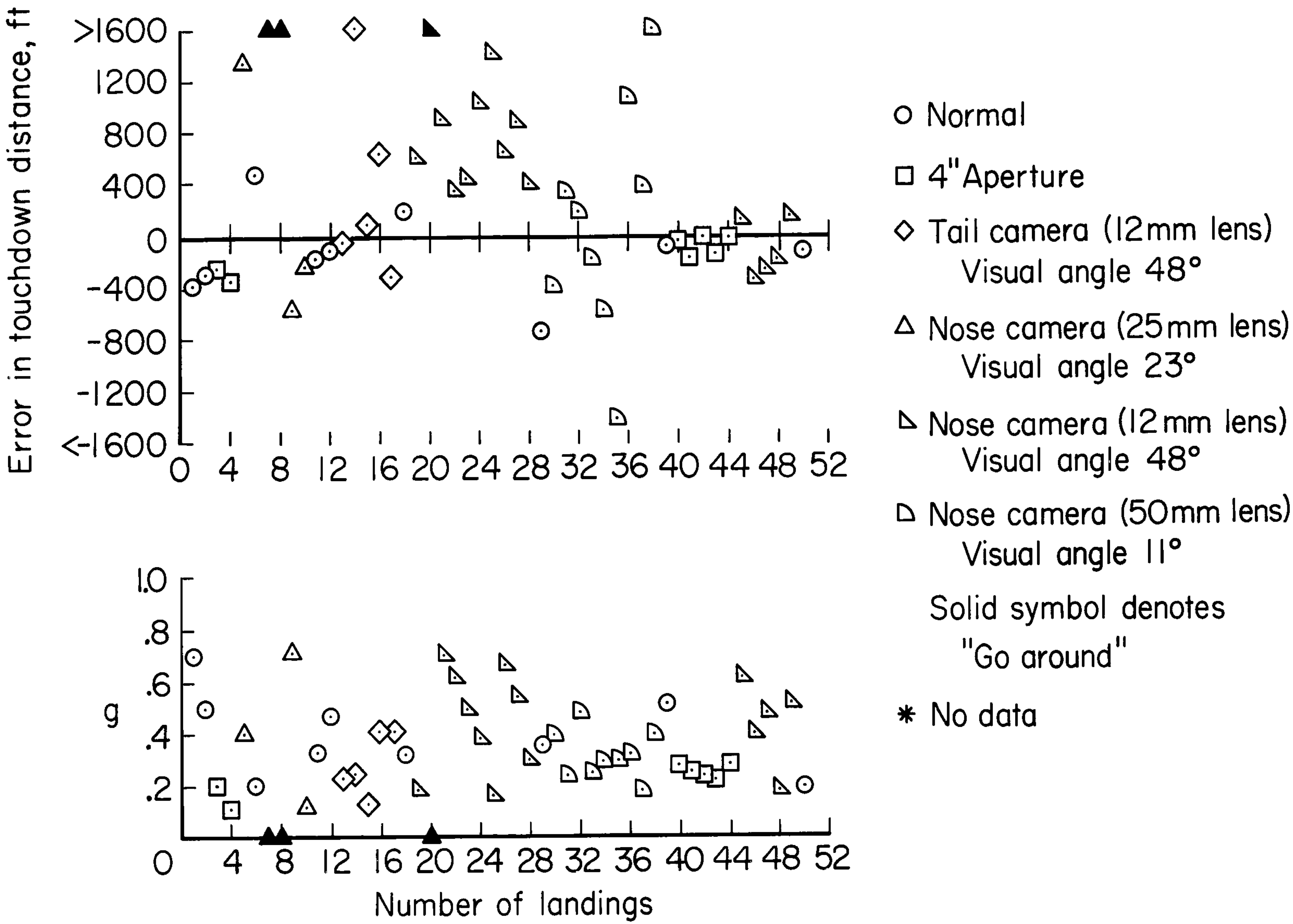
(f) Tail camera (12 mm lens) 48° visual angle.

Figure 8.- Concluded.



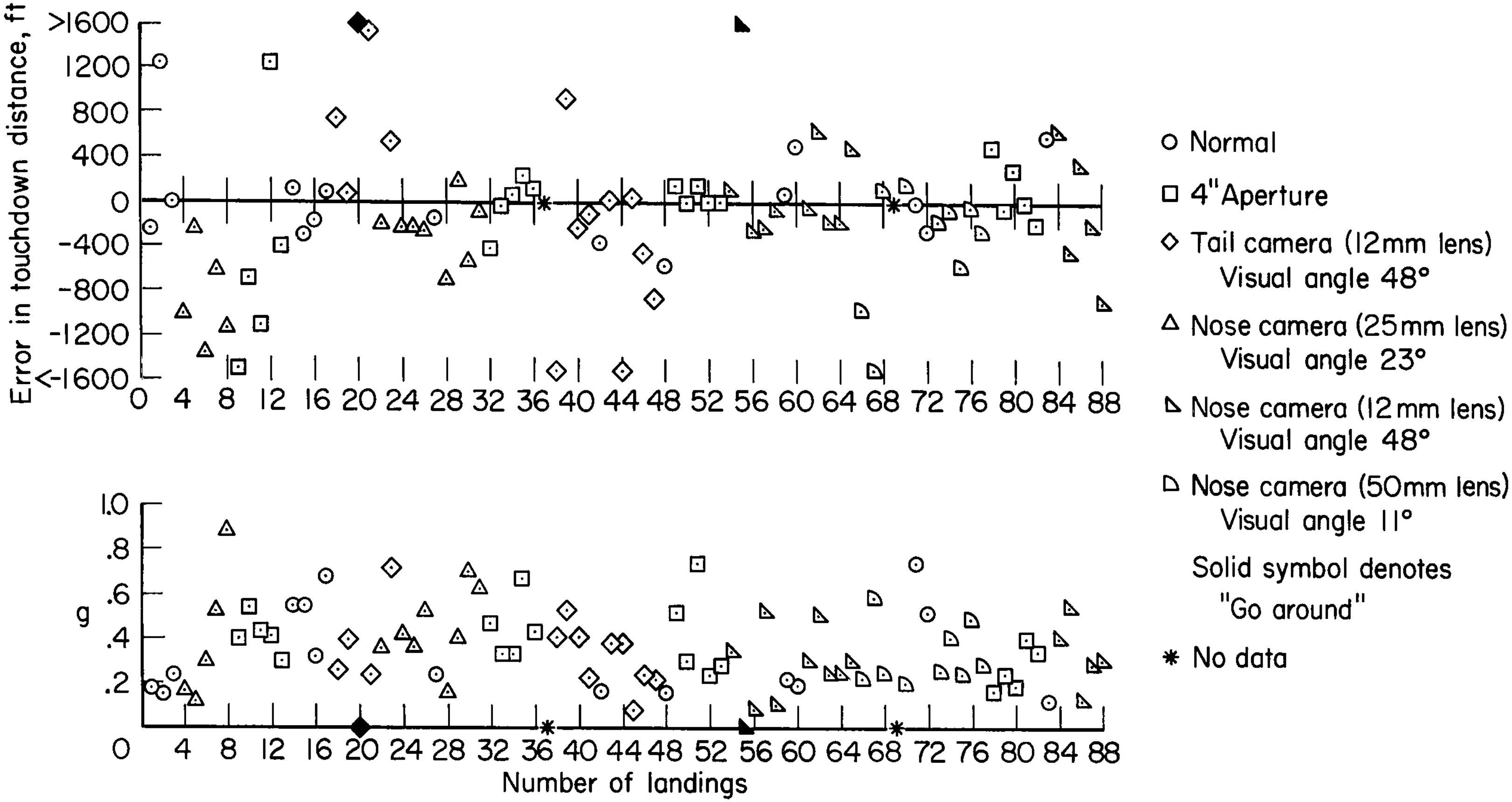
(a) Pilot A.

Figure 9.- Individual pilot performance history during entire program.



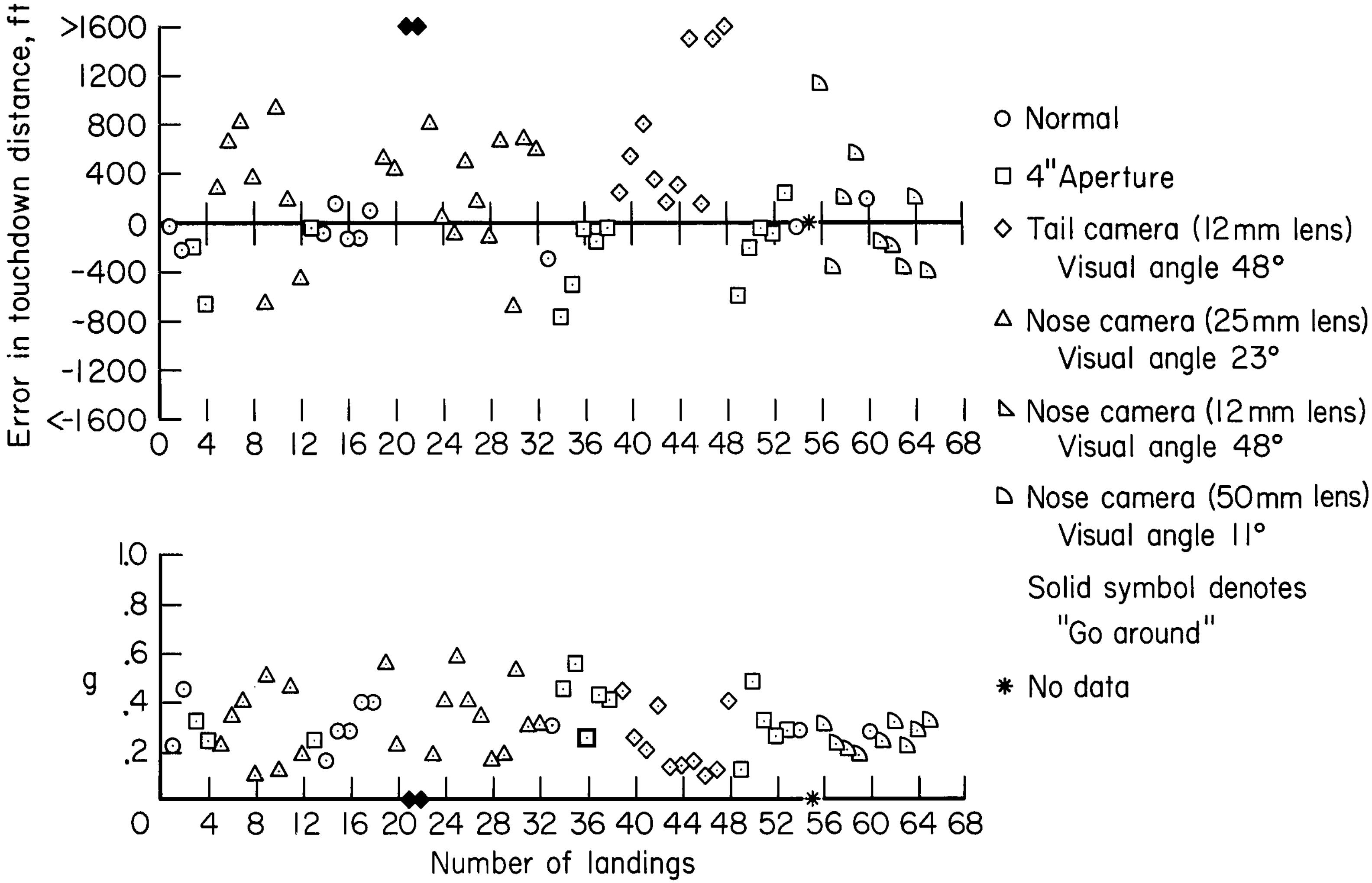
(b) Pilot B.

Figure 9.- Continued.



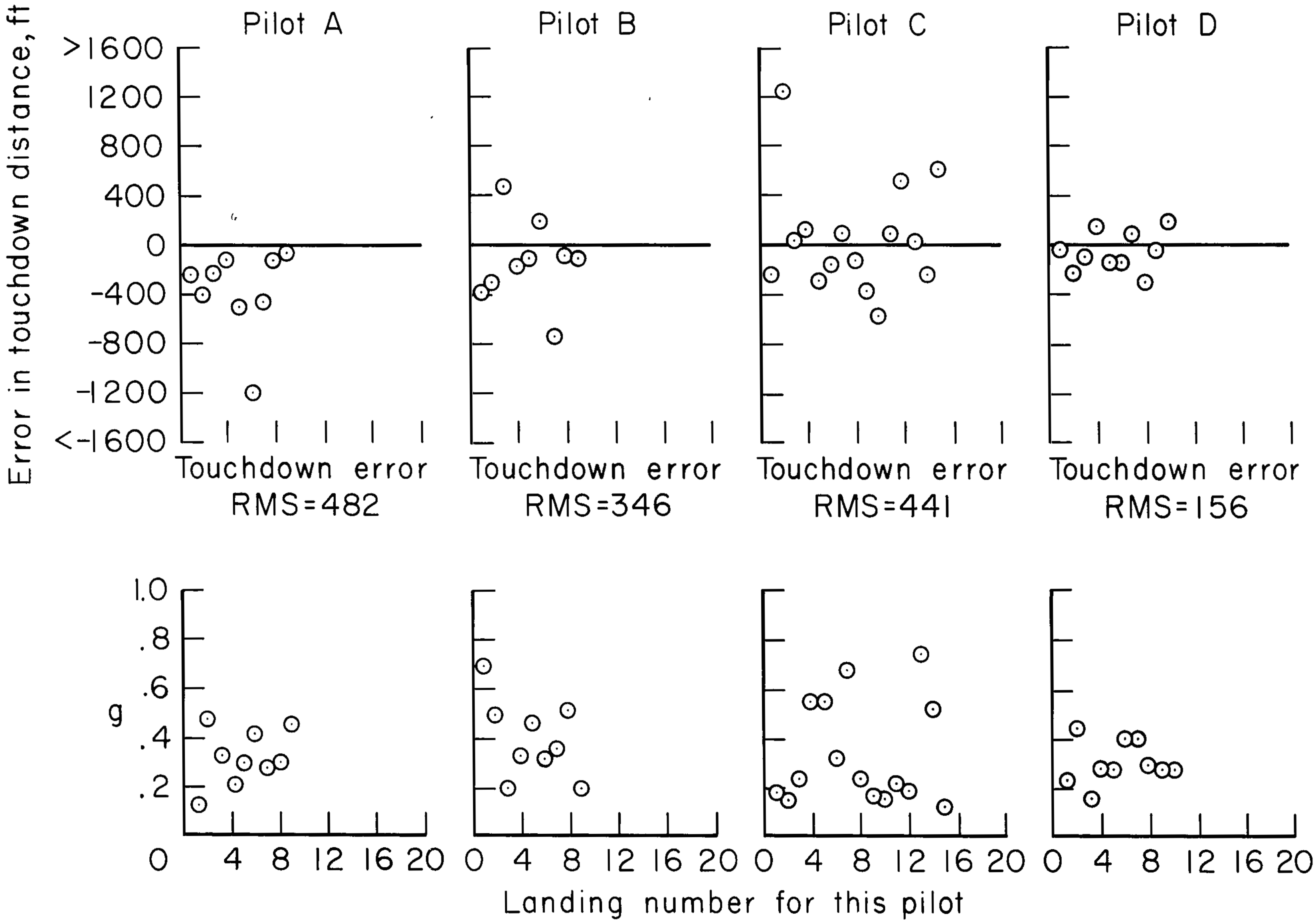
(c) Pilot C.

Figure 9.- Continued.



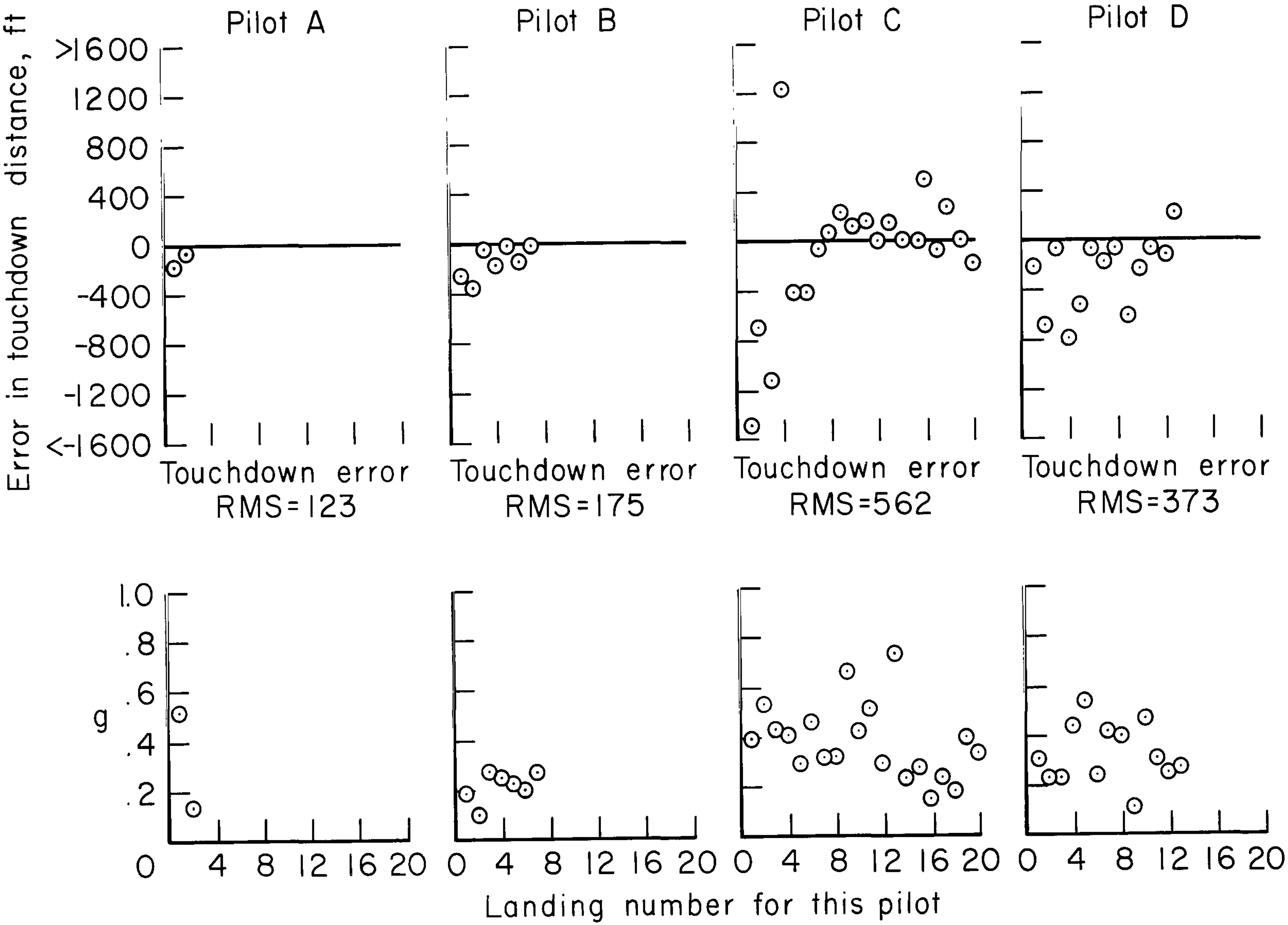
(d) Pilot D.

Figure 9.- Concluded.



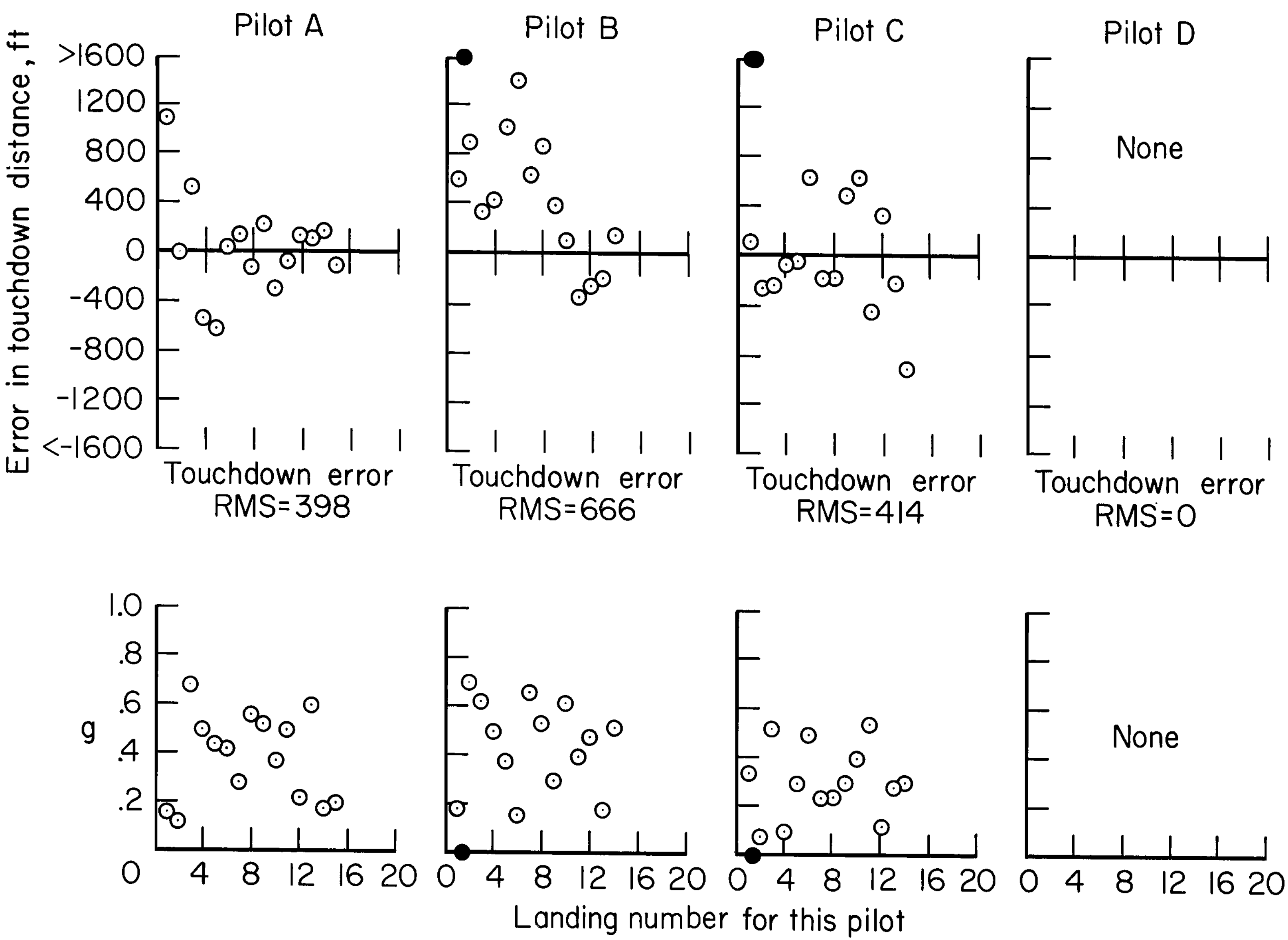
(a) Normal visual landing.

Figure 10.- Pilot performance by display.



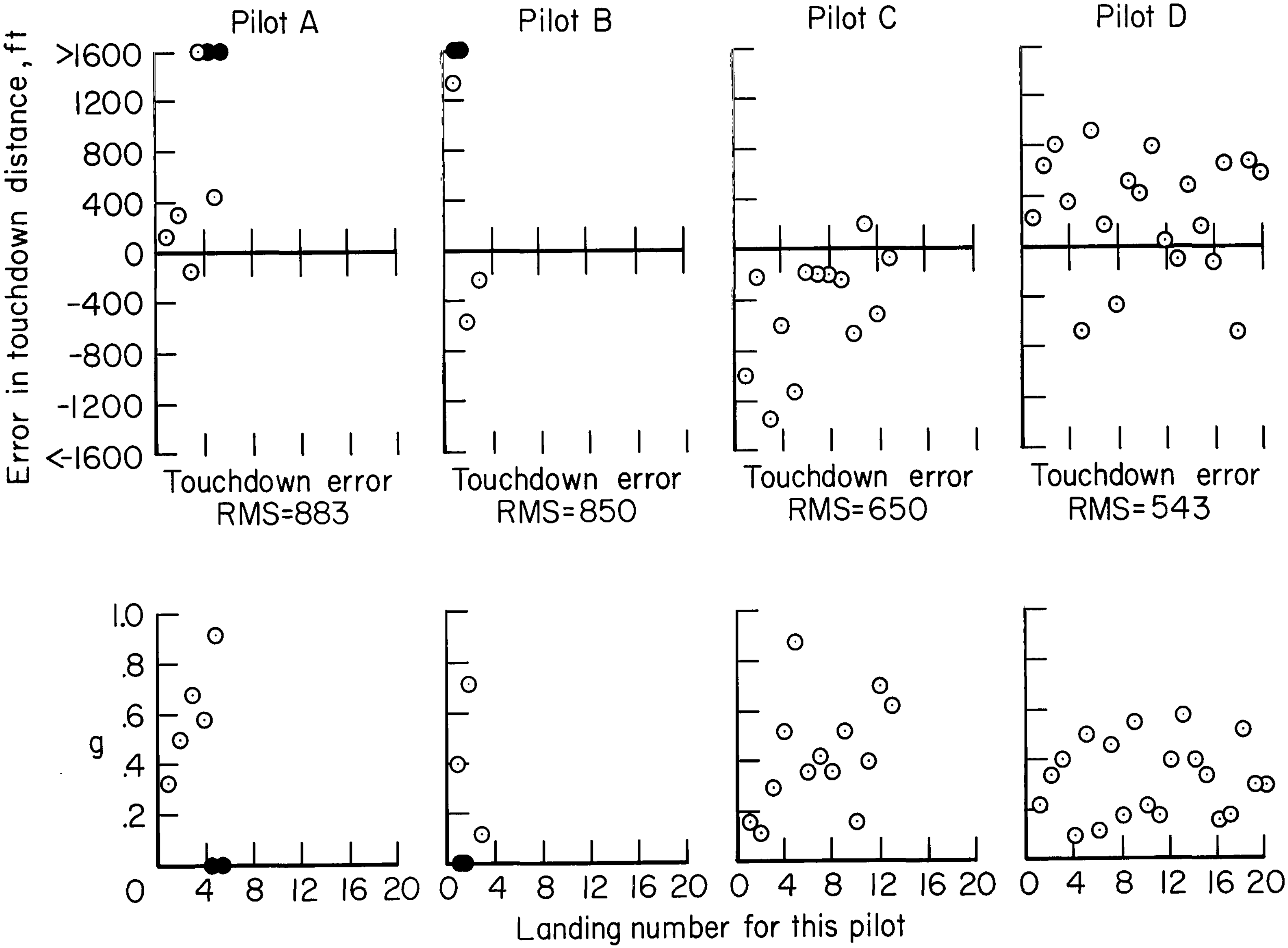
(b) 4-inch aperture.

Figure 10.- Continued.



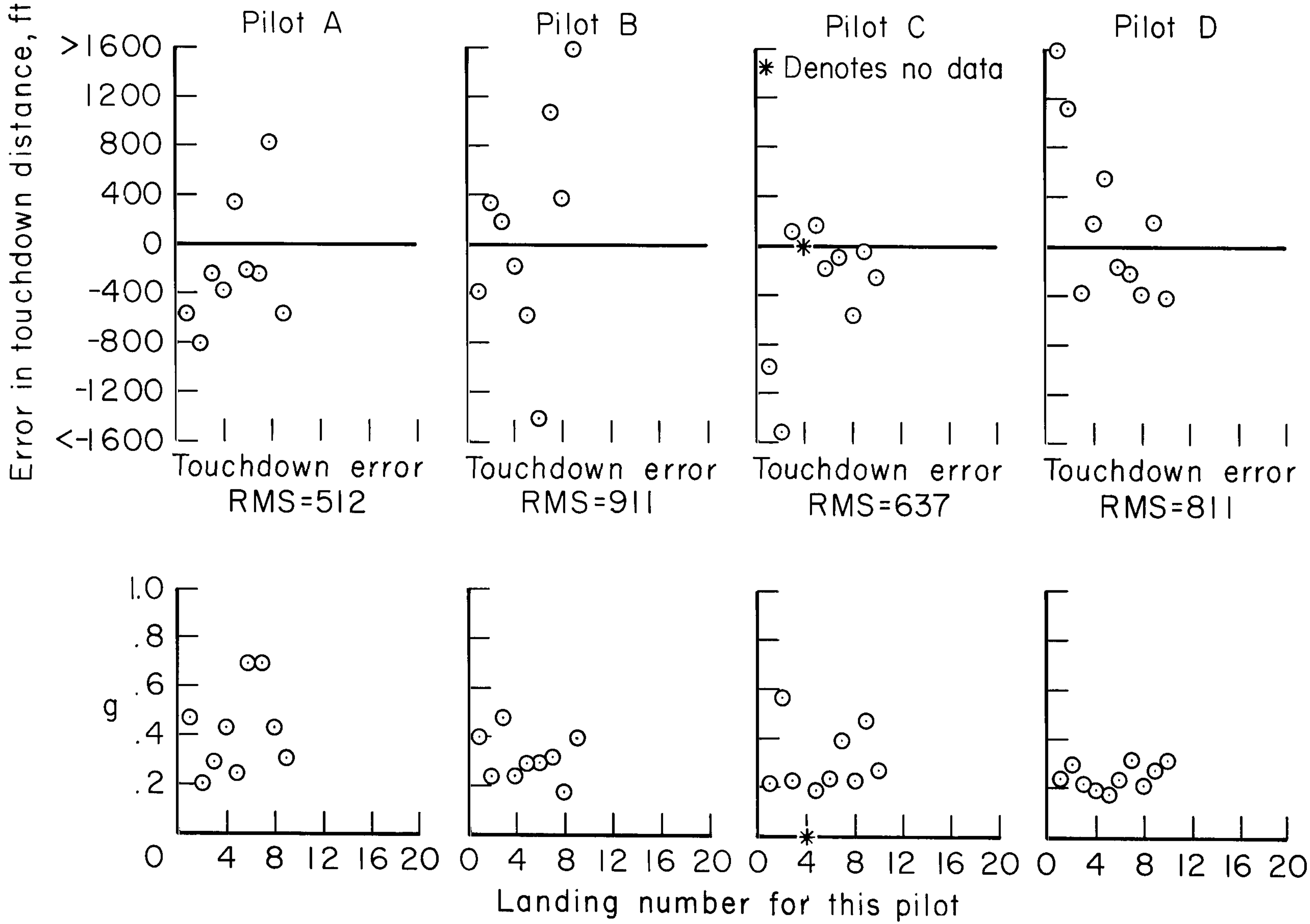
(c) Nose camera (12 mm lens).

Figure 10.- Continued.



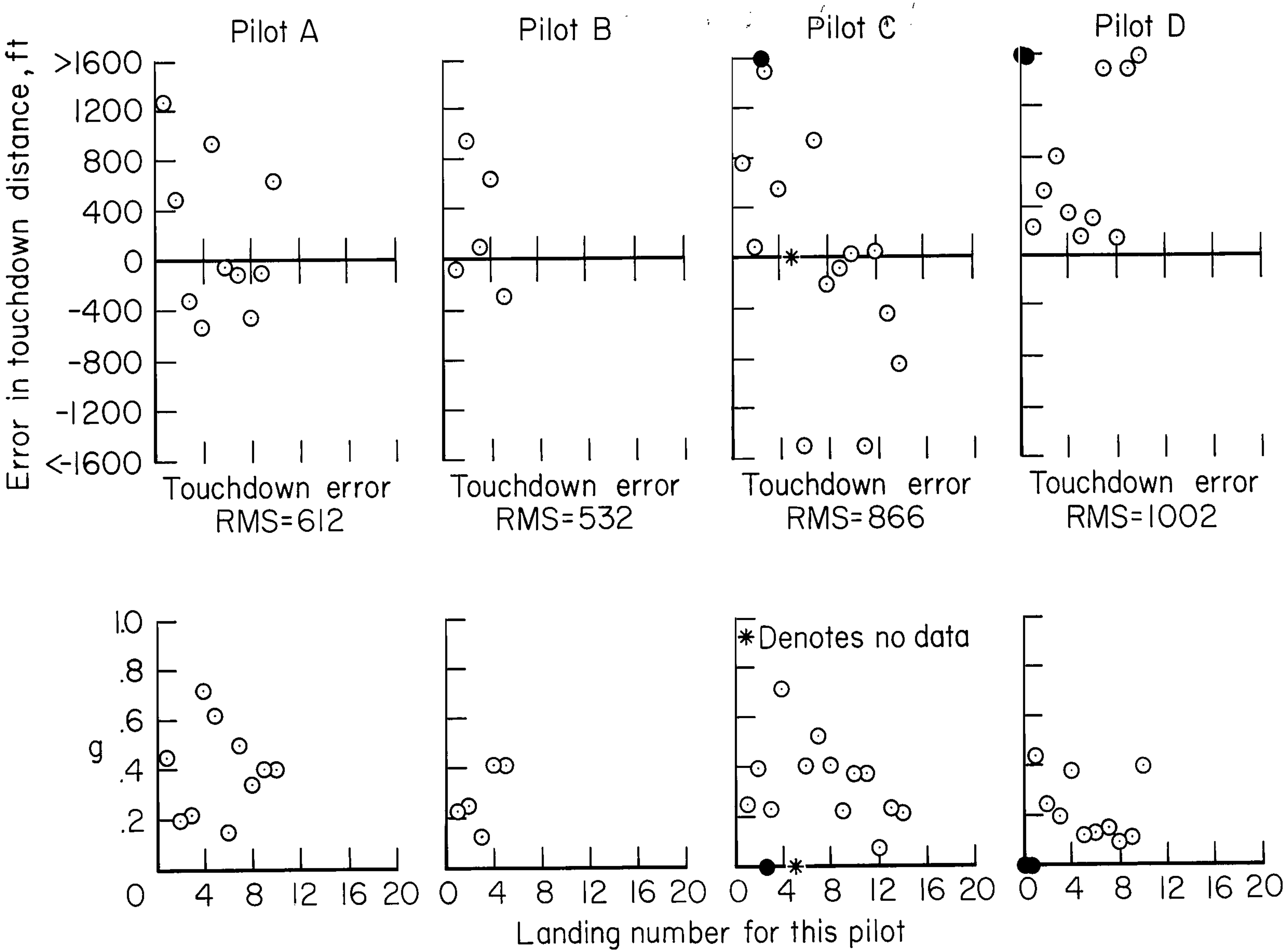
(d) Nose camera (25 mm lens).

Figure 10.- Continued.



(e) Nose camera (50 mm lens).

Figure 10.- Continued.



(f) Tail camera (12 mm lens).

Figure 10.- Concluded.

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