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RESEARCH MEMORANDUM

FLIGHT DETERMINATION OF THE EFFECTS OF RUDDER-PEDAL-FORCE CHARACTERISTICS ON THE AIMING ERROR IN AZIMUTH OF A CONVENTIONAL FIGHTER AIRPLANE

By Lee Winograd and Rudolph D. Van Dyke, Jr.

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NATIONAL ADVISORY COMMITTEE
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FLIGHT DETERMINATION OF THE EFFECTS OF RUDDER-PEDAL-FORCE CHARACTERISTICS ON THE AIMING ERROR IN AZIMUTH OF A CONVENTIONAL FIGHTER AIRPLANE

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SUMMARY

Flight tests were conducted to study the effect on the aiming error in azimuth of a change in the rudder-pedal-force characteristics of a conventional fighter airplane equipped with an illuminated fixed gunsight. Simulated gunnery runs were made on both ground and aerial targets with the normal rudder and with a rudder so modified that the rudder-pedal-force variation in sideslip was approximately zero. The effect of the modification on the mean azimuth tracking errors was insignificant (less than 1 mil); however, the pilots noted that with the modified rudder it was fatiguing to fly the airplane for any length of time.

INTRODUCTION

The Ames Aeronautical Laboratory is currently conducting an extensive flight and theoretical investigation of the effect of changes in stability and control parameters on the dynamic handling qualities of airplanes.

Among the points of interest is the effect of changes in lateral- and directional-stability characteristics on the ability to track a target in azimuth. Previous experience indicated that a reduction in pilot-applied rudder-pedal force to the point of zero or slightly unstable force variations in steady sideslips would result in a marked deterioration in handling characteristics. This point was studied in the present investigation by comparing the azimuth tracking ability of a conventional fighter airplane with the normal rudder installation to that with the rudder modified by trailing-edge strips to give approximately zero force variation in steady sideslip.

A number of simulated gunnery runs made on both fixed and moving targets for both rudder configurations were compared on the basis of the mean azimuth tracking error as evaluated from the records of a gun camera

so mounted in the cockpit as to photograph the target and the illuminated fixed-gunsight reticule as seen by the pilot.

TEST AIRPLANE AND INSTRUMENTATION

The test airplane was a conventional single-engine, single-place, low-wing shipboard fighter. Figure 1 presents a three-quarter front view of the aircraft as instrumented for flight.

Details of the rudder modifications are shown in figure 2. The trailing-edge strips extended 1/2 inch perpendicular to the rudder skin, and covered the straight portion of rudder trailing edge except for the rudder trim tab.

Standard NACA recording instruments were used to measure indicated airspeed, rudder position, rudder-pedal force, and sideslip angle. The sideslip vane was mounted on the right wing-tip boom and the airspeed head on the left wing-tip boom (fig. 1).

Figure 3 illustrates the gunsight and gunsight-camera installation. The illuminated fixed gunsight (AN Mark 8, model 6) was mounted on standard brackets and projected the reticule image on the wind screen. A type N-6 gunsight aiming-point camera equipped with a 75 mm lens was attached by brackets to the gunsight and so oriented as to photograph the target and the reticule image as viewed by the pilot. A synchronized timing system was used to coordinate the various records.

TESTS AND ANALYSIS METHODS

All gunnery runs were made at an indicated airspeed of 300 knots in smooth air on a ground target at sea level or on a target airplane at a nominal pressure altitude of 10,000 feet.

Characteristics in Steady Sideslips

Steady sideslips were performed with both rudder configurations at 200 and 350 knots to determine rudder-angle and rudder-pedal-force characteristics.

Simulated Gunnery Runs on Fixed Ground Target

The initial simulated gunnery runs were made with a straight-in approach on a fixed ground target, a large and easily visible tetrahedron.

Records were obtained during the final 10 to 15 seconds of the approach to the target. The azimuth tracking error ϵ, measured as the lateral angular deflection between the target and the gunsight pipper, was plotted as a function of time; the mean error ϵ_m was then evaluated by integrating the positive and negative areas of the time history individually with a planimeter and dividing the sum of the absolute values of the areas by the gunnery time interval. The average values of ϵ_m over a series of flights were very low (in the order of 1.5 mils), and there was no significant difference in average error for the two rudder configurations. It appeared that the test maneuver was not sufficiently severe to show any effect of the rudder-pedal-force change on the azimuth tracking ability.

Therefore, a procedure using an abrupt roll as an initial disturbance was devised in an attempt to find any significant difference due to rudder-pedal-force characteristics. This procedure is illustrated in figure 4. At the start of the run the airplane was flown with an initial 100-mil azimuth tracking error with respect to the target. From this position an abrupt coordinated turn was made toward the target. The gunsight camera was turned on when the azimuth tracking error was reduced to 50 mils. The pilot completed the run by maneuvering the aircraft so as to reduce the azimuth tracking error to a minimum.

As indicated in figure 4, ϵ_m for these runs was evaluated between the time when the error first reduced to 10 mils and 4.5 seconds thereafter. Figure 5 presents sample gunsight-camera frames with the corresponding time history of the azimuth tracking error evaluated directly from the camera record. Two pilots (A and B) each made at least 50 usable runs with both rudder configurations.

Simulated Gunnery Runs on Target Airplane

Pilots' opinions and analysis of the data obtained in the ground-target runs just described indicated that the maneuver still was not severe enough to give significant differences in error due to the rudder modification. Therefore, a tail-pursuit procedure was devised.

The test airplane made tail-pursuit runs on another fighter-type plane used as a target which performed a series of abruptly entered left and right turns. As shown in figure 6, the run was started from straight level flight when the wing span of the target plane subtended 50 mils in the gunsight; this corresponds to about 750 feet between airplanes. The target airplane held straight flight for 3 seconds and then made a series of abruptly entered 45° left and right banks; each bank was held for 3 seconds.

The pilot of the target airplane arbitrarily varied the direction of initial bank. The pursuit airplane followed the target airplane throughout the maneuver, and the pursuit pilot, while coordinating his controls,

attempted to keep the pipper of the gunsight on the point of intersection of the horizontal and vertical tail of the target airplane, as illustrated in the camera frames of figure 7.

The azimuth tracking error was read directly from the camera records and plotted in the corresponding time histories shown in figure 7. The mean azimuth tracking error, the average of the absolute error, was evaluated by integration of such time histories. The evaluation interval was taken from the start to the end of the run.

RESULTS AND DISCUSSION

The rudder-pedal force and deflection in steady sideslips for the normal and modified rudder are presented in figure 8. The test airspeeds of 200 and 350 knots include the airspeed range used in gunnery runs. The effect of strips on the rudder-pedal-force variation with sideslip was approximately as desired for this investigation. The modified rudder produced a small and erratic force variation over sideslip angles $\pm 2^{\circ}$ or 3° from trim value. The strips resulted in an increase in the variation of rudder deflection with sideslip angle, particularly at the higher speed, but the change was not of sufficient magnitude to be directly noticeable to the pilots.

No data are presented for the gunnery runs involving a straight-in approach on the ground target as the mean tracking errors were very low for both configurations and showed no significant differences. The results of the runs on the ground target using the abrupt roll-in approach (figs. 4 and 5) are summarized in table I(a). The mean azimuth tracking error ϵ_m averaged over the flight is tabulated for the various combinations of rudder configuration and pilot. The six successive flights of pilot A with the normal configuration were his first attempts with the abrupt roll-in technique, and, as might be expected, the values of ϵ_m indicate a learning tendency. This is shown more clearly in figure 9, in which ϵ_m is plotted as a function of flight number. It appears that the mean error after learning would have been about 1 to 1-1/2 mils. Little learning tendency is indicated by the data for the modified configuration, which show an average error of about 1-1/2 mils. Although there were sizable intervals of time between the flights of pilot B (note flight numbers in table I(a)), the data for the normal rudder indicate some learning tendency, with an estimated eventual ϵ_m of 1-1/2 to 2 mils. The data for pilot B with the modified rudder show an average ϵ_m of about 2 to 2-1/2 mils. Study of the absolute magnitude and run-to-run variation of the values of ϵ_m obtained in this and other tracking projects indicated that ϵ_m differences due to rudder modification of less than 1 mil could be considered insignificant. Thus for both pilots it appears that the increase in azimuth tracking error due to rudder modification can be considered insignificant for practical purposes.

For the aerial-target technique, only two flights were made by each pilot with each configuration, and, in the case of pilot A with the normal rudder, readable gun-camera data were not obtained on one of these flights. Additional flights to obtain a statistically sounder evaluation of mean error ϵ_m were not considered warranted, since, as shown in table I(b), the trends were so close to those for the ground-target runs. It is seen in each case that a learning tendency is indicated between the first and second flights, and it appears that for each pilot-configuration combination ϵ_m after learning would be at most 1 mil greater than the ground-target runs. As was the case for the ground-target runs, there was no significant (greater than 1 mil) difference in ϵ_m for the normal and modified rudder. Pilot A data indicate a slightly deleterious effect of strips, but for pilot B the effect is slightly favorable. These results are opposite to those for the ground-target technique.

It was considered possible that, even though the modified rudder had a negligible effect on the azimuth tracking error, there might be deleterious effects on other characteristics of the airplane motion in the azimuth plane which influence the "miss distance" of a projectile. For example, it was thought that the low-pedal-force gradient with the modified rudder might result in large inadvertent sideslip during gunnery runs. The four aerial-target flights by pilot B, two flights with normal rudder and two flights with modified rudder, were evaluated to find the effect of the modified rudder on the average sideslip. Figure 10 presents time histories of sideslip for typical runs in each flight. It is seen that there were large variations in sideslip angle for both configurations; examination showed that, in general, the airplane was skidding in the turns. The pilot thought the pedal forces were too low, even with the normal rudder, and that this led to overcontrolling with the rudder.

Mean values β_m of sideslip angle β measured from a mean trim value and, hence, representative of error due to piloting, were determined by integration and summation of the absolute values of the areas of the time histories. The average value β_m for each flight is tabulated in table I(b). It is seen that β_m was of the order of $1\text{-}1/2^{\circ}$ for each configuration, and that rudder modification had little effect.

The relative effects of azimuth tracking error ϵ and sideslip angle β on projectile miss distance in a simple gunnery problem are indicated in the appendix. It is shown that the miss distance can be approximated by $\epsilon+K\beta$, multiplied by a constant where K is proportional to the ratio of airplane velocity to projectile velocity and ϵ and β represent instantaneous values. The mean miss distance during a run is then proportional to $(\epsilon+K\beta)_m$, the mean value of $\epsilon+K\beta$. Values of $(\epsilon+K\beta)_m$ for several runs were computed by integration of the time history of the absolute value of the quantity $\epsilon+K\beta$, and showed slightly larger values for the modified rudder than for the normal rudder. The nonequivalent but related parameter $\epsilon_m+K\beta_m$ gives a more convenient basis for comparison than $(\epsilon+K\beta)_m$ since computation of $(\epsilon+K\beta)_m$ is tedious and since ϵ_m

and β_m have already been evaluated. The ϵ_m and β_m data of table I(b) yield slightly larger values of $\epsilon_m+K\beta_m$ for the normal rudder than for the modified rudder, the opposite of the tendency indicated by the brief $(\epsilon+K\beta)_m$ evaluation. Since the difference due to rudder modification was less than 1 mil for either expression, it was concluded that the effect on miss distance would be very small. It is believed that these conclusions would apply if more complicated gunnery problems and computing gunsights were considered, even though this might change the nature and magnitude of the quantities important from an azimuth-miss-distance viewpoint.

It is interesting to note that the pilots could not use rudder-pedal force as a guide in flying with the modified rudder because of the small and erratic variation with sideslip angle. The pilots reported that they compensated in part for the lack of pedal-force feel by exerting about 25- to 50-pounds force on each rudder pedal at all times, and using rudder-pedal displacement as a guide in controlling. Although remarkable precision was obtained in the gunnery runs with this special control technique, over a period of time it was a fatiguing flight method and was considered intolerable in routine flying.

CONCLUSIONS

A study of azimuth tracking ability using a conventional fighter airplane, equipped with a fixed gunsight, has been made with the normal rudder (characterized by stable-pedal-force variations in steady sideslips) and with the rudder modified by strips on the trailing edge (characterized by small and erratic-pedal-force variations).

Comparison of the results of simulated gunnery runs by two pilots on a stationary ground target and on a maneuvering target airplane leads to the following conclusions:

1. The mean azimuth tracking error was small (less than 4 mils) for all configurations, pilots, and techniques. The effect of rudder modification was insignificant (less than 1 mil).

2. Low and erratic rudder-pedal-force variation with the modified rudder necessitated a special rudder-control technique which was fatiguing over a period of time, and was considered intolerable in routine flying.

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APPENDIX

CALCULATION OF THE RELATIVE EFFECTS OF VARIOUS FACTORS IMPORTANT TO PROJECTILE-MISS DISTANCE

A simplified tail-pursuit situation is illustrated in figure 11, where

R range, feet

T time for projectile to reach target, seconds

V_a velocity of target and pursuit airplanes, feet per second

V_b muzzle velocity of projectile, feet per second (assumed constant along a straight path)

l distance from center of gravity of pursuit airplane to the point where projectile leaves airplane, feet

t time, seconds

y lateral miss distance of projectile from target plane, feet

$\dot{y}$ dy/dt, feet per second

β sideslip angle, degrees

ϵ azimuth tracking error, mils (1 mil = $\frac{2\pi}{6400}$ radians)

$\dot{\psi}$ angular velocity of pursuit airplane in azimuth, degree per second

It is assumed that the target airplane instantaneously is flying in a steady straight path and that ϵ and β are small, so that the sine of the angle is equal to the angle in radians.

Then the component of y due to ϵ is given by

$$y_\epsilon = \left(\frac{2\pi R}{6400}\right)\epsilon$$

The component of y due to β is given by

$$y_\beta = \dot{y}_\beta T$$

$$T = R/V_b$$

$$\dot{y}_\beta = V_a\ (\beta/57.3)$$

therefore

$$y_\beta = \left(\frac{RV_a}{57.3V_b}\right)\beta$$

The component of y due to $\dot{\psi}$ is given by

$$y_{\dot{\psi}} = \dot{y}_{\dot{\psi}} T$$

$$\dot{y}_{\dot{\psi}} = l_{\dot{\psi}}$$

therefore

$$y_{\dot{\psi}} = \left(\frac{lR}{V_b\ 57.3}\right)\dot{\psi}$$

Then the total lateral projectile miss distance is

$$y = y_\epsilon + y_\beta + y_{\dot{\psi}}$$

$$y = \left(\frac{2\pi R}{6400}\right)\epsilon + \left(\frac{RV_a}{57.3V_b}\right)\beta + \left(\frac{lR}{V_b\ 57.3}\right)\dot{\psi}$$

In order to determine the relative importance of the three components, the following typical values will be used in an example:

$\beta = 1.40^\circ$	$l = 5$ feet
$\dot{\psi} = 1.39^\circ$ per second	$R = 750$ feet
$V_a = 507$ feet per second	$\epsilon = 2$ mils
$V_b = 2900$ feet per second	

Substitution of these values in the derived equation gives:

$$y = \frac{(6.28)\ (750)\ (2)}{6400} + \frac{(750)\ (507)\ (1.4)}{(57.3)\ (2900)} + \frac{(5)\ (750)\ (1.39)}{2900 \times 57.3}$$

$$y = 1.47 + 3.21 + 0.03$$

$$y = 4.71 \text{ feet}$$

It is seen that the effect of $\dot{\psi}$ on y is negligible, and that the contributions of ϵ and β are about 31.4 and 68 percent, respectively.

The equation for the total miss distance can be approximated by

$$y = \left(\frac{2\pi R}{6400}\right)\epsilon + \left(\frac{RV_a}{57.3V_b}\right)\beta$$

$$y = \frac{2\pi R}{6400}\left[\epsilon + \frac{RV_a 6400\ \beta}{(2\pi R)\ (57.3V_b)}\right]$$

which is in the form of $\epsilon + K\beta$ multiplied by a constant.

TABLE I.– SUMMARY OF MEAN AZIMUTH TRACKING ERRORS AND AVERAGE SIDESLIP

Pilot	Configuration	Flight number	Number of runs	ϵ_m (mils)	β_m (deg)
(a) Ground target					
A	Normal rudder	20	8	4.02	– – –
		21	8	3.08	– – –
		22	8	2.71	– – –
		24	14	2.31	– – –
		25	8	1.78	– – –
		26	11	1.18	– – –
	Modified rudder	41	4	1.57	– – –
		42	8	1.98	– – –
		43	16	1.61	– – –
		45A	16	.79	– – –
		45B	8	1.41	– – –
		47B	8	1.95	– – –
		48B	8	1.43	– – –
		49	16	1.06	– – –
B	Normal rudder	14	5	2.74	– – –
		19	5	3.36	– – –
		29	2	2.29	– – –
		31	20	2.05	– – –
		32	19	1.81	– – –
	Modified rudder	52	9	1.21	– – –
		53	9	2.17	– – –
		54	7	2.47	– – –
		55A	8	2.05	– – –
		58	15	2.06	– – –
		59	8	2.20	– – –
(b) Aerial target					
A	Normal rudder	69	12	1.90	– – –
	Modified rudder	60	8	3.36	– – –
		61	7	2.04	– – –
B	Normal rudder	70	11	3.47	1.34
		71	12	2.41	1.47
	Modified rudder	65	12	2.92	1.66
		66	12	2.12	1.02

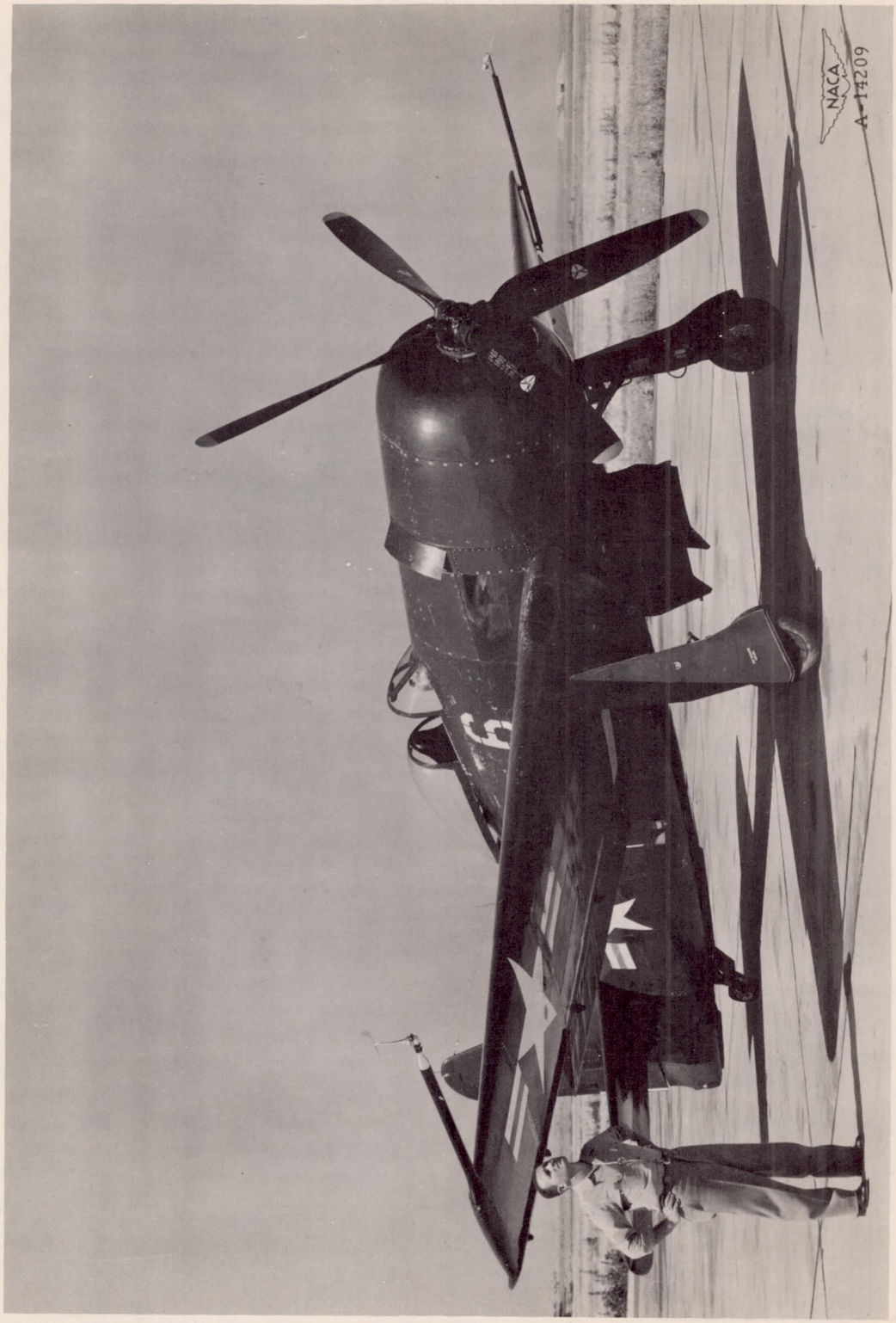
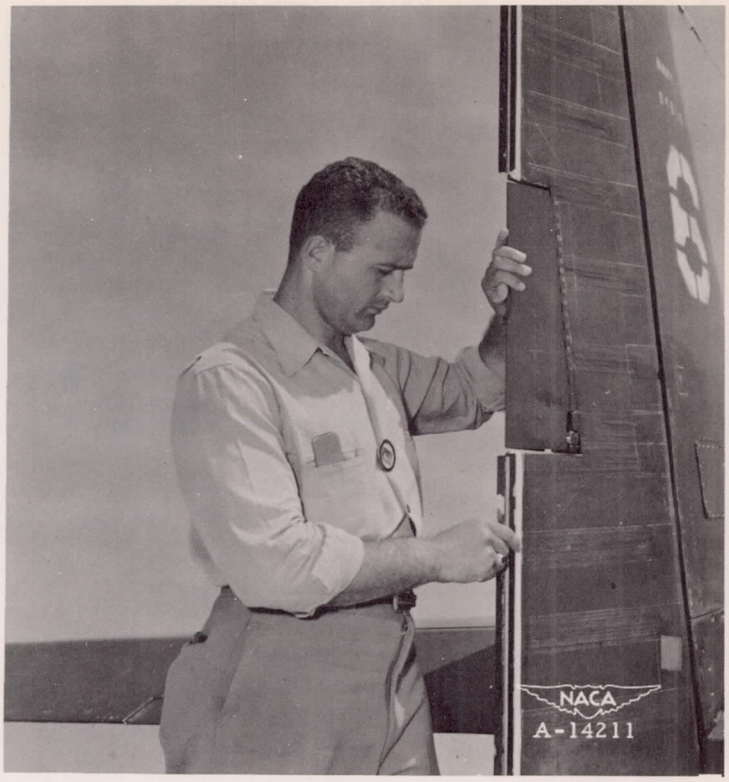
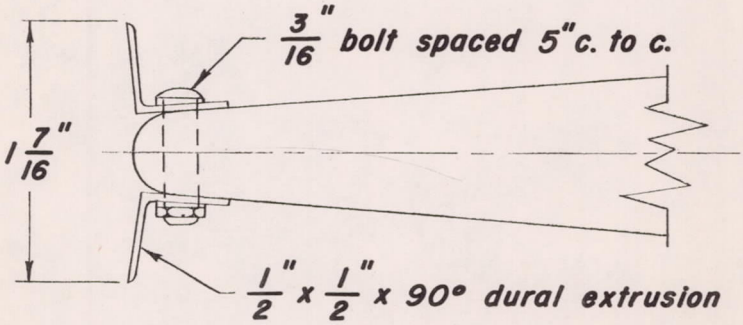


Figure 1.- Test airplane as instrumented for flight.



(a) Three-quarter rear view of rudder strips.



(b) Cross section of modified rudder showing strips added; full scale.

Figure 2.- Details of rudder-trailing-edge modification.

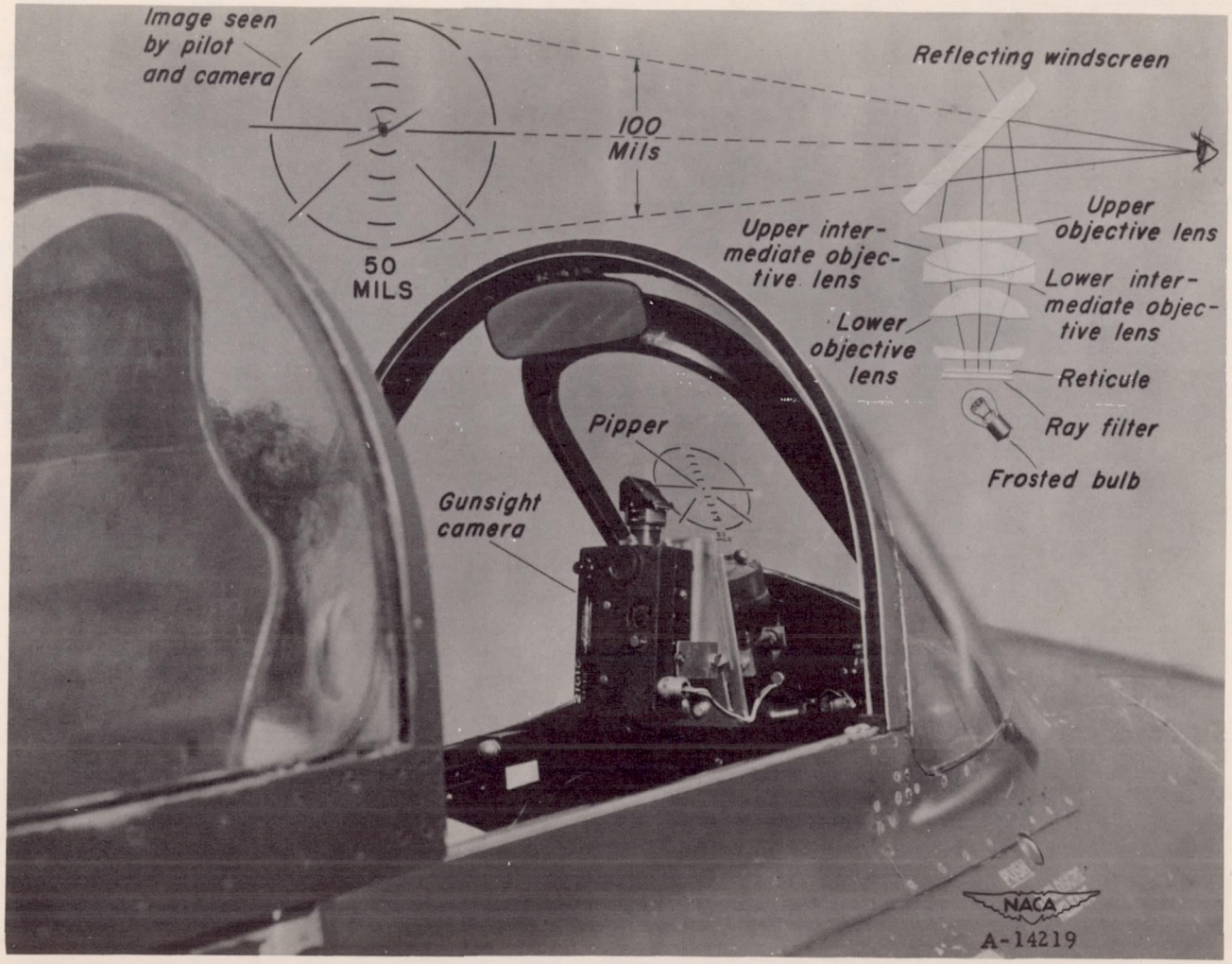


Figure 3.- Gunsight camera and illuminated fixed gunsight installation.

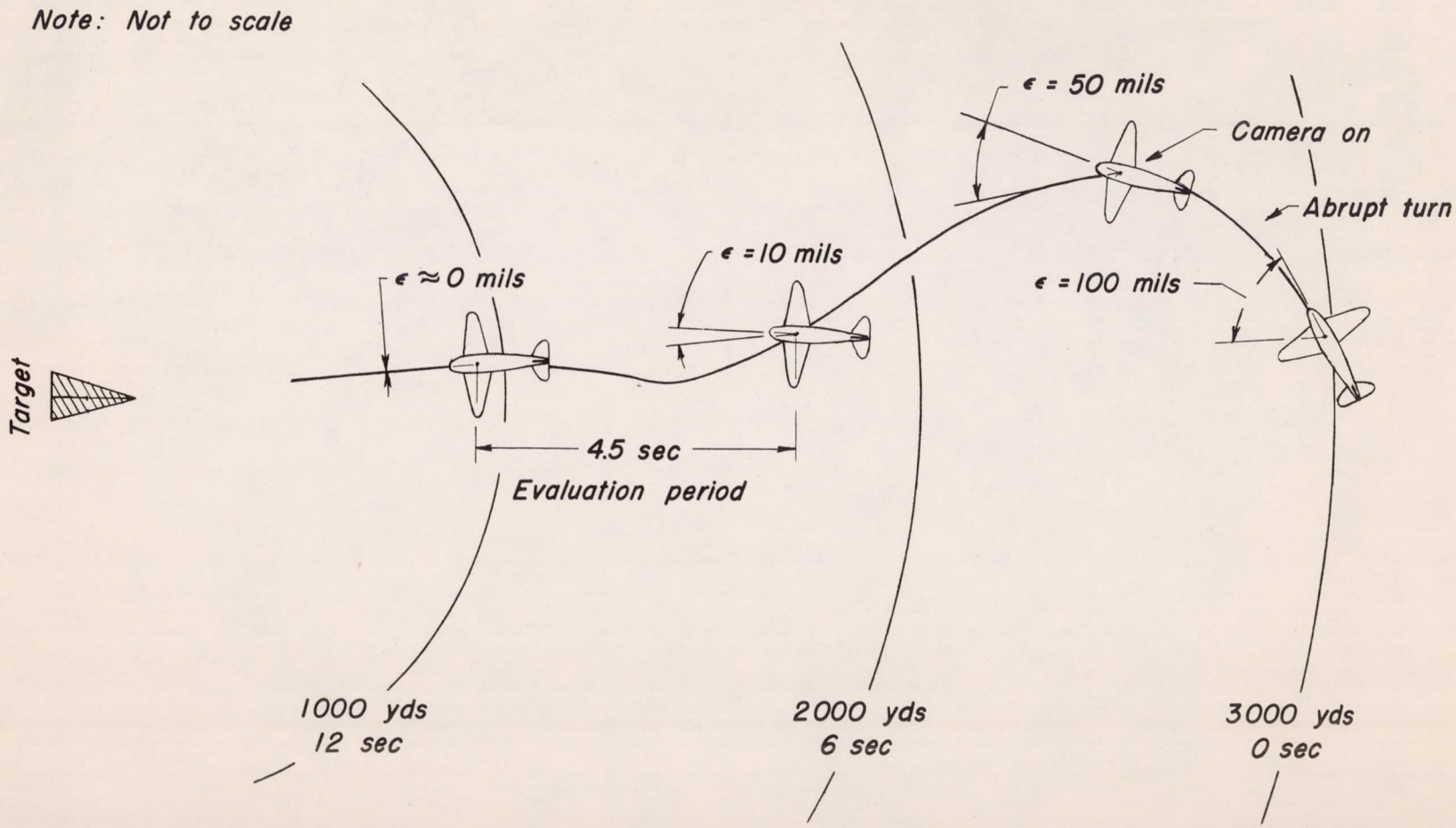
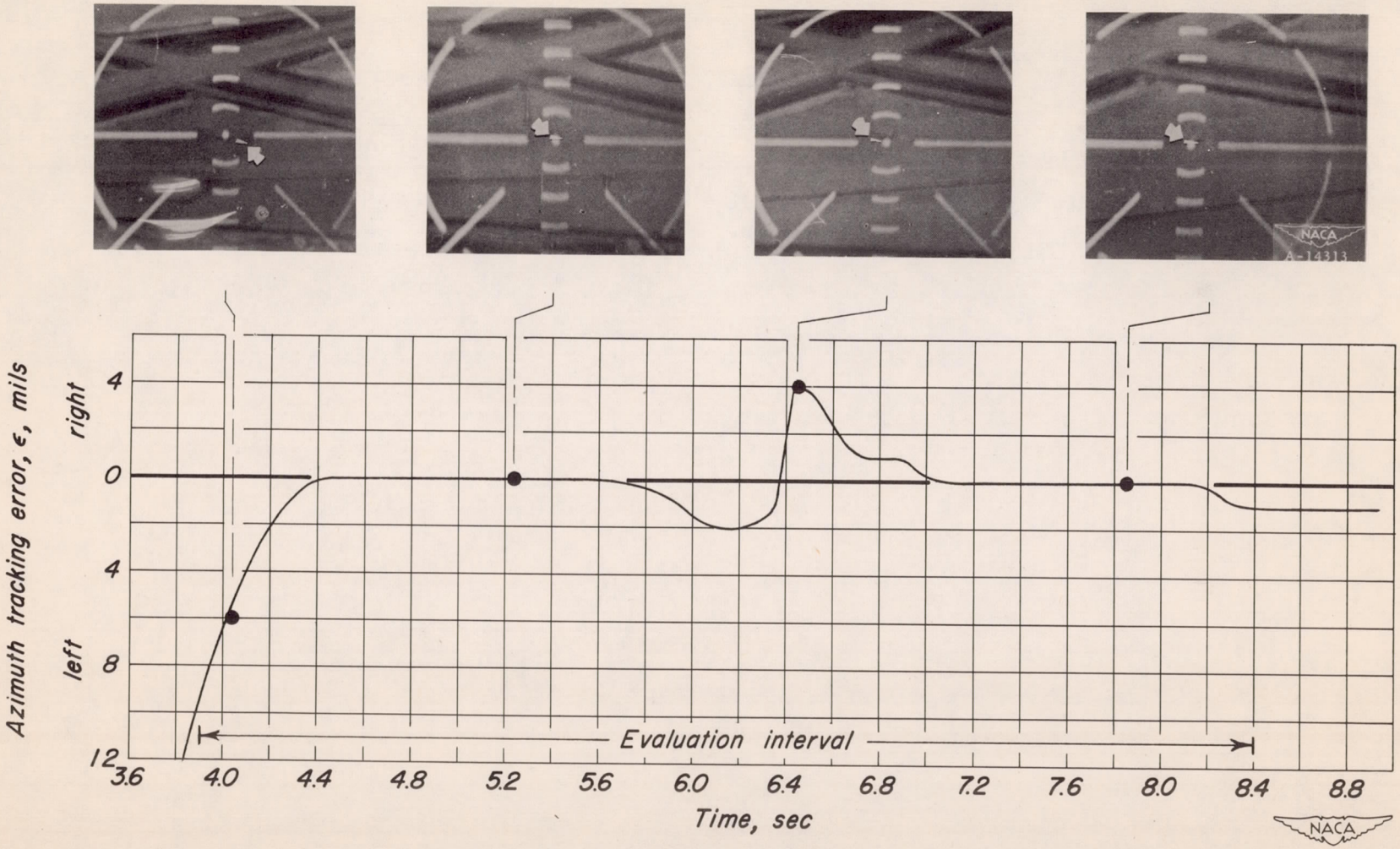
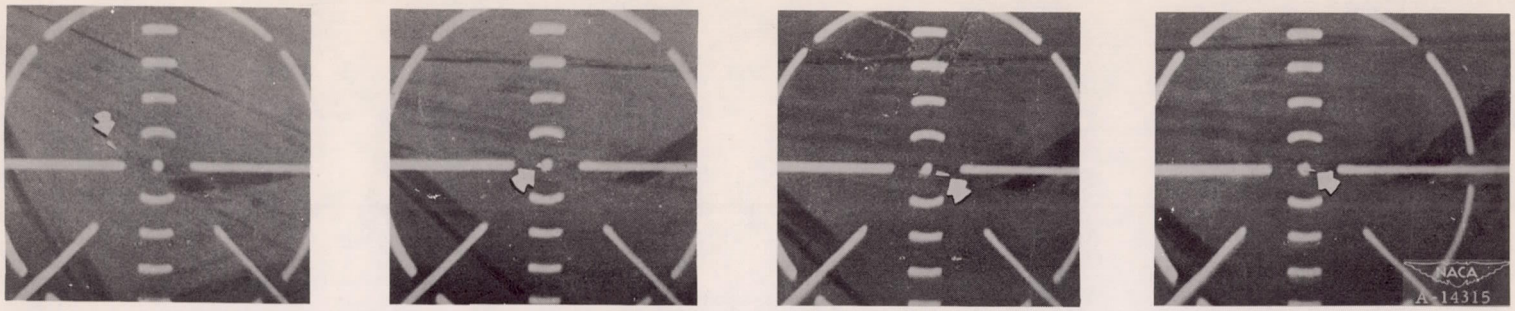


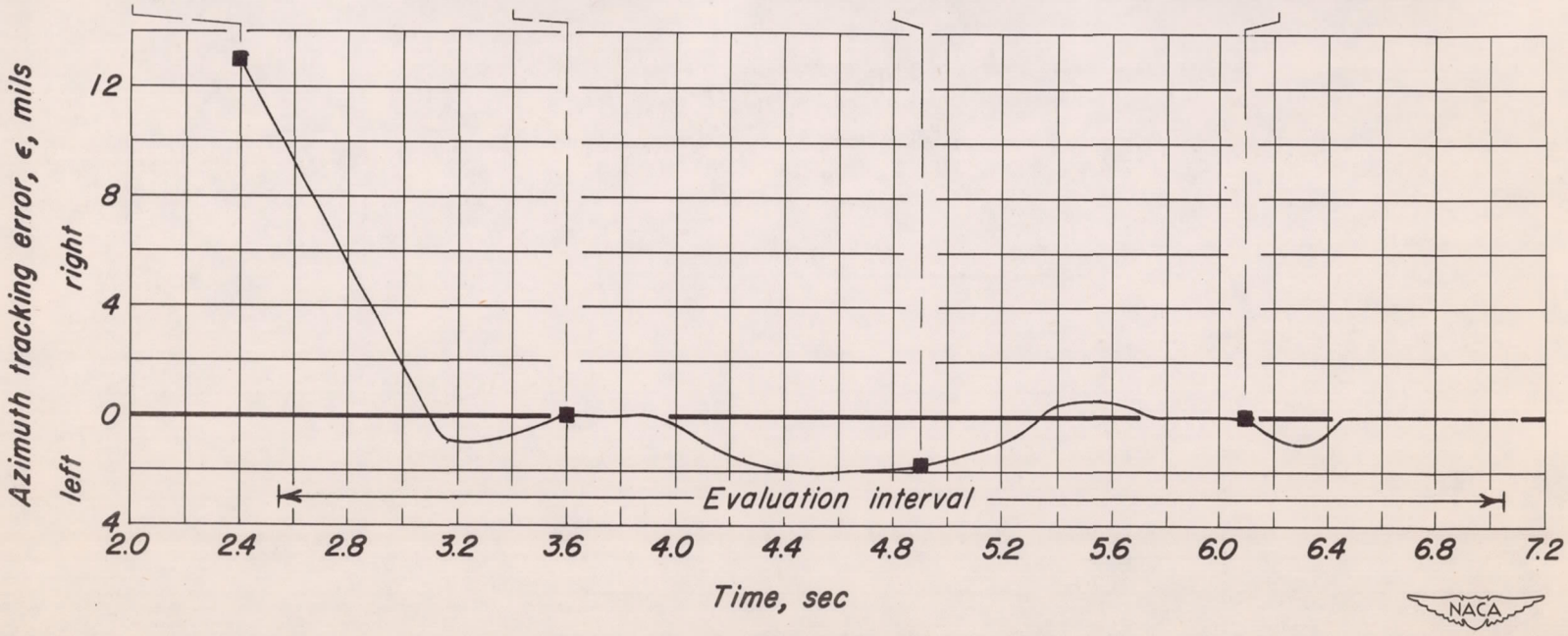
Figure 4.- The technique used in ground-target runs with abrupt roll-in; V_i = 300 knots.



(a) Normal rudder.

Figure 5.- Sample gunsight-camera frames with corresponding time histories of azimuth tracking error in ground-target run.





(b) Modified rudder.

Figure 5.- Concluded.

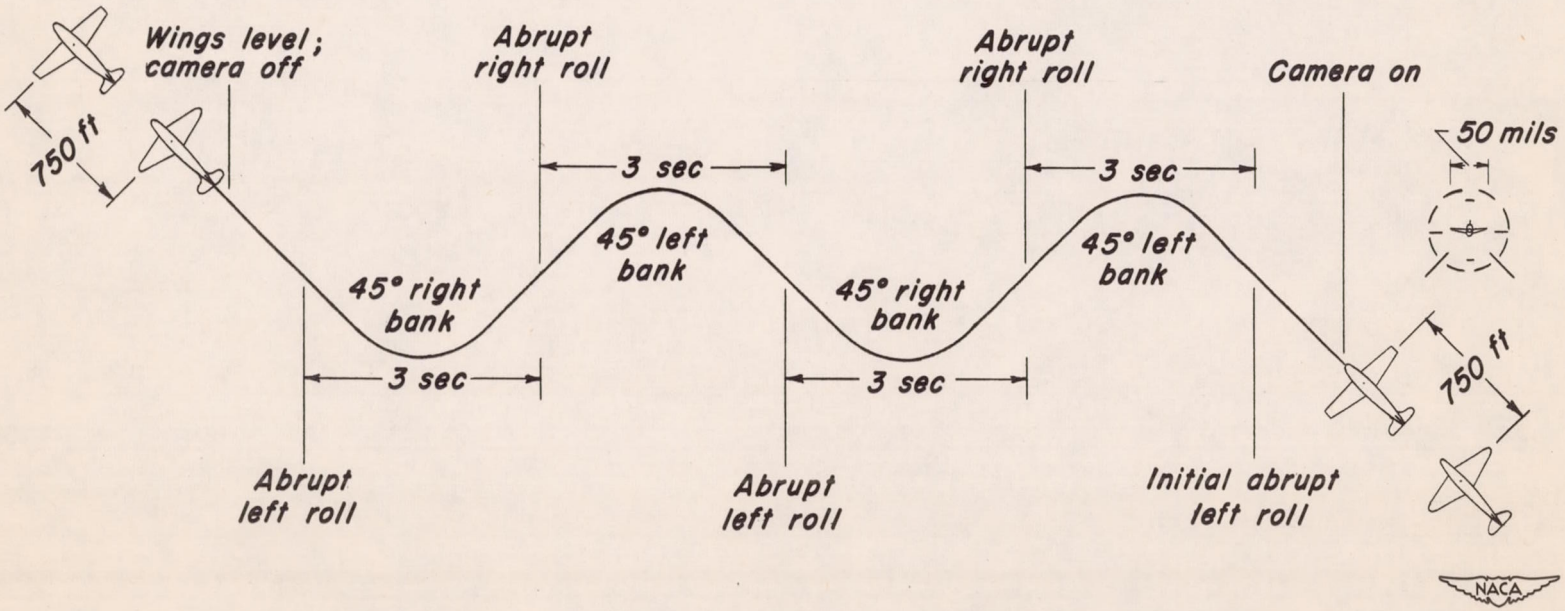
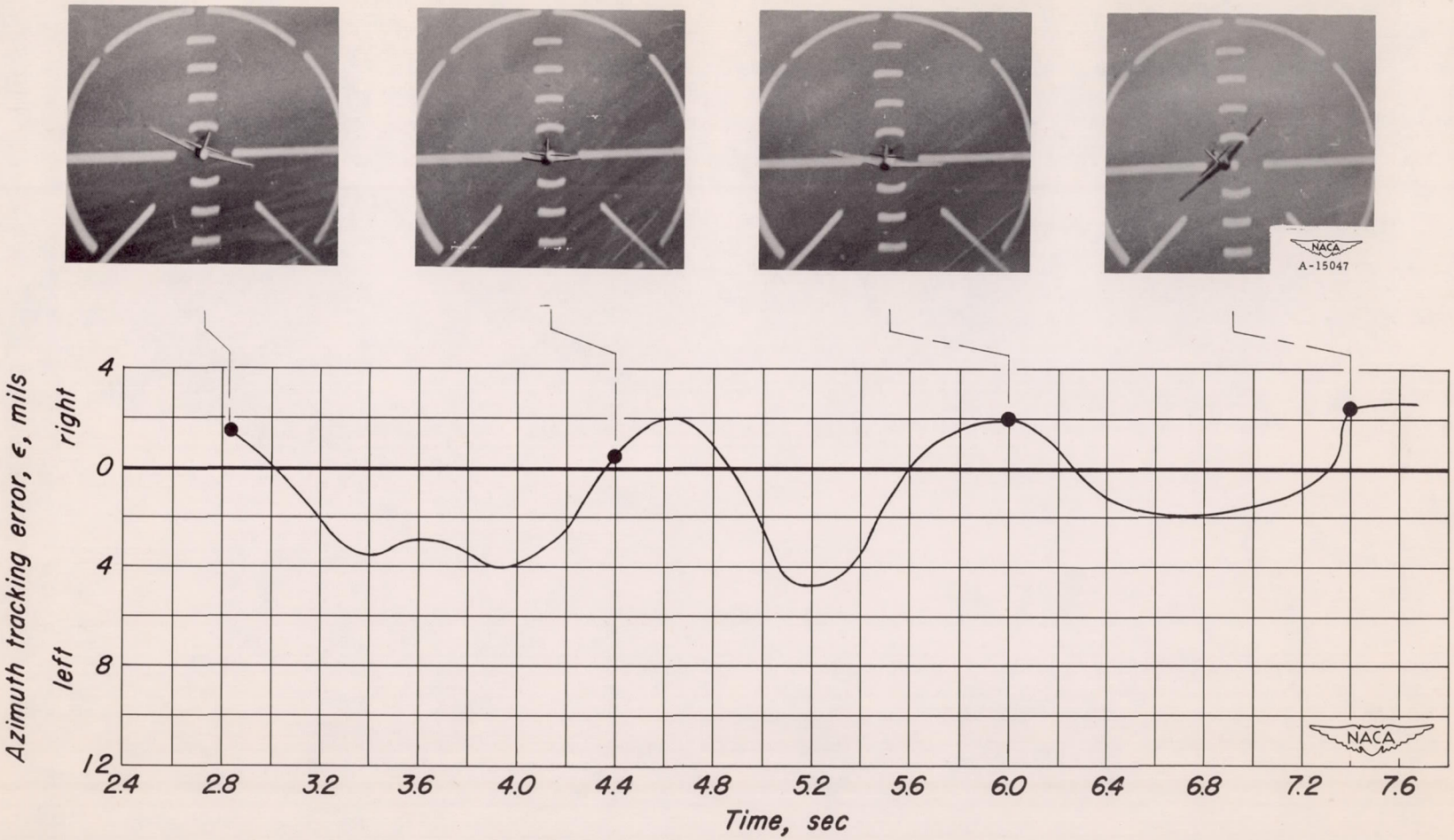
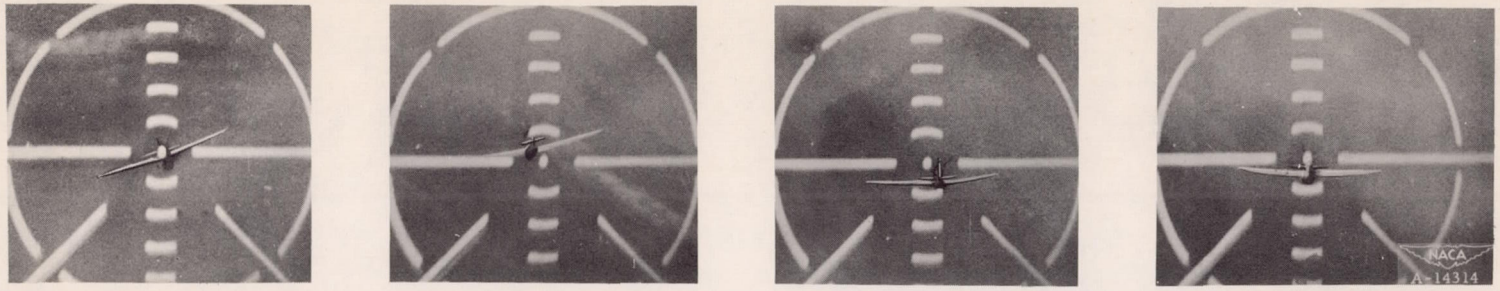


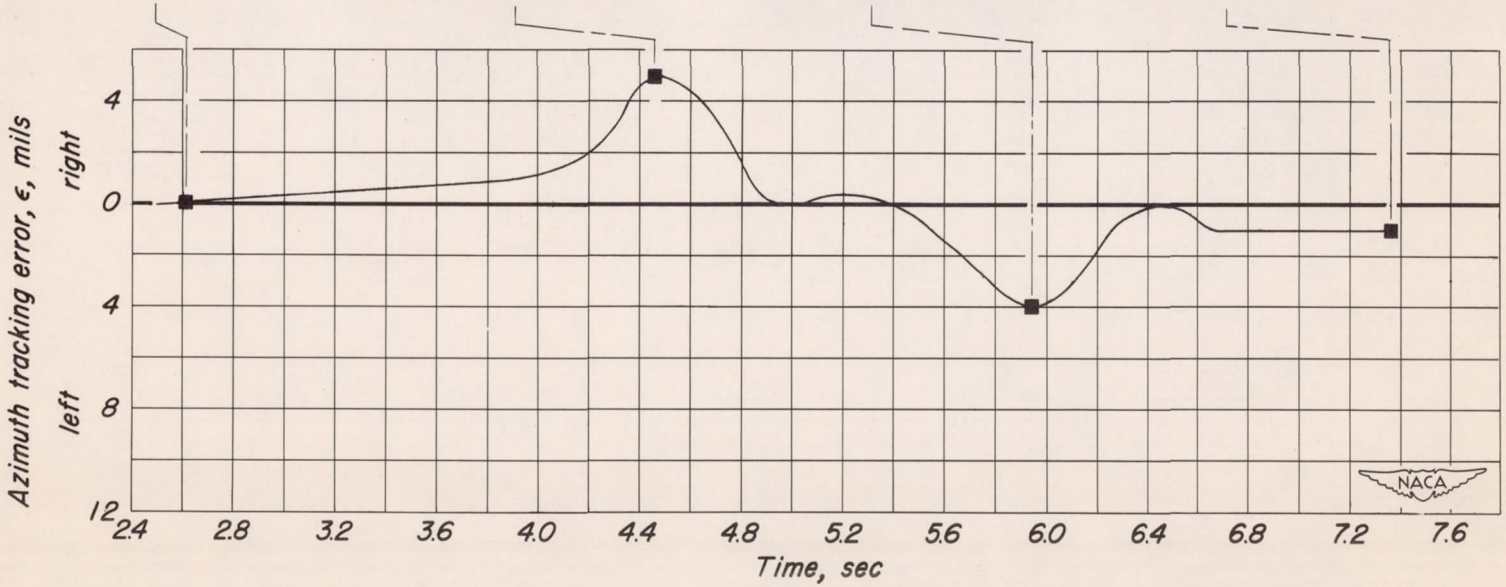
Figure 6.– The technique used in aerial-target runs with abrupt rolls. Level flight at V_i = 300 knots.



(a) Normal rudder.

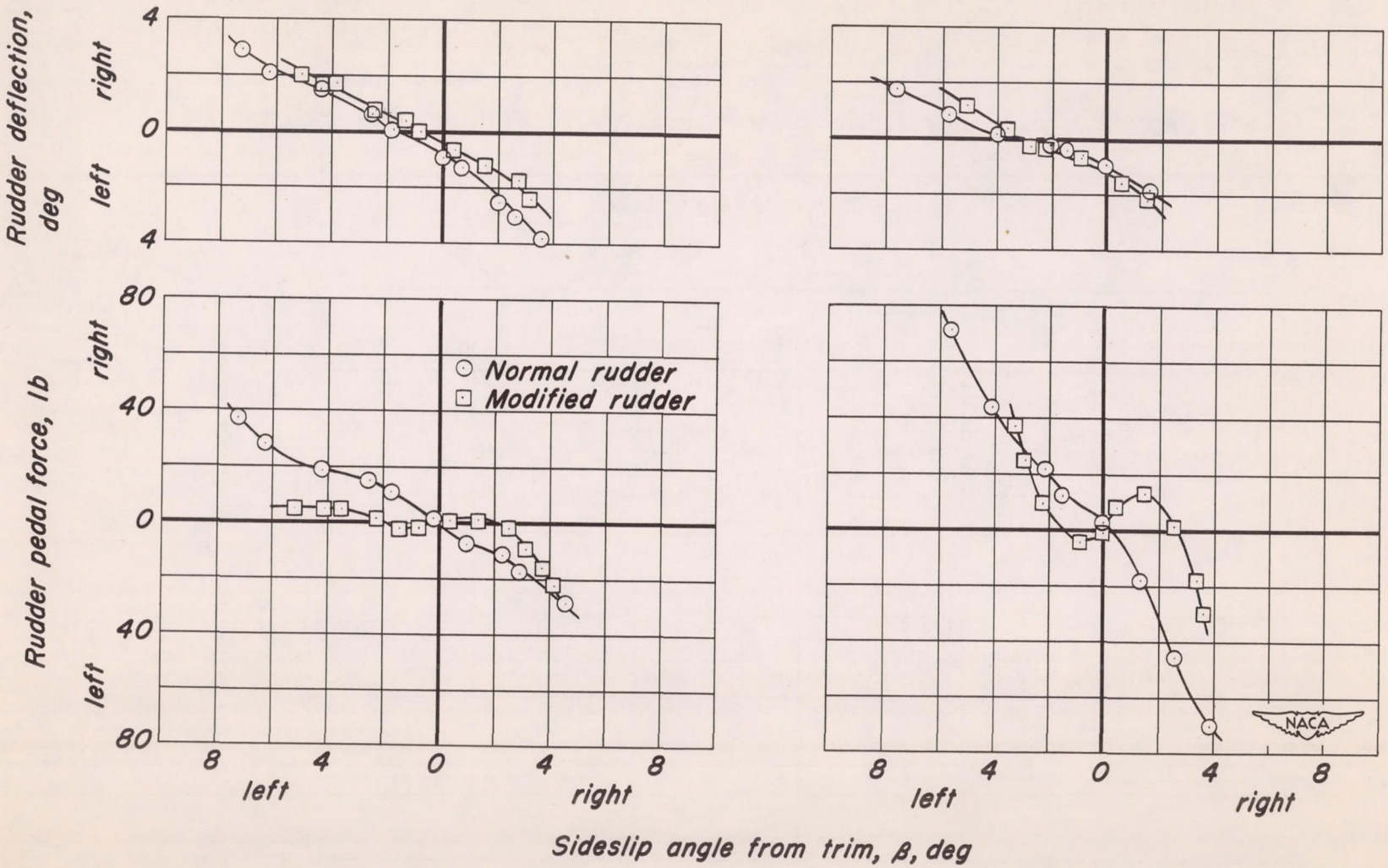
Figure 7.- Sample gunsight-camera frames with corresponding time histories of azimuth tracking error in aerial-target run.





(b) Modified rudder.

Figure 7.- Concluded.



(a) V_i = 200 knots.

(b) V_i = 350 knots.

Figure 8.- Rudder control characteristics in steady sideslip.

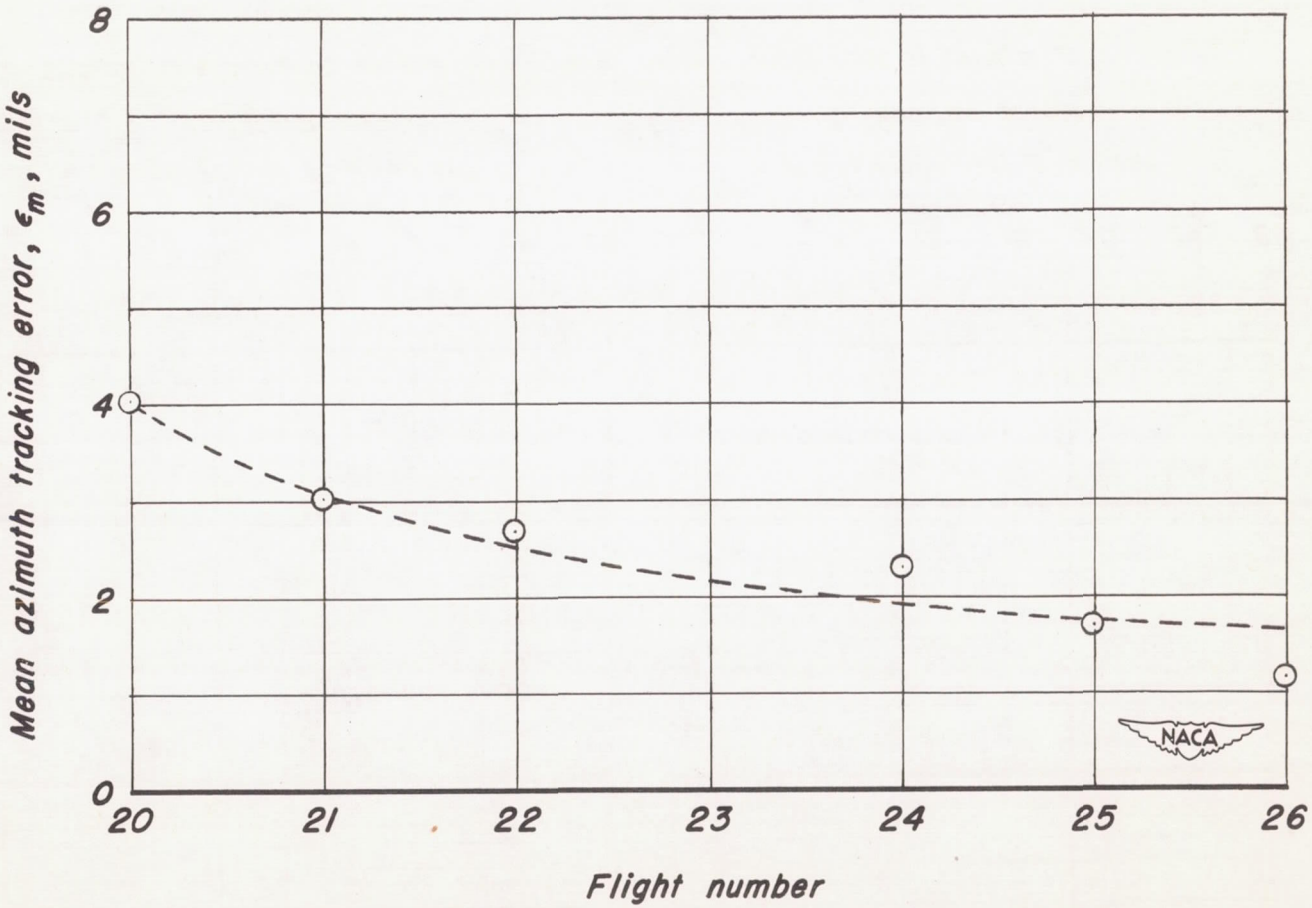
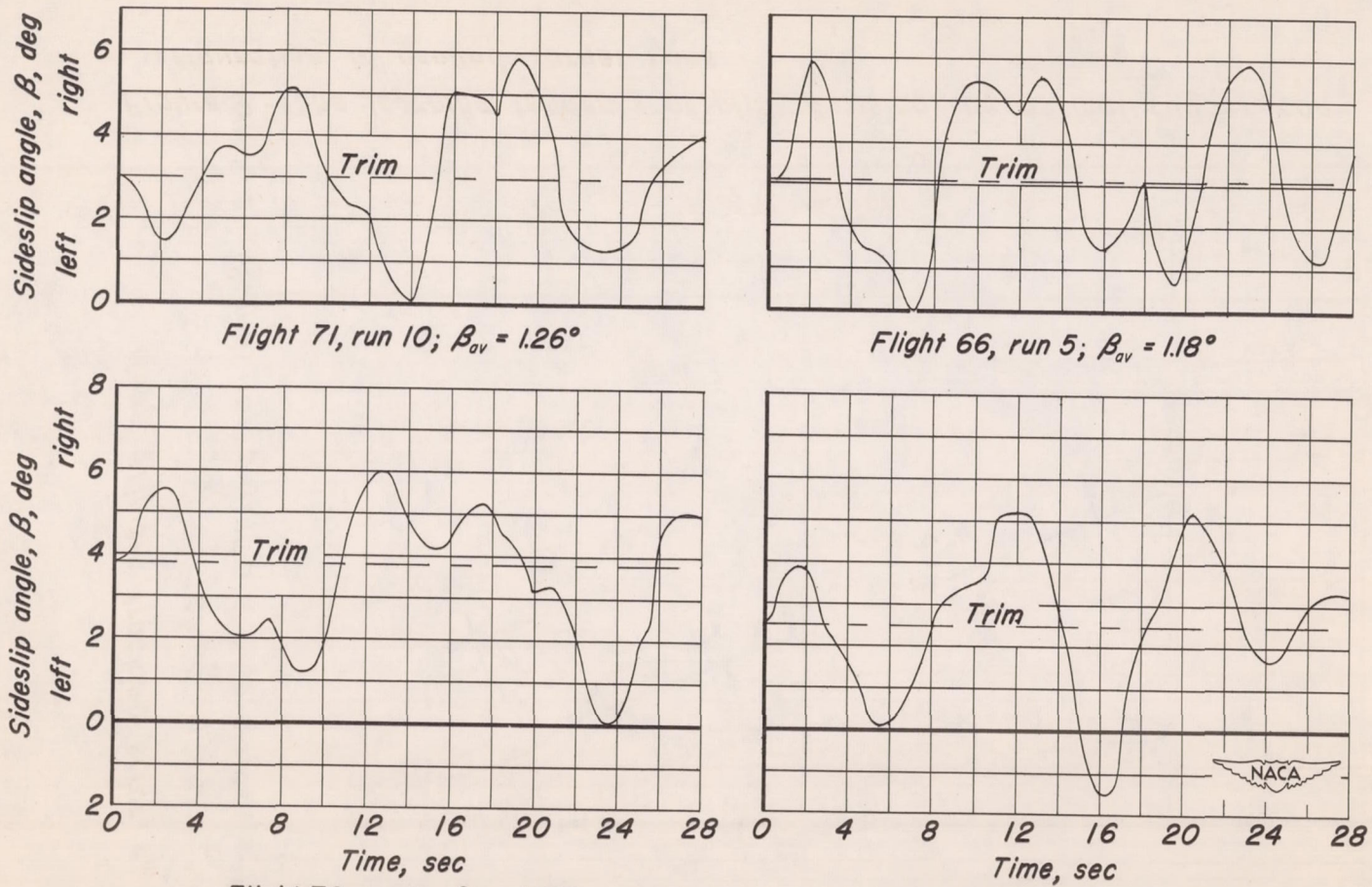


Figure 9.- The learning tendency of pilot A using the normal rudder configuration in ground-target runs.



Flight 71, run 10; β_{av} = 1.26°

Flight 66, run 5; β_{av} = 1.18°

Flight 70, run 7; β_{av} = 1.36°

(a) Normal rudder.

Flight 65, run 4; β_{av} = 1.48°

(b) Modified rudder.

Figure 10.- Sample time histories of sideslip angle in aerial-target runs by pilot B.

Note: Not to scale

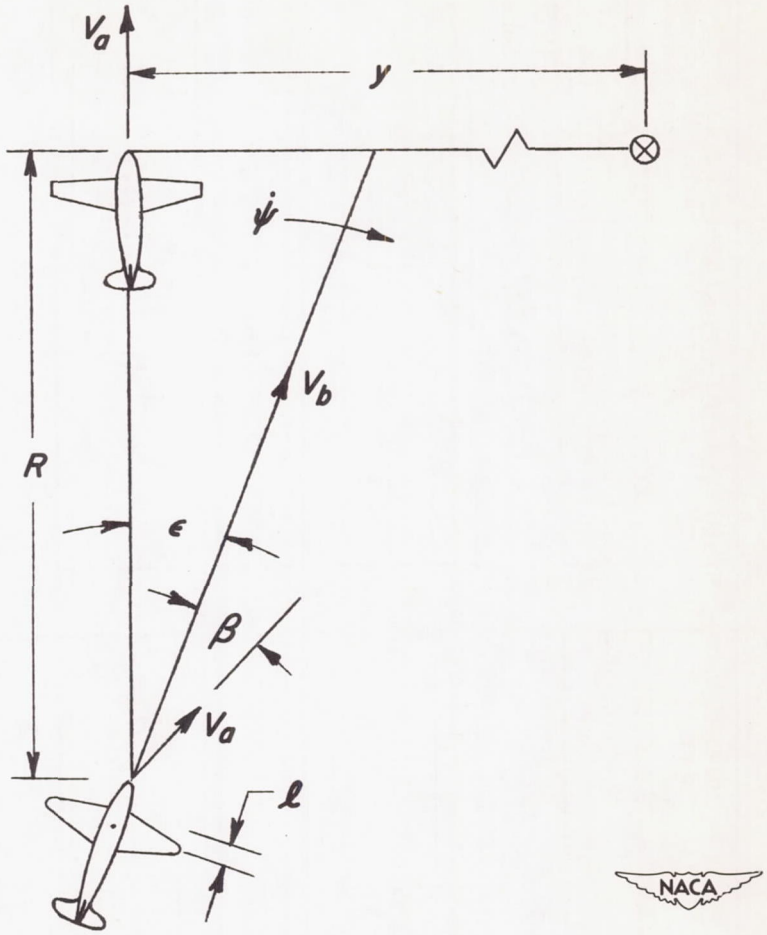


Figure 11.- Sketch of a simplified tail pursuit situation in the azimuth plane.