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FLIGHT TEST TO DETERMINE FEASIBILITY OF A PROPOSED AIRBORNE WAKE VORTEX DETECTION CONCEPT

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SUMMARY

This investigation was conducted to determine the radial extent at which aircraft-mounted flow vanes or roll rate gyros can sense the circulatory flow field that exists around the lift-induced vortex system generated by an aircraft in flight. It has been proposed that the circulatory nature of the flow field may provide a basis for designing a feasible airborne wake avoidance detection system, if found to be of sufficient strength and span to activate instrumentation onboard a following aircraft.

A flight test was conducted using a Lockheed P-3 as a vortex generating aircraft and a Piper PA-28R to laterally probe the vortex flow field. The probe aircraft was equipped with wingtip sensors for measuring angle of attack and angle of sideslip, and with a fuselage-mounted gyroscope for measuring roll rate. Smoke generators mounted below each wingtip of the P-3 aircraft were used to make the wingtip vortices visible. During flight tests, the probe aircraft would approach one of the wingtip vortices at approximately a 6-degree closure angle while flying at the same altitude. The lateral separation was determined, after the test, by analyzing video images made with cameras mounted in each wingtip of a Beech T-34C observation aircraft. The cameras recorded the proximity of the probe aircraft with respect to the smoke-marked core of the vortex and were time-correlated with probe aircraft's sensor measurements. The effects of the circulatory flow field around the vortex were obtained without the probe aircraft having to penetrate the vortex.

Analysis of the flight test data indicated that the vortex was detectable at a lateral distance of approximately 105 feet (best results) using unsophisticated instrumentation. Measurements were made from the centerline of the probe aircraft to the center of the nearest vortex with the probe aircraft flying between ½ and 1½ miles behind the vortex generating aircraft.

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INTRODUCTION

The growth of aviation has placed a great demand on airport facilities to accommodate increased air traffic. However, the longitudinal separation distances required between aircraft to avoid the very strong wake vortices created by the large transport aircraft in use today remains an obstacle to increasing landing capacity. The Federal Aviation Administration (FAA) is investigating ground and airborne vortex warning systems which will detect the presence of a wake vortex. With an effective warning system, the required separation might be reduced and landing capacity increased.

A theoretical airborne system, currently being considered, would employ onboard sensors to identify the proximity of a vortex system and provide a warning to the pilot in sufficient time to take evasive action. Knowledge of the furthest distance from the vortex where its effect can first be detected (by onboard sensors) is of vital importance since it establishes the time available for a pilot to execute an avoidance maneuver. A recent analytical study conducted for the FAA (Ref. 1) concluded that, within specified limits, state of the art sensors (e.g. flow direction vanes, roll rate gyros and accelerometers) could be used to detect trailing vortices early enough for vortex avoidance to take place. Following this study, NASA's Langley Research Center (LaRC) and the FAA's Langley Engineering Field Office conducted a flight investigation of behalf of the FAA's Wake Vortex Program Office to validate the analytical findings and help determine if continuing research in this area was warranted. This investigation evaluated the distance at which the vortex flow field could be detected by an instrumented aircraft. NASA's Wallops Flight Facility (WFF) was a joint participant in this flight program having the responsibility for instrumenting and operating the generator aircraft used for vortex generation. Wallops also provided the test range and control/monitoring facilities.

This report presents data obtained from the wake vortex detection flight test showing the effects of proximity to the vortex as recorded by aerodynamic sensors on the probe aircraft. The significance of these results relative to the conclusions reached in the analytical study (Ref. 1) is also discussed.

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SYMBOLS

h	altitude (ft)
P	roll rate; positive for rolling right wing down (deg/sec)
q	pitch rate; positive for nose pitching up (deg/sec)
r	yaw rate; positive for nose right
V	true velocity (ft/sec)
X_b	X body axis through Probe Aircraft center of gravity
Y_b	Y body axis through Probe Aircraft center of gravity
Y	lateral distance between the cg of the probe airplane and the vortex core (ft)
Z_b	Z body axis through the Probe Aircraft center of gravity
α	angle of attack; positive for trailing edge up (deg)
ß	angle of sideslip; positive for trailing edge left (deg)
ϵ	approach intercept angle to the vortex (deg)
δ_a	aileron deflection; positive for right aileron trailing edge down (deg)
δ_r	rudder deflection; positive for trailing edge left (deg)
δ_s	stabilator deflection; positive for trailing edge down (deg)

DESCRIPTION OF TEST
Airplanes and Instrumentation

To carry out this flight investigation, an orchestration of three aircraft was required; the first, a large airplane, was used to generate wingtip vortices of sufficient strength to be detected. Vortices generated by this aircraft were made visible by smoke from generators attached under the wingtips. The second airplane, used to probe the vortex, was instrumented to detect the aerodynamic effects attributed to the vortex flow field when flown into the wake of the generating aircraft. Measurements made onboard were recorded for later analysis. The third airplane, equipped with video recording equipment, was used to observe the smoke-highlighted vortex and the probe aircraft in order to determine their lateral separation distance. Specifically, the three NASA airplanes employed in this test were: a Piper PA-28R (Fig. 1) used to "probe" the vortical flow field; a modified T-34C (Fig. 2) used to videotape the interaction of probe aircraft with the vortex; and a Lockheed P-3 (Fig. 3) used to generate the vortex. Smoke generators (Fig. 4) were mounted under each wingtip of the P-3. Figures 5 and 6 show the P-3 aircraft in flight (at altitude and near the ground, respectively) with its wingtip vortices made visible by the smoke. Physical characteristics of the probe and generator aircraft are outlined in Table 1 and shown in Figures 7 and 8.

For this experiment, flow direction vanes were installed at the end of booms mounted at each wingtip of the probe aircraft, as shown in Figures 9 and 10, and used as vortex detection sensors to measure angle of attack (α) and sideslip (β). Other sensors mounted onboard the probe aircraft included three-axis accelerometers, rate and attitude gyros, and control surface position transducers (to measure control deflection angles). A list of key measurement parameters, ranges and resolutions is given in Table 2. Data collected onboard the probe aircraft were sampled 125 times per second and were filtered at 10 Hz. All probe aircraft measurements were referenced to a set of orthogonal axes with the origin at the aircraft's center of gravity as shown in Figure 11.

Data were collected on the position of the probe aircraft's control surfaces, particularly that of the ailerons, in order to isolate the effect of the induced vortex flow from any pilot control

inputs. This was accomplished by examining the control surface deflection data for the same time periods over which any change in roll rate or α/β vane position was noted; if no control deflection was recorded, it was assumed that the effect noted had been due to a vortex encounter. Instrumentation for this test permitted only the position of the right aileron of the probe aircraft to be recorded; however, for the small aileron deflections encountered in this test, the effect of the left aileron was assumed to be equal and opposite to that of the right aileron.

The observation aircraft was outfitted with a dual camera video recording system as shown in Figures 12 and 13. Instrumentation onboard consisted of:

- downward-looking video cameras mounted in each wingtip with their associated VHS recorders and control units in the cockpit,
- a time code generator and device for inserting the time code on the video tape,
- a downward-looking video camera mounted on the bottom of the fuselage (having a wider field of view than the wingtip cameras) used together with a video monitor for initial visual acquisition of the probe aircraft, and
- control switches in the cockpit permitting the display of any one of the three video cameras on the monitor.

During the data collection runs, the observation aircraft was flying directly above the probe aircraft which severely limited the pilot's view. To alleviate this problem, a wide-angle camera and a video monitor were installed in the aft cockpit to aid the observer pilot as he maneuvered to establish and maintain position while tracking the probe aircraft as it traversed the wake generated by the P-3. The monitor also enable verification that each wingtip camera was operating properly during the test.

To obtain the strongest wake possible, for this test, the generator aircraft was fully loaded with fuel; this brought the take-off weight of the airplane to approximately 91,000 pounds, the maximum allowable weight. In support this experiment, the airplane was modified to accommodate the installation of a smoke generator at each wingtip. The generators (Fig. 4)

were self contained; each was 83 inches long, 10 inches in diameter and weighted 90 pounds. A thick white smoke was released in flight when Corvus oil was vaporized by a gasoline-fed heater inside each unit. The duration of the smoke available from each generator ranged from 9 to 10 minutes. Controls installed in the aircraft made it possible to operate the generators separately or in unison.

FLIGHT TEST PROCEDURE AND CONDITION

During flight testing, the generator and probe aircraft were separately acquired and tracked by Wallops range control using independent radar tracking systems. This scheme permitted processing of the radar data to provide a digital readout of the "in-trail" separation distance between the two aircraft, a condition mandated for operational safety considerations. Radar data processing also provided a rough indication of lateral separation distance and aircraft velocity data.

Measurement of the lateral distance between the probe aircraft and the vortex, while looking for the earliest indication of an encounter, was the fundamental objective of this investigation and posed a significant problem. Several techniques were considered. The first, a photogrammetry technique described in Reference 2, required that the location of the vortex core be marked by some means, other than smoke, to make it distinct enough for a pair of cameras to focus on. Separation distance could then be determined by geometrically combining the dual photographs. An attempt was made to "seed" the vortex using small balloons released from the rear door of Wallops Flight Facility's "Skyvan" aircraft. It was expected that the balloons would become entrained within the vortex core and provide suitable objects on which to focus. Several tests conducted at WFF, using air-filled and neutrally buoyant balloons, showed that this method was not feasible for vortex visualization, as very few balloons actually behaved as desired.

The videographic technique described in Reference 3 was ultimately employed where information derived from time-coded video images provided the basis for determining the lateral distance between the probe aircraft and the vortex core. After each data flight, an

analysis was conducted, in the laboratory, by "freeze-framing" selected video images taken with the charge coupled device (CCD) video cameras onboard the observation aircraft, see Figures 14 and 15. These cameras operate with finite, measurable, picture elements that were physically related to the image in order to determine precise separation distances with respect to a know reference, in this case the probe aircraft's wingspan. Camera lenses were corrected for image distortion by means of a sophisticated computer mapping program to remove any measurement errors due to geometric curvature. Only a single CCD camera was required onboard the observation aircraft to make use of this technique, although two cameras were actually installed. As a back-up means and for estimation purposes, rough measurements of aircraft/vortex separation distance were made by accurately knowing the wingspan of the probe aircraft and scaling the distance between the aircraft and the vortex core by this know dimension.

The flight test technique used to probe the vortex flow field is illustrated in Figure 16. After reaching the test altitude of approximately 5000 feet, the generator aircraft would fly a large circular path while waiting to rendezvous with the probe and observation aircraft. Upon reaching test altitude, the probe and observation on aircraft flew circular paths inside that of the generator. To start a test run, the generator aircraft would roll out on a predetermined heading and fly a straight course while holding a constant altitude. The other aircraft would continue to circle until the desired spacing between the generator and probe aircraft was attained; at this point the probe would roll out of its turn onto the generator aircraft's heading and follow, in-trail, at a predetermined distance ready to collect data.

The generator aircraft was constrained to fly at an airspeed as close as possible to 130 kts, since the probe could not fly faster. This constraint provided an additional degree of safety during the test since the generator would always be out-running the probe. Immediately prior to starting a run, the observation aircraft would climb to an altitude 500 feet above the probe aircraft. Using the CRT display from the wide-angle video camera (mounted in the fuselage) to initially acquire the probe, an observer in the rear seat would attempt to maintain a position directly above the probe airplane during the data run. Once the observation aircraft had a video image of the probe on the monitor, the probe aircraft would move laterally

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toward the smoke-highlighted vortex at a shallow angle (approx. 6 degrees) and activate instrumentation onboard to measure and record the effect of the circulatory flow field of the vortex. When the probe aircraft had approached the vortex far enough to become noticeably affected by the vortex, the pilot would take positive control and move away from the vortex, never actually penetrating the vortex core. One of the ground rules for the test was that corrective control would be applied only when the probe aircraft had reached a roll condition beyond which pilot intervention was required to maintain control of the aircraft; the ailerons were otherwise maintained in a neutral position to avoid corrupting the data.

Movement of the vortices behind the generator aircraft (occurring under the influence of the wing downwash, vortex interaction and atmospheric effects) presented somewhat of an alignment problem for the pilot of the probe aircraft. As a result, it was necessary for the probe pilot to make a judgement as to where the vortex would level off and begin his probe at that point.

In addition to flying shallow approaches to the vortex flow field, several test runs were flown having the probe aircraft fly a course parallel to the vortex but at a fixed lateral offset distance. This was done in an attempt to see if the instrumentation was more sensitive to the vortex flow field when the angular intercept was eliminated. This technique also prolonged the time available to observe a particular flow condition assuring that the complete effect of the vortex was measured. Data were obtained during the flight test for cases where the landing flaps of the generator aircraft were placed in both the retracted and extended positions. This was done to investigate the potentially greater strength of the vortex expected to be generated in the landing condition when the aircraft velocity was reduced from 130 to 118 knots with its flaps extended.

To maximize the time aloft available for data collection during each flight, the wingtip generators were operated singularly for a particular test configuration, since there was no visual contribution to be gained from illuminating the alternate vortex. When smoke was expended from the first generator, testing continued using the second, with the probe aircraft

changing position to allow penetration of the other vortex. Operating in this manner allowed for 18-20 minutes of test time per flight.

Atmospheric conditions were an essential consideration for each test flight. Smooth stable air was required to prevent the resulting data from being degraded by the presence of turbulence. Preflight weather briefings were always conducted and, in some cases, pretest turbulence surveillance flights were flown to verify stable atmospheric conditions in the test area.

Four test flights were flown at the Wallops Flight Facility during the vortex detection experiment.

RESULTS AND DISCUSSION

General Observations

A sampling of the data, collected by the acquisition system onboard the probe aircraft, is shown in Figure 17 for a representative test run. The parameters are shown plotted against time, for a period of approximately one minute, and were obtained while the probe aircraft made a shallow-angle approach to the vortex generated by the right wingtip of the generator aircraft; i.e., the probe approached from the right to left. The data in Figure 17 are typical of results obtained for most of the test runs and represent the best data obtained during the test. The more significant parameters, actively responding to a vortex encounter, were roll rate and angle of attack/angle of sideslip. Figure 18 presents data showing the lateral separation distance between the probe aircraft and the vortex for the vortex encounter described above.

A number of test runs were conducted to determine the greatest distance at which it was possible to detect the vortex flow field; a sampling of results from various test runs is shown in Figure 19. These data are presented in chronological order based on earliest detection of a change in the aircraft's roll rate. Data are presented for both aircraft configurations tested: first with landing flaps retracted and then with flaps extended. With the flaps extended, the

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airspeed of the generator aircraft was reduced from 130 to 118 knots. Deployment of flaps, together with the attendant reduction in speed of the aircraft, classically results in an increased circulatory flow around the wing (a requirement for maintaining lift) and, hence, vortices of greater magnitude. The anticipated increase in strength was expected to make the vortex more detectable; however, separation distances recorded with the flaps deployed did not reflect the increase expected when compared with data obtained when the flaps were retracted (see Table 3).

Several theories have been suggested as to why no increase in vortex strength was observed. First, it is possible that the separate vortices generated by the flaps and wingtips had not yet fully merged at the in-trail distances where the measurements were taken, approximately ½ mile to 2 miles, behind the generator aircraft (see Table 3). Deployment of the flaps could conceivably have reduced the strength of the wingtip vortex by diverting part of the energy generated by the wingtip vortex to the flap vortex, thus decreasing the detectibility of the wingtip vortex (see Ref. 4). Finally, wash from the propellers could have imparted turbulence of sufficient strength to reduce the overall effect attributed to the deployed flaps. Although the atmospheric and flight test conditions were essentially the same for each particular configuration, the variations observed in the separation distances shown in Figure 19 could have been due to an undetected vertical offset between the probe aircraft and the vortex. Approaching the vortex at a higher or lower altitude would have resulted in a reduced flow field acting on the instrumentation.

Roll Rate Analysis

In practice, as an aircraft approaches a vortex flow field from the outside, the wing panel nearest the vortex experiences an increase in lift caused by the vertical velocity associated with the circulatory flow around the vortex. This vertical velocity, when combined with the forward velocity of the aircraft, results in a local increase in the angle of attack of the wing panel. For the case where the left wing of the encountering aircraft is nearest the vortex, this phenomenon would cause the aircraft to begin a roll to the right if unchecked. The ability to measure the resulting roll was expected to validate the premise of using this scheme as a

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means to detect the onset of a vortex encounter; hence, roll rate was closely analyzed during data reduction. (The roll damping for various types of aircraft will differ considerably, however, and will have a decided effect on the usefulness of this technique for a particular aircraft.)

After looking at all of the data obtained from the probe aircraft, roll rate turned out to be the primary metric most useful in the early detection of a vortex encounter. For the particular run illustrated, analysis of the data indicated that the vortex effect was first noted at a time-code reading of 15 hours, 4 minutes and 5 seconds. The best results obtained during the entire flight test are represented by the data in Figure 17 which shows the greatest separation distance to be approximately 105 feet.

For analysis and comparison purposes, it was assumed that the probe aircraft encountered the vortex in the same lateral plane (i.e., at the same altitude.) Although vertical position data were not available for comparison of either the probe aircraft's altitude or that of the trailing vortex, conservative estimates indicate that there would be a maximum error in observed separation distance of 2 feet resulting from a ± 20 foot altitude differential. The test pilot was assumed to have maintained the probe aircraft's position within these tolerances.

The roll rate can be seen in Figure 17 to gradually increase as the PA-28 aircraft moved closer to the center of the vortex, as would be expected, reaching a maximum roll rate of approximately 8 degrees-per-second at a separation distance of 50 feet. At this point, the indicated roll to the right (caused by the vortex encounter) was counteracted by the pilot's control input, which can be seen in the data for aileron deflection. At the same time, a positive rudder deflection was applied to overcome the positive yawing moment caused by the vortex flow. The pilot's input commanded an aircraft roll rate in the opposite direction sufficient to effectively cancel the vortex-induced roll. The corresponding data for "roll attitude" indicated that the aircraft had rolled 20 degrees to the right while the recovery control action returned the aircraft to its original position of zero degrees.

Angle of Attack and Sideslip Analysis

During the approach from which the data in Figure 17 was derived, the α/β vane on the left wingtip was on the side nearest the vortex. Observation of angle of attack and sideslip data show the first signs of disturbance began at a distance of 105 feet from the vortex core (at the time 15:04:05) but did not exhibit a noticable trend at this time. After an initial rise, these data returned to their average quiescent levels before indicating continuous deflections which started approximately two seconds later (15:04:07) at a separation distance judged to be 90 feet. The right wingtip (outboard) α/β vane was also affected by the vortex, but to a lesser degree, and not until the aircraft was positioned approximately 50 feet from the vortex core. This observation was considered valid since the right wingtip vane was located further from the vortex, initially, by the wing span (35.3 feet).

Comparison with Theory

As stated initially, the objective of this flight test was to evaluate the feasibility of using aircraft-mounted flow vanes or a roll rate gyro to provide airborne wake vortex detection. Theoretical distances were predicted by Bilanin (Ref. 1) for lateral vortex detection based on the use of both flow angle vanes and roll rate sensors. These distances are presented in Figure 20 according to aircraft weight, ranging from 0 to 600,000 pounds. (The generator aircraft used for this flight test weighed 91,000 pounds.) Comparing flight test results with theoretical predictions of separation distance reveals that the best vortex detection distance (105 feet) was approximately 30 feet less than the prediced value. (Distance measurements were made from the probe aircraft centerline to the centerline of the nearest vortex core.) This discrepancy could be attributed to the fact that the flight test measurement system was not sensitive enough to provide earlier detection or that the theoretical model may have been optimistic in predicting the actual detection distance.

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CONCLUDING REMARKS

A flight test investigation was conducted to determine the lateral distance at which flow vanes or a roll rate gyro onboard an aircraft could detect the presence of a wake the vortex flow field. Key results and findings are listed below:

1. The best data obtained from this test indicated the presence of a trailing vortex, as detected by instrumentation onboard the probe aircraft, at a lateral distance of approximately 105 feet. (This was 78% of the theoretically predicted distance).

2. The presence of a vortex could be sensed by changes in angle of attack and sideslip (measured with an α/β vane mounted on each wingtip) and by the roll rate of the aircraft (measured with body-mounted gyros). Roll rate gyros gave the earliest indications which were later substantiated by α/β indications.

3. Lateral detection distances were found to be approximately the same for cases where landing flaps were extended and retracted on the vortex-generating aircraft. This finding could have resulted from prop wash turbulence diminishing the flap vortices or incomplete merging of the individual flap and wingtip vortices at the close in-trail location, behind the P-3, where measurements were made. Whatever the mechanism, the vortex detected was weaker than expected for the case where flaps were extended.

4. Determination of lateral separation distance between the aircraft and the vortex by pixel analysis and interpretation (Ref. 3), with a charge coupled device (CCD) video camera, was a useful technique (assuming both the aircraft and the vortex are at approximately the same altitude).

Based on the findings of this flight test, it is recommended that further testing be conducted to expand the database using larger aircraft and more sensitive instrumentation. Since the

vortex is a direct function of the weight of the generating aircraft, the flight results presented herein (for a 91,000 pound aircraft) fall far below the weight limit of 250,000 pounds established by the FAA as the lower limit for vortices that are considered hazardous. Vortex strength and corresponding detection distances can be expected to increase as the weight of the generating airplane increases; hence, further flight tests utilizing larger vortex-generating aircraft should be conducted to assess this theory in the higher weight range. (Vortex detection distances have already been theoretically predicted for a range of weights encompassing most transport airplanes flying today, Figure 20 and Reference 1.)

It is possible that more sensitive instrumentation could be developed and tested which would permit earlier detection of the vortex flow field. For example, it may be possible to design a sensor that would more directly sense the vortex rotational flow. The wingtip sensors used in this flight test were only designed to measure the angle of attack, angle of sideslip and the forward velocity of the aircraft. While vortex action did deflect the α/β vanes to some extent, no change was measured in velocity as recorded by the anemometer. This was due to the fact that the instrument was free to move and align itself with incoming vortex flow.

If future flight tests are pursued, additional techniques for probing the vortex should be investigated. During this test, the probe aircraft consistently approached the vortex from a lateral position at approximately the same altitude as that of the vortex. Future tests should be conducted with approaches made to the vortex from above, below and at various angles between these two limits. The instrumentation, as well as the aircraft, could be expected to react differently to the alternate approach techniques.

REFERENCES

1. Bilanin, Alan J.; Teske, Milton E.; and Curtiss, Howard C., Jr.: *Feasibility of an Onboard Wake Vortex System.* NASA CR-187521, April 1987.

2. Snow, Walter L.; Burner, Alpheus W.; and Goad, William K.: *Photogrammetric Technique Using Entrained Balloons for In-flight Ranging of Trailing Vortices.* NASA TM-4129, October 1989.

3. Childers, Brooks C. and Snow, Walter L.: *Video Photographic Considerations for Measuring the Proximity of a Probe Aircraft with a Smoke Trailing Wingtip Vortex.* NASA TM-102691, June 1990.

4. Patterson, James C., Jr.; and Jordan, Frank L., Jr.: *An Investigation of the Increase in Vortex Induced Rolling Moment Associated With Landing Gear Wake.* NASA TM X-72786, November 1975.

TABLE 1

AIRPLANE CHARACTERISTICS

PROBE AIRCRAFT = Piper PA-28R (single engine/propeller)

Average Test Weight	2,400 pounds
Wingspan	35.43 feet
Wing Area	173.7 square feet
Aspect Ratio	7.24
Tip Chord	42.2 inches
Mean Aerodynamic Chord	62.16 inches

GENERATOR AIRCRAFT = Lockheed P-3 (4 engine/propeller)

Typical Test Weight	91,000 pounds
Wingspan	99.0 feet
Wing Area	1,300 square feet
Wing Taper Ratio	25:1
Root Chord	227 inches
Tip Chord	91 inches
Flaps	tested fully extended and retracted

TABLE 2

KEY MEASUREMENTS LIST FOR PA-28
DATA SYSTEM

Measurement	Type of Sensor	Range	Resolution
Altitude	Pressure Altimeter	0-10,000 ft	39 ft
Airspeed	Tachometer	30-150 kts	0.6 kt
Elevator Deflection	Control Position Transducer	± 10°	0.1°
Aileron Deflection (right wing)	Control Position Transducers	+30°, -16°	0.2°
Rudder Deflection	Control Position Transducer	±28°	0.2°
Vertical Acceleration	Accelerometer	-1g, +3g	.015g
Longitudinal Acceleration	Accelerometer	±0.5g	.004g
Angle of Attack (left and right wingtips)	Flow Direction Vane Potentiometer	±15°	0.12°
Angle of Sideslip (left and right wingtips)	Flow Direction Vane Potentiometer	±15°	0.12°
Pitch Attitude	Attitude Gyro	±30°	0.24°
Roll Attitude	Attitude Gyro	±60°	0.5°
Pitch Rate	Rate Gyro	±60 deg/sec	0.5 deg/sec
Roll Rate	Rate Gyro	±60 deg/sec	0.5 deg/sec
Yaw Rate	Rate Gyro	±60 deg/sec	0.5 deg/sec

TABLE 3

TEST CONDITIONS AT
THE DETECTION THRESHOLD

Run No.	Probe-vortex Separation Distance (feet)	Probe Aircraft Velocity (Knots)	Test Altitude (feet)	In-trail Distance (N. Mi)	Generator Aircraft Flap Configuration
2-6/1	88	——	——	1.80	Retracted
2-10/1	72	120	5100	1.90	Retracted
2-10/5B	63	113	5100	2.25	Retracted
2-10/6	105	112	5200	1.45	Retracted
2-11/1.2	85	122	5170	0.47	Retracted
2-11/1.3	80	128	5140	0.48	Retracted
2-11/1.4	90	130	5100	0.48	Retracted
2-10/9B	102	118	5200	0.50	Deployed
2-10/10	61	118	5300	0.62	Deployed
2-11/7.2	95	118	5200	0.56	Deployed

Figure 1. Probe Aircraft. Piper PA-28R airplane equipped with wingtip boom-mounted vanes to detect vortex flow.

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Figure 2. Observation Aircraft. Beech T-34C equipped with wingtip-mounted video cameras to determine separation distance.
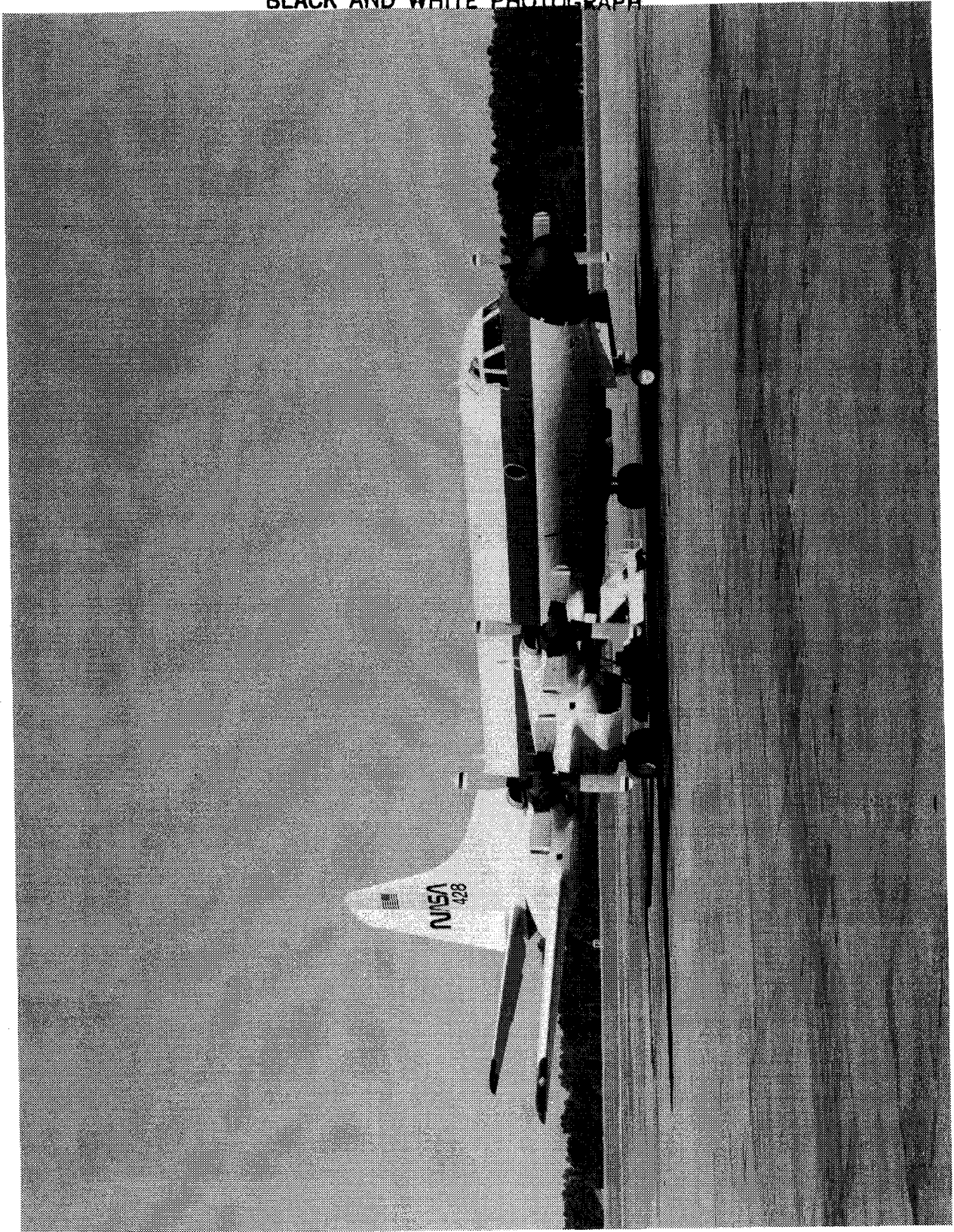
Figure 3. Lockheed P-3 vortex generating airplane.
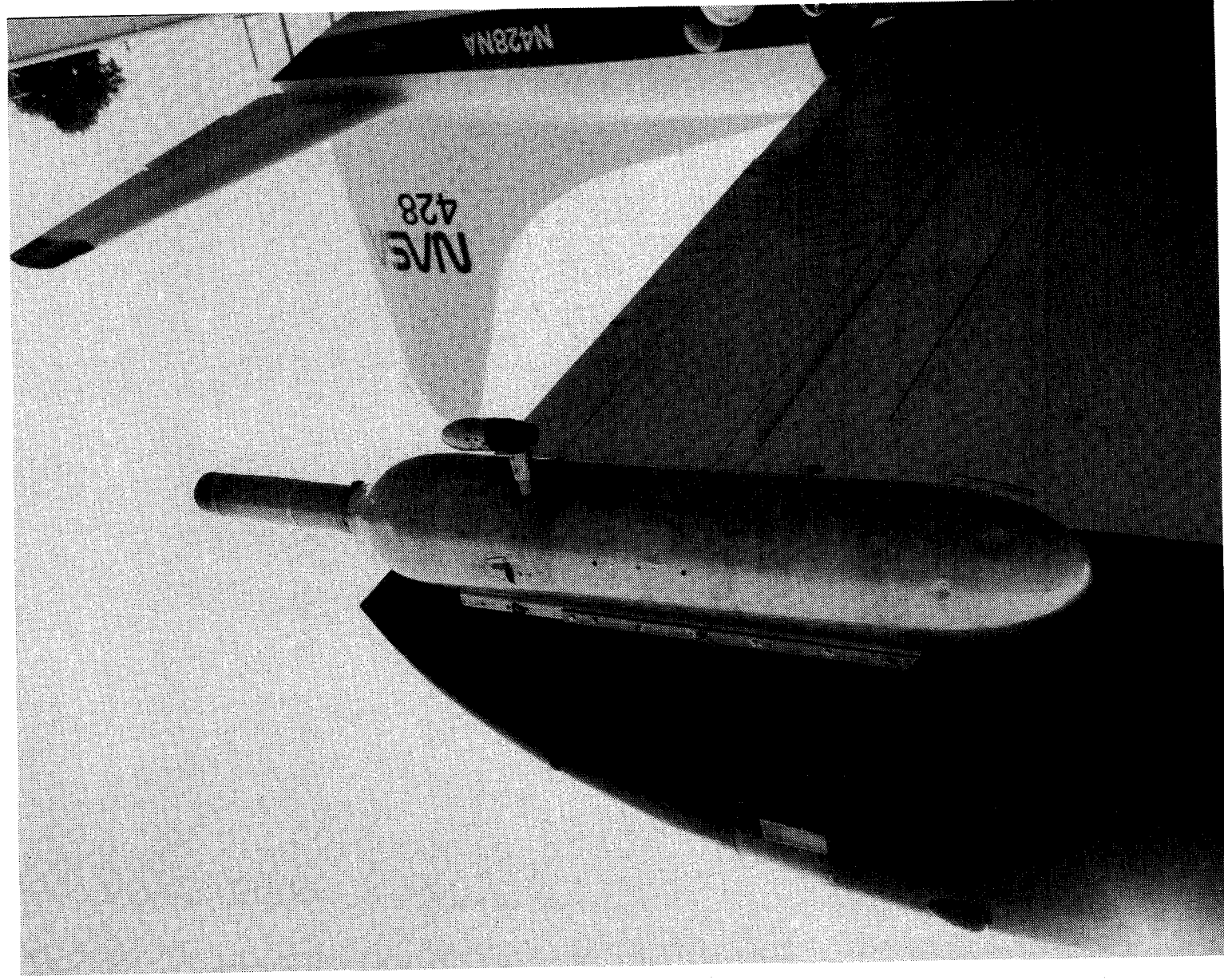
Figure 4. Smoke generator, one mounted on each wingtip of the P-3 aircraft.

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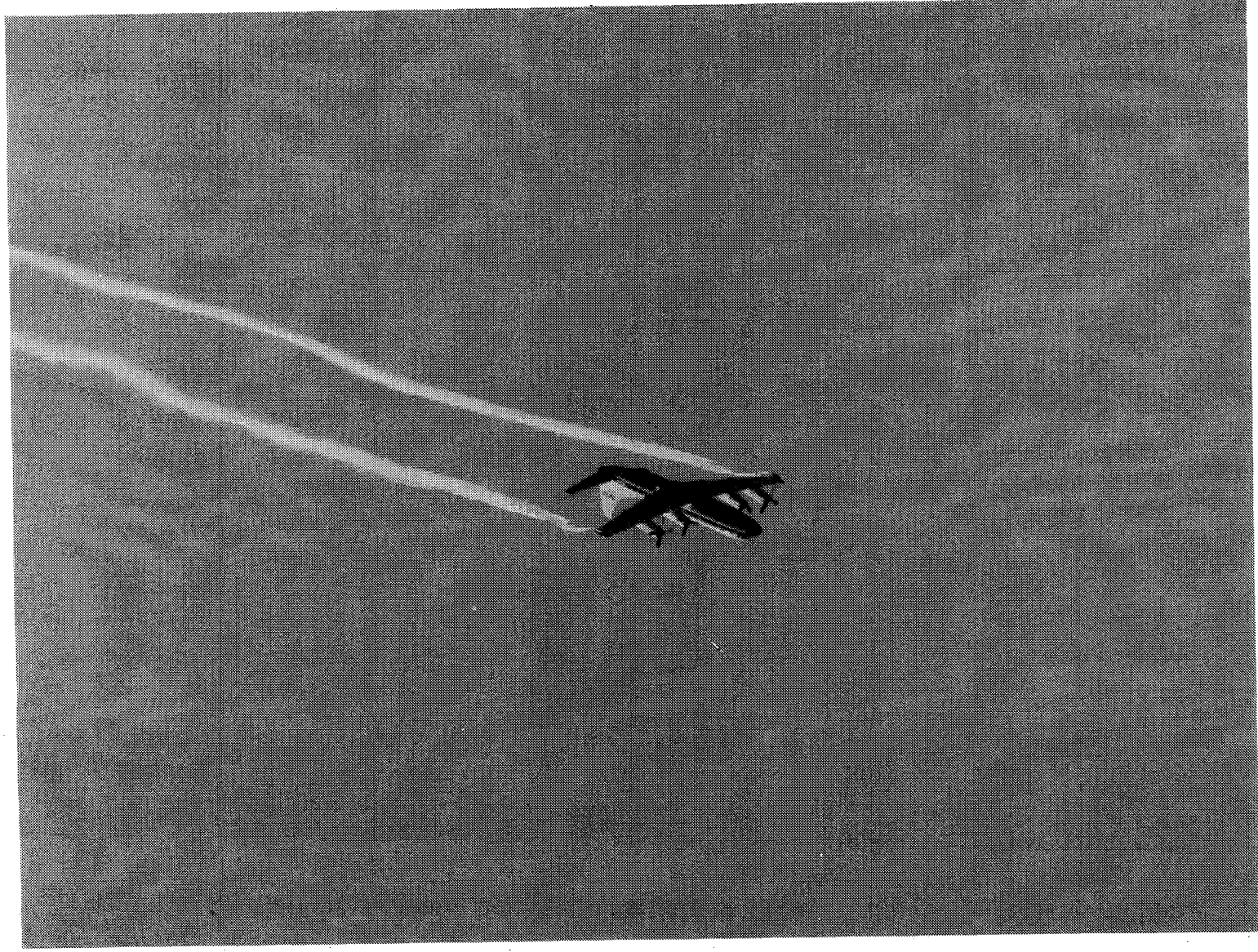
Figure 5. P-3 aircraft with wingtip vortices made visible by smoke. (Shown at test altitude, 5,000 ft.)
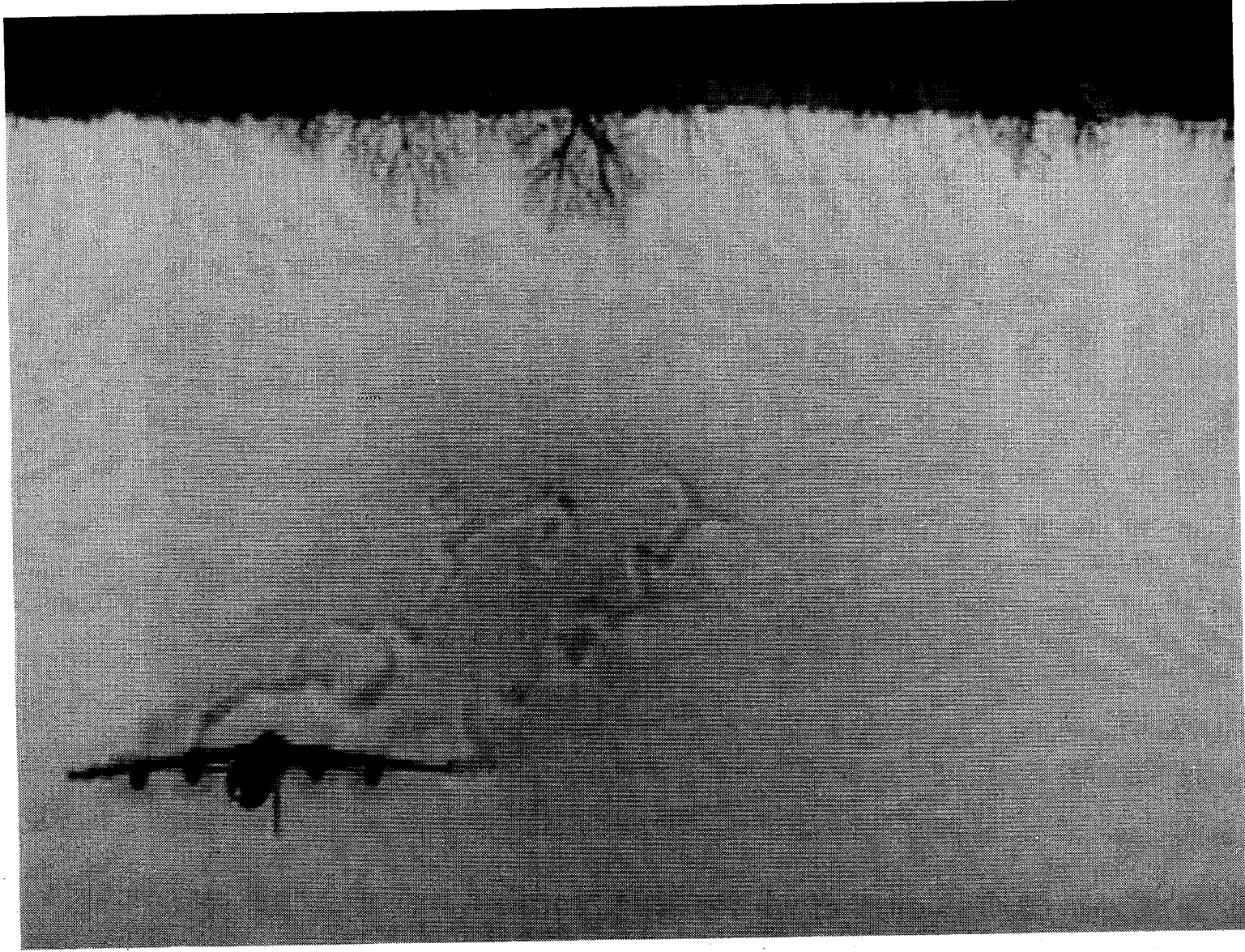
Figure 6. P-3 aircraft with wingtip vortices made visible by smoke. (Shown on low approach.)
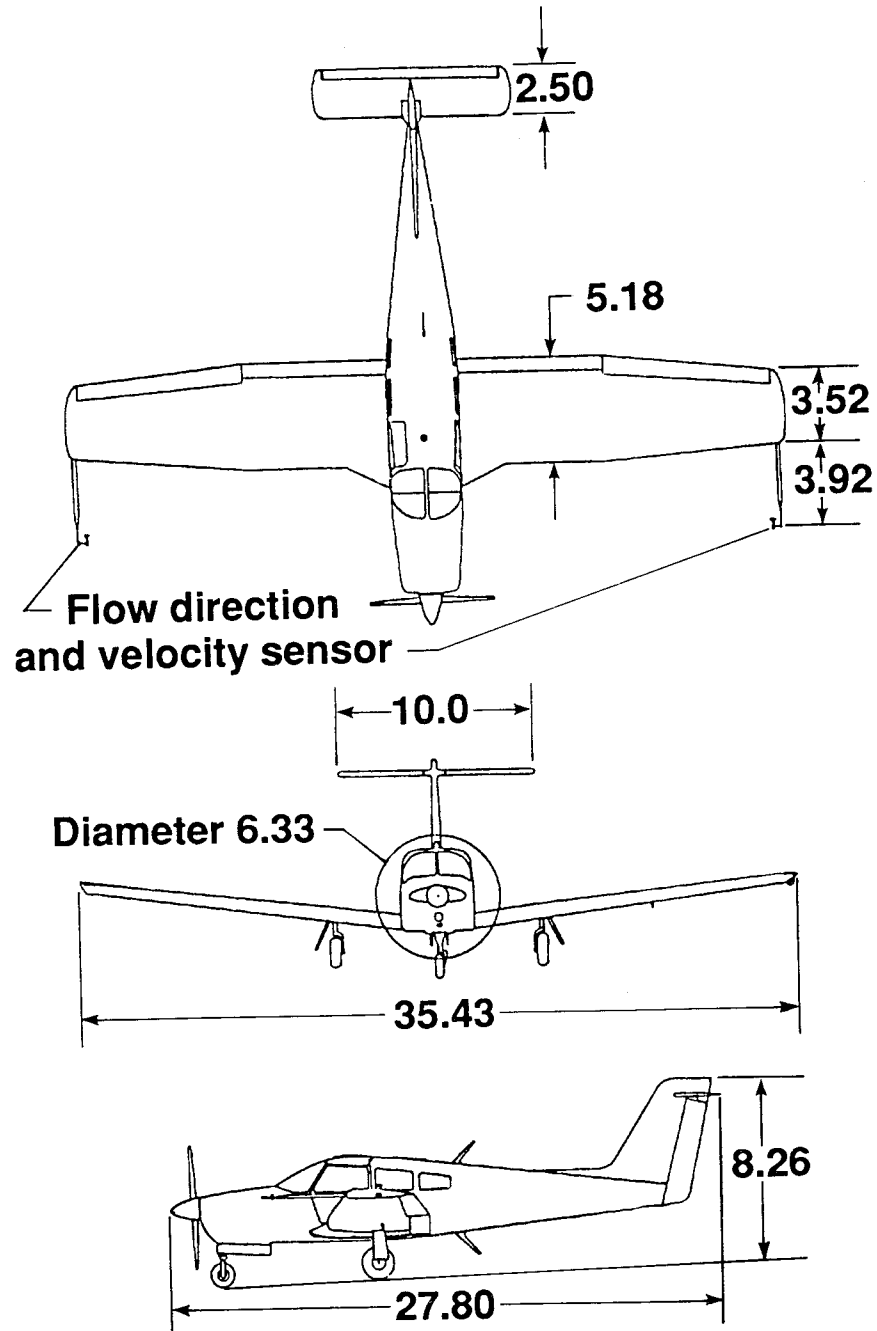
**Figure 7. Three view drawing of the PA-28 probe airplane.
(All dimensions are in feet.)**
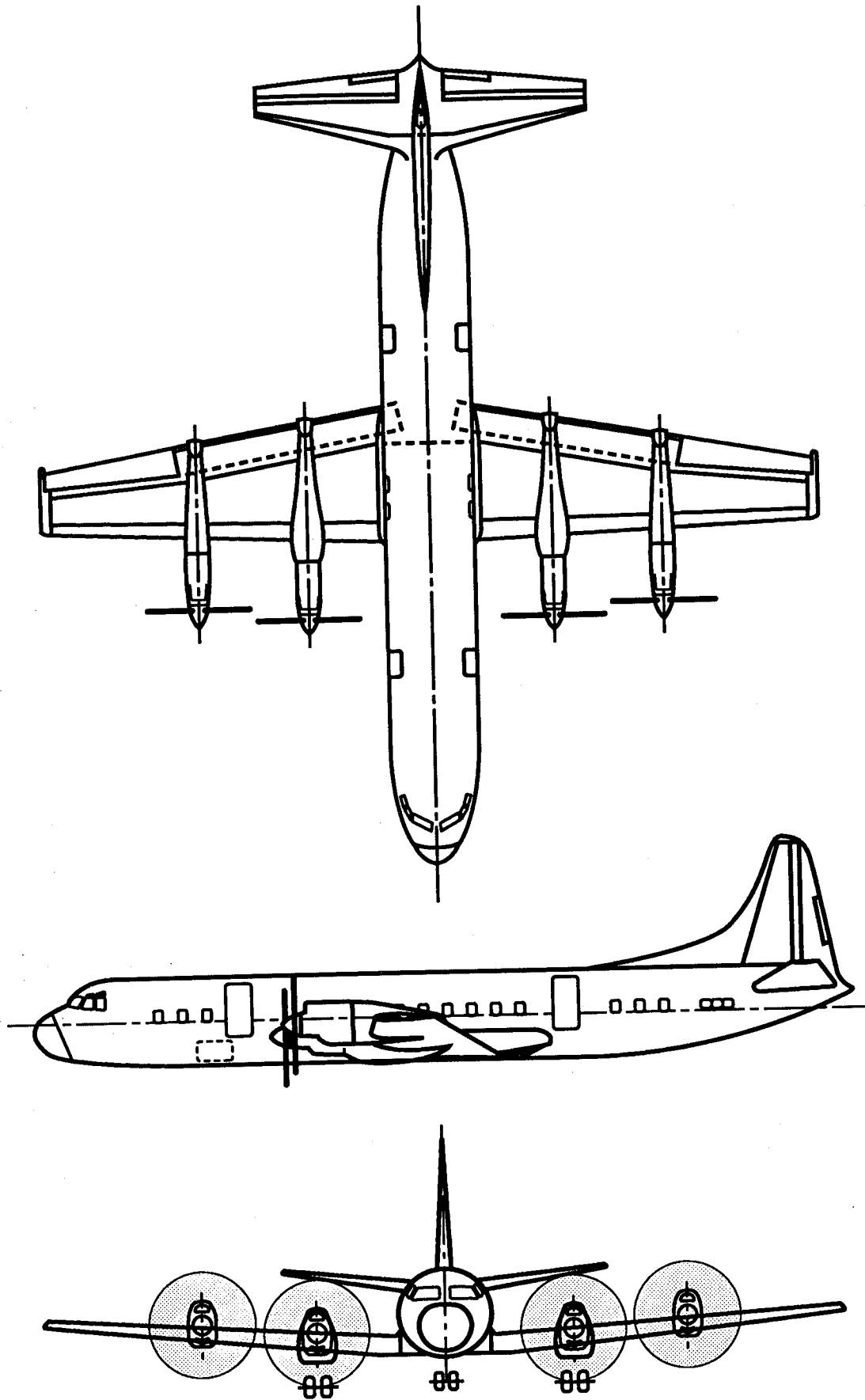
Figure 8. Three-view drawing of P-3 vortex generator airplane.
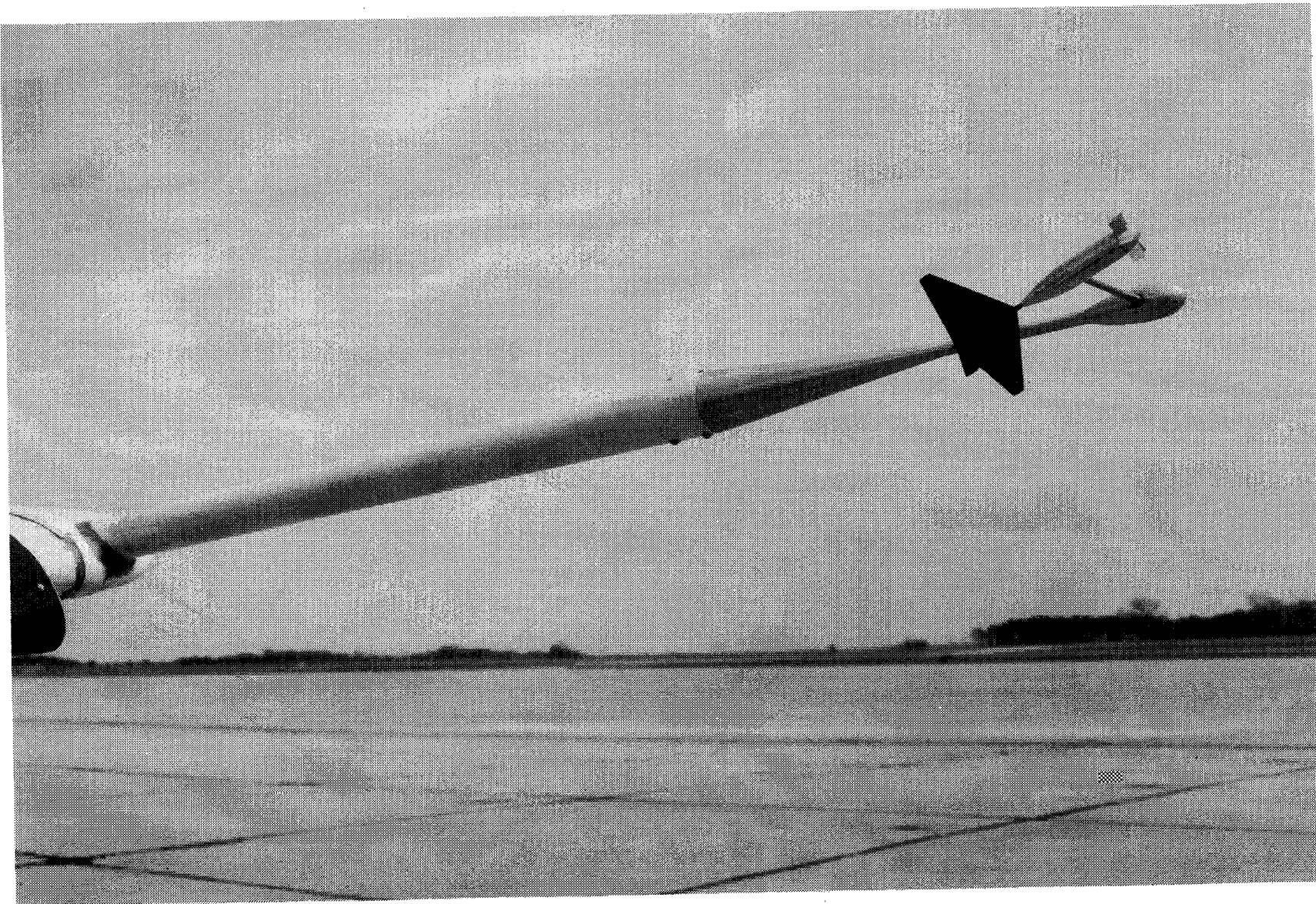
Figure 9. Flow direction vane and velocity sensor shown with boom support. (Typical of those attached to each wing tip of probe aircraft.)
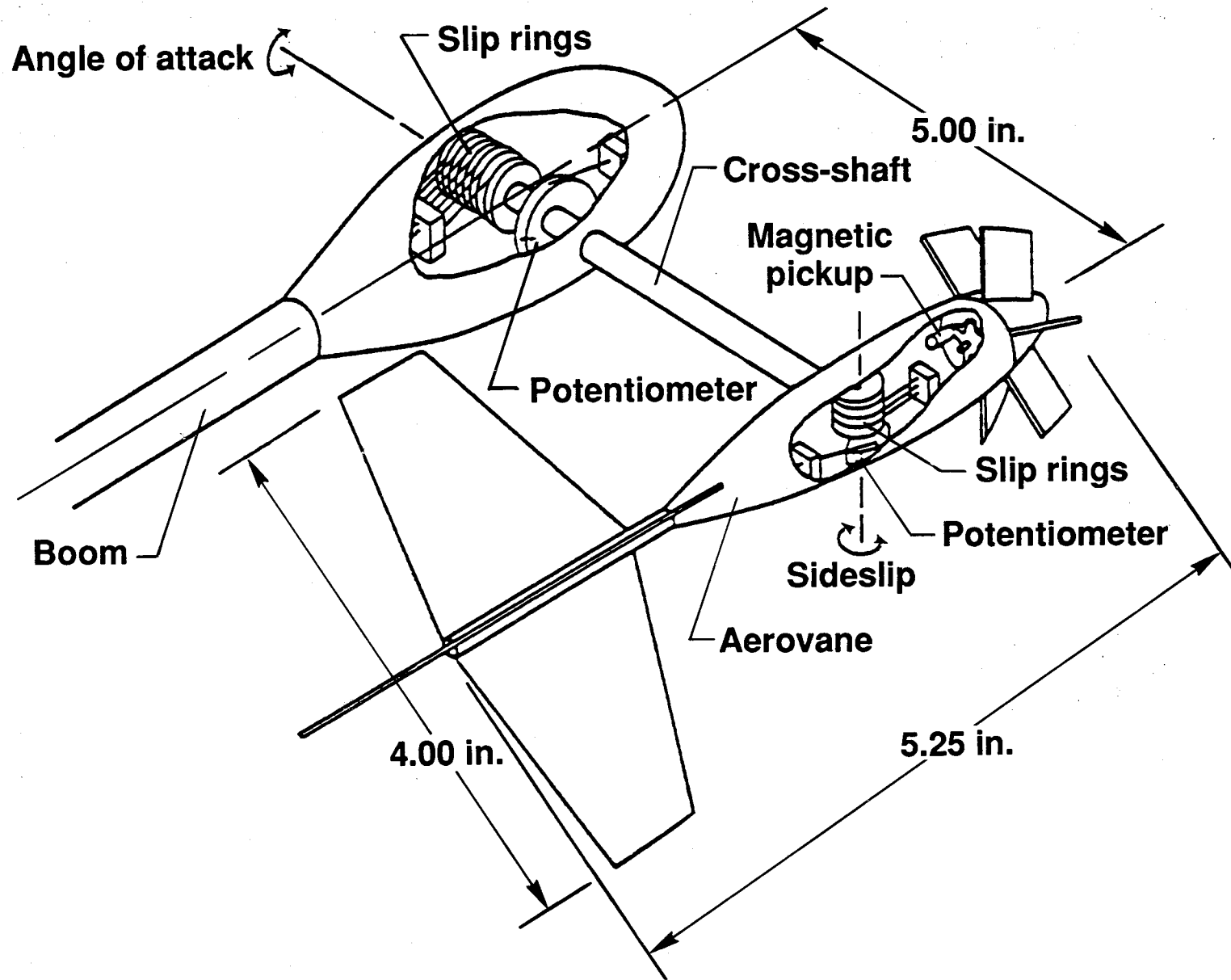
Figure 10. Detail of flow direction and velocity sensor mounted on wingtip probe support.
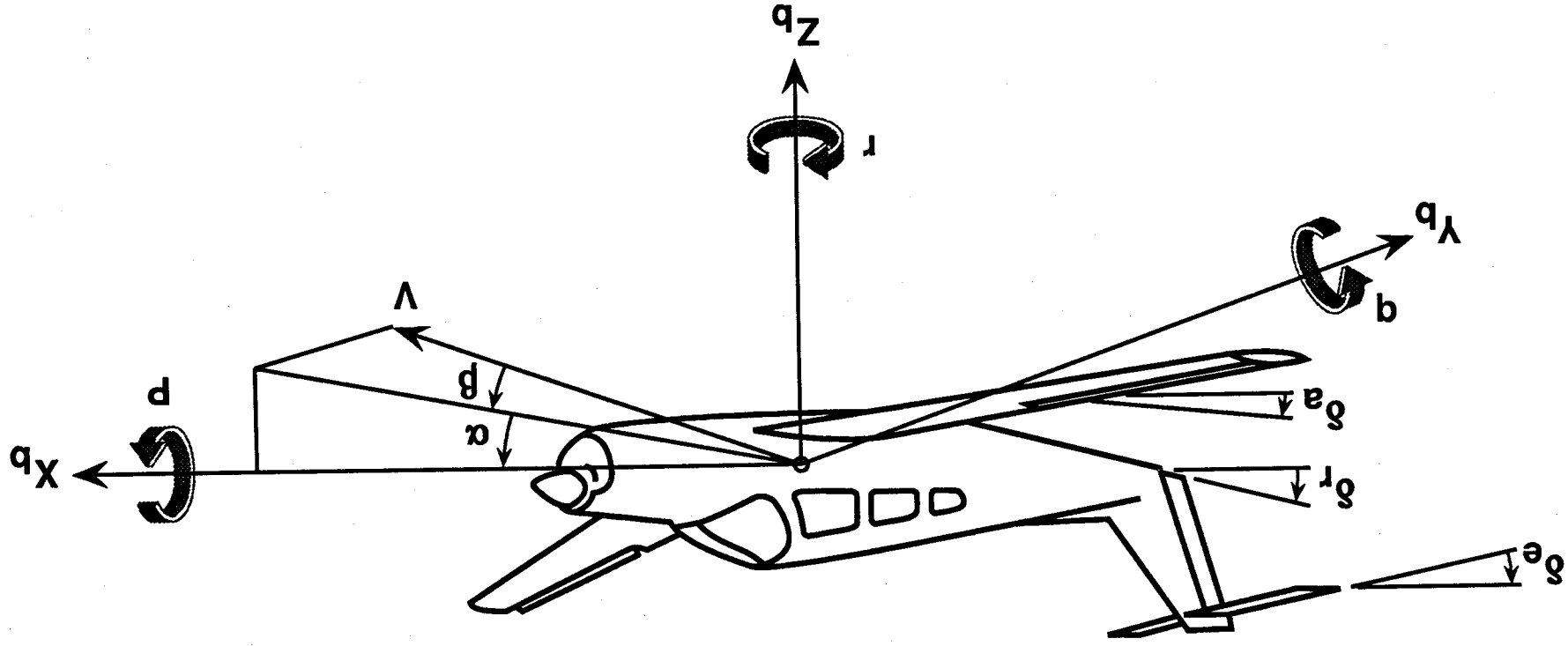
Figure 11. System of probe aircraft body axes. (Arrows indicate positive direction.)
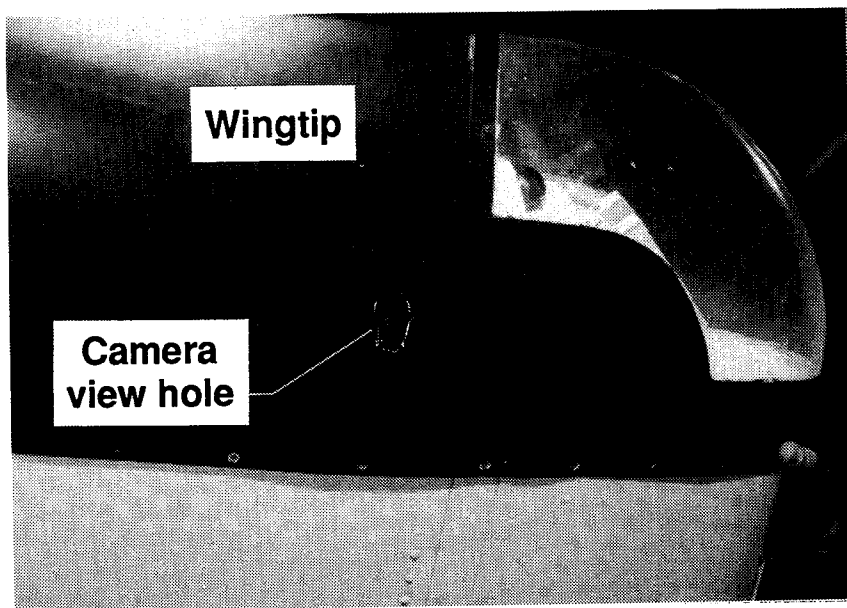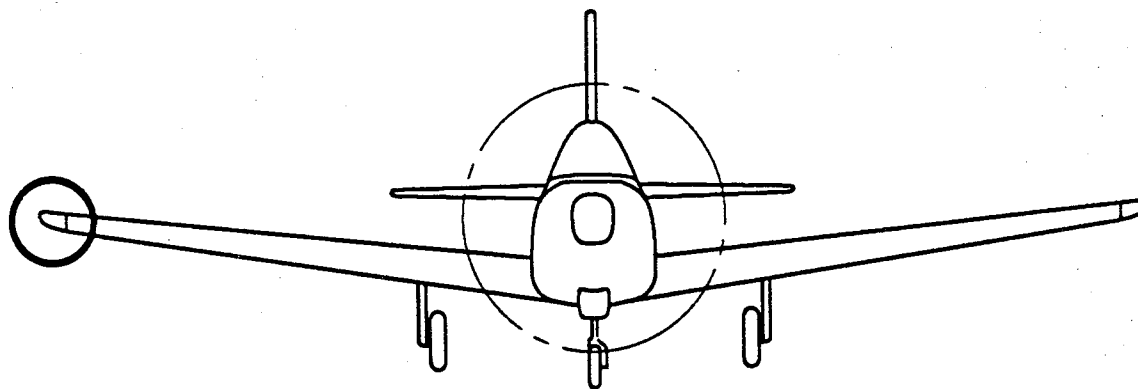
(a) Right wingtip fairing installed
showing opening for camera.
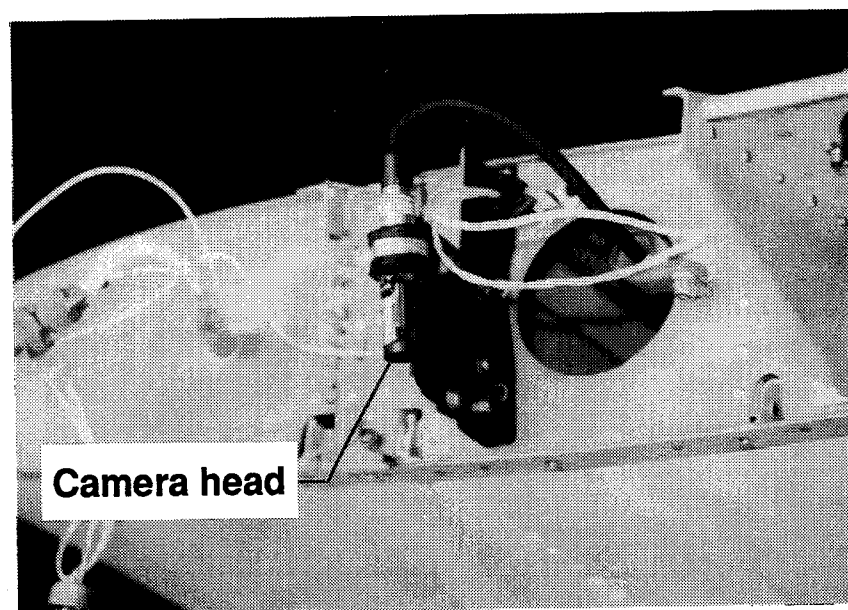
(b) Left wingtip cover removed
showing camera and mount.

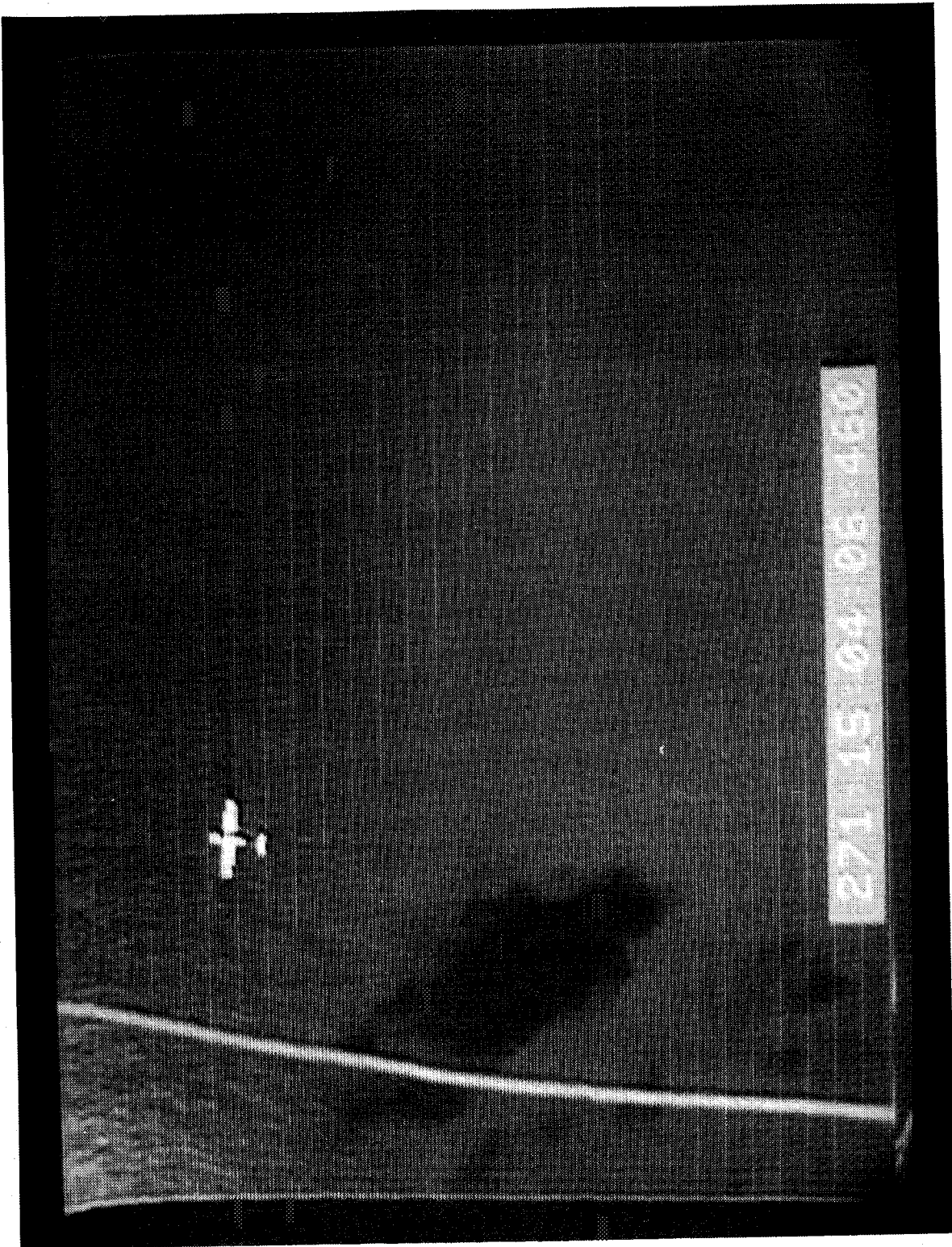Figure 12. Video camera location and mounting arrangement.

Tip
camera

**Camera
control
unit**

Recorder

Switch

**Power
supply**

**Video
time
inserter**

**Time
code
generator**

Monitor

**VHS
remote
unit**

Tip
camera

**Camera
control
unit**

Recorder

Switch

Fuselage
camera
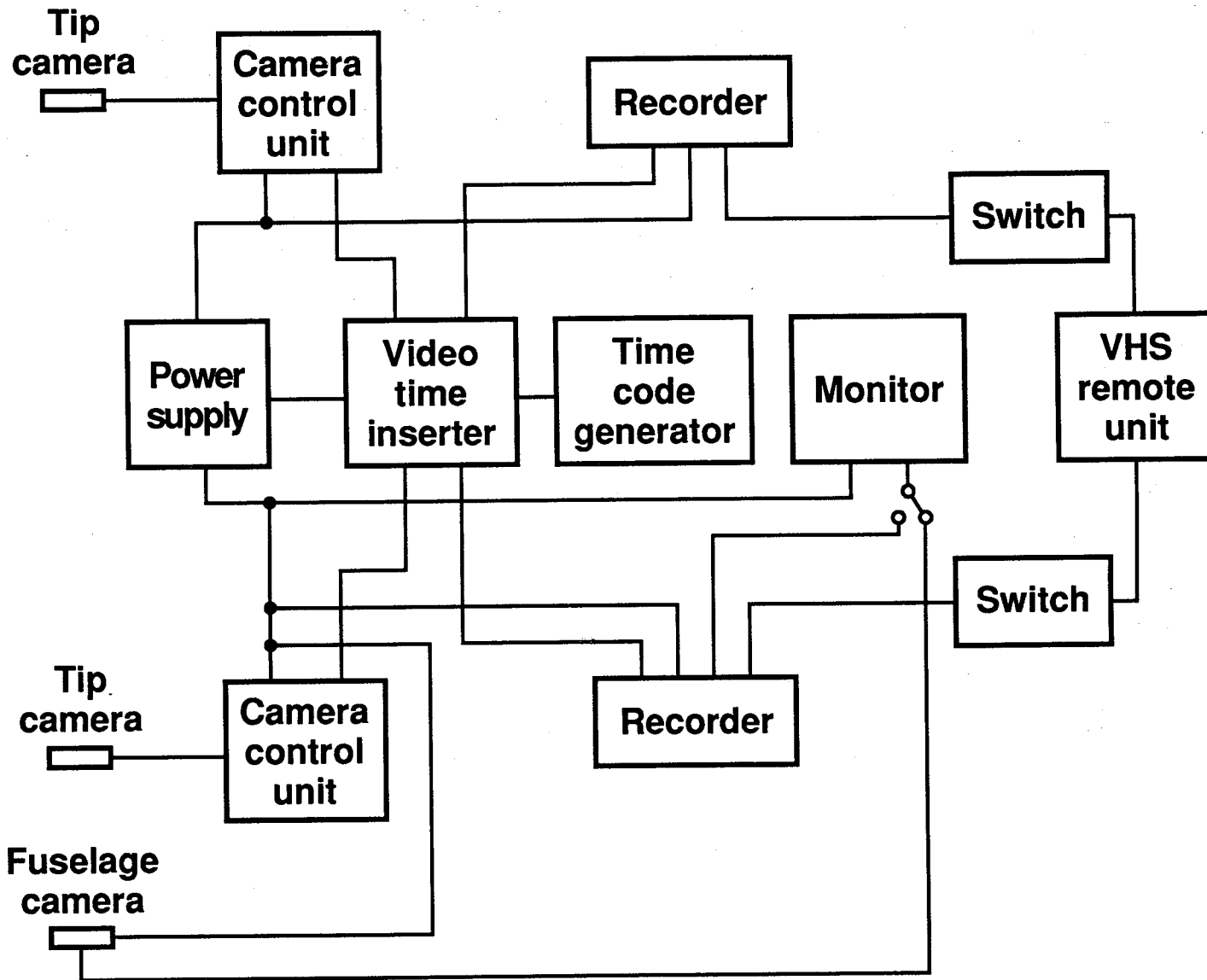
**Figure 13. Schematic diagram of the video camera system in the T-34C
observation airplane.**
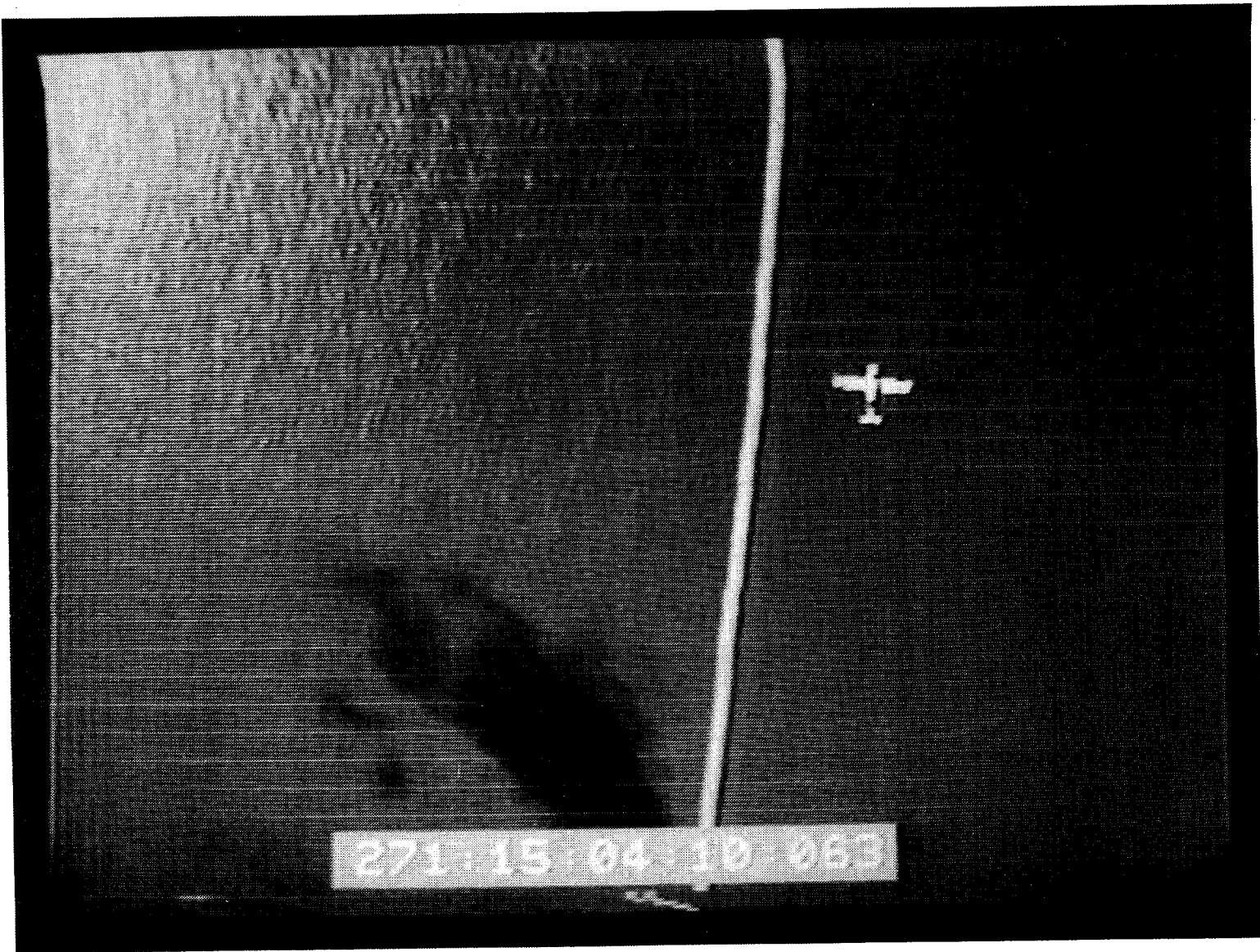
Figure 14. Video image of the Piper PA-28 and the smoke visable vortex. (Lateral separation distance approximately 50 feet.)

Figure 15. Piper PA-28/vortex separation distance approximately 90 feet.

Generator flight path

Probe ↓ **flight path**

ε

Y

Observation aircraft

500 ft. (min.)

Vortex generator aircraft

Probe aircraft

5,000 ft.
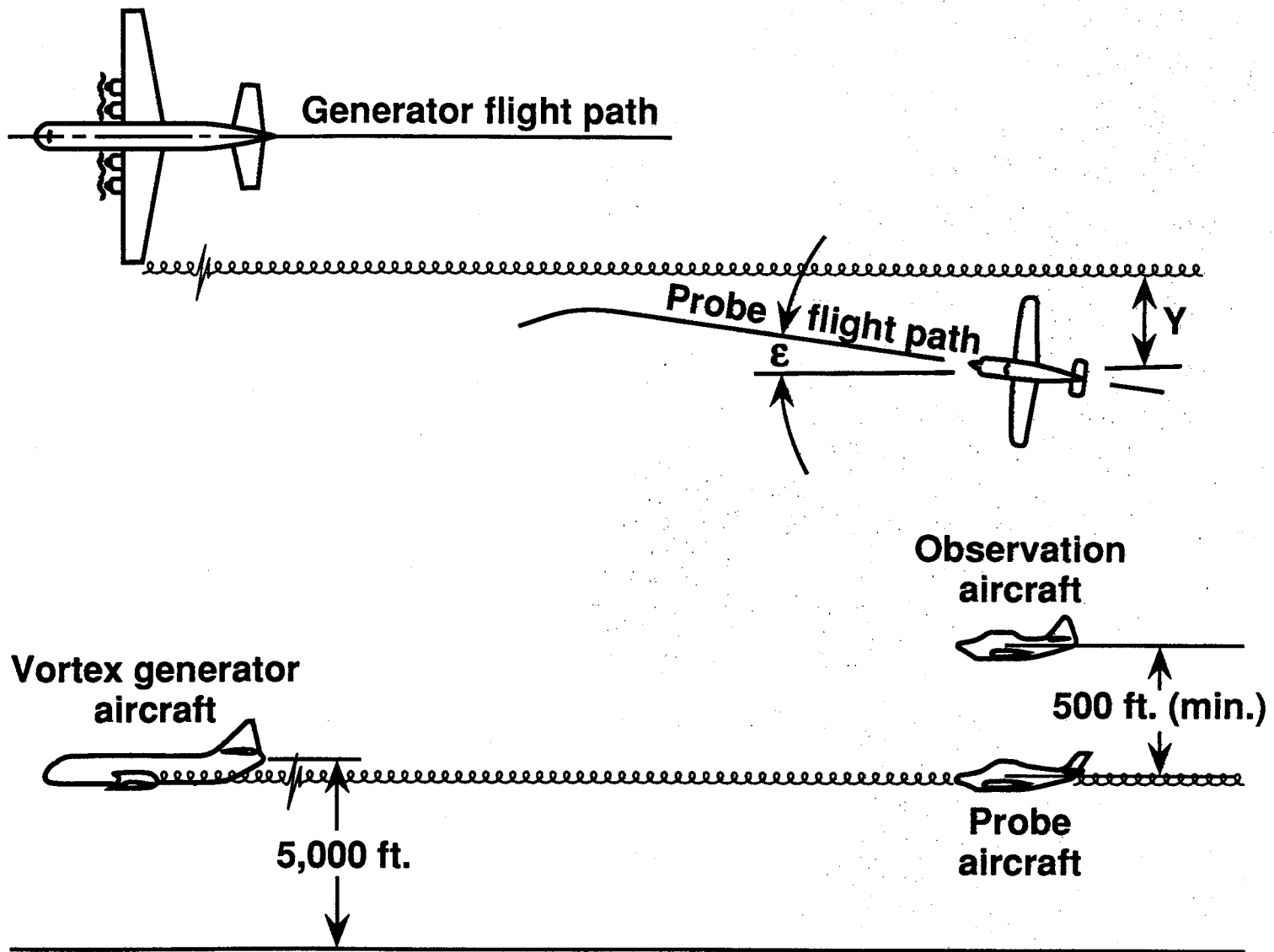
Figure 16. Scenario of a typical vortex approach.

Figure 17(a). A time history of data obtained from Flight 2-10, Run 6.
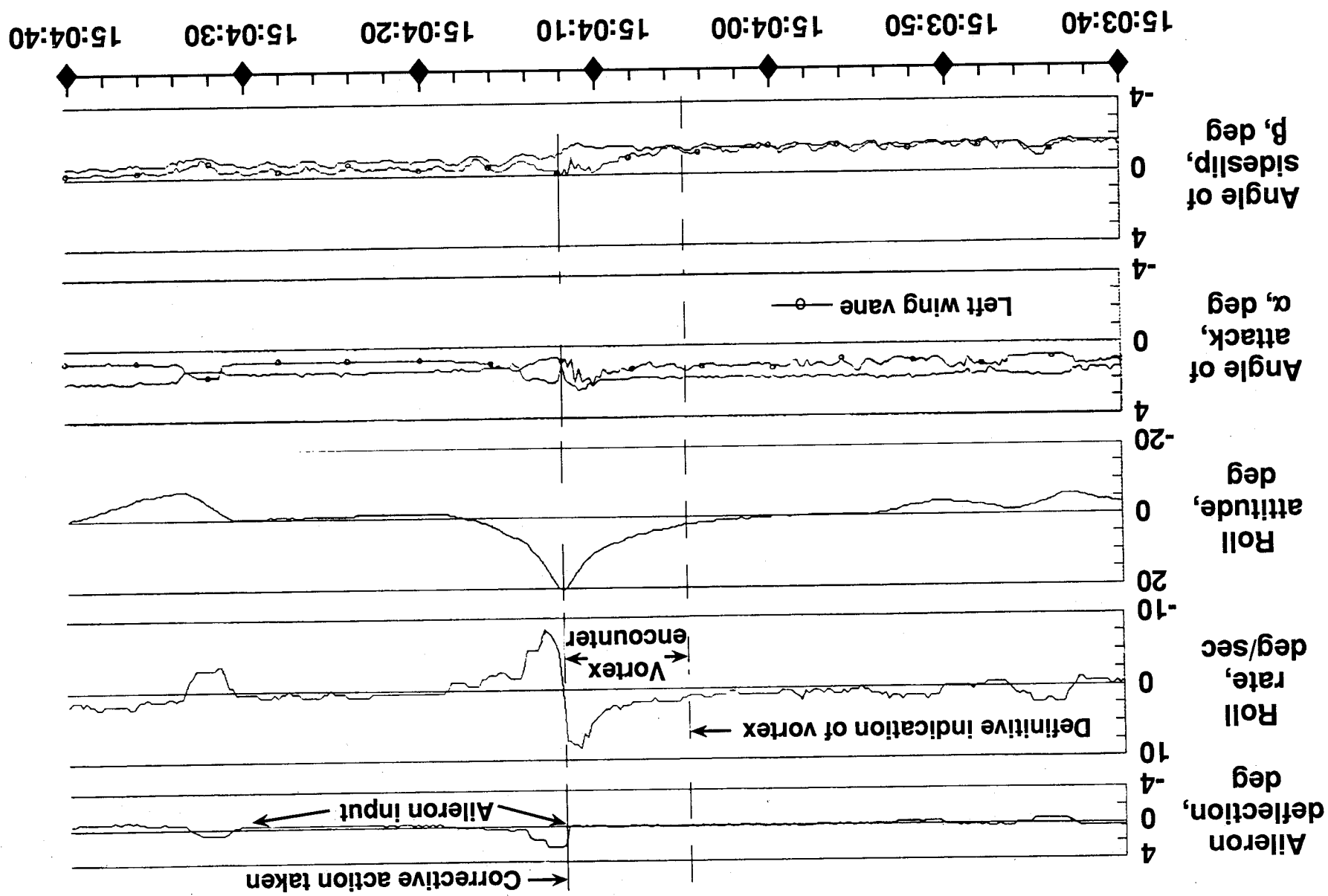
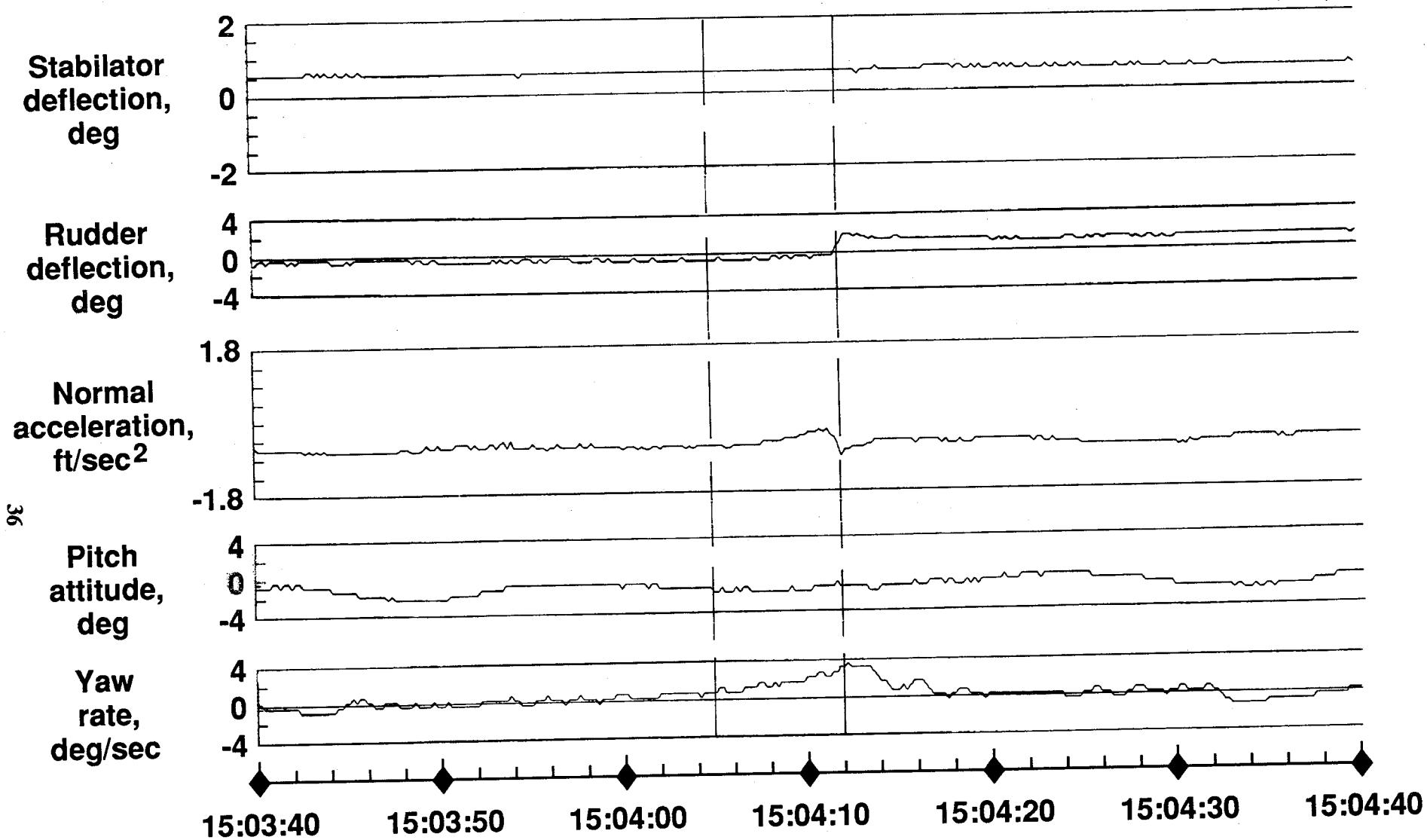Figure 17(b). A time history of data obtained from Flight 2-10, Run 6.
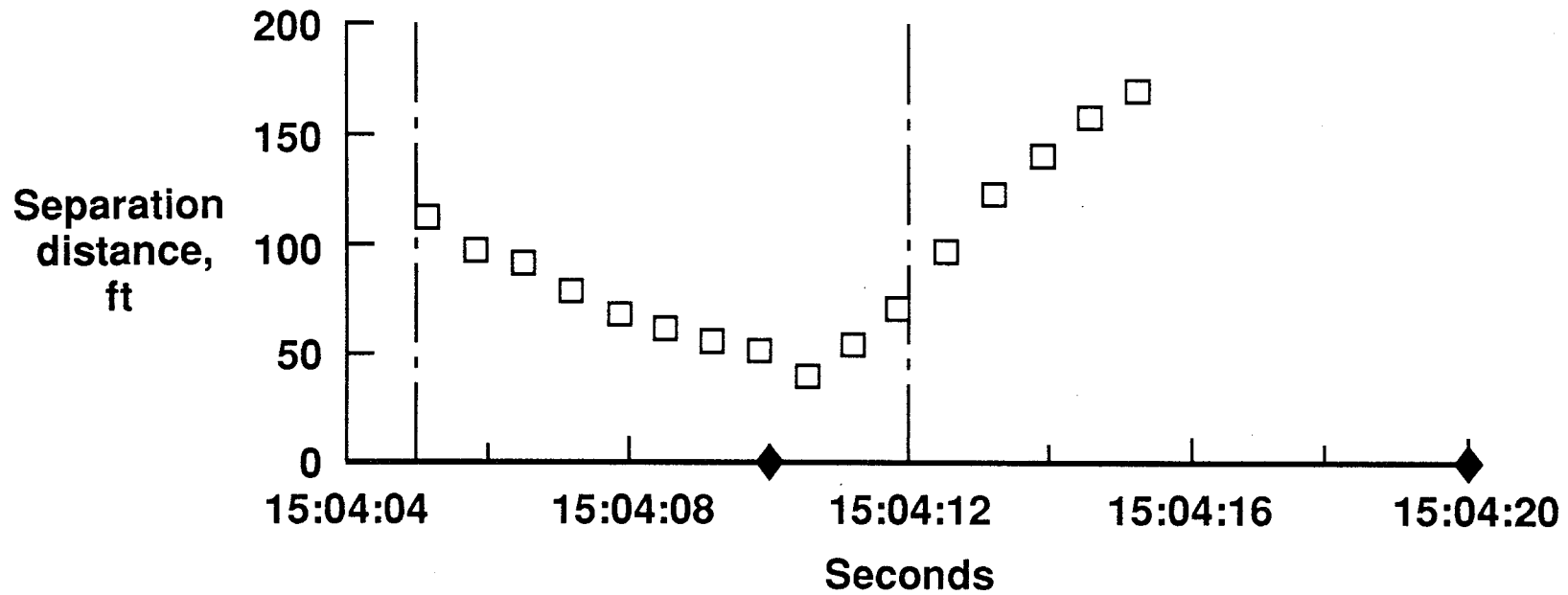
G/stbltr dflctn|91-512

Figure 18. Distance between probe airplane c.g. and vortex core for Flight 2-10, Run 6. (Determined from video camera mounted on right wingtip of observation aircraft.)
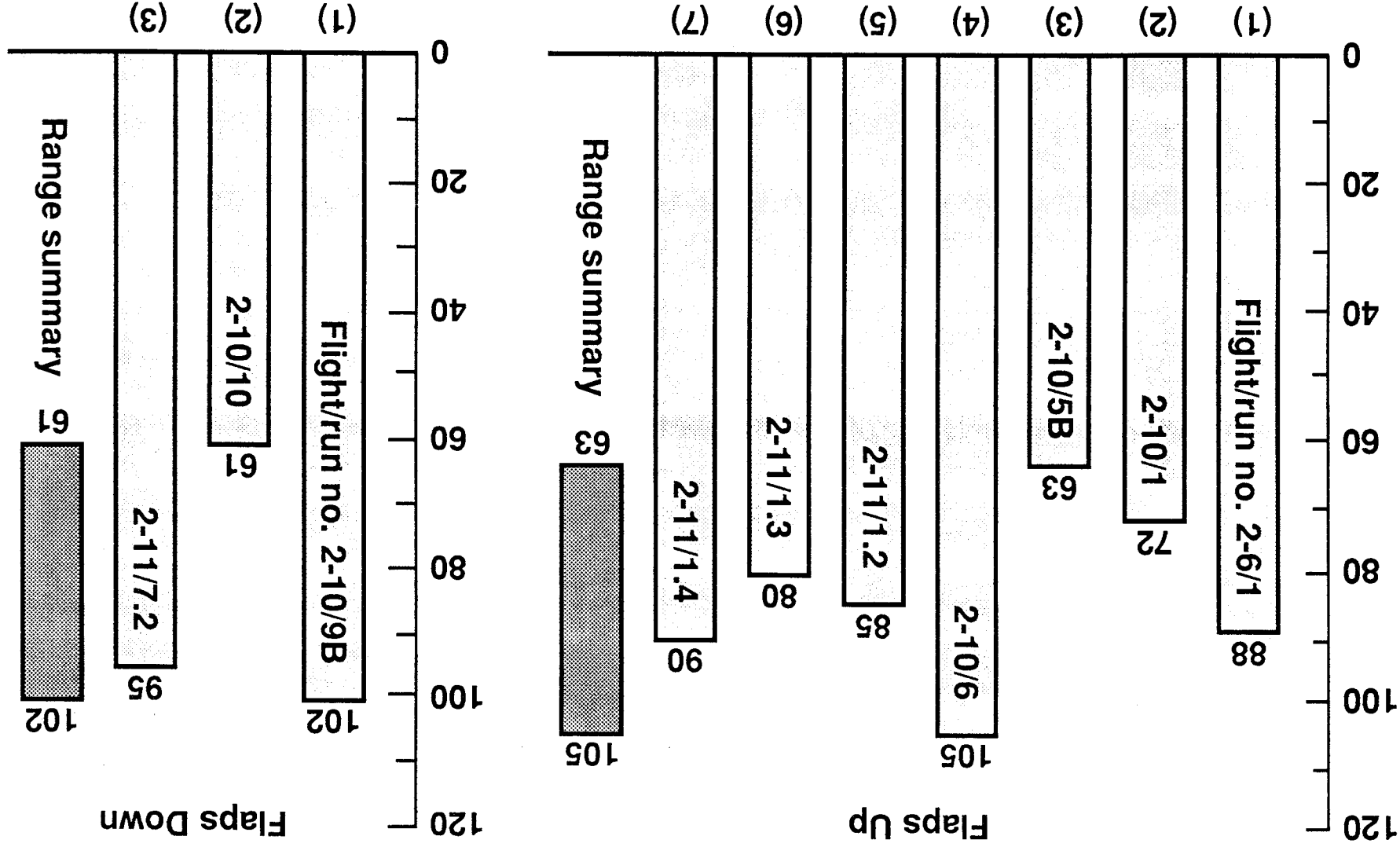
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Figure 19. Comparison of vortex detection threshold distances.
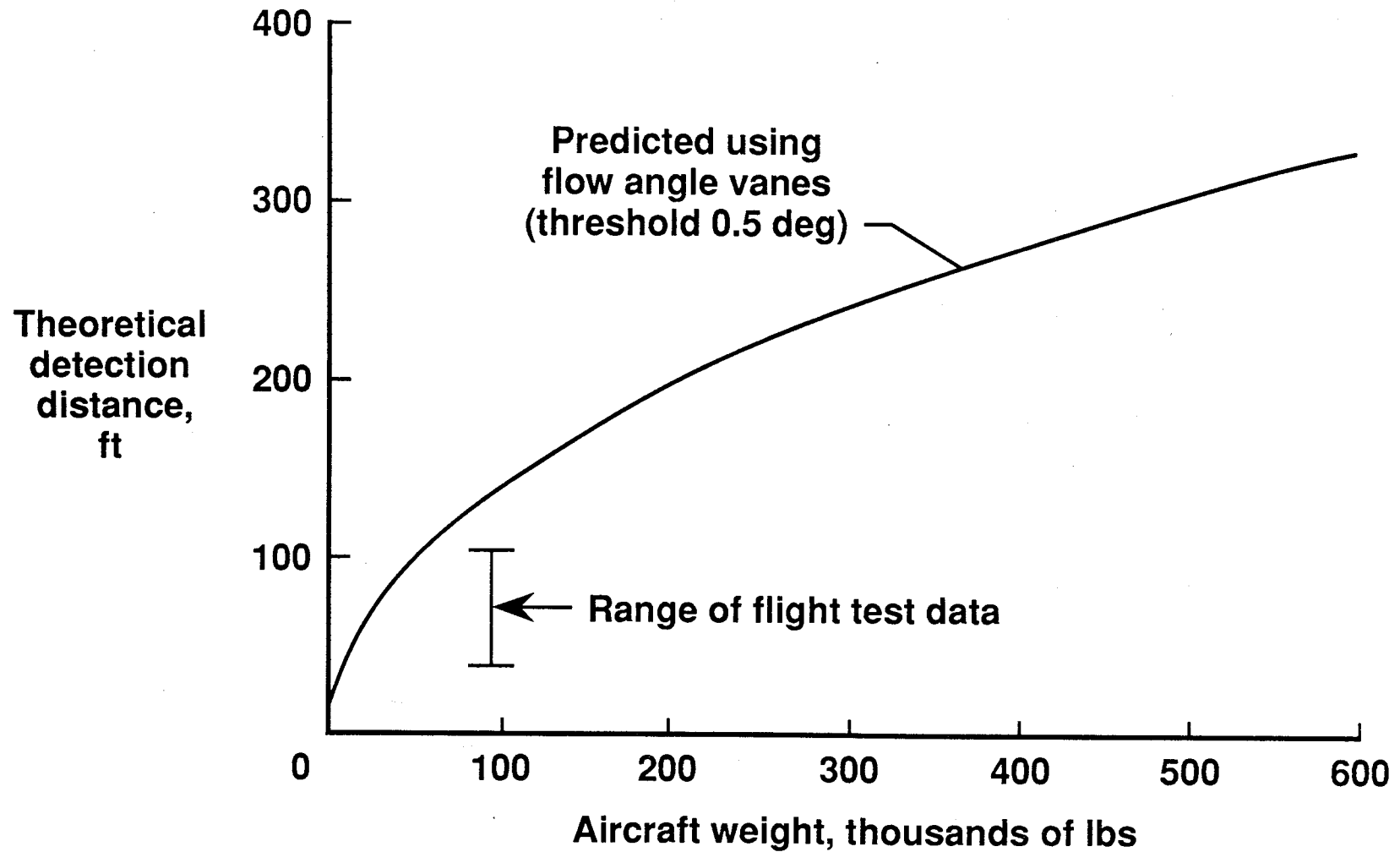(Probe aircraft centerline to vortex core.)

Figure 20. Comparison of theoretically derived vortex detection distance and flight test data.

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16. Abstract

An investigation was conducted jointly by the FAA and NASA to determine the radial extent of the circulatory flow field around the lift-induced vortex system of an aircraft in flight. This flow field, if found to be of sufficient strength and span to activate instrumentation onboard a following aircraft, may provide the basis for designing a feasible airborne wake detection and avoidance system.

A small probe aircraft was flown behind a larger wake generator aircraft to measure the lateral separation distance at which the vortex could be detected using conventional instrumentation. This report discusses the results and mechanics of the flight test and proposes recommendations for future tests.

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