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FLIGHT EVALUATION: ROSEMOUNT ORTHOGONAL LOW AIRSPEED SYSTEM LOW AIRSPEED SENSOR

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Army Aviation Engineering Flight Activity
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Tests were conducted on the Rosemount Engineering Company Model 853 orthogonal true airspeed sensor to determine its suitability for operational and flight test use as an airspeed system for helicopters. The sensor has no moving parts, and operates on the principle that differential pressures, measured between a pair of orthogonal chambers, are proportional to the airspeed in a given direction. Flight tests at Edwards Air Force Base, California, were started on 24 January 1974 and

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20. Abstract

were continued as additional hardware became available. The tests were completed on 9 September 1974, with a total of 8.9 productive flight hours. The test aircraft was a NUH-1M helicopter, and the sensor was evaluated in two locations: on top of the rotor mast and mounted on the cabin roof. Sensor location was a factor in system accuracy, with the mast-mounted sensor yielding the greater accuracy. This location provided a usable true airspeed indication down to 4.5 knots in forward, rearward, and lateral flight. The Rosemount system is acceptable for use as a test instrument, and may be suitable for operational use. Desirable features of the Rosemount system include relatively low cost, light weight, and simplicity.

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INTRODUCTION

BACKGROUND

1. The requirement exists in engineering flight testing for an inexpensive, lightweight, reliable, accurate low airspeed system capable of measuring lateral and longitudinal airspeed. To satisfy this need, a request for proposal was issued (ref 1, app A). Conventional helicopter fixed pitot-static tube systems and swiveling boom-mounted probes are generally inoperative below approximately 15 knots indicated airspeed (KIAS) and are sideslip limited. The United States Army Aviation Systems Command (AVSCOM) Test Request No. 71-30 (ref 2) authorized the United States Army Aviation Systems Test Activity (USAASTA) to conduct conceptual flight evaluations of low airspeed systems. Five experimental or prototype low airspeed systems have previously been tested by USAASTA under Project No. 71-30. These systems included the single- and double-axis Elliott system, the Aeroflex true airspeed vector system, the LORAS II system, and the J-Tec system (refs 3 through 7). The current evaluation was to determine the suitability of the Rosemount orthogonal airspeed sensor for flight test and operational use, and to provide basic airspeed system performance data for other applications.

TEST OBJECTIVES

2. The overall objective was to determine the feasibility of the Rosemount system for use as a helicopter airspeed instrument. Specific objectives were as follows:

a. Evaluate the system operation, accuracy, and reliability as a longitudinal and lateral airspeed instrument.

b. Determine variation of sensor performance with location on the helicopter.

c. Determine effects of ground proximity, angle of sideslip, and angle of attack on sensor performance.

d. Compare flight test and wind tunnel data.

DESCRIPTION

3. The Rosemount orthogonal airspeed sensor is manufactured by Rosemount Engineering Company, Minneapolis, Minnesota. The system includes a sensor, airspeed, indicator, transducer/analog multiplier unit, and tubing, as shown in photo A. A detailed description is contained in reference 8, appendix A.

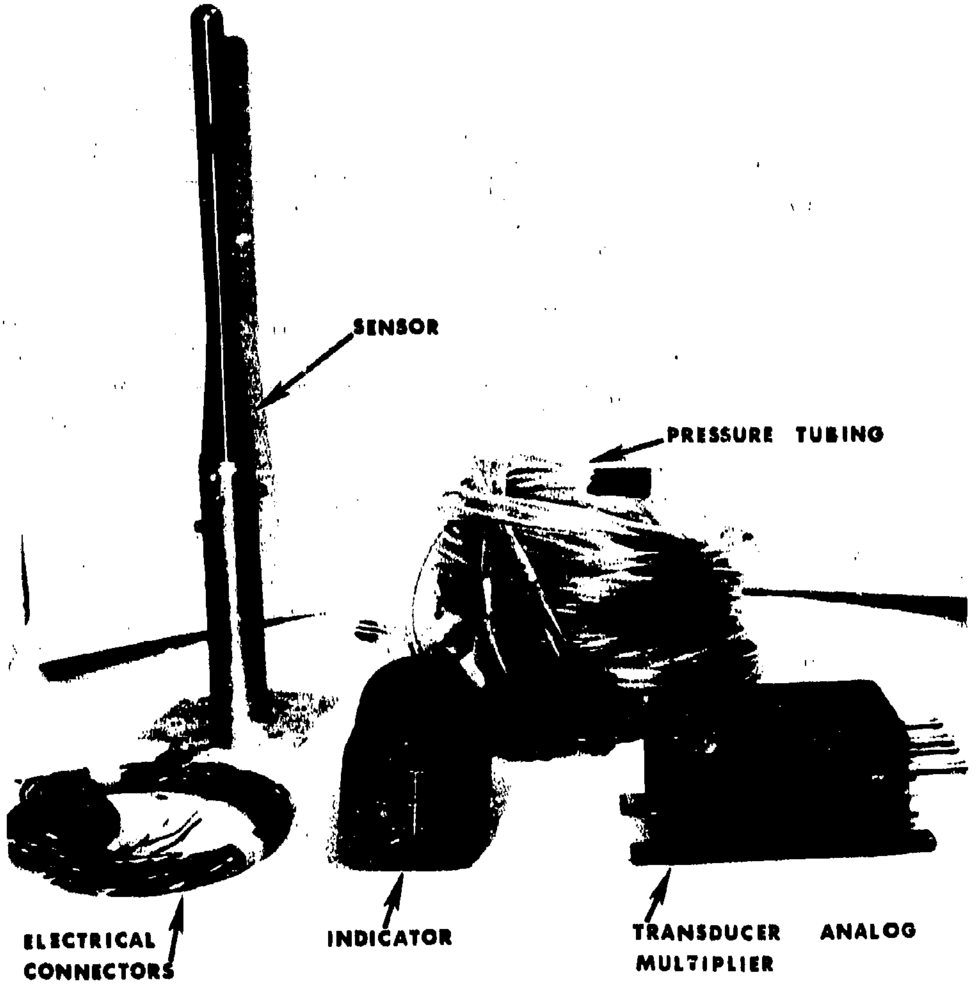


Photo A. Rosemount Airspeed System.

4. The sensor is a stationary, hemispherically-ended cylinder consisting of four internal chambers. Each chamber has a set of pressure sensing ports located on the cylindrical portion of the probe. Chambers 1 and 2 are aligned in the fore-aft direction with chambers 3 and 4 aligned left and right. To provide longitudinal and lateral airspeed information, the probe is mounted with the long axis of the sensor parallel to the aircraft's vertical axis. Rate of climb and angle of attack can be obtained by mounting an additional sensor parallel to the aircraft's lateral axis.

5. The orthogonal airspeed probe shown in photo 1, appendix C, is a pressure-type sensor. As illustrated in figure A, the airspeed sensor generates pressure signals in orthogonal directions to determine a relative airflow (v). The pressure differences in the orthogonal directions are transmitted by tubing to pressure transducers. Substitution of the pressure differentials into equations 1, 2 or 3 will provide the longitudinal, lateral or resultant true velocities, respectively.

$$V_x = (\Delta P_x/\beta\rho)^{1/2} \quad (1)$$

$$V_y = (\Delta P_y/\beta\rho)^{1/2} \quad (2)$$

$$V = [(\Delta P_x + \Delta P_y)/\beta\rho)]^{1/2} \quad (3)$$

$$\theta = \tan^{-1}\frac{V_y}{V_x} = \tan^{-1}\frac{\Delta P_y}{\Delta P_x} \quad (4)$$

Where:

V_X = Longitudinal velocity.

V_y = Lateral velocity.

V = Resultant velocity.

ΔP = Differential pressure.

ρ = Density in slug/ft^3.

β = Calibration constant.

In a complete operational system, these calculations are performed in the analog multiplier module, and longitudinal and lateral velocities or resultant velocity (v) and inflow angle (θ) displayed in the cockpit.

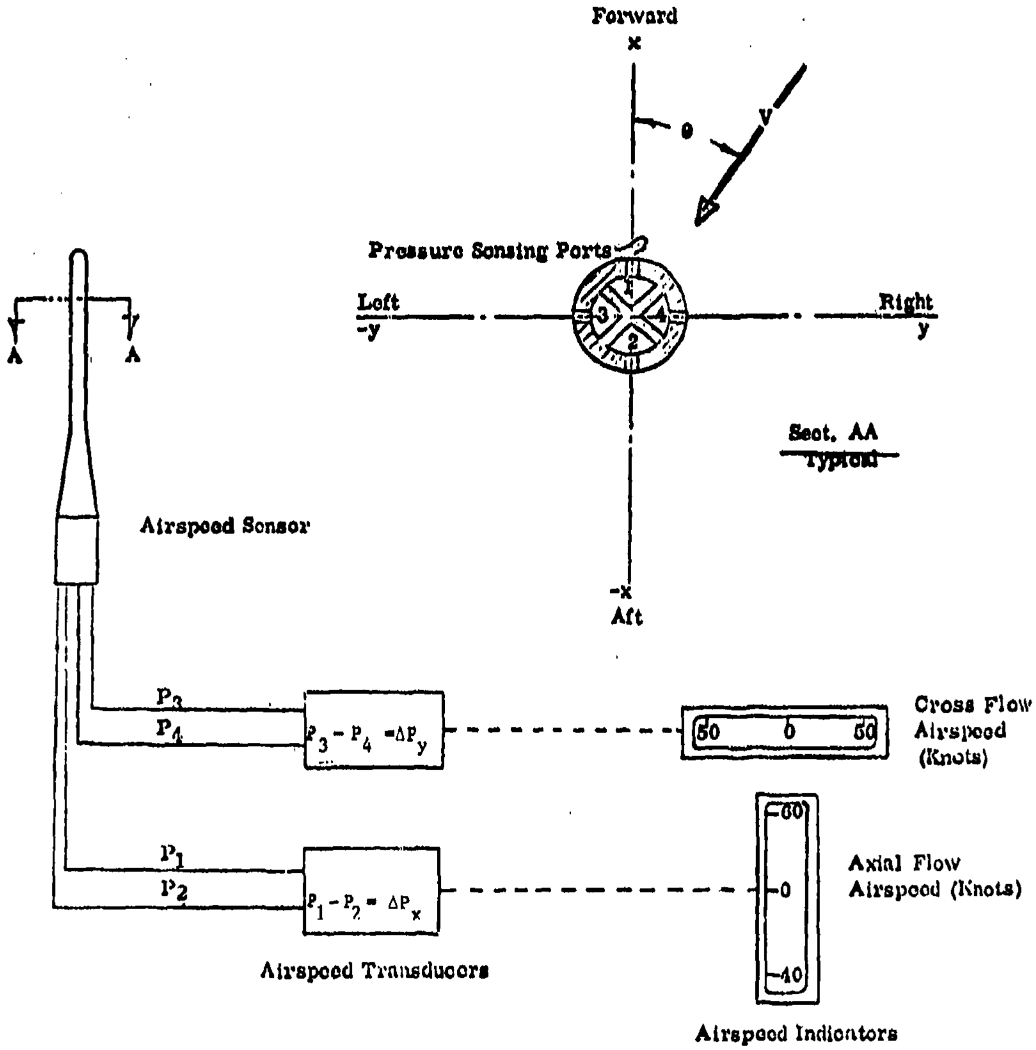


Figure A. Rosemount Orthogonal Airspeed System Schematic

6. The sensor contains internal electrical wiring for deicing. Power consumption with deicing operating is 250 watts in flight and 150 watts in still air. The deicing was not operative during the tests and any influence on system output was not determined.

7. The Rosemount sensor and transducer/analog multiplier module unit are depicted in photos 1 and 2, appendix C. The Rosemount transducer accepts differential pressure signals from the airspeed sensor and transduces them into electrical signals linear with differential pressure. The voltage output from the pressure transducer is then supplied to an analog multiplier module, which generates the square root function of the input ΔP signal. The module can be altered by means of an offset and gain adjustment, and the correct adjustment usually determined by flight test or wind tunnel test. The desired scaling of output voltage with indicated airspeed in each orthogonal axis is made possible by the output amplifier circuitry. A Rosemount signal processing schematic is presented in figure B.

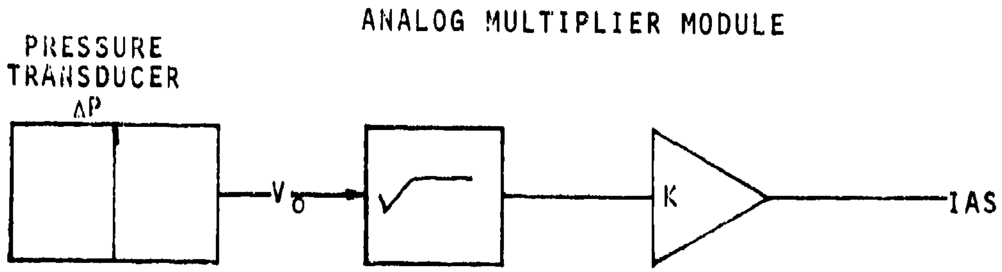


Figure B. Rosemount Signal Processing Schematic

Where:

Differential pressure = ΔP

Voltage output linear with differential pressure ΔP = V_o

Multiplier constant $K = \sqrt{\frac{1}{\beta \rho_o}}$

8. The Rosemount transducers have a ±0.1-psi full scale range. Throughout the transducer range, the performance specifications were ±0.1 percent for linearity, ±0.02 percent for repeatability and hysteresis, and infinitesimal error for resolution. The Rosemount transducers were not available at the beginning of the flight test. The USAAEFA transducers had similar percentages of full scale errors; however, transducer range was ±0.5 psi.

9. The Rosemount orthogonal airspeed indicator is a dual pointer instrument, with both pointers moving rectilinearly. The indicator is shown in photo 2, appendix C. The dual transversing pointers are driven by DC signals from the Rosemount transducer and move the pointers through scales representing 60 knots forward to 40 knots aft, and 50 knots left to 50 knots right, respectively, when the airspeed sensor is mounted parallel to the aircraft's vertical axis. Those indicator limits were chosen to provide maximum sensitivity while encompassing the expected range of helicopter operation.

10. The indicator scale is presented in the form of concentric rings located at 10-knot increments, with zero located at the geometric center of the indicator and a 40-knot circle being the most distant ring. The horizontal pointer reflects forward velocity by moving upward, and rearward by moving downward. The vertical pointer indicates transverse velocity (right, left). A left vertical pointer deflection indicates flow coming from the left and, similarly for right deflection, a flow from the right. Viewing the intersection of the horizontal and vertical pointers will depict the vector resultant of airspeed.

TEST SCOPE

Wind Tunnel Tests

11. The wind tunnel tests were conducted from 11 to 13 February 1974 in the United States Army Aeronautical Research and Development Laboratory (USAAMRDL) 7 by 10-foot wind tunnel located at the National Aeronautics and Space Administration Ames Research Center, Moffett Field, California. The tests were performed by USAAMRDL at conditions specified by USAAEFA. A description of the wind tunnel is contained in references 3 and 4, appendix A. The wind tunnel tests were to provide data for comparative analysis with the flight tests. The wind tunnel test conditions are presented in table 1.

Table 1. Wind Tunnel Test Conditions.[1]

True Airspeed (kt)	Sideslip (deg)	Angle of Attack (deg)
Zero to 120	Zero	Zero
25	Zero to 30, left and right	±30
65	Zero	±30

[1]Density altitude: -180 feet.

Flight Tests

12. The Rosemount low airspeed system was tested by USAAEFA at Edwards Air Force Base, California, between 24 January and 9 September 1974. Eight test flights were flown for a total of 8.9 productive flight hours. The test aircraft was a NUH-1M helicopter, S/N 63-8684, manufactured by the Bell Helicopter Company. A detailed description of the standard UH-1M is contained in the operator's manual (ref 9, app A). The nonstandard designation N is assigned pending installation of current avionics and a crashworthy fuel cell.

13. Flight conditions for all tests were within the flight envelope and operating limitations in the operator's manual. All flights were performed at a mid center of gravity (cg), with an average gross weight of approximately 6980 pounds.

14. The sensor was tested at two locations in forward, rearward, sideward, vertical and forward climbing, and descending flight. The locations, as shown in figure C, and photos 3 and 4, appendix C, were on top of the rotor mast (position No. 1) and atop the left side of the cabin (position No. 2).

15. The effects of sideslip, ground proximity, and dynamic conditions were investigated. Primary emphasis was on identification of airspeed system discrepancies and performance capability. Representative test conditions for high and low airspeed flight are shown in tables 2 and 3, respectively. In addition, vertical climb and descent tests were conducted at various vertical airspeeds between ±1000 feet per minute (ft/min).

16. The testing included evaluation of the sensor with USAAEFA-provided 0.5-psi transducers, as well as with the Rosemount 0.1-psi transducer incorporated with the analog multiplier module. In addition, rotor influence at the rotor mast location was evaluated by placing the sensor at two different heights above the rotor plane.

Figure C. Airspeed Sensor Locations

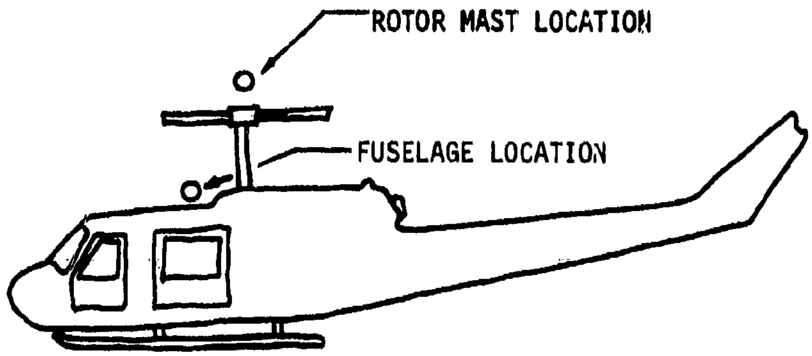


Table 2. Representative High Speed Flight Conditions.[1]

Flight Condition	Boom Indicated Airspeed (kt)	Sideslip Angle (deg)	Vertical Speed (ft/min)
Level	30 to 80	Zero	Zero
Level	53	Zero to 30, left and right	Zero
Climb	53	Zero	200 to 1250

[1]Average flight conditions:
Density altitude: 5000 feet.
Rotor speed: 324 rpm.
Gross Weight: 6600 pounds.

Table 3. Representative Low Airspeed Flight Conditions.[1]

Flight Condition	Ground Speed (kt)	Skid Height (ft)	Sideslip Angle (deg
Forward	Zero to 45	5,15,30,50	Zero
Forward	Zero to 45	30	Zero to 30, right
Rearward	Zero to 30	50	Zero
Left and right lateral	Zero	5,50	90

[1]Average flight conditions:
Density altitude range: 500 to 1450 feet.
Rotor speed: 324 rpm.
Gross weight: 7000 pounds.

FLIGHT TEST METHODOLOGY

17. The low airspeed (zero to 40 knots) tests were conducted in ground effect (IGE) and out of ground effect (OGE), using a calibrated pace vehicle for ground speed reference. Wind speed and direction were obtained from a ground-stationed anemometer. Reference airspeed was obtained by adjusting the ground speed data with the wind speed and direction information. Tests were conducted in winds less than 5 knots. Aircraft height above the ground was obtained from a radar altimeter.

18. The high-speed data (25 to 85-knot) reference was the calibrated swivel head boom system. Sideslip angles were measured with a boom-mounted sideslip vane and rate of climb was derived from the aircraft altimeter data. A trim airspeed of 65 knots true airspeed (KTAS) was used during the climbs, descents and dynamic maneuvers.

19. Vertical climbs and descents were conducted using the Elliott Mark II low airspeed system as a reference. Longitudinal and lateral airspeed indicated by the Elliott system were maintained at zero during the maneuvers.

20. The airspeed sensor and aircraft parameters were recorded by an airborne magnetic tape system. Test data were obtained by averaging the recorded data over 10 to 20 seconds of steady flight conditions. Test instrumentation type and range are included in appendix B.

RESULTS AND DISCUSSION

GENERAL

21. The Rosemount orthogonal low airspeed sensor demonstrated adequate performance for use as a flight test airspeed instrument. Although the purpose of the test was not to optimize the sensor location, the rotor mast location was least affected by rotor disturbance and provided the largest usable flight envelope of the two test positions. The rotor mast location can provide accurate airspeed information above 4.5 KTAS throughout the aircraft flight envelope. The cabin-mounted position provided repeatable and accurate airspeed information above 25 KTAS.

WIND TUNNEL TESTS

Effects of Airspeed

22. The wind tunnel airspeed tests were conducted with the sensor centrally located in the tunnel test section. Test data are presented in the bottom plot of figure 1, appendix D. The accuracy of tunnel airspeeds less than 20 knots is questionable, due to turbulence level and precise airspeed determination. The sensor appears to have an error of 1.5 knots for tunnel airspeeds between 20 and 30 KTAS. The error then gradually increases with higher airspeeds up to 80 knots. Above 80 knots, the error increase is essentially linear, with airspeed to a maximum error of 16.5 knots at the highest test airspeed of 131 KTAS.

Effects of Angle of Attack

23. The wind tunnel strut mechanically limited the angle-of-attack tests to ±30 degrees. Tests were conducted at tunnel airspeeds of 25 and 65 KTAS, and data are presented in the middle plot of figure 1, appendix D, which produced angle-of-attack relationships, as shown in figure D.

24. The zero angle-of-attack trim points duplicated those obtained during the airspeed tests. For both test airspeeds, the error increased with angle of attack and was greater for positive angles of attack. The sensitivity with angle becomes greater as airspeed is increased and the maximum error of 13 KTAS was recorded at 65 KTAS with a positive angle of attack equal to 29 degrees.

Effects of Angle of Sideslip

25. Sideslip tests were performed at 25 KTAS and zero angle of attack. The sensor error was essentially symmetrical with sideslip, and the error became larger with increased sideslip angle. The maximum longitudinal error of 4.5 knots occurred at the highest test sideslip angles of 30 degrees left. These data are presented in the top plot of figure 1, appendix D.

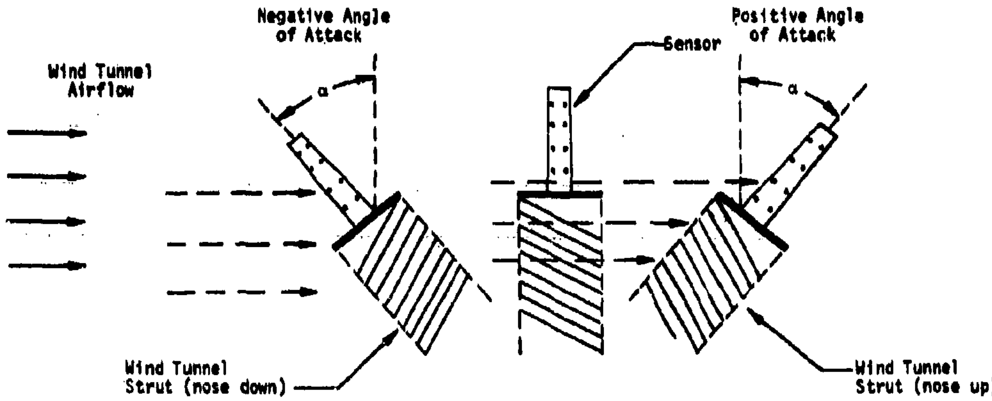


Figure D. Sensor and Wind Tunnel Airflow Orientation.

FLIGHT TESTS

Rotor Mast Location

Longitudinal and Lateral Low-Speed Flight:

26. The sensor was installed directly above the rotor mast with the use of the terminal communication systems (TACSAT) antenna base. The TACSAT base provided a nonrotating platform for the sensor.

27. The system performance in longitudinal and lateral low-speed flight is obtained from figures 2 through 8, appendix D. The pressure sensing limitation of the data recording system was ±0.001 inches of mercury (Hg), which introduces a ±4.5-knot area of uncertainty in the hover data. The threshold of the airspeed system is apparently within the data recording capability. At the test cg, the aircraft attitude was 2 degrees nose up during hover, which would allow a small component of any vertically induced flow to act on the sensor. This could account for the system usually indicating a small forward airspeed during hover. The tests were conducted at a mid cg location, and additional tests would be needed to establish the induced flow errors caused by changes in aircraft attitude.

28. Hover tests were conducted as part of the sideward, forward and rearward tests. In figure 2, appendix D, the aircraft was aligned with a head or tail wind, while in figure 5 the prevailing wind was from either the left or right. This test method minimizes the corrections to the data. The measured crosswind component was subtracted from the indicated values; however, in all cases there was still an error on the crosswind axes. The variations appeared to be random, and the error was within the recording capability of the data system. It is suspected that the error is caused by a small negative pressure, rather than impact pressure, causing the ΔP to be unusually large. The values for the primary axis show very small errors.

29. The low-speed forward and rearward test results with the USAAEFA transducers are presented in figure 2, appendix D. Sensor error remained at nearly 5 KTAS up to approximately 40 KTAS, where the error began to decrease to +3 KTAS in forward flight. In rearward flight, the system characteristics were essentially the same as for the forward flight case. The lateral airspeed component in forward and rearward flight was unrepeatable and shows an error band similar to that recorded during hover.

30. As depicted in figure 3, appendix D, forward and rearward tests with the Rosemount transducers yielded only slight improvement in the data. Generally, the same approximate 5-knot error for the primary axis at airspeeds up to 40 KTAS was realized. The crosswind axis error was greatly improved in rearward flight and in forward flight up to 20 KTAS, was well within 5 KTAS. However, at forward airspeeds greater than 20 KTAS, the lateral error began to rapidly diverge, and random errors of up to 12 KTAS were observed.

31. Figure 4, appendix D, shows the sensor performance with the Rosemount transducers and a 15-inch vertical extension to the sensor. Forward and rearward errors were reduced from 5 KTAS to approximately 3 KTAS. Additionally, the lateral airspeed error was greatly improved above 20 KTAS and remained at 5 KTAS or less.

32. In OGE sideward flight, with USAAEFA transducers, the system performance for the primary axis was essentially the same as in forward flight, as can be seen in figure 5, appendix D. The longitudinal axis was the crosswind axis for lateral flight, and the average error was approximately 5 KTAS.

33. The lateral flight IGE results, with USAAEFA transducers, are presented in figure 6, appendix D. The characteristics for the primary axis are the same as for OGE; however, the magnitude of the error is slightly reduced. The error is a maximum of 9 knots at a true sideward airspeed of 32 knots. The crosswind axis showed a different response from that recorded for the OGE tests, with the error being near zero throughout the test range.

34. Data depicting Rosemount sensor and transducer performance in lateral flight OGE are presented in figure 7, appendix D. The sensor characteristics are similar to the forward and rearward data with Rosemount transducers. The lateral airspeed error was only slightly improved, and a nearly constant 5-KTAS error at airspeeds above hover observed. The aft axis longitudinal error was essentially the same in magnitude; however, it was considerably more random than lateral data with USAAEFA transducers.

35. With the sensor extension and the Rosemount transducers installed, the primary axis data in lateral flight was improved. These results are shown in figure 8, appendix D. The lateral error was nearly constant for airspeeds above hover at 3 KTAS. The longitudinal error in lateral flight was random; however, the magnitude of error was decreased from 8 to 5 knots.

Effects of Sideslip:

36. The effect of sideslip on the sensor is presented in figure 9, appendix D. Since wind tunnel results showed the effects to be symmetrical, tests were conducted in only right sideslip. The test data show very little effect on low airspeeds for sideslips of 30 degrees or less.

Effects of Ground Proximity:

37. Ground proximity tests were conducted at three skid heights, and data are presented in figure 10, apppendix D. There was no significant influence of ground effect on the system performance when the sensor was mounted above the rotor mast. The 10-foot and 42-foot skid heights showed similar characteristics and fluctuated within 5 KTAS of a zero longitudinal error. The tests at a skid height of 22 feet produced a constant error of 8 knots from hover to 20 knots forward airspeed. These results are not consistent with other results, and may have been caused by atmospheric conditions or a peculiar rotor flow at that skid height. Additional tests would be required to resolve the discrepancy.

High-Speed Flight:

38. Flight test data for high-speed flight are presented in figure 11, appendix D. During high-speed flight, the limitations of the pressure transducer restricted the airspeed to a maximum of 65 KTAS. For the test airspeed range, the error was a constant 4 knots. However, since the wind tunnel indicates an increasing error above 80 knots, additional testing is necessary to determine suitability of the system for the full airspeed range of Army fixed wing, VSTOL, and rotary wing aircraft.

39. The effects of sideslip at 65 KTAS are shown in figure 12, appendix D. The recorded longitudinal error was zero in trimmed flight and became more negative as sideslip was decreased in both directions. The error was slightly larger in right sideslip and was 7 knots at 30 degrees, right sideslip. The lateral error was at

a maximum of approximately ±10 knots with a 10-degree sideslip both left and right. The error then decreased to ±4 knots with sideslip to 30 degrees. These results are different than those obtained during the low airspeed sideward tests.

Climbs and Descents:

40. Forward flight climbs were performed at 65 KTAS and a density altitude of 5000 feet. Test results are presented in figure 13, appendix D. Longitudinal error for climbs and descents was less than 2 KTAS for vertical rates of 1500 ft/min or less ($\alpha = \pm 12°$). For vertical rates in excess of 1500 ft/min, the error increased linearly with vertical airspeed. The lateral true airspeed error was symmetrical with positive and negative angles of attack. The error was 7 knots in trimmed level flight, and decreased to zero at vertical airspeeds of 2000 ft/min.

41. Vertical climb and descent test results are presented in figure 14, appendix D. For vertical rates of climb of zero to 1000 ft/min, the Rosemount longitudinal error was zero. In vertical descents, the longitudinal airspeed error was +17 KTAS at the highest rate of descent, 1600 ft/min. Less than 2-KTAS lateral airspeed error was found in vertical climbs and descents of 500 ft/min or less. At vertical rates in excess of 500 ft/min, the lateral airspeed showed increasing error in the negative sense for descents and increased in the positive direction for climbs.

Fuselage Location

Longitudinal and Lateral Low-Speed Flight:

42. The performance in hover conditions with the sensor mounted on the cabin roof is presented in figures 15 and 16, appendix D. The longitudinal airspeed indication was influenced by the rotor, and there were variations from +10 to +20 KTAS. This performance was not nearly so good as that obtained with the sensor mounted above the rotor disc.

43. Forward and rearward low-speed test results are presented in figure 15, appendix D. The sensor was unusable at forward flight airspeeds from hover to 25 KTAS. Between 18 and 25 knots, there was a sharp discontinuity as the sensor transitioned from the rotor wash to free stream air. For forward airspeeds greater than 25 KTAS, the performance was better than for the rotor mast location, and the error was within ±1 knot. From hover to 7 knots rearward, the indicated airspeed changed from 20 knots forward to 8 knots rearward. At rearward airspeeds greater than 7 knots, the error was nearly constant at 2 knots. The indicated lateral airspeed was essentially a constant 10 knots left for all forward airspeeds, and was apparently not altered by either longitudinal airspeed or rotor wash. In rearward flight, the error increased to +10 KTAS, right, when the sensor was in the rotor wash.

44. Lateral flight data from 30 KTAS left to 30 KTAS right sideward flight is presented in figure 16, appendix D. From hover to 15 knots in right lateral flight, the error was 18 to 21 knots. The sensor then transitioned from the rotor wash,

and at 25 knots and above, the error was reduced to 1 knot. For left sideward flight, the transition began at hover and was completed at 10 knots, where the error was 7 knots. The error then decreased slightly as higher airspeeds were attained. The nonsymmetry and the different transition airspeeds are attributed to the sensor being located on the left side of the cabin roof.

Sideslip Effects:

45. The influence of sideslip at low airspeeds is shown in figure 9, appendix D. The sensor performance was relatively independent of sideslip, with the maximum error for a 20-degree change being 3.5 knots. This performance was similar to that recorded for the rotor mast location. The lateral airspeed error in forward flight with right sideslip generally reflected the 10-knot bias to the left, which was evident during the zero sideslip forward and rearward tests.

Ground Proximity Effects:

46. Figure 10, appendix D, shows the fuselage location to be more sensitive to ground proximity than was the rotor mast installation. At skid heights of 22 and 42 feet, the performance was essentially the same as that obtained during the OGE tests. For a 10-foot skid height, the error was reduced by half for airspeeds from hover to 20 knots. The transition airspeed was 20 knots for all skid heights, and above 30 knots, the performance was essentially the same for all skid heights and was similar to the OGE results.

High-Speed Flight:

47. High-speed flight data for the fuselage position are presented in figure 11, appendix D. The effect of the rotor wash was to shift the longitudinal error from 4 knots positive at the rotor mast location to a negative 4-knot error at the fuselage location. The error was constant for the airspeed range of 40 to 60 knots. These results are within 2 KTAS of the low-speed tests (fig. 15).

48. High-speed sideslip effects on the sensor were evaluated at 65 KTAS, and a nominal density altitude of 5000 feet. Sideslips of 30 degrees left to 30 degrees right were tested, and results are presented in figure 12, appendix D. The sensor showed longitudinal errors less than 2 KTAS for left sideslips up to 30 degrees. A 1-KTAS error was observed in right sideslips of 10 degrees or less. In right sideslips greater than 10 degrees, the sensor error was effected by sideslip, and the longitudinal error increased with increasing angles of sideslip. These results are opposite of those for the rotor mast location, and similar to the wind tunnel results shown in figure 1.

49. The lateral airspeed characteristics with sideslip were similar to those for the rotor mast location. The largest error recorded was for the trim condition, and the error was then less for sideslip in either direction.

Climbs and Descents:

50. High-speed climbs and descents were conducted at 65 KTAS and a density altitude of 5000 feet. The test data for rates of descent of 1300 ft/min and rates of climb of 750 ft/min are presented in figure 13, appendix D. There was very little longitudinal true airspeed error throughout the test range, and the maximum error was +2 KTAS. The sensor performance for climbs and descents was essentially the same as that obtained with the rotor mast installation. The lateral airspeed results were more significant than those obtained for the rotor mast position. Descents reduced the indicated left lateral airspeed, and a zero airspeed error occurred at a descent of 1250 ft/min. The effect of climb was to increase the position error, which reached a maximum of 20 KTAS left in a 750 ft/min climb. The indicated left airspeed was 20 knots.

51. Vertical climbs and descents were performed at a nominal density altitude of 3400 feet and results are presented in figure 14, appendix D. The longitudinal true airspeed error was +23 KTAS for the vertical rates of climb tested (zero to 800 ft/min). In vertical descent, the longitudinal error increased with rate of descent and was 33 knots at 700 ft/min. The results were characteristically the same as for the rotor mast location; however, the effect of descent rate on the airspeed error was more pronounced, and for the fuselage location, the sensor was unusable for vertical climbs and descents.

52. The lateral component of true airspeed was significantly affected by vertical motion. For descents greater than 350 ft/min, the lateral error increased by 10 knots with an additional 350-ft/min descent rate. Although the characteristics were the same, the fuselage position was more sensitive to vertical motion than was the rotor mast location.

RELIABILITY AND MAINTAINABILITY

53. Installation of the Rosemount sensor required no special tools or technical skills. Existing supply hardware was used, with very little fabrication necessary. The only postinstallation system check was the standard pitot-static leak check. No system checks, such as electrical alignment (nulling), were required during preflight or in flight. No environmental or operational testing has been conducted for any part of the system. The transducers used for the evaluation were the most sensitive units available at the time of installation. However, to obtain the desired resolution, transducer scale changes were required for airspeeds above approximately 50 KTAS. Preflight scale adjustments on the Rosemount transducer, which was later tested, were not necessary.

54. The absence of mechanical moving parts in the Rosemount sensor enhances its effectiveness for use on operational aircraft. No failure of the system occurred during the course of the program. The sensor is simple in construction and demonstrated a high degree of reliability.

CONCLUSIONS

GENERAL

55. When mounted on the rotor mast, the Rosemount orthogonal low airspeed system is a workable concept for the helicopter environment. The system has significant potential and can be developed into a useful source of airspeed information. The nature of the airflow relative to the aircraft influenced the system operation, and each flight regime produced different system operating characteristics.

WIND TUNNEL TESTS

56. In the wind tunnel, the Rosemount system measured true longitudinal airspeed within +5 KTAS for an airspeed range of 16 to 80 KTAS (para 22).

57. The sensor error was +6 KTAS or less for angles of attack of ±10 degrees in wind tunnel tests (para 24).

58. The Rosemount system measured airspeed within +5 KTAS in sideslip up to 30 degrees in wind tunnel tests (para 25).

FLIGHT TESTS

59. The Rosemount system with a rotor mast mounted sensor produced reliable airspeed with an essentially constant position error for airspeeds from 30 knots rearward to 30 knots forward (para 29).

60. There was no significant difference in data obtained with the 0.5-psi transducers, and the 0.1-psi Rosemount transducers (paras 30 and 34).

61. With the sensor mounted on the rotor mast, ground effect did not degrade performance during low-speed flight in any direction (paras 33 and 37).

62. With the sensor mounted on the top of the cabin, rotor wash prevented obtaining useful data until the system had transitioned into a free stream environment (para 43).

63. The longitudinal airspeed error was less than 5 knots during forward flight climbs or descents up to 2000 ft/min for both locations (paras 40 and 50).

64. Vertical climb and descent significantly increased the position error when mounted on the cabin roof (para 51).

65. Sideslip angles below ±30 degrees normally encountered in forward flight did not introduce any sizable errors in the indicated airspeed (paras 36, 39, 45, and 48).

66. Increasing the vertical distance of the sensor above the rotor plane produced an improvement in the airspeed system performance (paras 31 and 35).

RECOMMENDATIONS

67. Flight tests should be conducted to optimize sensor location for best performance (para 48).

68. The Rosemount orthogonal low airspeed sensor should be further evaluated during test involving low airspeed and/or omnidirectional flight.

69. Future tests should include the following items:

a. Effects of gross weight variations on sensor performance (para 27).

b. Horizontal installation of the sensor to determine its ability to measure rate of climb and descent and allow calculation of angle of attack (para 4).

c. System performance in forward flight above 65 KTAS (para 38).

APPENDIX A. REFERENCES

1. Request for Proposal, Air Force Flight Test Center, Edwards Air Force Base, California, RFP Nr. F 04611-68-R-0080.

2. Letter, AVSCOM, AMSAV-EF, 20 July 1971, subject: Flight Test of Low Airspeed Sensors.

3. Final Report I, USAASTA, Project No. 71-30, *Flight Evaluation, Elliott Low Airspeed System*, September 1972.

4. Final Report VI, USAASTA, Project No. 71-30, *Elliott Mark II Low Airspeed System*, in preparation.

5. Final Report II, USAASTA, Project No. 71-30, *Flight Evaluation, Aeroflex True Airspeed Vector System, Low Airspeed System*, March 1973.

6. Final Report III, USAASTA, Project No. 71-30, *Pacer Systems, Inc., LORAS II Low Airspeed System*, March 1974.

7. Final Report IV, USAASTA, Project No. 71-30, *Flight Evaluation, J-TEC Airspeed System, Low Airspeed Sensor*, April 1974.

8. Report, Rosemount Engineering Company, No. 5691, Revision B, *Description of the Rosemount Orthogonal Airspeed Sensor*, 1 February 1973.

9. Technical Manual, TM 55-1520-220-10, *Operator's Manual, Model UH-1C/M Helicopter*, November 1968 with Changes 1 through 4.

APPENDIX B. TEST INSTRUMENTATION

Test instrumentation was installed and maintained by USAAEFA personnel. The following test parameters are presented:

GROUND EQUIPMENT

Pace vehicle airspeed
Ambient wind airspeed
Ambient wind direction

HELICOPTER INSTRUMENTATION

Pilot/Engineer Panel

Airspeed (boom system)
Altitude (boom system)
Rate of Climb
Rotor speed
Gas producer speed
Engine torque
Angle of sideslip
Exhaust gas temperature
Outside air temperature
Fuel counter
Engine fuel flow
Event counter
Altitude (radar)
Airspeed (ship's system)
Altitude (ship's system)
Collective stick position
Pedal position

Magnetic Tape	Unit	Range
Time of day	Sec, min, hr	0000 to 2400
Event counter	Count	0 to 127
Fuel counter (fine)	Gal.	0 to 26.1
Fuel counter (coarse)	Gal.	0 to 6685.0
Engine fuel flow	Gal/hr	-4.1 to 246.8
Fuel temperature	°C	-10.4 to 61.2
Outside air temperature	°C	-10.9 to 61.5
Airspeed (boom)	Knot	11.8 to 135.5
Altitude (boom)	Feet	-281.2 to 5470.7
Altitude (boom) (medium)	Feet	4665.0 to 10,549.0
Altitide (boom) (high)	Feet	7216.4 to 17,497.8
Altitude (radar) (fine)	Feet	136.6 to -.25
Altitude (radar) (coarse)	Feet	975.4 to -9.6
Longitudinal stick position	Percent	0.82 to 103.7
Collective stick position	Percent	-2.07 to 102.5
Pedal position	Percent	-1.48 to 103.2
Lateral stick position	Percent	1.6 to 110.1
Angle of attack (boom)	Degree	-31.2 to 30.5
Angle of sideslip (boom)	Degree	-29.9 to 31.0
Pitch attitude	Degree	31.9 to -32.1
Roll attitude	Degree	-62.3 to 62.2
Rosemount longitudinal dynamic pressure	in. of Hg	-0.12 to 0.1248
Rosemount lateral dynamic pressure	in. of Hg	-0.12 to 0.1248
Rosemount longitudinal dynamic pressure for high-speed flight	in. of Hg	0 to 0.2435
Rosemount longitudinal velocity	Knot	-50 to 52.0
Rosemount longitudinal velocity for high-speed flight	Knot	0 to 71
Rosemount lateral velocity	Knot	-50.0 to 52.0

APPENDIX C. PHOTOGRAPHS

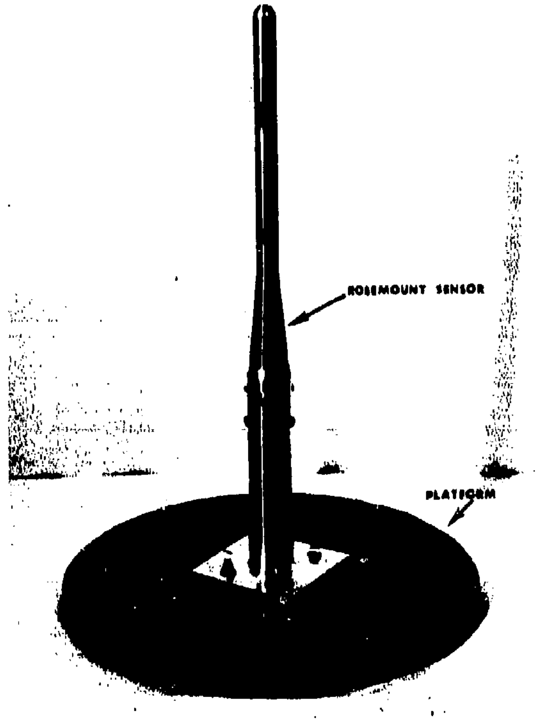


Photo 1. Rosemount Orthogonal Airspeed Sensor.

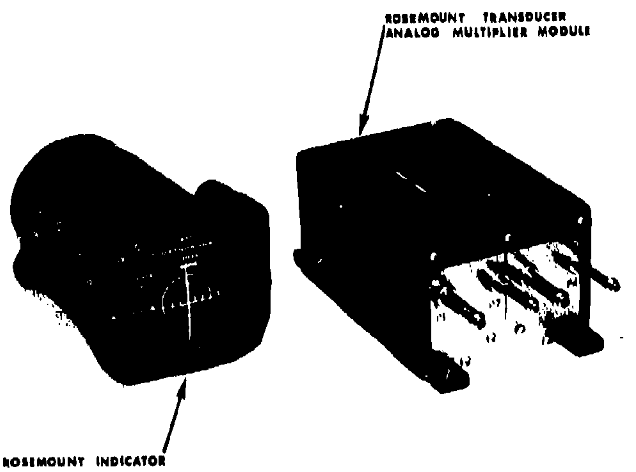


Photo 2. Rosemount Airspeed Indicator and Transducer/Analog Multiplier Module.

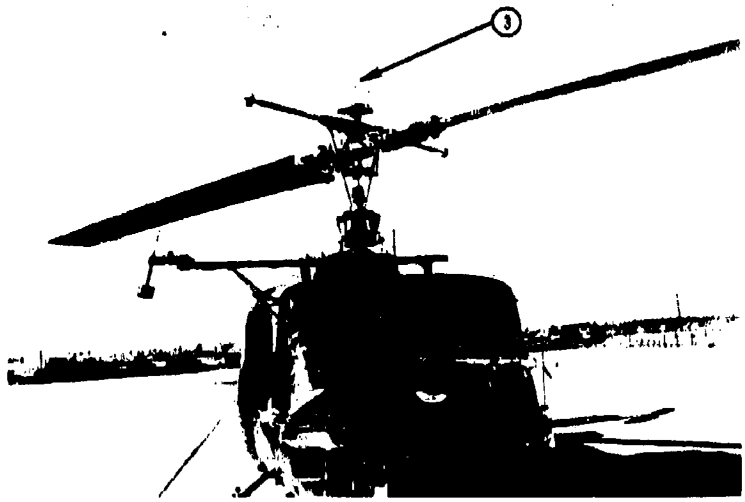


Photo 3. Rotormast Position.

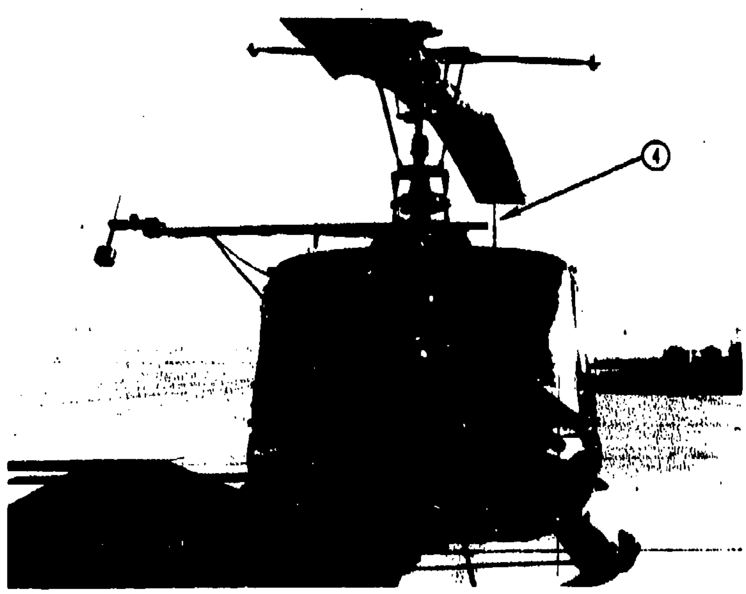
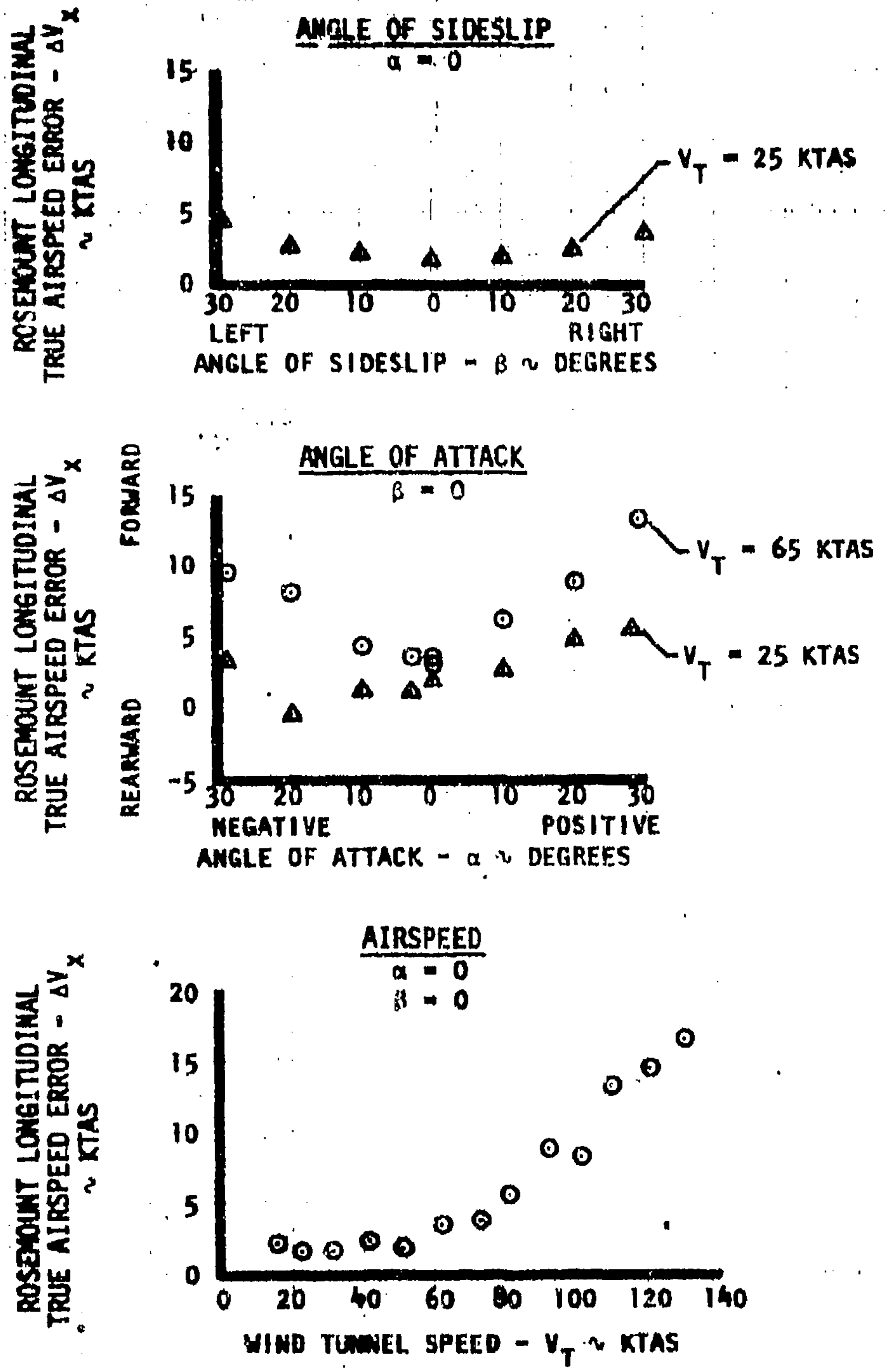


Photo 4. Fuselage Position.

APPENDIX D. TEST DATA

FIGURE 1
WIND TUNNEL CALIBRATION
OF ROSEMOUNT AIRSPEED SYSTEM

NOTE: 1. Rosemount Airspeed Sensor S/N 1
2. USAAEFA Transducers
3. Amb. Air Temp. ~ °C = 17
4. Density Alt. ~ ft = 380



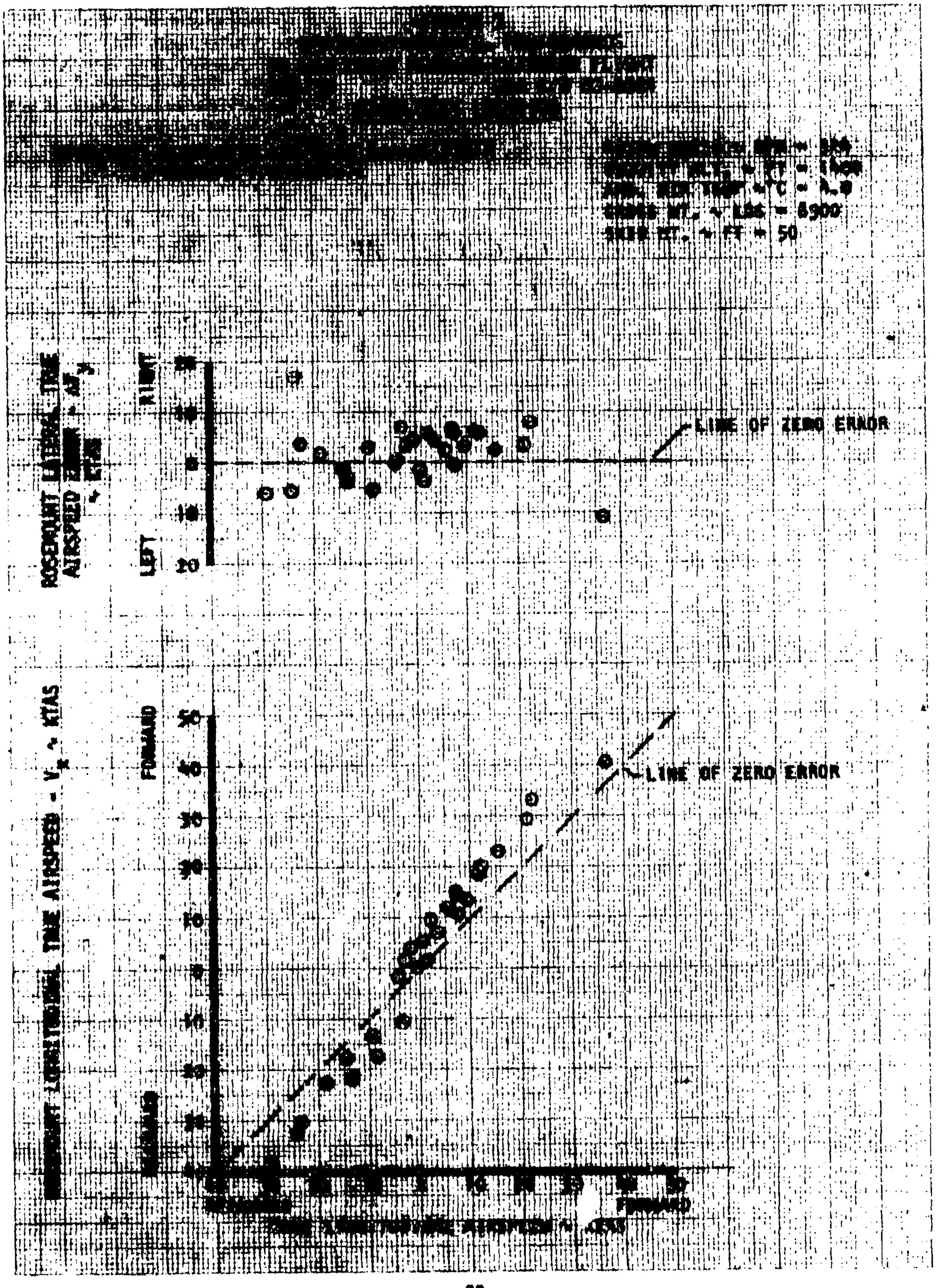
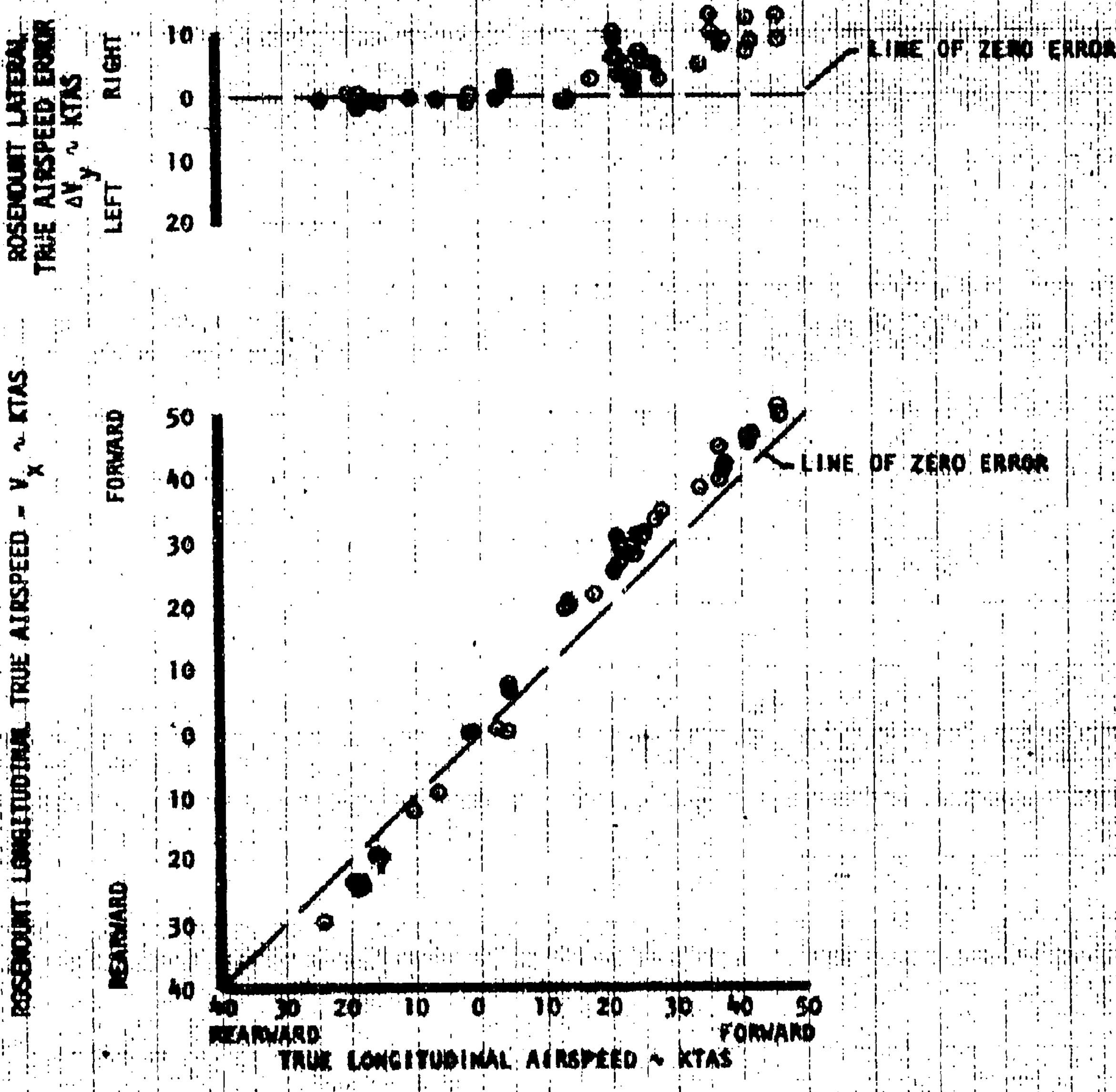

LINE OF ZERO ERROR
LINE OF ZERO ERROR
SKID HT. ~ FT = 50
LEFT
RIGHT
FORWARD
AIRSPEED
KTAS

FIGURE 3
ROSEMOUNT AIRSPEED PERFORMANCE
IN LOW SPEED FORWARD-REARWARD FLIGHT
NUH-1M USA S/N [illegible]
ROTOR MAST LOCATION

NOTES: 1. Rosemount Airspeed Sensor S/N 1
2. Rosemount Transducers

ROTOR SPEED ~ RPM = [illegible]
DENSITY ALT. ~ FT = 3460
AVG. AIR TEMP ~ °C ~ 20
GROSS WT. ~ LBS = 7200
SKID HT. ~ FT = 57



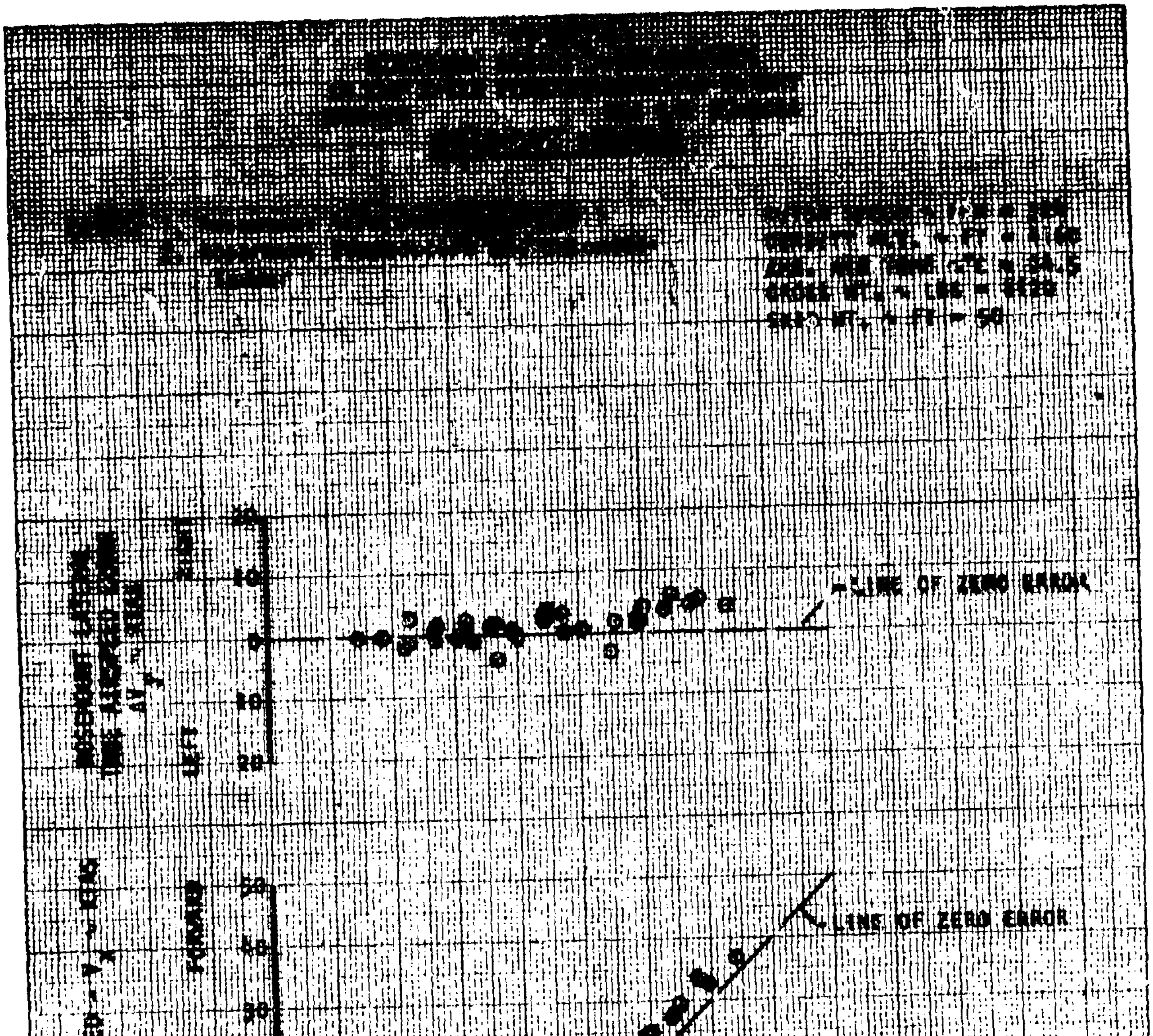

LINE OF ZERO ERROR
LINE OF ZERO ERROR
LEFT
FORWARD
REARWARD
TRUE LONGITUDINAL AIRSPEED ~ KTAS

FIGURE 5
ROSEMOUNT AIRSPEED PERFORMANCE
IN LOW SPEED LATERAL FLIGHT
[illegible] USA S/N 63-[illegible]
ROTOR MAST LOCATION

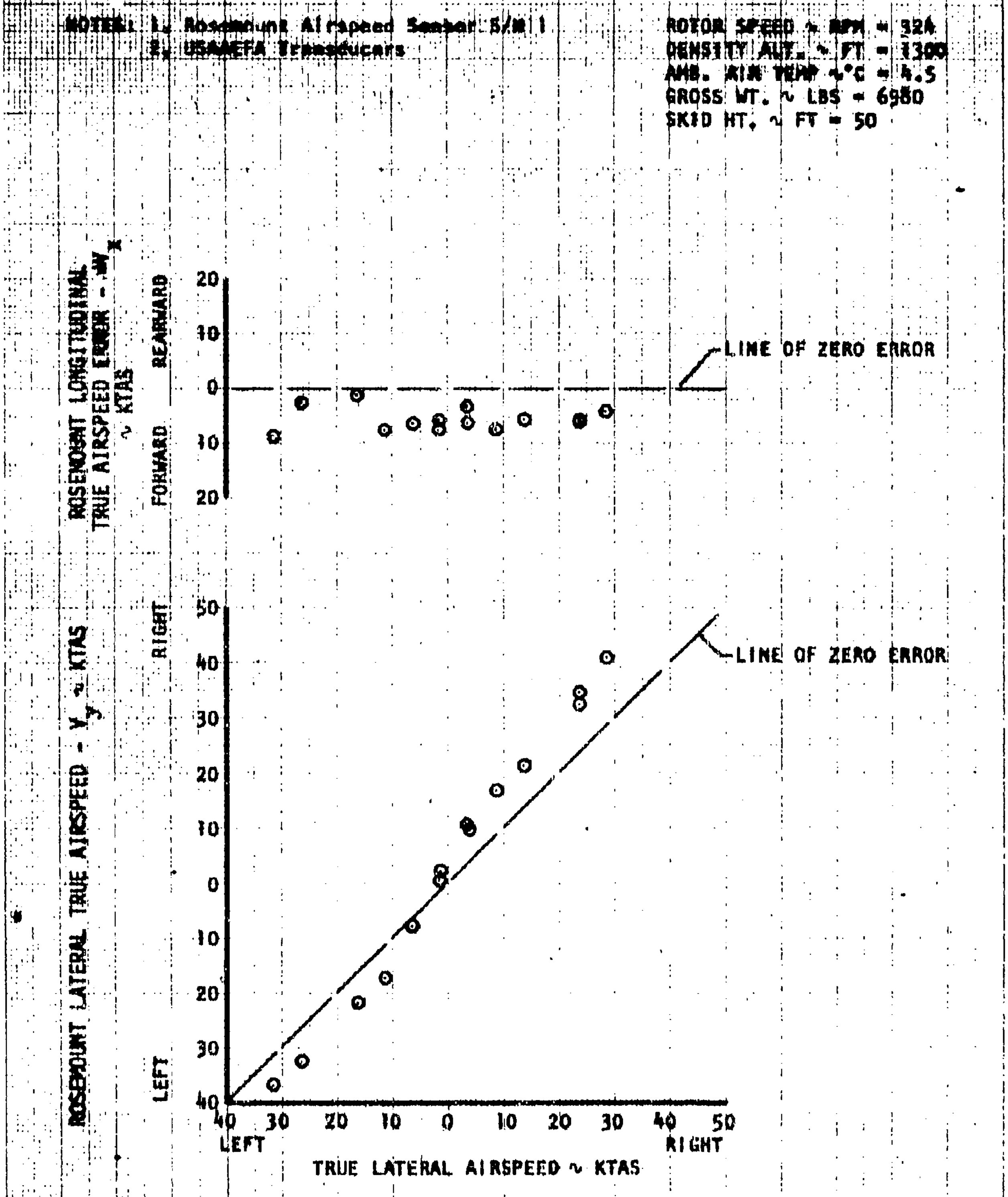


FIGURE 6
ROSEMOUNT AIRSPEED PERFORMANCE
IN LOW SPEED LATERAL FLIGHT
NUH-1H USA S/N 63-8684
ROTOR MAST LOCATION

NOTES: 1. Rosemount Airspeed Sensor S/N 1
2. USAAEFA Transducers

ROTOR SPEED ~ RPM = 324
DENSITY ALT. ~ FT = 1380
AMB. AIR TEMP ~°C = 4.0
GROSS WT. ~ LBS = 6740
SKID HT. ~ FT = 16

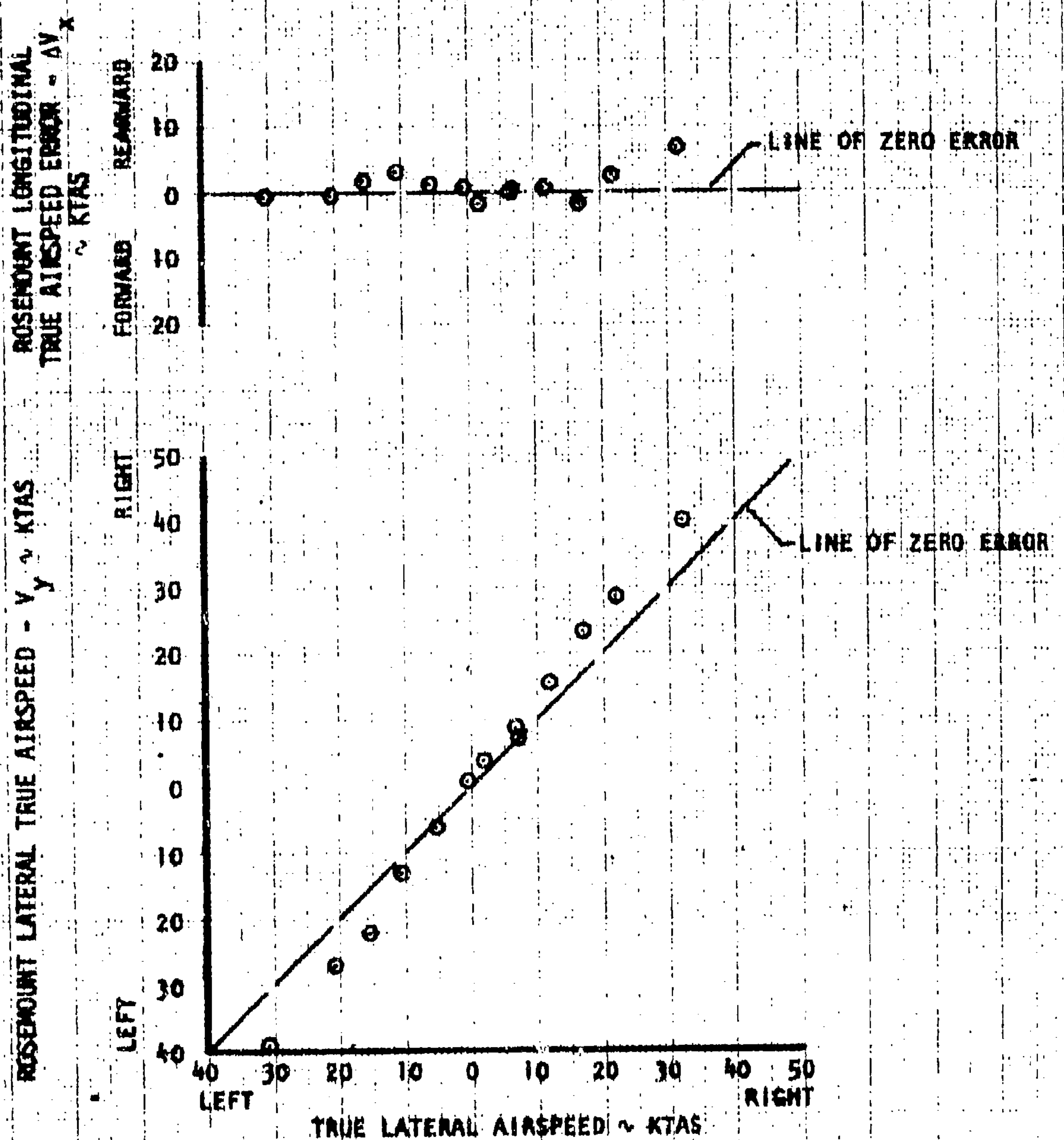


FIGURE 7
ROSEMOUNT AIRSPEED PERFORMANCE
IN LOW SPEED LATERAL FLIGHT
NUH-1H USA S/N 63-8684
ROTOR MAST LOCATION

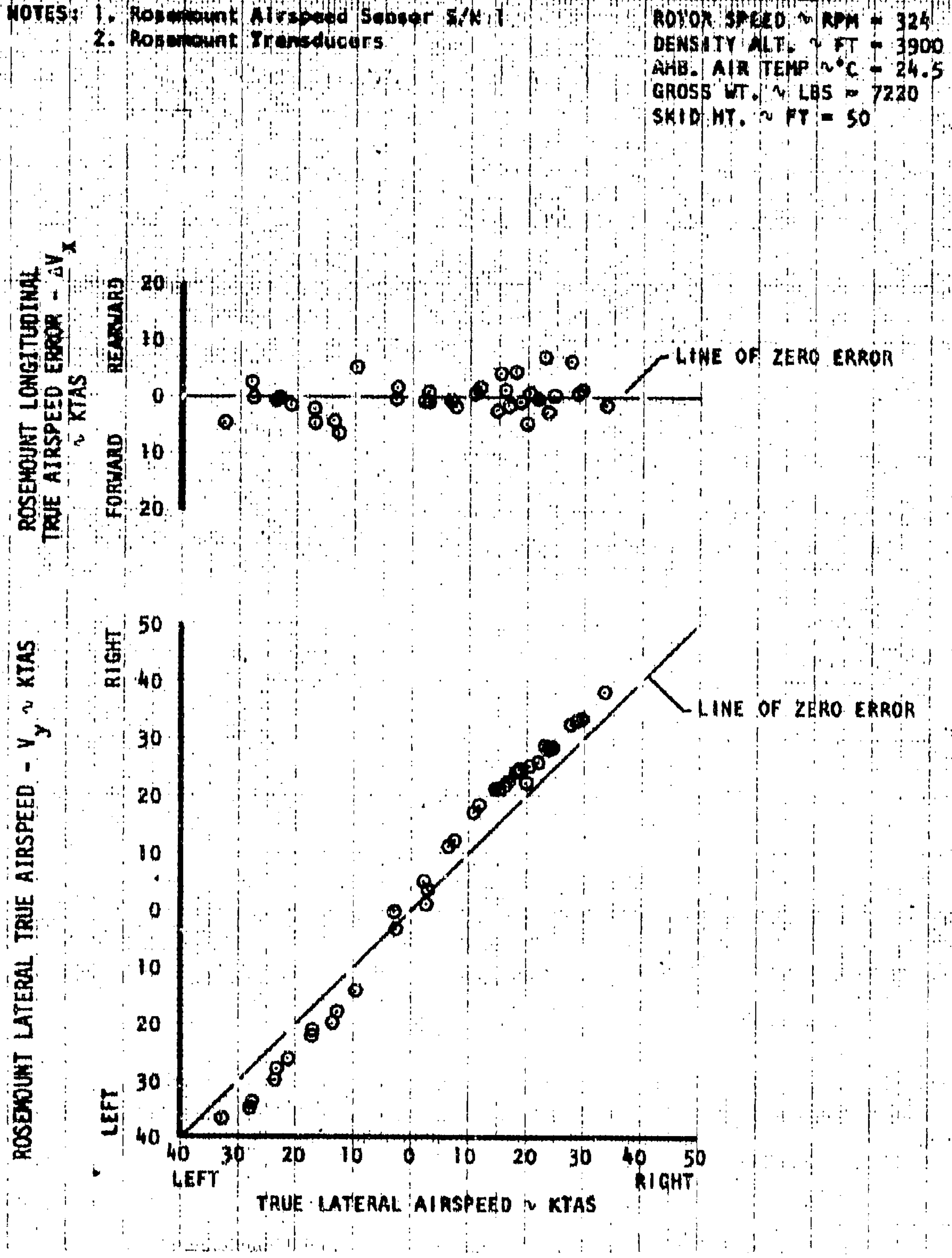


FIGURE 8
ROSEMOUNT AIRSPEED PERFORMANCE
IN LOW SPEED LATERAL FLIGHT
NUH-1M USA S/N 63-8684
ROTOR MAST LOCATION

NOTES: 1. Rosemount Airspeed Sensor S/N 1
2. Rosemount Transducers and Extended Sensor

ROTOR SPEED ~ RPM = 324
DENSITY ALT. ~ FT = 3980
AMB. AIR TEMP ~ °C = 22
GROSS WT. ~ LBS = 8220
SKID HT. ~ FT = 55

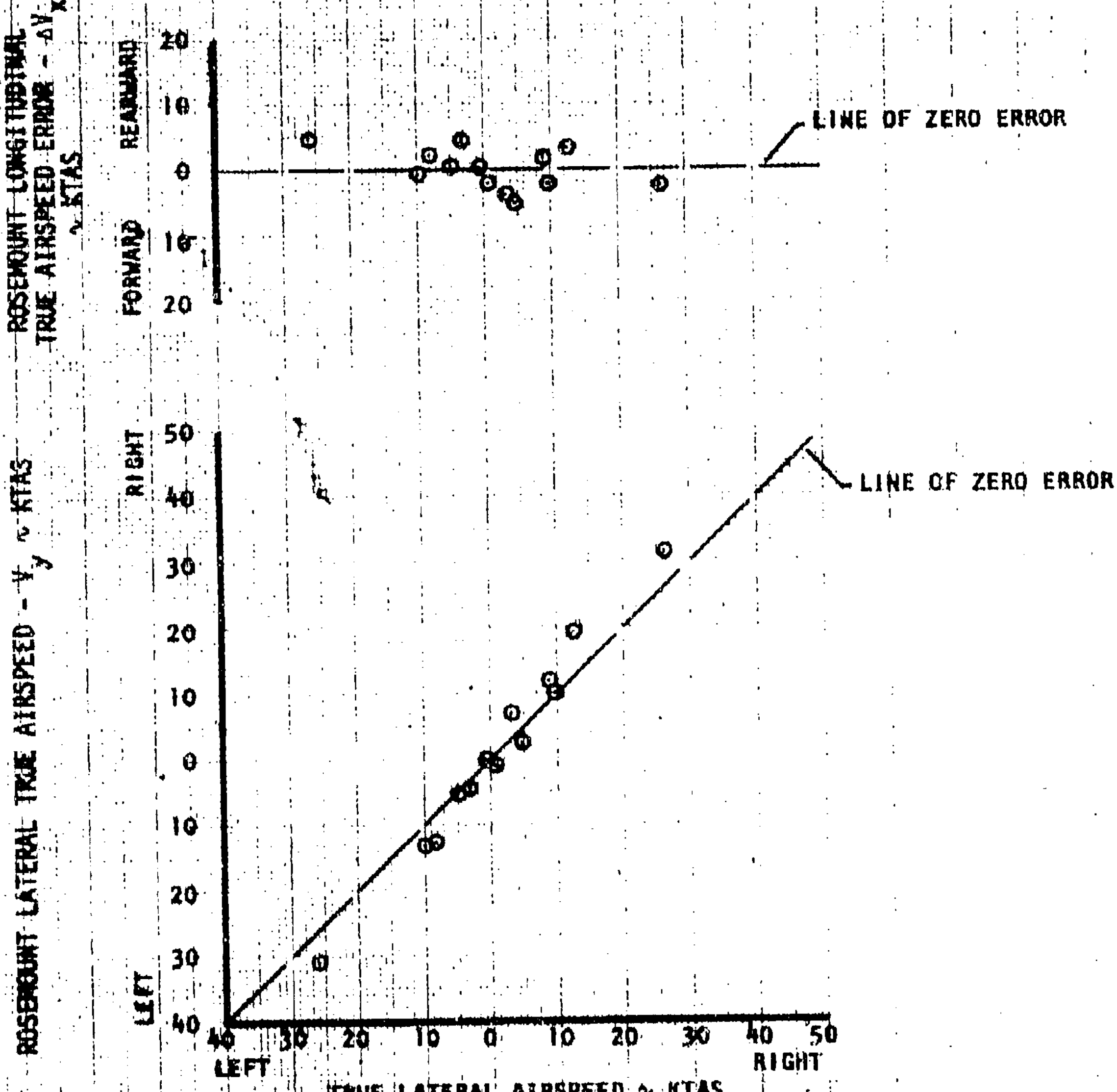
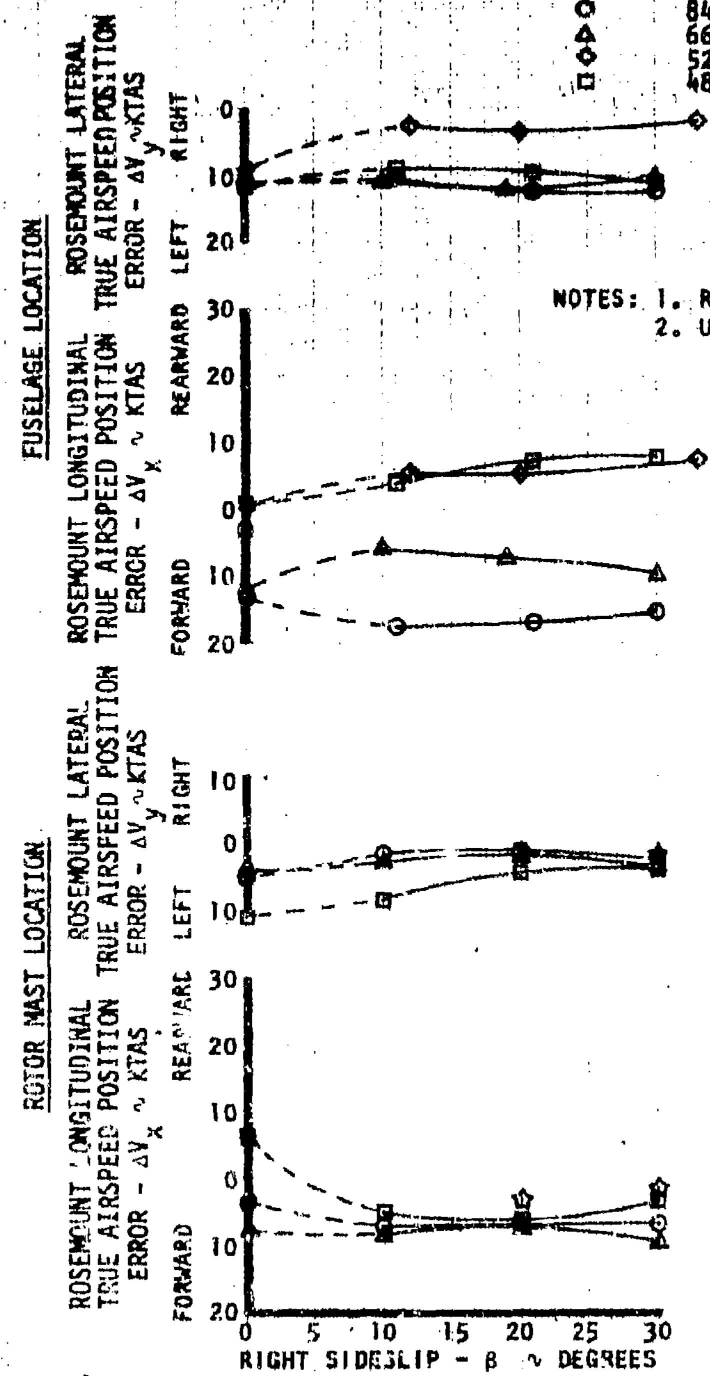


FIGURE 9
ROSEMOUNT AIRSPEED PERFORMANCE IN LOW SPEED
FORWARD FLIGHT WITH SIDESLIP

NUH-1H USA S/N 63-8684

ROTOR SPEED ~ RPM = 324
GROSS WEIGHT ~ LBS = 6940
SKID HEIGHT ~ FT = 50

SYMBOL	DENSITY ALTITUDE ~FT	TRUE LONG. AIRSPEED ~KTAS	AMB. TEMP. ~°C
✩	560	0	1.0
○	840	10	1.5
△	660	20	1.0
◇	520	30	-2.0
□	480	40	-1.5



NOTES: 1. Rosemount Airspeed Sensor S/N 3
2. USAAEFA Transducers

FIGURE 10
ROSEMOUNT AIRSPEED PERFORMANCE
IN LOW SPEED GROUND PROXIMITY
NUH-1M USA S/N 63-8684

ROTOR SPEED ~ RPM = 324
GROSS WEIGHT ~ LBS = 6400

SYMBOL	DENSITY ALTITUDE ~FT	AMB. TEMP. ~°C	SKID HEIGHT ~FT
○	480	1.5	42
△	480	7.0	22
□	500	1.5	10

NOTES: 1. Rosemount Airspeed Sensor S/N 1
2. USAAEFA Transducers

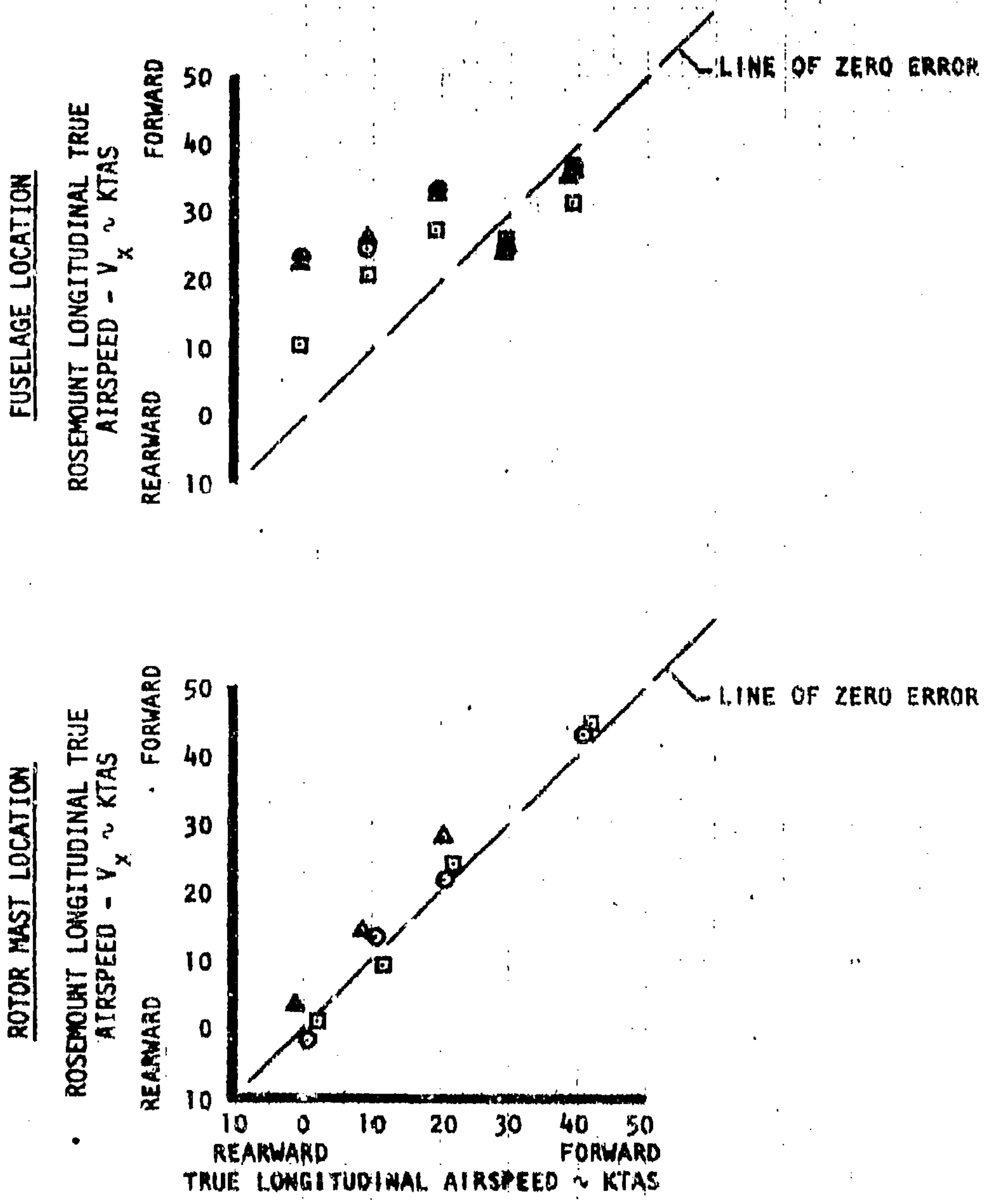


FIGURE 11
ROSEMOUNT AIRSPEED PERFORMANCE
IN HIGH SPEED FORWARD FLIGHT
NUH-1M USA S/N 63-8684

NOTES: 1. Rosemount Airspeed Sensor S/N 1
2. USAAEFA Transducers

ROTOR SPEED ~ RPM = 324
DENSITY ALT. ~ FT = 5100
AMB. AIR TEMP ~°C = 9.0
GROSS WT. ~ LBS = 6600

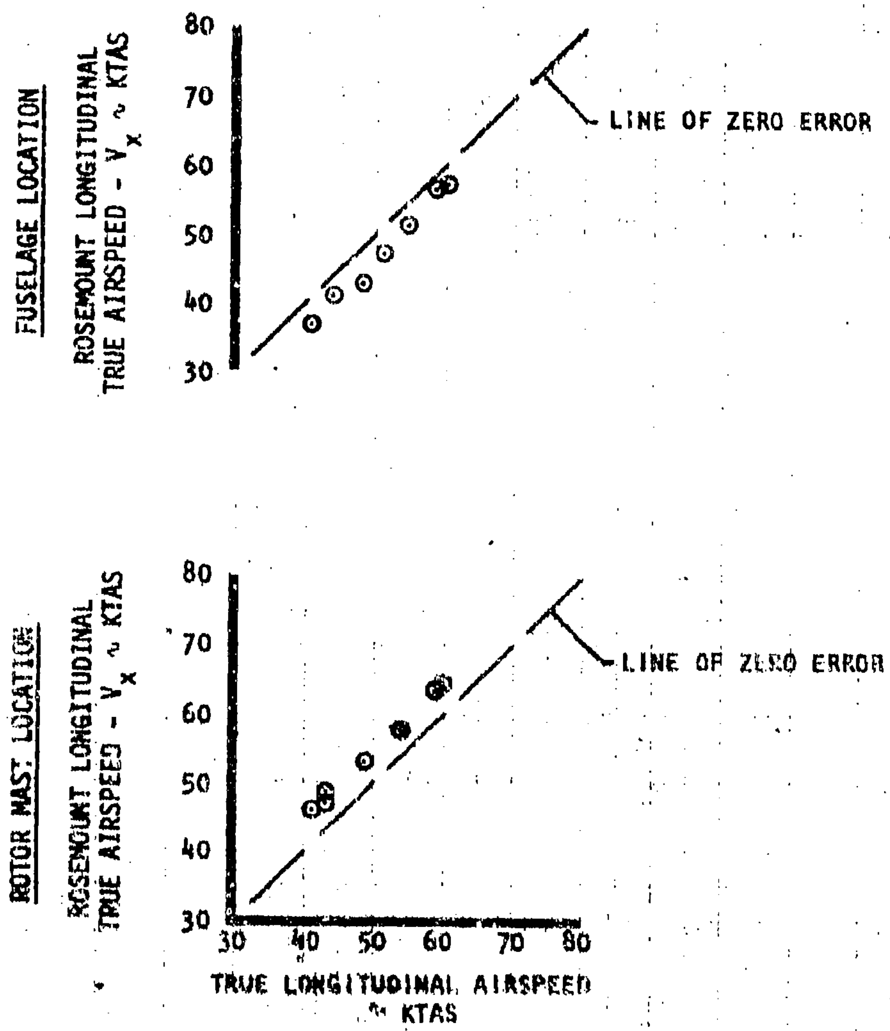


FIGURE 12
ROSEMOUNT AIRSPEED PERFORMANCE IN
HIGH SPEED FLIGHT WITH SIDESLIP
NUH-1M USA S/N 63-8684

ROTOR SPEED ~ RPM = 324
DENSITY ALT. ~ FT = 5000
AMB. AIR TEMP ~°C = 9.0
GROSS WT. ~ LBS = 6620
TRIM AIRSPEED ~ KTAS = 65

SYMBOL	SENSOR LOCATION
O	ROTOR MAST
□	FUSELAGE

NOTES: 1. Rosemount Airspeed Sensor S/N 1
2. USAAEFA Transducers

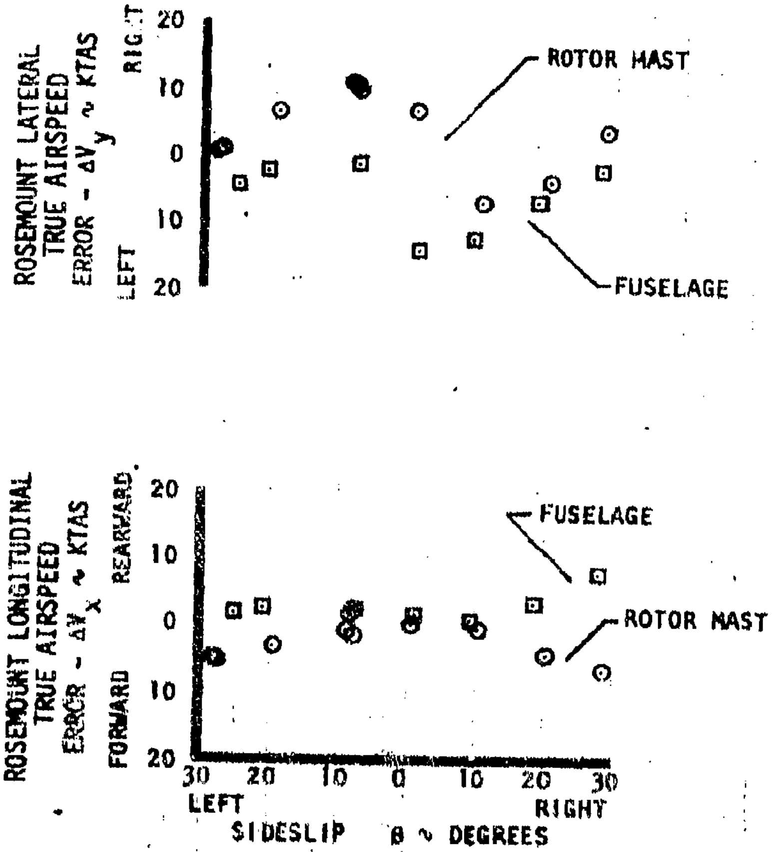


FIGURE 13
ROSEMOUNT AIRSPEED PERFORMANCE
IN HIGH SPEED CLIMBS AND DESCENTS
NUH-1M USA S/N 63-8684

ROTOR SPEED ~ RPM = 324
DENSITY ALT. ~ FT = 5000
AMB. AIR TEMP ~°C = 9.0
GROSS WT. ~ LBS = 7130
TRIM AIRSPEED ~ KTAS = 65

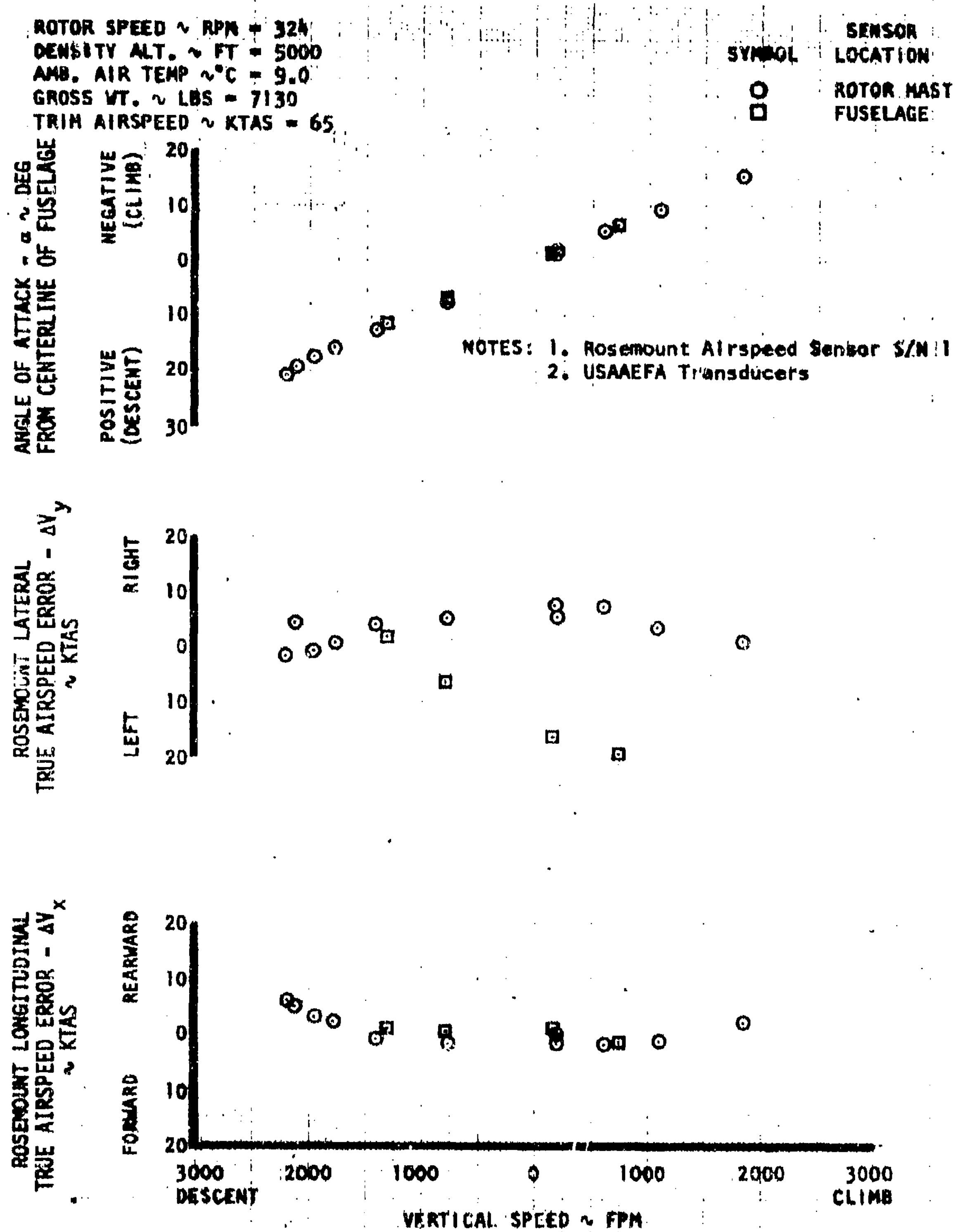


FIGURE 14
ROSEMOUNT AIRSPEED PERFORMANCE
IN VERTICAL CLIMBS AND DESCENTS
NUH-1M USA S/N 63-8604

ROTOR SPEED ~ RPM = 324
DENSITY ALT. ~ FT = 3400
AMB. AIR TEMP ~°C = 6.0
GROSS WT. ~ LBS = 6300

SYMBOL	SENSOR LOCATION
O	ROTOR MAST
□	FUSELAGE

NOTES: 1. Rosemount Airspeed Sensor S/N 1
2. USAAEFA Transducers

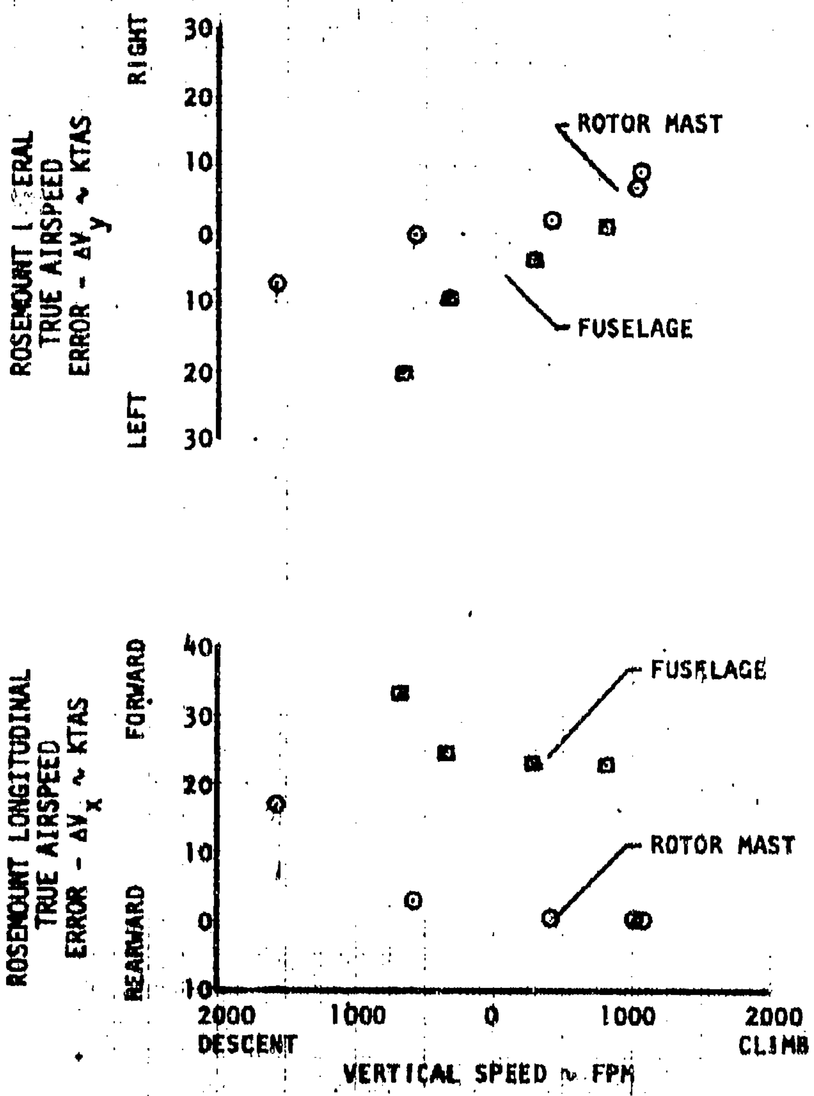


FIGURE 15
ROSEMOUNT AIRSPEED PERFORMANCE IN
LOW SPEED FORWARD-REARWARD FLIGHT
NUH-1H USA S/N 63-8684
FUSELAGE LOCATION

NOTES: 1. Rosemount Airspeed Sensor S/N 1
2. USAAEFA Transducers

ROTOR SPEED ~ RPM = 324
DENSITY ALT. ~ FT = 800
AMB. AIR TEMP ~°C = .5
GROSS WT. ~ LBS = 7200
SKID HT. ~ FT = 50

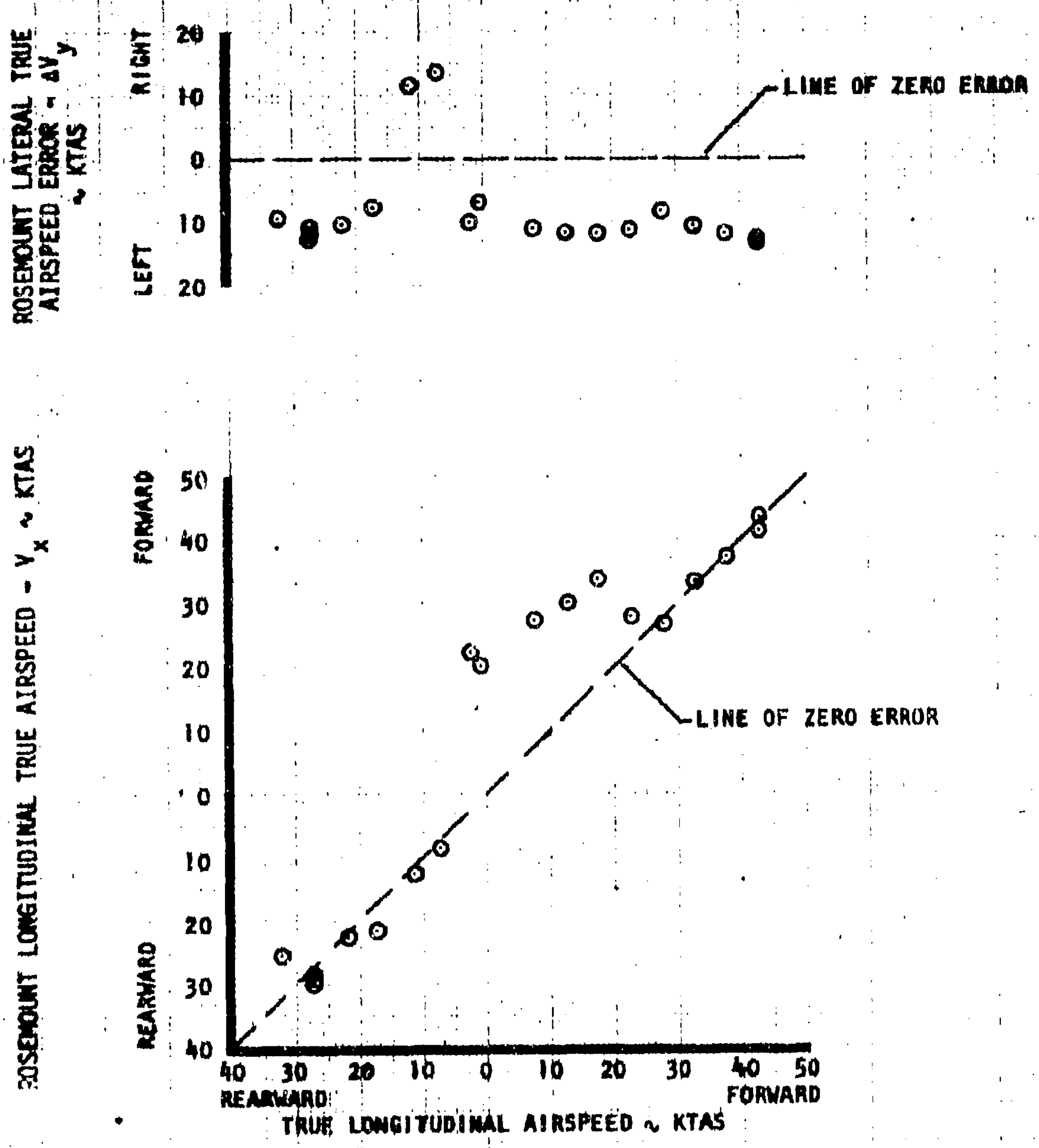


FIGURE 16
ROSEMOUNT AIRSPEED PERFORMANCE
IN LOW SPEED LATERAL FLIGHT
NUH-1H USA S/N 63-8684
FUSELAGE LOCATION

NOTES: 1. Rosemount Airspeed Sensor S/N 1
2. USAAEFA Transducers

ROTOR SPEED ~ RPM = 324
DENSITY ALT. ~ FT = 1440
AMB. AIR TEMP ~°C = 3.5
GROSS WT. ~ LBS = 7040
SKID HT. ~ FT = 50