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A COMPARATIVE ASSESSMENT OF THREE METHODS OF MEASUREMENT OF PRESSURE ERROR CORRECTIONS

by

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SUMMARY

This report describes three methods of evaluating the pressure error of an aircraft pitot-static system and compares the relative merits of each method. In particular the determination of static pressure error by a trailing cone is considered as a method suitable for use on light aircraft and comparison is made between the pressure error measured by the cone and the other methods.

CONTENTS

FIGURES

NOTATION

SYMBOL	DESCRIPTION
p_s	Free Stream Static Pressure
p_p	Free Stream Pitot Pressure
p_S	System Static Pressure
p_P	System Pitot Pressure
Δp_S	System Static Pressure Error Correction $= (p_s - p_S)$
Δp_P	System Pitot Pressure Error Correction $= (p_p - p_P)$
p_d	Free Stream Dynamic Head $= (p_p - p_s)$
p_D	System Dynamic Head $= (p_P - p_S)$
Δp_D	System Dynamic Head Error Correction $= (p_d - p_D)$
V_R	Indicated Airspeed
V_r	Rectified (or Calibrated) Airspeed
ΔV_R	Indicated Airspeed Error Correction $= (V_r - V_R)$
γ	Ratio of Specific Heats $= C_p/C_v$
a	Speed of Sound
ρ	Air Density

Suffix o denotes I.S.A. sea level conditions.

1. INTRODUCTION

The calibration of the pitot-static system is one of the most important calibrations to be carried out on an aircraft, since nearly all flight test analysis and several other calibrations depend on an accurate knowledge of the aircraft speed and height. Consequently it was decided to calibrate the system against a trailing cone static and pitot-in-venturi as sources of true static and total pressures, this being the simplest method available and known to be of high reliability. The results would then be checked by some other independent method for verification, and the kinetheodolite was chosen as a suitable system which was available for use at short notice. A further check was made against a calibrated aircraft using a formation flying technique. The details of the methods involved are dealt with in Section 3.

By comparing the calibrations obtained from the three methods for the same pitot-static system it has been possible to compare the merits of the calibration methods.

These tests were carried out at airspeeds from 80 to 160 knots on a Piper Twin Comanche 'A' which was being instrumented for research activities.

2. THE PITOT-STATIC INSTALLATION

The pitot-static system under calibration consisted of a Mk. 9A pitot-static head which fed the observers airspeed indicator and altimeter, and also a flight recorder pack. The head is mounted on the internal structure of the aircraft and protrudes 1 ft. above the apex of the nose cone to a distance of 4ft. 6 ins. ahead of the apex (see Figure 1). No thermal de-icing is used as the system is not a primary flight system. The pitot and static lines were tapped to provide for calibration instruments; differential pressure gauges or an aneroid altimeter could be used to measure the system errors. Figure 2 shows the layout of the system.

3. METHODS OF CALIBRATION

3.1. Trailing Static and Pitot-in-venturi Method

This method of calibration has the advantage of being self contained in the aircraft and therefore independent of the need to position the aircraft relative to a fixed or moving datum. The tests can be carried out at any time and place where the conditions are suitable.

The reference static pressure was measured by a Douglas Cone trailed behind the aircraft on a 60ft. long nylon tube (Ref. 1). The static vents were located in a short length of stainless steel tube let into the nylon tube about 6ft. ahead of the cone (see Figure 3). The reference static pressure was fed to a differential pressure gauge for comparison with the system static pressure.

The reference pitot pressure was sensed by a shielded pitot mounted on the nose boom (see Figure 4). Although this instrument is not a true pitot-in-venturi, and the effect of the shield is simply to remove the effects of incidence or side-slip by straightening the flow in the vicinity of the pitot head there is no reason to believe that it was not producing a good recovery of total head. It was not anticipated that any significant error in pitot pressure would occur at a head mounted so far forward with respect to the aircraft nose and no significant error was found. Therefore, after the first flights the shielded pitot was removed, together with the incidence vane, as it was suspected to be a probable source of static pressure error. Subsequent analysis was based on the static pressure only and allowance made for the pitot pressure error of a standard Mk. 9A head (Ref. 4).

The stability of the cone was observed to be good and no rotation or whipping was evident at any airspeed. Although a high trailing point is generally recommended, e.g. from the fin tip, the low attachment seemed to offer no disadvantages and is recommended for light aircraft as there is usually a strong point in this region which does not interfere with any control surface. (Further comments on attachment points are made in Ref. 1). Due to the problems of designing a suitable winch mechanism it was decided to trail the cone for take-off and landing. No problems were encountered using this technique either on grass or paved runways, and damage to the cone was mainly limited to scuffing of the edge of the cone base. The cone itself, being a simple glass fibre fabrication could be treated as a throwaway item for practical purposes. Comparison of the damage caused on the grass with that caused on the runway showed little difference probably due to the shorter take-off and landing runs possible on the paved surface.

The test method consisted of flying in steady conditions, holding speeds at a constant height and reading the pressure errors from differential pressure gauges. This method allows lag effects to be eliminated and readings to be taken over a reasonable time, thereby increasing the accuracy of interpolation.

3.2. Formation Method

This method involves flying the aircraft to be calibrated in formation with a calibrated aircraft and making a direct comparison of speed and height. The pitot and static pressure errors can then be calculated from the speed and height errors.

The success of the formation calibration depends largely on pilot technique, his ability to maintain station, and the position error with respect to the other aircraft. Formation flying is difficult at all times and is made more so if two different types of aircraft are being used, consequently the pilot of the formating aircraft will choose some reference on the leading aircraft to use as a formation indicator. This may be the leading edge of the wing or tail or some other convenient or unmistakable feature. This reference may very easily give an error in the relative positions of the pitot static heads of the two aircraft. In this test, the leading aircraft had an underwing pitot-static head and the formating aircraft had a nose-boom pitot-static head. The reference point taken was the leading edge of the tailplane which implies that the formating aircraft would be slightly above the leading aircraft datum. This has been estimated at about 2ft. Accurate height data is not easily read from the standard flight instruments on the two aircraft and consequently the static pressure error can only be deduced from the airspeed error, on the assumption that the pitot pressure error is negligible.

The comparison of airspeed data is made directly from simultaneous readings of the two systems. It is usually only possible to read airspeed indicators to the nearest half knot and so an accuracy of ± 1 knot is all that can be expected for any observation. In many cases that may be the magnitude of the error to be detected.

The leading aircraft pitot static system will also be subject to a pressure error correction, and the formation calibration method can only be as good as the calibration of leading aircraft. The leading aircraft used in these tests was the H.S. Dove, G-APSO, operated by Cranfield Institute of Technology. The pitot and static system errors of this aircraft are very well known and were calibrated by a trailing static bomb and pitot-in-venturi, and checked by the kinetheodolite method. The airspeed indicators and altimeters in both aircraft were re-calibrated before the tests.

During the formation flights the trailing cone static was used to measure the static pressure error directly, but due to the relative inaccuracy of the airspeed readings it was not possible to determine the pitot pressure error separately. The static pressure error readings taken supplemented other trailing static data and were indistinguishable from them.

3.3. Kine-theodolite Method

The kine-theodolite installation at R.A.E. Bedford was used to determine the static pressure error of the aircraft by comparison of the true distance between the aircraft and a fixed vertical datum, and the distance above that datum measured by the aircraft static system.

The aircraft static system was connected to a sensitive aneroid to give a direct reading, in feet, of height in the standard atmosphere. The instrument was capable of being read to the nearest 5ft. The kine-theodolite system, using two kine-theodolites and computing results from direct readings corrected from a film record, claimed accuracy to ± 1ft.

The test method used a datum provided by positioning the aircraft on the ground on a predetermined mark on the runway. Reference kine-shots were taken and the aneroid read. The aircraft was then flown over the runway at a series of steady speeds and at about 50ft. altitude, (or greater than 1 span to avoid ground effects). Each run recorded the pressure altitude and geometric altitude of the aircraft and comparison of these results provided the static pressure error of the system.

The major problem of this method of calibration is the simultaneous serviceability of aircraft and kine-theodolite system, suitability of the weather and availability of the test airfield. Of these the most uncertain is the weather and the ideal requirement is a clear day with a wind not more than 10 knots at 90^{o} to the runway. Less wind will usually be accompanied by poor visibility and consequent loss of accurate kine-tracking. More wind requires a large drift angle at low speeds with consequent flying problems associated with it. A significant headwind component, particularly if the wind is not uniform will further add to the problems of determining airspeed from kine-theodolite data.

The system is basically as accurate as the aneroid in the aircraft, and therefore the reading or recording of this instrument is the key to success of the method. Visual reading was performed and it was found that reliable readings could be made to an interpolation of 5ft. on the scale. There was sufficient vibration to ensure elimination of hysteresis, and zero error shift is eliminated by the datum readings. The deviation of the atmosphere from I.S.A. can be accounted for by a temperature correction to the recorded height interval. In the tests performed the temperature was within two degrees of I.S.A.

Data reduction of the kine-theodolite readings, corrected for observation error from the film trace record, is processed automatically to give the coordinates of the aircraft datum point position from a datum point of the ground. The data reduction programme takes in all known sources of error including the refractive index of the air and the earths curvature at the airfield latitude. One source of error does however remain. The kine-theodolite is zeroed on a known point and not on the aircraft itself. Therefore, a constant error equal to the height of the aircraft datum point above the ground when the aircraft is standing at the ground datum is present in the kine-theodolite data. This is a height of 4.75ft. in the case considered (see Figure 6). This error must be subtracted from the kine-theodolite heights.

It was also possible to compute airspeeds from the kine-theodolite tracking data and this could be included in the output data. However, the airspeed error calculated from the kine-theodolite system showed considerable scatter and no resemblance to the errors calculated by the other methods. It is thought that as the speeds are calculated from position data taken from seven consecutive observations at intervals of 0.2 sec. the overall interval of 1.2 sec. is too short to eliminate the turbulence errors even though corrections for headwind component were made.

4. DISCUSSION OF RESULTS

The pressure errors determined by each method of calibration were reduced to indicated airspeed error according to the theory given in Appendix A.

The three methods each produce pressure error correction curves of a very similar form (see Figures 7, 8 and 9). The error is shown to increase with speed and, to a first order approximation appears to be a constant percentage error (see Figure 10). Since the pressure field around a body of revolution, then produces a constant percentage pressure error at a given point and as the forward fuselage approximates to a body of revolution, then the pressure error sensed by the pitot-static system is of the form expected. The curvature of the $\Delta V_R - V_R$ curve is caused by the effect of incidence change with speed.

Taken together the curves produced by the kine-theodolite and formation methods are very similar (see Figure 10), and when the formation method curve is corrected to allow for pitot pressure error Δp_P due to the pitot head (Ref. 4.), the slight discrepancy between the curves at low speeds is almost entirely eliminated. This indicates that the static pressure error correction found by these methods is the same, since the one case static pressure only is being considered and in the other the pitot error has been accounted for.

The Douglas cone pressure error correction curve shows a similar form but is displaced from the other curves by -1 knot at 80 knots V_R and -0.5 knots at 160 knots V_R. Since all three methods of calibration have been reduced to the assessment

ΔV_R from static pressure error only, and since they are all measuring the static pressure error of the same static source there must be an error in the static pressure sensed by the trailing cone static or in the differential pressure gauge used to sense the static pressure error.

Considering these errors and using the relationship

$$\frac{2\,\Delta V}{V} = \frac{\Delta p_S}{q}\text{, where } q = \frac{1}{2}\rho V^2$$

it can be seen that the speed error gives a static pressure error Δp_S of 0.54 lb/ft^2 throughout the speed range. This is equivalent to a height error ΔH_P of 7.1 ft.

Since this error is constant throughout the speed range it would indicate that this is a calibration error in the system. Although it has not been possible to locate the error it is thought to have been in the differential pressure gauge calibration.

Correcting the trailing cone results for the constant error produces a static pressure error correction curve of ΔH_P against V_R for the cone within 2 ft. of that for the the kine-theodolite method (see Figure 11). This is within the experimental limits of the system.

The trailing cone was photographed in flight at various speeds (see Figure 5), and it was found that the angle of trail was small. Comparison of the static pressure error correction derived from the cone and kine-theodolite methods indicate that the trail angle was insufficient to cause any significant error. Calibration of similar trailing cone devices (Ref. 5) confirm that the static pressure error is very small over the speed range of the tests and can be regarded as negligible.

The relative accuracy of the methods can be estimated by comparing the standard deviation of the data points from the best curve through them. The kine-theodolite method and the trailing cone method showed standard deviation of 0.14 knots and 0.145 knots respectively and the formation method showed a standard deviation of 0.615 knots. The latter could probably be improved by using flight recorders for speeds and identing the record from each aircraft at the same instant. Usually this is only feasible when both aircraft are fully instrumented for test flying. The very low standard deviation of the first two methods indicate their suitability for accurate calibration of test aircraft.

5. CONCLUSIONS

The results of the tests show that the accuracy of all three methods of calibration is generally good but that the trailing cone method is preferable for use on a light aircraft, since there is no need for above average pilot skill in executing the tests. So long as a steady height and a series of steady speeds can be flown, good results can be obtained. The installation of the test equipment can be reasonably simple depending on the extent of the tests, but if a pitot-in-venturi is required then it could present installation problems.

Kine-theodolite calibration can only be undertaken with the assistance of the ground tracking installation and could be very costly. It also requires a larger degree of pilot skill in holding steady speeds at low altitudes and accurately positioning the aircraft over a target point. Although the internal equipment is minimal, an aneroid altimeter, it is expensive, and unless it is in regular use may suffer from calibration problems. This method will only provide a static pressure error unless it is possible to perform the test in calm conditions.

Formation flying requires a high degree of pilot competency for success. It also requires a calibrated aircraft and good flying conditions, which makes the method one for specialist organisations only to undertake. The aircraft under calibration does not require any particular test instrumentation, and so could be calibrated at very short notice if necessary. However, although speed error is easily determined, height error is not since the reading accuracy of a standard altimeter is usually too coarse. Therefore, this method is only recommended for very limited applications where the other method cannot be employed.

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2.		Engineering Sciences Data Sheets. Aeronautical Series, Performance sub-series, RG1/1 Corrections to Indicated Altitude for Static Pressure Error, RG1/2 Corrections to V_R for Pressure Error.
3.		A.G.A.R.D. Flight Test Manual, Vol. 1. Performance, Chapter 1.
4.	J. E. NETHAWAY	Low Speed Wind Tunnel Calibration of a Mk.9A Pitot-Static Head. A.R.C. Tech. Report C.P. No. 244, (1956).
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APPENDIX A

Calculation of Airspeed Indicator Pressure Error Correction V_R

Let the Pressure Error Correction of the system static pressure p_S be Δp_S

Let the Pressure Error Correction of the system pitot pressure p_P be Δp_P

$\therefore \quad p_s = p_S + \Delta p_S$

and $p_p = p_P + \Delta p_P$

Now the exact-law calibration of the A.S.I. gives, for $\dfrac{V_r}{a_o} < 1$

$$p_d = p_p - p_s = p_{s_o}\left\{\left[1 + \frac{(\gamma-1)}{2}\left(\frac{V_r}{a_o}\right)^2\right]^{\frac{\gamma}{\gamma-1}} - 1\right\}$$

and by binomial expansion this can be reduced to the simplified law

$$p_d = p_{s_o}\left\{\left[1 + \frac{\gamma}{2}\left(\frac{V_r}{a_o}\right)^2 + \frac{\gamma}{8}\left(\frac{V_r}{a_o}\right)^4 + \ldots\ldots\right] - 1\right\}$$

$$= p_{s_o}\frac{\gamma}{2}\left(\frac{V_r}{a_o}\right)^2\left[1 + \frac{1}{4}\left(\frac{V_r}{a_o}\right)^2 + \ldots\ldots\right]$$

$$= \frac{1}{2}\rho_o V_r^{\,2}\left[1 + \frac{1}{4}\left(\frac{V_r}{a_o}\right)^2\right]$$

Now $p_d = p_p - p_s = (p_P + \Delta p_P) - (p_S + \Delta p_S)$

$$= (p_P - p_S) + (\Delta p_P - \Delta p_S)$$

$$\therefore \quad \Delta p_D = \frac{1}{2}\rho_o (V_R + \Delta V_R)^2\left[1 + \frac{1}{4}\left(\frac{V_R + \Delta V_R}{a_o}\right)^2\right] - \frac{1}{2}\rho_o V_R^2\left[1 + \frac{1}{4}\left(\frac{V_R}{a_o}\right)^2\right]$$

Where V_R is the indicated airspeed and V_r the rectified or calibrated airspeed and

$$V_r = V_R + \Delta V_R$$

The indicated airspeed pressure error correction ΔV_R is thus formed in terms of the indicated airspeed V_R, and the differential pressure error correction Δp_D. Figure 12 shows V_R as a function of Δp_D and V_R.

(Source - Refs. 2 and 3)

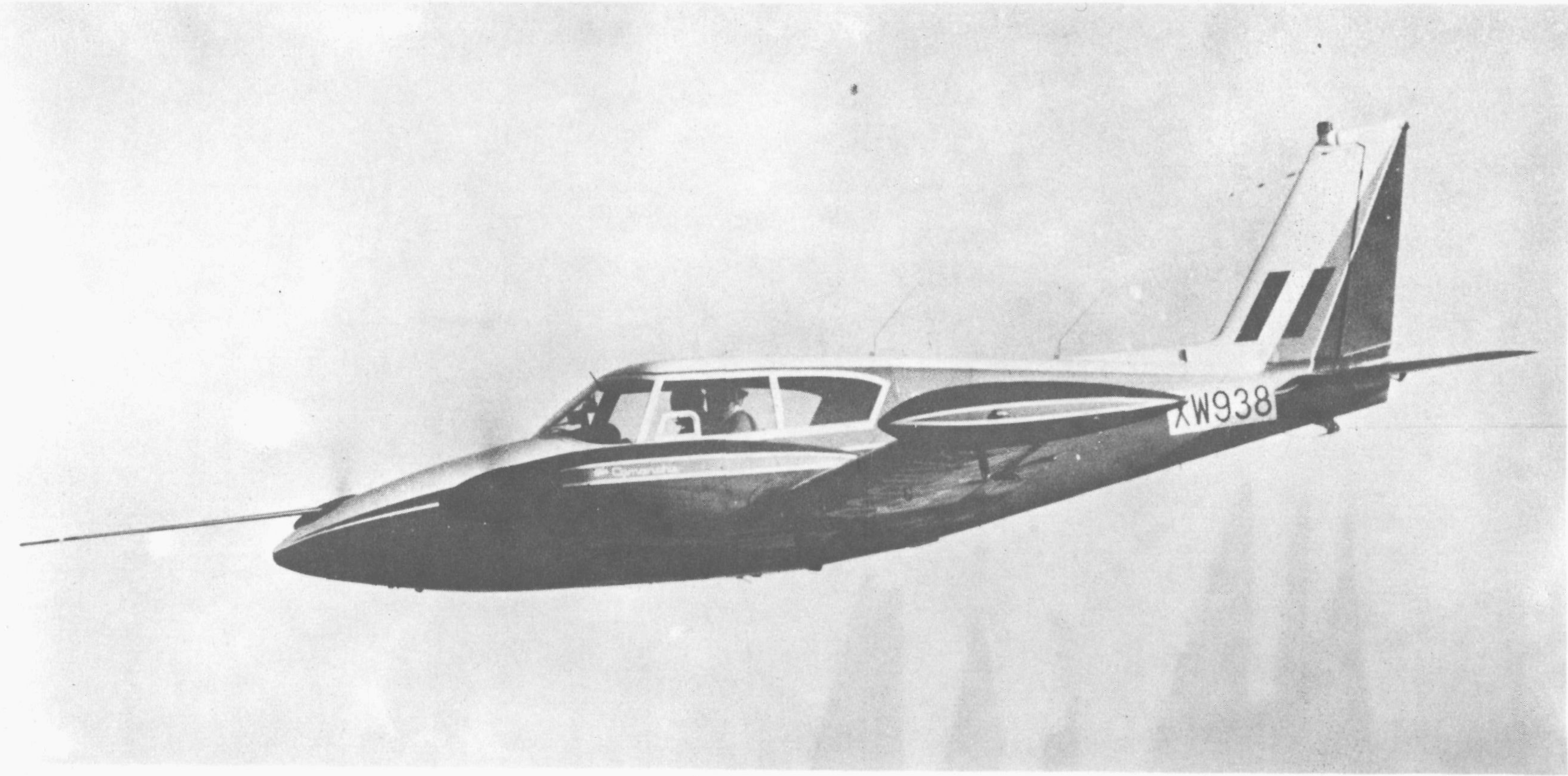

FIG. 1 TEST AIRCRAFT showing nose boom pitot-static head and trailing static attachment

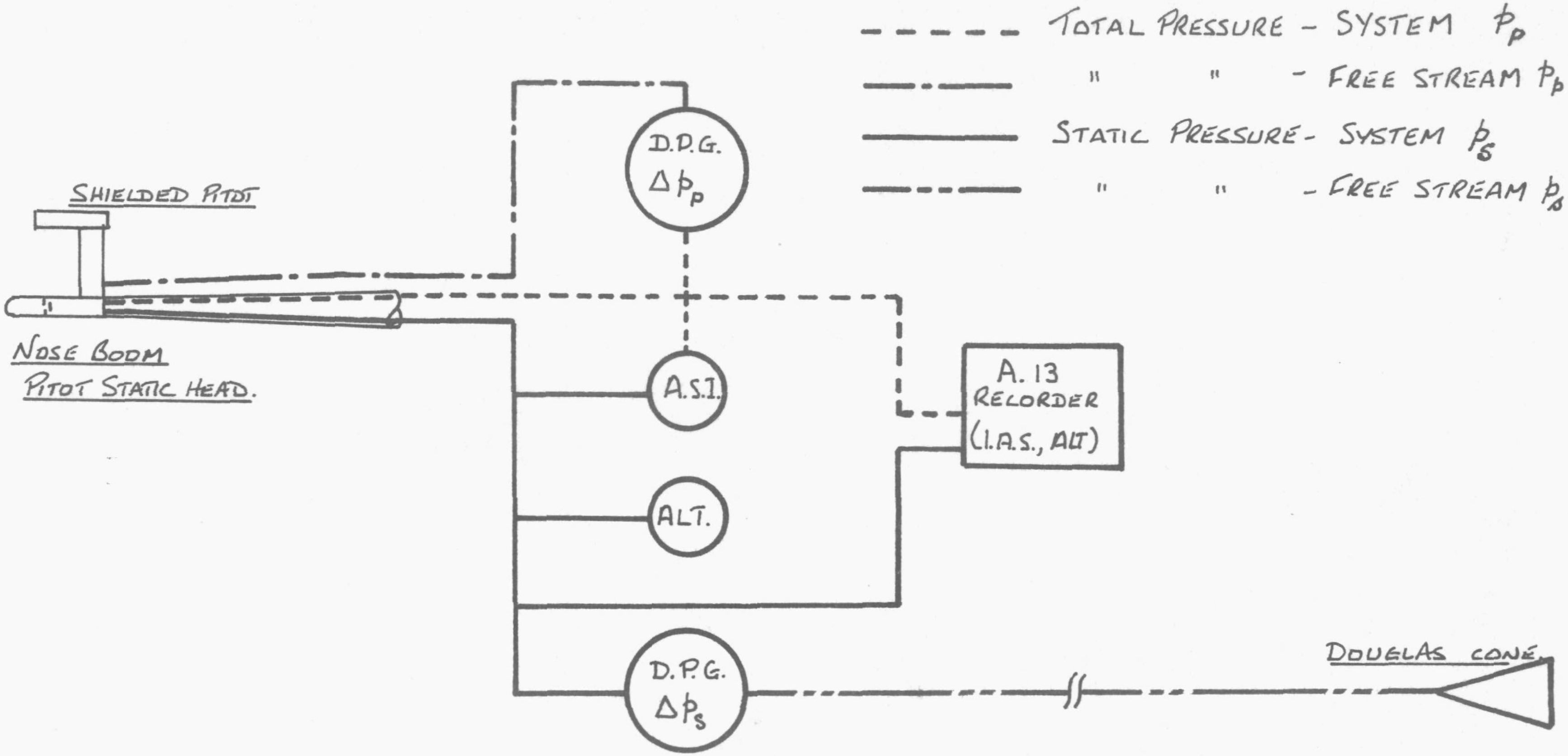

FIG. 2 SCHEMATIC ARRANGEMENT OF TEST PITOT-STATIC SYSTEM

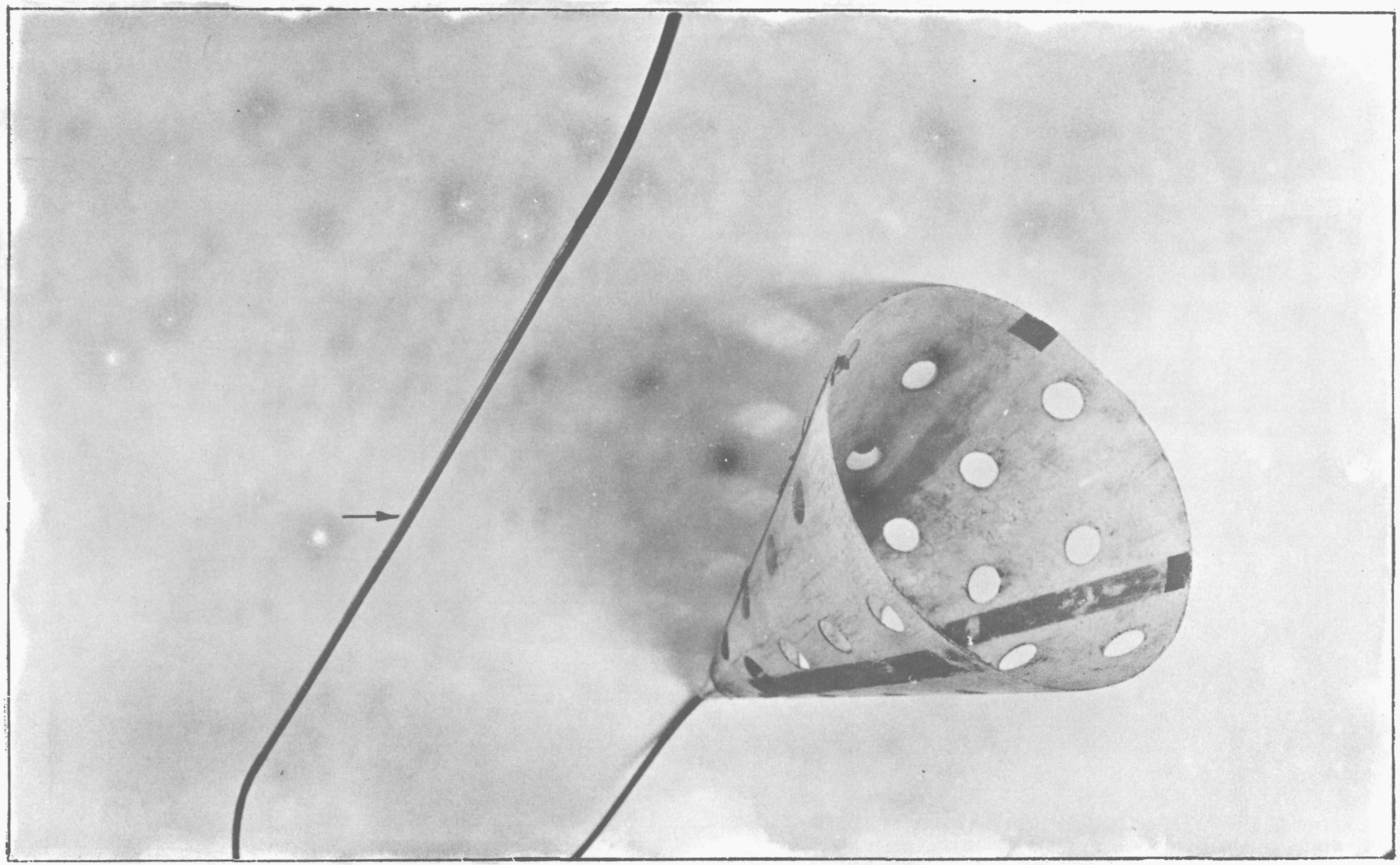

FIG. 3 DOUGLAS TRAILING CONE STATIC
Arrow shows location of static vents in stainless steel insert

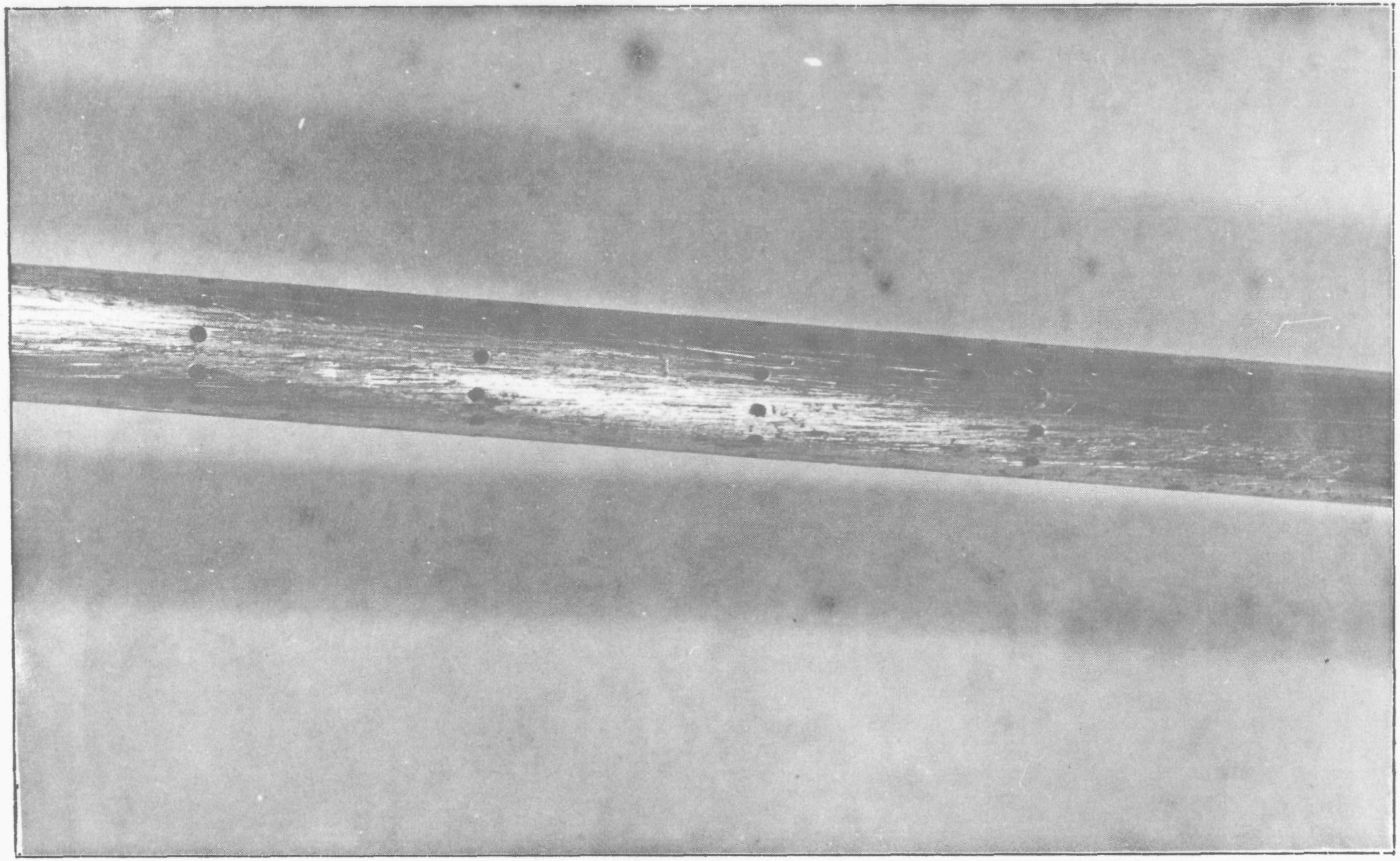

FIG. 3a. DOUGLAS CONE, detail of the static vents

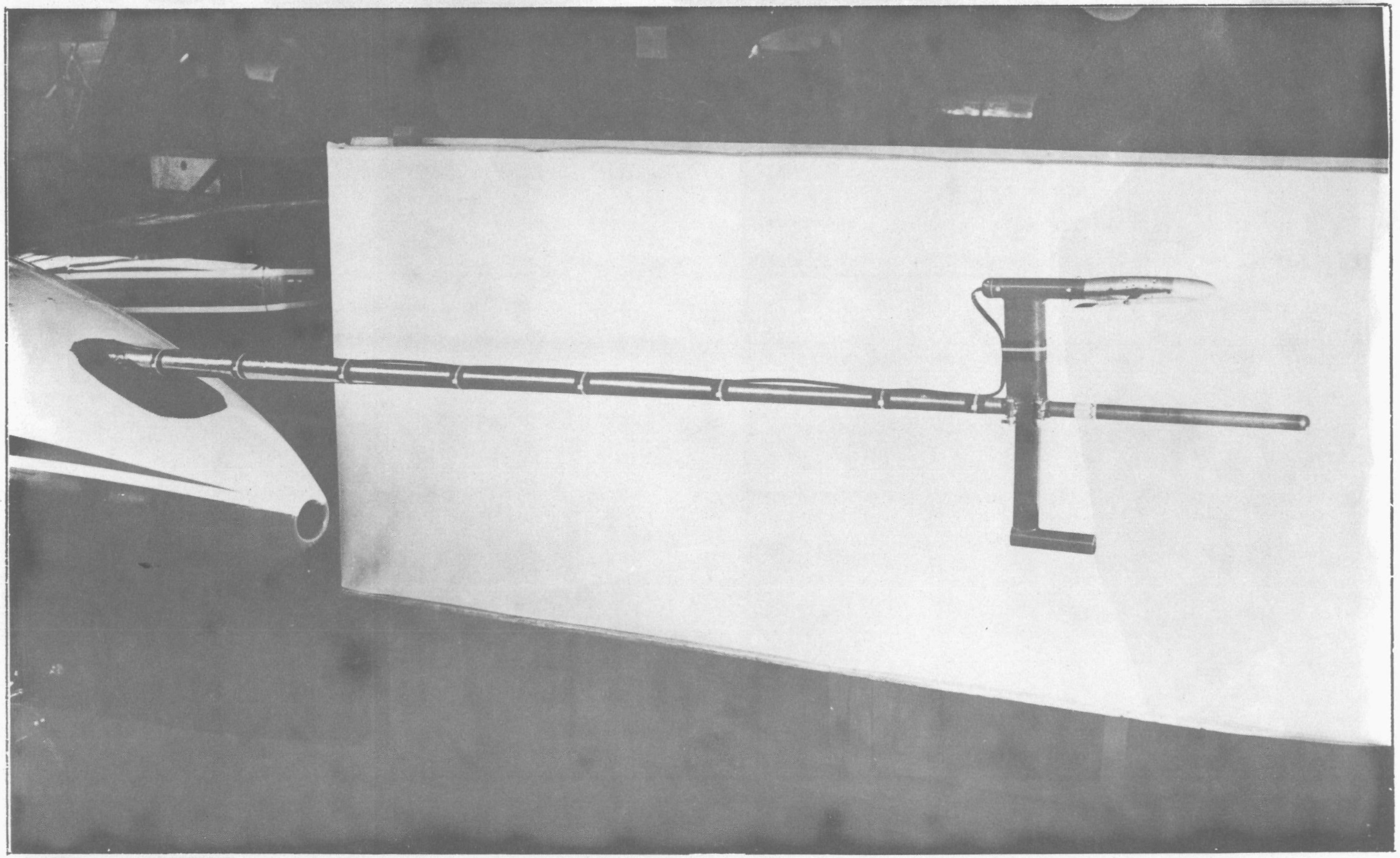

FIG 4 NOSE BOOM PITOT STATIC INSTALLATION with shielded pitot and incidence vane

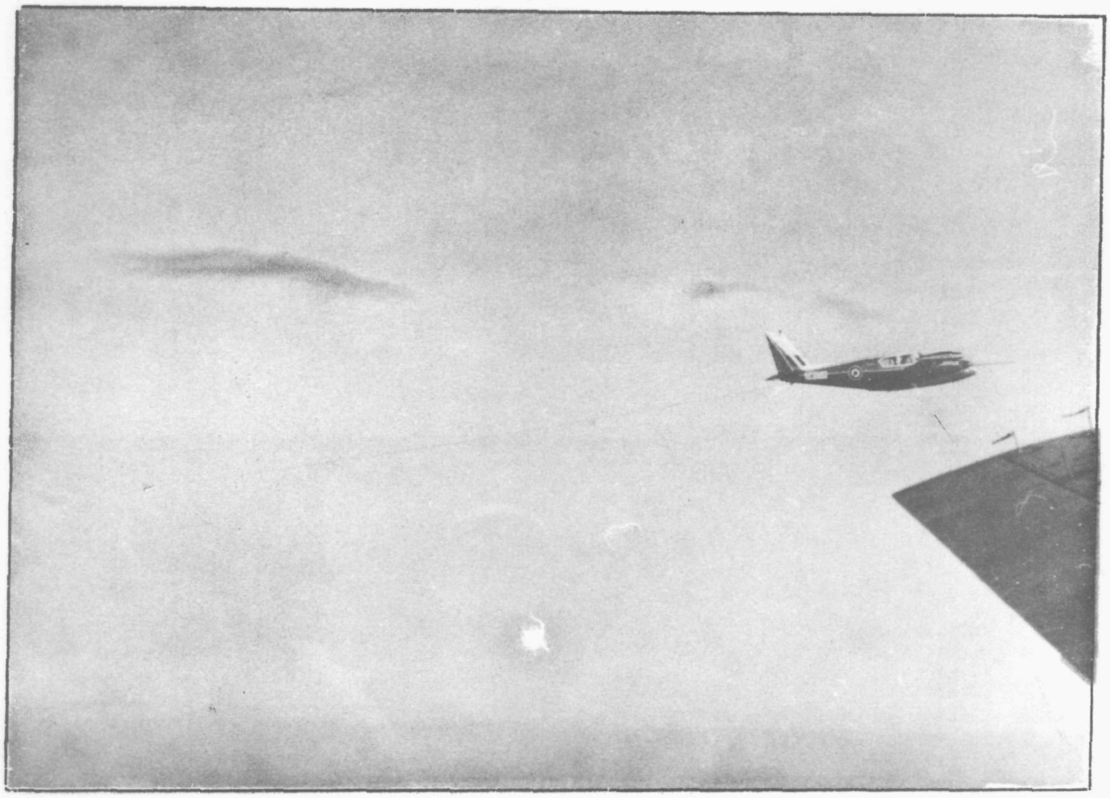

FIG. 5 (i) 85 kts.

FIG. 5 (ii) 95 kts.

FIG. 5 DOUGLAS TRAILING CONE STATIC IN FLIGHT

FIG. 5 (iii) 125 kts.

FIG. 5 (iv) 155 kts.

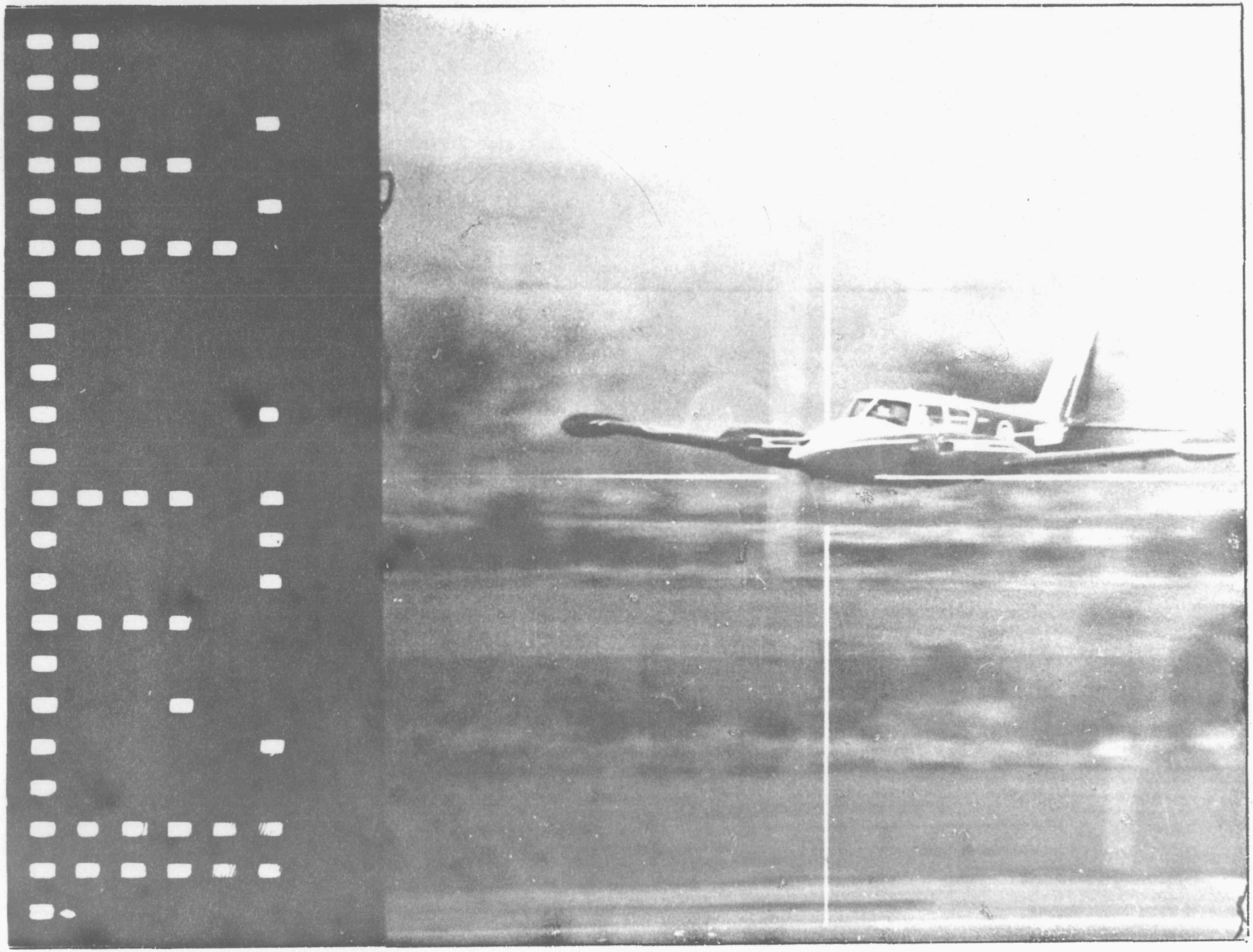

FIG. 6 Sample frame taken from Kine-theodolite film record

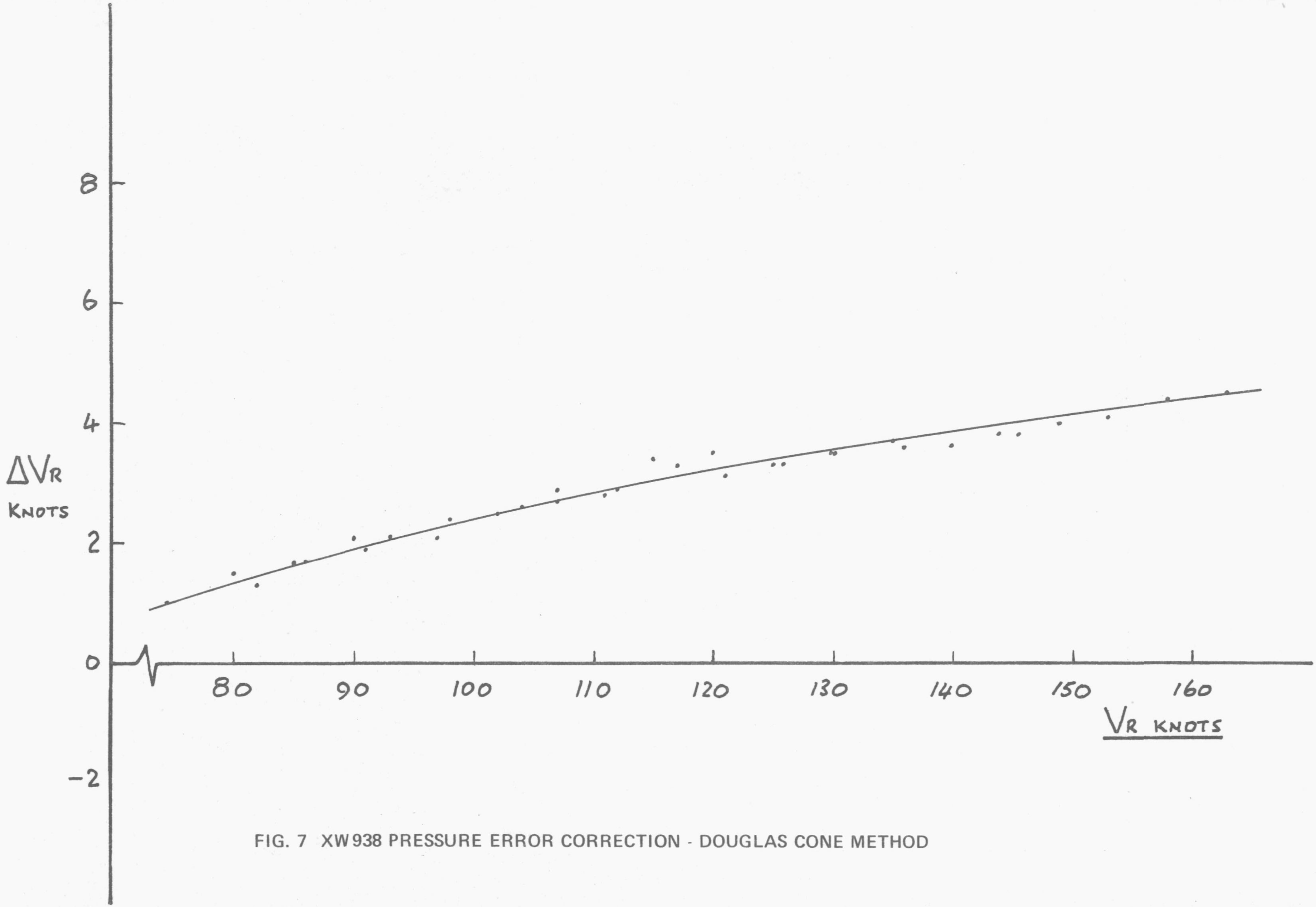

FIG. 7 XW938 PRESSURE ERROR CORRECTION - DOUGLAS CONE METHOD

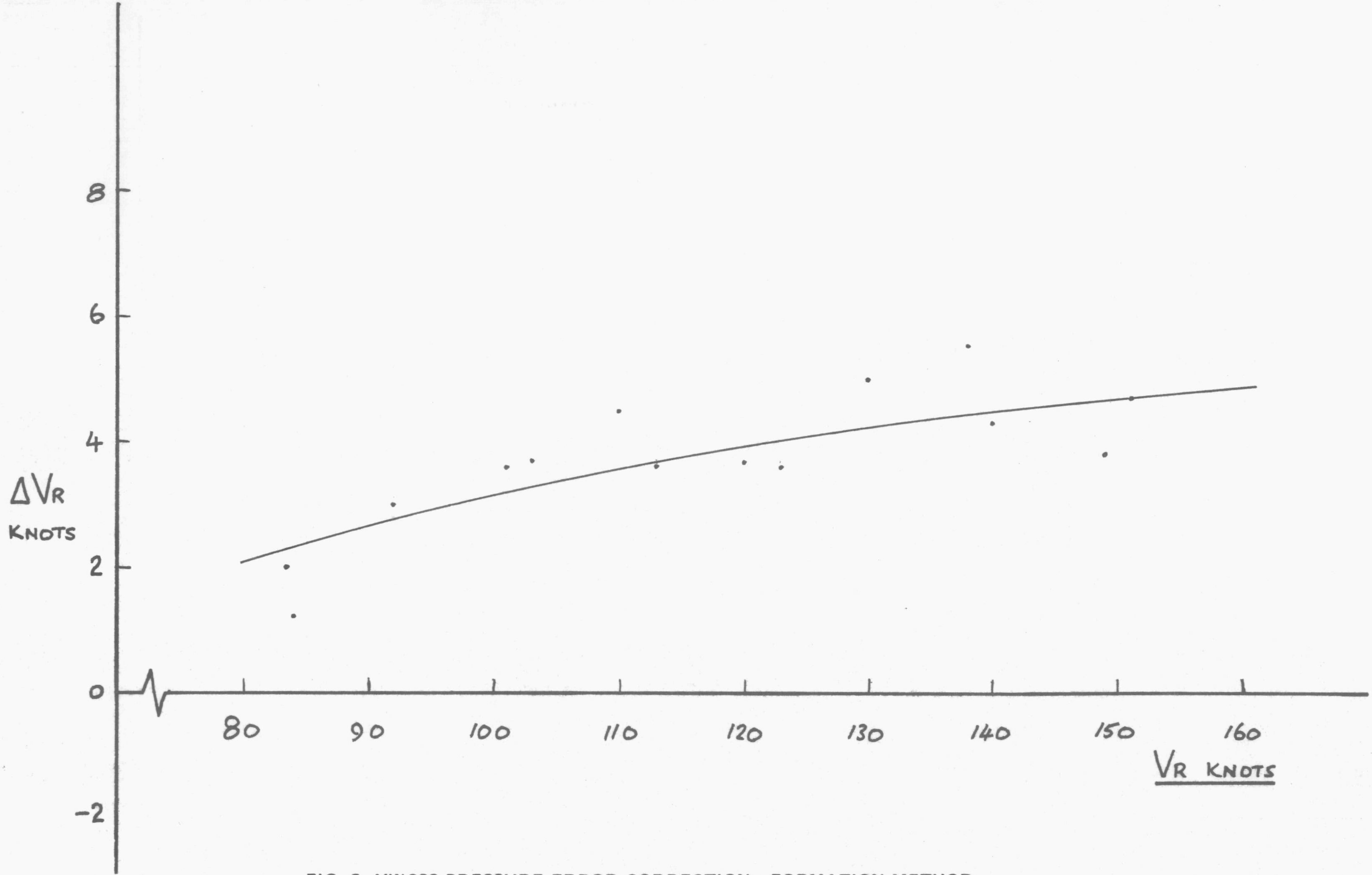

FIG. 8 XW938 PRESSURE ERROR CORRECTION - FORMATION METHOD

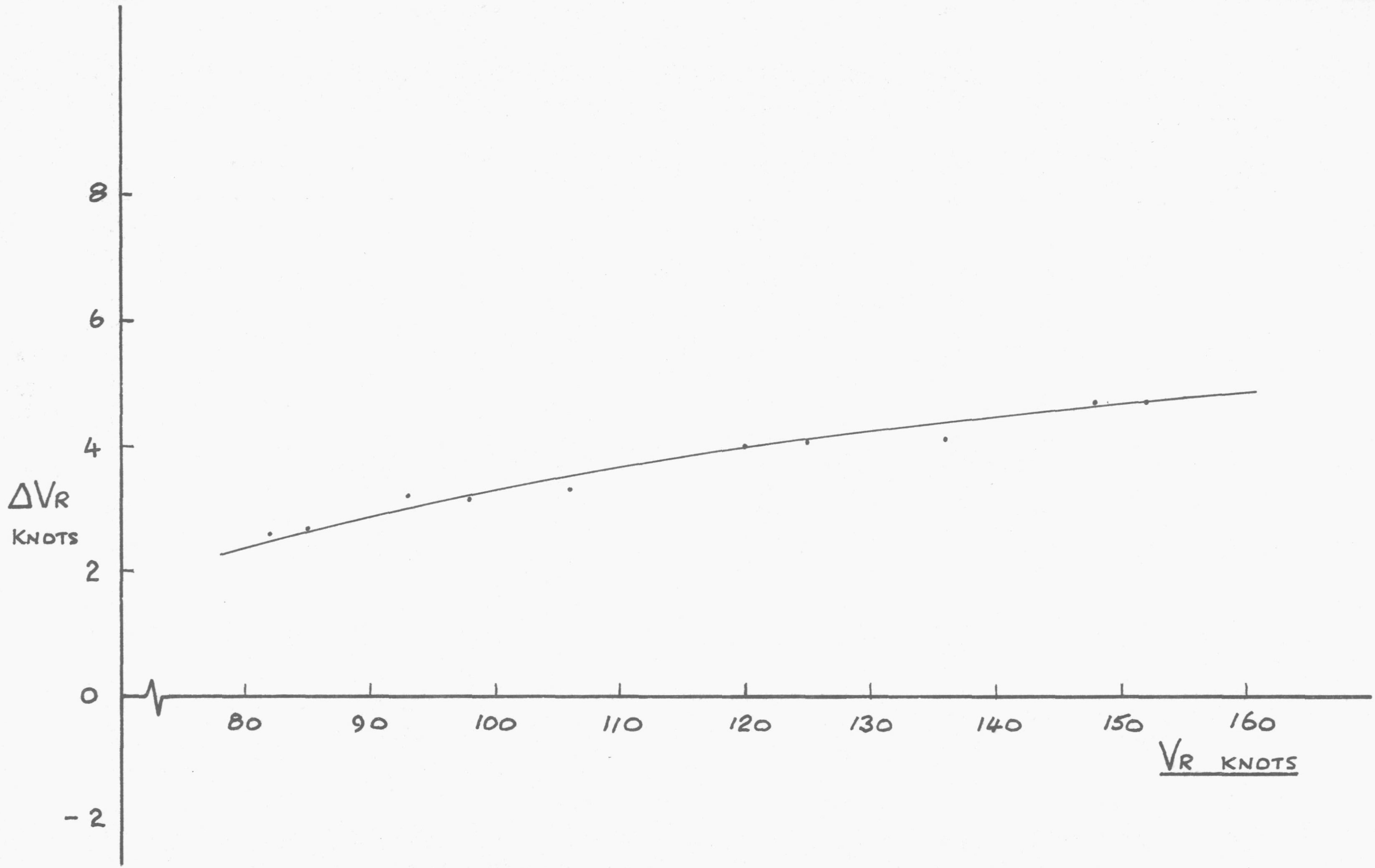

FIG. 9 XW938 PRESSURE ERROR CORRECTION - KINETHEODOLITE METHOD

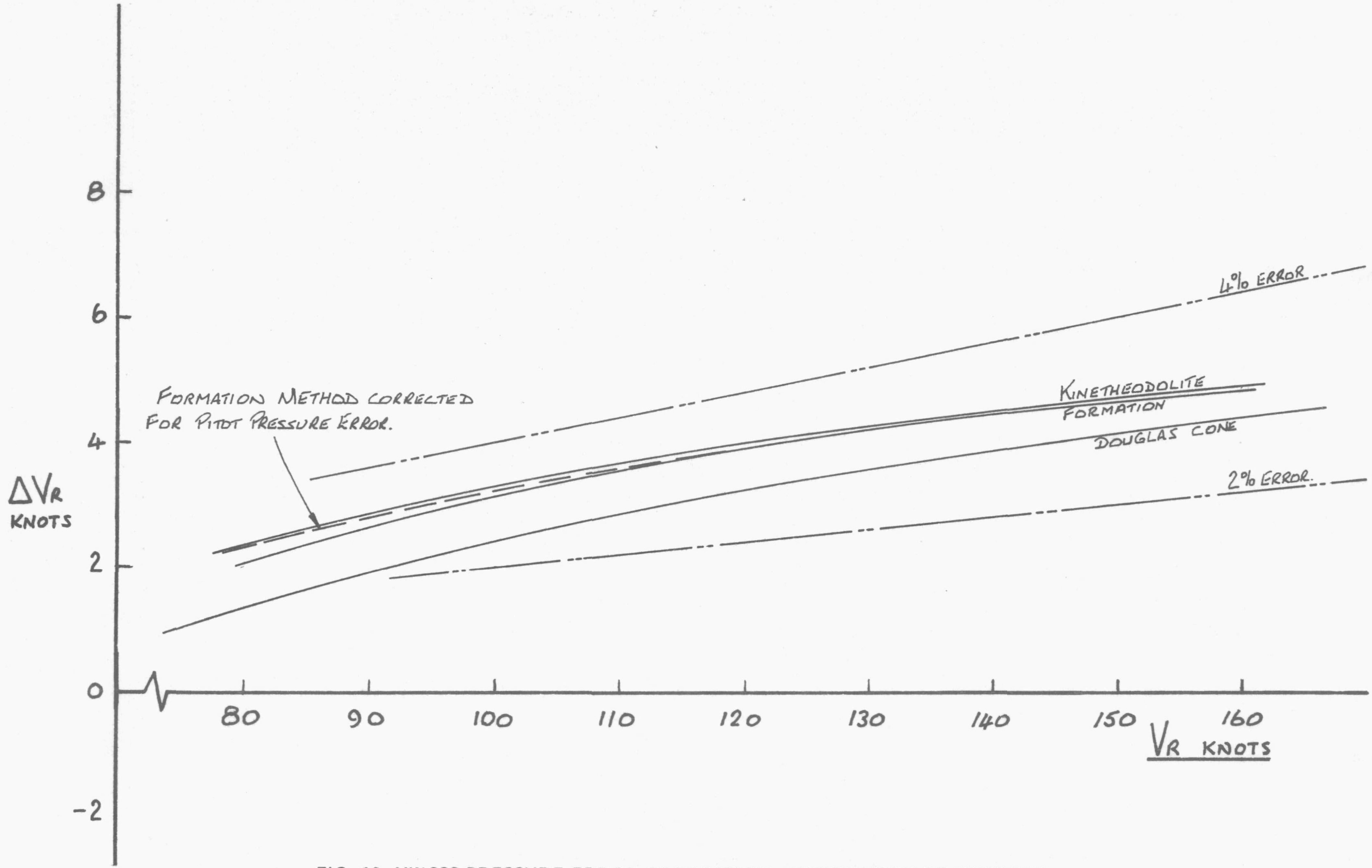

FIG. 10 XW938 PRESSURE ERROR CORRECTION - COMPARISON OF METHODS

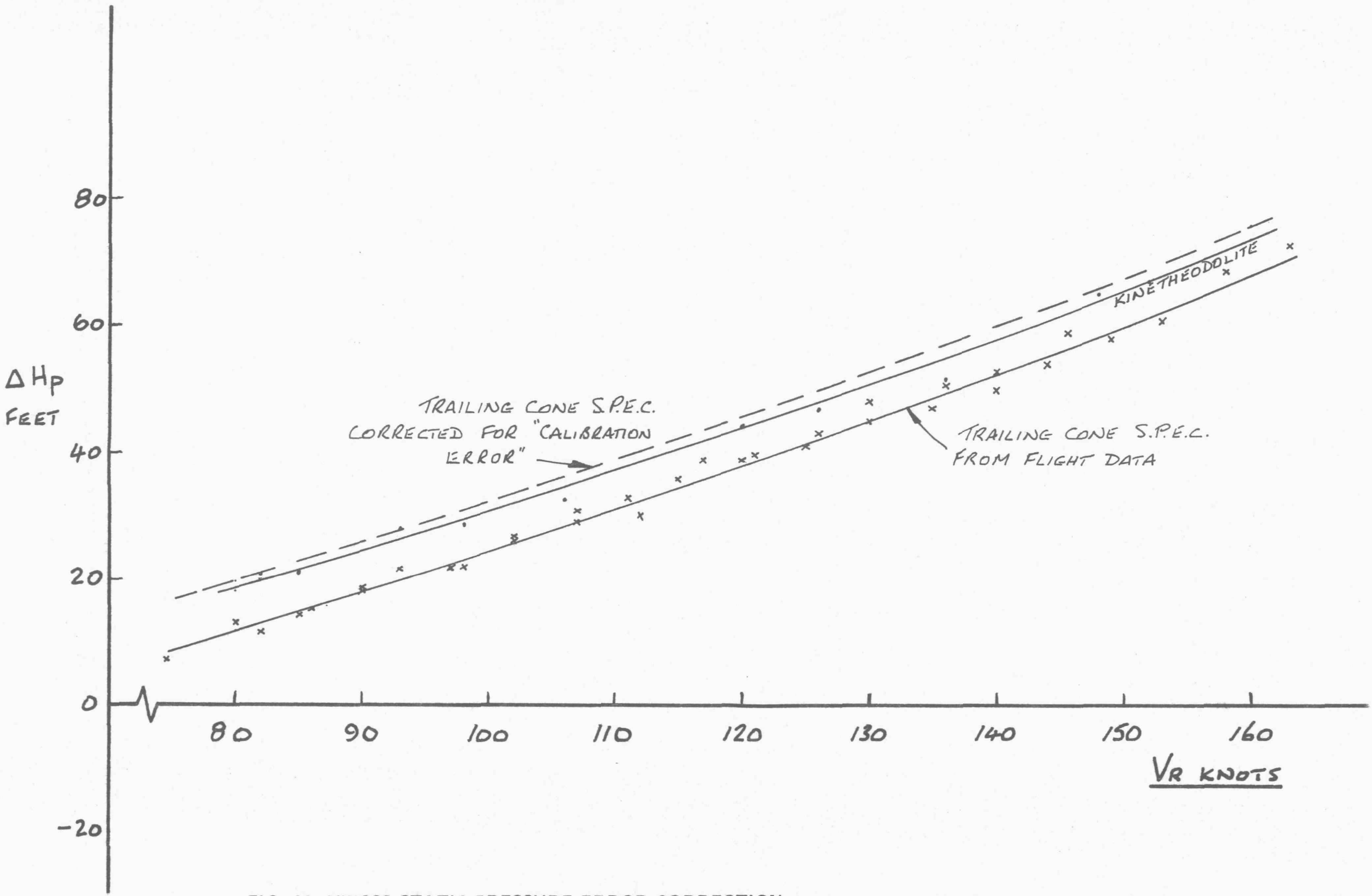

FIG. 11 XW938 STATIC PRESSURE ERROR CORRECTION

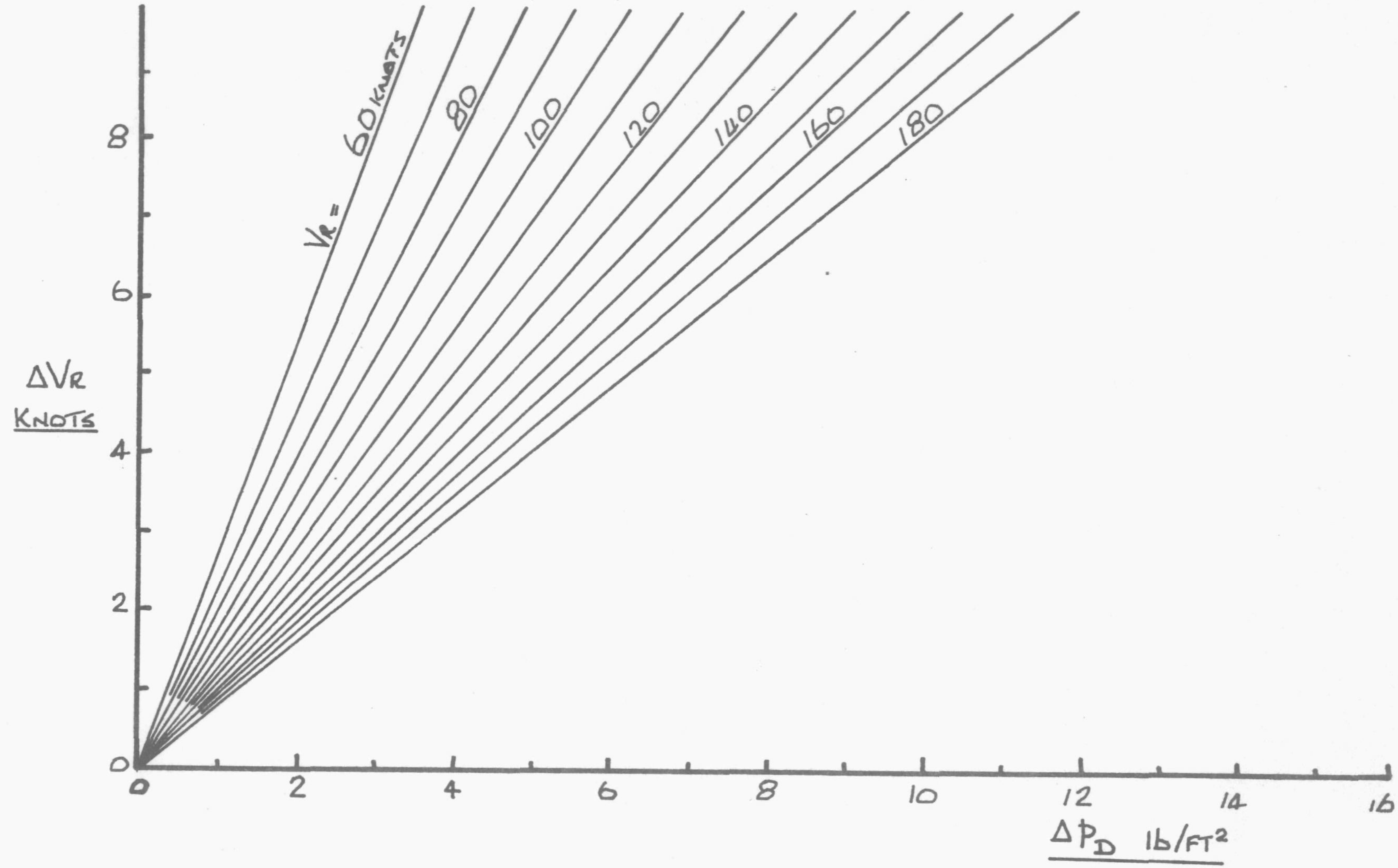

FIG. 12 INDICATED AIRSPEED PRESSURE ERROR CORRECTION