GEZ

TURBULENCE AND DIFFUSION NOTE NO. 8

THE 1969 COMPARISON OF AFCRL AND CARDINGTON TURBULENCE SENSORS

C. J. Readings and H. E. Butler

Introduction

During October 1969 one of the Cardington turbulence probes (P7) was taken to Hanscom Field (Bedford, Mass) and its performance compared with those of two AFCRL sonic anemometers - the instruments being mounted on the top of a 50' tower built of scaffolding. Although this tower was surrounded by trees and buildings of comparable heights there was to the west, between the tower and the nearest obstructions, an area of rough grass extending for about 300 yards. Therefore all the runs were done with the wind coming from this direction.

2. The sonics were mounted at each end of a 2 metre pole which was turned before each run so that it was approximately perpendicular to the wind direction. Another piece of scaffolding supported the rod on which the Cardington turbulence probe was mounted so that it was positioned mid-way but slightly above the two sonics.

3. Cable telemetry was used to relay all the signals back to a caravan situated about 20 yards to the east of the tower. Here they were passed through low pass filters with cut offs at 10 Hz and recorded in analogue form on magnetic tape. A computer inside this caravan processed the data and the results were available about five minutes after the run finished. Most of these were of ten minutes duration.

Description of the Cardington turbulence probe and its associated circuits

4. During the runs the Cardington turbulence probe was attached at the balance point to a piece of rod about which it was free to rotate (see figure 1). This enabled the vanes to keep it facing into wind.

5. The instantaneous inclination of the wind in the vertical was measured by an inclinometer consisting of a yawmeter supported by a metal tube. It was mounted on a platform inclined at 45° to the horizontal. This platform was fixed to an upright which was pivoted so that it could swing about a horizontal axis, and which was maintained in a vertical orientation by the weight attached to its lower end. Any oscillations were minimised by the oil dashpot.

6. The actual yawmeter, consisted of two hot-wire "V"s made of 13μ platinum and inclined at 80° - the component wires making an angle of 120° (Jones, 1961). These "V's" were connected to a head amplifier (see figure 2a) mounted in the vane which was adjusted to give a sensitivity of 20 mv/degree over a linear range of $\pm 40^{\circ}$ with direction changes of up to $\pm 30^{\circ}$.

7. A photo-electric cup anemometer similar to that described by Jones (1965) was used to measure the total instantaneous wind speed. It was mounted on its side so that the plane of the cup rotor could be maintained in the instantaneous wind direction by the vane. This rotor consisted of eight expanded polystyrene cups. The instrument's response time was about 0.1 seconds at 5 m/sec and 120 pulses were produced per revolution.

8. The instantaneous temperature was measured with a resistance element consisting of about 180 cm of 25μ platinum wire wound non-inductively onto a clear plastic former. It was connected to an amplifier (see figure 2b) mounted in the vane. This was adjusted to give an output of 250 mV/$^{\circ}$C over a linear range of $\pm 4^{\circ}$C - the zero could be switched in 3°C steps between -3°C and $+18^{\circ}$C.

9. The various sensor signals were telemetred back to the recording caravan by cable via a connecting box which also contained a voltage stabiliser (see figure 3a) - the necessary 16 volt d.c. supply being taken from the recording caravan by cable.

10. Inside the caravan the pulses from the anemometer were fed into a ratemeter (see figure 3b) and converted into a fluctuating voltage lying in the range ± 1 volt. This output and those from the other two sensors were fed into the AFCRL data processing equipment via a low pass filter having a cut-off at 10Hz.

11. It should be noted that the anemometer was recalibrated and the electrical circuitry checked prior to the comparison experiment; furthermore the ratemeter was calibrated before every run using a signal generator which had previously been checked using a pulse counter.

General comments on the runs and the processing of the results

12. Owing to the nature of the site, runs could only be made when the wind was westerly. This meant that only sixteen ten minute and four five minute runs were done during the visit. Of these, five runs (ie three of ten minutes duration and two of five minutes) were done during one day and the rest were done in one night.

13. In this analysis one of the sonics (ie Sonic 2) is used as a standard and its results compared with those of the other sonic (ie Sonic 1) and the Cardington Probe. This choice was forced by the failure of Sonic 1 after only seven runs. Incidentally for the purposes of this report the four five minute runs have been combined to give two of ten minutes duration.

14. In TDN No. 7 the importance of knowing the absolute value of the wind inclination was stressed and the difficulty of doing this instrumentally pointed out. Thus it was decided to define the true vertical axis by assuming $\overline{w}$ to be zero for each of the runs. As this was only done with the data from the Cardington probe (the sonics being lined up to better than 0.1°), there was a chance that the two types of probe would use different frames of reference which could lead to artificial agreement or disagreement. Thus in this report not only are the usual turbulent parameters compared but also two quantities that are invariant with respect to rotation of the axis.

<u>The turbulent velocity components</u>

15. From the output from the inclinometer and the ratemeter it is possible to derive σ_u, σ_w and $\overline{u'w'}$ to quite a good degree of approximation. These quantities may then be compared with the corresponding values derived from the two sonics. Figure 4 shows the values derived from Sonic 1 and the Cardington Probe against those from Sonic 2. These three graphs include plots of the "best" lines, as given by the "least-squares" technique, for each set of data.

16. Although the regression line shown in figure 4a) for the two sonics does not differ significantly from the ideal one of unit slope, that for the Cardington Probe versus Sonic 2 is systematically different from both of them. This means that the value of σ_w derived from the Cardington Probe is systematically smaller than those obtained from the two sonics - the discrepancy increasing with wind speed to a maximum value of about 9%. However the various estimates of σ_u are indistinguishable (see figure 4b)).

17. When corresponding values of the quantity $\sqrt{(\sigma_w^2 + \sigma_u^2)}$, which is invariant with respect to rotation of the axes, are regressed against each other as in figure 5a) it is found that although the values derived from the Cardington Probe are

still systematically smaller than those obtained from the two Sonics the maximum value of the discrepancy is now only about 5% . Thus part of the discrepancy can be explained by the use of two (or three?) frames of reference. Incidentally this also accounts for the agreement between the σ_w's being worse than that between the $\sqrt{(\sigma_w^2 + \sigma_u^2)}$ while that between the σ_u's is slightly better.

18. The residual discrepancy could be due to the fact that the instruments were exposed differently. However the high correlation that existed between the various σ_w's (it was greater than 0.9 and was higher between the Cardington probe and the individual sonics than between the two sonics) makes this seem rather unlikely unless there was a marked scaling with height. Another possible cause is the lower response of the cup anemometer. However this hypothesis is not in agreement with the slight tendency for the discrepancy to increase with wind speed unless the turbulent flow was of a rather unusual nature. Thus it seems reasonable to conclude that although part of the lack of agreement can be explained by the use of different frames of reference, the cause of the residue cannot be determined from the results alone - though undoubtedly the nature of the site and the lack of response of the cup anemometer played an important part.

19. In figure 4d) the various estimates of u_* are compared and it can be seen that there is no significant disagreement between the two regression lines. Although there is a tendency for the value derived from sonic 2 to be larger than the other two estimates, the situation changes somewhat when the invariant quantity $[(\sigma_w^2 - \sigma_u^2)^2 + 4u_*^2]^{\frac{1}{4}}$ is considered. This depends on the momentum flux as well as the two variances and is plotted in figure 5b) from which it can be seen that the two sonics are now in better agreement - illustrating the fact that the two sonics were not aligned in exactly the same way. However it must be emphasized that quite a small angular discrepancy could cause this rather small effect. The values obtained from the Cardington probe differ from those derived from the sonics by a few percent but this difference varies in quite a complex fashion. It probably results from a combination of several effects - viz lack of response of cup anemometer, calibration errors, differences in exposure.

20. Incidentally it may be noted at this juncture that the complex nature of the site probably means that the scale of turbulence was not necessarily what one would expect 50' above smooth ground.

21. In figure 6a) the various estimates of σ_w are plotted against the corresponding values of u_* and it can be seen that the regression lines are indistinguishable. The slopes of the two more reliable are lines about 1.55 which is quite different from the value of 1.30 quoted by Busch and Panofsky (1968). Although this discrepancy might be due to the nature of the site, it is interesting to note that a similar value was obtained at Cardington (see TDN No. 7).

22. The relation between the σ_u's and the σ_w's is shown by figure 6b) and once again there is no significant difference between the slopes, though they vary between 1.38 and 1.63. These estimates give values of c (where $\sigma_u = cu_*$) lying within the range of values quoted by Lumley and Panofsky (1964), taking $\sigma_w = 1{\cdot}55u_*$ in accordance with the value given in paragraph 20.

<u>The temperature fluctuations and the heat flux</u>

23. Unfortunately the rather small magnitudes of σ_T and $\overline{w'\theta'}$ precludes any critical comparison of these quantities. However, the "sonic" temperatures were derived from platinum resistance elements which should not differ from those obtained from the Cardington resistance element. This expectation was realised by the regression analysis of the σ_T's which gave two indistinguishable lines almost superimposed on a line of unit slope passing through the origin.

24. The regression analysis for the $\overline{w'\theta'}$ was quite interesting inasmuch as although the line for the Cardington probe was parallel to the ideal line, that for Sonic 1 was of significantly different slope. This could have been a positional effect but may merely reflect scatter in the data. Cardington $\overline{w'\theta'}$ tended to be larger which is probably a reflection on the complex nature of the site. The smallness of the measured heat fluxes precludes any more detailed discussion.

The mean wind speed

25. The calibration of a normal cup anemometer varies with the intensity of turbulence, and an overestimate of the wind speed will be obtained if wind tunnel calibration constants are used in the field. Clearly, this comment does not apply to sonic anemometers and hence the error may be estimated by comparing mean wind speed estimates obtained from the cup anemometer using its wind tunnel calibration constants with those derived from a sonic anemometer.

26. When such a comparison was made during the October visit it was found that the cup anemometer used on the Cardington Probe did not overestimate the mean wind speed. This is illustrated by figure 7 in which the usual regression lines are plotted using the results from twenty-one runs. These lines are indistinguishable between themselves and with respect to a line of unit slope passing through the origin.

27. However as there was a slight difference in the exposures of the two sonics and the Cardington Probe, it was decided to do some experiments with the cups at the same level as the two sonics - the line of the instruments being perpendicular to the mean wind direction. To achieve this it was necessary to mount the eight polystyrene cup rotor on a different photo-electric anemometer body of the "Cassella" type with the cups rotating about a vertical axis instead of the usual horizontal one. The resultant system was then recalibrated using the wind tunnel facility in an adjacent caravan. It was interesting to find that the calibration line only differed from that obtained with the Cardington anemometer system with respect to the starting speed.

28. In all some four runs each of ten minutes duration were made during one afternoon and the results are listed in the table. It can be seen from this that the Cardington cup system was once again indistinguishable from the sonics - the fourth column shows the values obtained with another "Casella" type photo-electric anemometer fitted with metal cups and it can be seen that the error is of the order of 12%. This would seem to confirm

COMPARISON OF ESTIMATES OF MEAN WIND SPEED

Sonic 1	Sonic 2	Cardington cups	CRL cups
5.24 m/sec	5.24 m/sec	5.27 m/sec	5.90 m/sec
5.70 m/sec	5.71 m/sec	5.71 m/sec	6.33 m/sec
6.53 m/sec	6.39 m/sec	6.45 m/sec	7.24 m/sec
5.43 m/sec	5.45 m/sec	5.45 m/sec	6.18 m/sec

that by the correct design of cups this overspeeding error may be eliminated.

Concluding remarks

29. The aim of these experiments was to compare the Cardington probe with the performance of a correctly used sonic anemometer as a first step in collaborative work with the Boundary Layer Branch of AFCRL. Without doubt this comparison has been very successful and planning of the next stage (ie a comparison of balloon-borne instruments with tower mounted ones) has already started.

30. Although the residual discrepancy between the instruments would be expected to disappear with a more compatible exposure at heights where the lack of anemometer response is not important, the error due to the use of different frames of reference could well increase. Thus it is imperative to ensure that the instruments use the same frames of reference.

31. The performance of the eight-polystyrene cup system in giving correct wind speeds was quite unexpected and more work will have to be done to determine why it and Tribble's system are unique in this respect. Incidentally it is interesting to note that miniaturised Cassellas with plastic cups suffer from the usual defect.

References

Busch N. E. and Panofsky H. A. (1968) "Recent spectra of atmospheric turbulence" Q.J. 94 pp 132-148.

Jones J. I. P. (1961) "The measurement of turbulence near the ground" Porton Technical Paper No. 786.

Jones J. I. P. (1965) "A portable sensitive anemometer with proportional d.c. output and a matching wind velocity component resolver" J. Sci. Inst. 42 pp 414-417.

Lumley J. L. and Panofsky H. A. (1964) "The structure of atmospheric turbulence". J. Wiley (New York).

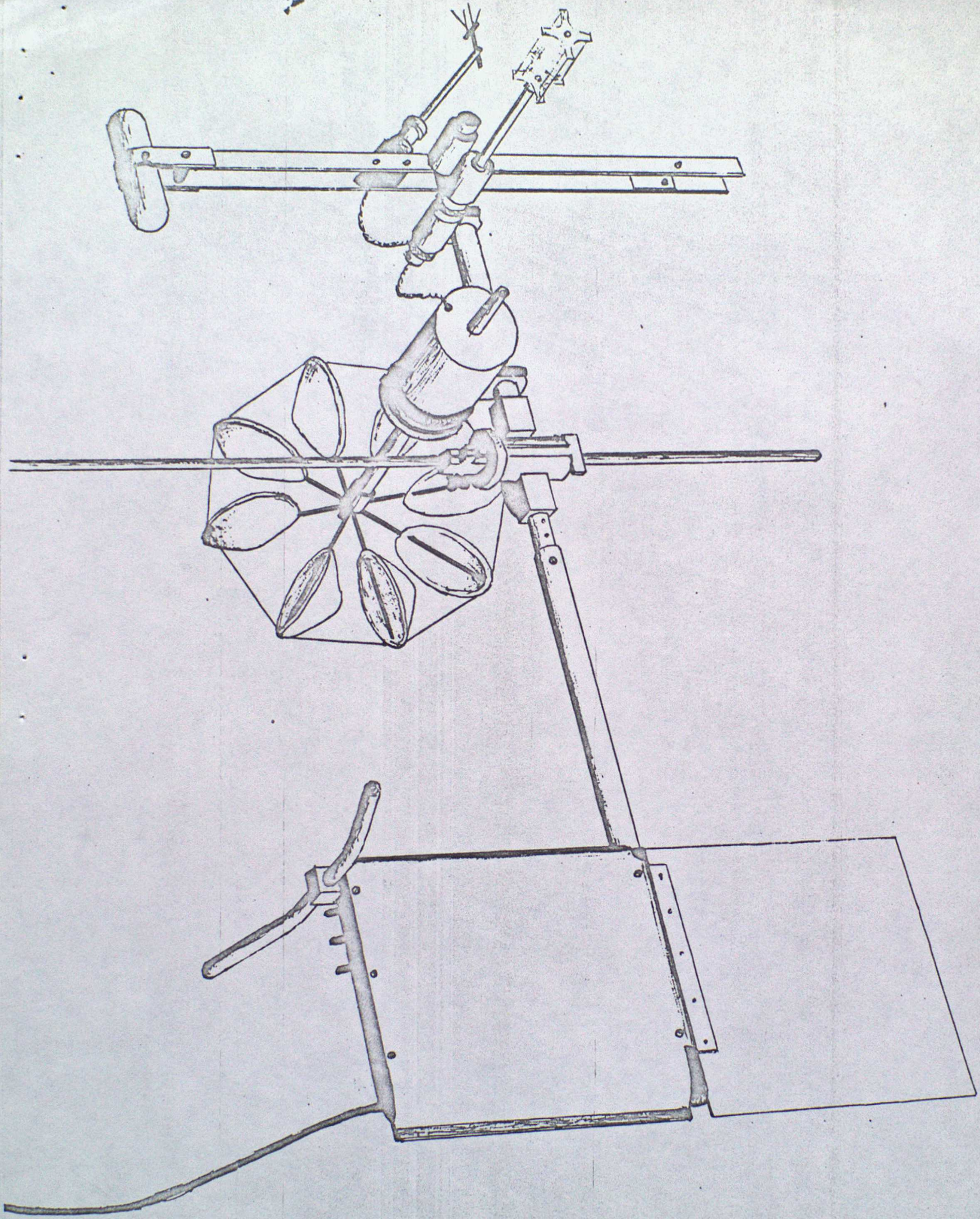

Figure 2 The electrical circuitry associated with the temperature element and the inclinometer.

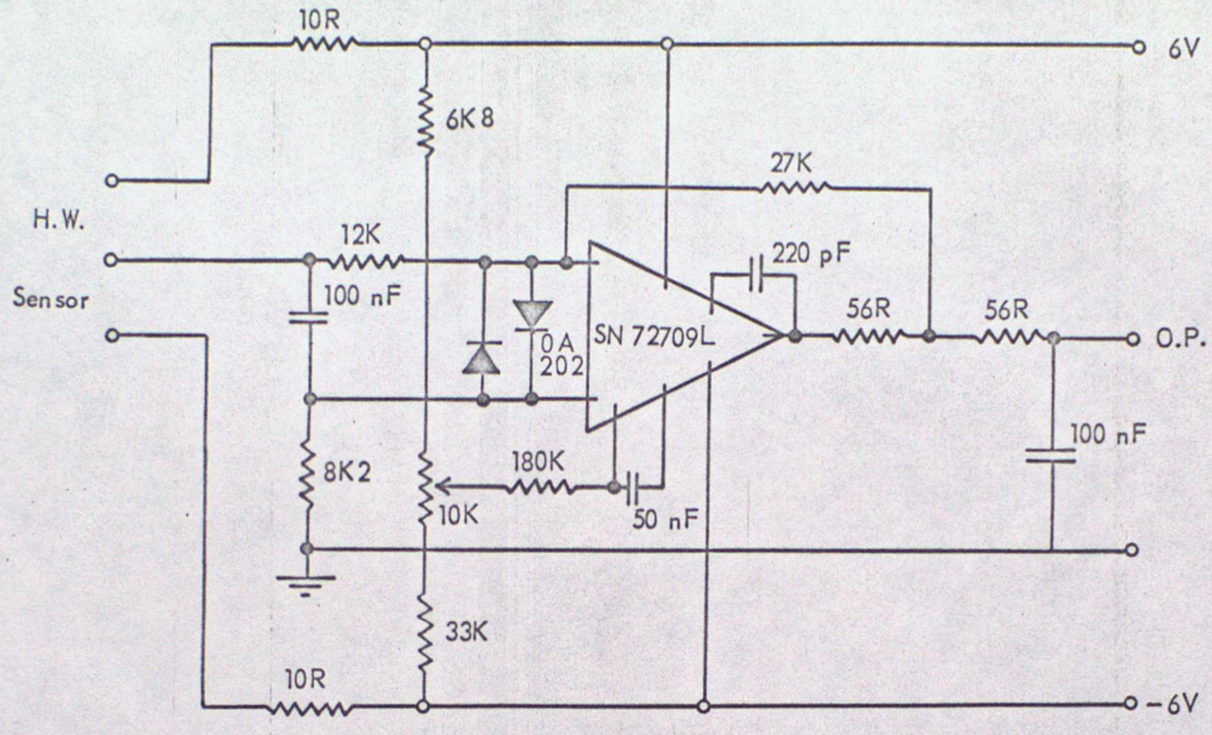

Figure 2a The amplifier for the inclinometer.

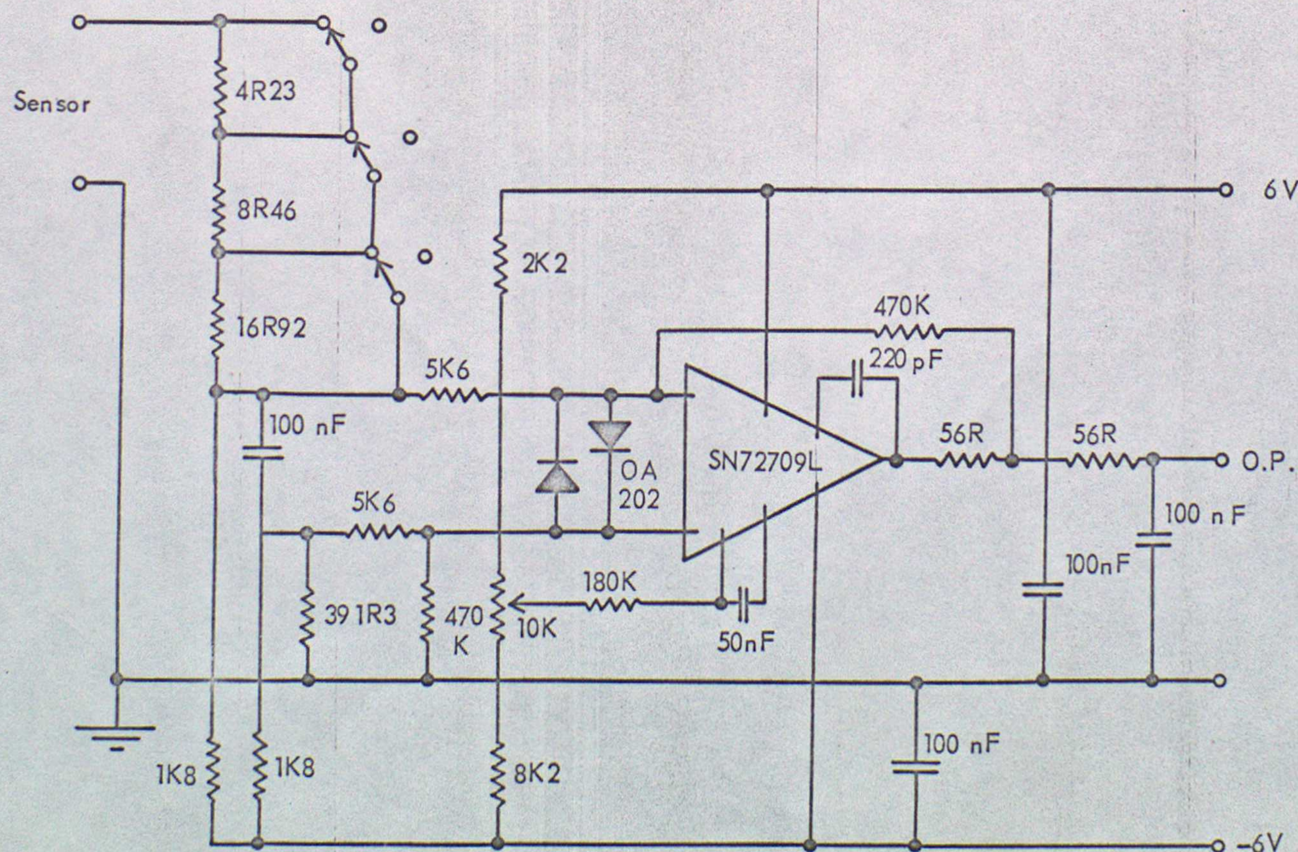

Figure 2b The amplifier for the temperature element.

Figure 3 The voltage stabiliser and the ratemeter

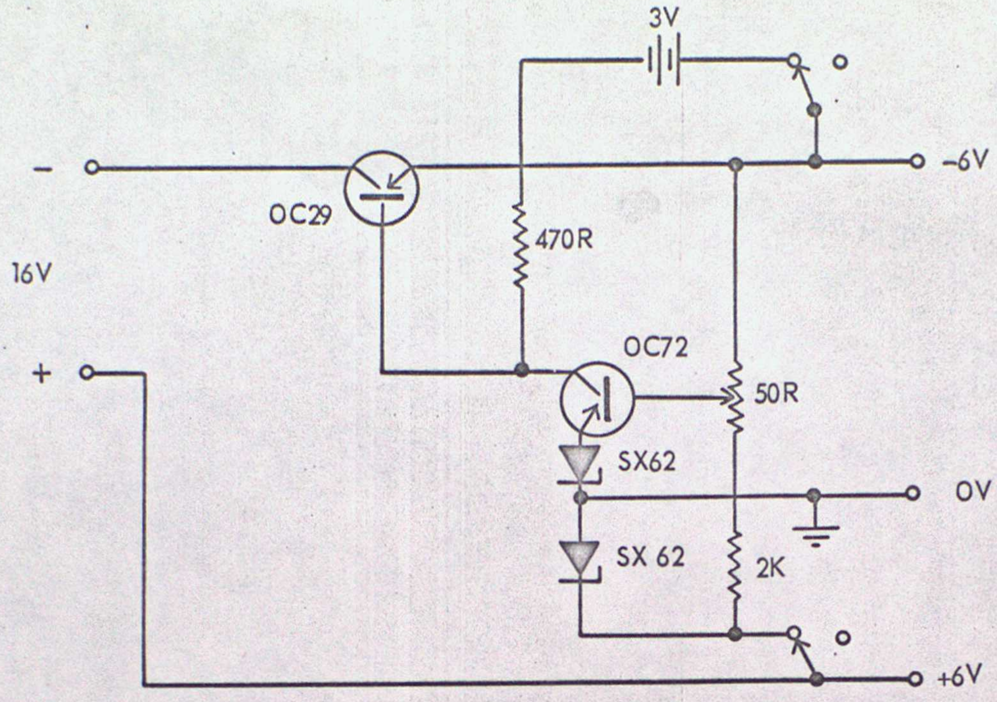

Figure 3a The voltage stabiliser

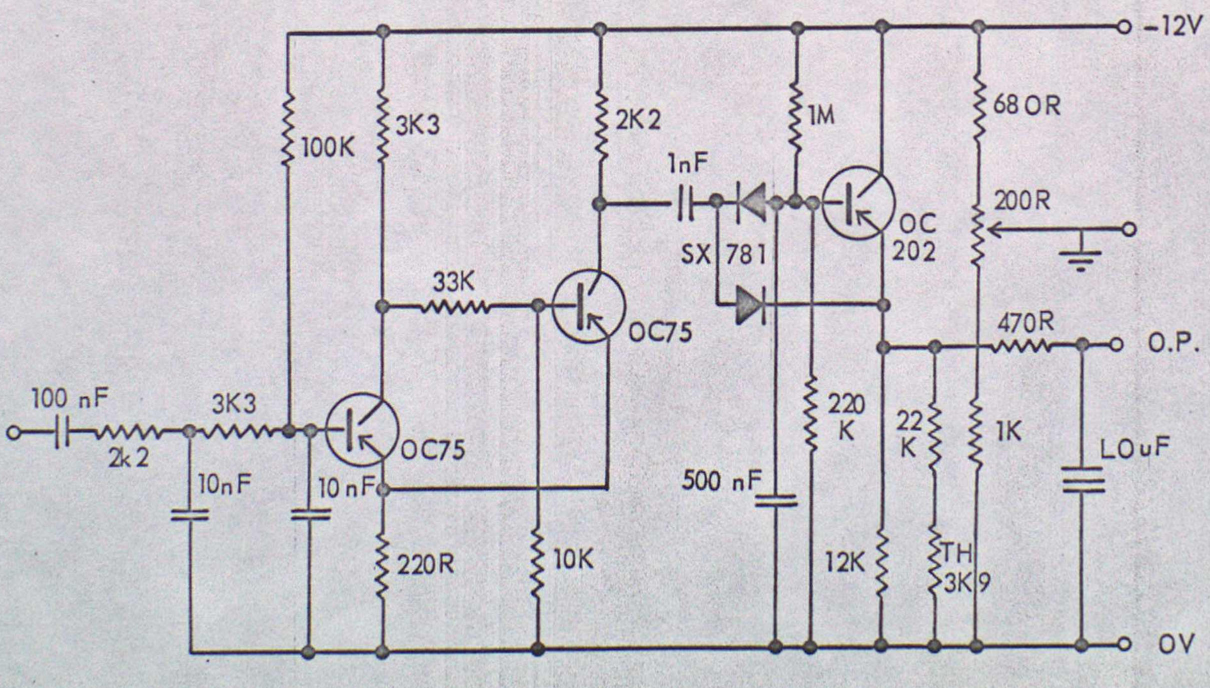

Figure 3b The ratemeter.

Fig.4 THE REGRESSION OF THE TURBULENT VELOCITY COMPONENTS

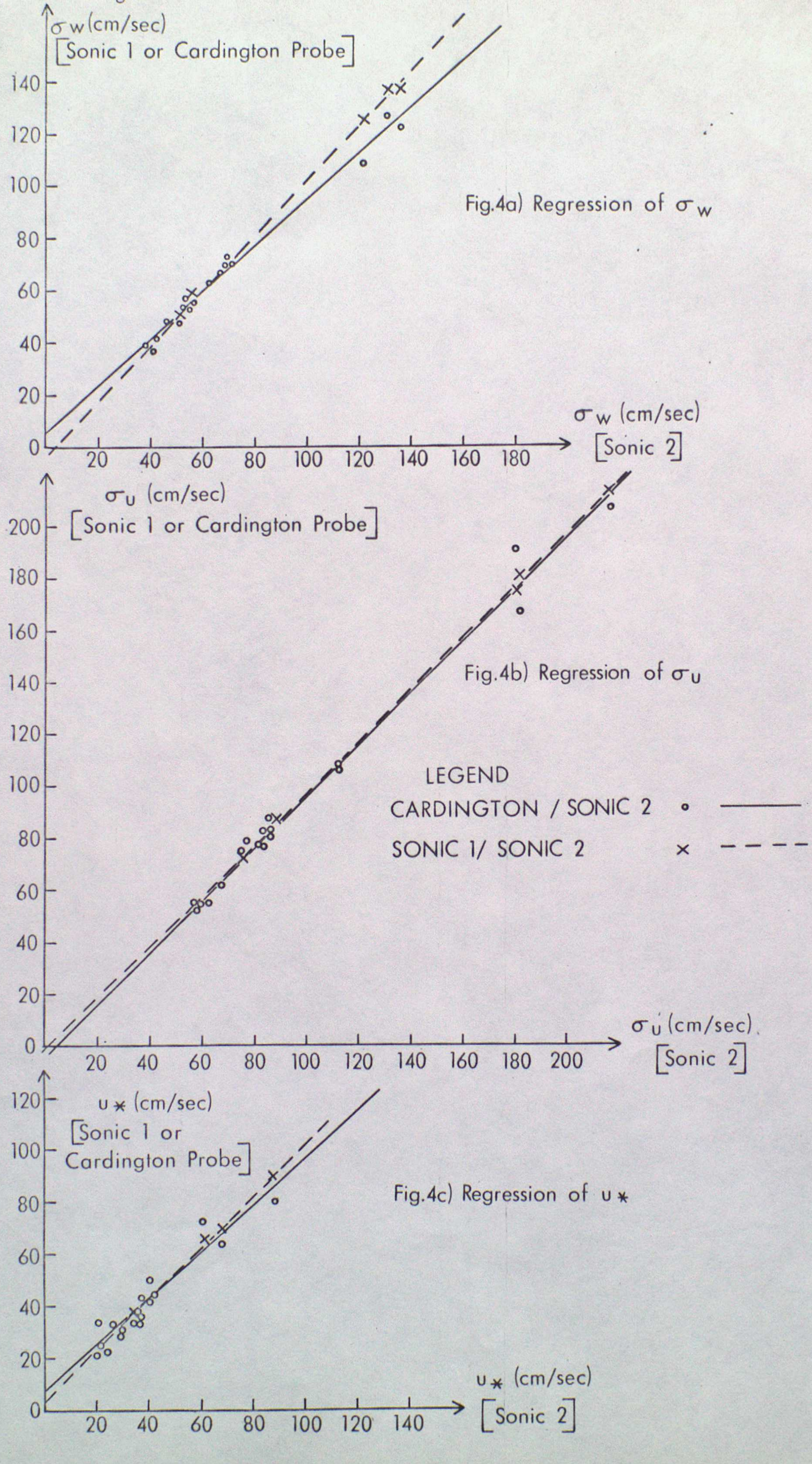

Fig.5 THE REGRESSION OF TURBULENT INVARIANTS

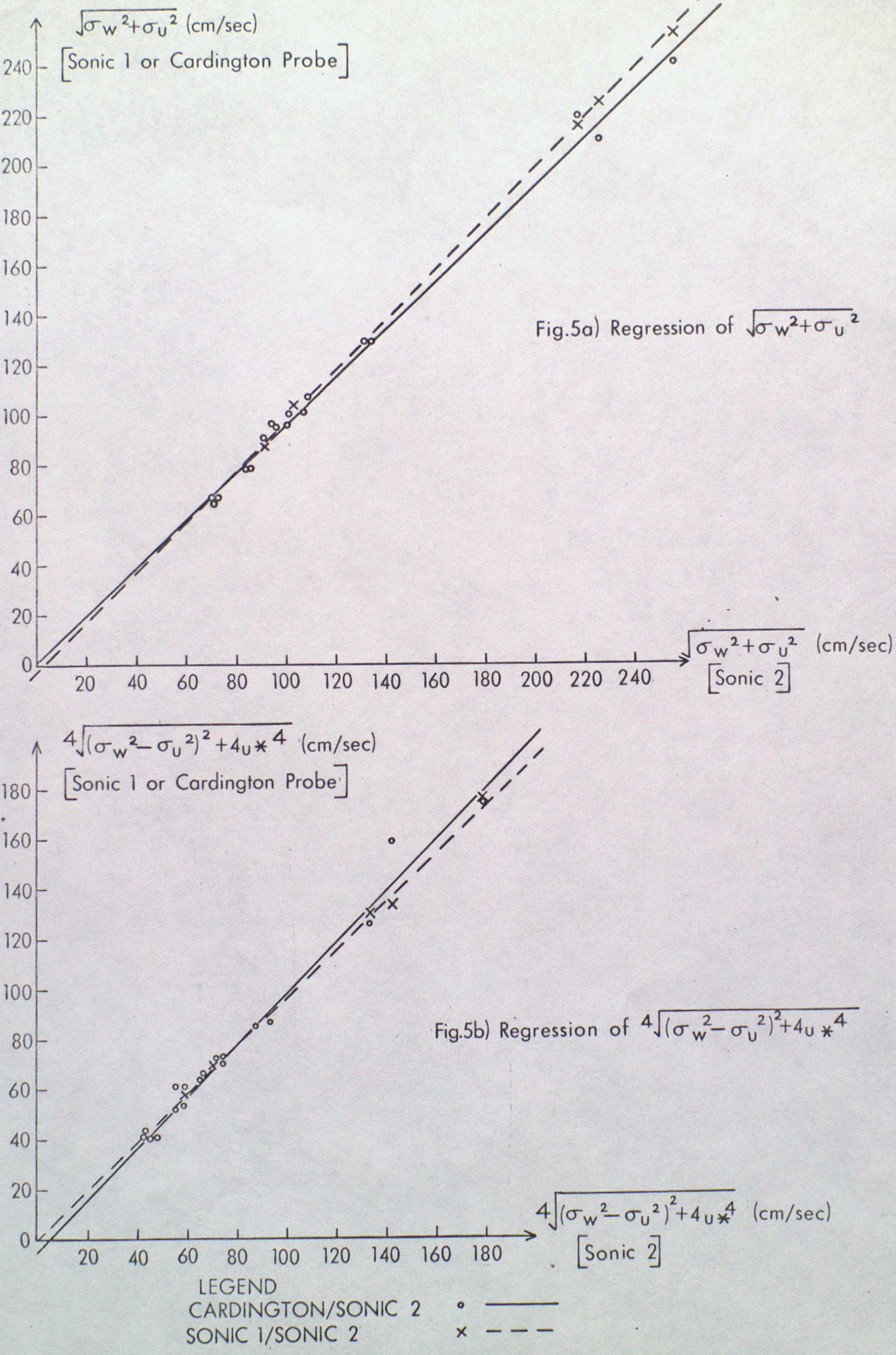

Fig.6 RELATIONS BETWEEN THE TURBULENT VELOCITY COMPONENTS

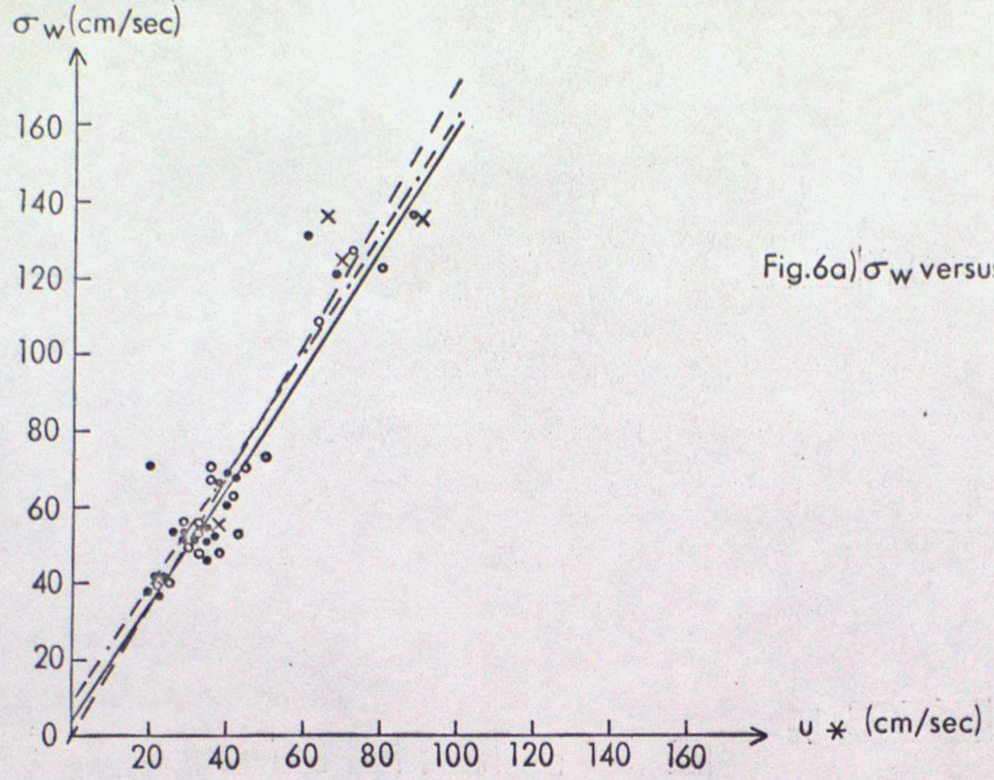

Fig.6a) σ_w versus u_*

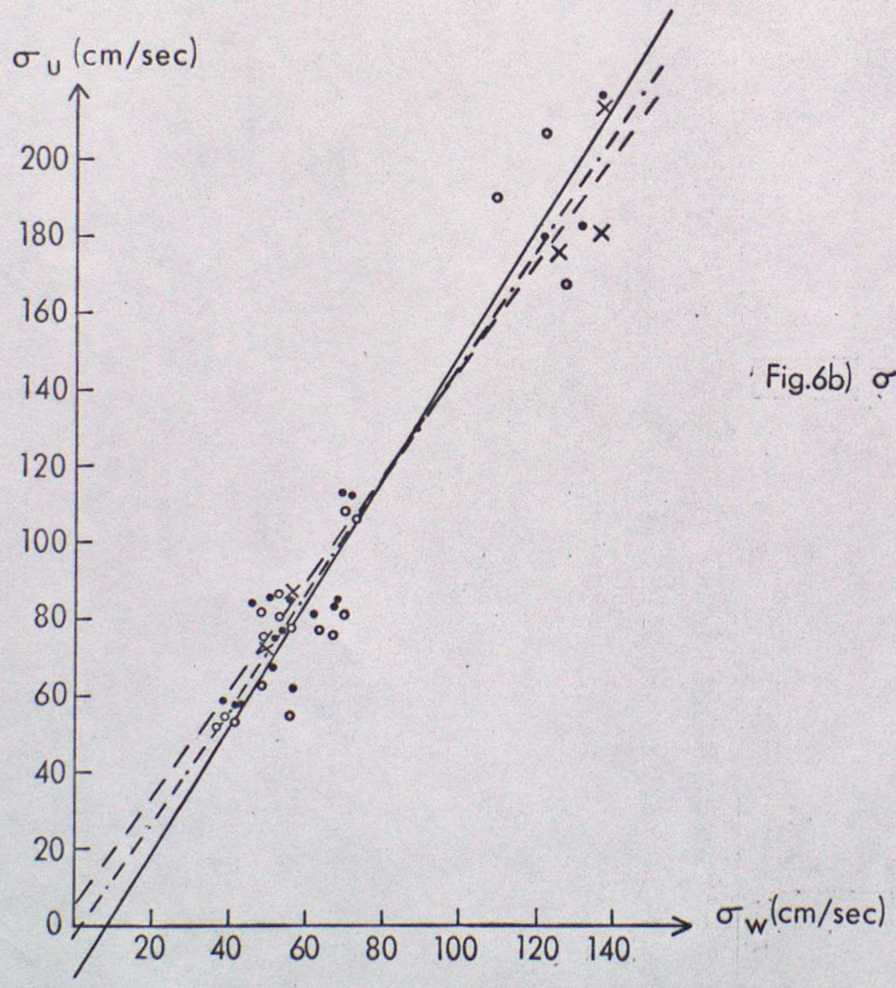

Fig.6b) σ_u versus σ_w

LEGEND

CARDINGTON PROBE ∘ ————

SONIC 1 × – – – – –

SONIC 2 • – – · – – ·

Figure 7 The regression of the mean wind speeds