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THE CARDINGTON TURBULENCE PROBE

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The measurement of atmospheric turbulence from a captive balloon

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Abstract

This paper describes an instrument which has been designed to measure wind and temperature fluctuations from the flying cable of a tethered kite balloon. Its performance has been evaluated from measurements close to the ground with the probe mounted on a fixed support. These enabled both its reproducibility and its performance relative to a sonic anemometer to be assessed.

Some preliminary studies of the effect of the balloon motion were carried out using a reference instrument mounted on a 43 metre tower. These showed that though variances were not much affected, quite serious errors may be introduced into the flux measurements but that these might be reduced by adequate vertical operation of the instrument and the balloon. A more comprehensive series of measurements is required to establish these features.

1. Introduction

Although the structure and properties of the constant stress layer are now quite well understood, the relative inaccessibility of the rest of the Earth's boundary layer means that quite the converse is true of this part of the atmosphere; despite its obvious relevance to the energetics of the troposphere. Furthermore this situation cannot be remedied just by studying the structural details revealed by applying some of the recent developments in the field of remote probing (e.g. frequency-modulated-continuous-wave Radar-Gossard et al, 1970); direct measurements are essential if the effects of the fine structure are to be correctly interpreted and the terms in the various balance equations evaluated.

Though aircraft and tall towers have been extensively used in studying these lower regions of the atmosphere, neither of these provides the perfect "platform" from which to make measurements. A less familiar technique is to mount the instruments on the flying cable of a tethered balloon. This paper describes a turbulence probe which has been designed to operate in such a fashion (it does not discuss the use of tethered balloons in general for scientific studies - for which the reader may care to consult Readings 1971).

The paper is divided into three main parts - first the probe is described, then its performance on a fixed support is assessed and finally the complications introduced by the balloon's movement are considered.

2. Description of the probe

One of the 1958 issues of the Quarterly Journal of the Royal Meteorological Society contains an article entitled "The measurement of gustiness in the first few thousand feet of the atmosphere" (Jones and Butler, 1958). This describes the first instrument used to study in detail the vertical component of turbulence from the flying cable of a tethered late balloon.

The present instrument (see figure 1) is a development from this and is designed to measure with adequate reponse the fluctuations required for evaluating heat and momentum fluxes:

(a) Temperature - the sensor consists of 180 cm of 25 μ platinum wire wound non-inductively on a plastic former. It is connected to an amplifier (mounted in the vane) which gives a linear output of 0.5 volts/ $^{\circ}$C over a range of $\pm 10^{\circ}$C; the three switches at the bottom of the vane enable the centre zero to be adjusted in 3°C steps between -3°C and $+18^{\circ}$C.

(b) Total wind speed - as the vane is free to rotate about the flying cable, the probe is kept facing into wind and the anemometer measures the instantaneous values of the total wind speed. The anemometer is fitted with an 8-cup polystyrene rotor (Jones, 1965), the pulses from which are converted to an analogue voltage by a ratemeter located in the laboratory - 120 pulses being produced per revolution.

(c) The inclination of the wind to the horizontal - a hot-wire yawmeter consisting of two 120° V of 13 μ platinum wire making an angle of 80° (Jones, 1961) is attached to the vertical upright pivotted at the front of the probe. This is kept vertical despite any tilting of the balloon cable, by the combination of the weight at its lower end and an oil dashpot which damps oscillations, hence enabling the yawmeter to measure the instaneous inclination of the wind relative to some fixed reference which is near the vertical (see later). The yawmeter is connected to a bridge situated inside the vane which gives a sensitivity of 0.5 volts/radian. Its output is linear over $\pm 40^{\circ}$ and it will accept lateral flow variations of $\pm 30^{\circ}$ (with respect to the vane) without any errors being introduced.

A battery box is attached to the flying cable just below the probe. This provides the stabilised voltage necessary to operate the two bridges and also acts as a link from which the signals are relayed to the ground by cable (a radio system is being tested at present). There they are sampled once a second by a data-logger whose output is recorded on paper tape. This logger has a resolution of one part in a thousand which corresponds to 0.01°C, 2 cm/sec or 0.02 radians. The higher frequency fluctuations of inclination and temperature are studied with the aid of a series of band pass filter units (see Readings and Rayment, 1969).

Although at present the probe does not measure the instaneous direction of the wind in the horizontal, it is hoped to remedy this in the near future by the addition of a second yawmeter and a magnetic flux-gate device providing an azimuth reference. Furthermore, by early 1972 it is planned to record all the information on magnetic tape hence eliminating the sampling restriction referred to above.

The electrical and mechanical parts of the system were subject to certain tests both in the laboratory and the wind tunnel. However in view of the complexity of the system and of the environment in which it has to operate it was necessary to carry out a series of field trials to establish that the atmospheric variables were being measured properly.

3. The performance of the probe on a fixed support

(a) Comparison of probes

As a first step in this evaluation two of these probes were mounted on fixed vertical rods so that they were 2 metres apart at a height of about 8.5 metres at the Cardington, Bedfordshire field station; a suitably flat and unobstructed site for low-level work. A series of one hour runs were carried out with the horizontal boom to which the rods were attached approximately perpendicular to the mean wind direction during each run. Thirty three runs were carried out under various stability conditions (z/L at 8.5 metres varying between 0 and -2.0).

Unfortunately many of the quantities of interest are sensitive to slight rotations of the frame of reference (see Rayment and Readings, 1970); so as the axes of these probes cannot be determined with sufficient accuracy using only instrumental techniques, it was decided to fix them by assuming that $\bar{w} = 0$ during each run. This produced an axial reference reproducible to within 0.3° and even this uncertainty may well be atmospheric in origin as the mean inclinations of the flow derived from the two probes invariably agreed to within 0.1°.

Although some slight troubles were experienced with the cup anemometers and their associated circuitry, these were not serious and it would be fair to conclude that normally the mean winds would be expected to agree within a few cms sec^{-1}. It was also found that the twenty minute temperature differences were consistent to $\pm$ $0.02^{\circ}C$ after correcting for the difference in the resistances of the two temperature elements at $0^{\circ}C$.

The degree of agreement between the other variables was assessed by plotting the cumulative differences on probability paper - a Gaussian distribution would produce a straight line. Some examples of the sort of results obtained are shown in figure 2 (a) for the twenty minute values. Although the spread in the differences between the standard deviations (or $\overline{ws}$) is larger than would have been expected from the preliminary laboratory and wind tunnel tests, the complexities of the full operating system in the natural air flow mean that it would be unsafe to conclude that the discrepancies are purely atmospheric in origin. However it seems fair to state that these quantities can be measured <u>at least</u> to the statistical accuracies implied by these comparisons (see Table 1).

With the two vertical fluxes the situation is complicated by their dependence on the frame of reference used and the variations in their absolute values by orders of magnitude. This makes it more sensible to compare the percentage differences as is done in figure 2 (b). Though it is well known that these two quantities vary considerably in both space and time (e.g. Haugen et al 1971), the additional uncertainty introduced by the frame of reference makes it even more unwise to state that the spread merely reflects atmospheric variability; though it is relevant to note that the more extreme differences vanish when 'hour' as opposed to '20 minute' values are compared. However it does seem reasonable to conclude that statistically the individual fluxes may be determined to 20%* or better (see Table 1). These conclusions may be considered to be quite general as during the cause of these tests, a whole series of sensors and circuit elements were used; thus making them a comparison of a series of probes.

(b) Comparison with profile estimates of u_*

During some of these comparative runs a vertical wind profile was available from three single slot photo-electric anemometers mounted 4.3, 8.5 and 17.1 metres above the ground; ordinary Sheppard, anemometer with metal cups, being used. Estimates of u_* were obtained by applying the method described by Webb (1970) to the hourly means and these results are compared with those derived from one of the probes in figure 3 - the comparison being restricted to occasions when z/L at 8.5 metres was greater than -0.10. The agreement is very encouraging and it is interesting to note that the scatter of the differences between the estimates is not much different from that found when two probes are compared.

A similar exercise was carried out by applying the formulation discussed by Dyer and Hicks (1970) to the results - the profile winds being used in conjunction with the z/L values from one of the probes (no temperature profile being available at that time). These estimates also agreed very well with the probe values; a similar scatter being observed as with Webb's technique.

(c) Comparison with a sonic anemometer

During October 1969 one of these probes was compared in Boston USA with the Air Force Cambridge three component sonic anemometers (see Haugen et al, 1971). These tests were carried out by mounting

*see footnote to Table 1.

the two instruments about 2 metres apart on the top of a 15.5 metre tower - a vertical rod supporting the Cardington probe. Owing to obstruction around the site, runs could only be done when the wind was coming from the West so it was only possible to do sixteen ten-minute and four five-minute runs in the time available. The signals were processed on data logging equipment with a frequency cut-off at 10 Hz and a sampling rate of twenty cycles per second. (see Haugen et al, 1970).

Although the definition $\bar{w} = 0$ was used to determine the reference axes for the Cardington probe, the sonic anemometer was lined up using purely instrumental techniques. Thus the sonic anemometer values refer to gravitation axes while those of the Cardington probe refer to the $\bar{w} = 0$ axes - using a sampling period of only ten minutes. This means that the two sets of values are not strictly compatible and that the spread in the difference between the estimates of u_* may be greater than was found at Cardington; especially as the uncertainty in the axes was a degree or two in this case (probably because of the poorer nature of the site). A further complication may have been introduced by the relatively slow response of the cup anemometer which would cause the Cardington probe to underestimate the momentum flux if there was a significant high frequency contribution. (Incidentally this should not matter at the heights for which the captive balloon system is designed). The rather small heat fluxes precluded any meaningful comparison of the heat fluxes or the temperature fluctuations.

In comparing the results of these tests (figure 4) with those obtained from the mast runs (see figure 2 and Table 1) it is important to remember that only eighteen values were available on this occasion; thus no significance can really be attached to the tails of the distribution. It would therefore seem reasonable to conclude that the results are roughly compatible though the agreement between the σ_w's is slightly improved and that between the σ_u's and u_*'s slightly **worse**; these small changes are probably no more than a reflection of the shorter averaging period and the points raised above.

It is relevant to note that the ten minute wind speeds agreed within a few cm/sec so these results were not biased by overspeeding (see Readings 1971 (b) for further details). Furthermore on the few occasions when a second sonic was available, the correlation between the two sonics was slightly less than that between the Cardington probe and each of them individually - the Cardington probe being positioned midway between them. This also points to the instruments having equivalent performances.

4. A preliminary study of the effects of balloon movement

The movement of a tethered balloon is transmitted to any instrumental packages attached to the cable. As these motions can be quite appreciable there is a strong possibility that they may introduce 'apparent' contributions to the measured turbulence variables; though mean quantities such as $\bar{V}$ and $\bar{T}$ should not be affected provided the averaging period is long enough. For a given balloon/cable system, the motion of the balloon will depend mainly on the structure of the atmosphere and the position of the balloon in it. The movements of the actual instrument will also depend on its position on the cable relative to the balloon and may well be a scaled down version of the balloon motion. However, the measurement errors will depend not only on these movements but also on any corresponding changes in temperature or wind in the vicinity of the instrument.

Although at present it is not possible to predict the magnitude of the errors, the equations relating them to the motion of the instrumental package can be written down:

$$\% \Delta\sigma_u = \frac{50}{\sigma_u^2}\left[\left\langle\left(\frac{dx}{dt}\right)^2\right\rangle - 2\left\langle u_z\left(\frac{dx}{dt}\right)\right\rangle\right] \qquad (1)$$

$$\% \Delta\sigma_w = \frac{50}{\sigma_w^2}\left[\left\langle\left(\frac{dz}{dt}\right)^2\right\rangle - 2\left\langle w_z\left(\frac{dz}{dt}\right)\right\rangle\right] \qquad (2)$$

$$\% \Delta \overline{u'w'} = \frac{100}{\overline{u'w'}} \left[\left\langle \left(\frac{dx}{dt}\right)\left(\frac{dz}{dt}\right) \right\rangle - \left\langle u_z \left(\frac{dz}{dt}\right) \right\rangle - \left\langle w_z \left(\frac{dx}{dt}\right) \right\rangle \right] \qquad (3)$$

$$\% \Delta \sigma_T = \frac{50}{\sigma_T^2} \left[\langle z^2 \rangle \left(\Gamma^2 + 1 \right) - 2 \Gamma \langle z T_z' \rangle \right] \qquad (4)$$

$$\% \Delta \overline{w'T'} = \frac{100}{\overline{w'T'}} \left[\left\langle T_z' \left(\frac{dz}{dt}\right) \right\rangle + \Gamma \left\langle z \left(w_z - \frac{dz}{dt} \right) \right\rangle \right] \qquad (5)$$

[where $\% \Delta$ = percentage difference between the apparent value and true value; (x, y) are the instantaneous coordinates of the instrument relative to its mean position; subscript z denotes value of atmospheric quantity at height z ; T_z' denotes a temperature fluctuation relative to the mean profile; Γ is the mean lapse rate (a positive quantity; the bar and $\langle$ signs refer to time-averaging); u and w are atmospheric velocity fluctuations]. In deriving these equations it has been assumed that σ_T does not vary rapidly with height at 43 metres, but this is unlikely to be important as it is only a small corection.

Approximate estimates of the effect of these motions on measurements of momentum flux have been made by Thompson (unpublished) using two theodolites to monitor the movement of a fore-runner of the present Cardington probe as it recorded the instantaneous values of u and w. His analysis showed that the probe tended to underestimate the momentum flux. However this examination only took into account the second term in equation (3).

In view of the relevance of this problem to balloon borne measurements it was decided to try and measure the errors directly by comparing measurements made from a fixed support at the top of the 43 metre tower at Cardington with those made simultaneously with another instrument mounted on the flying cable of a tethered balloon. A series of one hour runs were done with the balloon at one of four standard heights above the instruments. However from the outset it was clear that these measurements must be regarded as very preliminary in nature, as they were only made at 43 metres and also as facilities for monitoring the movements of the balloon borne probe were not available at that time. Their aim was therefore limited to ascertaining whether the errors were large enough to warrant a full-scale investigation.

It had been hoped to use the tower mounted probe to provide the "true" values but unfortunately the $\bar{w} = 0$ assumption did not enable the axial reference to be fixed to better than a few degrees. Furthermore this variability could not be reduced by doing a "calibration" run at 8.5 metres above the ground because the probe had to be dismantled to get it into position on top of the tower. As this uncertainty in the reference axes could well mask any effects due to balloon movement, it was decided to apply the $\bar{w} = 0$ assumption for the tower instrument when the balloon was at its maximum height (i.e. 600 metres above the two probes). Then the axial reference of the balloon probe was determined by forcing the hourly mean momentum fluxes to be equal during these runs. These two sets of axes were used for all the other runs done on that particular day - a 600 metre run always being done.

The effect of balloon motion on the turbulence quantities was assessed only in respect of its variation with balloon-instrument separation, by comparing the difference-curves (i.e. balloon minus tower values) for the other balloon heights with those obtained with the 600 metre spacing. It does however seem likely that the 600m balloon values were less affected by balloon movement and that therefore the foregoing comparison provides a first approximation to the absolute effect. Some evidence supporting this assumption was provided later by making some single theodolite observations of changes in the elevation of a probe attached to a balloon cable at the same height as during the runs. The elevation angle was recorded every 15 seconds and measurements were made with the balloon at all the standard heights used during the original experiments. Figure 5 is typical of the results obtained with the balloon in the atmospheric turbulence layer and shows how the amplitude of the probe's vertical motion decreases as the balloon height increases. However it must be realised that although it seems reasonable to assume that the 600 metre runs were less (if not negligibly) affected by balloon motion than were the others, it does not necessarily follow that the motion of the instrument decreased steadily as the balloon height increased.

In all some twenty four usable one hour runs were done under various atmospheric conditions with z/L at 43 metres varying between -1.0 and -0.03; though on three of the four days $z/L \sim -1.0$. The probes were about 50 metres apart and for all but one day the tower was downwind of the balloon; on this occasion they were crosswind.

As a first step in the analysis the successive twenty minute values of σ_u, σ_w, σ_T, $\overline{u'w'}$ and $\overline{w'T'}$ were compared on a day to day basis - two examples are shown in figure 6. It was found that although the values did not agree as closely as during the mast runs described earlier, they nevertheless tended to follow each other quite well. Also, the scatter between the two sets of values seemed less on the non-convective day. However as it was impossible to discern any correlation between the degree of agreement and the balloon height, it was decided to combine the results of all the days and compare the percentage difference as a function of balloon height. (These results are summarised in figure 7 and Table 2). In considering these results it is important to realise that even if there were no effects of balloon motion, the 600 metre curves will not be straight lines of zero mean and zero slope as the two probes were 43 metres apart - for reference the corresponding figures for the masts runs are also listed in Table 2. Furthermore the distributions could be affected either way by the balloon motion (i.e. the apparent agreement may improve or worsen according to which terms dominate the appropriate equation).

Although $\% \Delta \sigma_u$ and $\% \Delta \sigma_w$ show a slight dependence on balloon spacing the changes are only of the order of a few percent and are therefore of not much concern though they do imply that while the first term dominates (1) (i.e. more positive values of Δ at lower heights) both terms contribute to (2). However with $\% \Delta \overline{u'w'}$ quite large differences are observed and it appears that the balloon borne measurements could be in error by 100 or more in <u>either sense.</u> This implies that at least two of the terms in (3) can be significant and that if Thompson had been able to measure the other two terms, his results could have been drastically changed - as he pointed out at the time. However the smaller range of $\% \Delta \overline{u'w'}$ for both 600 and 300 m curves raises the possibility of making the error insignificant by positioning the equipment sufficiently far below the balloon.

The curves of $\% \Delta \sigma_T$ are probably the most intriguing as the irregular way their separations change with height implies that both terms are significant - this means that local changes in temperature are associated with upward movements of the balloon probably through the action of convective elements. However the errors are not really large except for the 150 m spacing. The $\% \Delta \overline{w'T'}$ curves are also separated and the sense of this separation implies that the last term in (5) is probably very important. The errors are quite significant even with the 300 m spacing which makes this quite a serious consequence of balloon motion.

5. <u>Concluding Remarks</u>

From the preceeding discussions it may be concluded that on a fixed support the Cardington probe measures the various turbulence quantities <u>at least</u> to the accuracies summarised in Table 1. Furthermore these upper limits to the accuracy of the probe may well reflect atmospheric variability rather than instrumental inaccuracies. Thus the use of this relatively inexpensive instrument on fixed supports as well as on the tethering cable of a balloon becomes a very attractive proposition.

The preliminary studies of the effects of balloon motion seem to show that though σ_u, σ_w and σ_T are only marginally affected, the momentum and heat fluxes could be seriously in error if the instrument is mounted too close to the balloon. They thus point to the necessity of carrying out an extensive series of measurements at greater heights above the ground with continuous monitoring of the probe and balloon movements. However until these measurements have been made and analysed, it is advisable to fly the instruments as far below the balloon as possible and to monitor their motions.

6. Acknowledgements

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References

Gossard E E, Richtor J H and Atlas D (1970) "Internal waves in the atmosphere from high resolution radar measurements". J. Geophysical Res. 75 3523 - 3536.

Readings C J (1971 (a)) "Atmospheric probing using a tethered balloon". Lecture presented at the 1971 Nato Advanced Study Institute on Statistical Methods and Instrumentation in Radio-Meteorology" (to be published).

Readings C J (1971 (b)) "Some comments on making measurements of wind and temperature in the atmosphere" - as above.

Jones J I P and Butler H E B (1958) "The measurement of gustiness in the first few thousand feet of the atmosphere" Quart J Roy Met Soc 84 17 - 24.

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

Jones J I P (1961) "The measurement of turbulence near the ground" Technical Paper No 786 14p. Chemical Defence Establishment, Porton Down, Porton England.

Readings C J and Rayment R (1969) "The high-frequency fluctuations of the wind in the first kilometre of the atmosphere" Radio Sci 4 1127 - 1131.

Haugen D A Kaimal J C and Bradley E F (1971) "An experimental study of Reynolds stress and heat flux in the atmospheric surface layer". Quart. J. Roy. Met. Soc. 97 168 - 180.

Webb E K (1970) "Profile relationships - the log-linear range and extension to strong stability". Quart J. Roy. Met. Soc. 96 67 - 90.

Dyer A J and Hicks B B (1970) "Flux gradient relationships in the constant flux layer". Quart J. Roy. Met. Soc. 96 715 - 721.

Rayment R and Readings C J (1971) "The importance of instrumental tilt on measurements of atmospheric turbulence". Quart J Roy Met Soc 97 123-130.

Table 1

The accuracies implied by the comparative runs on fixed supports (using 20 minute values)

Quantity	Accuracy*	Mean Difference ± Standard Error
Mean vertical wind $\bar{w}$	± 3 cms/sec	(0.0 ± 0.3) cms/sec
Standard deviation of temperature fluctuations, σ_T	± 0.02°C	(0.006 ± 0.001)°C
Standard deviation of horizontal wind fluctuations, σ_u	± 3 cm/sec	(0.0 ± 0.3) cms/sec
Standard deviation of vertical wind fluctuations, σ_w	± 3 cm/sec	(-1.7 ± 0.3) cms/sec
Momentum flux, $\overline{u'w'}$	± 30 %	(9 ± 2) %
Heat flux, $\overline{w'}$	± 30 %	(8 ± 2) %

* at least 90 % of the values lie within these limits.

Table 2

Percentage Mean Differences between various turbulence quantities, as measured at 43 m on a fixed support and on the balloon cable, as a function of the height of the balloon above the instruments

Quantity	Height of balloon above instruments				Mast runs
	60 m	150 m	300 m	600 m	
σ_u	9 ± 3	7 ± 3	6 ± 3	3 ± 2	-0.2 ± 0.5
σ_w	1 ± 3	-4 ± 4	4 ± 2	3 ± 4	-3.1 ± 0.6
$\overline{u'w'}$	51 ± 48	2 ± 22	-6 ± 11	3 ± 10	9 ± 2
σ_T	14 ± 5	-1 ± 3	3 ± 5	4 ± 7	2 ± 0.6
$\overline{w'T'}$	27 ± 31	-22 ± 12	-4 ± 13	33 ± 21	8 ± 2

(Tabulated figures are mean % difference ± Standard Error)

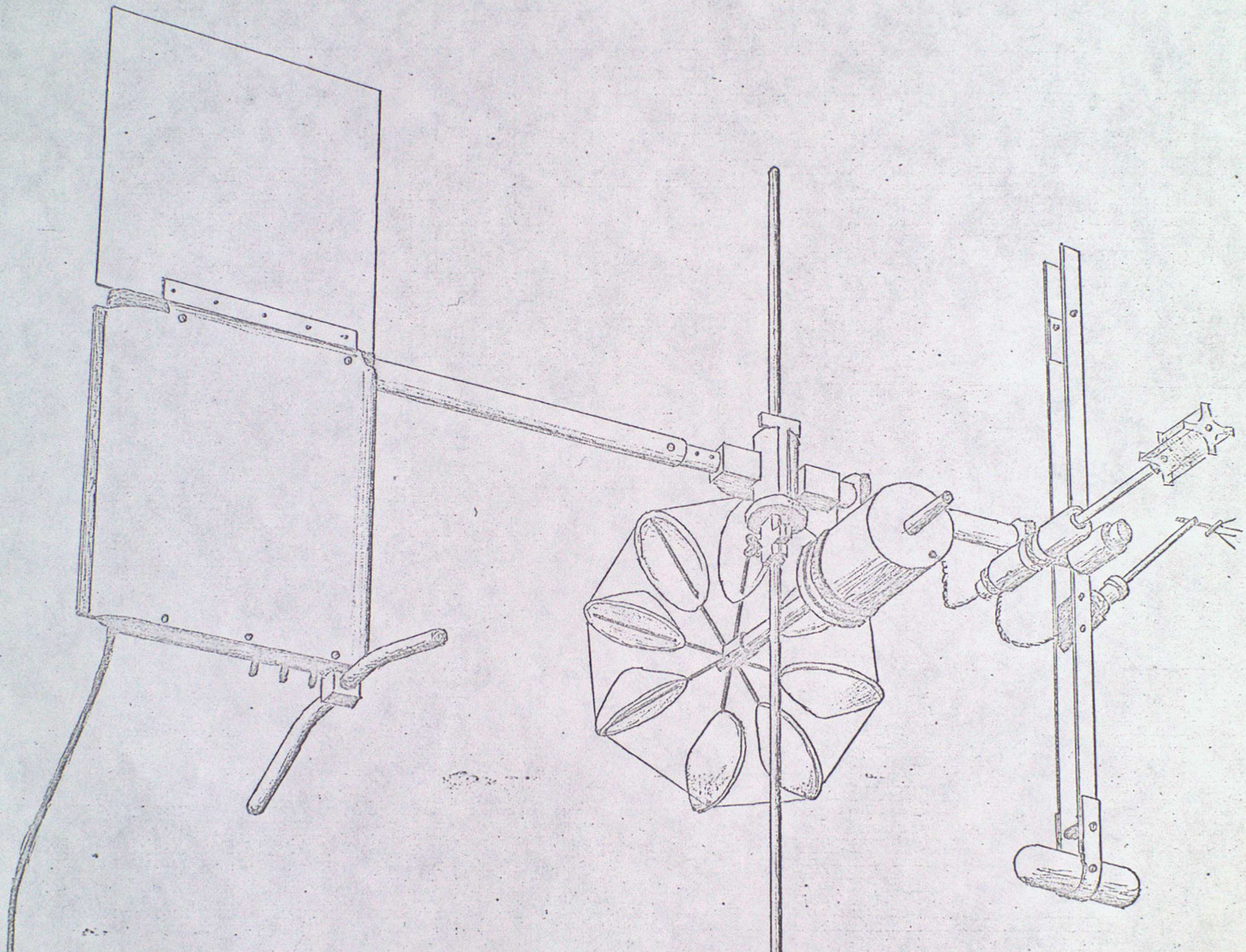

Figure 1. THE CARDINGTON PROBE

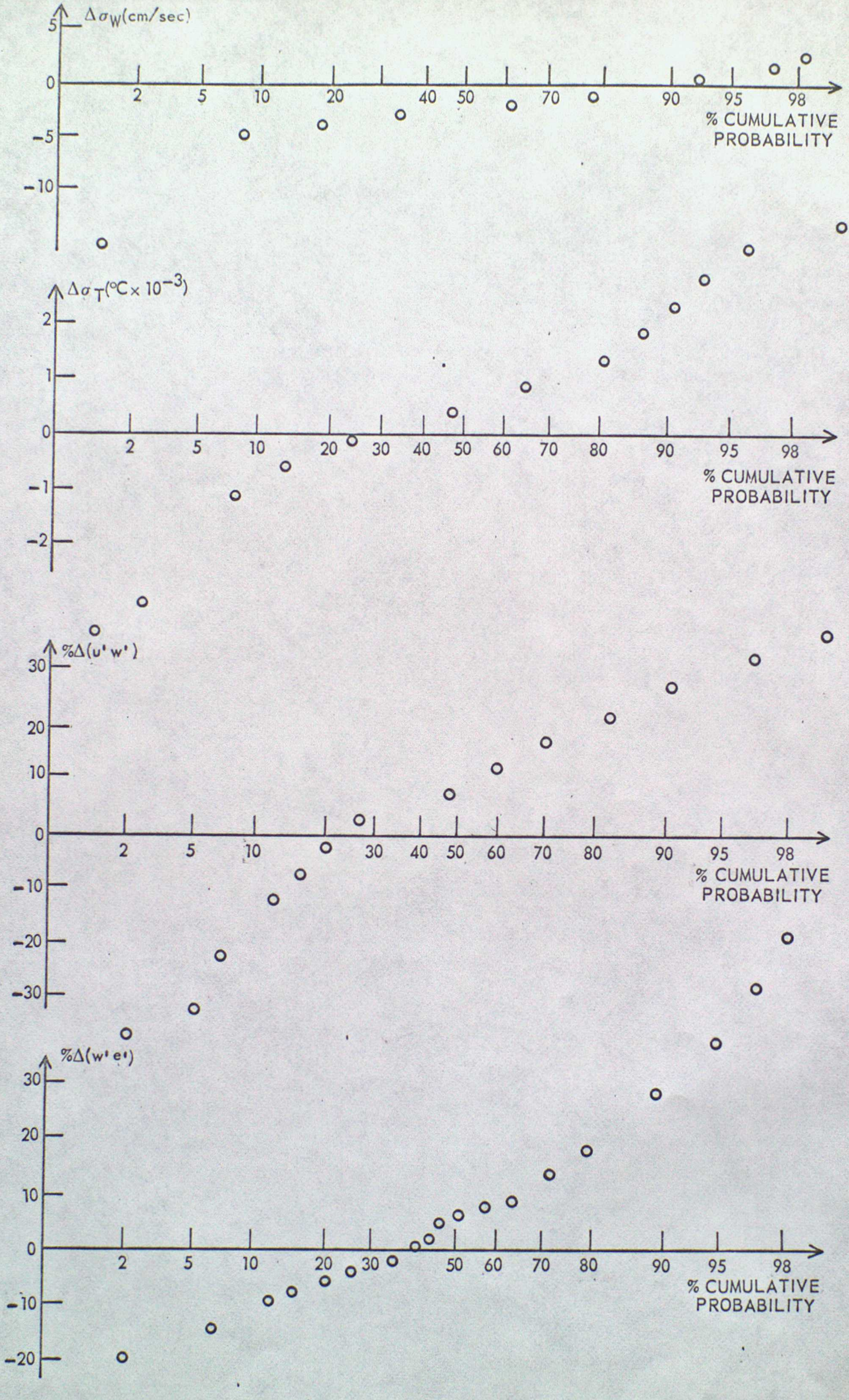

Figure 2 Comparison of two instruments on fixed supports at a height of 8.5 m., 2m. apart
(20 minute samples)

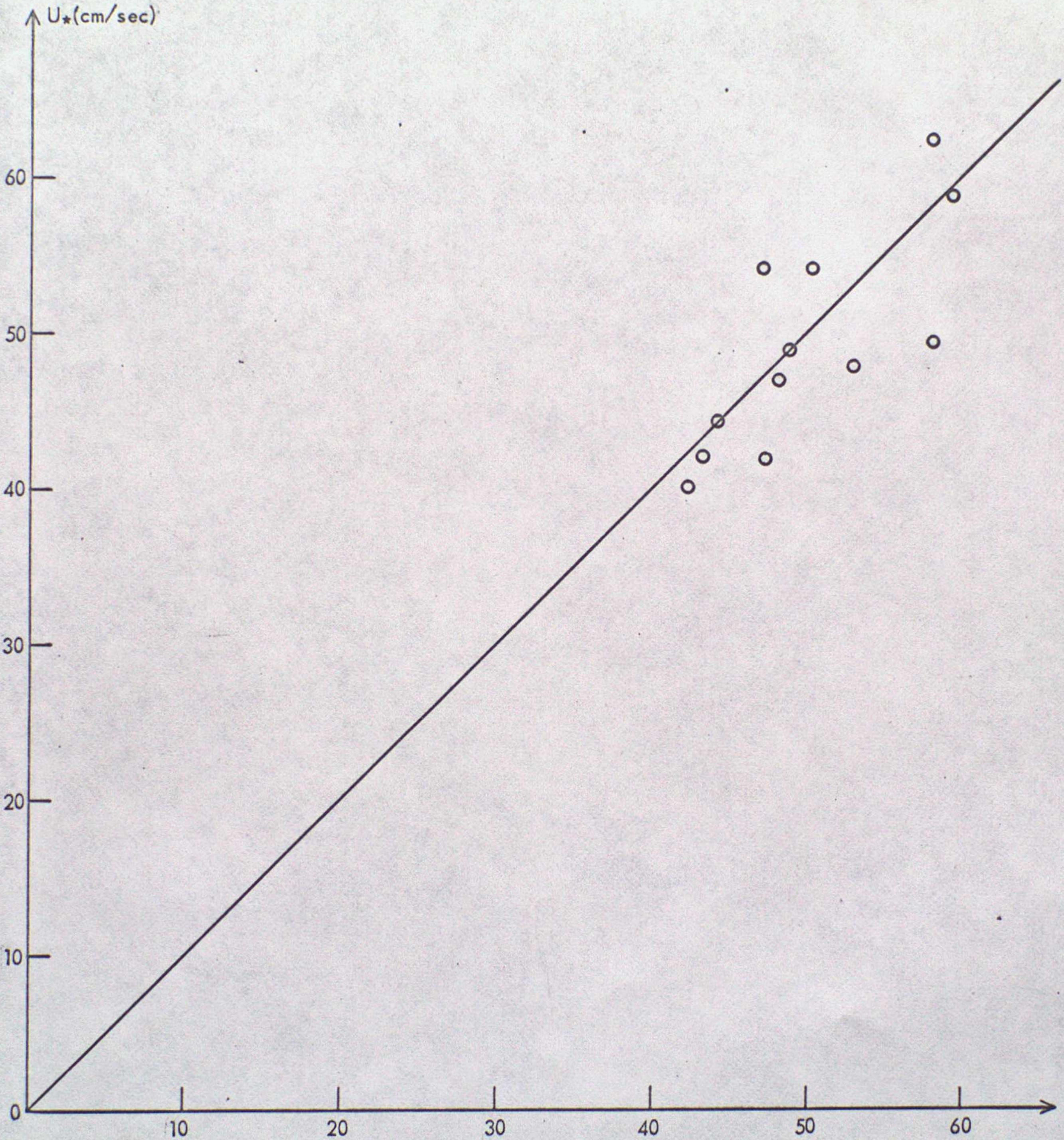

Figure 3 Comparison of the hourly values of $\sqrt{-u'w'}$ and u obtained from profile measurements using Webb's technique.

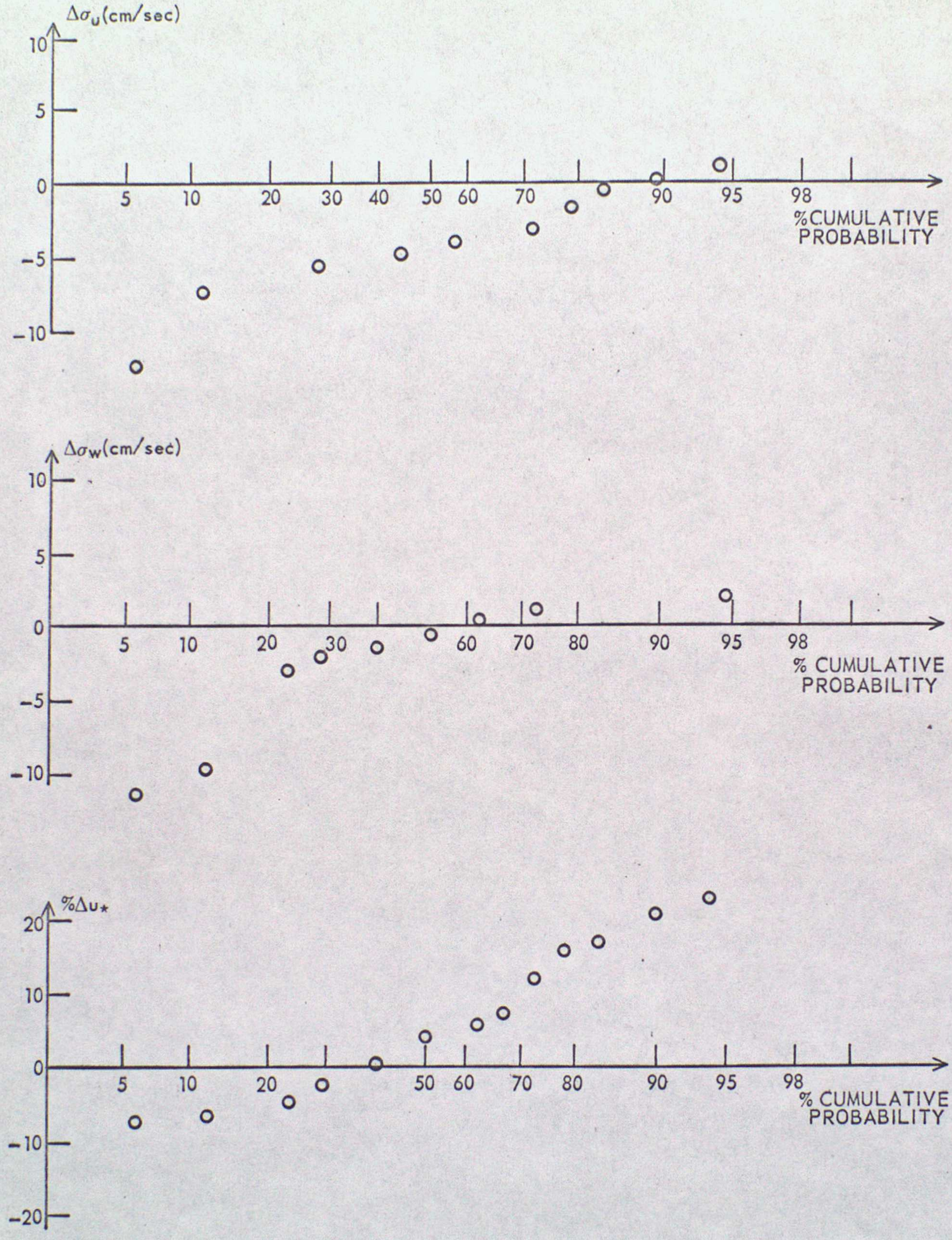

Figure 4 The distribution of the differences between the Sonic and Cardington Probe (10 minute samples)

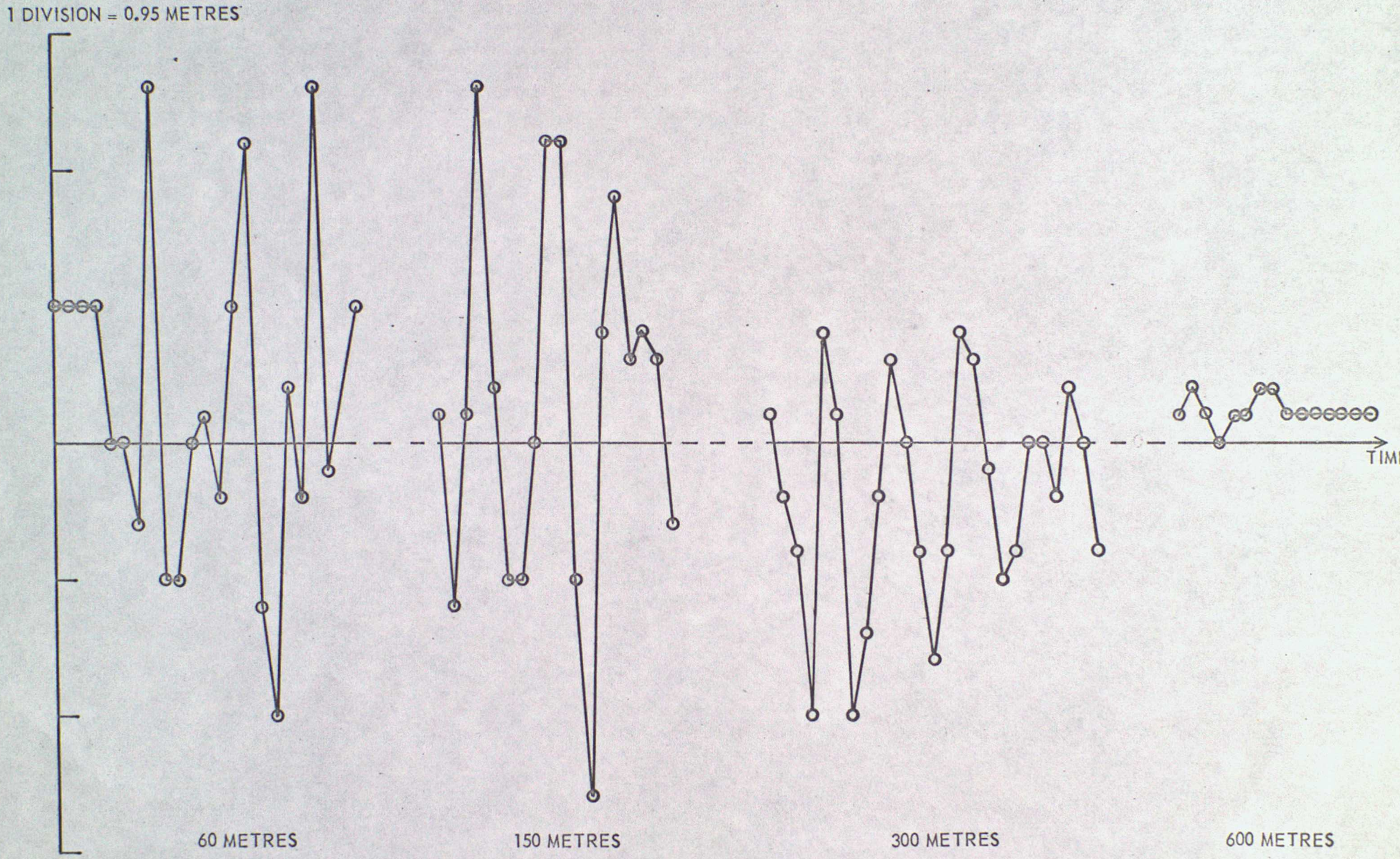

Figure 5 Example of the variation in the height of a probe above the ground as a function of its distance beneath the balloon (measurements every 15 seconds)

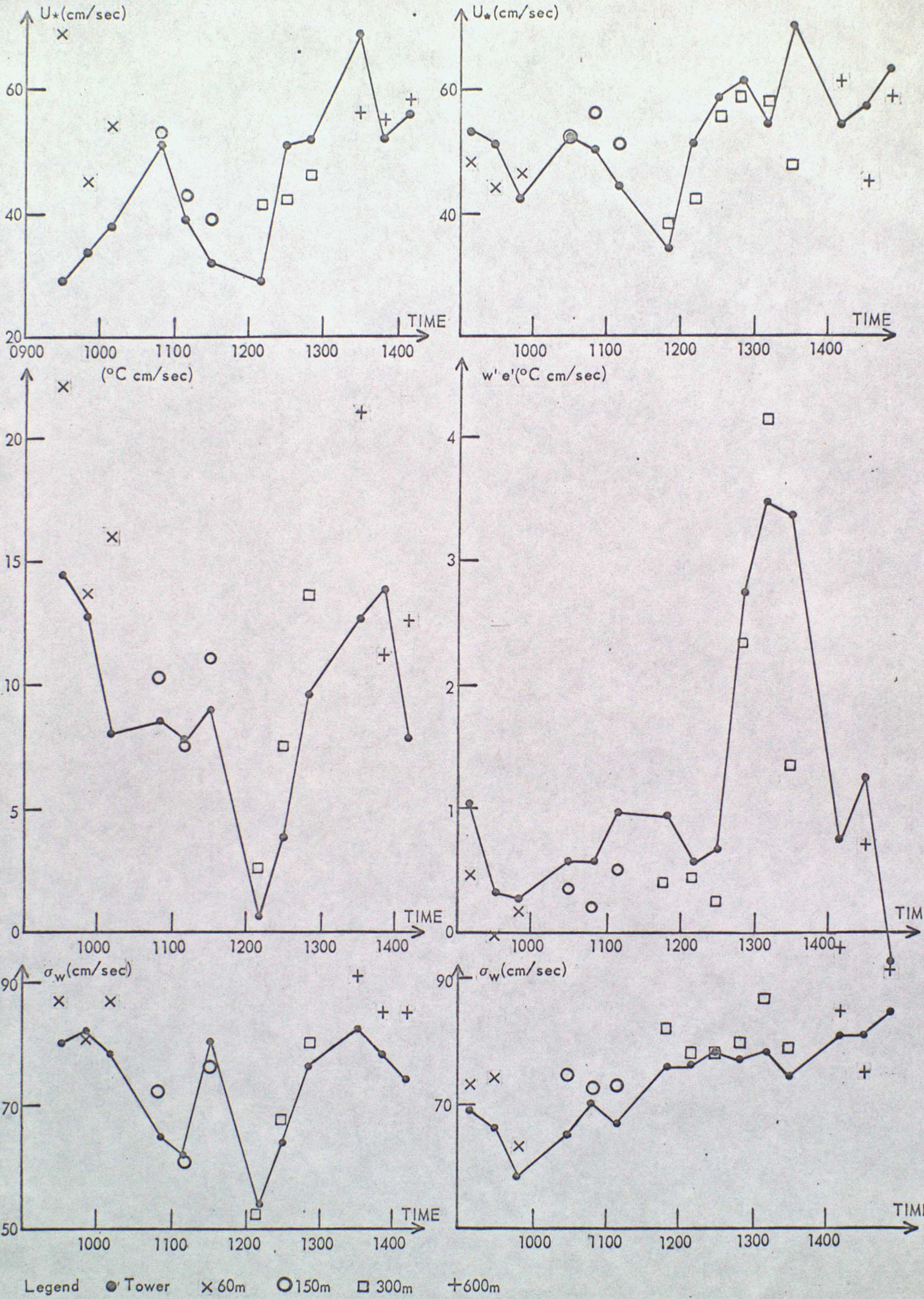

Figure 6 Comparison of 20 minute values measured at 43m. on the balloon and on the tower (L.H. ℘/L = −0.5; R.H. ℘/L = −0.03)

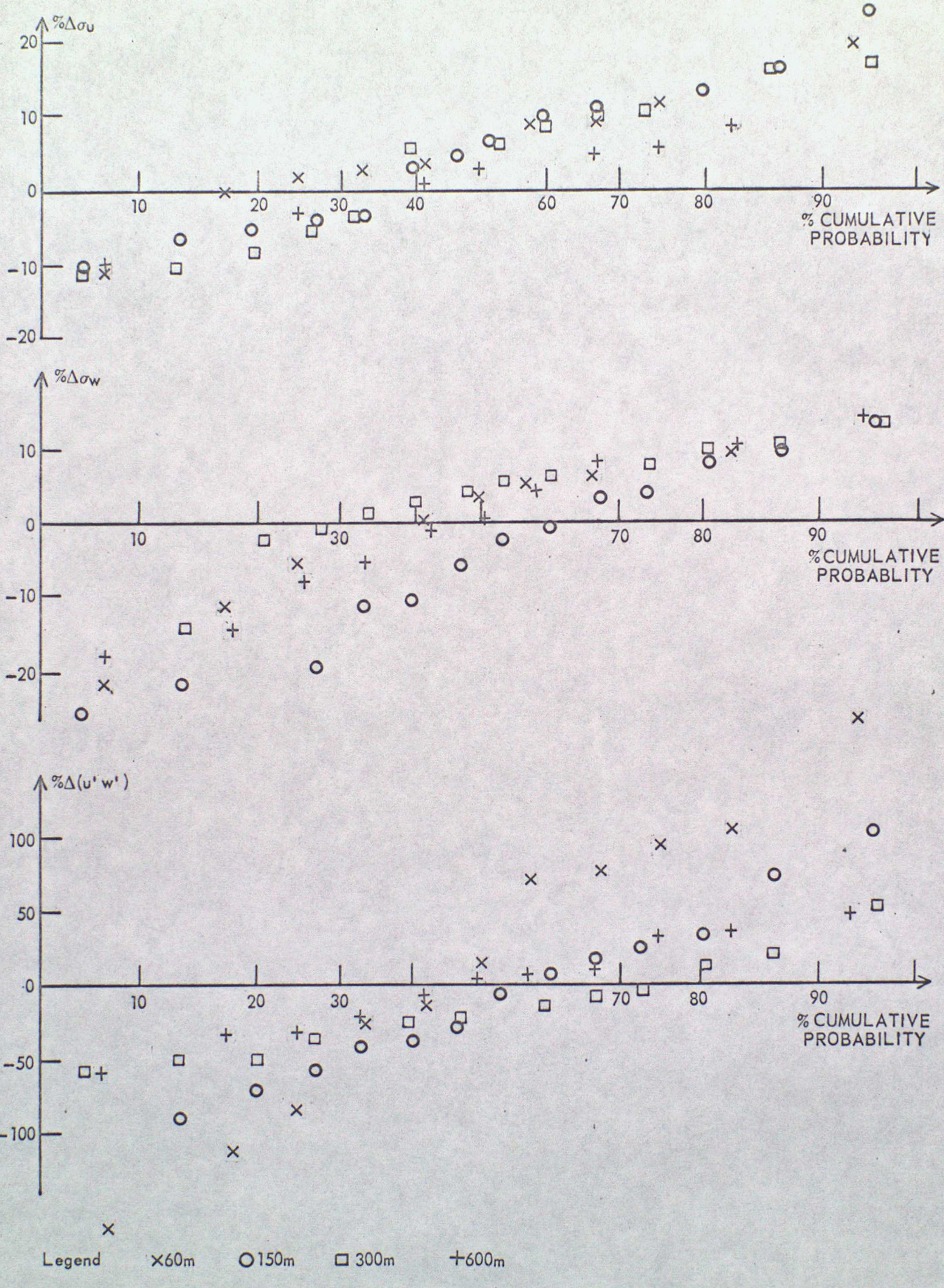

Figure 7a. σ_u, σ_w and u' w'

Figure 7. Comparison of two instruments – one on a 43 metre tower and the other at the same height on a balloon cable (20 minute samples) The results are plotted for various balloon heights.

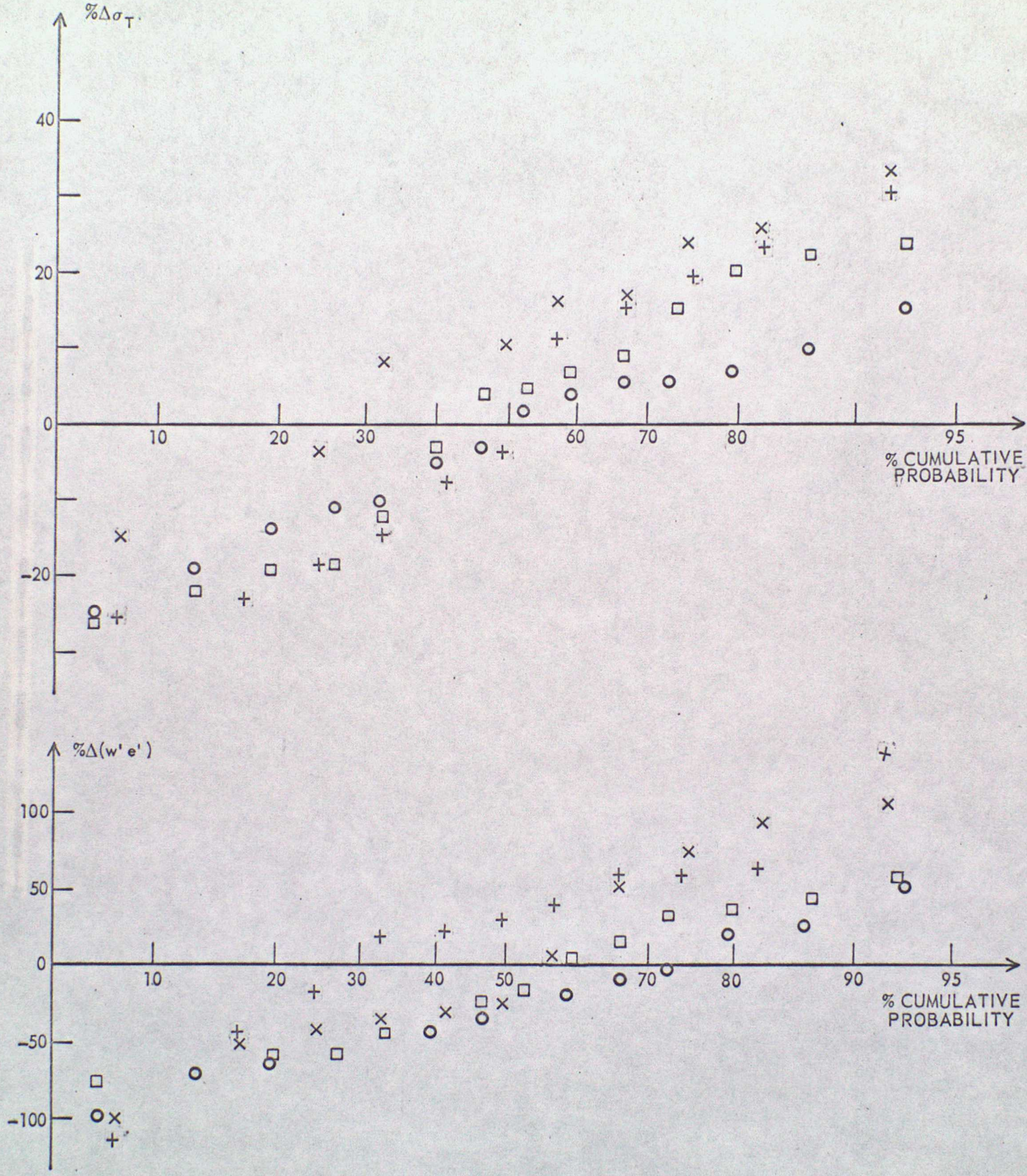

Figure 7b σ_T and w' e'