

THE EFFECT OF SENSOR MOTION ON DATA COLLECTED BY
CAPTIVE-BALLOON-BORNE TURBULENCE INSTRUMENTATION

by N. Thompson

1. Introduction

Captive balloons have been used for a number of years in the Meteorological Office research programme for supporting turbulence sensors above ground level, but only a limited effort has been made to establish the effects of balloon movements on sensor outputs (e.g. Jones (J.I.P.) and Butler 1958, Jones (R.A.) 1958). These effects have been considered small usually, but there is obviously a need for a more critical investigation before drawing more definite conclusions. The present note describes the results of a number of experiments carried out specifically to measure balloon-induced sensor motions, and their effect on vertical momentum fluxes.

2. Background to the experiments

If u_s, v_s, w_s are the three components of sensor motion at some instant of time, and u, v, w are the corresponding wind velocity components (with the usual orientation of axes), then the horizontal and vertical wind components inferred from the sensor outputs are $\left((u-u_s)^2 + (v-v_s)^2 \right)^{1/2}$ and $w-w_s$. The Cardington instrumentation cannot measure the individual horizontal components, so that even if all three components of sensor motion can be measured, it is not yet possible to correct the measured horizontal wind for sensor motion (However, later in this note an approximate method for correcting the horizontal wind is suggested, which may have some uses). Nevertheless, corrections for vertical sensor motion alone may still be very valuable in the context of the vertical flux of momentum. Thus, the measured momentum flux is

$$\tau = - \rho (w-w_s) \left\{ \left((u-u_s)^2 + (v-v_s)^2 \right)^{1/2} - \left((u-u_s)^2 + (v-v_s)^2 \right)^{1/2} \right\}$$

(It is assumed that $\bar{w} = \bar{w}_s = 0$).

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Note

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A closer approximation to the true flux is likely to be obtained by correcting for vertical sensor motion, equivalent to putting $W_s = 0$ in the above expression. Further, in the event of u_s and v_s being uncorrelated with W , and with u and v respectively, one would have then the true flux, but in practice there is no good reason to suppose that this is the case. A complete correction procedure must await the development of a technique for measuring wind direction by balloon-mounted instrumentation.

When considering the vertical flux of quantities other than momentum, although the sensor motion may still introduce spurious correlations between vertical velocity and fluctuations of the quantity being transported in the vertical, the effect is likely to be smaller than in the case of momentum, and may well be eliminated almost entirely by a correction for vertical sensor motion.

Most of the remainder of this note describes a series of experiments in which measurements of the movements of the "BALGUST" instrument⁽¹⁾ when attached to the cable of a captive balloon were made using theodolite techniques, the intention being to obtain data on the typical magnitude of balloon-induced sensor movements, and particularly their effect on measured momentum fluxes.

3. The experiments

A short pilot series was carried out in September 1967, in which a single theodolite was mounted very near the tethering point of a captive balloon, and used to follow balloon movement over periods of about twenty minutes. The turbulence-measuring instrumentation was not flown on these occasions. The theodolite was one of a pair normally used at Porton for pilot-balloon tracking, in which helical potentiometers were connected to the azimuth and elevation controls by suitable gearing. The outputs were voltages proportional to azimuth

(1) As used at Cardington since 1968: described in MRCP 234

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and elevation and these were recorded on the Cardington data-logger (DDR8) at 5-second intervals (on subsequent analysis this 5-second interval was found to be too large, and later experiments used 1-second sampling). Use of a single theodolite for these measurements was based upon the assumption that the balloon cable was an effectively rigid structure which pivoted around its tethering point. On this basis, observations of azimuth and elevation were converted to components of balloon motion in all three dimensions. Of course, such a technique provided no information on vertical velocities of the balloon resulting from changes in shape of the cable catenary, and hence possibly underestimated the vertical velocities. However it should have given good estimates for horizontal velocities. "Good" in this context is a relative term, depending on both the skill of the observer in following the balloon motion and also the resolution of the data-logger. Because the Porton theodolites had been modified specifically for tracking pilot balloons, the resolution was rather low for the present usage (0.06 degrees for elevation, 0.2 degrees for azimuth). Maximum vertical velocities appeared to be in excess of 20 cm/sec^{-1} , and horizontal velocities up to about 1 m sec^{-1} were also measured.

In the main series of experiments the two theodolites were set up at either end of a base-line about 700m long. Optimum resolution of the vertical motion of the sensor system attached to the balloon cable is obtained when the angle of elevation of the sensors with respect to each theodolite is 45 degrees. It was not possible to make the base-line long enough to achieve this, so that the elevations were usually in the range 50 to 60 degrees. The base-line orientation was dependent on the position of various obstructions on the Cardington site, and it was not the ideal one for resolving horizontal sensor motions (the ideal occurs when the bearing of the sensors from the base-line is 45 degrees at each theodolite: The angles usually subtended were between 20 and 30 degrees). Errors in tracking the horizontal motion of the sensors of course introduce errors in calculated values of the vertical sensor motion so that in the present series of experiments, the

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conditions for minimising random errors in the measured vertical velocities were not achieved. It was therefore anticipated that smoothing of the apparent sensor velocity components would be necessary to obtain coherent data on the sensor motions.

In this second series of experiments the "Balgust" instrument was mounted on the balloon cable about 70m below the balloon and approximately 600m above ground, and movements of this instrument, rather than those of the balloon, were followed using the theodolites. The "Balgust" inclination and wind speed signals, together with the theodolite outputs, were led to the data logger which sampled the six inputs every second. Details of the experiments appear in the Appendix. All experiments were carried out in unstable conditions, with the exception of No. 9, when the "Balgust" instrument remained above the convective layer throughout the experiment.

4. Data analysis

The data tapes were processed on the "Mercury" computer at Porton. The theodolite data were reduced to give "Balgust" positions at 1-second intervals, using a right-handed coordinate system with origin at the Southern theodolite, X - axis along the base-line and Z - axis vertical (Thyer 1962). The components of sensor velocity along the axes can then be evaluated but usually these axes are not conveniently aligned with respect to the mean wind direction at the sensors. However a method of alignment can be obtained from consideration of the general characteristics of the balloon motion. Thus, a feature of the behaviour of these large captive balloons is that they tend to drift from side to side, across the mean wind direction, in preference to alongwind. Therefore one expects the successive sensor positions, referred to a horizontal plane, to lie near an arc symmetrically orientated acrosswind. This suggests a method of estimating the mean alongwind direction at the balloon level (more approximately at the sensor level also) from the theodolite data. Referring to Figure 1, the dotted line has been drawn to enclose the projection of the successive sensor positions onto the

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horizontal ($x-y$) plane. If a line AA' is drawn through the points as shown, by a least-squares method, then the perpendicular BB' defines approximately the mean wind direction at the sensor level (note in this example that the wind blows from B to B'). If BB' makes an angle Θ with the x -axis, then by rotating the horizontal axes about the vertical through this angle, the new positions of these axes (x', y') define the mean alongwind and acrosswind directions. In practice this technique fails to distinguish between BB' and $B'B$, and supplementary wind data are needed to do this.

The method outlined above was used with the present data to define the successive coordinates of the "Balgust" instrument (x', y', z) and by subtraction the sensor velocities (u_s, v_s, w_s) were obtained. Due to the lack of resolution involved in the theodolite technique, and also the impossibility of following the instrument motion exactly, the sensor velocities fluctuated wildly in magnitude, and it was clear that some quite drastic smoothing was necessary to obtain a coherent picture. Initially this was done by using observations in pairs up to 6 seconds apart (i.e. $u_s = (x'_{n+6} - x'_n)/6$), but this smoothing was found to be insufficient, and finally an additional smoothing by groups was incorporated:

$$u_s = (x'_{n+7} + x'_{n+6} + x'_{n+5} - x'_{n+1} - x'_n - x'_{n-1})/18 \quad \text{etc}$$

Even this smoothing was insufficient to remove all "noise", and because w_s was usually the smallest of the components, its behaviour was still very erratic. By comparison, u_s and v_s showed smoother variations with time. It was felt that further smoothing was undesirable, leading as it would to further reduction in the magnitude of the true fluctuations of sensor velocity.

In all, there were seven experiments in which usable data were obtained. In three of these, the wind occasionally became too light to operate the anemometer; the wind speed was then taken to be the stopping speed of the anemometer. The data were used to compute fluxes of momentum in two ways. The "Balgust" instrument gave outputs proportional to total wind speed and wind inclination, and from these the instantaneous apparent horizontal and vertical velocities u_a and w_a were
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obtained. In the first flux computation, it was assumed that the sensor motion was negligible; then

$$\tau_1 = -\rho \overline{(w_a - \bar{w}_a)(u_a - \bar{u}_a)}$$

\bar{w}_a and \bar{u}_a were evaluated from the whole length of each record, but the record was also divided into 1-minute lengths and the contributions to τ_1 were also evaluated for these short periods: the results appear in Table 1.

The second computation involved correcting w_a for both non-zero mean and for vertical sensor motion, giving

$$\tau_2 = -\rho \overline{(w_a + w_s - \bar{w}_a + \bar{w}_s)(u_a - \bar{u}_a)}$$

This was again done for the whole record, and for one-minute periods, for direct comparison with τ_1 , and the results appear also in Table 1.

(No use has been made of the wealth of data on horizontal sensor motion. Any attempt to take this into account in the present context can only be speculative because of lack of measured horizontal wind data in component form, and for this reason it was felt that any approximate treatment to try to correct momentum fluxes for horizontal as well as vertical sensor motion would be too crude to be of real value. On the other hand, if the data could be used in a plausible way to provide better estimates for mean wind speed this would be very valuable. The nature of the data precludes precise treatment: but making the assumption that alongwind movements of the sensors can be ignored because their effect will tend to be averaged out of the mean speed, then, provided the lateral fluctuations of the actual wind are not too large one can write

$$u_a^2 \approx V^2 + u_s^2 \quad (\text{where } V \text{ is the true horizontal wind speed})$$

$$\text{or } V \approx (u_a^2 - u_s^2)^{1/2}$$

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Now, U_s is approximately a linear function of height (because the balloon cable tends to swing as a whole), whereas V increases with height as Z raised to a power less than 1. Hence $\frac{\partial U_a}{\partial Z}$ will be greater than $\frac{\partial V}{\partial Z}$, a point of some importance in kinetic energy balance studies).

5. Discussion of results

The computed vertical (downward) momentum fluxes are given in detail in Table 1. They appear here as the 1-minute averages, calculated using values for \overline{W} and \overline{U}_a derived for the complete runs. Thus, the averages of these 1-minute fluxes is the momentum flux for the whole period (Table 2). An obvious feature of the results is the enormous variation that can occur in the flux on both short and long term bases. The experiments listed were all carried out in unstable conditions, and it seems that very long sampling times, or alternatively ensemble averaging, are required in order to obtain meaningful momentum fluxes in convective conditions with cumulus development.

Table 2 summarizes the main results. The point of interest is that there appears to be a strong correlation between wind speed and the difference between corrected and uncorrected values for momentum flux. Apparently even in winds as light as 5 m sec^{-1} it is not permissible to ignore the effects of sensor motion on computed momentum fluxes. However, as pointed out earlier it is uncertain how horizontal sensor motion affects the measured flux. If the correlation between vertical wind speed and horizontal sensor motion is small (as would probably be the case if the balloon was several hundred metres above the sensors), then a precise correction for vertical sensor motion should effectively eliminate the contribution of sensor motion to the measured momentum flux. Confirmation of this point must await instrumented developments now in progress to enable measurements of wind direction to be made by balloon-borne devices.

It appears from Table 2 that the momentum flux was directed upwards rather than downwards in a number of the experiments, implying a decrease of wind with height at the sensor level on these occasions. To see whether this was the case,

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the wind speeds were extracted from the relevant Balthum ascents. (Table 3). However, none of the Balthum ascents coincided with the experimental runs, and so no satisfactory confirmation of this point could be obtained.

Finally, Table 4 gives data to assess the effectiveness of the technique used to define the mean wind direction from the double theodolite observations. Of the six occasions when the wind direction was reasonably specified by the vane mounted on the 40m tower, in four cases the directions from this agreed to within about 20 degrees with those derived from the theodolite data. Errors in the other two cases were 50 and 60 degrees, and while in one of these the wind was very light, in the other the wind speed was around 5 m sec^{-1} . This casts doubt on the effectiveness of this method for assessing the wind direction at the balloon: unless the point is clarified by further experiments, it suggests the tower wind direction is probably a more reliable estimate of the wind at the sensors in cases where the boundary layer is well-mixed.

6. Conclusions

The results of these experiments appear to indicate that except in very light winds, vertical eddy-fluxes of momentum derived from Balgust data may be in error due to balloon-induced motions of the Balgust instrument. This conclusion must remain tentative until both wind speed and direction are measured by the balloon-supported equipment, so that corrections for sensor motion can be applied to both the measured vertical and horizontal wind speeds. Until this is done it is recommended that in future measurements by the Balgust instrument, the balloon should be flown several hundred metres above the sensor level and the vertical sensor motion should be observed. Then, correcting the Balgust data for vertical sensor motion should lead to better estimates for the vertical eddy flux of momentum.

The technique described in this note for determining the sensor motion is cumbersome and it would appear worthwhile to investigate the use of accelerometers for this purpose. Strictly the accelerometer measurements should be supplemented by observations on the variation with time of the tilt of the accelerometer array from the true vertical, as well as its orientation in the horizontal plane, but

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the former is likely to be small in practice: if circumstances are found when this is not the case, then it would be necessary to define the vertical by, for example, a gyroscopic technique.

Acknowledgements

H. E. Butler undertook the Balgust measurements in the experiments. The computer programme was written by Miss S. A. Mathews.

References

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Table 1

Downward momentum fluxes over 1-minute periods (dynes cm^{-2}) (a) uncorrected (b) corrected for vertical sensor motion

22nd May		5th June (am)		5th June (pm)		21st Aug. (am)		21st Aug. (pm)		22nd August		27th August	
(a)	(b)	(a)	(b)	(a)	(b)	(a)	(b)	(a)	(b)	(a)	(b)	(a)	(b)
0.47	0.59	2.22	2.21	-5.61	-6.69	10.21	9.72	39.10	30.38	-0.87	-1.51	-4.33	-5.85
0.18	0.10	0.41	0.36	-1.18	-2.10	-1.67	-1.85	3.08	3.20	-0.15	-0.14	8.32	2.78
0.16	0.09	-0.69	-0.80	3.20	3.21	-1.38	-1.39	6.36	5.47	-2.35	-2.84	2.73	1.41
0.12	0.04	0.93	0.92	3.19	3.26	-4.50	-4.94	-11.73	-15.31	0.71	0.51	3.21	3.30
-0.04	-0.05	-1.52	-1.61	7.48	6.77	-3.06	-3.39	0.35	0.53	0.29	0.18	12.34	12.52
0.48	0.50	3.06	3.12	2.99	2.97	-2.19	-2.98	-2.61	-2.20	-1.38	-1.21	12.66	11.57
-0.10	-0.08	-0.13	-0.16	-4.19	-4.32	1.69	1.73	-1.02	-1.18	2.36	2.33	7.27	6.99
-0.46	-0.57	4.18	4.27	-10.67	-11.08	-2.35	-2.25	-0.40	-0.40	-0.95	-0.88	-1.81	-2.04
-0.10	-0.12	3.36	3.28	-1.75	-2.18	-3.22	-3.05	-3.47	-3.73	1.86	1.27	-3.25	-3.25
0.57	0.65	3.70	3.74	-0.92	-1.30	-16.72	-16.73	-1.34	-2.26	2.31	2.15	-4.91	-5.16
-0.01	-0.05	3.71	3.65	-1.78	-1.82	-8.55	-9.07	-0.09	-0.34	-2.31	-2.45	-4.17	-3.88
0.51	0.60	2.01	1.99	1.38	1.02	-8.21	-8.43	-4.42	-4.48	3.43	3.45	-7.58	-6.23
0.39	0.37	1.89	1.97	-2.05	-2.13	4.03	3.82	-2.68	-3.95	3.63	3.20	-4.18	-3.68
-0.11	-0.05	0.19	0.23	-4.34	-4.15	1.77	1.31	0.77	0.03	-1.43	-1.25	-1.09	-1.25
0.24	0.30	0.43	0.43	1.59	1.63	1.76	-0.31	-2.38	-2.41	3.40	3.15	6.35	5.37
0.65	0.69	0.46	0.46	-0.99	-1.08	-1.30	-1.91	5.96	5.11	0.71	0.31	4.90	3.27
0.47	0.48	0.07	0.09	-5.11	-5.51	-11.36	-13.28	-1.45	-1.54	2.07	2.08	-3.01	-2.90
0.33	0.41	3.08	3.08	-3.05	-3.11	-14.04	-18.04	-0.30	-0.06	3.17	2.68	6.76	-0.54
0.81	0.86	-0.20	-0.19	4.45	2.89	6.03	6.07	2.00	1.80	0.39	0.30	1.47	0.71
0.50	0.41	-0.66	-0.64	-2.33	-2.67	-8.98	-9.91	0.53	0.49	-0.35	-0.85	5.40	5.84
0.29	0.28	-2.23	-2.32	-1.12	-1.13	0.95	-0.78	-1.85	-3.74	-21.00	-21.68	8.30	8.05
0.89	0.95	1.84	1.82	-8.07	-7.91	-5.45	-5.23	5.47	3.76	-33.80	-33.81	-1.09	-4.70
1.78	1.83	0.83	0.72	-4.24	-4.15	-2.87	-2.72	1.19	0.84	-1.34	-1.51	5.32	5.13
0.98	0.98	0.75	0.80	0.93	0.73	-3.61	-3.81	-11.64	-11.81	-2.98	-3.71	0.51	0.00
1.05	1.05	-0.13	-0.21	0.16	0.25	-0.38	-0.67	-7.12	-7.11			-0.14	-0.52
-0.07	-0.06	-1.48	-1.28	-0.52	-0.50	-18.31	-19.27	-0.62	-1.13			0.49	0.55
		-2.07	-2.20	-0.71	-0.60	-1.55	-1.65	1.15	0.96			-1.37	-2.08
		1.92	1.84	-2.25	-2.36	-4.18	-4.44	-0.43	-0.28			2.07	2.03
				-0.29	-0.33	-0.74	-0.83	0.34	0.35			1.03	0.52
				-0.89	-0.84	6.76	6.30	-0.53	-0.34			0.55	0.61
				-1.05	-1.11	4.39	4.55	-5.29	-4.91			-0.84	-1.78
				0.35	0.24	-2.73	-3.86	-6.72	-7.65			0.62	-0.18
				-0.12	-0.22	13.46	11.98	1.21	0.76			0.03	-0.08
				-0.29	-0.32	-1.87	-1.99					-3.52	-2.26
				0.11	0.08	1.48	1.27					3.71	-2.09
				0.01	-0.01	6.49	6.26					3.24	2.58
				-0.11	-0.09	2.43	2.30					0.57	0.63
				-0.11	-0.13								
				-1.41	-1.42								
				1.98	2.16								
				2.32	1.68								
				-4.37	-4.60								

Table 2

Mean downward momentum fluxes and mean wind speeds.

Date	Downward momentum fluxes (dynes cm ⁻²)		Wind Speed m sec
	uncorrected	corrected	
22nd May	0.32	0.33	1.2
5th June(am)	0.92	0.91	2.0
5th June(pm)	-0.95	-1.12	5.1
21st Aug.(am)	-1.87	-2.37	4.6
21st Aug.(pm)	0.04	-0.64	5.0
22nd Aug.	-2.53	-2.79	2.7
27th Aug.	1.35	0.62	9.8

Table 3

Mean wind speeds (m sec⁻¹) from Balthum ascents

Height (m)	22nd May		5th June			21st Aug.			22nd Aug		27th Aug	
	1200Z	1800	0600	1200	1800	0600	1200	1800	1200	1800	1200	2400
300	02	04	08	02	06	06	05	05	04	04	08	08
450	01	04	07	01	06	06	05	05	04	04	09	10
600	02	04	06	02	07	05	06	05	04	04	09	08
750	02	05	05	01	-	05	07	05	03	05	10	10
900	02	03	06	04	-	06	07	04	02	07	10	08

Table 4

Date	Mean wind directions (degrees)		
	From tower vane		From least-squares fit of double-theodolite data
22nd May	010 → 050		020 or 200
5th June(am)	300		170 or 350
5th June(pm)	260		020 or 200
21st Aug.(am)	220		020 or 200
21st Aug.(pm)	230		040 or 220
22nd Aug.	Variable		180 or 360
27th Aug.	030		030 or 210

Appendix: Experimental details

Balloon: Approximately 25m long, 90 cubic metres
BALGUST instrumentation: Inclinator, air damped, double "V" hot-wire
 Anemometer, 3 - cup contact (expts. 1-6): 3 - cup photo-electric (expts. 7-11)
Baseline: Orientation, 140°-320°
 Length, 661m (expts. 1 & 2): 735m (expts. 3-11)

Experiment Number	Date	Period (GMT)	Length of cable to sensors (m)	Mean Wind m sec ⁻¹ (From sensor data)	Mean wind at 40m (degrees, m sec ⁻¹)	Cloud	Notes
1	21-5-68	1514-1544	610	Not evaluated	010/4	3-6/8 Cu. 700m 8/8 Sc. 1200m	(i) Anemometer output intermittent due to faulty contact, output virtually unusable (ii) Zero of inclinometer displaced about 15°, but sensitivity apparently unaffected (iii) Data logger produced many punching faults.
2	22-5-68	1451-1517	610	1.2	030/1-2	3/8 Cu. 700m 4/8 Sc. 1200m 7/8 Ac. 2500m	(i) Wind fell very light at times, anemometer apparently stopped rotating on occasions, mainly in first half of run
3	5-6-68	0945-1013	610	2.0	300/2	4/8 Cu. 800m 5/8 Sc. 1100m 7/8 Ac. 2500m	(i) Wind fell almost calm for short periods a few minutes before end of run
4	5-6-68	1515-1557	610	5.1	260/5	3/8 Cu. 900m 8/8 Sc. 1400m	Nil
5	6-6-68	0910-0955	610	Not evaluated	300/6	4/8 Cu. 700m) Overnight rain which had entered a plug and socket rendered the data from the southern theodolite useless. No analysis of data attempted
6	6-6-68	1530-1615	690	Not evaluated	270/6	4/8 Cu. 900m 5/8 Sc. 1400m	
7	21-8-68	0932-1009	533	4.6	220/3-4	4/8 Cu. 800m 5/8 Ac. 3000m	Nil
8	21-8-68	1417-1450	610	5.0	230/4	3/8 Sc. 1300m 4/8 Ac. 3500m	Nil
9	22-8-68	0915-1000	610	Not evaluated	170/3	1/8 St. 400m	(i) Convection had not built up to level of sensors: insignificant sensor motion throughout period: no data analysis attempted
10	22-8-68	1415-1440	610	2.7	Variable 1 - 5	Nil	(i) Wind fell very light on a number of occasions during the period
11	27-8-68	1338-1415	457	9.8	030/8	4-6/8 Cu. 500m	(i) Sensors set at lower level than before because of low cloud base

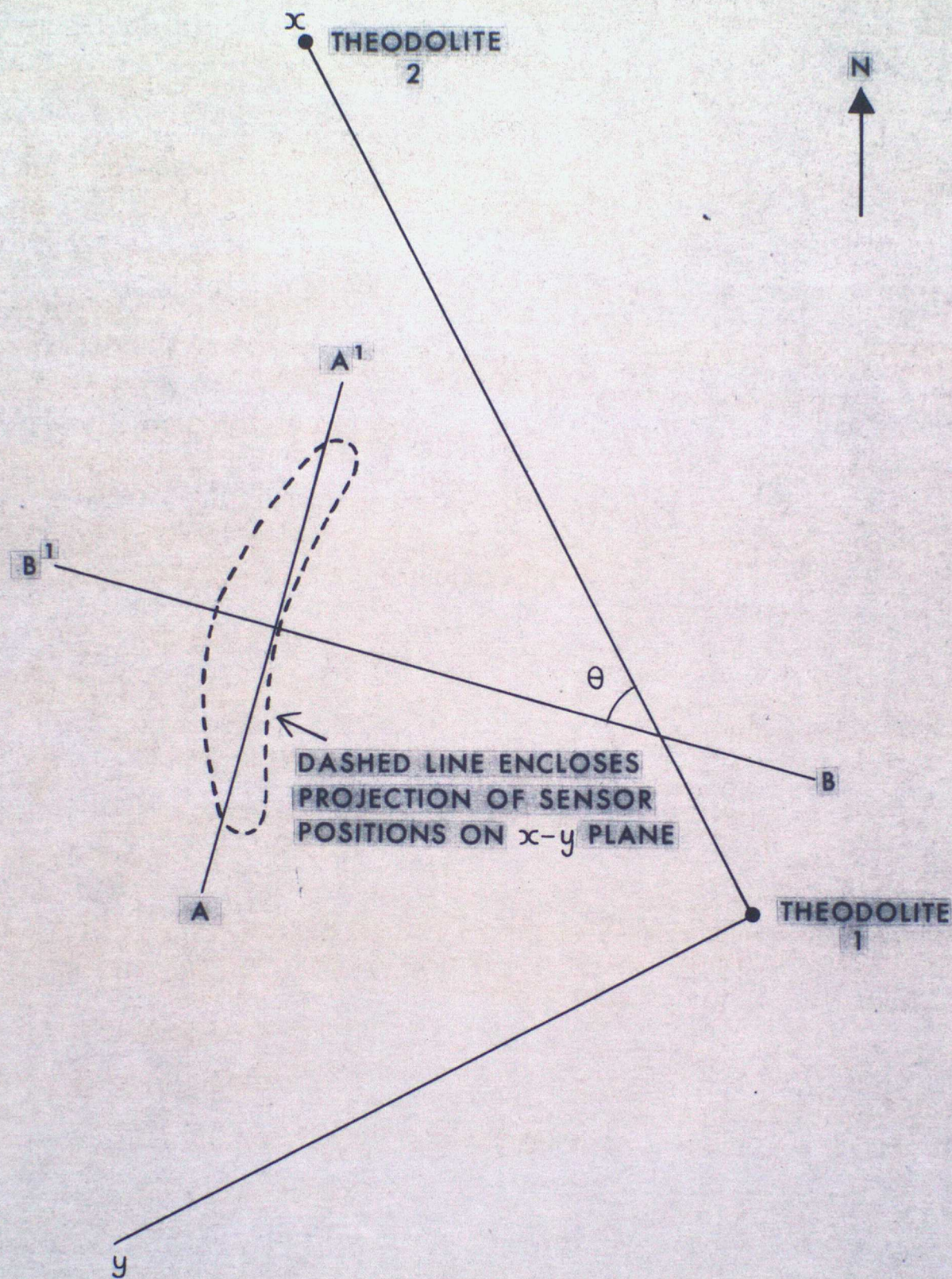


FIGURE 1