OBSERVATIONS OF HEAT AND MOMENTUM FLUXES AT 55 FT ON THE TOWER AT CARDINGTON, 1967

by

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1. Introduction

The work was a sequel to that described in T.D.N. No. 2 "Preliminary Observations at Cardington Concerning the Turbulent Energy Balance in the Planetary Boundary Layer", which will be referred to as A. The object was to repeat the work on a stationary platform, and at a height where some check on the computed fluxes was possible. Three summer runs were made, with the emphasis on comparing computed heat fluxes with fluxes derived from the surface energy balance. One winter run, in near-neutral conditions, was made, to check the momentum flux against the wind profile.

2. Instrumentation

The instruments for recording fluctuations were substantially as in A, and were installed at 55 ft, on a boom projecting 2 m from the tower into the mean wind. Wind speed was measured at 28, 55 and 120 ft on the tower, on fixed 5 ft booms chosen as far as possible to be at rightangles to the mean wind. Temperatures were measured at the same heights by aspirated platinum resistance thermometers recording on a multipoint potentiometric recorder. Wind and temperature were also measured some distance from the tower at a height of 4 ft. The following instruments to measure the components of the surface energy balance were in use:

(i) Soil balance, on 5 kg full scale range

(ii) Ventilated net radiometer at 1 m height

(iii) Soil heat flux plate installed at as shallow a depth as possible.

The fourth component of the surface energy balance, the sensible heat flux, was not obtained directly, but as a residual of the other three.

3. Data logging equipment and computer processing

These were as in A, except that half way through the season, the 1000 sec sampling periods were altered to 1200 sec, and similarly for the longer periods (2400 instead of 2000, etc.). This was done so that the 1200 sec computed fluxes would exactly correspond to the 20 min averages of the profile and energy balance components.

4. General weather conditions

These are summarised in table 1. Cloudless conditions were aimed at in the summer, and the table shows that these were not completely attained. Large heat fluxes were in fact found on each occasion. Good stationary, neutral conditions were obtained on the fourth occasion.

5. Heat Fluxes

(a) Effect of averaging time on the computed fluxes This is shown in figs 1-5. Fig. 1 is for 3 hours record on 16 June, and Fig. 2 shows the results for the three hours computed separately. Figs. 4 and 5 are the corresponding diagrams for 22 August. On 11 July, it was only possible to process the first hour of record, (due to a fault in the data-logging equipment) and this is shown in Fig. 3. There is an immediate fall-off in the computed fluxes on going from 1 to 2 sec averaging time, showing that the high-frequency response of the equipment was not fully adequate. This had been anticipated from prior knowledge of spectra at this height. On the other hand the curves fall to low values for large averaging times, so that the low frequency coverage was adequate.

(b) Effect of sampling time on computed fluxes This is shown in table 2 below. Units are mW/cm^2.

Table 2. Computed heat fluxes for various sampling times

Sampling time (secs)	16 June	11 July	22 August
1000	11.0		
1200		7.5	15.9
2000	12.1		16.2
3600		7.6	
5000	12.1		17.0
10,000	12.1		17.2

The small increase in computed flux with increase in sampling time confirms the good low-frequency coverage.

(c) Comparison of eddy fluxes with energy balance fluxes and temperature gradients Figs 6, 7 and 8 compare the sensible heat flux computed by the eddy method at 55 ft, with that calculated from the surface energy balance at the ground. Results are for 20 min periods in each case. Although the curves do not agree in detail, they move in a broadly similar way, with that for the eddy method at a generally lower level. Some loss of high-frequency flux was to be expected from the variation with averaging time discussed in (a), and this loss may now be estimated.

Table 3. Ratio of Eddy Heat Flux to Heat Flux from Surface Energy Balance

	16 June	11 July	22 August
Ratio $\frac{\text{Eddy flux}}{\text{Energy balance flux}}$	0.71	0.64	0.74

Fluxes are averages of 1000 or 1200 sec periods, for the whole of the processed part of each run.

The ratios are about the same for each day, and indicate a high-frequency loss of about 30%. This result assumes that all the discrepancy is due to high-frequency loss. Other factors, such as radiometer errors, flux divergence and horizontal divergence will also contribute, but none is likely to make a change of 30%. For instance, on 16 June, the temperature rose about 3°C at all levels during the 3 hour run. The corresponding flux divergence is about $\frac{1}{2}$ mW/cm^2, compared with an average flux of 15.4 mW/cm^2 by the surface energy balance. Similarly, although difficulty was experienced with radiometer calibrations during this period, errors should be within 10%.

Under the graphs of heat flux are those of temperature difference, 120-28 ft for each occasion. The dry adiabatic lapse over this height interval is about 0.3°, so each day is quite unstable. The notable feature, partly concealed by the expanded scale used in plotting, is the small variation of temperature compared with the variation in heat flux. In particular, Priestley's free convection regime, with heat flux dependent on the $^3/2$ power of the temperature gradient and on no other variable (at fixed height) does not seem to be applicable.

6. Momentum fluxes

(a) Effect of averaging time This is shown in Figs 1, 3 and 4 for the full computed periods. The curves are very anomalous, executing erratic oscillations, and with negative portions, suggesting momentum flux against the wind gradient. To check if the source of difficulty was localised in part of the record, the 16 June and 22 August occasions were each analysed as three separate hours. Results are shown in Figs 9 and 10. On each occasion the first hour shows a tolerably smooth variation, but on 22 August the sign is the opposite of that expected. The other four hours are very erratic.

(b) Effect of sampling time The erratic variations and changes in sign demonstrated in (a) also appear here. It did not seem worth while computing the variation with sampling time formally.

(c) Comparison of eddy fluxes with wind gradients This is shown in Figs 11 and 12. No obvious relation emerges.

7. Neutral occasion, 30 November

The aims of this experiment were rather different from the three summer ones, so it will be considered separately. Neutral conditions, i.e. zero heat flux and adiabatic temperature gradient, were desired. Fig 13 shows the heat fluxes by the two methods used before. All are small, those by the eddy method being less than 1 mW/cm^2. Values change from positive to negative between 1300 and 1400 hrs. Similarly the temperature difference between 120 and 28 ft changes from slightly super- to slightly sub-adiabatic, passing through the adiabatic value of 0.3^oC at about the same time. Neutral conditions were therefore approached closely. Variation of heat flux with sampling and averaging time will not be discussed, as the computed values are too small for differences between them to be meaningful.

(a) Effect of averaging time on momentum flux This is shown in Fig 14. The variation is erratic, and the sign opposite to that expected.

(b) Comparison of momentum flux with wind gradient This is shown in Fig 15. No obvious relation emerges. The computed momentum flux varies widely and goes slightly negative at one point. Consequently no satisfactory average value for the whole period can be found for comparison with wind profiles.

(c) The wind profiles It was expected that the wind would vary as the logarithm of the height, but the plotted profiles show considerable curvature. It is thought that this is primarily due to the influence of the tower itself. It was only possible to get order-of-magnitude values for friction velocity and surface roughness. These were broadly comparable with values quoted in the literature for rough grassland.

8. A numerical experiment on the momentum flux anomalies

The total wind speed is measured by a cup anemometer which produces a train of pulses. A ratemeter follows which converts the pulse rate into a proportional voltage. It is known that there is some zero drift in the ratemeters. If the drift is linear, it is taken out in the computation, but is it linear? If not, how much influence does it have on the computed fluxes? To test this, arrangements were made to superpose artificial non-linear "drifts" on the data before processing, of the form

$$\text{"drift"} = a \sin \frac{\pi n t}{T}$$

where a = amplitude of "drift"

n = number of half-cycles of "drift"

t = time in secs from start of record

T = length of records in secs

Two periods were chosen, the 1st and 2nd hours of record on 16 June, when the momentum flux had the expected and anomalous behaviour respectively. a was chosen as 0.2 m/sec, on the basis of drifts experienced. Some results are shown in table 4.

Table 4. Trial momentum flux calculations for 16 June.

Values are $\overline{-u'w'}$ in $m^2\ sec^{-2}$

Averaging time, secs	1st hour Unmodified	1st hour With "drift" n=1	1st hour With "drift" n=2	2nd hour Unmodified	2nd hour With "drift" n=1
1	0.0676	0.0706	0.0610	-0.0188	-0.0158
2	0.0632	0.0674	0.0674	-0.0186	-0.0180
5	0.0549	0.0586	0.0586	-0.0202	-0.0198
10	0.0518	0.0550	0.0550	-0.0228	-0.0225
20	0.0393	0.0419	0.0419	-0.0285	-0.0283
50	0.0348	0.0366	0.0366	-0.0334	-0.0335
100	0.0285	0.0313	0.0313	-0.0253	-0.0253
200	0.0255	0.0216	0.0261	-0.0200	-0.0202
500	0.0374	0.0384	0.0382	-0.0001	-0.0001

The "drift" has a marked effect, and certainly deserves to receive attention on the instrumental side, but is clearly not enough in itself to account for the anomalies.

9. Discussion

Heat flux results are generally satisfactory, apart from the high frequency loss. To combat this, a wind speed sensor with quicker response is needed, and also the new data logger soon to be ordered.

Momentum flux results are very unsatisfactory. The vertical component of the wind enters into the heat flux computations also, and as these are satisfactory, suspicion falls on the horizontal component, and therefore basically on the total wind speed. A thorough check of the whole chain for this element is required; instrument, recording, computation. The influence of the tower on measurements made from it needs to be investigated thoroughly. This has already been done for mean speed at the 55 ft level, but needs to be extended to other levels and to the turbulent components. This work is desirable in itself, and as a necessary part of the momentum flux check.

10th January 1968

J. B. Tyldesley

Table 1

Weather conditions - tower flux runs 1967

DATE	TIME	WIND Direction	WIND Speed	TEMP	DEWPOINT	CLOUD	
16.6.67	1300	030	12	15.3	9.3	6/8 Sc 2500'	
	1400	030	10	16.5	9.8	5/8 Sc 2500'	
	1500	040	08	17.0	9.4	2/8 Sc 2500'	
	1600	050	08	17.8	9.7	1/8 Sc 2500'	
	1700	060	08	18.1	10.6	Tr. Sc 2500'	
11.7.67	1000	040	05	21.8	14.8	1/8 Cu 2500'	2/8 Sc 4,000'
	1100	050	06	22.7	14.8	2/8 Cu 3000'	2/8 Sc 4,000'
	1200	090	08	24.0	15.3	3/8 Cu 3000'	
	1300	020	02	25.0	15.1	3/8 Cu 3000'	
	1400	090	06	25.5	15.3	6/8 Cu 3000'	
22.8.67	1000	140	06	19.7	15.0	Tr. Cu 2,000'	
	1100	140	10	22.1	14.9	Tr. Cu 2,000'	
	1200	140	10	23.8	13.6	1/8 Cu 2,000	
	1300	130	10	23.9	14.3	1/8 Cu 2,000'	
	1400	140	11	24.7	13.9	Tr. Cu 2,500'	1/8 Sc 6,000'
						Tr. Cc 20,000'	Tr. Ci 25,000'
30.11.67	1100	190	08	9.0	6.8	7/8 Ac 10,000'	6/8 Ci 25,000'
	1200	190	08	9.4	7.3	1/8 Sc 4,500'	7/8 Ac 9,000'
	1300	210	08	9.9	7.4	3/8 Sc 4,500'	7/8 Ac 9,000'
	1400	200	08	10.0	7.9	4/8 Sc 4,500'	8/8 Ac 9,000'
	1500	210	07	9.9	7.8	5/8 Sc 4,500'	8/8 Ac 9,000'
	1600	210	08	9.7	8.1	4/8 Sc 3,000'	8/8 Ac 8,000'

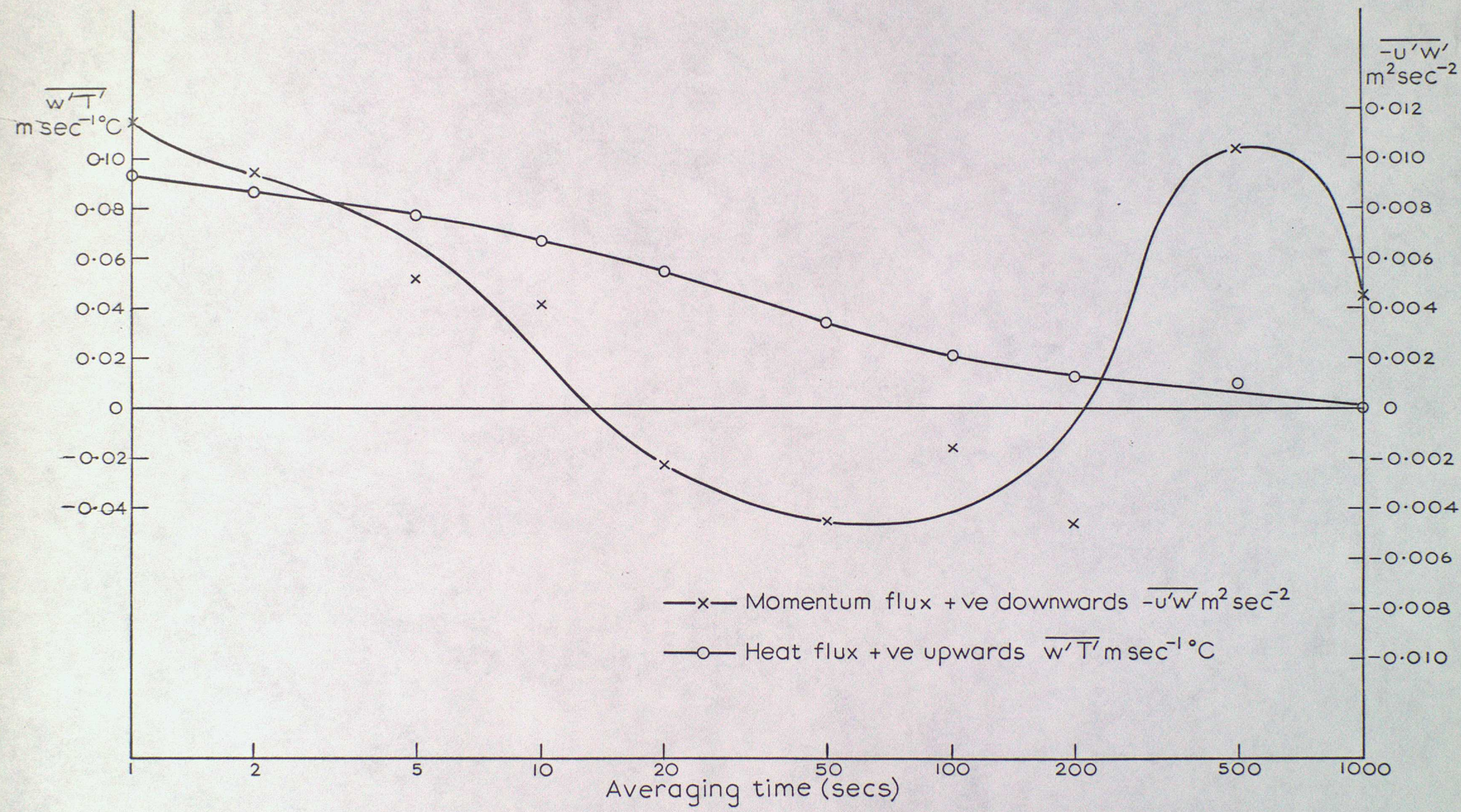

Fig I. Tower fluxes 16-6-1967

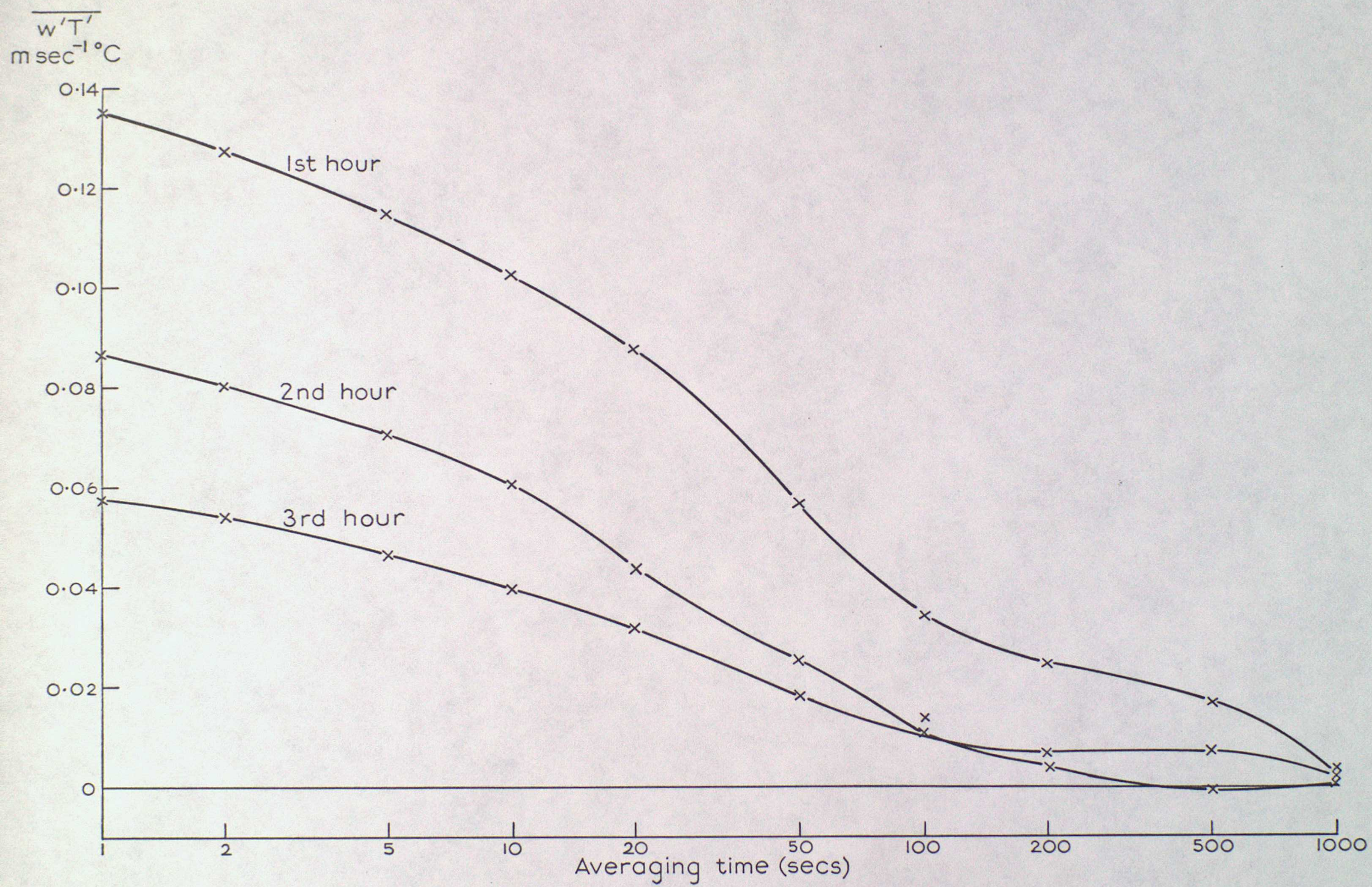

Fig 2. Tower heat fluxes 16-6-1967

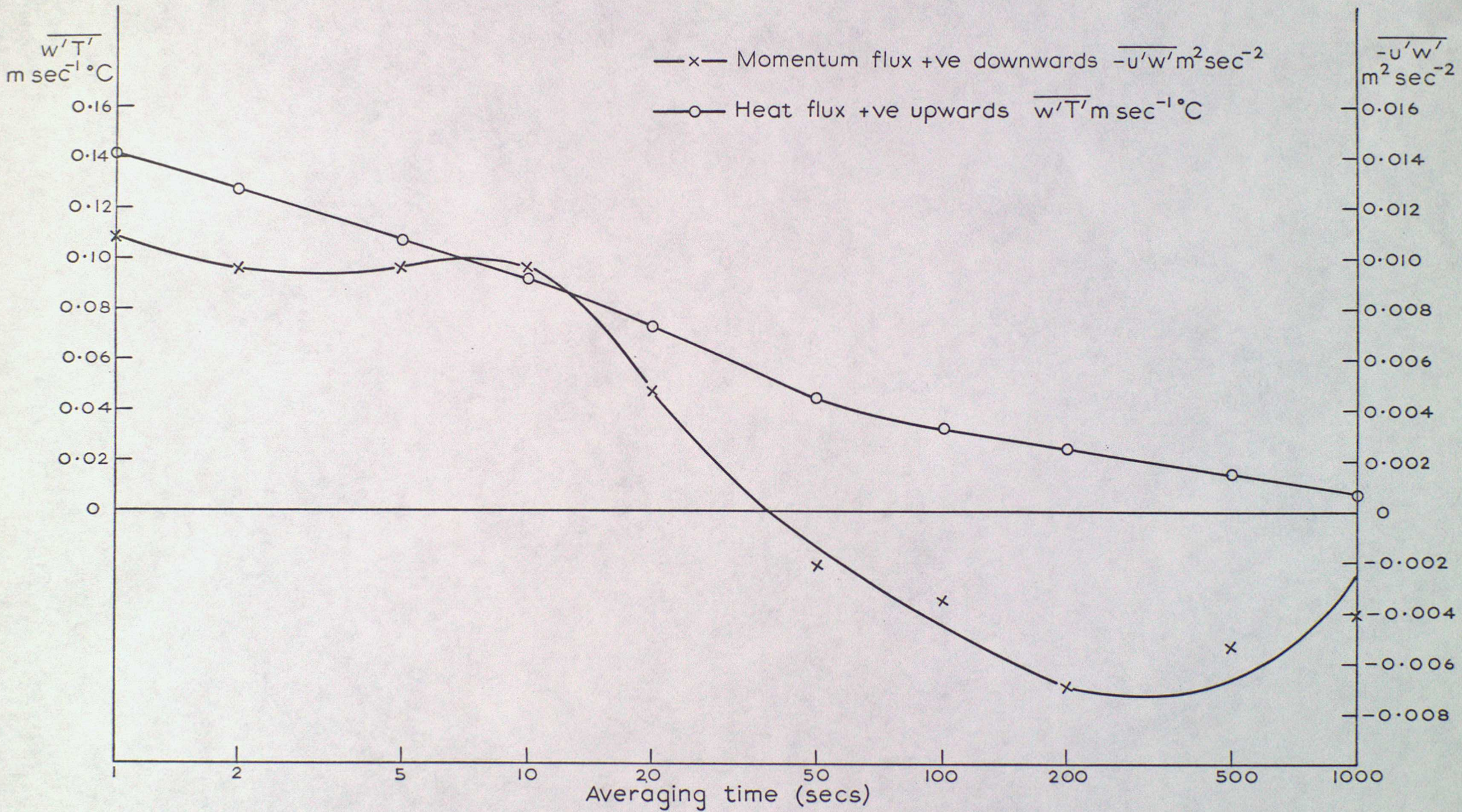

Fig 4. Tower fluxes 22-8-1967

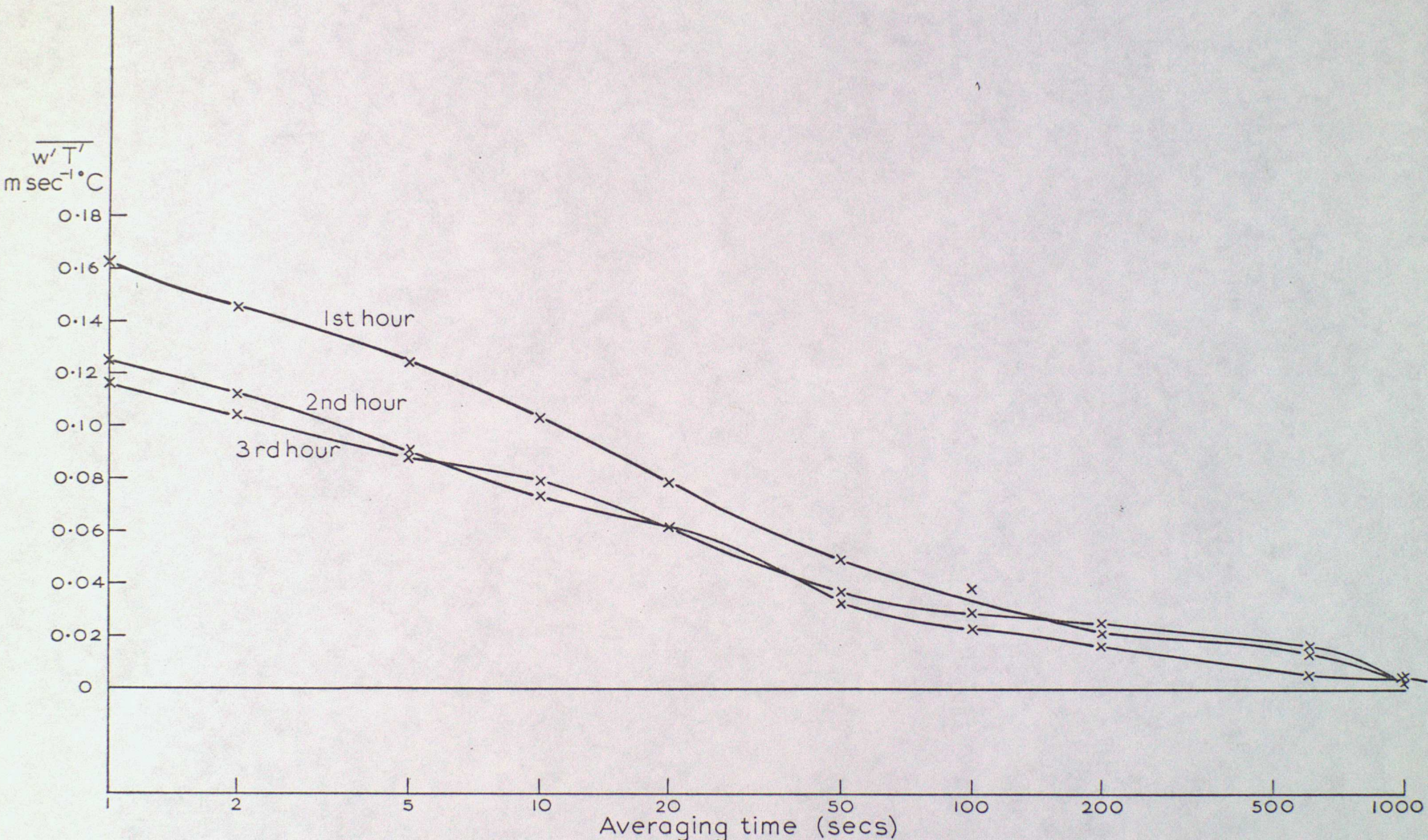

Fig 5. Tower heat fluxes 22-8-1967

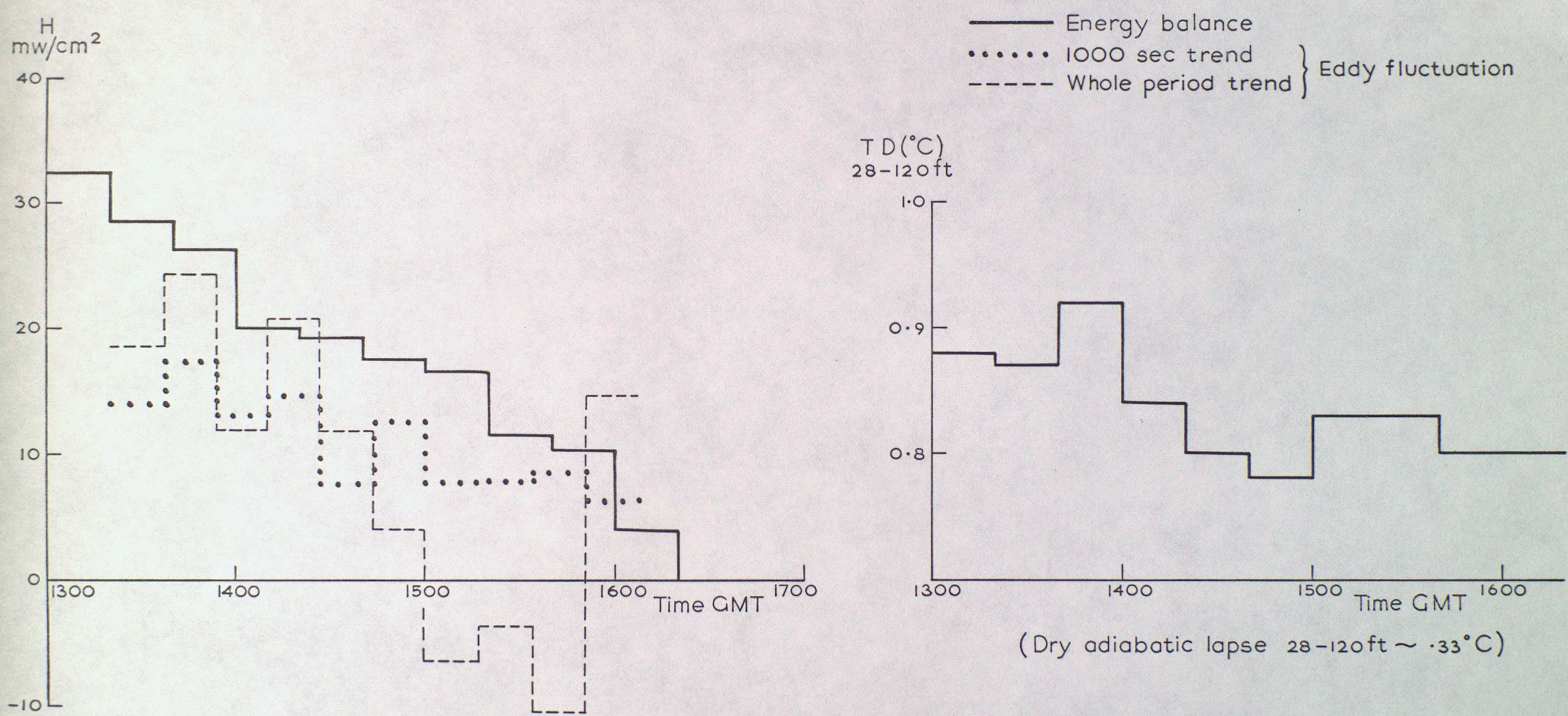

Fig 6. Heat flux and temperature gradient 16-6-1967

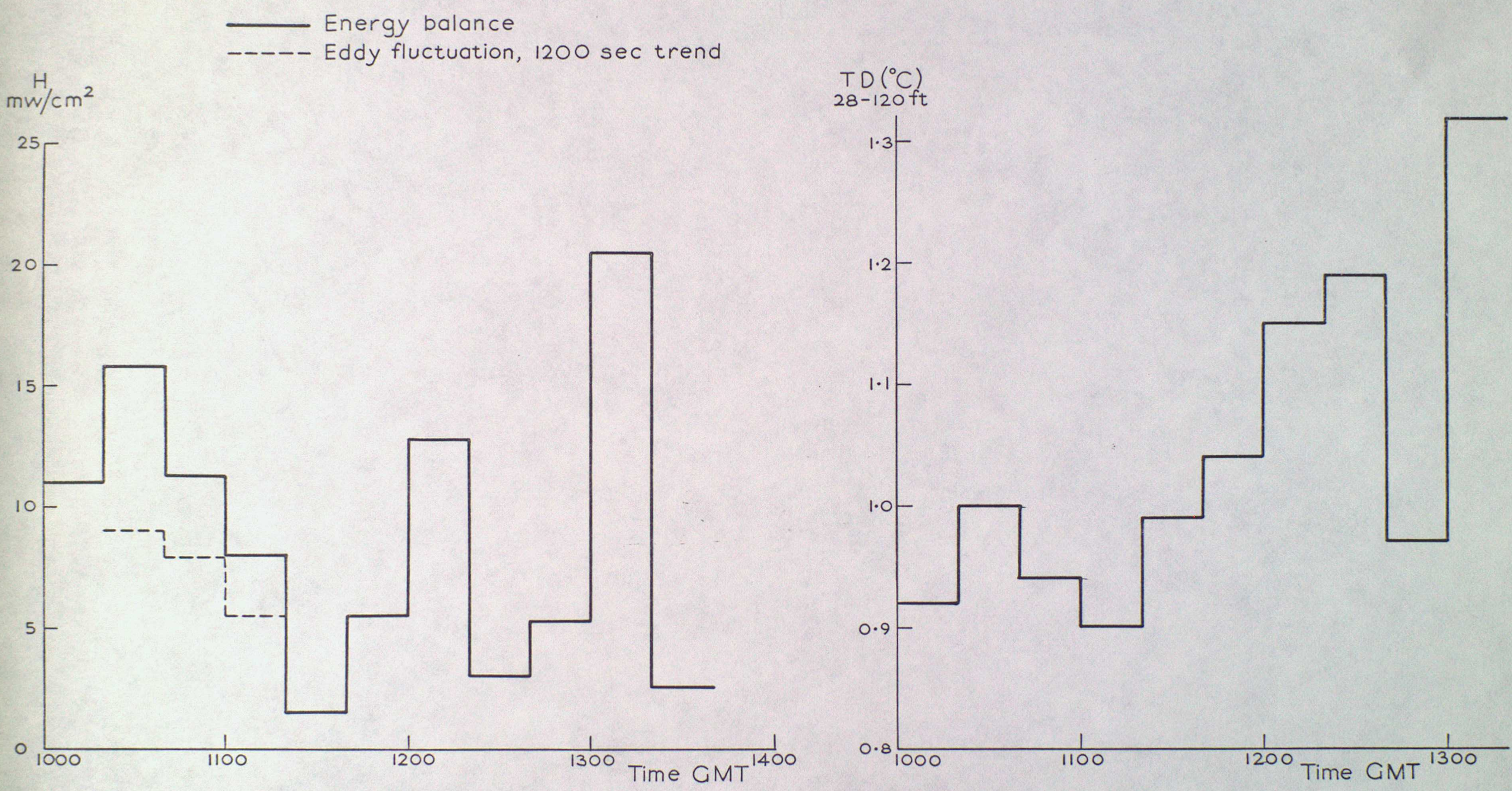

Fig 7. Tower, 55 ft, 11-7-1967

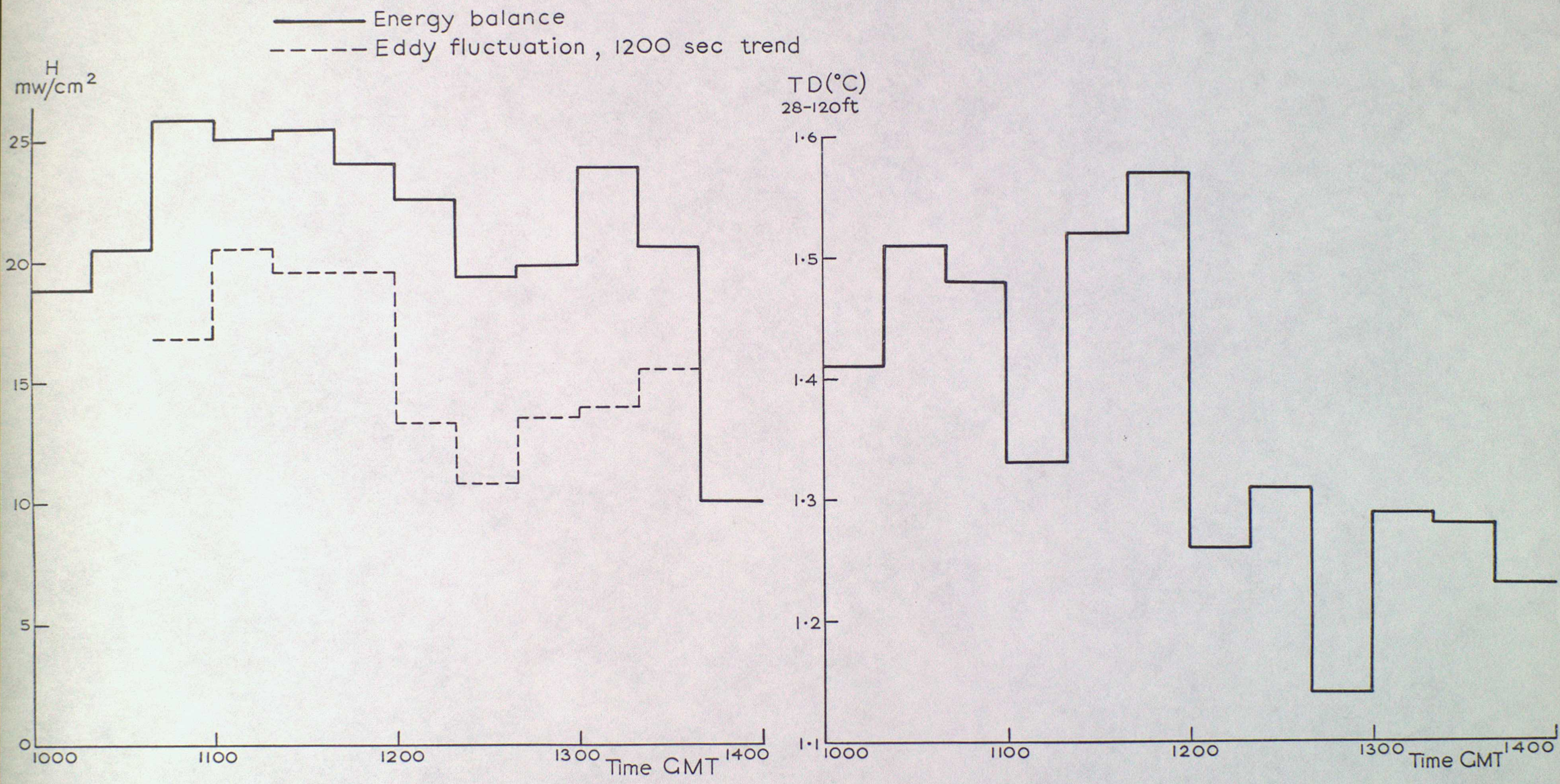

Fig 8. Tower, 55 ft, 22-8-1967

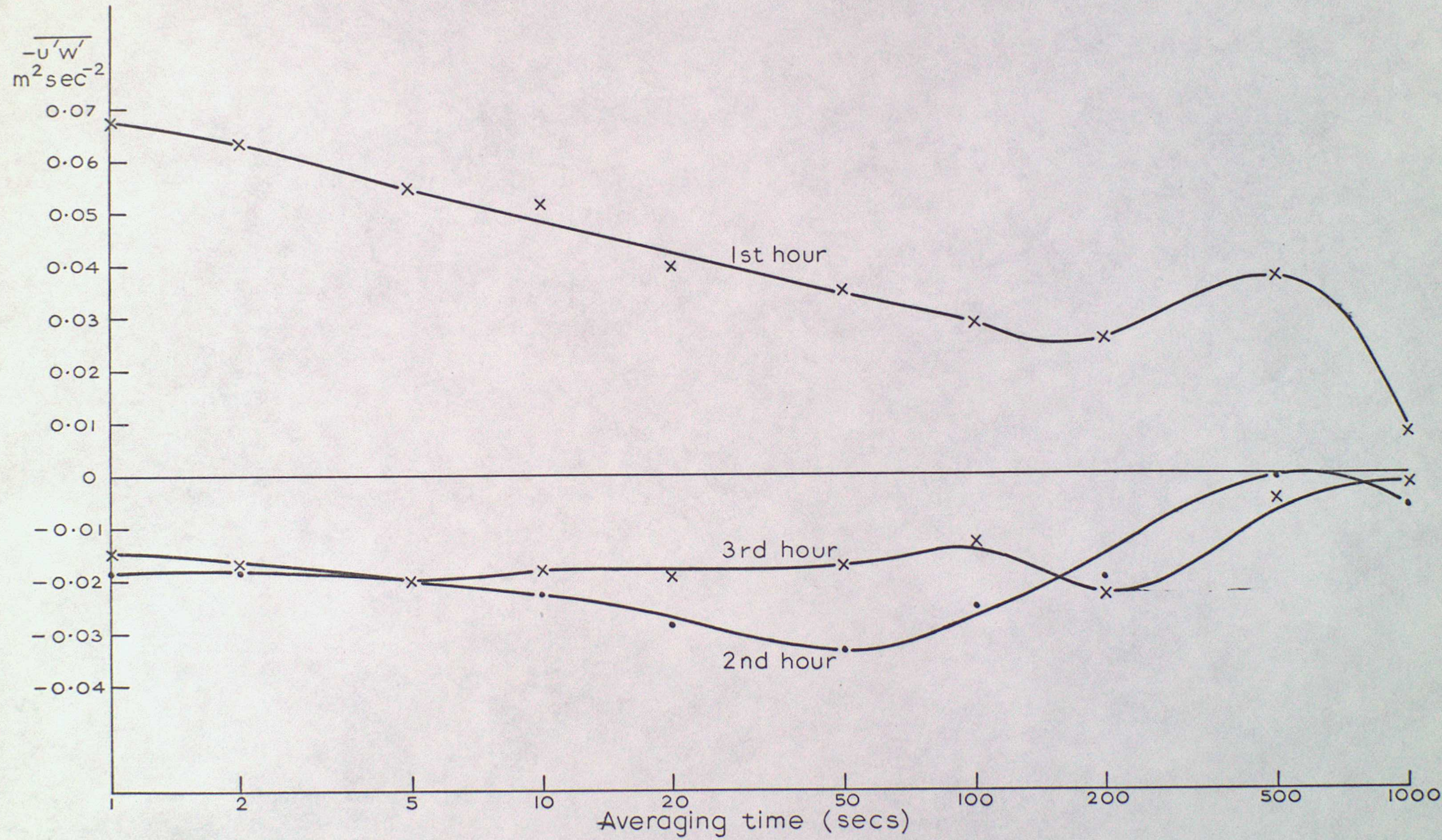

Fig 9. Tower momentum fluxes 16–6–1967 (hourly)

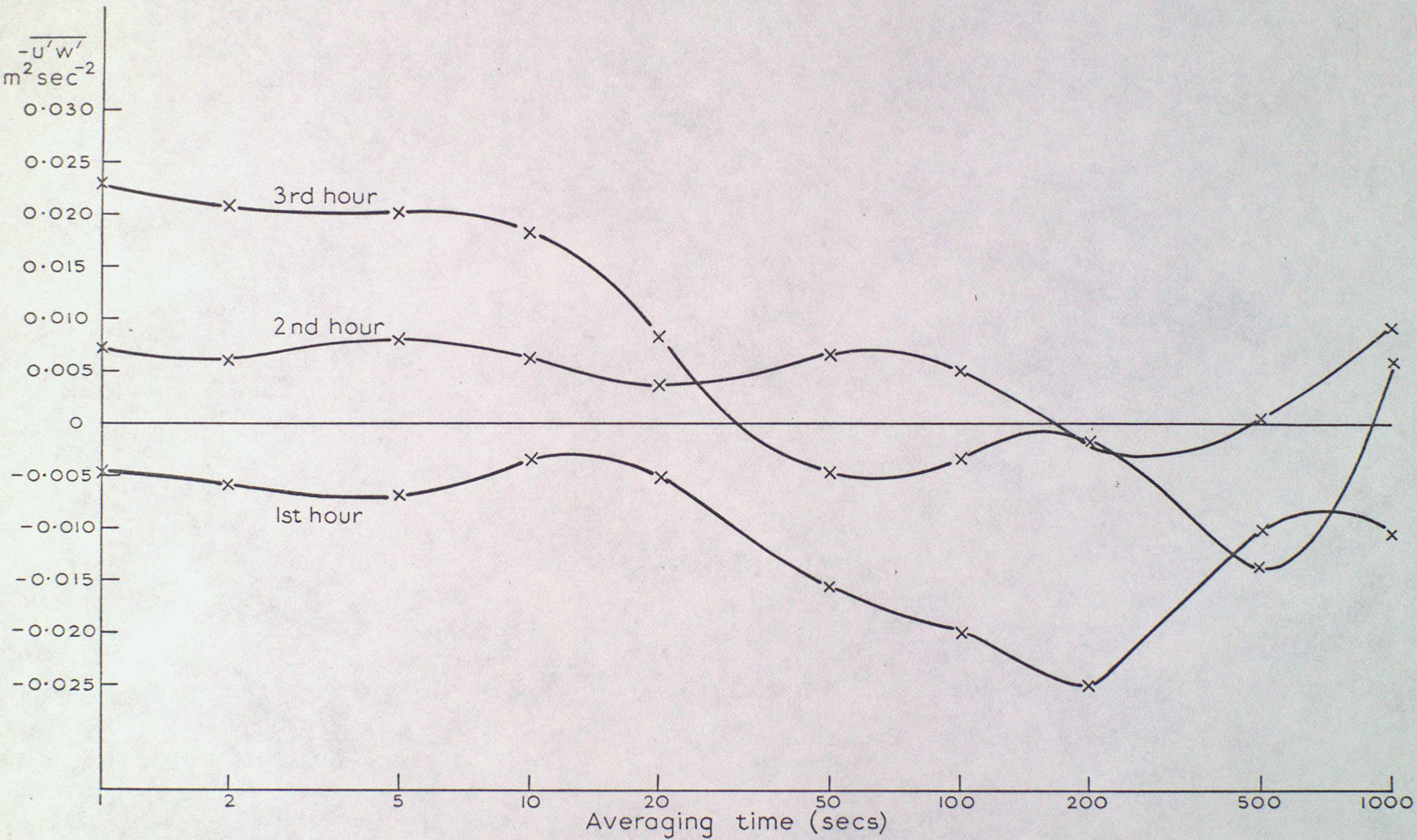

Fig 10. Tower momentum fluxes 22-8-1967

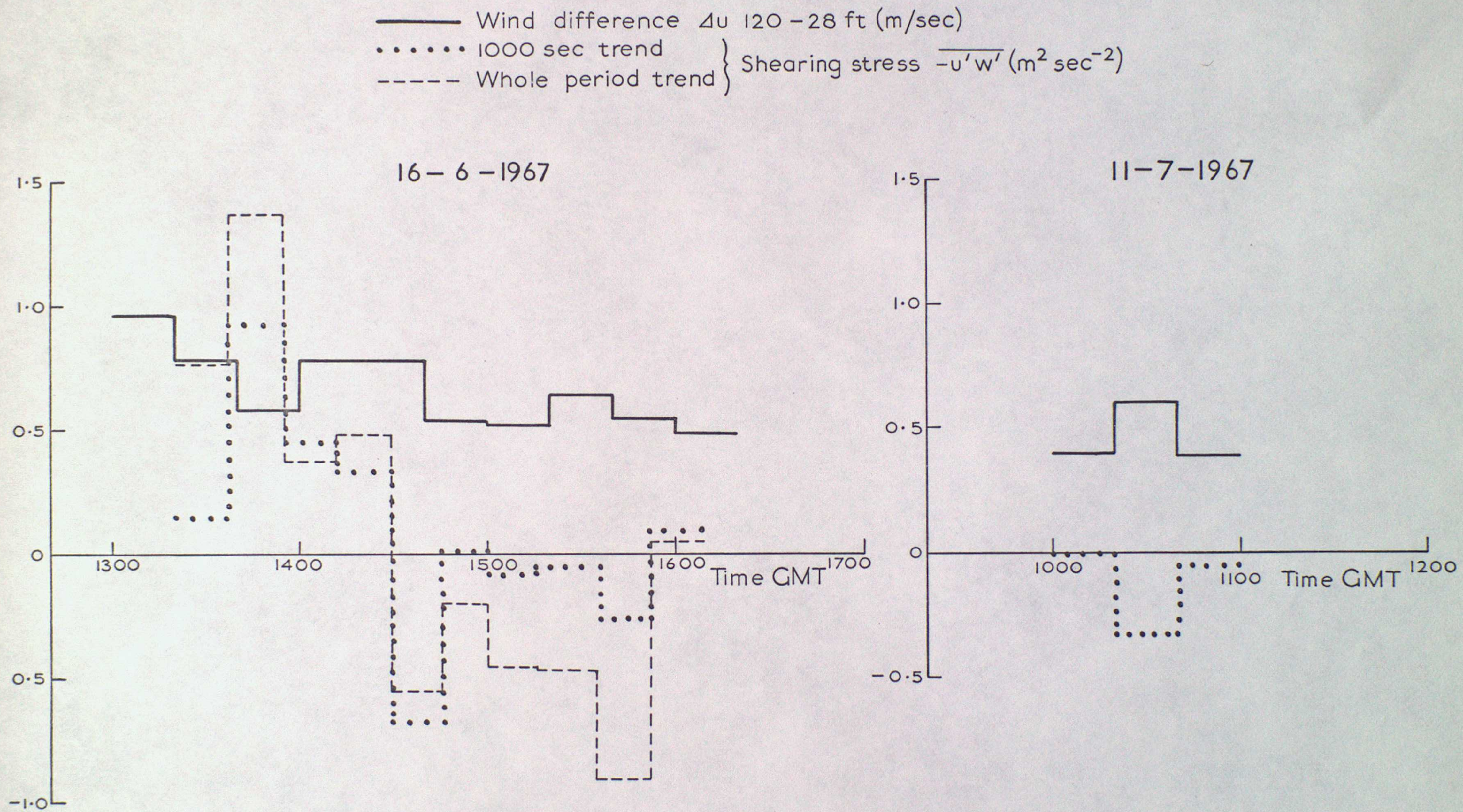

Fig 11. Tower, 55 ft, 16-6-1967 and 11-7-1967

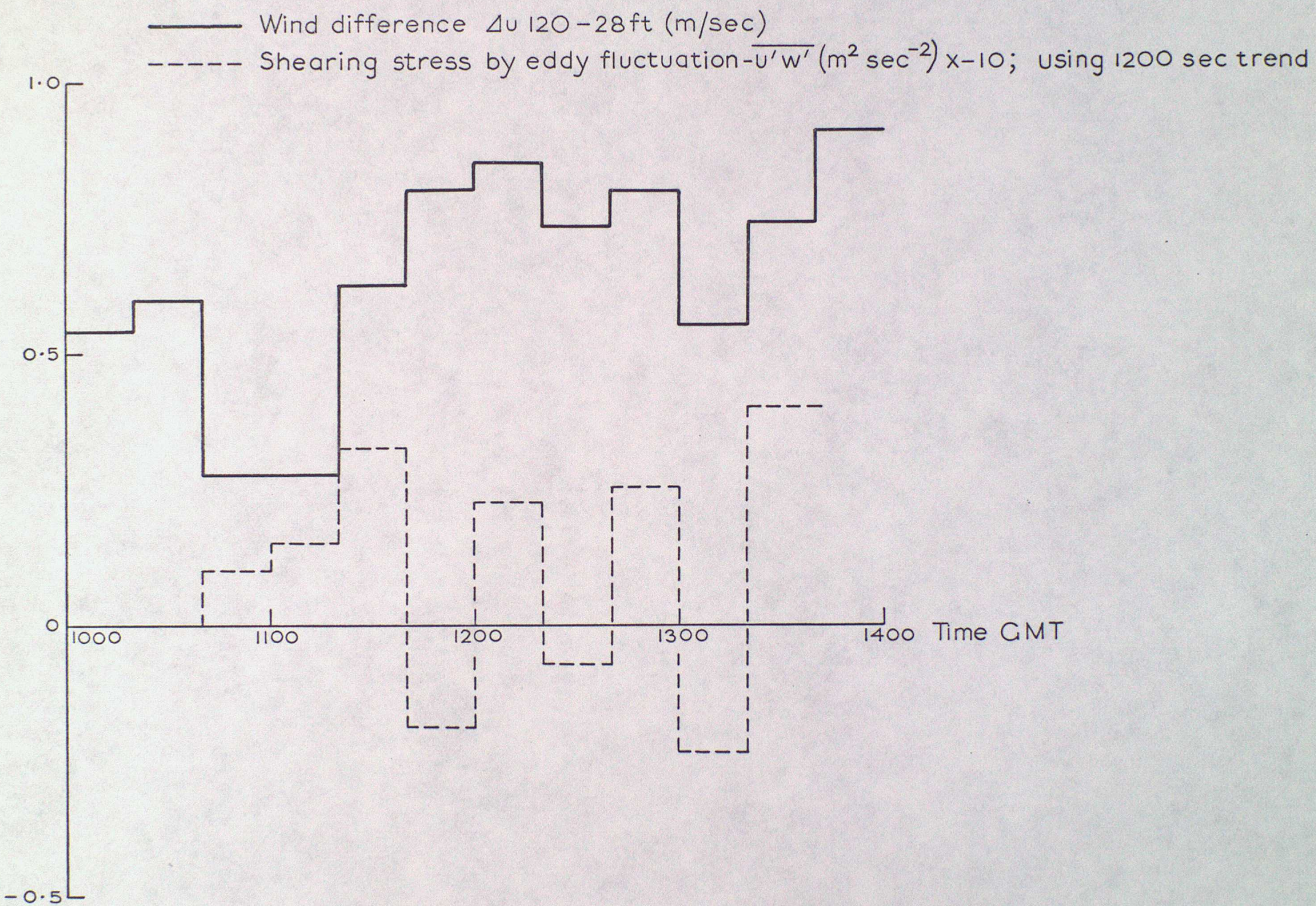

Fig 12. Tower, 55 ft, 22–8–1967

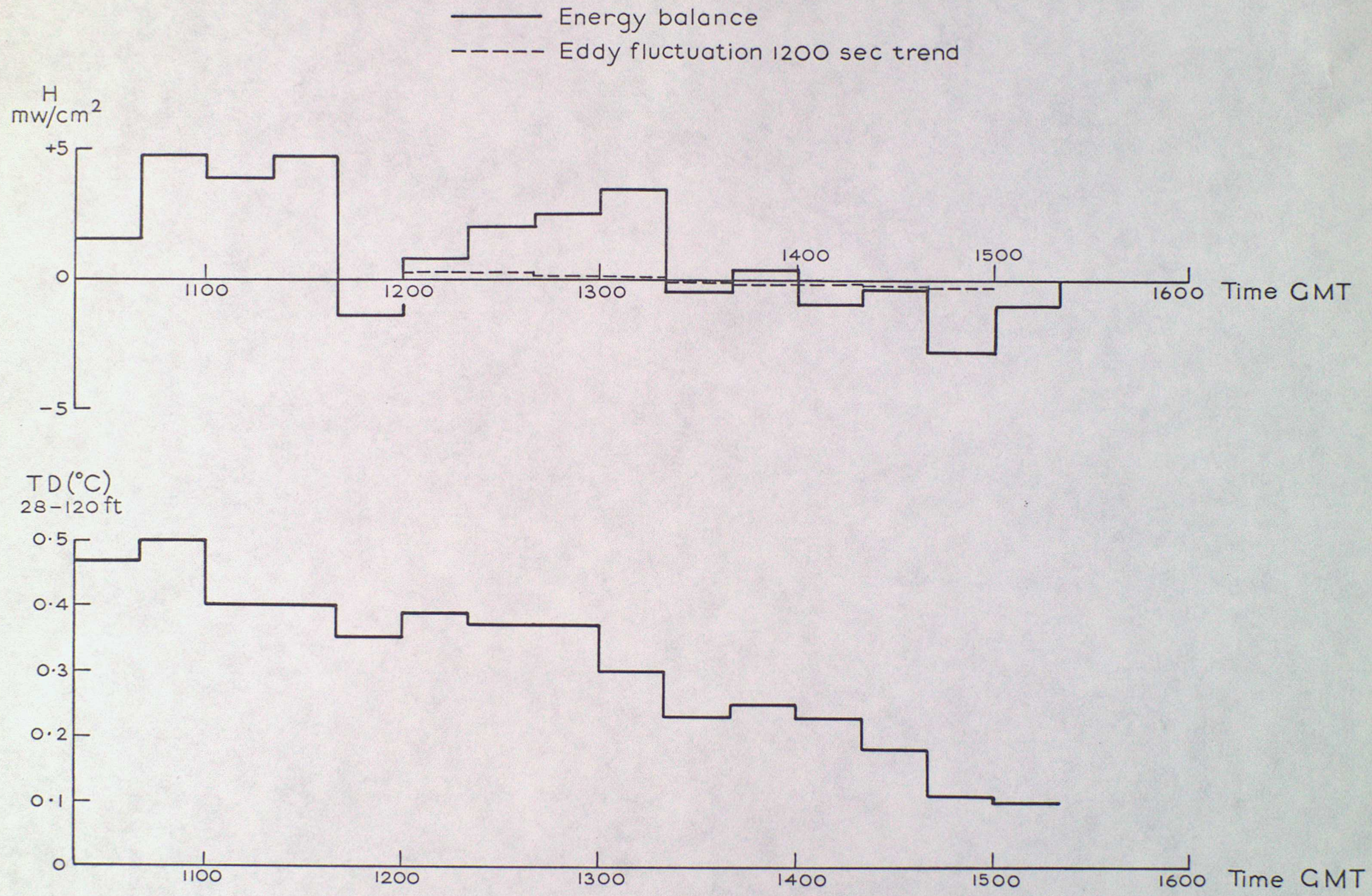

Fig 13. Tower, 55 ft, 30−11−1967

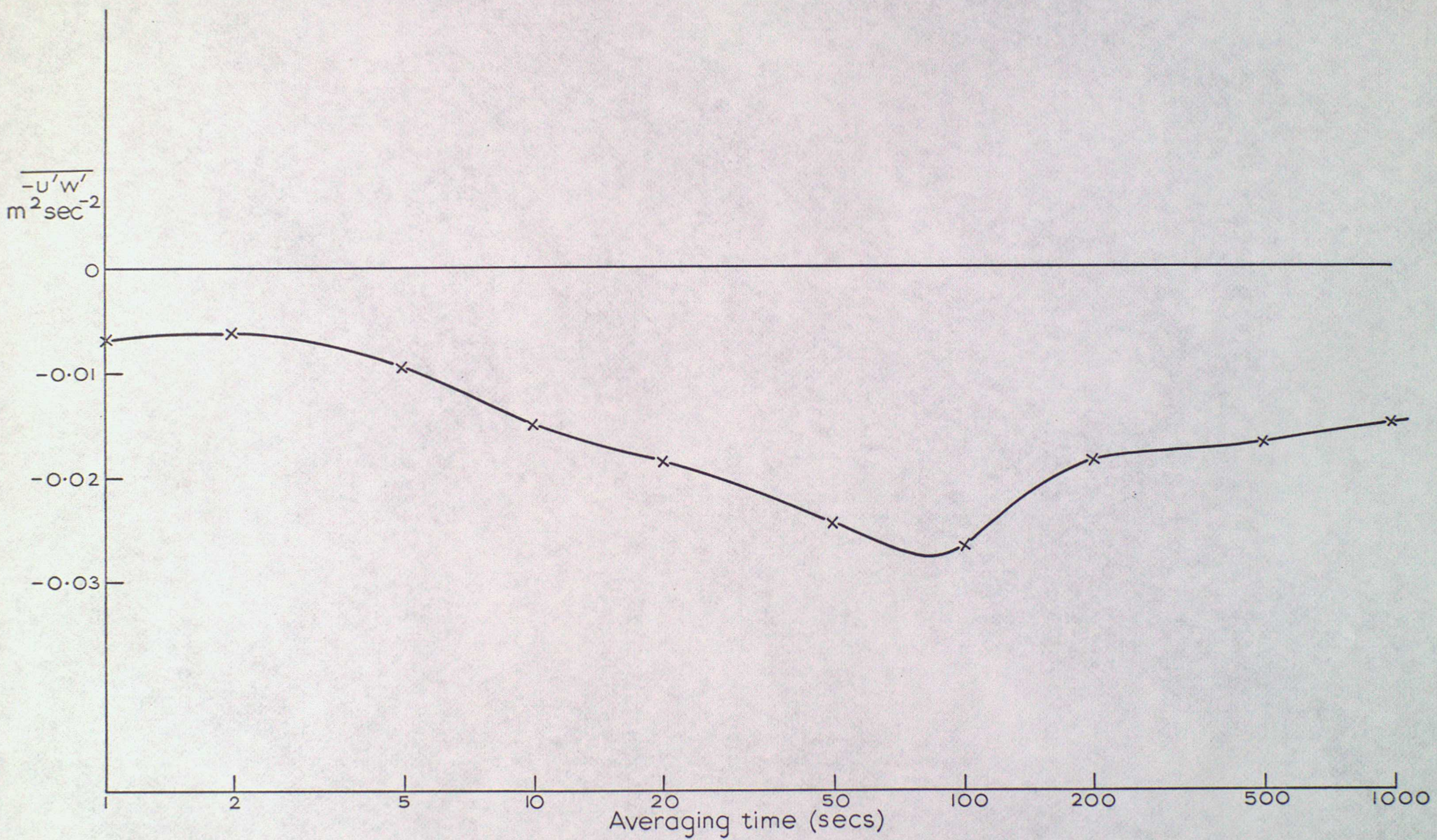

Fig 14. Tower momentum fluxes 30-11-1967

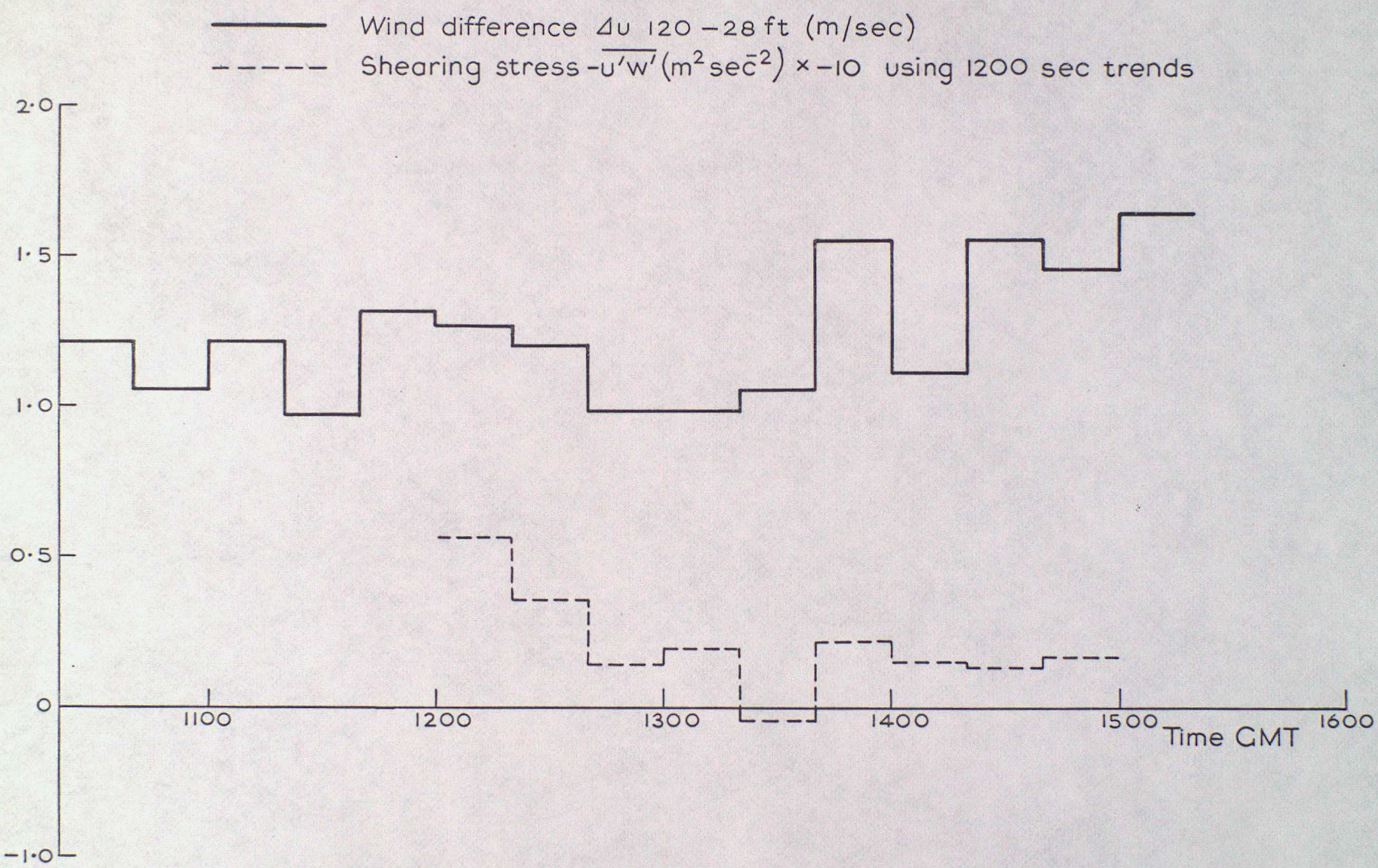

Fig 15. Tower, 55 ft, 30-11-1967