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*by*

*D. R. Roberts*

*Structures Dept., R.A E., Farnborough*

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# BOUNDARY-LAYER PRESSURE FLUCTUATIONS AT HIGH REYNOLDS NUMBERS ON A *FREE-FLIGHT TEST VEHICLE*

by

D. R. Roberts

## SUMMARY

Measurements have been made of the boundary-layer pressure fluctuations on the body of a free-flight aerodynamic test vehicle powered by a solid-fuel rocket motor. The vehicle reached a maximum Mach number of 2.2 with a maximum Reynolds number of about 215 millions.

Pressure spectra have been deduced, and have been found to compare reasonably with a theoretical spectrum for homogeneous isotropic turbulence.

The scale of the boundary-layer turbulence was found to fluctuate between 47% and 76% of the turbulence boundary-layer thickness over a range of Mach numbers from 1.5 to 2.2, while being essentially equal to 50% of this thickness over the range Ma = 2.0 to Ma = 2.2.

At Ma = 2.2 the root mean square boundary-layer pressure was equal to 0.0045 of the free stream dynamic pressure.

* Replaces RAE Technical Report 71033 - ARC 33171

CONTENTS

# ILLUSTRATIONS

## 1 INTRODUCTION

A series of three free-flight aerodynamic test vehicles, designated the 'Shark'* series, was envisaged for the investigation of boundary-layer characteristics at high Reynolds number.

On Shark 1, measurements were made of skin friction drag by means of surface pitot tubes, and boundary-layer pressure fluctuations using a piezo-electric pressure transducer. On Shark 2, it was planned to make direct measurements of skin friction drag by means of a modified force-balance accelerometer, for comparison with the results obtained from Shark 1. Difficulties with the instrument resulted in the abandonment of the experiment. On Shark 3, measurements were made of boundary-layer pressure fluctuations employing two piezo-electric pressure transducers, one at a rear station similar to that used on Shark 1, and the other at a station positioned to give a Reynolds number half that at the rear station. This Report presents the pressure-fluctuation results from Shark 1.

## 2 DESCRIPTION OF TEST EXPERIMENT

### 2.1 Description of test vehicle

#### 2.1.1 General

The vehicle consisted of a 4 calibre tangent circular ogival nose fitted to a cylindrical body 8 calibre long followed by a 2 calibre tail section, to the tail section were fitted three stabilising fins, radially equally distributed. The body and tail tube were constructed of resin bonded paper tube, and the nose was a glass fibre moulding. The vehicle was propelled by a non-separating solid-fuel rocket motor mounted inside the body. The overall length was about 233 inches (5.92 m) and the launch weight was about 1204 pounds (546 kg). A general arrangement drawing is given in Fig.1a.

#### 2.1.2 Instrumentation

Transducers were installed to measure:

(a) Boundary-layer pressure fluctuations (special piezo-electric lead-zirconate bimorph transducer, ±0.2 $lbf/in^2$ [±1379 $N/m^2$]).

*These vehicles were designed and constructed by Aerodynamics Department, RAE, and launched by them at the RAE Aberporth firing range.

(b) Pitot and static pressure differential at each of five surface pitot tubes (variable inductance pressure transducers).

(c) Acceleration normal to the vehicle body surface near the boundary-layer pressure measuring station (piezo-electric accelerometer).

(d) Accelerations normal and perpendicular to a given vehicle-body radius (variable inductance accelerometers).

The output signals of these transducers were translated through suitable sequence-switches and modulator units to frequency-modulate the transmission of three 465 MHz oscillator units. The signals from these oscillators were received and translated at the ground receiving station, and recorded on magnetic tape and oscilloscope record films.

One transmitter was used to telemeter the data from (b) and (d), to give measurements of vehicle accelerations and skin-friction. The second transmitter telemetered the output of (c) to give measurements of the environmental vibration local to the boundary-layer pressure-fluctuation transducer. The third transmitter telemetered the output from (a); the information derived from this transducer is considered in this paper.

## 2.2 Aerodynamic environment

The maximum Mach number achieved was about 2.2 [$q_{max} \simeq 6870$ lbf/ft$^2$ (330 kN/m$^2$)].

The maximum local Reynolds number was about 215 millions.

Maximum altitude was about 1456 ft (444 m).

## 2.3 Range facilities

In addition to the telemetry receiving and recording station, the firing range provided the following:-

(a) a number of observation posts suitably sited, equipped with high-speed cine cameras and kinetheodolites, which tracked the vehicle during flight, and afforded data from which was deduced velocity and altitude information.

(b) Radar cover to provide additional velocity and altitude data, particularly when the vehicle was beyond optical range of the observation posts, or obscured by cloud.

(c) A central source of timing pulses which were transmitted to all the data recording systems, and also initiated a firing sequence which resulted in the electrical pulse sent to the rocket motor igniter circuit. Measurement of the roll of the vehicle was also made by the telemetry receiving station.

The transmission of data from the boundary-layer pressure fluctuation transducer ceased after about 5 seconds of flight. This record deals with the data received during this time.

## 3 METHOD OF DATA ANALYSIS

The signal representing the output of the boundary-layer pressure fluctuation transducer was frequency-translated after reception and recorded on ½ inch magnetic tape at 60 inches per second. It was later played back at 7.5 inches per second, and re-recorded at 30 inches per second. Thus one second of vehicle flight time was represented by 240 inches of magnetic tape. This operation was carried out by Instrumentation and Ranges Department at the Royal Aircraft Establishment, Farnborough, using the equipment known as BRAMBLE[1]. This analogue record was digitised by means of a high-speed digital recorder made to an RAE design by English-Electric/Leo/Marconi Ltd., the output from which was taken to a five-hole paper tape punch. For ease of handling, the record of the five seconds of flight time was divided into fifty punched paper tapes, each representing approximately 0.1 second of flight time, and designated runs 00 to 49, the designation representing the approximate time of the beginning of that section of data. Thus run 23, for instance, refers to the data received during the section beginning at about 2.3 seconds after the commencement of the flight.

Each of these fifty runs consisted of approximately 6170 discrete readings of pressure amplitude, expressed in units of analogue/digital converter output. For convenience in the computing process, these output units were retained throughout the analysis. The relationship between these units and standard physical units is given below:-

$$1 \text{ pressure unit} = 0.0031163 \text{ lbf/in}^2 = 0.02149 \text{ kN/m}^2$$

$$1(\text{pressure})^2 \text{ unit} = 9.7113 \times 10^{-6} (\text{lbf/in}^2)^2 = 0.4618 \times 10^{-6} (\text{kN/m}^2)^2 .$$

The readings were spaced at intervals of 15.5 microseconds of flight time. Figs.2a, 2b and 2c show plots of pressure-readings for the first 5 milliseconds of each of the three runs, 32, 33 and 34.

Using the RAE Mathematics Department ICL 1907 computer, the data for each run was treated separately, the following operations being performed.

(a) The arithmetic mean of all the values in the run was found, and subtracted from each value in turn:-

$$y_t = (\text{recorded value}) - (\text{arithmetic mean}) \quad .$$

(b) The root mean square of the pressure fluctuations was evaluated using the expression

$$\sigma_p = \left[\frac{1}{(N+1)} \sum_{t=1}^{N+1} y_t^2\right]^{\frac{1}{2}}$$

where $(N + 1)$ is the number of discrete values contained in the run.

(c) The autocorrelation function is defined as

$$R_\tau = \frac{1}{(N+2-\tau)} \sum_{t=1}^{N+2-\tau} y_t \, y_{(t+\tau-1)}$$

where $\tau = 1, 2, 3 \ldots\ldots (M+1)$

where $M$ is the number of correlated intervals used in the spectral density analysis.

The expression was evaluated for $\tau = 1, 2, 3 \ldots\ldots (100)$.

(d) The unsmoothed spectral density estimates were calculated from[2]:-

$$V_k = \Delta t \left\{R_1 + R_{(M+1)} \cos\left[(k-1)\pi\right] + 2\sum_{\tau=2}^{M} R_\tau \cos\left[\frac{[(k-1)(\tau-1)\pi]}{M}\right]\right\}$$

where $k = 1, 2, 3, \ldots\ldots (M+1)$

and $\Delta t$ is the time interval between each two consecutive discrete values.

Tabulated values of unsmoothed spectral density are presented in Table 1.

(e) The frequency to which this estimate refers is given by:-

$$f_k = \frac{(k-1)}{2\Delta t M} \quad .$$

Values of $k$ with the corresponding values of frequency are presented in Table 2.

The expression in (d) and (e) were evaluated for $k = 1, 2, 3 \ldots\ldots 100$.

(f) The estimates of hanning-smoothed and hamming-smoothed spectral densities are given by:-

hanning smoothing

$$W_k = 0.5\ V_1 + 0.5\ V_2 \qquad k = 1$$

$$= 0.25\ (V_{k-1} + V_{k+1}) + 0.5\ V_k \qquad 1 < k < M$$

$$= 0.5\ V_M + 0.5\ V_{M+1} \qquad k = M + 1$$

hamming smoothing

$$Z_k = 0.54\ V_1 + 0.46\ V_2 \qquad k = 1$$

$$= 0.23\ (V_{k-1} + V_{k+1}) + 0.54\ V_k \qquad 1 < k < M$$

$$= 0.46\ V_M + 0.54\ V_{M+1} \qquad k = M + 1$$

These expressions were also evaluated for k = 1, 2, 3 ..... 100.

Autocorrelation functions plotted against $\tau$, and smoothed and unsmoothed spectral density estimates plotted against k, are presented for a number of representative runs in Figs.6a to 6e. The maximum value of unsmoothed spectral density and the frequency $f_m$ at which it occurred, were determined, for each run. It should be noted that $f_m$ was taken as the frequency of the peak value of the unsmoothed spectral density, regardless of fluctuations about the mean path through the experimental points. In a few runs, two peaks of similar magnitudes occurred at fairly close frequencies, causing some doubt as to which represented the proper value of $f_m$. In such a case, reference was made to the plots of smoothed spectral density, which indicated one sensible peak value. The frequency of this value was taken as the value of $f_m$.

(g) For very high Reynolds numbers (non-dimensional viscosity function A = 0) it was shown[3] that the maximum (pressure)$^2$ spectral density occurred at

$$X = 2.111$$

where X, the non-dimensional frequency, was defined as

$$X = a\omega = \frac{2\pi f a}{U}$$

where $\omega$ was the wave-number, f the measured frequency, U the velocity of the stream relative to the measuring station, and a was a length to make wave-numbers non-dimensional.

The frequency at which the spectral density is a maximum is defined as $f_m$ so that

$$2.111 = \frac{2\pi f_m a}{U}$$

or

$$a = \frac{2.111U}{2\pi f_m} \quad .$$

The scale of the turbulence was defined as

$$\ell_u = LUa$$

and

$$LU = 0.74677 \quad \text{when} \quad A = 0 \quad .$$

If the frequency position of the maximum value of the experimental spectrum is made to coincide with that of the theoretical spectrum, the scale of the turbulence is therefore given by -

$$\ell_u = \frac{2.111\ (0.74677U)}{2\pi f_m}$$

$$= \frac{0.25088U}{f_m} \quad .$$

This expression was used to calculate the value of $\ell_u$ for each run.

(h) The local Reynolds number $R_x$ was calculated for each run, assuming that the effective start of the turbulence was at a distance x upstream of the measuring station, equal to the axial distance of the station from the nose of the test vehicle, and using the data of velocity and altitude.

(i) Taylor[4] has concluded that a reasonable estimate of the turbulence thickness $\$_T$ is equal to about 80% of the total boundary-layer thickness $\$$ predicted by Spalding[5], so that

$$R_{\$_T} = 0.8\ R_{\$} \quad .$$

The relationship between $R_{\$}$ and $R_x$ has also been defined by Spalding, and using this relationship together with the expression

$$\$_T = \left(\frac{0.8\ R_{\$}}{R_x}\right)x$$

the values of $\$_T$ were calculated for each run.

(j) The ratio $\ell_u/\$_T$ was then calculated for each run.

3.1 For runs 00 to 20, (Ma = 0 to Ma ~ 1.2) the signal/noise ratio of the recorded data was too small for the effective determination of a peak in the plot of spectral density against frequency factor. Under these conditions, a spurious peak imposed by the reading frequency was often apparent, at the lowest frequency used. This would lead, of course, to a false value of $\ell_u$ being obtained if this frequency was used in the calculation of the scale of the turbulence in the expression given in 3(g) above. For this reason, the values of the computed spectral density estimates for these runs have not been tabulated, or used in analysis.

The data for runs 21 to 24 inclusive have not been fully analysed because the signal/noise ratios, though higher than those for earlier runs, were still too low for really adequate identification of a significant peak. The data have been included in Table 1 merely for possible use in transonic studies.

The spectral density estimates for runs 21 to 49 are tabulated for a range of k = 1 to k = 100, in Table 1, and for runs 25 to 49 (Ma ≃ 1.5 to Ma ≃ 2.2) the values of the scale of the turbulence $\ell_u$ and of the ratio $\ell_u/\$_T$ were calculated. For runs 33 and 49, however, the spectral density plots show very low mean values and low signal/noise ratios, and in these cases the results have not been tabulated. It is suspected that these two runs were affected by transient telemetry faults, and immediately after run 49, the transmission of data effectively ceased.

The values of $\ell_u$ obtained are plotted against time in Fig.7a and against Mach number in Fig.7b. The positions of runs 33 and 49 are indicated, but no values plotted. Similarly, positions are indicated, but no values plotted, for runs 33 and 49 in the plots of $\ell_u/\$_T$ against time (Fig.10) and against Mach number (Fig.11).

Values of all the environmental experimental data and derived quantities are presented in Table 3, and the vehicle trajectory data in Figs.3, 4 and 5.

3.2 To reinforce the conclusions derived from the analyses described above, the computing technique was modified to accept the pressure readings for five consecutive runs and use them as the data for one run.

The readings for runs 41 to 45 were used as the data for this collective run, which thus contained about 30800 discrete readings, separated by intervals $\Delta t$ = 15.55 microseconds. The mean velocity and mean altitude over the considered time span were used to derive Reynolds numbers and hence $\$_T$, and the autocorrelation function, unsmoothed and smoothed spectral density estimates, scale $\ell_u$, ratio $\ell_u/\$_T$ and root mean square pressure $\sigma_p$ were obtained as for the individual runs.

The unsmoothed spectral density estimates are shown in graphical form in Figs.9 and 12c, and the experimental environmental data are given in Table 4.

## 4 DISCUSSION OF RESULTS

The pressure-transducer used to measure the wall pressure was carefully mounted and inspected to ensure that the measuring diaphragm was flush with the exterior skin of the vehicle. The diaphragm diameter was 0.125 inch (3.175 mm) and the maximum projection above the surrounding surface was 0.003 inch (0.076 mm).

It was arbitrarily assumed that pressure-fluctuations having a wavelength of less than ten times the diameter of the transducer diaphragm would be attenuated to such an extent that they should be regarded as being unreliable, i.e. the highest usable frequency of pressure-fluctuation is given by

$$f = \frac{v}{10d}$$

where $v$ is the vehicle velocity and $d$ is the diaphragm diameter. For the range of vehicle velocities considered (i.e. 1692 ft/s to 2444 ft/s) and the transducer diaphragm diameter of 0.01042 ft, the value of $f$ lies in the range 16.24 kHz to 23.45 kHz, corresponding to values of $k = 51$ to $k = 73$. Since all the significant peaks in the plots of spectral density against $k$ occur well below $k = 40$, it is assumed that errors due to spatial resolution of the transducer may be ignored.

The data obtained from the piezo-electric accelerometer (c) showed that although the vibration local to the piezo-electric pressure transducer was of considerable amplitude in the frequency-range 100 to 300 Hz, the amplitude at higher frequencies was very much smaller, and would have negligible effect on the accuracy of the pressure data.

### 4.1 Comparison of experimentally determined spectra with a theoretical spectrum for homogeneous isotropic turbulence

In Ref.3, Taylor tabulated a theoretical $(\text{pressure})^2$ spectrum for very high Reynolds numbers, $(A = 0)$ in a non-dimensional form, and this was used as a basis for comparison with the experimental spectra.

Figs.12a, b and c show respectively the experimental spectra determined for run 35 (Ma = 2.060), run 45 (Ma = 2.188) and the collective run described in section 3.2 (mean Ma = 2.193). The strong resemblance between these three spectra confirms a reasonably consistent state of turbulence throughout this portion of the available data.

The theoretical spectrum has been superimposed on each of these three figures. The full line indicates the spectrum so placed as to have its maximum value at the same frequency as that of the maximum experimental value, and to represent the same value of $(\sigma_p)^2$ as the experimental data. The broken line indicates the spectrum placed so as to obtain a good fit with the experimental points over the high frequency range, whilst retaining the same value of $(\sigma_p)^2$.

Although the test vehicle was subject to longitudinal acceleration ranging, over the time span considered, from +22 g to -4 g, and could not therefore be regarded as being in a steady state and thus not directly comparable with the theoretical case, nevertheless a surprisingly good agreement was apparent. It may be noted that the collective run considered in Fig.12c was derived from data obtained during the time span centred on the 'zero g' point of the flight.

### 4.2 The scale of the turbulence, $\ell_u$

The values of $\ell_u$ given in Tables 3 and 4 are based on the values of $f_m$ indicated by the coincident peaks of the experimental points, and the full-line theoretical spectrum. If the values of $\ell_u$ were to be based on values of $f_m$ given by the peak of the broken-line spectrum, they would be greater by a factor of about 2.6. The values of $\ell_u$ obtained from the two values of $f_m$ for the three runs illustrated in Figs.12a, b and c are given below:

| Run | (Full-line) $\ell_{u(f)}$ | (Broken-line) $\ell_{u(b)}$ | $\frac{\ell_{u(b)}}{\ell_{u(f)}}$ |
|---|---|---|---|
| 35 | 0.09849 ft (0.03002 m) | 0.2616 ft (0.0797 m) | 2.66 |
| 45 | 0.08953 ft (0.02729 m) | 0.2266 ft (0.0691 m) | 2.53 |
| Collective | 0.08970 ft (0.02734 m) | 0.2266 ft (0.0691 m) | 2.53 |

The true value of $\ell_u$ associated with the pressure fluctuations due entirely to turbulence probably lies somewhere between these two extremes.

The values of $\ell_u$ presented throughout this paper are obtained from calculations based on the frequency of the experimental peak values. However, since the flight of the test vehicle was of such short duration, it is possible that the turbulence was not fully established and that the values of $\ell_u$ given are somewhat low.

The plot of $\ell_u$ against elapsed time Fig.7a indicates a mean value of about 0.09 ft (27.4 mm), the individual points showing very little deviation in level after 3.3 seconds. Fig.7b, a plot of $\ell_u$ against Mach number, again shows very little deviation from the mean above a value of Ma = 2. As the value of $\$_T$ is sensibly constant over the considered range of Mach number, the values of $\ell_u/\$_T$ shown in Figs.10 and 11 also exhibit this constancy.

The mean value of $\ell_u$ for the runs 41 → 45 is 0.09245 ft (28.2 mm) and $\ell_u$ for the collective run is 0.0897 ft (27.3 mm). The mean value of $\ell_u/\$_T$ for the runs 41 → 45 is 0.5275, and the value for the collective run is 0.5128. Therefore, the results obtained from the collective run may be assumed to be representative of those from the individual runs.

Taylor[4] cites an example of experimental results derived from an investigation of turbulence at subsonic velocities, which are compared below with the results from the present investigation.

| | Ma | $R_{\$_T}$ | $\$_T$ | $\$$ | $\ell_u$ | $\frac{\ell_u}{\$_T}$ | $\frac{\sigma_p}{q}$ |
|---|---|---|---|---|---|---|---|
| Taylor | 0.176 | $3.8 \times 10^4$ | 0.328 ft (100 mm) | 0.410 ft (125 mm) | 0.0975 ft (29.7 mm) | 0.297 | 0.0056 |
| Shark | 2.2 | $2 \times 10^6$ | 0.175 ft (53.3 mm) | 0.219 ft (66.8 mm) | 0.0897 ft (27.3 mm) | 0.513 | 0.0045 |

It is seen that although the Mach number has increased from the first case to the second by a factor of 12.5, and the turbulence Reynolds number by a factor of 53, the scale of the turbulence has remained almost the same, and the ratio $\ell_u/\$_T$ has increased only by a factor of 1.73.

## 5 CONCLUSIONS

Measurements of boundary-layer pressure fluctuations have been made for a short flight-time on a free-flight aerodynamic test vehicle at Mach numbers in the range 1.5 to 2.2, and local Reynolds numbers of 1.51 to $2.15 \times 10^8$.

Autocorrelation functions and $(\text{pressure})^2$ spectral densities have been determined and are presented in tabular and graphical form. Representative experimental spectra are compared with a theoretical spectrum for homogeneous isotropic turbulence and are found to be in reasonable agreement.

Values have been obtained of the scale of the turbulence, and the ratio of scale of the turbulence to turbulence boundary-layer thickness, and these are similarly presented. Over the considered range of Ma = 1.5 to Ma = 2.2, the scale of the turbulence was found to fluctuate between 0.47 and 0.76 of the turbulence boundary-layer thickness. At Ma = 2.2 the scale of the turbulence was about 0.51 of the turbulence boundary-layer thickness, and the root mean square pressure was 0.0045 of the free-stream dynamic pressure.

**Table.1 Page 1 of 8 pages**

DENSITY OF (PRESSURE SQUARED X 10000) SPECTRUM WITH RESPECT TO FREQUENCY FACTOR "k". (100 PRESSURE UNITS = 0.3116 LB/SQ INCH)

| k | RUN NUMBER 21 | 22 | 23 | 24 | 25 | 26 | 27 |
|---|---|---|---|---|---|---|---|
| 1 | 499 | 366 | 404 | 623 | 269 | 245 | 257 |
| 2 | 490 | 454 | 338 | 207 | 265 | 331 | 482 |
| 3 | 662 | 551 | 469 | 164 | 311 | 482 | 710 |
| 4 | 539 | 399 | 387 | 176 | 187 | 262 | 614 |
| 5 | 431 | 535 | 525 | 184 | 418 | 464 | 677 |
| 6 | 394 | 529 | 430 | 217 | 353 | 324 | 676 |
| 7 | 352 | 317 | 436 | 202 | 381 | 294 | 252 |
| 8 | 425 | 345 | 432 | 340 | 336 | 449 | 636 |
| 9 | 412 | 400 | 351 | 241 | 608 | 465 | 1027 |
| 10 | 222 | 430 | 411 | 399 | 414 | 497 | 650 |
| 11 | 457 | 362 | 352 | 423 | 573 | 580 | 547 |
| 12 | 415 | 411 | 418 | 243 | 480 | 510 | 957 |
| 13 | 263 | 386 | 296 | 298 | 498 | 586 | 622 |
| 14 | 319 | 212 | 236 | 228 | 634 | 465 | 915 |
| 15 | 258 | 252 | 270 | 183 | 400 | 445 | 539 |
| 16 | 312 | 387 | 332 | 234 | 488 | 524 | 429 |
| 17 | 215 | 252 | 269 | 223 | 416 | 680 | 763 |
| 18 | 175 | 286 | 299 | 164 | 432 | 569 | 503 |
| 19 | 265 | 301 | 336 | 303 | 352 | 473 | 493 |
| 20 | 191 | 157 | 304 | 247 | 343 | 432 | 376 |
| 21 | 195 | 157 | 206 | 141 | 207 | 337 | 368 |
| 22 | 200 | 115 | 247 | 188 | 181 | 288 | 350 |
| 23 | 164 | 178 | 137 | 153 | 232 | 165 | 410 |
| 24 | 139 | 148 | 200 | 161 | 282 | 286 | 291 |
| 25 | 137 | 112 | 147 | 110 | 210 | 276 | 185 |
| 26 | 141 | 118 | 232 | 90 | 213 | 180 | 290 |
| 27 | 116 | 130 | 178 | 81 | 196 | 244 | 253 |
| 28 | 142 | 91 | 177 | 63 | 249 | 265 | 176 |
| 29 | 84 | 122 | 179 | 150 | 166 | 284 | 256 |
| 30 | 106 | 131 | 122 | 120 | 215 | 202 | 279 |
| 31 | 82 | 113 | 97 | 144 | 204 | 228 | 187 |
| 32 | 107 | 157 | 136 | 101 | 174 | 146 | 281 |
| 33 | 59 | 94 | 98 | 87 | 200 | 144 | 203 |
| 34 | 100 | 86 | 120 | 96 | 196 | 166 | 117 |
| 35 | 94 | 81 | 129 | 103 | 110 | 207 | 210 |
| 36 | 77 | 89 | 134 | 85 | 147 | 128 | 197 |
| 37 | 87 | 100 | 84 | 76 | 135 | 219 | 178 |
| 38 | 53 | 95 | 80 | 55 | 140 | 190 | 191 |
| 39 | 59 | 63 | 104 | 71 | 165 | 125 | 158 |
| 40 | 74 | 76 | 115 | 73 | 144 | 129 | 170 |
| 41 | 51 | 72 | 58 | 84 | 81 | 119 | 127 |
| 42 | 55 | 98 | 87 | 80 | 99 | 187 | 133 |
| 43 | 45 | 69 | 85 | 38 | 99 | 167 | 136 |
| 44 | 59 | 46 | 75 | 64 | 135 | 112 | 156 |
| 45 | 50 | 46 | 51 | 69 | 89 | 96 | 144 |
| 46 | 57 | 57 | 74 | 43 | 83 | 168 | 134 |
| 47 | 33 | 45 | 68 | 43 | 88 | 133 | 165 |
| 48 | 49 | 52 | 56 | 45 | 83 | 72 | 134 |
| 49 | 39 | 53 | 55 | 54 | 61 | 85 | 147 |
| 50 | 51 | 37 | 58 | 41 | 74 | 98 | 99 |

**Table.1. Page 2 of 8 pages**

DENSITY OF (PRESSURE SQUARED X 10000) SPECTRUM WITH RESPECT TO FREQUENCY FACTOR "K". (100 PRESSURE UNITS = 0.3116 LB/SQ INCH)

| K | RUN NUMBER | | | | | | |
|---|---|---|---|---|---|---|---|
| | 21 | 22 | 23 | 24 | 25 | 26 | 27 |
| 51 | 38 | 44 | 41 | 41 | 75 | 87 | 99 |
| 52 | 39 | 31 | 46 | 37 | 59 | 67 | 86 |
| 53 | 40 | 33 | 52 | 33 | 54 | 72 | 110 |
| 54 | 29 | 25 | 34 | 42 | 62 | 56 | 64 |
| 55 | 22 | 29 | 57 | 28 | 67 | 52 | 109 |
| 56 | 32 | 51 | 50 | 28 | 72 | 86 | 63 |
| 57 | 19 | 23 | 29 | 48 | 43 | 40 | 72 |
| 58 | 32 | 27 | 45 | 36 | 62 | 80 | 74 |
| 59 | 21 | 22 | 44 | 35 | 52 | 73 | 71 |
| 60 | 28 | 33 | 46 | 20 | 67 | 53 | 78 |
| 61 | 15 | 30 | 31 | 23 | 59 | 51 | 95 |
| 62 | 25 | 25 | 28 | 21 | 50 | 48 | 71 |
| 63 | 24 | 38 | 34 | 28 | 45 | 43 | 69 |
| 64 | 14 | 17 | 28 | 18 | 40 | 31 | 58 |
| 65 | 18 | 14 | 25 | 23 | 49 | 38 | 51 |
| 66 | 17 | 13 | 28 | 31 | 41 | 32 | 46 |
| 67 | 14 | 14 | 19 | 20 | 51 | 51 | 76 |
| 68 | 17 | 19 | 25 | 24 | 31 | 31 | 73 |
| 69 | 17 | 20 | 18 | 23 | 36 | 38 | 51 |
| 70 | 15 | 19 | 20 | 20 | 51 | 34 | 59 |
| 71 | 17 | 19 | 22 | 27 | 35 | 27 | 42 |
| 72 | 14 | 16 | 26 | 16 | 28 | 40 | 56 |
| 73 | 8 | 15 | 18 | 16 | 26 | 37 | 41 |
| 74 | 15 | 13 | 21 | 16 | 28 | 19 | 46 |
| 75 | 13 | 12 | 18 | 21 | 25 | 27 | 63 |
| 76 | 13 | 9 | 23 | 13 | 26 | 25 | 38 |
| 77 | 10 | 13 | 19 | 16 | 39 | 34 | 46 |
| 78 | 13 | 18 | 19 | 17 | 40 | 28 | 60 |
| 79 | 12 | 11 | 13 | 20 | 30 | 23 | 44 |
| 80 | 14 | 16 | 17 | 18 | 33 | 25 | 30 |
| 81 | 8 | 9 | 10 | 18 | 23 | 21 | 36 |
| 82 | 14 | 20 | 21 | 21 | 39 | 30 | 38 |
| 83 | 8 | 5 | 9 | 17 | 27 | 20 | 52 |
| 84 | 86 | 69 | 104 | 63 | 107 | 119 | 117 |
| 85 | 19 | 21 | 27 | 27 | 50 | 56 | 91 |
| 86 | 12 | 9 | 25 | 23 | 47 | 74 | 101 |
| 87 | 17 | 32 | 45 | 37 | 64 | 44 | 37 |
| 88 | 30 | 21 | 33 | 21 | 34 | 23 | 34 |
| 89 | 22 | 16 | 18 | 15 | 29 | 20 | 32 |
| 90 | 15 | 13 | 17 | 8 | 27 | 19 | 37 |
| 91 | 15 | 17 | 17 | 16 | 26 | 27 | 27 |
| 92 | 10 | 9 | 19 | 11 | 28 | 18 | 23 |
| 93 | 17 | 14 | 12 | 13 | 16 | 19 | 29 |
| 94 | 12 | 8 | 8 | 16 | 19 | 21 | 23 |
| 95 | 8 | 5 | 10 | 15 | 22 | 20 | 27 |
| 96 | 9 | 6 | 7 | 7 | 17 | 14 | 24 |
| 97 | 7 | 8 | 9 | 10 | 24 | 12 | 28 |
| 98 | 7 | 8 | 9 | 8 | 27 | 15 | 33 |
| 99 | 6 | 10 | 11 | 11 | 28 | 20 | 22 |
| 100 | 5 | 10 | 12 | 7 | 30 | 15 | 26 |

Table.1. Page 3 of 8 pages

DENSITY OF (PRESSURE SQUARED X 10000) SPECTRUM WITH RESPECT TO FREQUENCY FACTOR "K". (100 PRESSURE UNITS = 0.3116 LB/SQ INCH)

| k | RUN NUMBER | | | | | | |
|---|---|---|---|---|---|---|---|
| | 28 | 29 | 30 | 31 | 32 | 33 | 34 |
| 1 | 397 | 101 | 905 | 957 | 1530 | 498 | 436 |
| 2 | 1158 | 1693 | 2579 | 3036 | 2984 | 481 | 1131 |
| 3 | 1104 | 1829 | 1562 | 4379 | 4914 | 640 | 1282 |
| 4 | 1603 | 1761 | 2080 | 3574 | 2651 | 533 | 1608 |
| 5 | 1063 | 1655 | 2665 | 3650 | 4159 | 438 | 1275 |
| 6 | 866 | 1942 | 2198 | 2209 | 2526 | 398 | 857 |
| 7 | 971 | 1156 | 1762 | 2877 | 2592 | 332 | 1396 |
| 8 | 887 | 725 | 1685 | 2880 | 2450 | 411 | 1149 |
| 9 | 970 | 1216 | 1636 | 1860 | 2059 | 406 | 1447 |
| 10 | 820 | 1164 | 1468 | 2141 | 3183 | 219 | 1431 |
| 11 | 1225 | 1267 | 1880 | 1997 | 2214 | 438 | 1730 |
| 12 | 1020 | 1748 | 3627 | 2353 | 3039 | 398 | 2953 |
| 13 | 1264 | 1611 | 4036 | 4051 | 2787 | 255 | 2602 |
| 14 | 700 | 2026 | 2042 | 3147 | 3739 | 302 | 2031 |
| 15 | 780 | 1020 | 1595 | 2386 | 2321 | 252 | 3005 |
| 16 | 596 | 1269 | 1379 | 2379 | 2637 | 311 | 1248 |
| 17 | 1035 | 1337 | 2166 | 3945 | 3878 | 227 | 4176 |
| 18 | 525 | 1039 | 1742 | 2148 | 4427 | 177 | 4351 |
| 19 | 569 | 716 | 1247 | 2009 | 5747 | 254 | 4124 |
| 20 | 541 | 535 | 645 | 2313 | 3993 | 175 | 5093 |
| 21 | 425 | 493 | 670 | 1060 | 2837 | 188 | 3471 |
| 22 | 391 | 527 | 623 | 842 | 1443 | 192 | 3716 |
| 23 | 259 | 334 | 523 | 778 | 1029 | 165 | 2531 |
| 24 | 343 | 483 | 516 | 733 | 982 | 138 | 1524 |
| 25 | 403 | 400 | 703 | 728 | 941 | 137 | 1102 |
| 26 | 295 | 539 | 630 | 459 | 678 | 139 | 1172 |
| 27 | 493 | 414 | 432 | 795 | 851 | 114 | 996 |
| 28 | 271 | 395 | 442 | 518 | 663 | 143 | 867 |
| 29 | 312 | 325 | 446 | 587 | 488 | 84 | 441 |
| 30 | 440 | 449 | 298 | 500 | 490 | 100 | 711 |
| 31 | 325 | 365 | 379 | 700 | 523 | 80 | 679 |
| 32 | 233 | 270 | 384 | 589 | 472 | 101 | 730 |
| 33 | 192 | 269 | 421 | 456 | 588 | 61 | 518 |
| 34 | 254 | 311 | 531 | 402 | 434 | 93 | 577 |
| 35 | 237 | 335 | 409 | 419 | 451 | 97 | 548 |
| 36 | 221 | 220 | 311 | 476 | 695 | 71 | 546 |
| 37 | 232 | 237 | 373 | 516 | 477 | 81 | 536 |
| 38 | 235 | 350 | 259 | 416 | 472 | 52 | 419 |
| 39 | 173 | 282 | 375 | 415 | 418 | 56 | 424 |
| 40 | 241 | 154 | 337 | 350 | 456 | 75 | 494 |
| 41 | 183 | 244 | 162 | 336 | 290 | 50 | 355 |
| 42 | 191 | 111 | 250 | 341 | 410 | 56 | 326 |
| 43 | 148 | 198 | 320 | 262 | 268 | 43 | 361 |
| 44 | 141 | 127 | 261 | 307 | 451 | 57 | 321 |
| 45 | 75 | 159 | 238 | 275 | 344 | 44 | 385 |
| 46 | 191 | 196 | 157 | 206 | 220 | 59 | 350 |
| 47 | 122 | 147 | 219 | 219 | 362 | 38 | 303 |
| 48 | 121 | 167 | 265 | 293 | 250 | 47 | 318 |
| 49 | 115 | 174 | 198 | 244 | 346 | 38 | 360 |
| 50 | 129 | 151 | 167 | 275 | 303 | 47 | 297 |

**Table 1. Page 4 of 8 pages**

DENSITY OF (PRESSURE SQUARED X 10000) SPECTRUM WITH RESPECT TO FREQUENCY FACTOR "k". (100 PRESSURE UNITS = 0.3116 LB/SQ INCH)

| k | RUN NUMBER | | | | | | |
|---|---|---|---|---|---|---|---|
| | 28 | 29 | 30 | 31 | 32 | 33 | 34 |
| 51 | 120 | 123 | 184 | 210 | 196 | 39 | 265 |
| 52 | 141 | 164 | 140 | 195 | 230 | 38 | 239 |
| 53 | 119 | 115 | 174 | 171 | 244 | 39 | 172 |
| 54 | 117 | 142 | 113 | 159 | 221 | 30 | 224 |
| 55 | 123 | 93 | 163 | 166 | 162 | 22 | 203 |
| 56 | 87 | 90 | 122 | 121 | 175 | 30 | 182 |
| 57 | 76 | 109 | 100 | 165 | 275 | 21 | 215 |
| 58 | 86 | 112 | 140 | 134 | 213 | 31 | 218 |
| 59 | 91 | 106 | 107 | 174 | 153 | 23 | 213 |
| 60 | 61 | 104 | 93 | 82 | 217 | 29 | 172 |
| 61 | 84 | 98 | 94 | 145 | 173 | 14 | 245 |
| 62 | 79 | 72 | 136 | 184 | 122 | 21 | 278 |
| 63 | 50 | 81 | 78 | 108 | 136 | 25 | 119 |
| 64 | 57 | 60 | 120 | 125 | 110 | 13 | 199 |
| 65 | 66 | 53 | 116 | 86 | 151 | 17 | 154 |
| 66 | 54 | 64 | 108 | 109 | 135 | 18 | 160 |
| 67 | 61 | 53 | 86 | 90 | 125 | 14 | 171 |
| 68 | 71 | 58 | 87 | 136 | 129 | 17 | 276 |
| 69 | 64 | 48 | 90 | 125 | 118 | 16 | 193 |
| 70 | 33 | 65 | 87 | 118 | 131 | 14 | 169 |
| 71 | 51 | 57 | 87 | 116 | 128 | 17 | 168 |
| 72 | 56 | 54 | 64 | 75 | 136 | 16 | 215 |
| 73 | 42 | 57 | 63 | 96 | 117 | 8 | 157 |
| 74 | 40 | 60 | 59 | 66 | 80 | 15 | 165 |
| 75 | 50 | 61 | 67 | 107 | 121 | 9 | 131 |
| 76 | 35 | 38 | 60 | 117 | 85 | 14 | 170 |
| 77 | 31 | 44 | 62 | 81 | 148 | 11 | 95 |
| 78 | 46 | 52 | 62 | 119 | 112 | 16 | 107 |
| 79 | 43 | 44 | 66 | 109 | 135 | 9 | 112 |
| 80 | 24 | 55 | 62 | 87 | 83 | 14 | 128 |
| 81 | 38 | 51 | 74 | 101 | 107 | 7 | 66 |
| 82 | 47 | 66 | 95 | 86 | 107 | 15 | 80 |
| 83 | 39 | 60 | 68 | 88 | 80 | 8 | 85 |
| 84 | 134 | 180 | 124 | 135 | 172 | 78 | 178 |
| 85 | 110 | 89 | 64 | 80 | 82 | 19 | 98 |
| 86 | 43 | 25 | 57 | 49 | 72 | 11 | 104 |
| 87 | 35 | 43 | 43 | 80 | 103 | 18 | 79 |
| 88 | 31 | 22 | 43 | 60 | 88 | 26 | 87 |
| 89 | 36 | 44 | 41 | 66 | 88 | 16 | 75 |
| 90 | 23 | 28 | 43 | 51 | 70 | 14 | 97 |
| 91 | 30 | 34 | 48 | 70 | 73 | 11 | 67 |
| 92 | 28 | 31 | 37 | 51 | 69 | 11 | 68 |
| 93 | 29 | 30 | 49 | 47 | 69 | 15 | 89 |
| 94 | 20 | 23 | 41 | 51 | 69 | 9 | 60 |
| 95 | 34 | 36 | 32 | 58 | 62 | 7 | 62 |
| 96 | 18 | 30 | 30 | 50 | 71 | 6 | 74 |
| 97 | 28 | 22 | 45 | 61 | 76 | 7 | 74 |
| 98 | 19 | 21 | 47 | 57 | 72 | 7 | 86 |
| 99 | 29 | 42 | 34 | 54 | 73 | 8 | 69 |
| 100 | 13 | 27 | 34 | 62 | 78 | 7 | 57 |

## Table 1. Page 5 of 8 pages

DENSITY OF (PRESSURE SQUARED X 10000) SPECTRUM WITH RESPECT TO FREQUENCY FACTOR "k". (100 PRESSURE UNITS = 0.3116 LB/SQ INCH)

| k | RUN NUMBER | | | | | | |
|---|---|---|---|---|---|---|---|
| | 35 | 36 | 37 | 38 | 39 | 40 | 41 |
| 1 | 660 | 825 | 680 | 907 | 864 | 1078 | 1103 |
| 2 | 944 | 819 | 770 | 1010 | 775 | 1643 | 988 |
| 3 | 1911 | 876 | 826 | 997 | 1022 | 1251 | 1649 |
| 4 | 1559 | 884 | 1011 | 985 | 999 | 1336 | 1334 |
| 5 | 1002 | 1579 | 895 | 748 | 983 | 1289 | 1104 |
| 6 | 1150 | 1225 | 897 | 922 | 1154 | 1258 | 1307 |
| 7 | 1345 | 1239 | 1003 | 900 | 1111 | 1615 | 1358 |
| 8 | 1606 | 1435 | 1459 | 1159 | 1141 | 941 | 916 |
| 9 | 1292 | 1448 | 1199 | 1565 | 1194 | 1200 | 1432 |
| 10 | 1792 | 1864 | 1654 | 1169 | 1090 | 991 | 1424 |
| 11 | 1383 | 2313 | 1924 | 1206 | 1211 | 1598 | 1172 |
| 12 | 2452 | 3188 | 2289 | 1353 | 1611 | 1304 | 1414 |
| 13 | 1833 | 1244 | 1923 | 2091 | 2294 | 1936 | 1614 |
| 14 | 1832 | 2154 | 1756 | 1684 | 1927 | 1855 | 1101 |
| 15 | 1324 | 1594 | 1568 | 1883 | 1433 | 1523 | 1320 |
| 16 | 1896 | 2375 | 2080 | 1847 | 1879 | 1361 | 987 |
| 17 | 3424 | 2230 | 2320 | 3054 | 2085 | 2360 | 2748 |
| 18 | 4458 | 4492 | 3578 | 2569 | 2852 | 2537 | 2012 |
| 19 | 5602 | 7948 | 3125 | 3860 | 3182 | 4125 | 3320 |
| 20 | 4344 | 4831 | 4231 | 4145 | 3211 | 4379 | 2931 |
| 21 | 4829 | 5198 | 3901 | 3905 | 3938 | 4021 | 3771 |
| 22 | 3659 | 2731 | 4252 | 3466 | 3818 | 3242 | 3992 |
| 23 | 3321 | 2671 | 3878 | 2847 | 2951 | 3252 | 1953 |
| 24 | 2026 | 2235 | 2466 | 1648 | 2880 | 1814 | 2083 |
| 25 | 1197 | 1695 | 1427 | 1661 | 1703 | 1929 | 2113 |
| 26 | 1067 | 1018 | 1503 | 1807 | 944 | 1162 | 1406 |
| 27 | 1104 | 1126 | 1390 | 1052 | 1358 | 1356 | 1051 |
| 28 | 939 | 755 | 784 | 844 | 853 | 699 | 1118 |
| 29 | 797 | 855 | 989 | 709 | 941 | 725 | 1075 |
| 30 | 620 | 882 | 664 | 879 | 666 | 800 | 901 |
| 31 | 803 | 829 | 873 | 840 | 911 | 716 | 1091 |
| 32 | 689 | 468 | 619 | 901 | 775 | 687 | 905 |
| 33 | 734 | 631 | 847 | 564 | 560 | 593 | 769 |
| 34 | 436 | 535 | 459 | 943 | 550 | 782 | 483 |
| 35 | 638 | 743 | 851 | 673 | 802 | 328 | 573 |
| 36 | 664 | 394 | 499 | 539 | 655 | 711 | 674 |
| 37 | 553 | 583 | 467 | 482 | 576 | 571 | 577 |
| 38 | 415 | 578 | 464 | 405 | 414 | 499 | 539 |
| 39 | 585 | 710 | 498 | 546 | 480 | 596 | 364 |
| 40 | 423 | 507 | 466 | 573 | 428 | 417 | 628 |
| 41 | 566 | 519 | 586 | 320 | 345 | 541 | 348 |
| 42 | 393 | 710 | 435 | 444 | 447 | 492 | 435 |
| 43 | 390 | 645 | 424 | 559 | 353 | 446 | 645 |
| 44 | 385 | 363 | 466 | 408 | 422 | 493 | 580 |
| 45 | 485 | 489 | 526 | 483 | 424 | 379 | 511 |
| 46 | 363 | 294 | 396 | 395 | 287 | 428 | 368 |
| 47 | 352 | 299 | 473 | 406 | 397 | 366 | 513 |
| 48 | 364 | 275 | 492 | 301 | 417 | 288 | 307 |
| 49 | 376 | 273 | 459 | 383 | 425 | 387 | 301 |
| 50 | 372 | 284 | 288 | 342 | 289 | 413 | 471 |

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DENSITY OF (PRESSURE SQUARED X 10000) SPECTRUM WITH RESPECT TO FREQUENCY FACTOR "K". (100 PRESSURE UNITS = 0.3116 LB/SQ INCH)

| K | RUN NUMBER | | | | | | |
|---|---|---|---|---|---|---|---|
| | 35 | 36 | 37 | 38 | 39 | 40 | 41 |
| 51 | 238 | 357 | 403 | 347 | 269 | 284 | 372 |
| 52 | 357 | 295 | 296 | 288 | 308 | 224 | 241 |
| 53 | 247 | 278 | 346 | 321 | 256 | 226 | 276 |
| 54 | 348 | 275 | 401 | 231 | 314 | 177 | 261 |
| 55 | 232 | 270 | 274 | 225 | 255 | 256 | 240 |
| 56 | 252 | 227 | 233 | 280 | 270 | 226 | 281 |
| 57 | 263 | 284 | 211 | 295 | 243 | 125 | 256 |
| 58 | 178 | 191 | 174 | 227 | 198 | 202 | 293 |
| 59 | 302 | 348 | 304 | 364 | 263 | 270 | 341 |
| 60 | 177 | 262 | 263 | 215 | 182 | 207 | 245 |
| 61 | 183 | 308 | 270 | 213 | 191 | 221 | 215 |
| 62 | 268 | 405 | 174 | 193 | 193 | 181 | 250 |
| 63 | 191 | 292 | 257 | 181 | 186 | 188 | 254 |
| 64 | 269 | 243 | 218 | 180 | 218 | 239 | 193 |
| 65 | 174 | 221 | 213 | 201 | 216 | 132 | 211 |
| 66 | 172 | 252 | 158 | 263 | 178 | 175 | 191 |
| 67 | 280 | 239 | 173 | 170 | 183 | 160 | 247 |
| 68 | 166 | 204 | 202 | 140 | 176 | 185 | 236 |
| 69 | 184 | 109 | 142 | 148 | 181 | 170 | 207 |
| 70 | 217 | 162 | 180 | 80 | 164 | 150 | 145 |
| 71 | 164 | 135 | 99 | 170 | 208 | 174 | 201 |
| 72 | 181 | 112 | 109 | 167 | 154 | 151 | 198 |
| 73 | 155 | 124 | 158 | 147 | 177 | 138 | 197 |
| 74 | 154 | 183 | 130 | 155 | 132 | 119 | 197 |
| 75 | 155 | 108 | 96 | 140 | 182 | 182 | 123 |
| 76 | 159 | 141 | 155 | 123 | 147 | 110 | 129 |
| 77 | 133 | 103 | 102 | 118 | 122 | 152 | 112 |
| 78 | 115 | 78 | 137 | 137 | 164 | 130 | 141 |
| 79 | 100 | 66 | 121 | 122 | 108 | 87 | 137 |
| 80 | 101 | 97 | 107 | 110 | 140 | 112 | 108 |
| 81 | 129 | 124 | 111 | 111 | 117 | 99 | 70 |
| 82 | 125 | 84 | 109 | 138 | 90 | 158 | 109 |
| 83 | 87 | 108 | 73 | 127 | 99 | 96 | 104 |
| 84 | 170 | 173 | 184 | 142 | 190 | 170 | 197 |
| 85 | 119 | 102 | 92 | 74 | 134 | 97 | 149 |
| 86 | 67 | 86 | 106 | 111 | 89 | 92 | 136 |
| 87 | 97 | 110 | 111 | 86 | 89 | 112 | 142 |
| 88 | 89 | 71 | 105 | 69 | 107 | 117 | 98 |
| 89 | 118 | 87 | 86 | 96 | 93 | 89 | 110 |
| 90 | 80 | 69 | 92 | 81 | 95 | 104 | 110 |
| 91 | 83 | 85 | 98 | 98 | 85 | 61 | 97 |
| 92 | 69 | 51 | 95 | 85 | 74 | 150 | 118 |
| 93 | 54 | 69 | 120 | 103 | 79 | 106 | 113 |
| 94 | 92 | 80 | 73 | 76 | 94 | 96 | 82 |
| 95 | 87 | 98 | 93 | 72 | 81 | 89 | 71 |
| 96 | 83 | 84 | 80 | 56 | 88 | 127 | 83 |
| 97 | 77 | 101 | 98 | 84 | 105 | 119 | 85 |
| 98 | 46 | 65 | 89 | 65 | 110 | 123 | 112 |
| 99 | 95 | 79 | 92 | 80 | 103 | 88 | 102 |
| 100 | 78 | 107 | 104 | 97 | 64 | 79 | 127 |

**Table.1. Page 7 of 8 pages**

DENSITY OF (PRESSURE SQUARED X 10000) SPECTRUM WITH RESPECT TO FREQUENCY FACTOR "K". (100 PRESSURE UNITS = 0.3116 LB/SQ INCH)

| k | RUN NUMBER | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 42 | 43 | 44 | 45 | 46 | 47 | 48 | 49 |
| 1 | 1457 | 1003 | 1019 | 935 | 4251 | 2266 | 41520 | 5252 |
| 2 | 1495 | 1180 | 1308 | 2115 | 1696 | 1647 | 7619 | 1921 |
| 3 | 1582 | 1887 | 1903 | 2018 | 1559 | 2393 | 1092 | 1828 |
| 4 | 1660 | 1154 | 1487 | 1319 | 1598 | 1151 | 1902 | 1613 |
| 5 | 1675 | 1194 | 1623 | 1571 | 1751 | 1751 | 1482 | 1365 |
| 6 | 1610 | 1745 | 1223 | 1608 | 1715 | 1622 | 2034 | 1375 |
| 7 | 1495 | 1322 | 1717 | 1434 | 1538 | 1322 | 1563 | 1319 |
| 8 | 1392 | 1206 | 1624 | 1635 | 1875 | 1669 | 1157 | 1548 |
| 9 | 1353 | 1898 | 1211 | 1340 | 1183 | 1617 | 1711 | 1066 |
| 10 | 1390 | 1570 | 1371 | 1690 | 1639 | 1558 | 1500 | 1851 |
| 11 | 1472 | 1491 | 1407 | 1354 | 1404 | 2166 | 1424 | 1852 |
| 12 | 1552 | 1577 | 2621 | 1401 | 1884 | 1737 | 2463 | 1705 |
| 13 | 1602 | 1543 | 1755 | 1680 | 1485 | 1395 | 1394 | 1128 |
| 14 | 1640 | 1301 | 1408 | 1940 | 1668 | 1511 | 1464 | 913 |
| 15 | 1724 | 1566 | 1599 | 948 | 977 | 1594 | 1203 | 1166 |
| 16 | 1918 | 1465 | 1353 | 1487 | 1460 | 1730 | 955 | 1175 |
| 17 | 2242 | 2634 | 1762 | 2193 | 1776 | 2355 | 1489 | 1212 |
| 18 | 2652 | 2768 | 2254 | 2338 | 1882 | 2438 | 2033 | 1216 |
| 19 | 3041 | 2480 | 3266 | 1579 | 2966 | 1967 | 1821 | 1487 |
| 20 | 3284 | 2577 | 3479 | 2847 | 3294 | 3443 | 1939 | 1214 |
| 21 | 3289 | 3653 | 4188 | 2884 | 3930 | 2845 | 3104 | 597 |
| 22 | 3043 | 3342 | 3693 | 3799 | 3268 | 2646 | 2272 | 837 |
| 23 | 2610 | 1936 | 2262 | 1938 | 2194 | 1584 | 1202 | 1062 |
| 24 | 2108 | 2416 | 2111 | 1899 | 1174 | 1442 | 1360 | 891 |
| 25 | 1652 | 1528 | 1626 | 1610 | 1431 | 1345 | 1237 | 1145 |
| 26 | 1319 | 1415 | 1164 | 1152 | 1333 | 1211 | 1026 | 984 |
| 27 | 1122 | 1389 | 917 | 997 | 1021 | 801 | 1172 | 608 |
| 28 | 1029 | 883 | 1036 | 812 | 738 | 690 | 480 | 799 |
| 29 | 983 | 775 | 662 | 918 | 712 | 710 | 601 | 921 |
| 30 | 938 | 634 | 857 | 708 | 604 | 815 | 516 | 722 |
| 31 | 874 | 713 | 530 | 722 | 607 | 853 | 788 | 889 |
| 32 | 796 | 1002 | 624 | 444 | 760 | 534 | 436 | 989 |
| 33 | 722 | 589 | 619 | 536 | 540 | 713 | 568 | 504 |
| 34 | 670 | 689 | 668 | 290 | 605 | 673 | 565 | 1110 |
| 35 | 649 | 478 | 720 | 711 | 642 | 577 | 613 | 616 |
| 36 | 652 | 557 | 639 | 740 | 367 | 508 | 545 | 799 |
| 37 | 667 | 559 | 424 | 643 | 443 | 676 | 554 | 589 |
| 38 | 679 | 649 | 453 | 710 | 406 | 619 | 710 | 713 |
| 39 | 675 | 646 | 444 | 495 | 401 | 513 | 559 | 693 |
| 40 | 649 | 620 | 519 | 415 | 513 | 664 | 555 | 599 |
| 41 | 603 | 424 | 486 | 466 | 710 | 444 | 633 | 690 |
| 42 | 546 | 496 | 343 | 504 | 333 | 443 | 505 | 938 |
| 43 | 494 | 512 | 535 | 598 | 385 | 528 | 662 | 586 |
| 44 | 459 | 449 | 633 | 538 | 594 | 684 | 604 | 676 |
| 45 | 449 | 491 | 534 | 288 | 409 | 695 | 549 | 1063 |
| 46 | 459 | 453 | 364 | 441 | 454 | 514 | 458 | 537 |
| 47 | 479 | 400 | 665 | 359 | 556 | 734 | 441 | 745 |
| 48 | 492 | 490 | 515 | 489 | 372 | 503 | 504 | 752 |
| 49 | 492 | 379 | 458 | 474 | 389 | 407 | 658 | 634 |
| 50 | 479 | 512 | 450 | 541 | 504 | 620 | 421 | 630 |

**Table.1. Page 8 of 8 pages**

DENSITY OF (PRESSURE SQUARED X 10000) SPECTRUM WITH RESPECT TO FREQUENCY FACTOR "k". (100 PRESSURE UNITS = 0.3116 LB/SQ INCH)

| k | RUN NUMBER | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 42 | 43 | 44 | 45 | 46 | 47 | 48 | 49 |
| 51 | 464 | 410 | 485 | 774 | 685 | 641 | 590 | 671 |
| 52 | 459 | 539 | 513 | 563 | 346 | 459 | 570 | 880 |
| 53 | 466 | 350 | 451 | 423 | 450 | 719 | 628 | 619 |
| 54 | 477 | 410 | 463 | 511 | 568 | 774 | 583 | 651 |
| 55 | 479 | 408 | 464 | 556 | 745 | 863 | 548 | 806 |
| 56 | 460 | 254 | 417 | 437 | 403 | 711 | 601 | 655 |
| 57 | 422 | 339 | 551 | 559 | 519 | 398 | 541 | 556 |
| 58 | 376 | 323 | 333 | 360 | 558 | 613 | 508 | 705 |
| 59 | 345 | 298 | 381 | 472 | 430 | 551 | 413 | 563 |
| 60 | 340 | 292 | 290 | 289 | 326 | 504 | 352 | 586 |
| 61 | 362 | 242 | 224 | 282 | 346 | 600 | 447 | 580 |
| 62 | 393 | 254 | 235 | 338 | 272 | 555 | 277 | 493 |
| 63 | 412 | 264 | 273 | 334 | 282 | 421 | 313 | 934 |
| 64 | 404 | 271 | 282 | 233 | 258 | 458 | 315 | 536 |
| 65 | 371 | 275 | 217 | 191 | 204 | 327 | 347 | 483 |
| 66 | 328 | 279 | 155 | 176 | 212 | 329 | 324 | 510 |
| 67 | 294 | 174 | 198 | 196 | 233 | 341 | 250 | 348 |
| 68 | 281 | 228 | 176 | 193 | 275 | 359 | 316 | 364 |
| 69 | 287 | 223 | 184 | 155 | 148 | 257 | 231 | 630 |
| 70 | 298 | 134 | 165 | 203 | 183 | 372 | 286 | 420 |
| 71 | 299 | 124 | 203 | 173 | 168 | 285 | 291 | 407 |
| 72 | 285 | 139 | 163 | 129 | 174 | 310 | 217 | 414 |
| 73 | 263 | 164 | 214 | 148 | 207 | 333 | 317 | 574 |
| 74 | 247 | 142 | 196 | 121 | 138 | 295 | 244 | 539 |
| 75 | 245 | 144 | 111 | 131 | 158 | 351 | 166 | 629 |
| 76 | 258 | 106 | 83 | 115 | 175 | 243 | 132 | 711 |
| 77 | 275 | 139 | 153 | 136 | 136 | 299 | 281 | 439 |
| 78 | 283 | 151 | 173 | 129 | 111 | 264 | 380 | 523 |
| 79 | 277 | 150 | 133 | 129 | 108 | 247 | 241 | 455 |
| 80 | 264 | 188 | 83 | 96 | 121 | 397 | 265 | 463 |
| 81 | 255 | 117 | 170 | 116 | 135 | 288 | 297 | 390 |
| 82 | 262 | 119 | 207 | 120 | 153 | 259 | 131 | 567 |
| 83 | 285 | 168 | 81 | 101 | 97 | 239 | 291 | 455 |
| 84 | 310 | 206 | 248 | 203 | 165 | 293 | 305 | 471 |
| 85 | 322 | 143 | 122 | 106 | 120 | 226 | 227 | 428 |
| 86 | 311 | 130 | 93 | 80 | 110 | 260 | 180 | 422 |
| 87 | 282 | 129 | 101 | 99 | 111 | 199 | 292 | 493 |
| 88 | 249 | 145 | 116 | 73 | 123 | 263 | 231 | 467 |
| 89 | 230 | 126 | 119 | 121 | 86 | 246 | 244 | 270 |
| 90 | 233 | 116 | 150 | 86 | 72 | 247 | 242 | 622 |
| 91 | 252 | 123 | 110 | 120 | 93 | 204 | 293 | 484 |
| 92 | 270 | 80 | 162 | 99 | 105 | 245 | 247 | 452 |
| 93 | 274 | 113 | 112 | 94 | 112 | 261 | 262 | 403 |
| 94 | 259 | 85 | 75 | 73 | 110 | 351 | 297 | 607 |
| 95 | 235 | 103 | 115 | 89 | 98 | 215 | 278 | 458 |
| 96 | 217 | 111 | 143 | 79 | 110 | 169 | 221 | 327 |
| 97 | 215 | 129 | 67 | 116 | 107 | 312 | 180 | 344 |
| 98 | 229 | 105 | 109 | 86 | 91 | 261 | 231 | 468 |
| 99 | 247 | 106 | 92 | 110 | 105 | 271 | 268 | 352 |
| 100 | 255 | 79 | 111 | 131 | 148 | 293 | 149 | 488 |

**Table.2**
**Frequency and corresponding frequency factor 'k'.**

| k | FREQUENCY (Hz) | k | FREQUENCY (Hz) | k | FREQUENCY (Hz) | k | FREQUENCY (Hz) |
|---|---|---|---|---|---|---|---|
| 1 | 0.00 | 26 | 8119.77 | 51 | 16239.55 | 76 | 24359.32 |
| 2 | 324.79 | 27 | 8444.57 | 52 | 16564.34 | 77 | 24684.12 |
| 3 | 649.58 | 28 | 8769.36 | 53 | 16889.13 | 78 | 25008.91 |
| 4 | 974.37 | 29 | 9094.15 | 54 | 17213.92 | 79 | 25333.70 |
| 5 | 1299.16 | 30 | 9418.94 | 55 | 17538.71 | 80 | 25658.49 |
| 6 | 1623.95 | 31 | 9743.73 | 56 | 17863.50 | 81 | 25983.28 |
| 7 | 1948.75 | 32 | 10068.52 | 57 | 18188.30 | 82 | 26308.07 |
| 8 | 2273.54 | 33 | 10393.31 | 58 | 18513.09 | 83 | 26632.86 |
| 9 | 2598.33 | 34 | 10718.10 | 59 | 18837.88 | 84 | 26957.65 |
| 10 | 2923.12 | 35 | 11042.89 | 60 | 19162.67 | 85 | 27282.44 |
| 11 | 3247.91 | 36 | 11367.68 | 61 | 19487.46 | 86 | 27607.23 |
| 12 | 3572.70 | 37 | 11692.48 | 62 | 19812.25 | 87 | 27932.03 |
| 13 | 3897.49 | 38 | 12017.27 | 63 | 20137.04 | 88 | 28256.82 |
| 14 | 4222.28 | 39 | 12342.06 | 64 | 20461.83 | 89 | 28581.61 |
| 15 | 4547.07 | 40 | 12666.85 | 65 | 20786.62 | 90 | 28906.40 |
| 16 | 4871.86 | 41 | 12991.64 | 66 | 21111.41 | 91 | 29231.19 |
| 17 | 5196.66 | 42 | 13316.43 | 67 | 21436.21 | 92 | 29555.98 |
| 18 | 5521.45 | 43 | 13641.22 | 68 | 21761.00 | 93 | 29880.77 |
| 19 | 5846.24 | 44 | 13966.01 | 69 | 22085.79 | 94 | 30205.56 |
| 20 | 6171.03 | 45 | 14290.80 | 70 | 22410.58 | 95 | 30530.35 |
| 21 | 6495.82 | 46 | 14615.59 | 71 | 22735.37 | 96 | 30855.14 |
| 22 | 6820.61 | 47 | 14940.39 | 72 | 23060.16 | 97 | 31179.94 |
| 23 | 7145.40 | 48 | 15265.18 | 73 | 23384.95 | 98 | 31504.73 |
| 24 | 7470.19 | 49 | 15589.97 | 74 | 23709.74 | 99 | 31829.52 |
| 25 | 7794.98 | 50 | 15914.76 | 75 | 24034.53 | 100 | 32154.31 |

**Table 3**

| RUN NO. | VELOCITY (ft/s) | HEIGHT (ft) | MACH NO. | $R_X$ $(X10^{-6})$ | $R_{\delta_T}$ $(X10^{-6})$ |
|---|---|---|---|---|---|
| 25 | 1692 | 470 | 1.5168 | 151.478 | 1.934 |
| 26 | 1762 | 504 | 1.5797 | 157.613 | 2.005 |
| 27 | 1830 | 538 | 1.6409 | 163.559 | 2.074 |
| 28 | 1899 | 572 | 1.7030 | 169.584 | 2.143 |
| 29 | 1965 | 606 | 1.7624 | 175.331 | 2.209 |
| 30 | 2030 | 640 | 1.8209 | 180.980 | 2.274 |
| 31 | 2091 | 682 | 1.8759 | 186.226 | 2.334 |
| 32 | 2149 | 726 | 1.9282 | 191.185 | 2.390 |
| 33 | 2202 | 766 | 1.9761 | 195.709 | 2.442 |
| 34 | 2241 | 800 | 2.0113 | 199.010 | 2.479 |
| 35 | 2295 | 850 | 2.0601 | 203.556 | 2.531 |
| 36 | 2333 | 868 | 2.0944 | 206.836 | 2.568 |
| 37 | 2365 | 944 | 2.1237 | 209.284 | 2.595 |
| 38 | 2392 | 976 | 2.1482 | 211.509 | 2.620 |
| 39 | 2413 | 1018 | 2.1674 | 213.148 | 2.639 |
| 40 | 2429 | 1060 | 2.1821 | 214.342 | 2.652 |
| 41 | 2439 | 1104 | 2.1914 | 214.995 | 2.660 |
| 42 | 2444 | 1148 | 2.1962 | 215.206 | 2.662 |
| 43 | 2444 | 1192 | 2.1966 | 214.976 | 2.659 |
| 44 | 2440 | 1236 | 2.1933 | 214.396 | 2.653 |
| 45 | 2434 | 1280 | 2.1883 | 213.642 | 2.644 |
| 46 | 2426 | 1324 | 2.1814 | 212.713 | 2.634 |
| 47 | 2418 | 1368 | 2.1746 | 211.787 | 2.623 |
| 48 | 2409 | 1412 | 2.1668 | 210.775 | 2.612 |
| 49 | 2397 | 1456 | 2.1564 | 209.503 | 2.598 |

| $\delta_T$ (ft) | $k_m$ | S.D.$_{MAX}$ | SCALE $L_u$ (ft) | SCALE/$\delta_T$ | R.M.S. PRESSURE (lbf/in$^2$) | RUN NO. |
|---|---|---|---|---|---|---|
| 0.181 | 14 | 0.06335 | 0.10054 | 0.5559 | 0.0964 | 25 |
| 0.180 | 17 | 0.06800 | 0.08506 | 0.4720 | 0.1015 | 26 |
| 0.180 | 14 | 0.09150 | 0.10873 | 0.6056 | 0.1148 | 27 |
| 0.179 | 13 | 0.12635 | 0.12223 | 0.6825 | 0.1332 | 28 |
| 0.178 | 14 | 0.20259 | 0.11676 | 0.6541 | 0.1544 | 29 |
| 0.178 | 13 | 0.40361 | 0.13067 | 0.7342 | 0.1842 | 30 |
| 0.178 | 13 | 0.40512 | 0.13459 | 0.7578 | 0.2152 | 31 |
| 0.177 | 19 | 0.57465 | 0.09222 | 0.5207 | 0.2355 | 32 |
| 0.177 | * | * | * | * | 0.0835 | 33 |
| 0.176 | 20 | 0.50926 | 0.09111 | 0.5163 | 0.2184 | 34 |
| 0.176 | 19 | 0.56015 | 0.09849 | 0.5592 | 0.2232 | 35 |
| 0.176 | 19 | 0.79481 | 0.10012 | 0.5693 | 0.2269 | 36 |
| 0.176 | 22 | 0.42521 | 0.08699 | 0.4952 | 0.2171 | 37 |
| 0.175 | 20 | 0.41451 | 0.09725 | 0.5541 | 0.2112 | 38 |
| 0.175 | 21 | 0.39385 | 0.09319 | 0.5314 | 0.2094 | 39 |
| 0.175 | 20 | 0.43791 | 0.09875 | 0.5634 | 0.2126 | 40 |
| 0.175 | 22 | 0.39923 | 0.08971 | 0.5119 | 0.2100 | 41 |
| 0.175 | 21 | 0.32889 | 0.09439 | 0.5387 | 0.2261 | 42 |
| 0.175 | 21 | 0.36527 | 0.09439 | 0.5386 | 0.2130 | 43 |
| 0.175 | 21 | 0.41882 | 0.09424 | 0.5376 | 0.2167 | 44 |
| 0.175 | 22 | 0.37992 | 0.08953 | 0.5106 | 0.2111 | 45 |
| 0.175 | 21 | 0.39302 | 0.09370 | 0.5342 | 0.2146 | 46 |
| 0.175 | 20 | 0.34427 | 0.09830 | 0.5602 | 0.2321 | 47 |
| 0.176 | 21 | 0.31045 | 0.09303 | 0.5307 | 0.2475 | 48 |
| 0.176 | * | * | * | * | 0.2229 | 49 |

* REFER TO SECTION 3.1

**Table. 4**
**Environmental data and derived quantities for collective run.**

| | IMPERIAL UNITS | S.I. UNITS |
|---|---|---|
| MEAN VELOCITY | 2440 ft/s | 743.7 m/s |
| MEAN HEIGHT | 1192 ft | 363.3 m |
| MEAN MACH NUMBER | 2.193 | |
| $R_X$ $(X10^{-6})$ | 214.64 | |
| $R_{\$_T}$ $(X10^{-6})$ | 2.656 | |
| $\$_T$ | 0.175 ft | 0.053 m |
| $k_m$ | 22 | |
| $S.D._{MAX}$ | 0.3562 | |
| SCALE | 0.0897 ft | 0.027 m |
| SCALE/$\$_T$ | 0.5128 | |
| R.M.S. PRESSURE | 0.2153 $lbf/in^2$ | 1.4844 $kN/m^2$ |

## SYMBOLS

| | |
|---|---|
| A | non-dimensional viscosity function |
| LU | $\ell_u/a$ |
| Ma | Mach number |
| M | number of correlated intervals used |
| N | number of intervals in one run |
| $R_{\$}$ | boundary-layer Reynolds number |
| $R_{\$_T}$ | turbulence Reynolds number |
| $R_x$ | local Reynolds number at distance $x$ from the effective start of turbulence |
| $R_\tau$ | autocorrelation function for interval $\tau$ |
| U | stream velocity relative to measuring station |
| $V_k$, $SD_k$ | unsmoothed spectral density estimate at frequency $f_k$ |
| $SD_{max}$ | maximum value of unsmoothed spectral density estimate for one run |
| $W_k$ | hanning-smoothed spectral density estimate at frequency $f_k$ |
| X | $\omega a$ |
| $Z_k$ | hamming-smoothed spectral density estimate at frequency $f_k$ |
| a | a length to make wave numbers non-dimensional |
| $f_k$ | frequency corresponding to frequency factor $k$ (see Table 2) |
| $f_m$ | frequency at which the maximum spectral density occurs |
| k | integer included between 1 and $(M + 1)$; the frequency factor corresponding to frequency $f_k$ |
| $k_m$ | frequency factor corresponding to $f_m$ |
| $\ell_u$ | the scale of the turbulence |
| $\Delta_t$ | time interval separating each discrete value $y_t$ from the next |
| $y_t$ | recorded discrete pressure value at time $t$, referred to the mean value for that run |
| $\$$ | total boundary-layer thickness |
| $\$_T$ | turbulence thickness |

SYMBOLS (Contd)

| | |
|---|---|
| $\tau$ | integer included between 1 and (M + 1) |
| $\omega$ | wave number = $2\pi$/wavelength |
| $\sigma_p$ | root mean square pressure |
| q | free stream dynamic pressure |

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|---|---|---|
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| 5 | D.B. Spalding | A new analytical expression for the drag of a flat plate valid for both the turbulent and laminar regimes.<br>Int. J. of heat and mass transfer, Vol.5 (1962) |

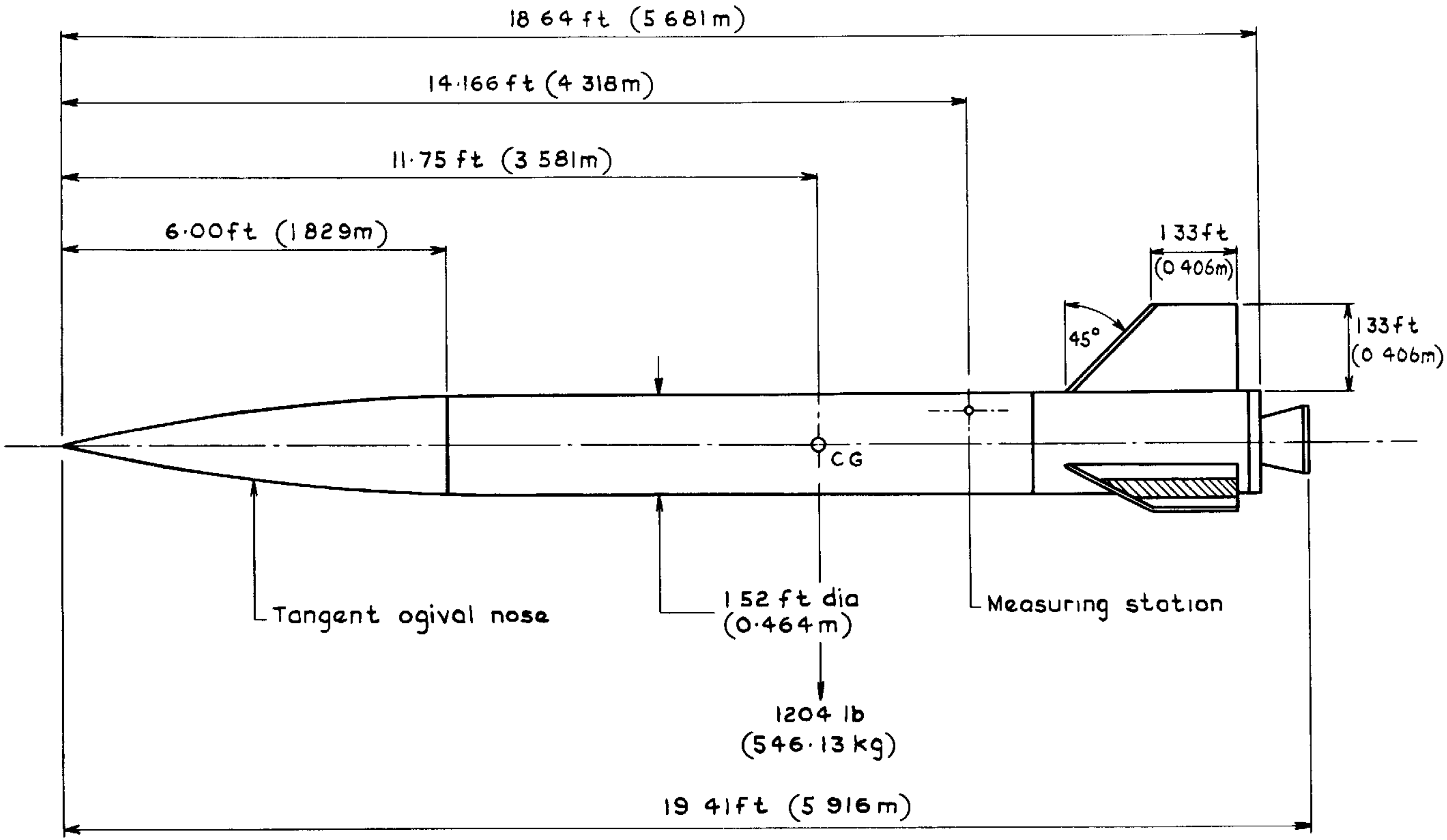


Fig. 1a General arrangement of 'Shark 1'

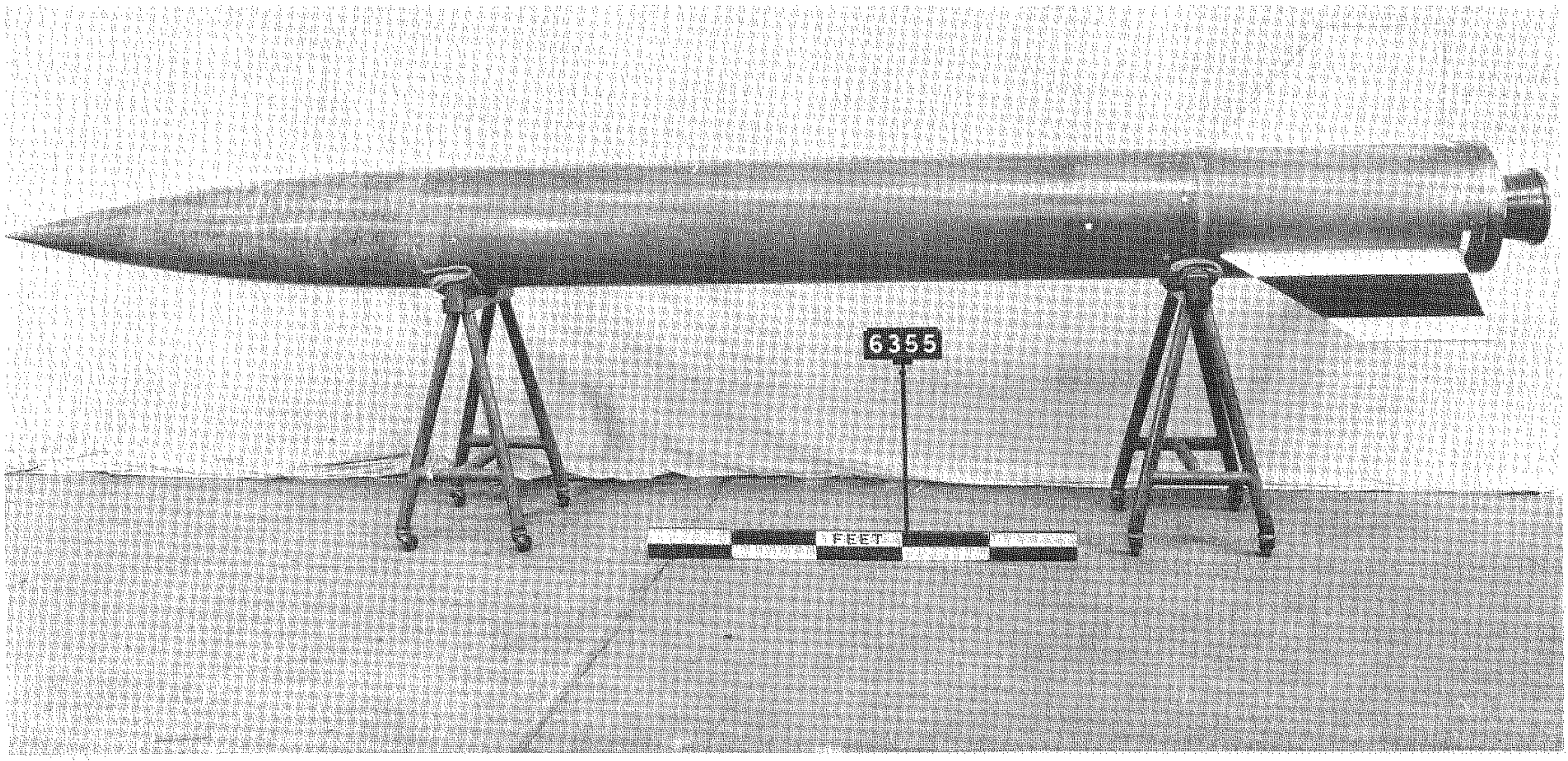


Fig1(b) Side view photograph of 'Shark 1'

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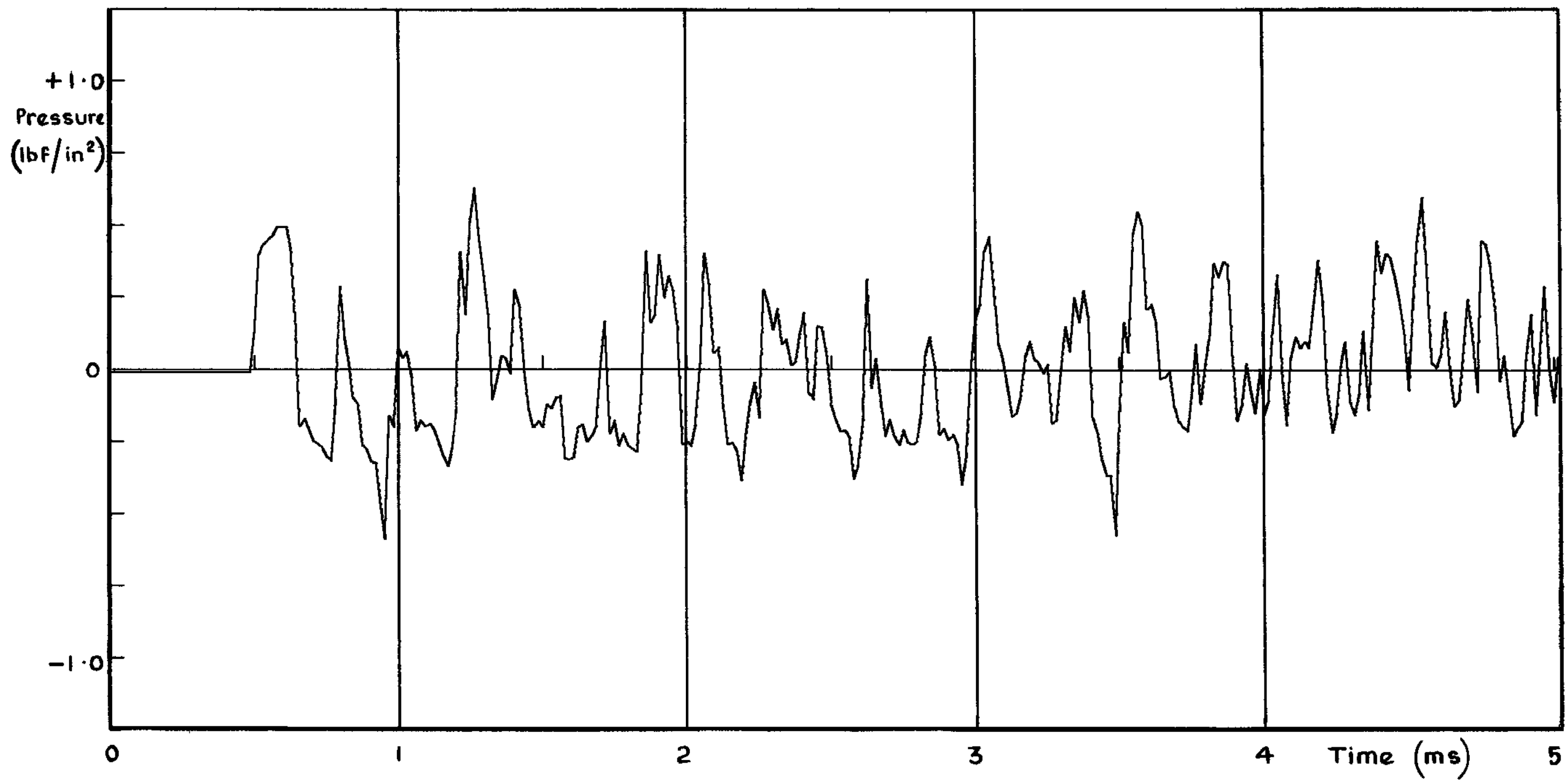


Fig 2a Plot of pressure against time for the first 5 milliseconds of run 32

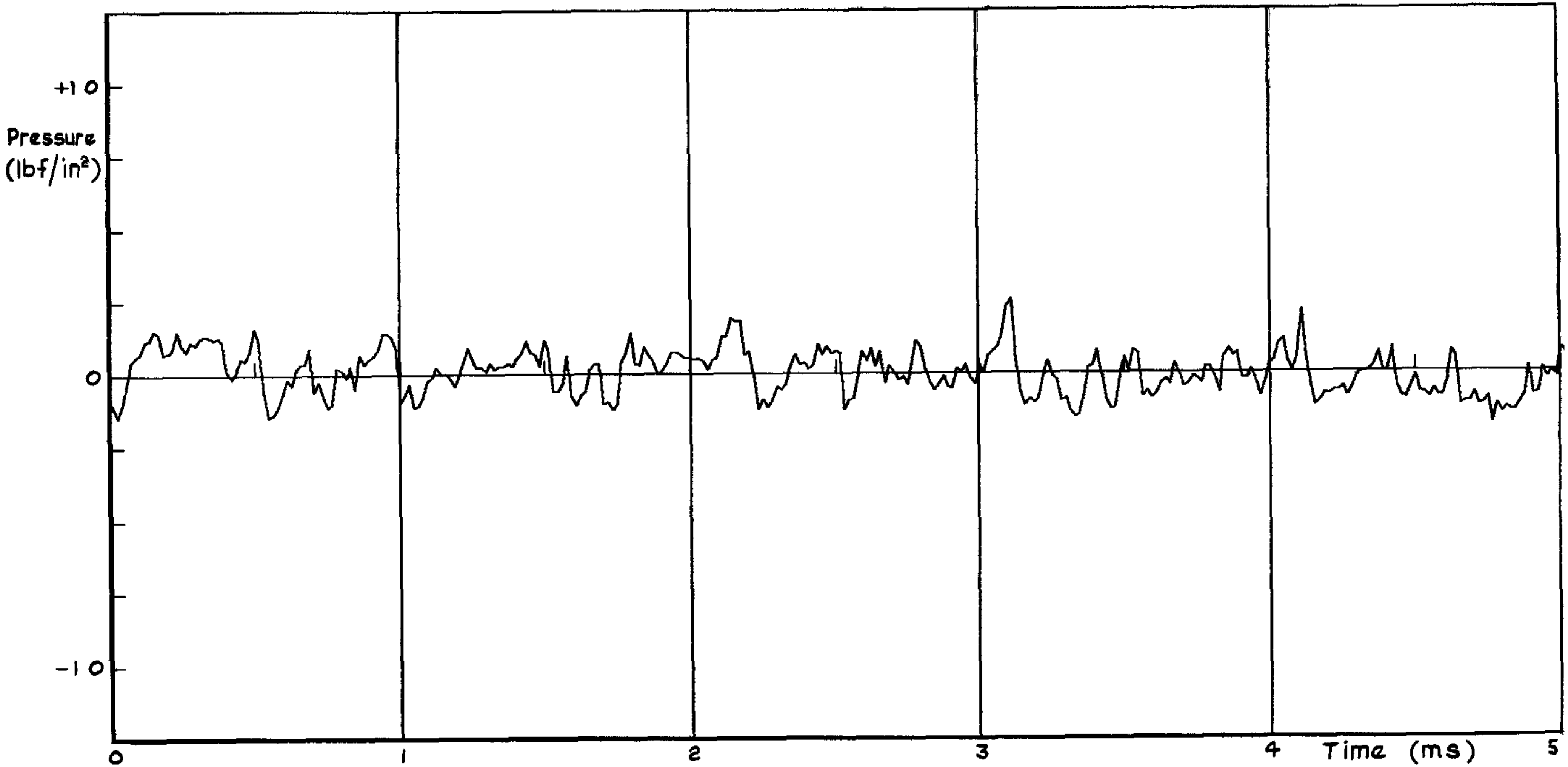


Fig.2b Plot of pressure against time for the first 5 milliseconds of run 33

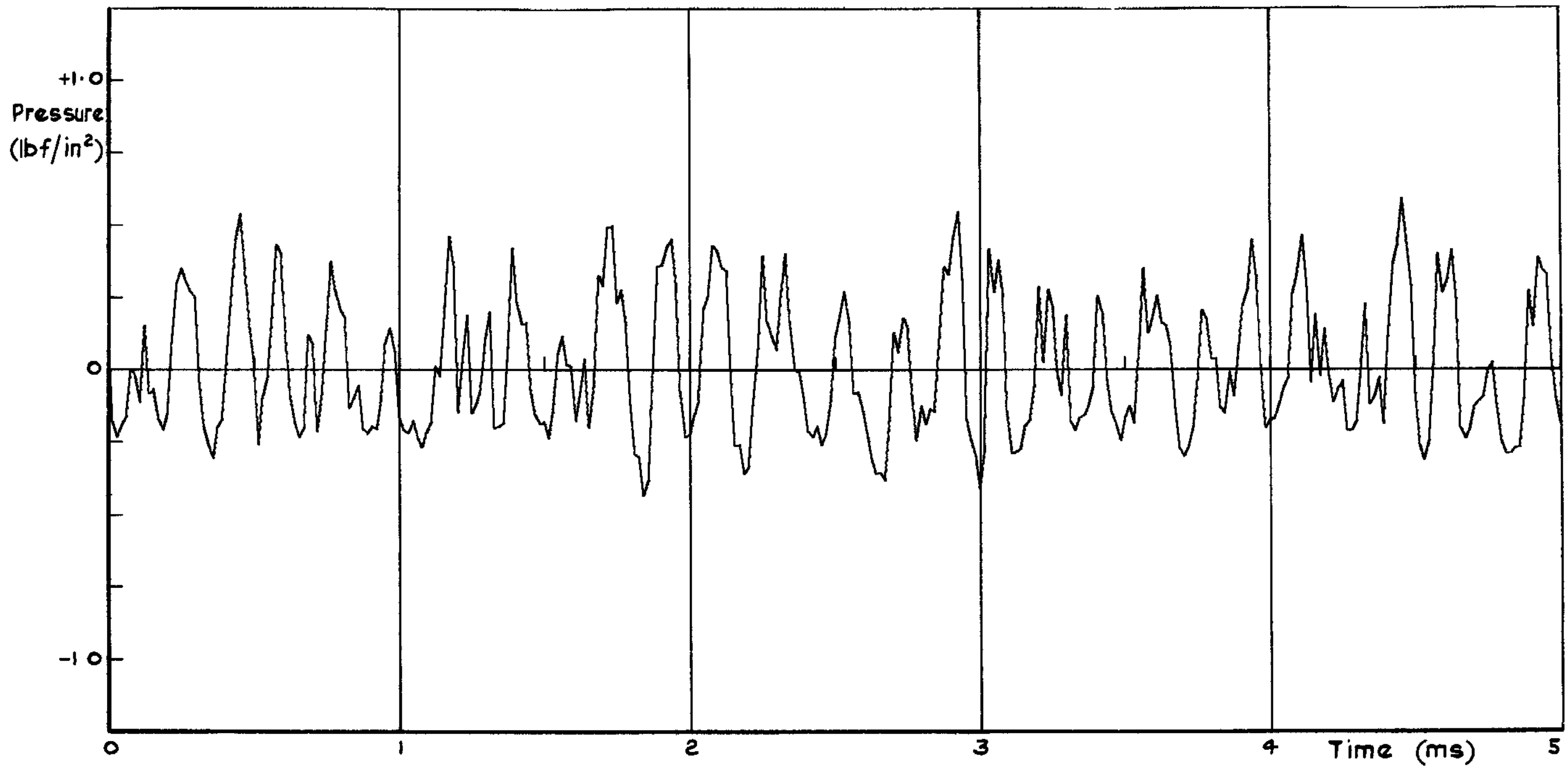


Fig. 2c Plot of pressure against time for the first 5 milliseconds of run 34

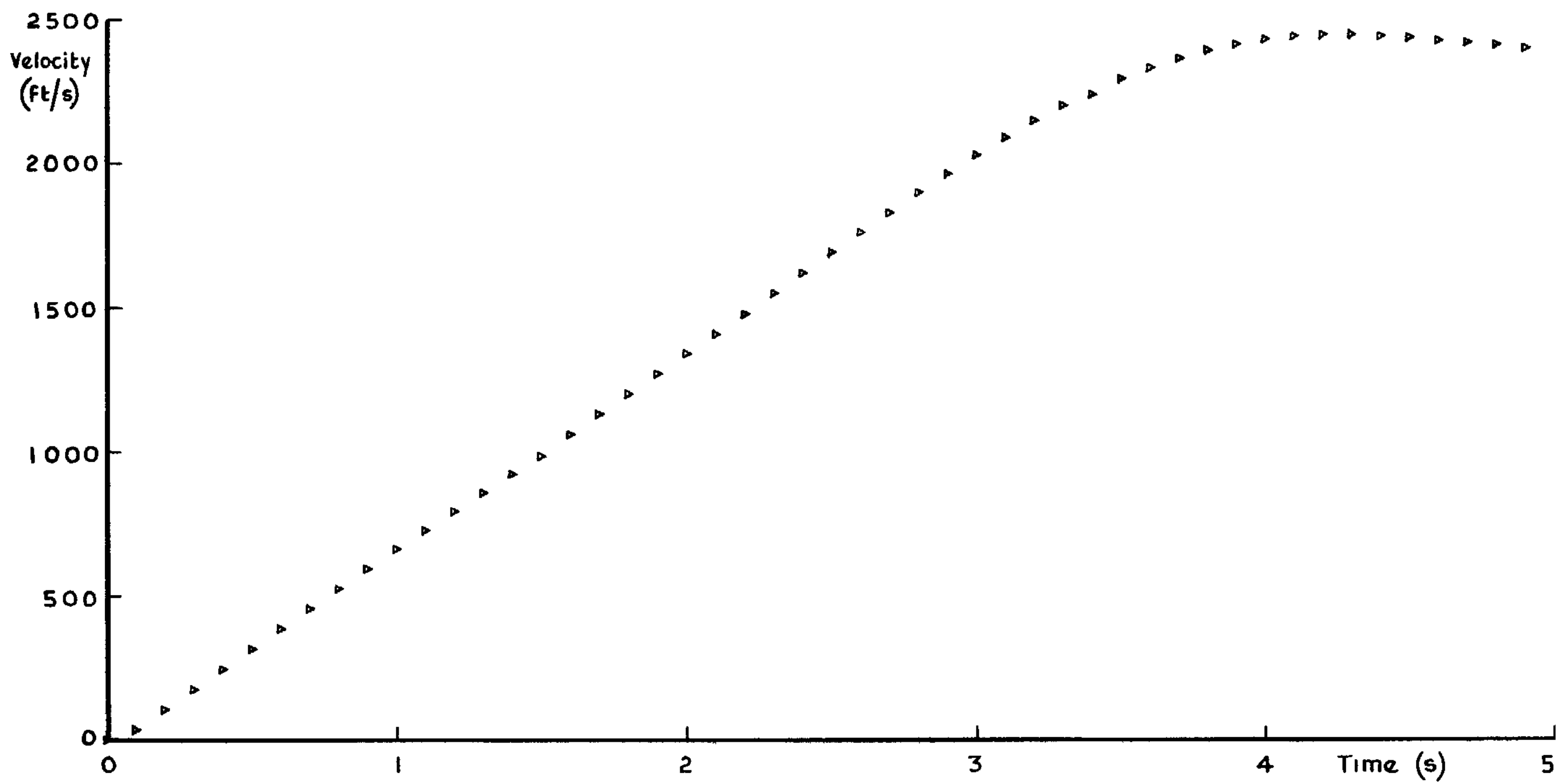


Fig. 3 Plot of vehicle velocity/elapsed time

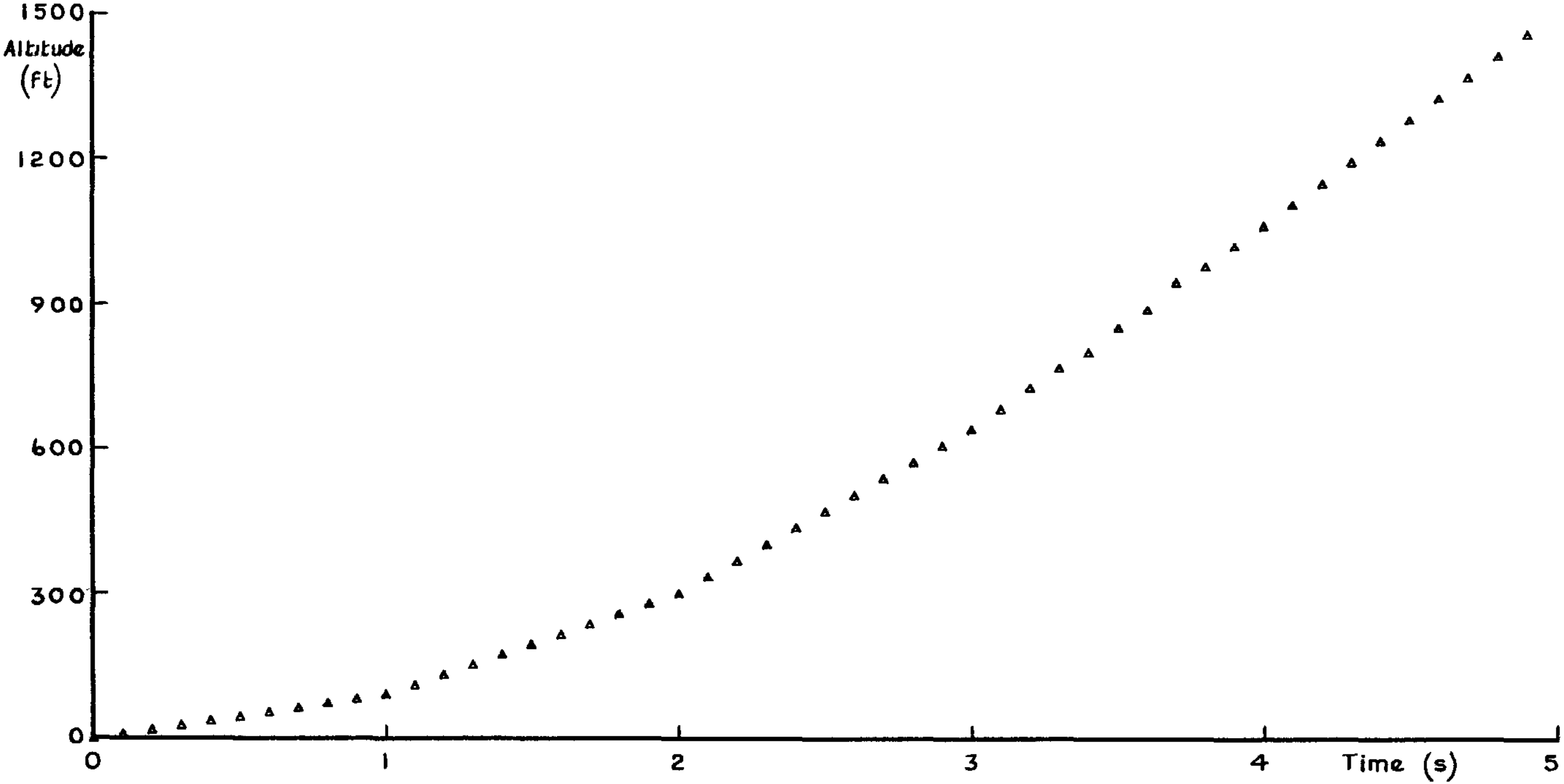


Fig. 4 Vehicle altitude/elapsed time

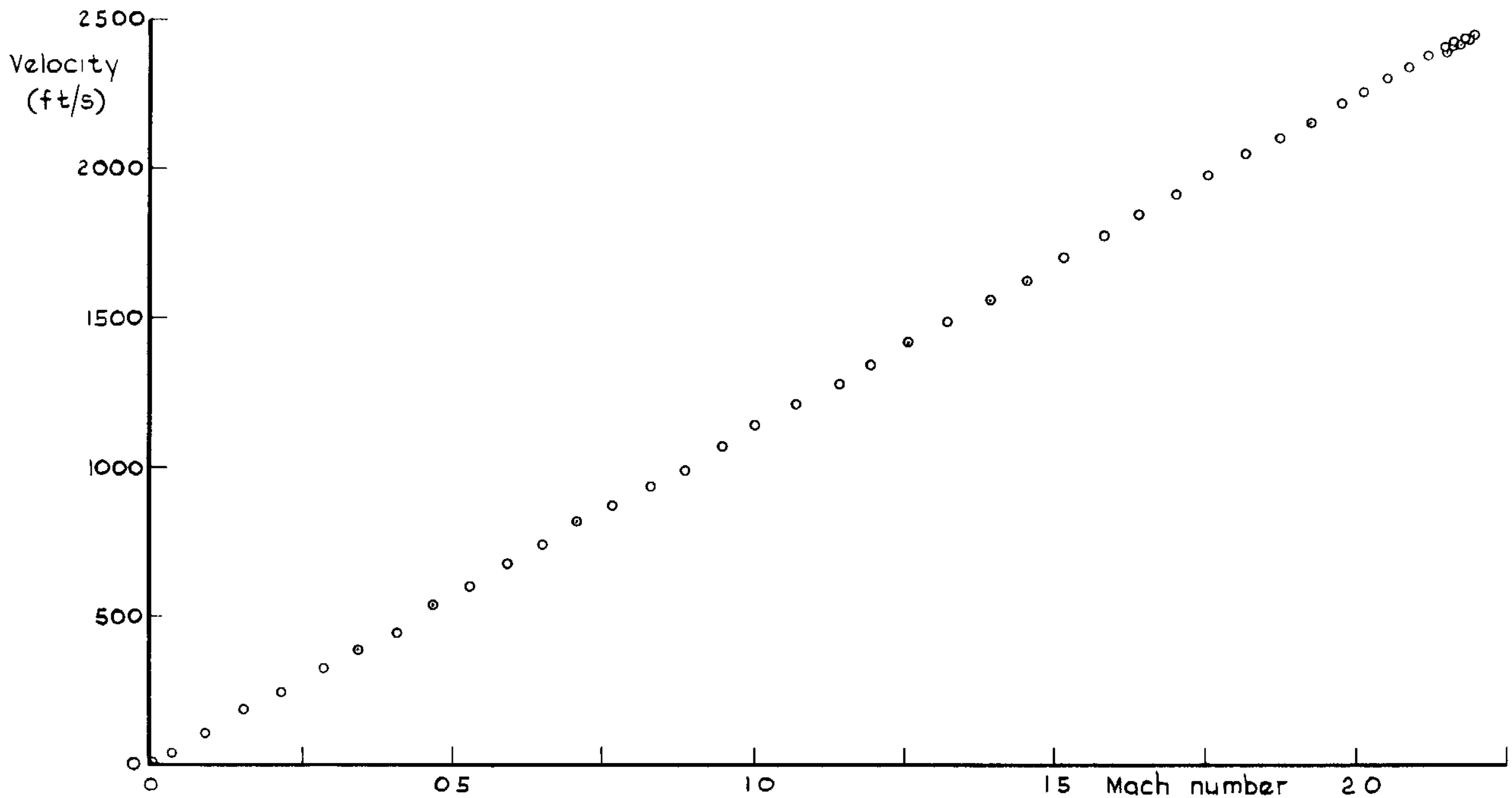


Fig 5 Plot of vehicle velocity/Mach number

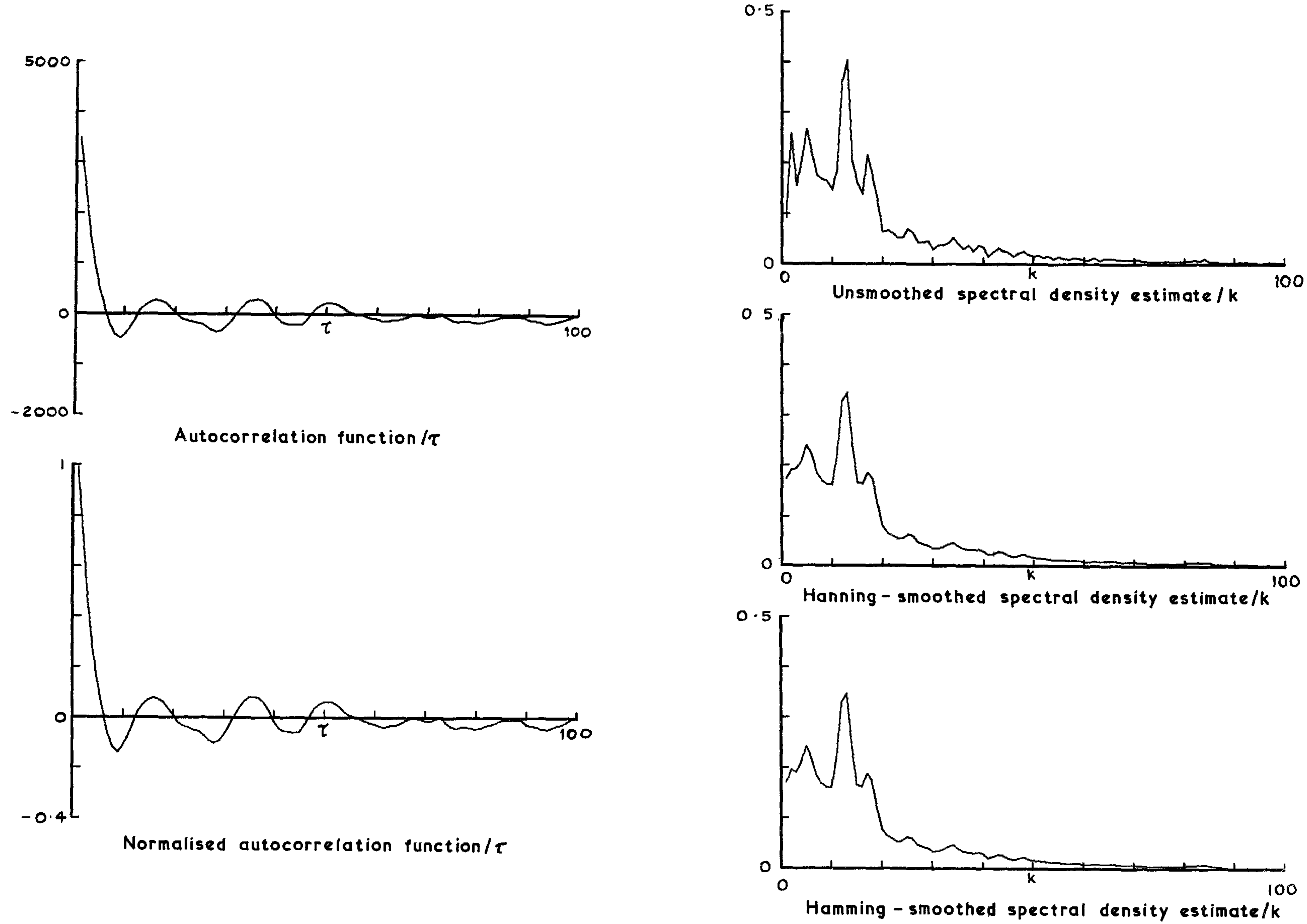


Fig. 6a Plots of derived quantities for run 30

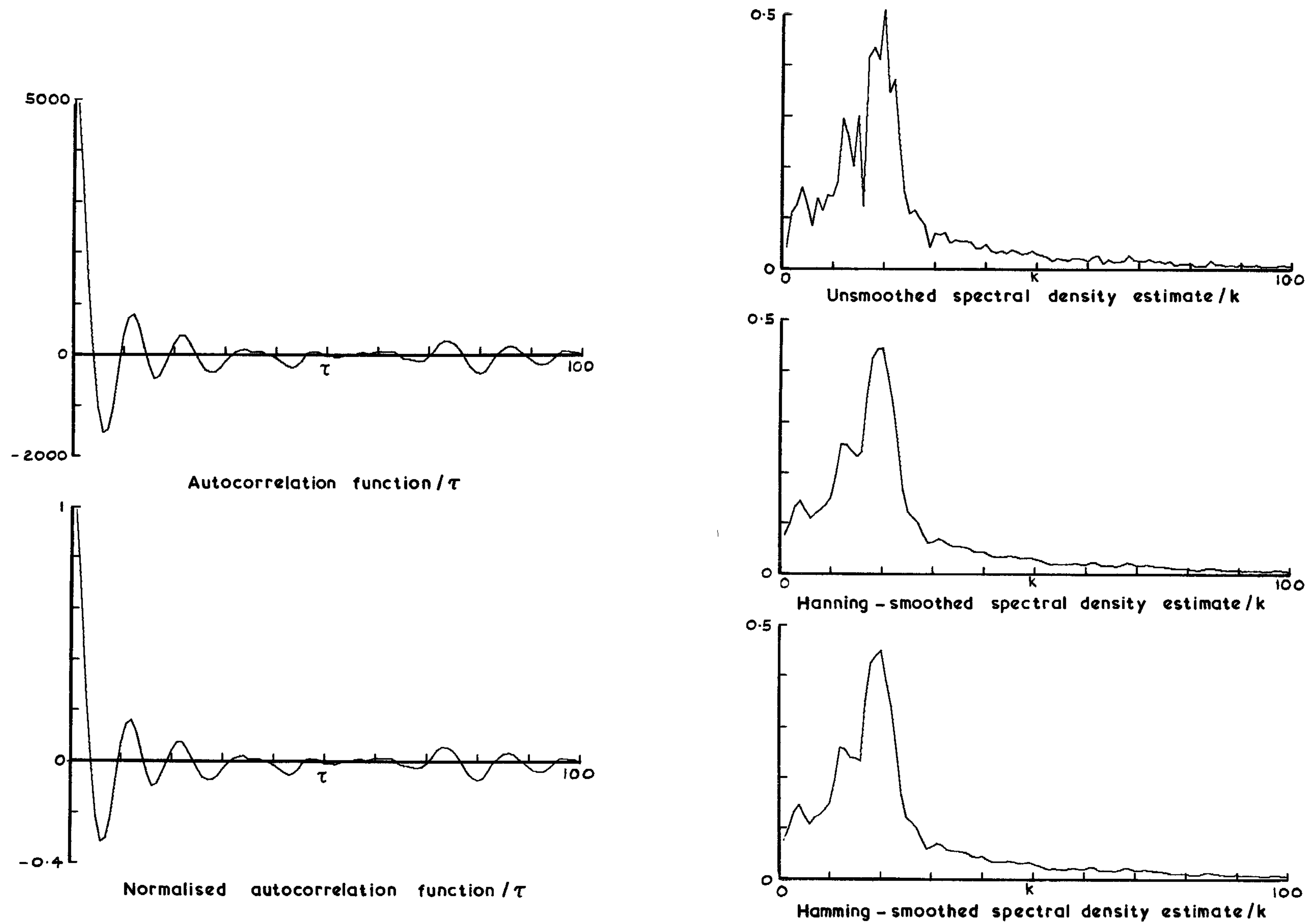


Fig. 6b Plots of derived quantities for run 34

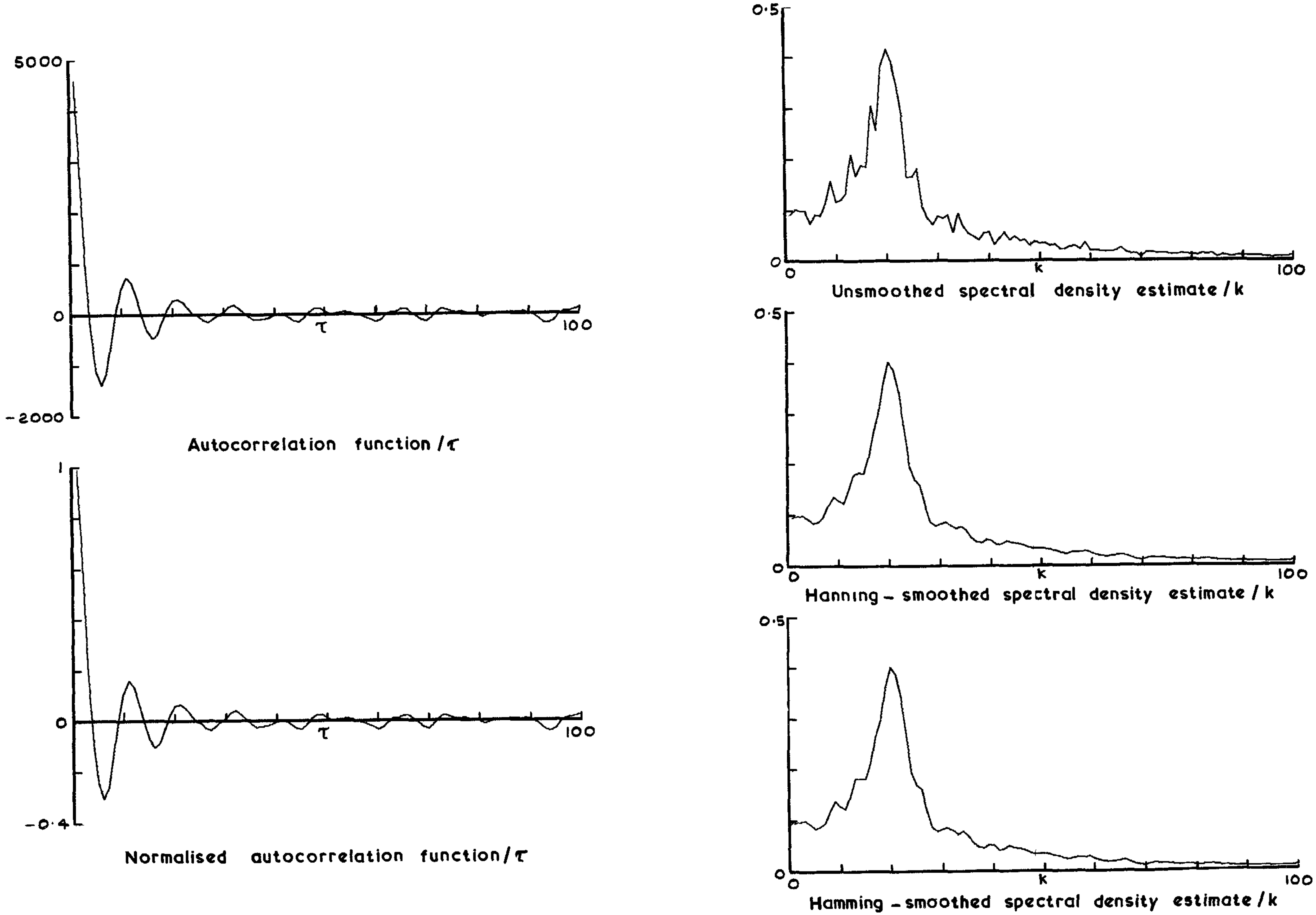


Fig.6c Plots of derived quantities for run 38

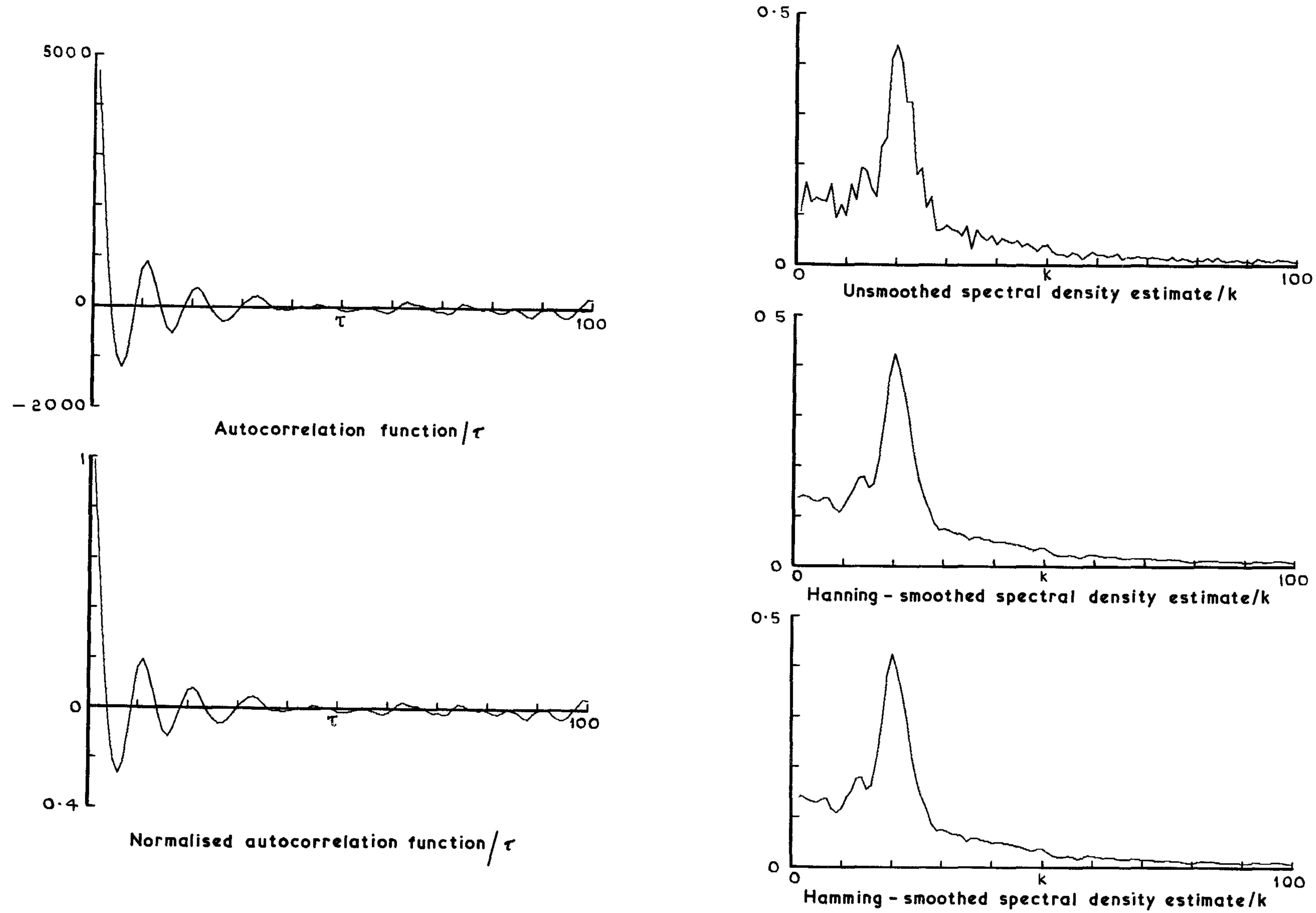


Fig. 6d Plots of derived quantities for run 40

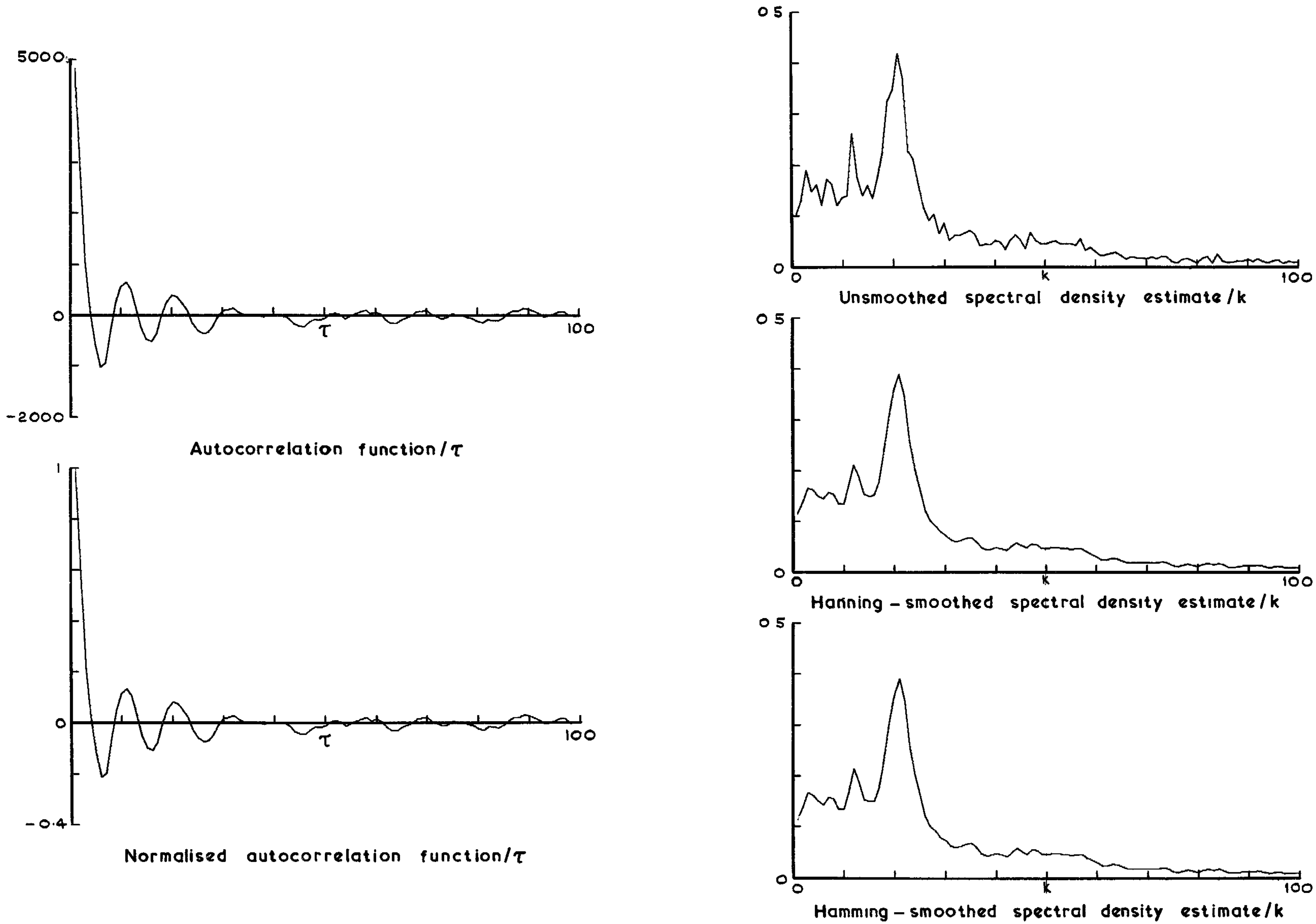


Fig.6e Plots of derived quantities for run 44

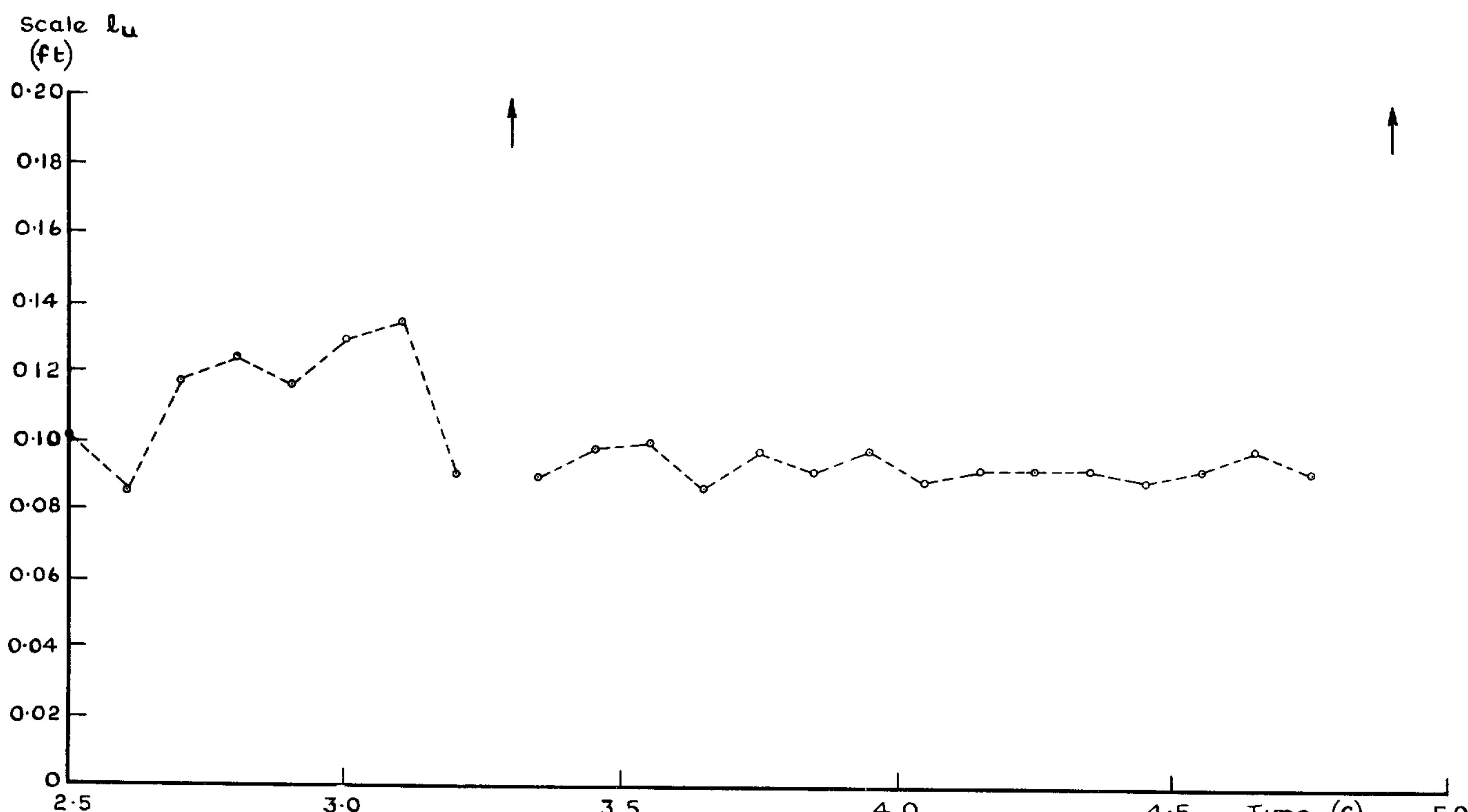


Fig. 7a Scale/elapsed time

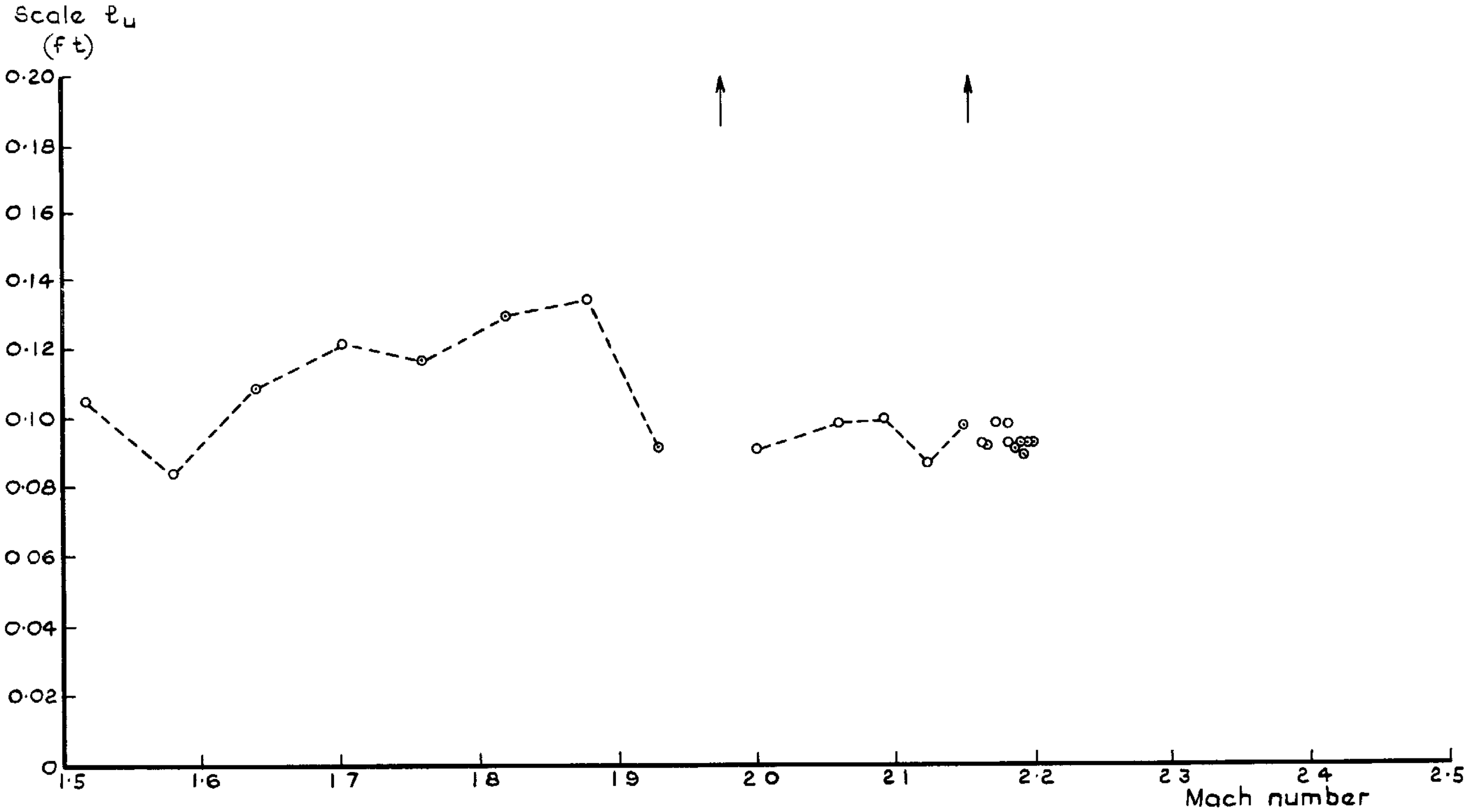


Fig 7b Scale/Mach number

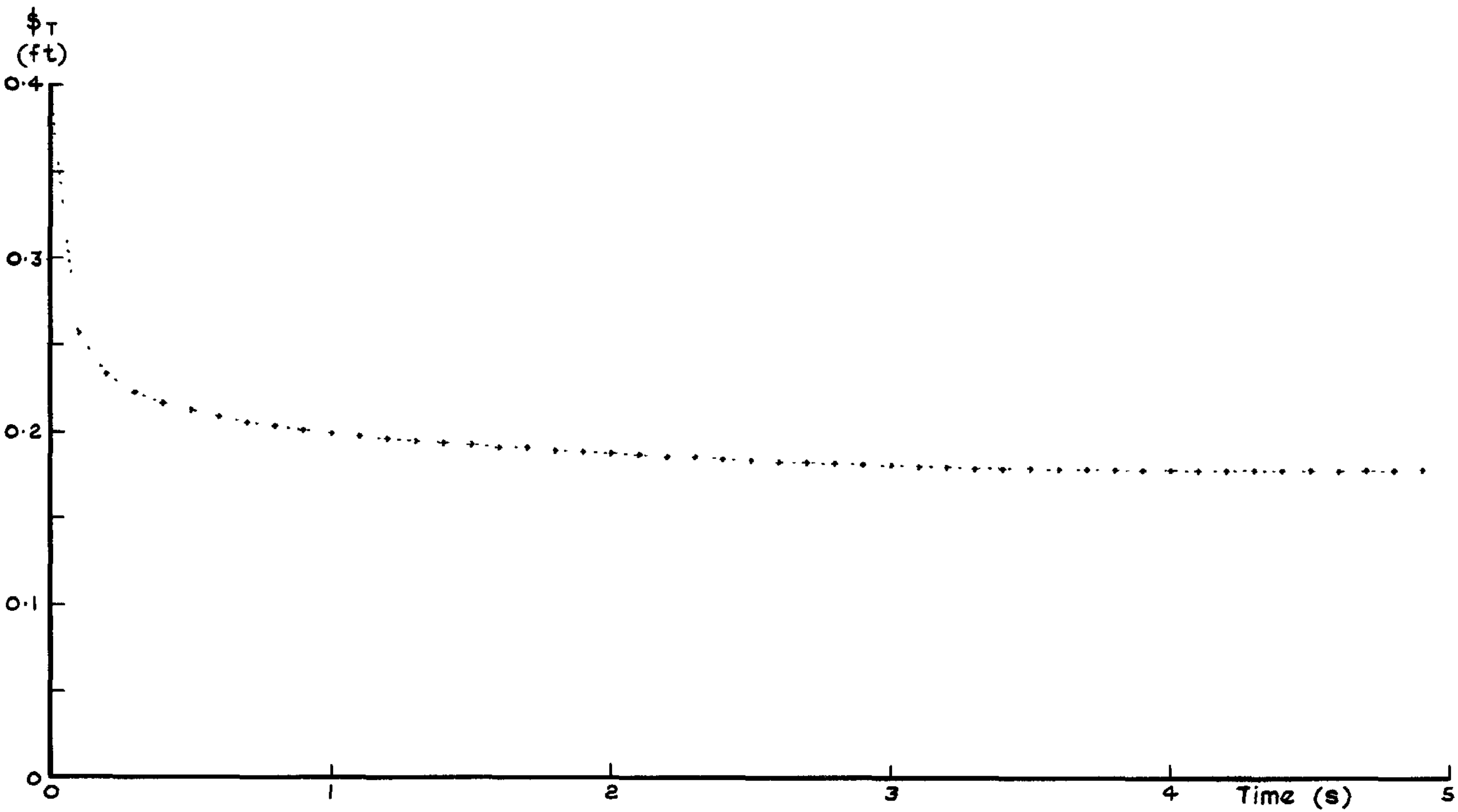


Fig. 8a $\$_T$ / elapsed time

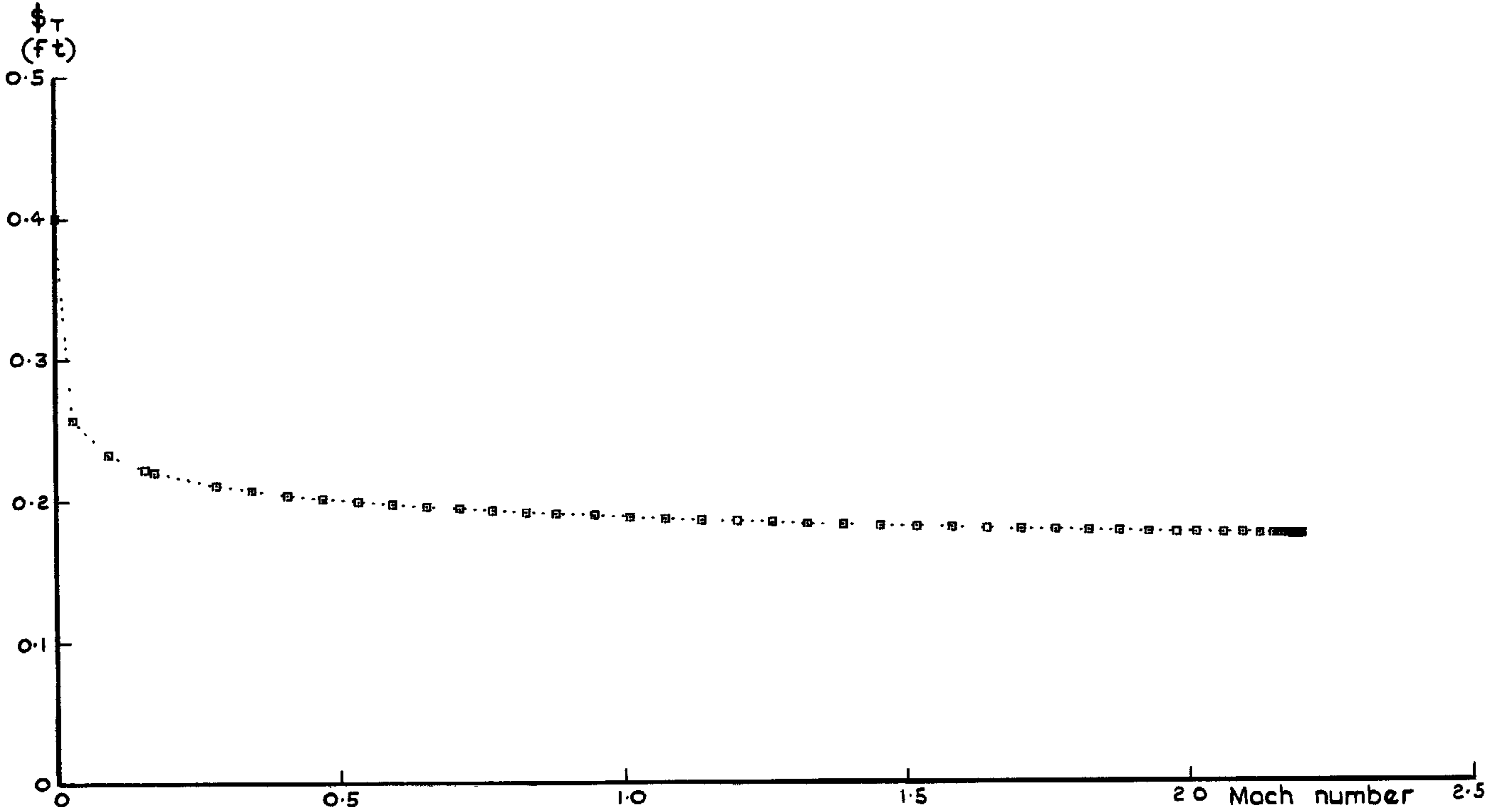


Fig.8 b $\$_T$ / Mach number

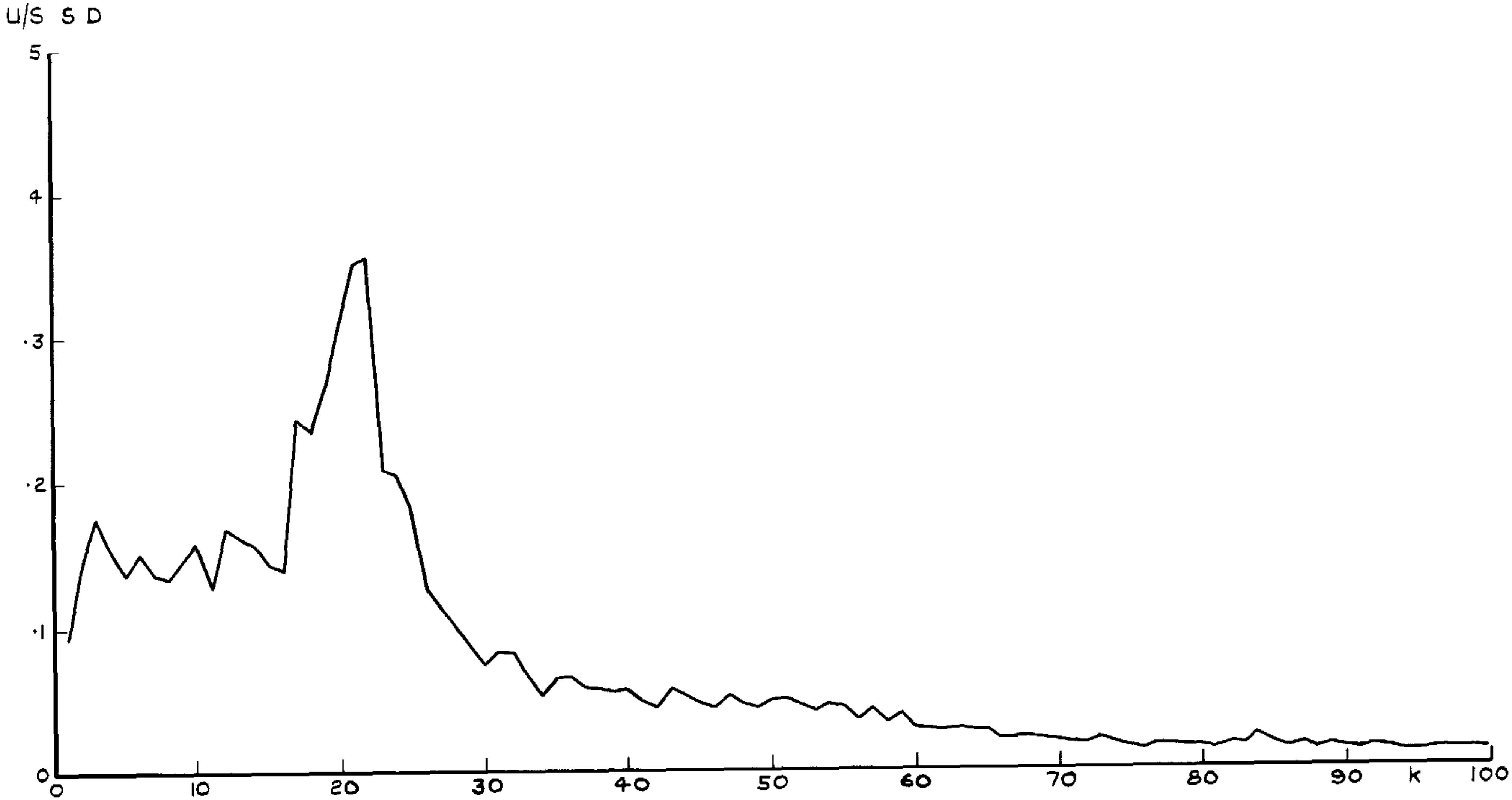


Fig 9 Collective run-unsmoothed spectral density/k

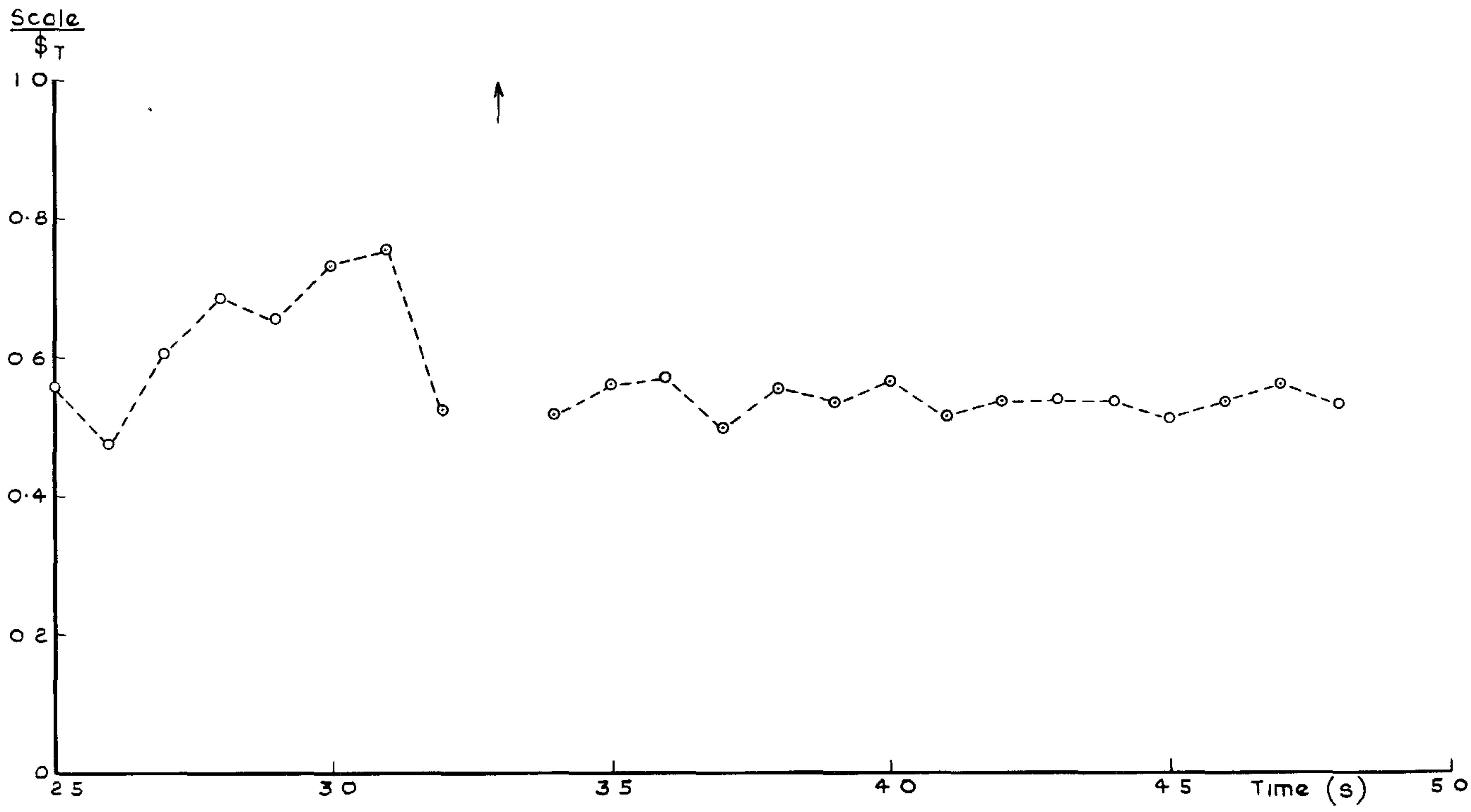


Fig 10 $\frac{\text{Scale}}{\$_T}$ / elapsed time

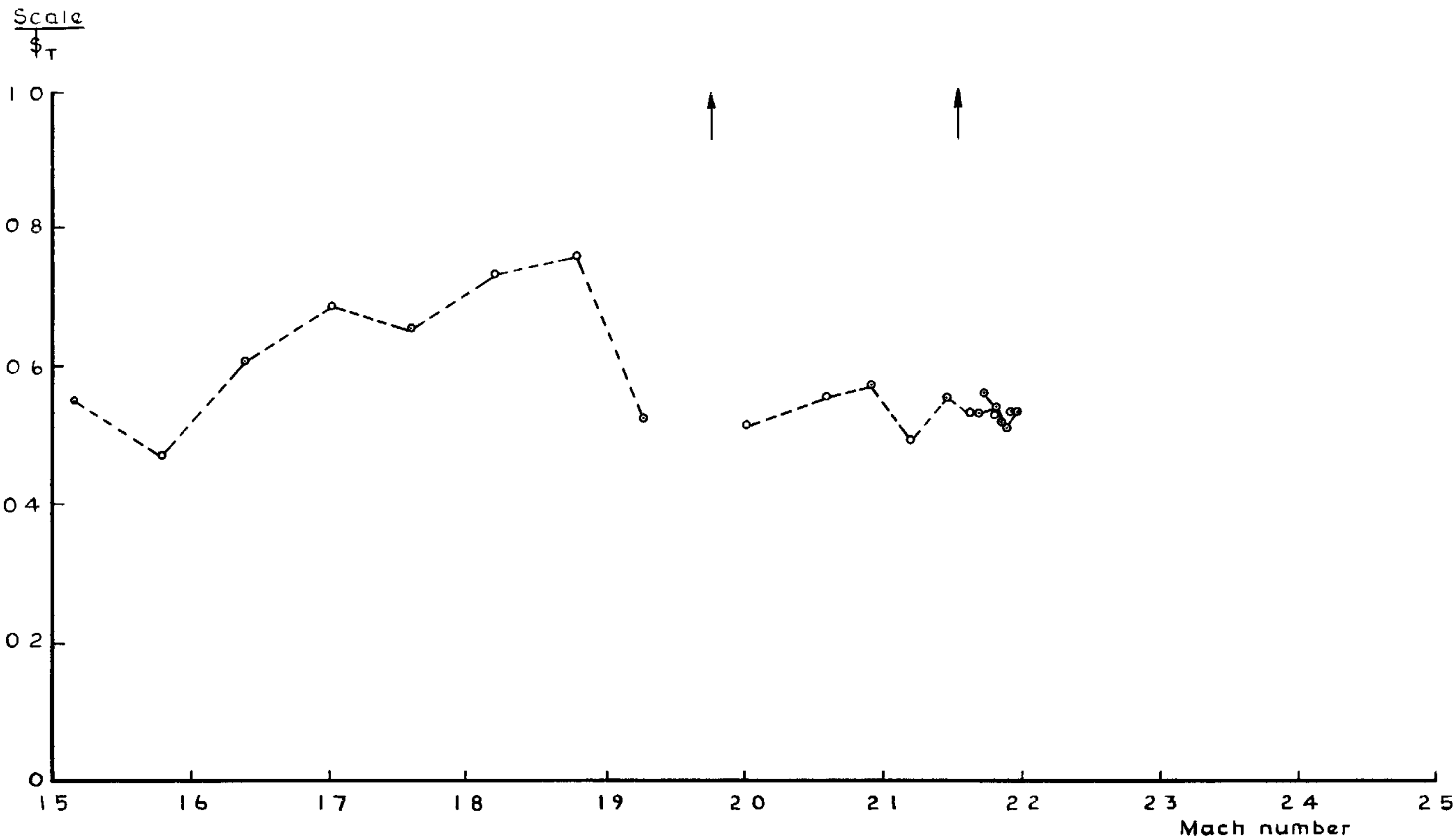


Fig. 11 $\frac{\text{Scale}}{\$_T}$ / Mach number

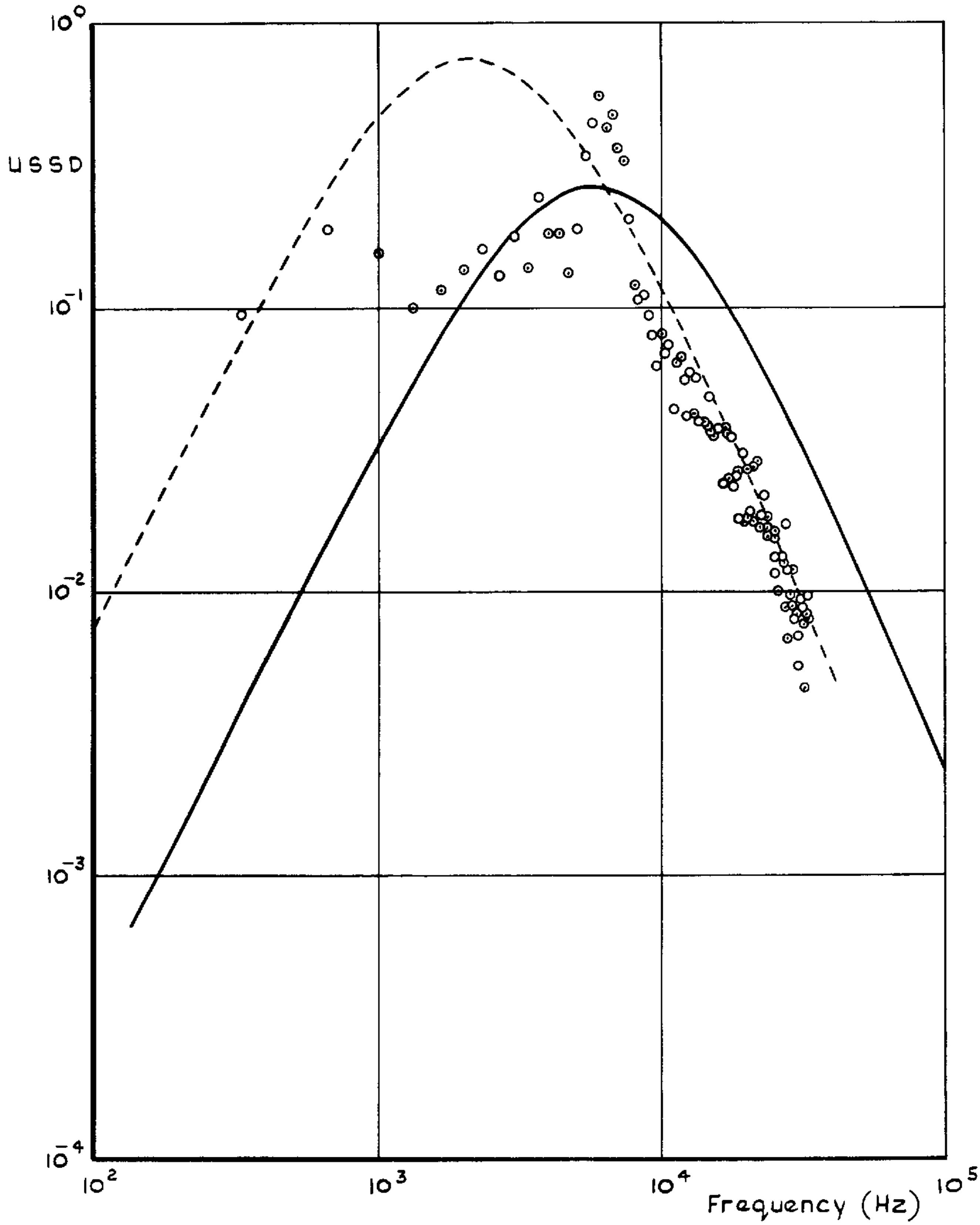


Fig. 12a Plot of unsmoothed spectral density (USSD) against frequency, for run 35

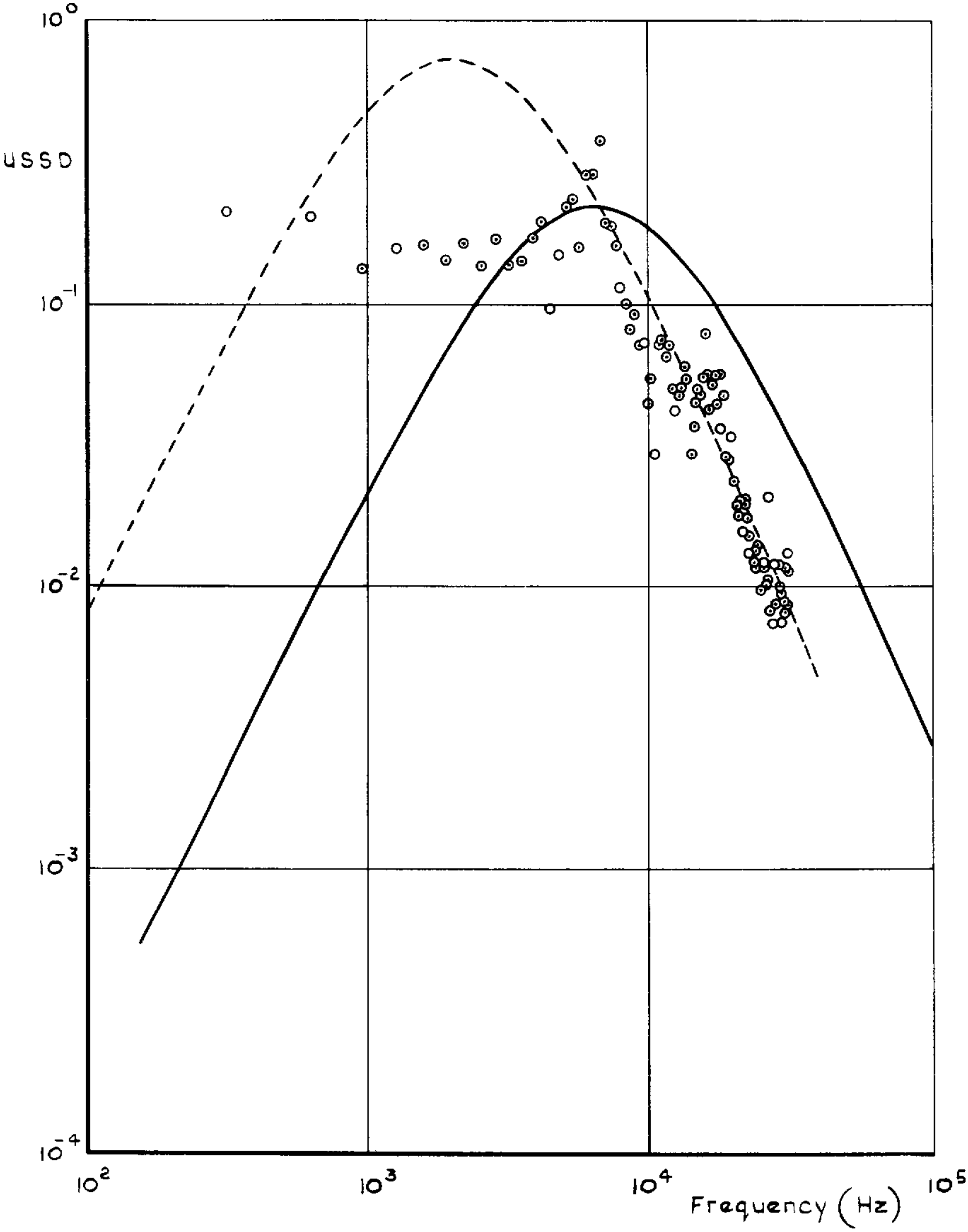


Fig 12b Plot of unsmoothed spectral density (USSD) against frequency, for run 45

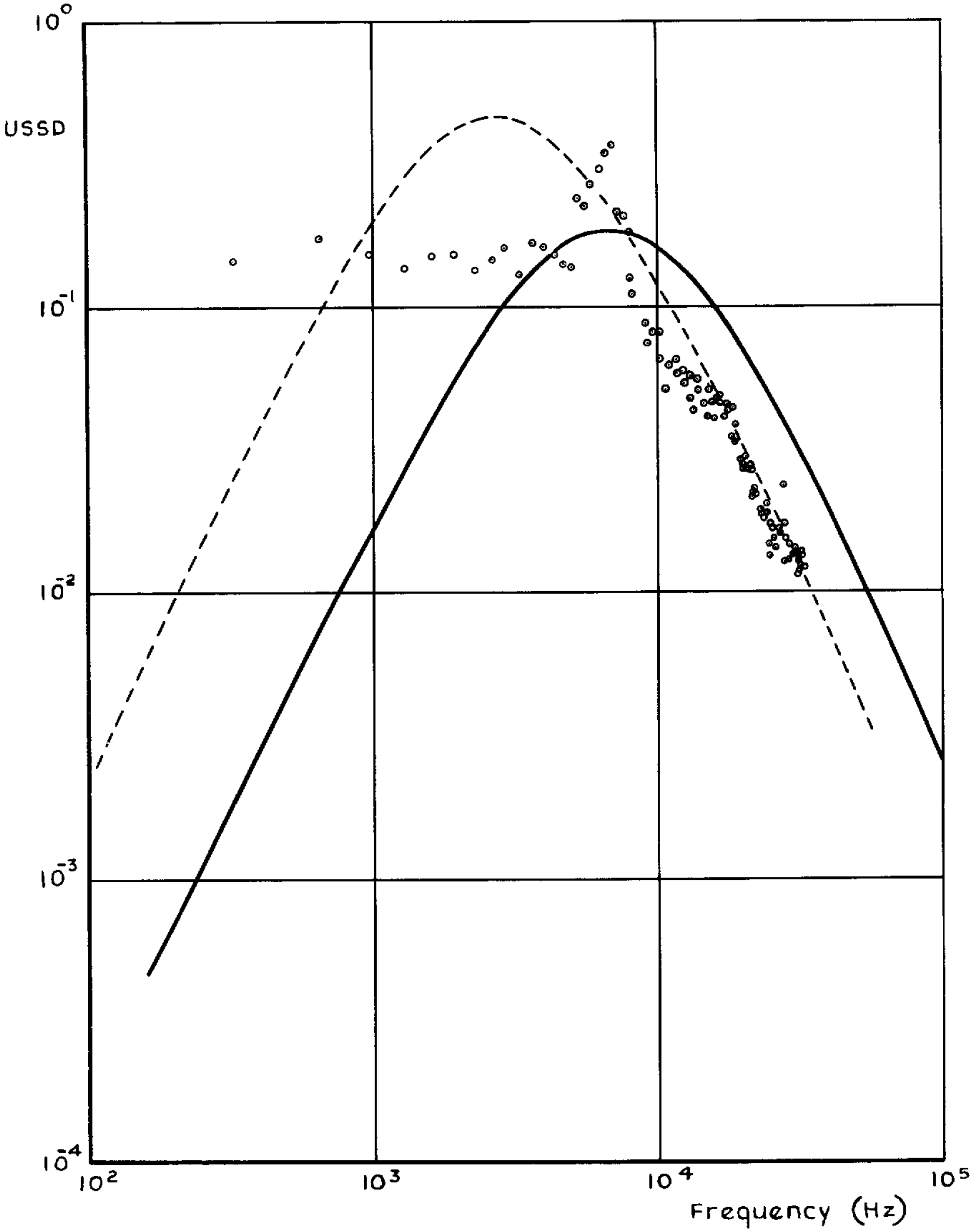


Fig.12c Plot of unsmoothed spectral density (USSD) against frequency, for collective run

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BOUNDARY-LAYER PRESSURE FLUCTUATIONS AT HIGH REYNOLDS NUMBERS ON A FREE-FLIGHT TEST VEHICLE

Measurements have been made of the boundary-layer pressure fluctuations on the body of a free-flight aerodynamic test vehicle powered by a solid-fuel rocket motor The vehicle reached a maximum Mach number of 2 2 with a maximum Reynolds number of about 215 millions

Pressure spectra have been deduced, and have been found to compare reasonably with a theoretical spectrum for homogeneous isotropic turbulence

The scale of the boundary-layer turbulence was found to fluctuate between 47% and 76% of the turbulence boundary-layer thickness over a range of Mach numbers from 1.5 to 2 2, while being essentially equal to 50% of this thickness over the range Ma = 2.0 to Ma = 2 2

At Ma = 2 2 the root mean square boundary-layer pressure was equal to 0 0045 of the free stream dynamic pressure

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