FIFTH AUSTRALASIAN CONFERENCE

on

HYDRAULICS AND FLUID MECHANICS

at

University of Canterbury, Christchurch, New Zealand

1974 December 9 to December 13

SIMULATION OF A STRONG-WIND URBAN BOUNDARY LAYER IN A WIND-TUNNEL

By

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SUMMARY

A method of simulating a strong-wind urban boundary layer in a wind tunnel is described for tunnels of medium working length to height ratios. Measured data on velocity, turbulence and Reynolds stress profiles and spectral distribution of longitudinal turbulence is presented and compared with other simulations, or where possible, full scale data.

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Knowledge of the structure of the atmospheric boundary layer enables investigations into structural, aerodynamic and environmental problems. Since many problems cannot be realistically treated by theory, wind tunnel modelling is used to derive full scale properties. Traditionally, several methods have been used to generate models of the atmospheric boundary layer in a wind tunnel.

(1) Generation of the boundary layer over a long fetch of surface roughness allowing the layer to develop naturally. Davenport and Isyumov (1) describe a tunnel in which this method is used.

(2) The "instantaneous" modification of the flow, a less satisfactory method than (1), but the only one available for many wind tunnels of small working length/height ratio. Methods used include a grid of rods (Owen and Zienkiewicz (2)), a curved gauze screen (Baines (3)), a grid of flat plates (Strom(4)), a spire array (Standen(5)), and elliptical-wedge vortex generators (Counihan (6)).

The method described attempts to simulate a strong-wind urban boundary layer in a tunnel of medium length/height ratio.

The simulation was carried out in an open-circuit wind tunnel of nominal cross-sectional area 0.3 m x 0.3 m, and a working length of 3m. The surface roughness (25mm x 25mm plan area blocks) of varying heights, plus a screen designed by the method of Cowdrey (7), slightly modified with vertical rods, is shown schematically in Fig. 1

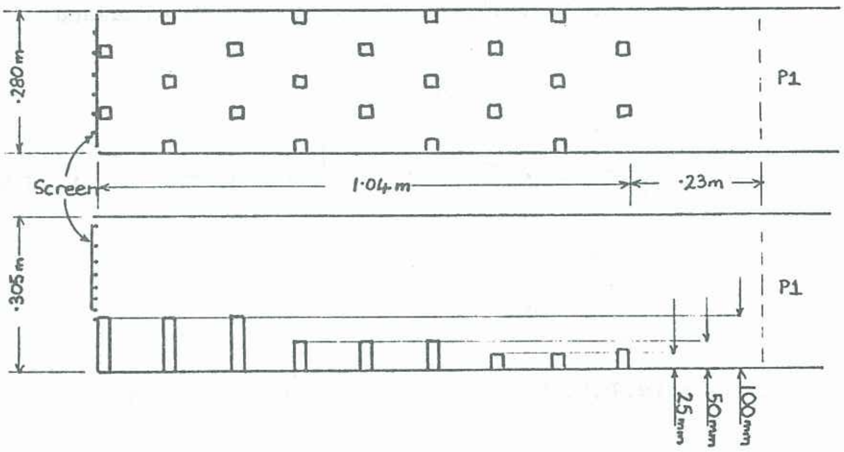

FIG. 1 TUNNEL LAYOUT

At point P1, lateral variation in the velocity profile was negligible. A constant temperature hot-wire anemometer was used to determine the velocity and longitudinal turbulence variation with height, the anemometer system consisting of an anemometer unit (DISA Type 55D01), linearizer (DISA Type 55D10), auxilary unit (DISA Type 55D25), RMS Unit (DISA Type 55D35) and a digital D.C. voltmeter (DISA Type 55D30). The Reynolds stress profile was obtained with a x-wire probe and two anemometer units as described above. The turbulence signal was recorded on an F.M. channel of a Hewlett-Packard 3960 Instrumentation tape recorder, and the spectrum was analysed using a Muirhead Low frequency analyser (D-788-A).

Davenport (8) suggested strong wind velocity profiles should take the form -

$$\frac{Vz}{Vg} = \left(\frac{z}{Zg}\right)^{\alpha}$$

where Vz is the local mean velocity at height Z, $(Z \leq Z_g)$

Vg is the gradient velocity at height Z_g (at which, the effect of surface friction on the flow is negligible)

α is the power law exponent.

In simulating an urban boundary layer in a wind tunnel, the following profile nomenclature was used -

$$\frac{\overline{U}}{\overline{U}max} = \left(\frac{y}{\delta}\right)^{\alpha}$$

where $\overline{U}$ is the local mean velocity at height y, $(y \leq \delta)$

Umax is the mean velocity at height δ (the boundary-layer thickness)

α is the power law exponent.

For strong-wind (neutral) conditions over a city centre, Davenport suggested a value of α=0.4 as being representative of average conditions, but quoted values of α=0.435 and α=0.625 measured in Paris and New York respectively. The achieved exponent in the wind tunnel simulation at point P1 was α=0.42 (See fig.2). The only significant deviation from the mean profile occurs low in the boundary layer, but this effect is not unknown in full scale measurements over rough terrain, as shown in Cermak (9). The boundary layer height at point P1 was 265mm in a tunnel height of 305mm. Counihan (10) found that when the roughness height was a significant part of the total boundary-layer height, a wide range of indicies could be fitted to the measured profiles depending on where the measurements were made relative to a fixed roughness element and the height range over which the profile was fitted. No such effect was discernible downstream of point P1 in the present simulation, the conclusion being that the graded heights of several rows of roughness elements of relatively small frontal area, quickly generate a "mean" flow due to the effect of successive rows of elements on the wakes generated by those upstream. Re-measuring the velocity profile at P2 (1.96m from the start of the working section) an exponent $\alpha=0.44$ was obtained. Harris (11) states that the form of the velocity profile over an urban area is an unknown quantity since the same power law that applies to the upper region of the boundary layer cannot be expected to apply to the region below the typical height of the buildings which make up a major part of the surface roughness, and which can also be an appreciable fraction of the boundary layer thickness in height. Thus a detailed model of upwind topography would still be needed to give realistic results, if an investigation were to consider any particular building or area in an urban complex.

Available information on turbulence measurements in urban environments is very scarce, the largest amount of data being determined for rural conditions. Harris (11) suggests that for urban sites, turbulence intensities measured relative to the gradient velocity should be little different from the rural data, but based on local velocities they should be 20-30% in the lower regions of the boundary layer. Helliwell (12) suggests, from measurements made over London, that values based on local velocities should be from 10-30% in the lower regions. From Fig.3. it can be seen that the peak turbulence intensity based on maximum (gradient) velocity is just over 10%. This is similar to values obtained in the simulation by Standen (5) whose profiles show a similar form. Based on local velocity, the peak intensity is 21% which has in the middle of the range suggested by Helliwell. A profile measured at P2 (1.96m downstream from the start of the working section) gave slightly higher intensities (1-2% higher) especially noticeable in the upper regions of the boundary layer, and peak intensities of 11% and 23% based on maximum (gradient) and local velocities respectively.

The Reynolds stress profile measured at P1 is shown plotted in Fig.4. The steep gradient in the lower region of the layer implies the flow is still accelerating. Little data exists with which to make relevant comparisons.

The power spectra measured at points P1 and P2 are plotted in Figs.5 and 6. Panofsky (13) stated that for the longitudinal gust spectrum, if nS(n) is plotted as a function of n, the spectral peak will shift little or not at all with height, and at high frequencies will obey the Kolmogorov law. Thus the forms of the rural and urban spectra should be similar. Davenport (14) derived an expression relating the proportion of energy per unit fractional increase of frequency (nS(n)), to the frequency (n).

$$nS(n) \quad \alpha \quad \frac{x^2}{(1 + x^2)^{4/3}} \qquad \text{where } x = \frac{1200\ n}{\overline{V}_1}$$

$\overline{V}_1$ = velocity at standard reference height of 10m

Harris (15) suggested an alternative form-

$$nS(n) \quad \alpha \quad \frac{x}{(2 + x^2)^{5/6}} \qquad \text{where } x = \frac{1800\ n}{\overline{V}_1}$$

This modification affects the distribution mainly at frequencies below the peak. Figs 5. and 6 show nS(n) plotted on a linear non-dimensionalised scale against frequency on a logarithmic scale, with Davenport's spectrum for comparison. In Fig.5, good agreement exists with Davenport's Spectrum except at 175 mm, where as expected, the effect of the rod screen produced a different turbulence structure. Further downstream at P2 (Fig.6) the growth of the boundary layer off the surface roughness produces acceptable spectral shape over a much greater proportion of the boundary layer height.

The derived model scale was 2200:1 in comparison with Davenport's full scale data, with a model $\overline{V}_1$ of 7.62 ms^{-1} and a scaled boundary layer height of 580m

Conclusion:

A 2200:1 scale model of an urban boundary layer produced a velocity profile with power law exponent $\alpha=0.42$, peak turbulence intensity based on gradient velocity of 10.2%, a scaled boundary layer height of 580m, and acceptable turbulence structure over at least 50-60% the height of the boundary layer and at least 70% if the flow was allowed to develop downstream. The minimum working length required to produce acceptable conditions was 4.8 boundary layer heights.

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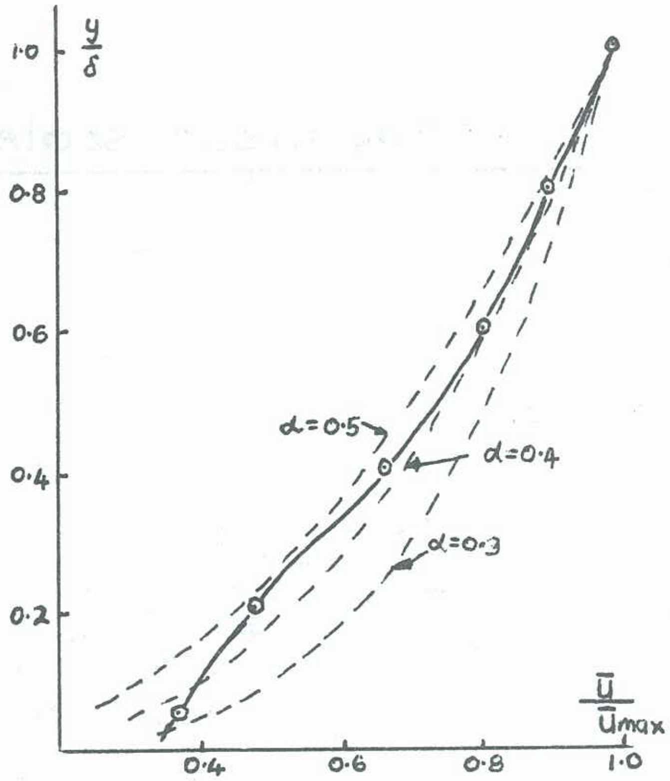
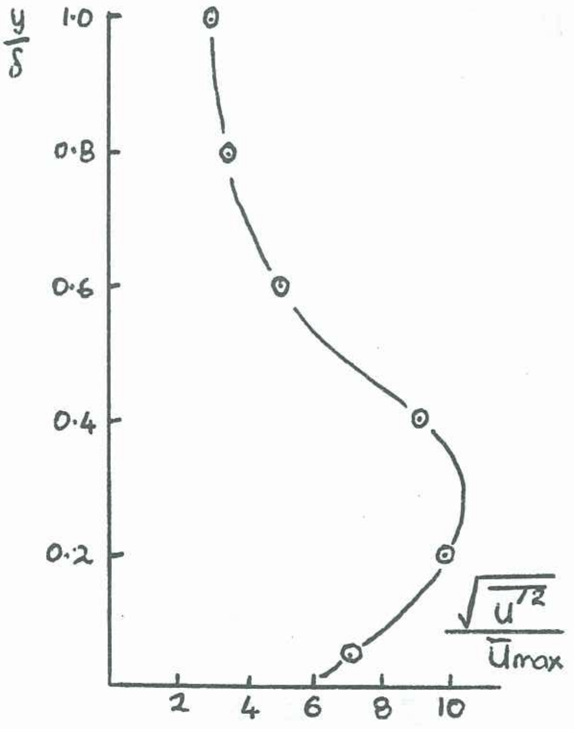


FIG. 2. VELOCITY PROFILE



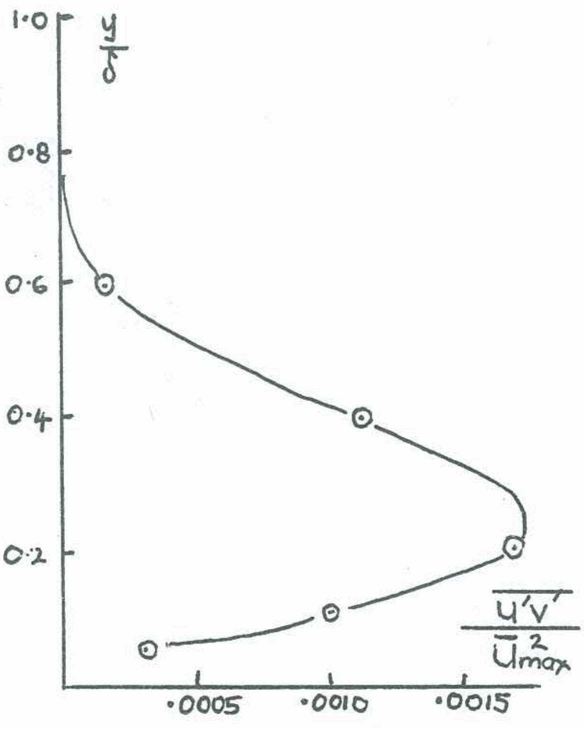


FIG. 3 TURBULENCE INTENSITY PROFILE

FIG. 4. REYNOLDS STRESS PROFILE

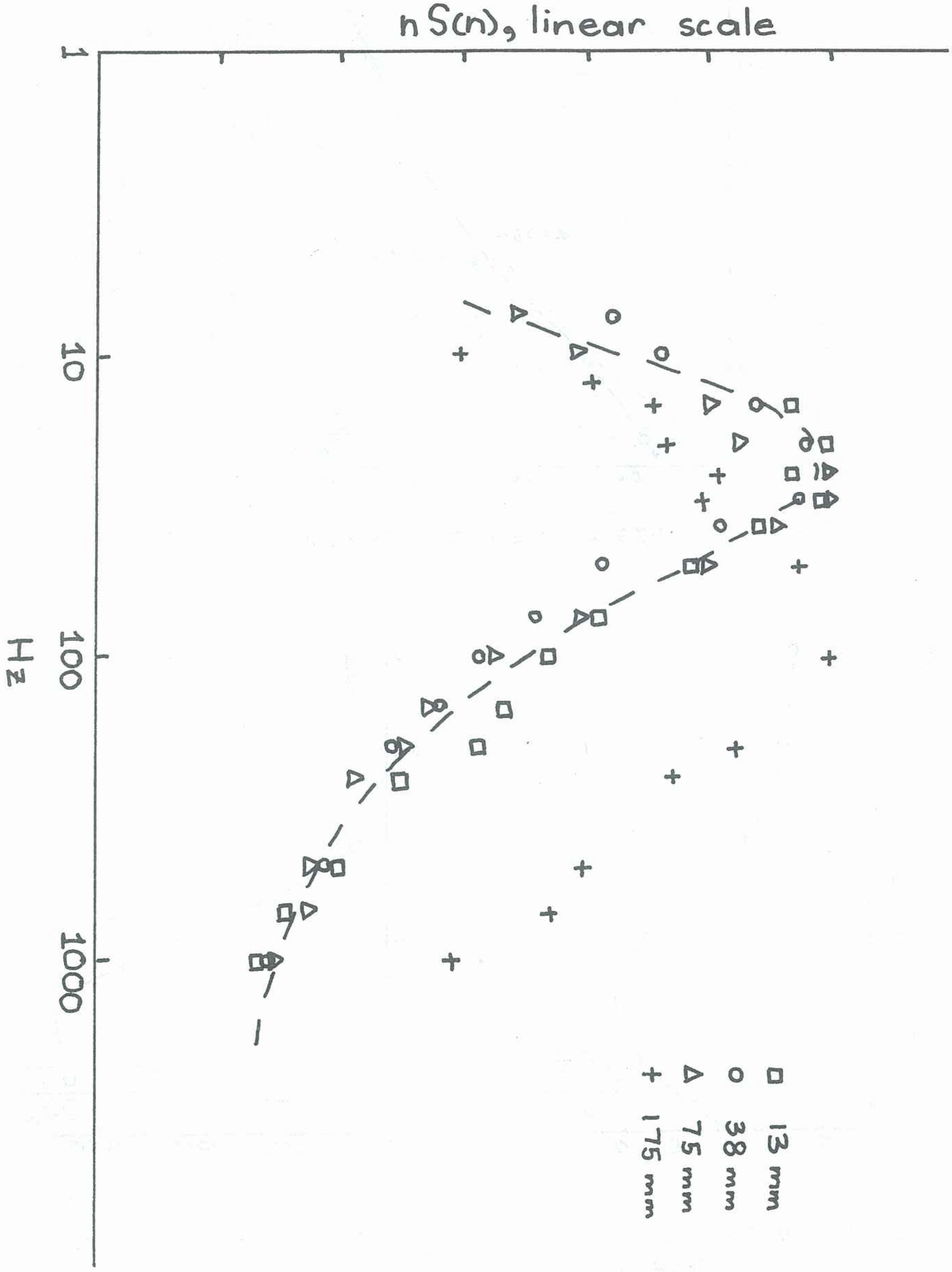


FIG. 5. SPECTRA AT P1

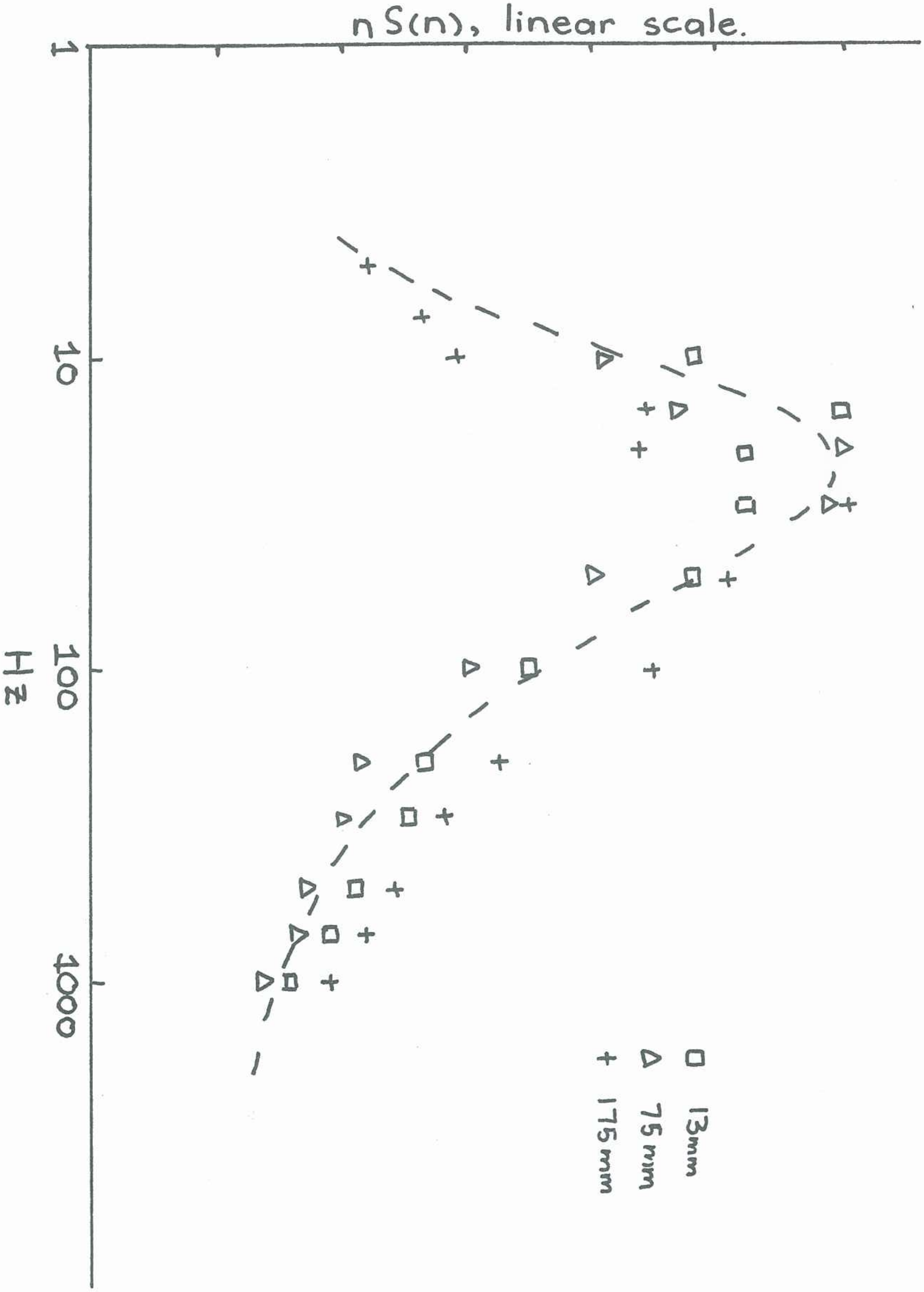


FIG. 6 SPECTRA AT P2