MORU Cardington Technical Note No. 13

A comparison between the Cardington turbulence probe and a sonic anemometer

by

A.L.M. Grant

4 November 1992

Met. Office Research Unit
RAF Cardington
Shortstown
Beds, MK42 0TH

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1 Introduction

The calculation of the instantaneous wind vector with the Cardington turbulence probe requires combining data from eight separate sensors (i.e. 3 Gill anemometers, 2 inclinometers and three components of the magnetic field). The effects of some types of errors in the outputs from these sensors or response limitations can be quantified through calculation. This is the case for errors in the magnetometer and inclinometer data used to calculate the probe orientation (Grant 1989). However, for other types of errors, such as the effects of flow distortion caused by the probe, theoretical calculations are only of limited use. Virtually all instruments used in boundary layer studies disturb the flow fields being measured (exceptions are remote sensing devices such as doppler lidar and sodar). The effects of flow distortion on turbulence measurements can be calculated (e.g. Wyngaard 19) but in general this is is rather difficult because it requires a knowledge of the flow field around complex three dimensional shapes. Wind tunnel studies can be valuable in estimating flow distortion errors, and may even provide corrections which can be applied to field data. Finally intercomparisons in the atmospheric boundary layer against established instruments, whose characteristics are well known, provide a good test of the overall performance of a new instrument and may indicate how large a problem flow distortion is. The problem with intercomparisons, is of course, that the reference instrument will also suffer from various types of error, including flow distortion errors. Sonic anemometers are currently considered to be amongst the best instruments available for boundary layer studies. They contain no moving parts and their response and calibration are largely determined by the geometry of the sensor head and the ability to measure time differences, something that can be done to a high degree of accuracy. The sensor heads generally have an open structure to help minimise flow distortion errors. The widespread use of sonic anemometers means that their characteristics are well understood. Even so it may be difficult to resolve systematic errors of less than 5-10% in the test instrument through intercomparisons, unless the unless the nature of the error makes the source clear.

2 Instrumentation and data collection

The reference instrument for this study was a Kaijo-Denki DAT-300 sonic anemometer thermometer. The head unit was mounted on rotator at the top of a tubular mast approximately 20m above the ground. The rotator allowed the sensor head to be rotated to point into the mean wind direction to minimise errors due to shadowing by the ultrasonic transducers. On the first two occasions the analogue outputs from the DAT-300 electronics unit were logged by a FLUKE 2204B datalogger at one sample per second. The logger was connected via serial line to a MicroVax II computer which was used to calculate statistics over ten minutes. Subsequently the ten minute statistics were combined to give means and linearly detrended variances and covariances averaged over thirty minutes. On all other occasions the sonic outputs were logged at 4 Hz through a turbulence probe logging unit attached by cable to the turbulence probe ground station. These data were subsequently processed to give statistics and spectra averaged over thirty minutes.

When mounted on the mast the sonic anemometer sensor head is not accessible and is therefore difficult to level accurately. SInce the tilt of the head was not measured directly it has been estimated by analysing the apparent wind inclination obtained from routine data that are logged continuously. The magnitude and direction of the tilt evaluated this way have been used to transform the wind components measured relative to the sonic head into a frame with the z-axis parallel to the local vertical. The wind components were further rotated into a frame with the x-axis parallel to the mean wind direction over the thirty minute averaging period.

The turbulence probe data were processed using the standard set of processing programs, which provided statistics and spectra averaged over thirty minutes. The filter period used to filter the probe orientation data was chosen by examining spectra of the inclinometers and the calculated probe velocity components. Generally the filtering removed contributions from the inclinometer data with frequencies greater than 10^{-2} Hz. The turbulence statistics were calculated over the same periods as the statistics obtained from the sonic data. When the sonic was logged on the FLUKE datalogger the synchronisation of the ends of the averaging periods was only around 5-10 seconds. With the sonic data logged through the probe ground station the synchronisation was within about 0.25 seconds. The sonic anemometer and turbulence probe were separated horizontally by 110m. The height of the turbulence probe should have been within 1-2m of the sonic height. During the six days on which data were obtained winds were light to moderate and conditions were generally convective.

3 Sampling error

Estimates of turbulence quantities are always subject to statistical error due to inadequate sampling. This means that in any comparison there will be a certain amount of scatter, which will depend on the separation of instruments, averaging time, height etc.

Lumley and Panofsky (1974) show that for averaging times, T, that are long compared to the integral timescale, τ the uncertainty, ϵ_v in a variance measurement is;

$$\epsilon_v^2 = \frac{2\tau}{T}(F-1) \quad (1)$$

where F is the Kurtosis of the quantity considered.

In the surface layer the kurtosis for second moments is usually about 3 (Wyngaard 1973). Lenschow and Stankhov (1986) give estimates of integral length scales in the convective boundary layer for several second order moments. For w^2 the integral scale is $\sim 0.13\Lambda_w$ where Λ_w is the position of the peak in the vertical velocity spectrum. For the present data the peak in the vertical velocity spectrum occurs at about 100m. Using Taylor's hypothesis to convert the length-scale to a timescale gives an integral timescale of 3 seconds for w^2 For an averaging time of 2000 seconds the uncertainty in estimates of σ_w^2 is around 8%. The integral length-scale is about 15m, which is small compared to the 100m separation between the probe and sonic anemometer, so the probe and sonic estimates of σ_w^2 can be considered statistically independent. Therefore the rms deviation between the probe and sonic data should be $\sqrt{2} \times 8\% \sim 11\%$

For a covariance measurement between two variables with correlation coefficient r the sampling uncertainty is:

$$\epsilon_c = \frac{2\tau}{T}(1 + \frac{1}{r^2} \quad (2)$$

Power spectra of the $u'w'$ timeseries indicate that the integral scale for $\overline{uw}$ is approximately the same as for w, i.e $\sim \Lambda_w/6$. Taking $r_{uw} = 0.25$ for the present data the rms deviation between the stresses measured by the turbulence probe and the sonic anemometer should be $\sim 30\%$.

4 Results

Before presenting the results of the comparison between turbulence probe and sonic statistics it is useful consider the power spectra and cospectra of the relevant quantities. Figures 1(a)-(d) show the average over all runs of the normalised power spectra of u, v and w and the cospectrum of u and w. The u and v spectra show that most of the respective variances are associated with long wavelength fluctuations. For wavenumbers greater than $0.1m^{-1}$ the turbulence probe spectra decrease more rapidly than the sonic spectra because of the longer length constant of the Gill propellers compared to the sonic (note that the Gill data have had a correction for response applied during processing). The probe v spectra show a bump at wavenumbers around $0.05m^{-1}$. This is caused by errors in the gill measurements, due to limited response and possibly inadequate corrections for non-cosine response, in the region where the vane response function has a maximum. The vertical velocity spectra are in good agreement, except for wavenumbers greater than $0.1m^{-1}$. Finally the agreement between the uw cospectra is fairly good, apart from a systematic difference at high wavenumbers.

Figure 2 shows the comparison between the sonic and turbulence probe windspeeds. The agreement is clearly very good with an average ratio between the probe and sonic of 0.99. The rms scatter is $\sim 0.3ms^{-1}$.

Figures 3(a)-(c) shows the comparisons between the velocity component variances σ_u^2, σ_v^2 and σ_w^2 For σ_u^2 the probe estimates are systematically smaller than the sonic estimates by about 15%. The agreement between mean windspeeds indicates that this underestimate of σ_u^2 by the probe cannot be due to a simple reduction in the x-component of the wind, for example due to blockage of the flow by the probe body. Comparison between power spectra provides more information on the nature of the error and is considered below. The probe and sonic estimates σ_v^2 and σ_w^2 are in good agreement. The rms scatter for all three variances is $15 - 20\%$, which for σ_w^2 is similar to that calculated from equation(1).

Estimates of the stress component $\overline{uw}$ are compared in Figure 4. Overall the agreement is reasonable. The rms difference between the two estimates of about 50%, but if the ringed point is excluded the rms difference is reduced to 30%, which is similar to that expected from the calculations above.

5 Comparison of spectra

Figures 5(a)-(c) show the ratios between the probe and sonic spectra of the three velocity components, u, v and w.

For frequencies less than 0.025Hz the probe u spectral estimates are systematically less than the sonic estimates, which explains why the probe u variances are smaller than those from the sonic. The ratios between the probe and sonic v and w spectra, whilst a little scattered, don't appear to differ systematically from one. In contrast for frequencies greater than 0.025Hz the probe and sonic u spectra are in good agreement whilst the v and w show systematic differences. For the v spectra this difference is caused by response errors in the Gill data at the frequencies where the vane response function has a large peak. In this frequency band the probe spectral levels for w are about 15% greater than the sonic spectral levels and although this error has little effect on the total variance it could lead to dissipation rates obtained from the vertical velocity spectrum being overestimated by about 25%. All of the probe spectra show a rapid fall off above 1Hz due to the response of Gill anemometers.

The frequency dependent differences between the probe and sonic spectra are difficult to explain. For a windspeed of $5ms^{-1}$, appropriate for these data, 0.025Hz corresponds to a length scale of 200m. Given that the package dimensions are $\sim 1m$ the behaviour of the u and w spectra around this frequency cannot be due to a change in the characteristics of any flow distortion induced by the package, since this would be expected to occur at scales comparable to the probe dimensions.

A turbulence probe is not a fixed instrument but is rotates about the balloon tether cable in response to changes in wind direction. Furthermore the orientation of the cable changes slowly in response to the motion of the balloon. In Figure 6a spectra of the cable tilt angle, normalised to the variance, for one flight are shown. The variations in the cable tilt are concentrated at frequencies below 0.02 Hz. Figure 6b shows the ratio between probe and sonic u spectra for this flight and it is clear that the differences between the sonic and probe spectra occur in the same frequency range as the variations in the cable tilt, suggesting that the error in σ_u^2 may be due to the changing orientation of the probe. I should be stressed that the error is not due to the velocity of the probe, which for these intercomparisons was relatively small and confined to a narrow frequency band, rather the error appears to be associated with the changing orientation of the probe z-axis.

6 Summary

A comparison of turbulence statistics measured by a sonic anemometer and a turbulence probe at the same height showed that there was good agreement between v and w variances and the stress component $\overline{uw}$. The probe u variances where about 15% smaller than those measured by the sonic.

Comparison between the probe and sonic u spectra showed that there was less energy in the probe spectra at frequencies below 0.02Hz. This appears to be related to changes in the cable orientation, although the way in which this error arises is not clear. Possibly there are errors in the Gill measurements, for example the specification of the non-cosine response may be incorrect, or there may be distortion errors. These sources of error would almost certainly depend on the relative wind direction and could lead to errors which were related to changes in the probe orientation. Evidence for the presence of orientation dependent errors is provided by wind inclination data. Figure 7 shows the wind inclination as a function of the pitch angle of the probe. The wind inclination changes more or less linearly by about 3° for a 10° change of pitch angle. Similar behaviour is found with other probes.

Further work is needed to find the source of the errors seen in this study and reduce them. In addition work is needed to determine how the accuracy of turbulence measurements made with the balloon borne probes depends on wind direction (or more properly the cable orientation). This is particularly important when the wind directions are close to North.

7 References

Lenschow, D. H. and Stankhov, B. B., 1986; Length scales in the convective boundary layer. J. Atmos. Sci., **12**, 1198-1209

Wyngaard, J. C., 1973; On surface layer turbulence. PP 101-149, Workshop on Micrometeorology.

Wyngaard, J. C. ,1981; The effects of probe induced distortion on atmospheric turbulence measurements. J. Appl. Meteorol., **20**, 784-794.

8 Figure Legends

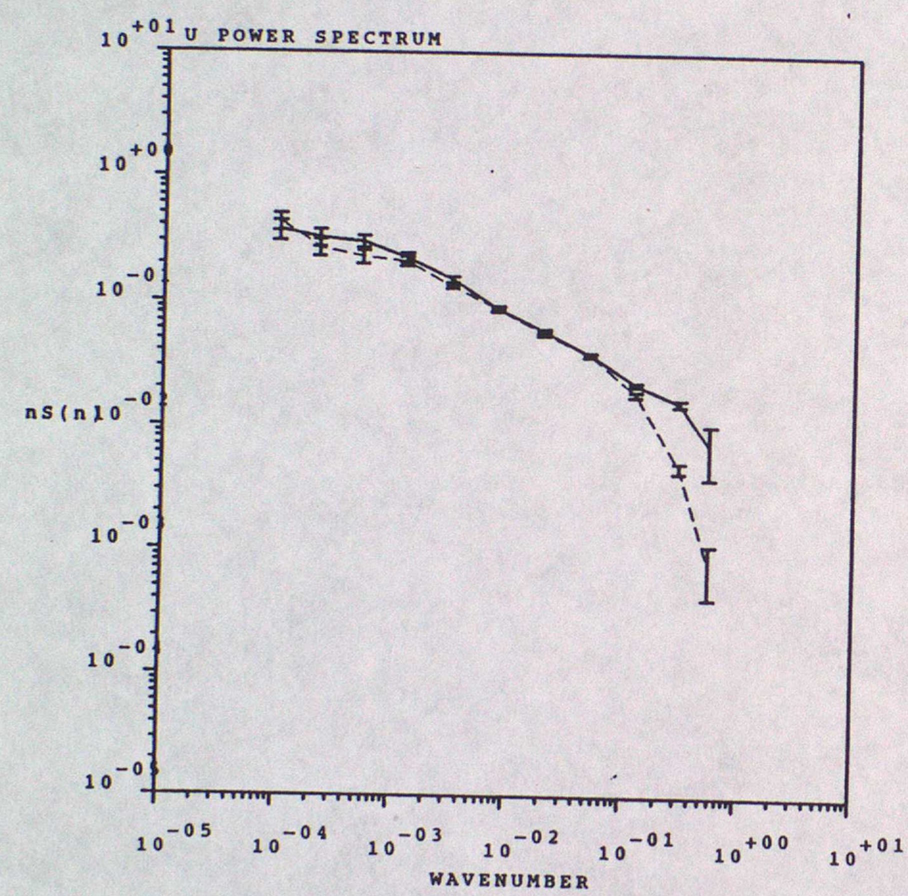
Figures 1 A-D. Average spectra and cospectra. The spectra and cospectra were normalised to their respective variances and covariances before averaging. A) uu, B) vv, C) ww and D) uw.

Figure 2. Comparison of mean windspeeds measured by the sonic anemometer and the turbulence probe. The line shows perfect agreement.

Figures 3 A-D. Comparison of velocity component variances measured by the sonic anemometer and the turbulence probe. A) uu, B) vv and C) ww. The line shows perfect agreement.

Figure 4. Comparison of the x component of the shear stress measured by the sonic anemometer and turbulence probe. The line show perfect agreement.

Fig 1a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WAVENUMBER

Fig 1b

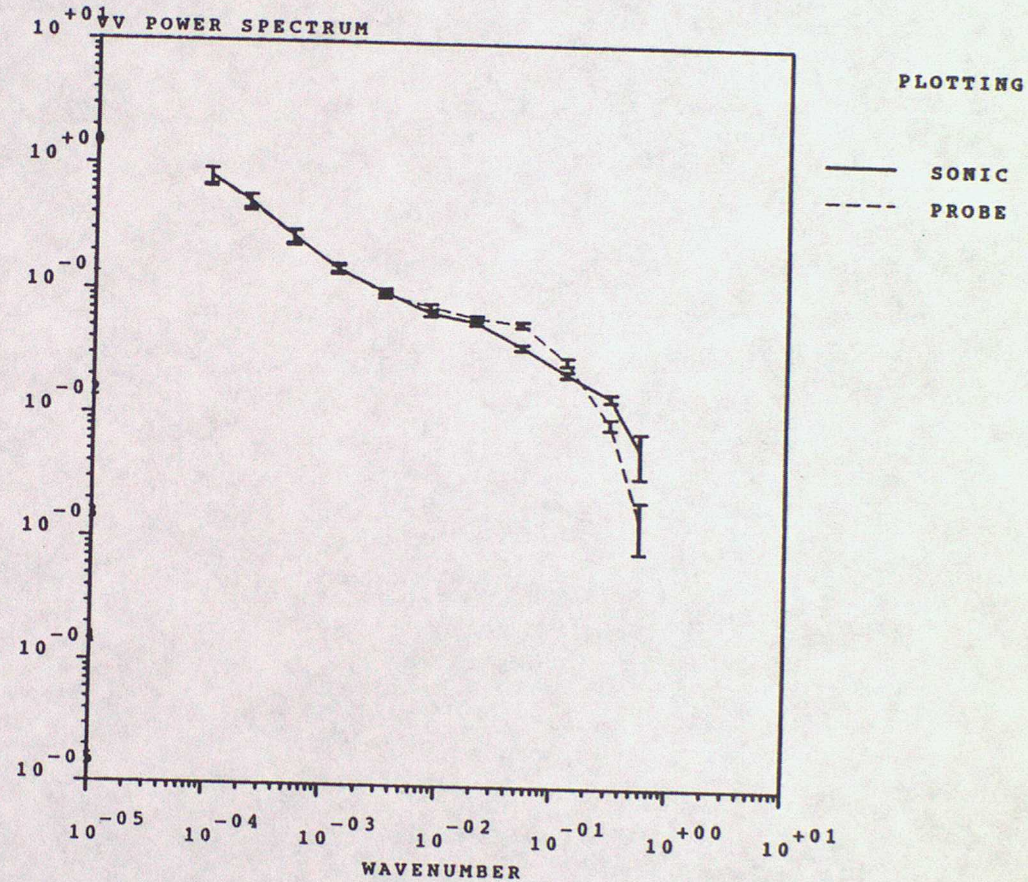

V POWER SPECTRUM
WAVENUMBER
PLOTTING KEY
SONIC
PROBE

Fig 1c

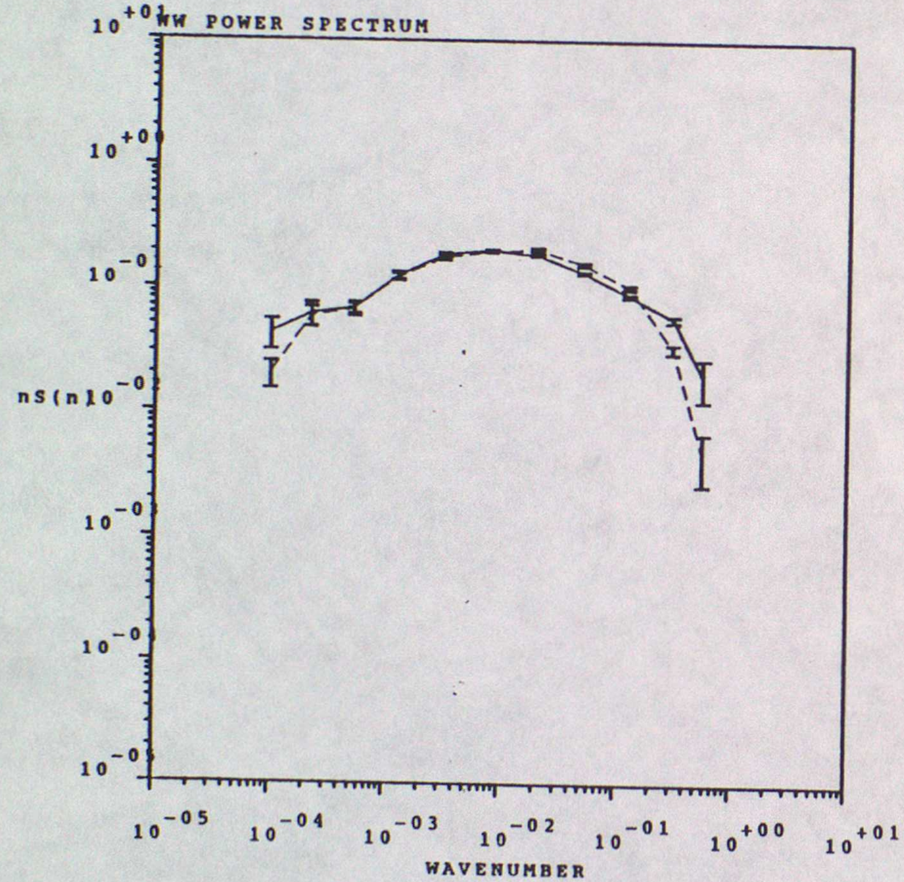
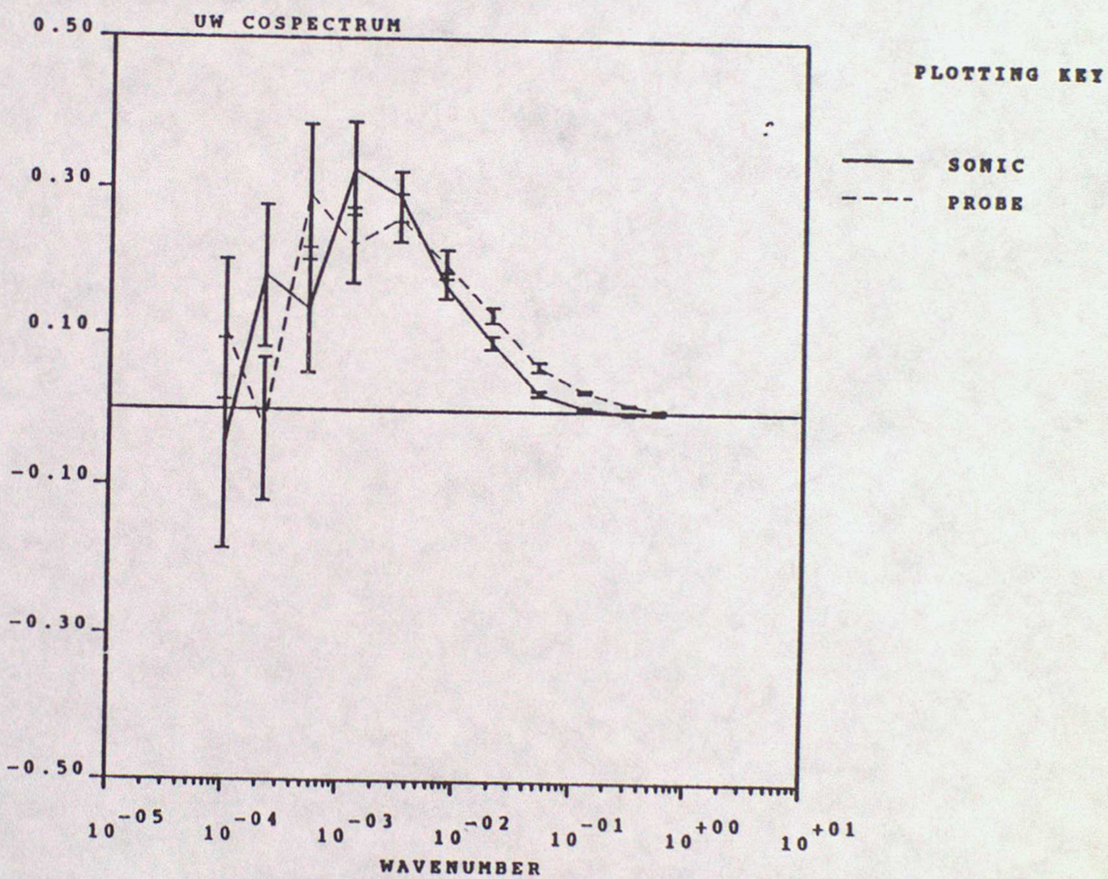

WW POWER SPECTRUM
nS(n)
WAVENUMBER

Fig 1d


UW COSPECTRUM
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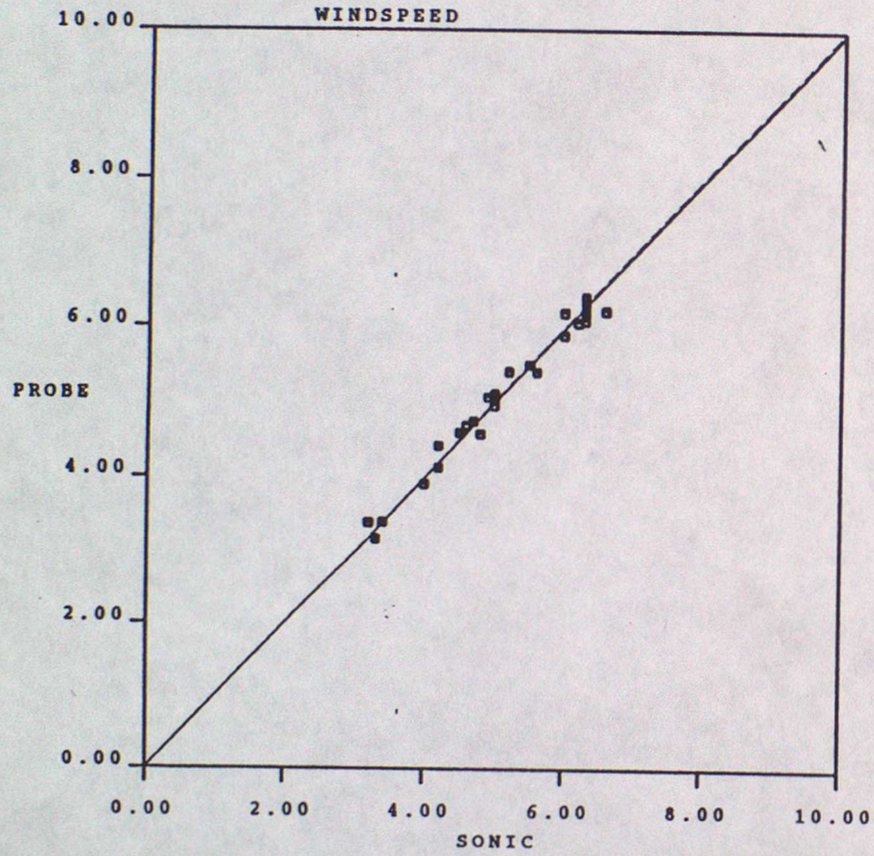
0.10
-0.10
-0.30
-0.50
WAVENUMBER
PLOTTING KEY
SONIC
PROBE

Fig (2)


WINDSPEED
PROBE
SONIC
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0.00
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4.00
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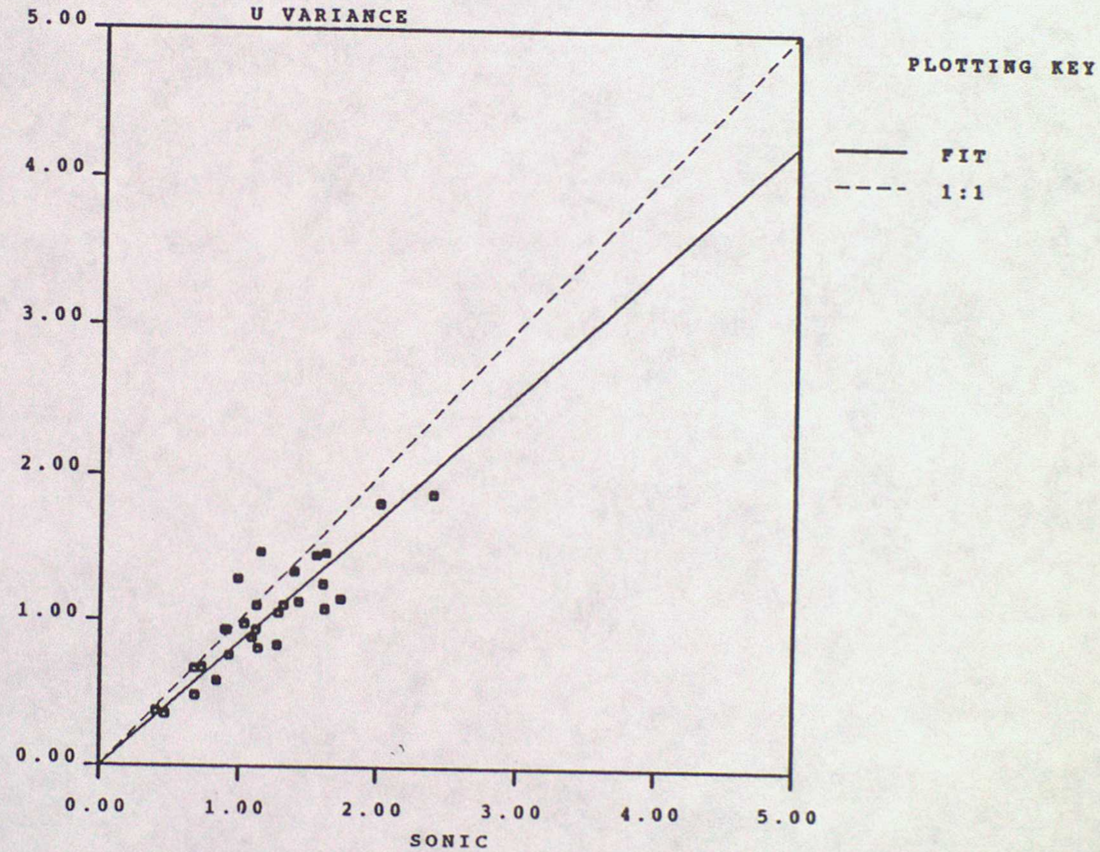
8.00
10.00

Fig 3a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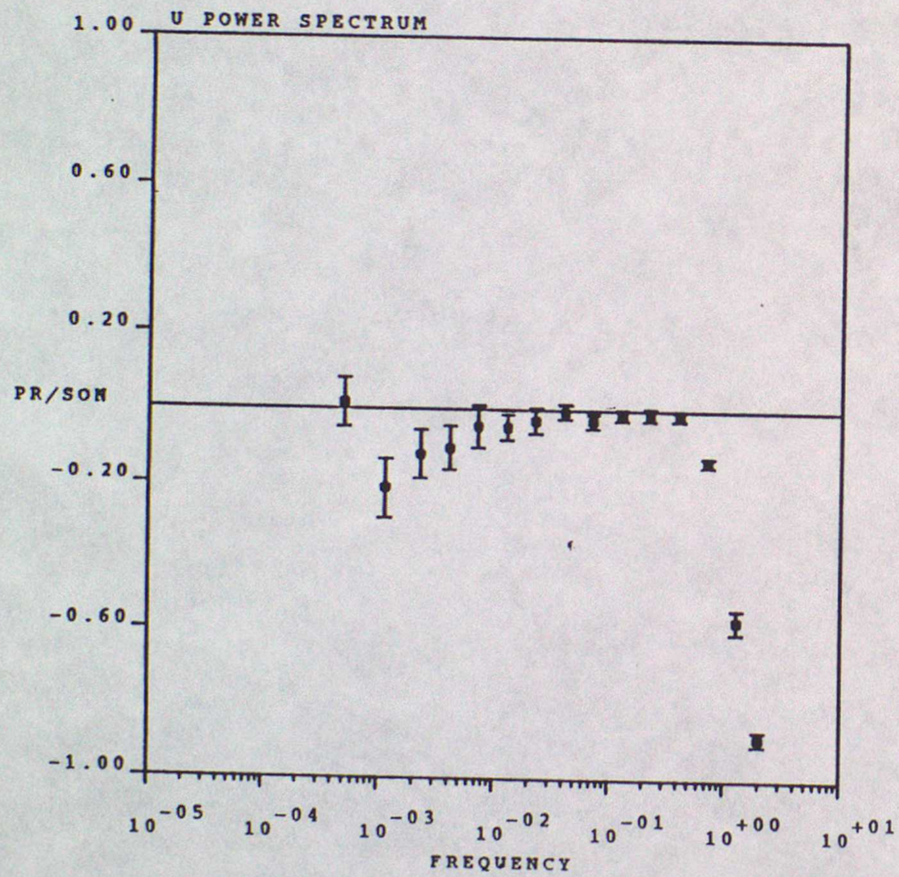
0.00
1.00
2.00
3.00
4.00
5.00
PLOTTING KEY
FIT
1:1

Fig 5a


U POWER SPECTRUM
PR/SOM
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0.60
0.20
-0.20
-0.60
-1.00
10^{-05} 10^{-04} 10^{-03} 10^{-02} 10^{-01} 10^{+00} 10^{+01}
FREQUENCY

Fig 5b

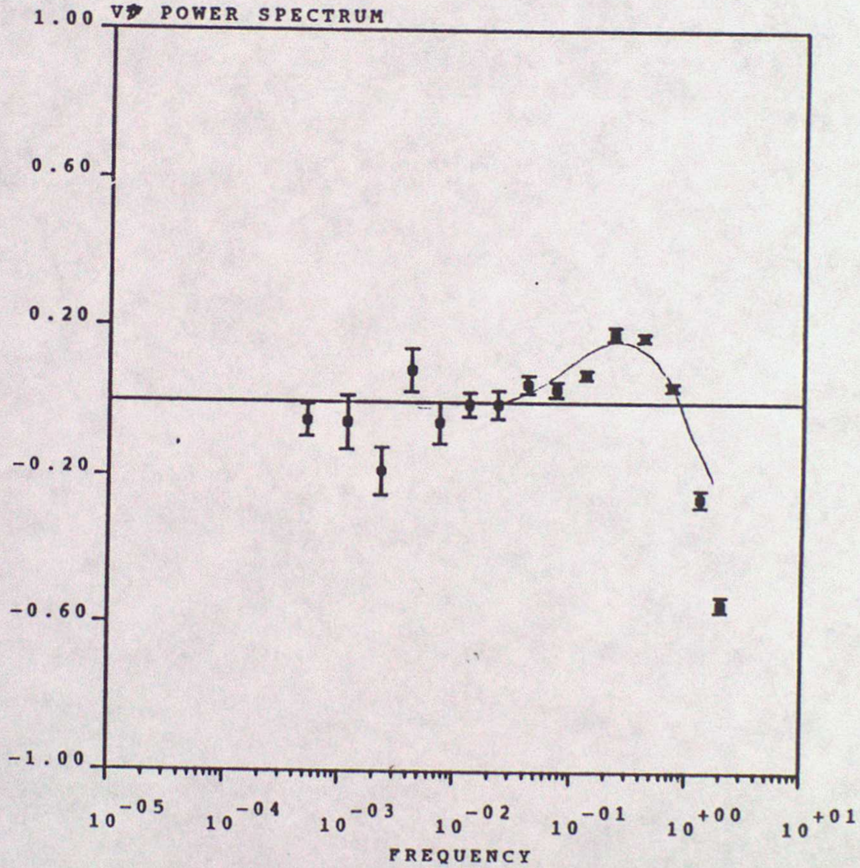
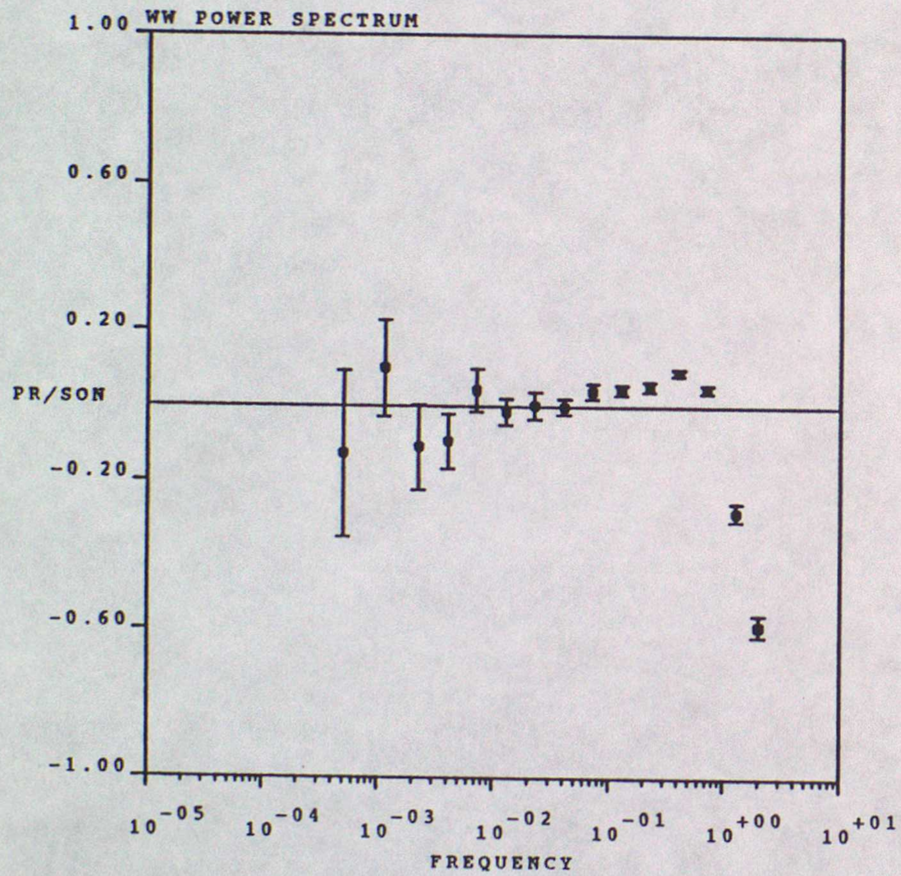

V POWER SPECTRUM
1.00
0.60
0.20
-0.20
-0.60
-1.00
10^{-05} 10^{-04} 10^{-03} 10^{-02} 10^{-01} 10^{+00} 10^{+01}
FREQUENCY

Fig 5c


WW POWER SPECTRUM
1.00
0.60
0.20
PR/SON
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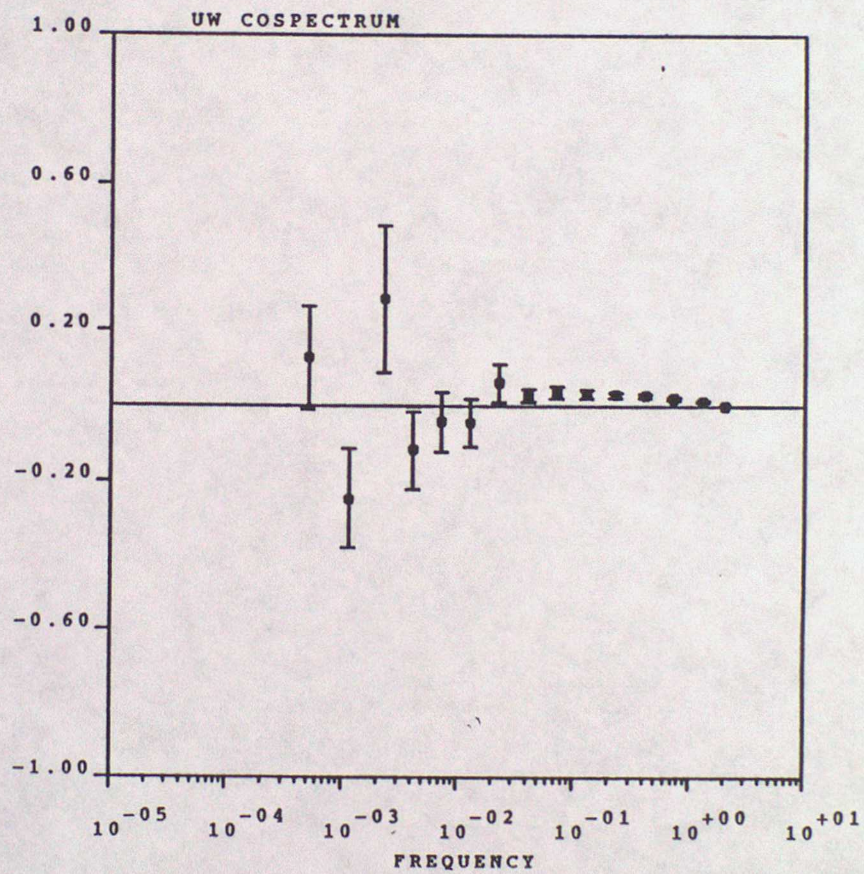
-1.00
10^{-05} 10^{-04} 10^{-03} 10^{-02} 10^{-01} 10^{+00} 10^{+01}
FREQUENCY

Fig 5d


UW COSPECTRUM
1.00
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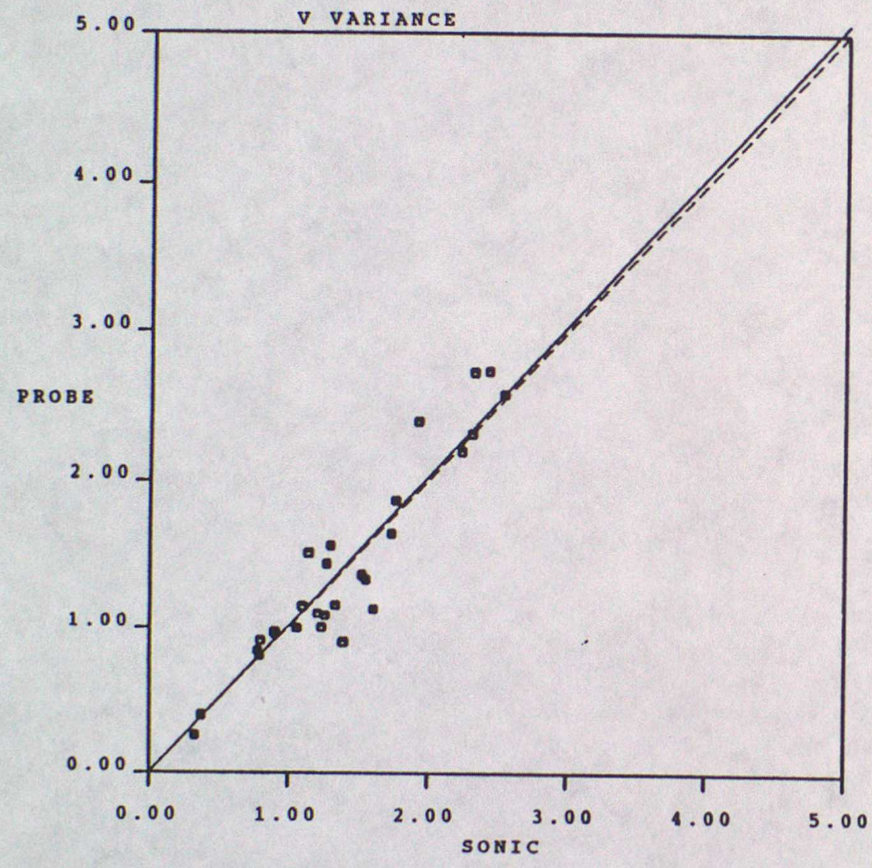
-1.00
10^{-05} 10^{-04} 10^{-03} 10^{-02} 10^{-01} 10^{+00} 10^{+01}
FREQUENCY

Fig 3b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PROBE
SONIC
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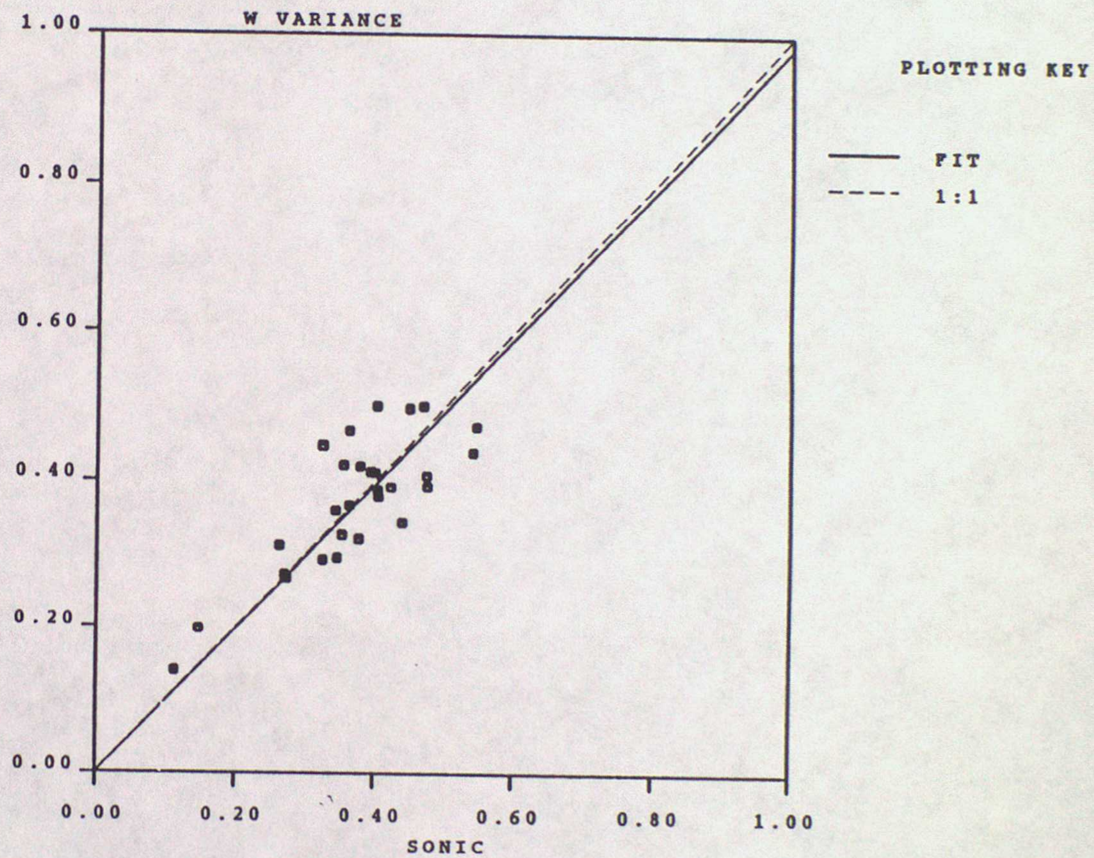
4.00
5.00

Fig 3c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1.00
PLOTTING KEY
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1:1

Fig 4

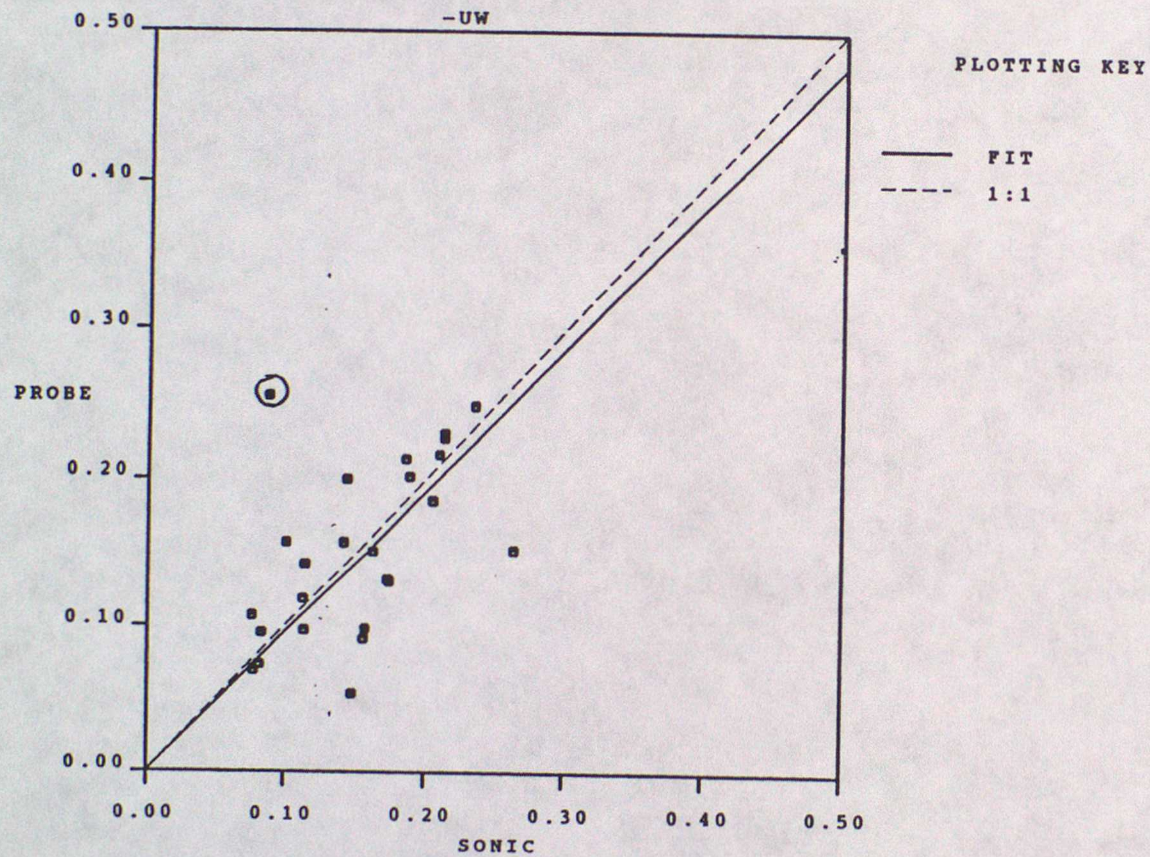
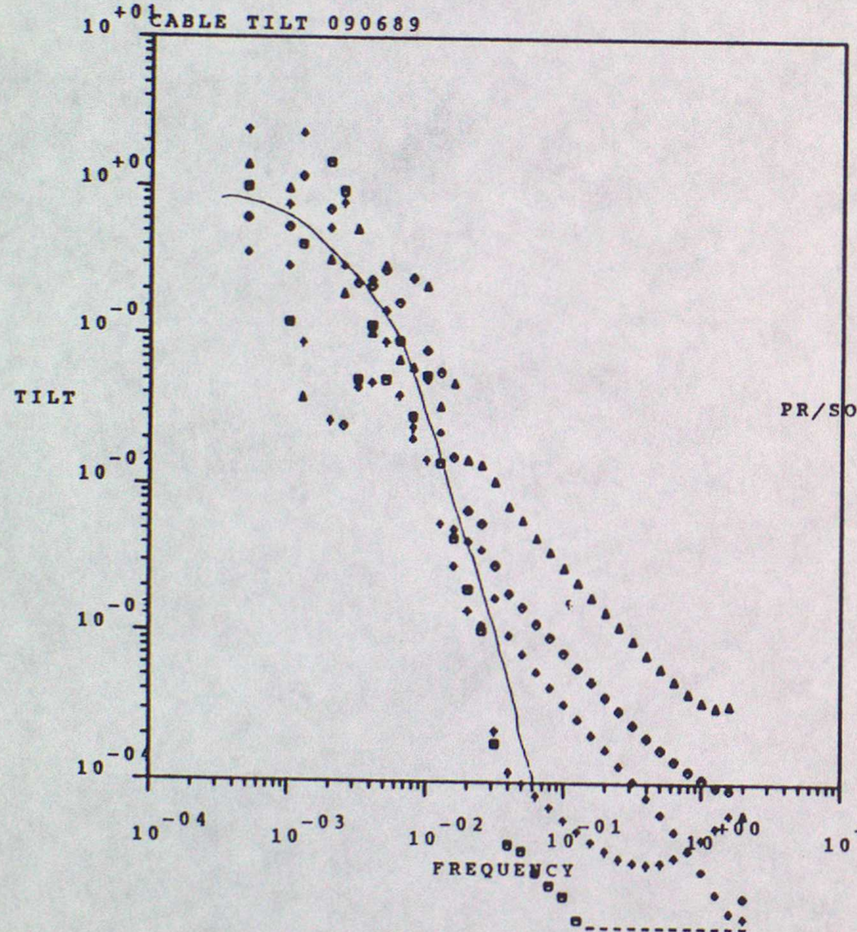


Fig. 6a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TILT
FREQUENCY
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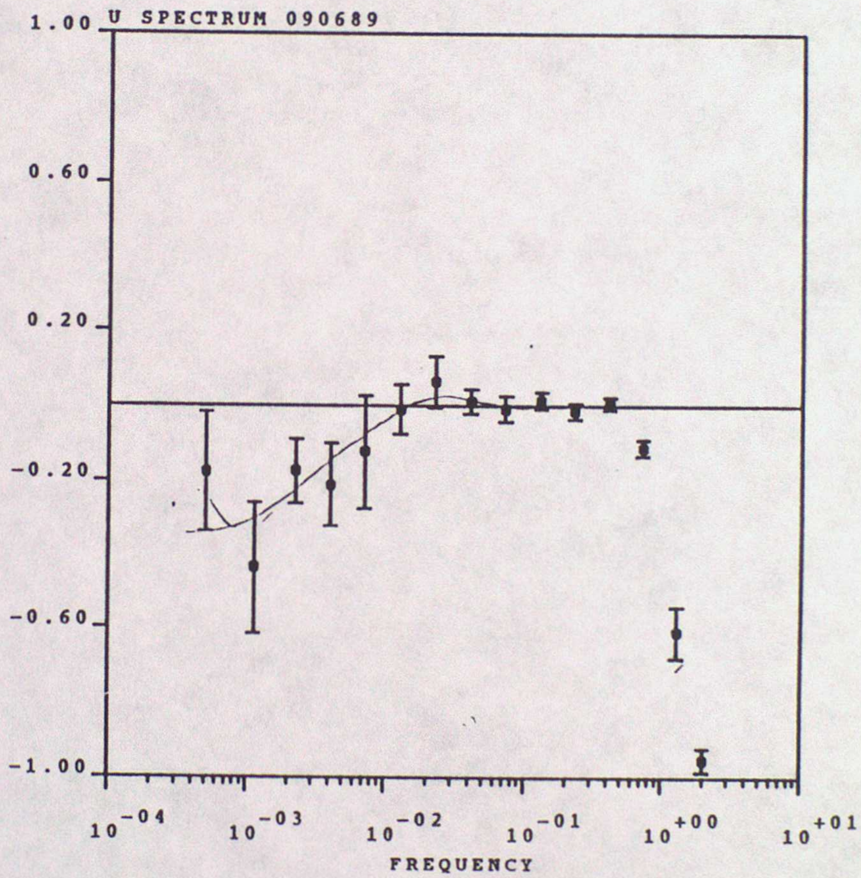
10^-03
10^-04

Fig 6b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PR/SON
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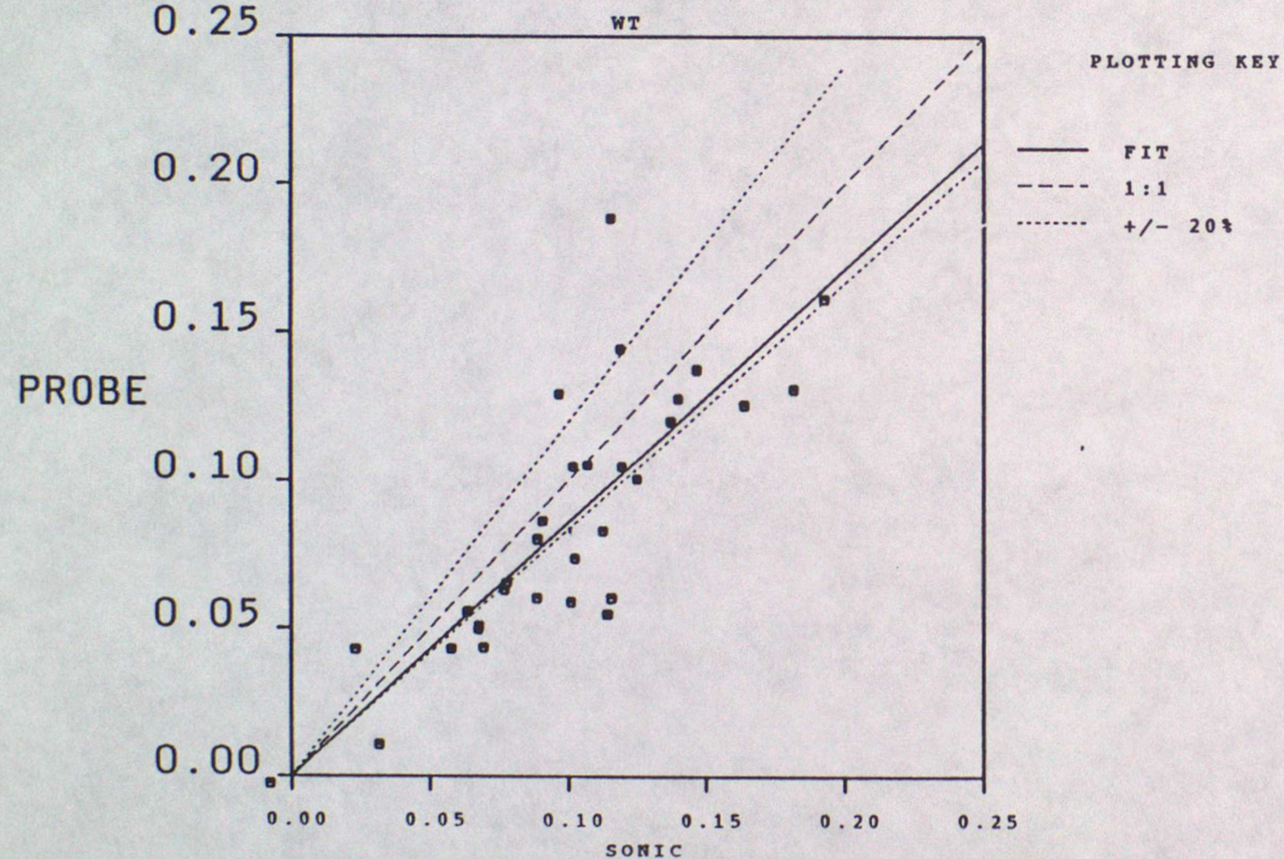

This figure is for interest and isn't referenced in the paper