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COMPARATIVE TESTS OF SEA LEVEL DATA FROM THE NEWLYN TIDE WELL AND AN AANDERAA PNEUMATIC SYSTEM

D.T. PUGH

REPORT NO 119
1981

NATURAL ENVIRONMENT RESEARCH COUNCIL
INSTITUTE OF OCEANOGRAPHIC SCIENCES

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Introduction.

Over the past ten years the Institute of Oceanographic Sciences has gradually adopted the pneumatic bubbler gauge as a standard instrument for measuring sea level at temporary stations, for example, where such information is needed as part of oceanographic research programmes. Pneumatic systems have the advantage of being relatively quick and easy to install, even where the low water line and a suitable recorder housing ashore are separated by distances up to 400m. They also have a closely defined datum level.

Long term measurements have traditionally been made using a stilling well and float gauge configuration, and perhaps the best and most complete British record is that made by the Ordnance Survey at their permanently manned gauge at Newlyn, Cornwall. In order to assess the potential of pneumatic bubbler systems for long term and permanent installations, a pneumatic system, using an Aanderaa differential data logger, was run for a year in parallel with the Newlyn pneumatic gauge. This report summarises the results of these comparisons.

The Ordnance Survey gauge

The Ordnance Survey gauge at Newlyn was established as part of the Second Geodetic Levelling of England and Wales (1912-1921), Close (1922), in conjunction with those at Dunbar and Felixstowe. Observations at Newlyn began a few days before 1 May 1915, and have continued without significant breaks ever since, principally because of the daily attention given by the succession of permanent local operators. Mean sea level at Newlyn was adopted as the Ordnance Datum for the whole survey, and was defined as the mean level from 1 May 1915 to 30 April 1921.

Data from the Newlyn gauge have been used in many scientific studies, some of which are listed in the References at the end of this Report. Figure 1 shows the well and connecting pipe dimensions as determined by direct measurement, and from a drawing supplied by the Ordnance Survey. The diameter of the orifice entry into the well was specified as $1\frac{1}{2}$" on the sketch provided, but has been measured as $1\frac{1}{4}$" by the gauge operator in 1977. The area of the well is unusally large, being equivalent to a circular well 1.50m in diameter. Levels in the well are recorded on a rotating drum chart, which is changed weekly on Monday mornings. Two level checks are made each day, using a lowered probe, on both the rising and falling tide, and the timing, which is checked each morning, is said to have a maximum error of $\pm$ 2 minutes.

The IOS Aanderaa bubbler gauge

Details of pneumatic sea level gauges and their design have been given elsewhere (Pugh, 1972). Measurements using an Aanderaa logger fitted with a Digiquartz differential pressure transducer, and associated pneumatic control circuitry, are reported by Browell and Pugh (1978). At Newlyn, the Aanderaa logger (No. 286) and pneumatic system were installed on 10 June 1978, and removed on 20 May 1979. Magnetic tapes, batteries and air supply were changed on 7 September 1978 and 20 February 1979. Apart from these routine services, no other attention was necessary. The following design parameters were applied during data reduction:

Atmospheric pressure air flow rate	3.0 ml/min
Gas supply pressure	4.0 bars
Gas viscosity	17.6×10^{-6} Si units
Tube length	20.0m
Tube radius	1.90mm
Gravitational acceleration	$9.812\ ms^{-2}$
Elevation of gauge above datum	13.0m
Sea water density	$1025.0\ Kgm^{-3}$

The pressure point outlet was fixed to the harbour wall adjacent to and level with the inlet pipe entrance. The level of the air outlet hole, which should be the gauge datum level, was connected to the Fundamental Bench Mark in the Observatory building; the values obtained were 4.944m below ODN during installation, and 4.936m during recovery. The difference of 0.008m is probably due to errors in the taping down from the harbour wall to the pressure point orifice, as there was no physical evidence of pressure point movement. At gauge recovery, the pressure point was completely covered with weed. The density used was based on an estimated average for the whole year. Subsequently an adjustment to the measured average was necessary. The true average was determined by weekly temperature and salinity measurements.

The recorder which was mounted in the Observatory building, logged pressures at 15-minute intervals, by integrating the quartz crystal transducer's frequency output over a 28-second period to average pressure fluctuations due to waves. These 15-minute values were converted to pressure using laboratory calibrations, and filtered and time shifted to give hourly measurements of pressure. These hourly pressures were then converted to levels using the specified water density and gravitational acceleration. This was in order to make direct comparisons with the data read from the charts of the well recorder, and supplied to IOS by the Ordnance Survey.

A constant sea water density was assumed at $1025.0 Kgm^{-3}$ whereas analysis of the sea water data showed a mean range between summer and winter from $1025.8 Kgm^{-3}$ to $1027.4 Kgm^{-3}$, averaging $1026.6 Kgm^{-3}$. After harmonic analysis, the amplitudes of the pneumatic harmonic constants were therefore reduced by a factor (1025.0/1026.6 = 0.9984) before comparison with the well harmonic constants. It should be realised however (Lennon, 1971) that the stilling well itself introduces distortions because of density effects, which we are unable to quantify.

Comparison between hourly levels from the two gauges

Figure 2 shows the monthly averaged differences between the mean values recorded by the two gauges (well level - pneumatic level). For the first month the mean levels are identical to within 0.001m, but for the following four months the pneumatic levels gradually increase relative to the well levels, stabilising at a level some 0.025m higher for the remainder of the recording year. The upper plot in Figure 2 shows the standard deviation in the difference between the two gauges, after allowing for the datum shift. This has a seasonal variability being greatest in the winter and least during the summer months. Throughout the year the standard deviation of these differences is 0.040m. Both of these comparisons show differences which are far greater than any effects which the density variations could produce.

Table 1 shows the results of identical 1-year harmonic analyses (TIRA) of the two parallel data sets, for the major tidal constituents. The full analysis included 103 constituent pairs. Note that the variance in the original observations for both gauges is very close, but in the non-tidal residuals, there is significantly more variance for the well gauge than for the pneumatic gauge. For the major semidiurnal constituents the amplitudes are very similar for the two gauges, but the phases of the well gauge systematically lag those of the pneumatic gauge by 1.7 , 1.3 , and 1.4 for N2, M2 and S2 respectively. For the other constituents the relationships are not so clearly defined, but these are very much smaller. The main conclusion from the comparison must be the consistency of the results from both gauges.

In order to investigate the nature of the non-tidal residual energy for each gauge, a spectral analysis was made of the residuals from day 300/78 to day 34/79 in each case. The results are shown in Figure 3 and Table 2. The main difference between the two gauges is in the residual energy level in the semidiurnal tidal band, which accounts for $2.26cm^2$ of the total $5.5cm^2$ difference in the residual variances. Figure 3c shows very high coherence at low frequencies and in the fourthdiurnal band, but lower coherence in the other tidal band, including the semidiurnal band.

Discussion

The reason for the difference between the monthly mean sea levels at the two gauges cannot be definitely identified. The original excellent agreement, and the progressive decline to a steady difference of 2.5cm, with the Aanderaa reading higher, is probably due, however, to a gradual blocking of the 3mm orifice in the pressure point during the spring and early summer period of maximum biological activity and marine growth. The standard pressure point used consisted of a 0.14m deep, 0.13m diameter hemicylindrical plastic container, with the orifice 0.02m above the open bottom. As the orifice became gradually smaller due to growth, the excess pressure required before air bubbles could escape (due to the surface tension of the water) rapidly increases. Figure 4 shows this relationship for water at 20°C, normal laboratory conditions, at which this excess pressure needed for air escape has been observed (W. Ainscow and A. Browell, personal communication). The upper limit to this excess pressure is reached when it becomes sufficient for air to escape through the bottom of the pressure point rather than through the orifice, effectively lowering the datum level by 2.0cm. Once this degree of growth was reached, air would cease flowing through the orifice and there would be nothing to inhibit growth blocking the orifice completely.

The differences between the principal constituents produced by the two analyses are remarkably small, and may be used to justify oceanographic conclusions based on data from instruments of either type. However, the consistent phase lag of the principal semidiurnal well phases on the pneumatic phases requires further examination. Noye (1974) has considered the theoretical behaviour of stilling wells, and shows that for a stilling well having an orifice connection, a well constant may be defined:

$$C = \sqrt{2g} \quad C_c\left(\frac{A_P}{A_W}\right)$$

where g is gravitational acceleration,

A_p is the orifice cross sectional area,

A_w is the well cross sectional area,

and C_c is an orifice contraction coefficient which relates the effective orifice area to the true area. For a circular orifice a value of 0.6 has been found appropriate.

For the Newlyn well, using the contemporary measured orifice diameter of 3.2cm ($1\frac{1}{4}$") rather than that specified in the Ordnance Survey diagram, $A_p = 0.000475\ m^2$ and $A_w = 1.765\ m^2$. Hence

$$C = 0.001191\ m^{\frac{1}{2}} s^{-1}$$

In terms of this constant, Noye shows that the phase lag and attenuation introduced by the well to a harmonic tidal change of external level of frequency and amplitude a is given by:

$$\text{phase lag} = \frac{8\beta^2}{3\pi}$$

$$\text{attenuation factor} = 1 - 0.64\,\beta^4$$

where β is a dimensionless frequency:

$$\beta = \frac{\omega\sqrt{a}}{C}$$

For M2, the principal semidiurnal tidal constituent, which has angular speed 1.405×10^{-4} radians s^{-1}, and an amplitude of 1.70m at Newlyn,

$$\beta = 0.154$$

and hence the theoretical well effects are:

$$\text{phase lag} = 1.2^{\circ}$$

amplitude attenuation = 0.9996.

The agreement between the observed phase lag and that predicted by theory is satisfying. However, it should be realised that even slight further contractions of the orifice area would have a serious delaying effect, as the phase lag depends inversely upon the square of the orifice area. Also, Noye's theory is a non-linear one, and superposition of several harmonic constituents is not valid.

This persistent lagging of the well levels, even by 1.3^{o} of M2 phase (2.7 minutes of time), will produce regular differences between the two gauges at tidal frequencies, and will therefore account for some of the standard deviation in the differences plotted in Figure 1. Consider the difference between two sea level tidal variations of equal amplitude, but slightly displaced in time:-

$$\Delta \zeta = a \cos \omega t - a \cos(\omega t + \Delta t)$$

The resulting harmonic variation has an amplitude a $\sin \Delta t$, and a variance $\frac{1}{2} a^2 \sin^2 \Delta t$. The corresponding standard deviation in the difference time series, in the absence of any other effects would be $\frac{a}{\sqrt{2}} \sin \Delta t$. For M2 at Newlyn, $\Delta t = 1.3^{0}$ and a = 1.70m giving a standard deviation of 0.027m. 37% of the variance in the difference time series is accounted for by the well lag of M2 alone.

The phase lag of the M2 harmonic constituent can account only for that part of the difference which is coherent with the astronomical tidal forcing. Table 2 and Figure 3 have shown that there is also twice as much energy in the non-coherent residuals from the well analysis than from the pneumatic gauge analysis. Such energy in the well signal could be introduced by intermittent partial blockages of the well orifice. For an earlier study of the probability of extreme levels (Pugh and Vassie, 1980), data from the Newlyn gauge were analysed for the period 23 April 1951 to 29 June 1969. Non-tidal residuals were computed and plotted year by year for visual examination. Figure 5 shows the plot for 1953. Apart from residuals with period from 2 to several days, these records showed considerable variability at semidiurnal tidal frequencies. There were also sharp discontinuities - see for example the trace for August 1953.

25 of the most obvious discontinuities were identified by the month and day number on the plots, and the corresponding day of the week was then determined from historical calendars. The distribution was:-

Sunday	3
Monday	19
Tuesday	0
Wednesday	1
Thursday	0
Friday	1
Saturday	1

The charts are changed regularly on a Monday morning, and from this pattern it is clear that errors, presumably due to time shifts, can be introduced at these times. In addition, 52 periods of large semi diurnal residuals were examined further, and for 22 of these periods there was sufficient evidence to prove partial blockage. Examples of such corrected periods include times when a sudden positive or negative surge has a maximum at mid-tide and persists for only 6 hours or so. Often at these times the well trace also appeared sluggish in its response to the characteristic local seiches which have a period of about 5 minutes. IOS divers reported crabs living in the 9" pipe when the pneumatic gauge was removed. Munk and Cartwright (1966) found energy cusps at semidiurnal frequencies in both the Newlyn and Honolulu data which they analysed. At least some of this energy at Newlyn ($5cm^2$) was probably due to well effects. The highly coherent nontidal energy in the fourthdiurnal bands of both gauges is probably indicative of real oceanographic variability in the nonlinear generation processes.

Conclusions

1) The differences in the levels of the two gauges had a standard deviation of 4.5cm. Despite this the amplitudes and phases of the tidal constituents obtained from the gauges agreed sufficiently to give confidence in analyses of data from either type of gauge.

2) There is consistent lag of 2.7 minutes in the well M2 tide due to the small orifice and the exceptionally large well area. This difference is in agreement with Noye's theoretical considerations. Normal stilling wells would have a much shorter phase lag. Also, residual energy at semidiurnal frequencies in the well is twice that for the pneumatic system; this is thought to be due to intermittent partial well blockages and to the limitations of setting the time accurately on a chart recorder. The attention given by the operators to the Newlyn well is much more dedicated than that associated with normal A-class gauges and operators, and so timing errors are likely to be even more significant at other gauges.

3) The pneumatic system and Aanderaa logger performed well, and proved suitable for longer term installations. However, a careful system of datum checks must be applied, and some redesign of the pressure point may be necessary to prevent orifice blockage.

Acknowledgements

The pneumatic gauge was prepared by A.J. Harrison and installed by D.L. Leighton and the IOS (Bidston) diving team. It is a pleasure to acknowledge both the dedicated attention given to the permanent Newlyn gauge by a succession of operators, and the cooperation of the Ordnance Survey in the making of these comparisons.

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Table 1. Newlyn Sea level gauge tests

1 year comparative harmonic analysis (161/78 to 140/79)

		PNEUMATIC AANDERAA		WELL GAUGE	
	ω °h^{-1}	H(m)	g°	H(m)	g°
Sa	0.0410686	0.1176	288.6	0.1087	286.6
Msf	1.0158958	0.0120	326.1	0.0137	336.4
O1	13.9430356	0.0528	340.4	0.0512	340.8
S1	15.0	0.0037	29.6	.0040	20.1
K1	15.0410686	0.0628	110.5	0.0625	111.6
μ_2 (2MS2)	27.9682084	0.0483	169.3	0.0507	166.7
N2	28.4397295	0.3226	114.2	0.3256	115.9
M2	28.9841042	1.7069	133.7	1.7067	135.0
S2	30.0	0.5665	177.5	0.5627	178.9
K2	30.0821373	0.1641	177.2	0.1614	177.3
2SM2	31.0158958	0.0182	28.5	0.0166	20.4
M3	43.4761563	0.0114	32.6	0.0115	29.8
M4	57.9682084	0.1116	166.3	0.1088	169.6
MS4	59.9841042	0.0723	218.4	0.0696	218.1
M6	86.9523127	0.0093	329.6	0.0082	334.7

Standard Deviation-	Observations	1.360m	1.359
	Residuals	0.1329m	0.1352
Variance	Observations	1.849m^2	1.847
	Residuals	0.01766m^2	0.01827

Table 2. Non-tidal residual variance distributions.

	BAND	WELL Cm^2	ANDERAA PNEUMATIC Cm^2
0.0→0.48 cpd	0	237.3	237.2
0.8→1.1	1	3.34	3.32
1.8→2.1	2	4.44	2.18
2.7→3.2	3	0.50	0.34
3.6→4.2	4	2.86	2.58
	5		
5.4→6.3	6	0.32	0.13
Total Residual Variance		269.1	263.6

Figures

1. Sketch of Newlyn stilling well (not to scale), based on a copy supplied by the Ordnance Survey. Imperial units are as supplied. Outlet diameter stated to be 1½", but measured in 1977 as 1¼". Position and size of inlet pipe reported verified by harbour diver, December 1952. The well has a rectangular cross section 4'0" by 4'9".

2. Monthly differences, as standard deviation and mean level divergence, between Newlyn well data and Aanderaa pneumatic data.

3. Spectral analyses of a) well and b) pneumatic gauge residuals, bandwidth 0.0010 cycles/hour; c) coherence and phase lag between gauges and d) cross spectral analysis of residuals, bandwidth 0.0025 cycles/hour.

4. Pneumatic gauge: relationship between excess bubble pressure needed for air escape and orifice diameter (at 20°C).

5. An example of a year (1953) of Newlyn well nontidal residuals. Note the intermittent semidiurnal signal.

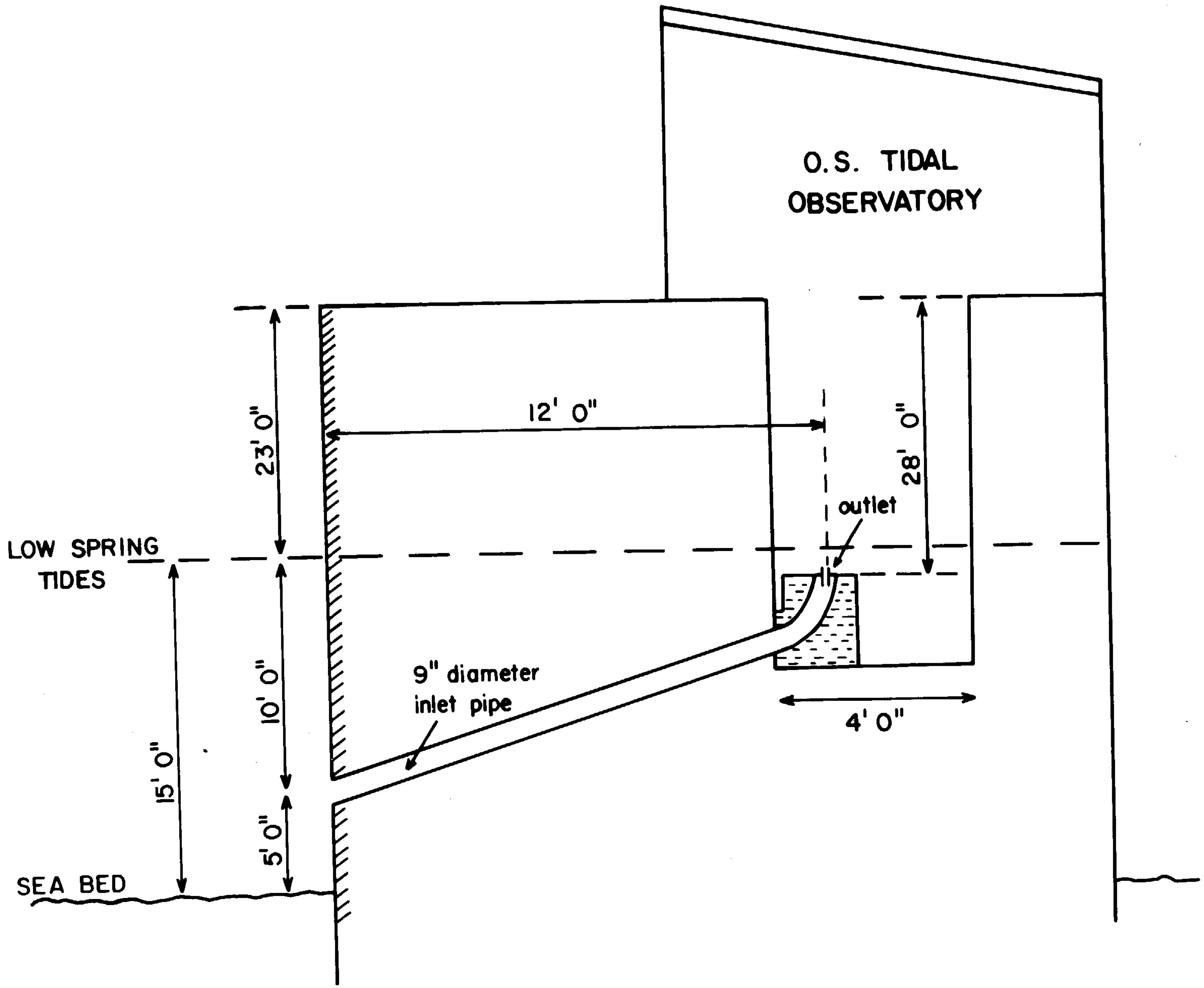

O.S. TIDAL
OBSERVATORY
23' 0"
12' 0"
28' 0"
outlet
LOW SPRING
TIDES
10' 0"
9" diameter
inlet pipe
4' 0"
15' 0"
5' 0"
SEA BED

Figure 1

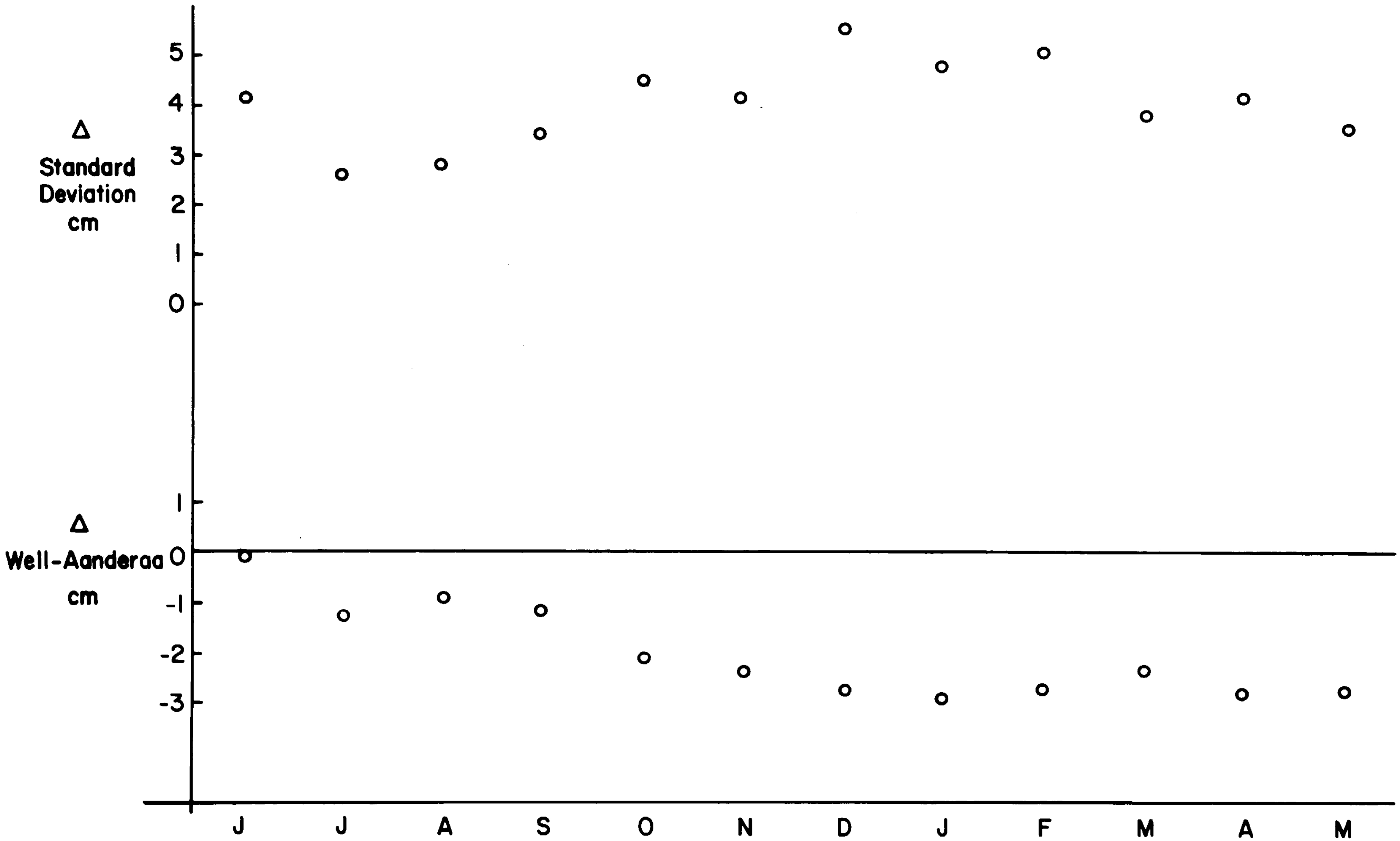
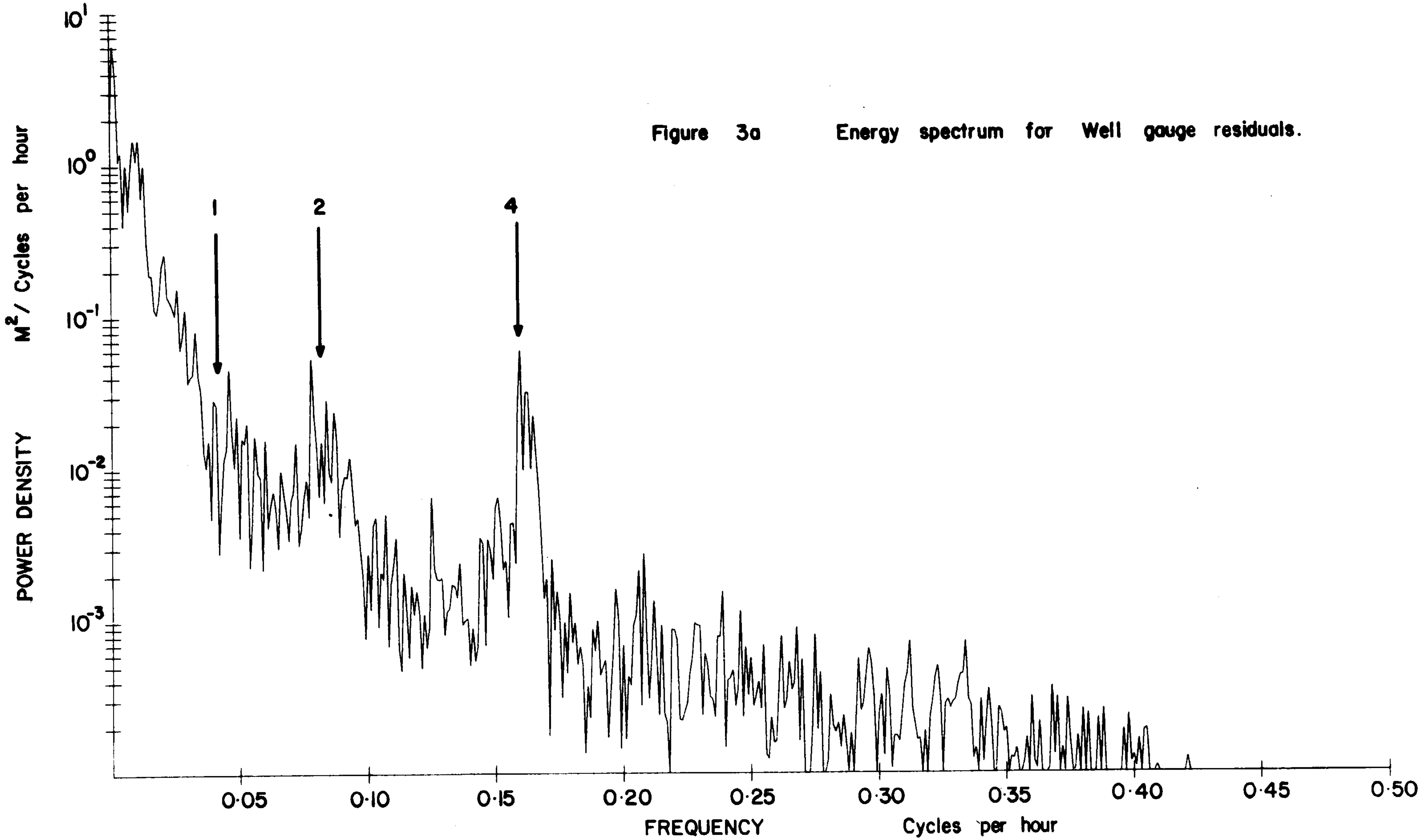


Figure 2 Monthly differences between Newlyn well data and Aanderaa pneumatic data.

Figure 3a Energy spectrum for Well gauge residuals.



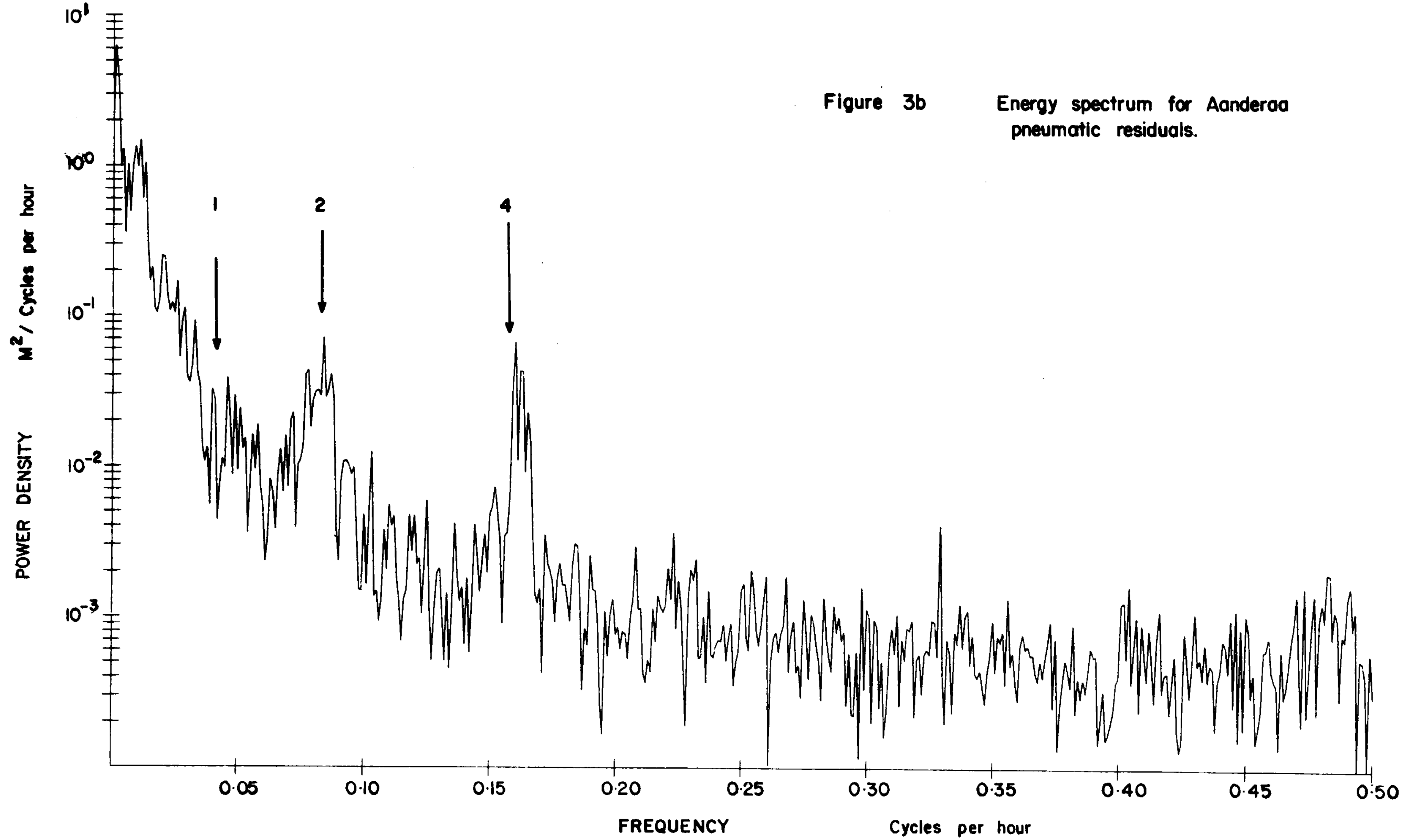


Figure 3b Energy spectrum for Aanderaa pneumatic residuals.

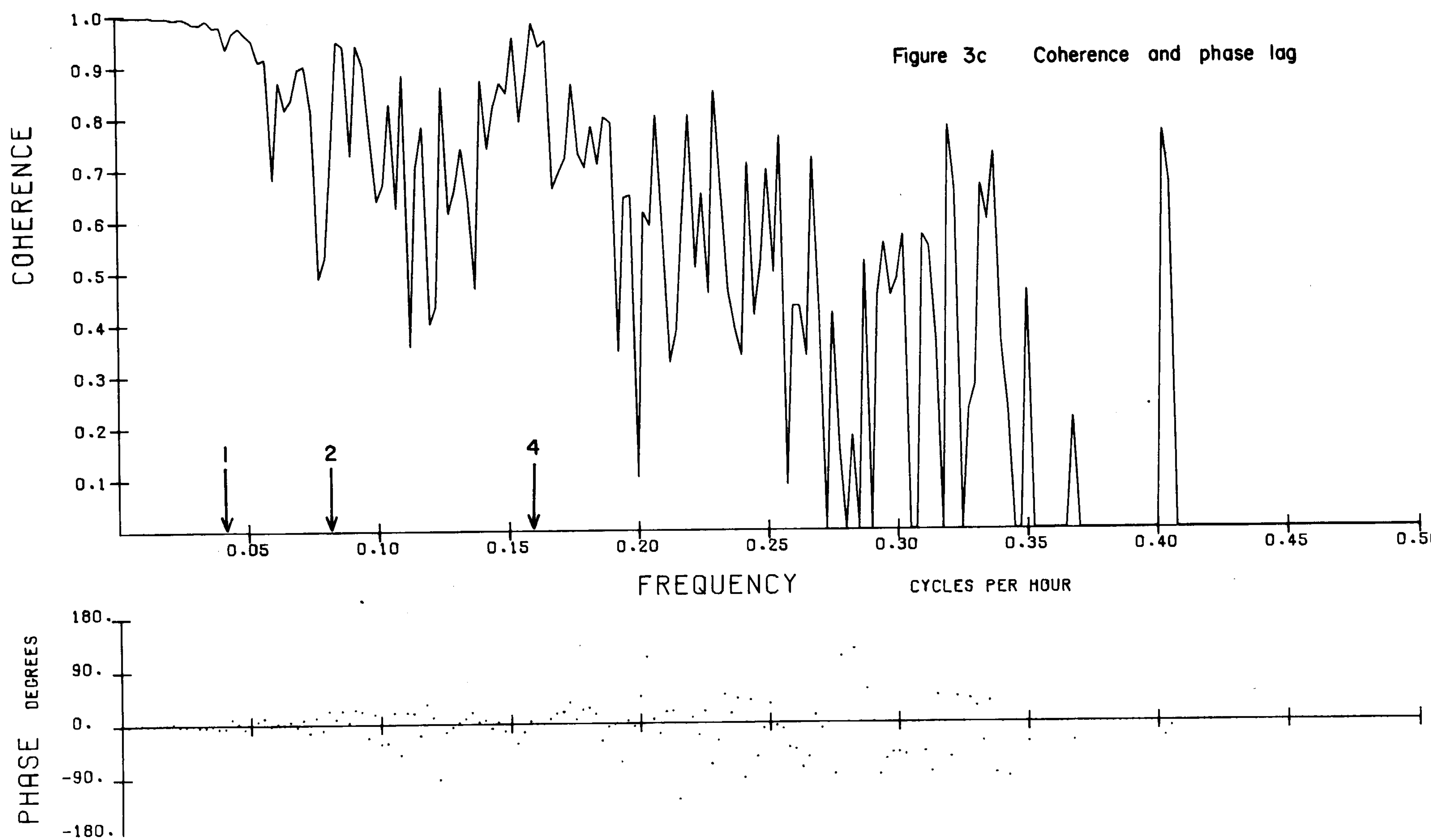


Figure 3c Coherence and phase lag

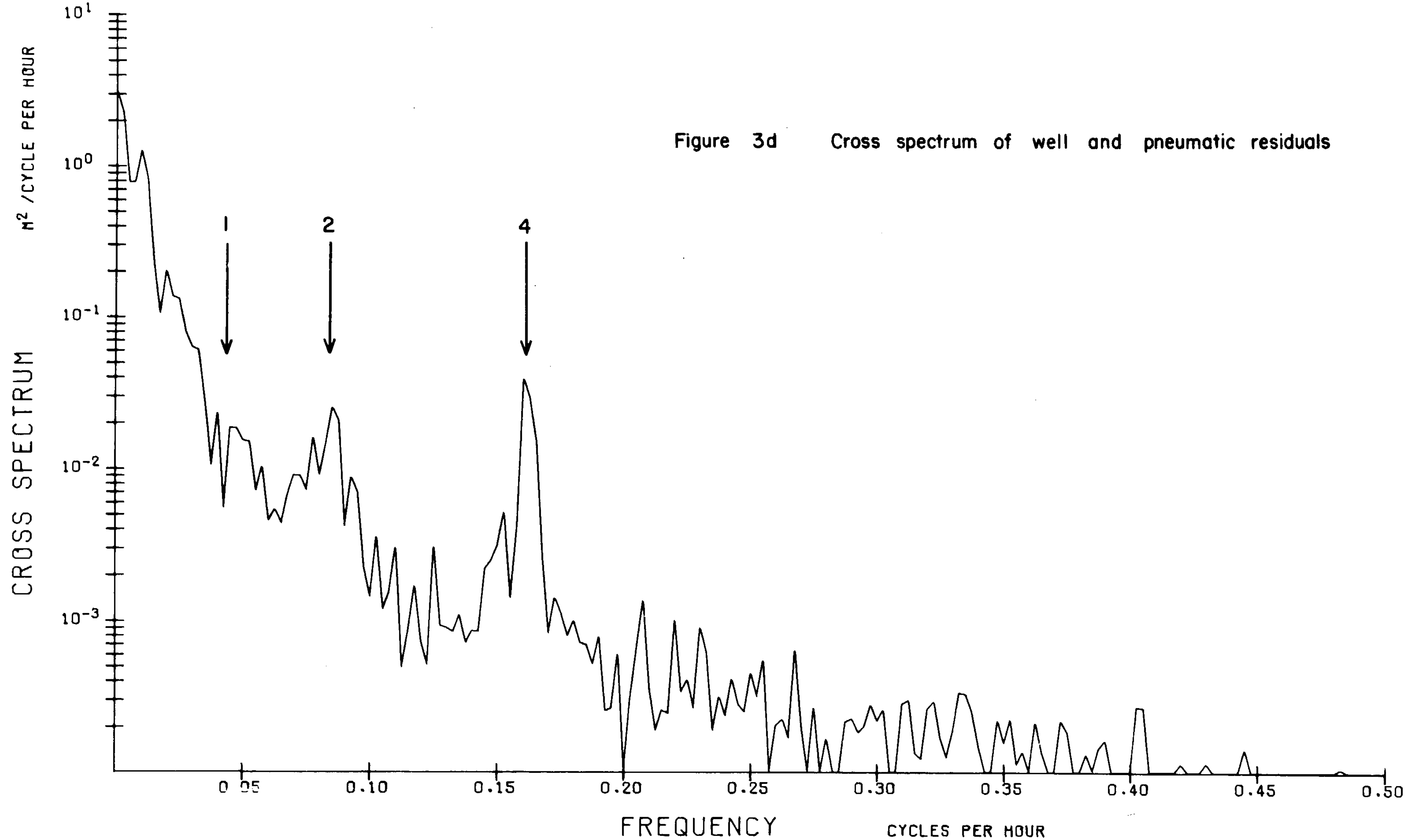


Figure 3d Cross spectrum of well and pneumatic residuals

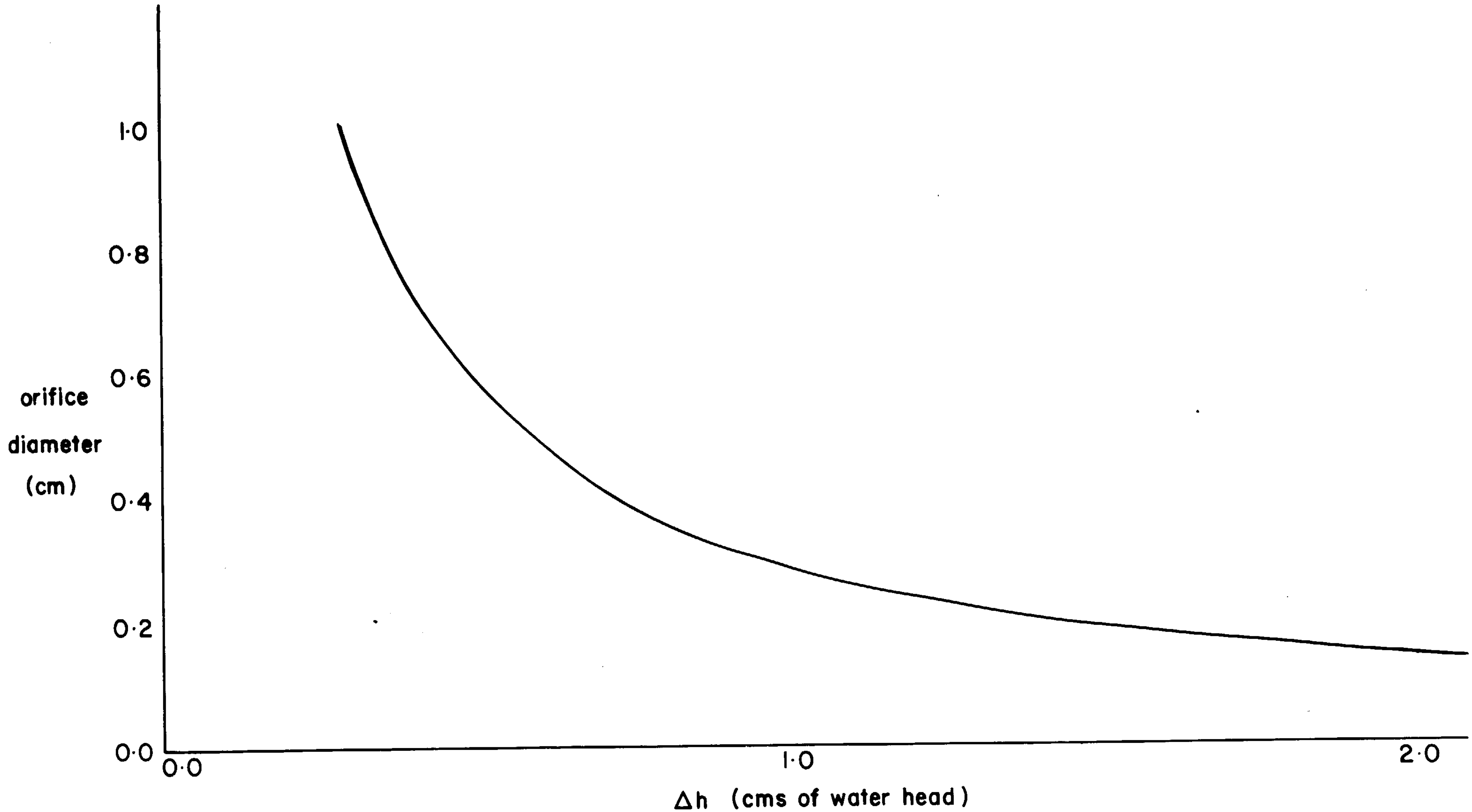

1·0
0·8
0·6
0·4
0·2
0·0
orifice
diameter
(cm)
0·0
1·0
2·0
Δh (cms of water head)

Figure 4

Figure 5 Newlyn well residuals 1953 metres