DISCHARGE AND TURBIDITY OF THE REGULATED RIVER TEES. VARIANCE SPECTRUM ANALYSIS

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Discharge and turbidity of the regulated River Tees. Variance spectrum analysis.

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Summary

Variance spectrum analysis was applied to a series of over 4000 paired daily turbidity and discharge readings in a regulated river.

The spectra for both turbidity and discharge are not significantly different to a red-noise spectrum at high frequencies although the climatic annual cycle is represented by a broad significant peak at low frequencies.

The 'flatness' of the spectra may be typical of regulated flow regimes where regular episodic releases of water are not required and the catchment soils are undisturbed.

Although a significant persistence in the turbidity record of twenty-two days could be identified in a partial autocorrelation plot, from a practical point of view, persistence is strong for only four days. This result demonstrates the rapid response of the stream sediment load and is in broad agreement with a previous investigation where the memory in the system was estimated to be between one and five days.

INTRODUCTION

High suspended sediment loads may be deleterious to adult salmonids and invertebrates in gravel-bedded streams. Further, the accumulation of fine material in the interstices of the gravel may have an adverse impact on the recruitment of the young stages of salmonids. It is important therefore not only to quantify the rates and degrees of silting but also to identify sediment sources and to determine both, the frequency of sediment inputs to the system and the duration of high sediment concentrations.

Sediment inputs to a river may be classified as temporally periodic and aperiodic and as spatially diffuse or point-source in origin. Catastrophic natural point-source inputs of suspended sediment (e.g. Crisp et al., 1964) are rare in the UK, of uncertain return period and are consequentially difficult to predict or mitigate. Periodic point-source inputs are easier to identify, especially if the inputs are anthropogenic in origin.

In a natural flashy river, periodic sediment pulses may be obscured by diffuse and quasi-periodic suspended sediment loads. In contrast, in a regulated river, periodic sediment pulses associated or independent of discharge pulses should be easier to detect.

This report explores the application of variance spectrum analysis to the isolation of sediment periodicities. For the particular river chosen for examination the method demonstrated the essentially undisturbed nature of the catchment.

The regulated river chosen for examination is the R. Tees in Northern England. A location map and details of the discharge and sediment regime are presented in Carling and Douglas (1984).

RATIONALE

Analysis of time-based data, using correlation and regression methods, although yielding relationships between variables, may mask feedback effects, temporal oscillations and discontinuities in series. Methods pertaining particularly to time-series, such as variance-spectrum analysis permit the identification of important frequencies, the degree of interaction and the lag between two series at various frequencies in the time-domain.

Turbidity in the R. Tees largely reflects suspended sediment concentration (SSC) (Carling & Douglas, 1984). Although SSC can be expected to exhibit periodicities and trend components it is dominated by stochastic inputs (Thornes, 1982) and so spectrum analysis cannot be expected to identify input frequencies as easily as might be achieved with a conductivity or temperature record; the variance being much less in the latter two cases. This fact, in addition to problems of interpreting the results (e.g. Dowling, 1974), has limited the application of the method to suspended sediment regimes.

Applications of spectrum analysis to fluid and sediment discharge are given, for example, by Rodriguez-Iturbé & Nordin (1968) and to fluid discharge and water chemistry by Edwards & Thornes (1973). Introductory texts describing the basic theory are given by Kisiel (1969), Rayner (1971), Bloomfield (1976) and Chatfield (1980).

With the limitations of the method in mind, temporal regularities in the turbidity record may reflect either process controls limiting sediment supply at source, or transit controls reflected in the behaviour of the discharge record. Periodic fluctuations might be attributable to such factors as climate, operational policy of reservoirs and land-use: whilst any long-term trend might be consequent upon the imposition of an impoundment, at Cow Green, on the system.

METHODS

River discharge is abstracted for public water supply at Broken Scar near Darlington, and the flow is regulated for this purpose by Cow Green reservoir, some 64 km upstream of the sampling point.

A series of 4125 daily paired (0900 G.M.T.) observations of turbidity and water discharge were available for the N.W.A. gauging station at Broken Scar. The record is unusually complete and covers the eleven year post-impoundment period following the completion of Cow Green reservoir in 1971.

Summary statistics of the time-series are given in Table 1. Basic data histograms and an analysis of the data using correlative methods and least-squares regression analysis are presented by Carling & Douglas (1984) in an analysis of the total annual suspended load. Fig. 1 is an example of the time-series for the water year 1979.

Time-series need to be stationary for variance spectrum analysis. Least-squares linear regression analysis indicated that although the turbidity record had the same average level over the eleven year period, the discharge record exhibited a significant ($P < 0.05$) non-zero positive increment of $0.75 m^3 s^{-1} yr^{-1}$ (Fig. 2). The increment may be explained by a progressive operational requirement for higher discharges over the period in question (Archer, pers. comm.). After linear interpolation of short gaps (the longest being five days) the record was corrected by linear detrending.

For the trend-corrected data both the raw and a series of smoothed spectra were calculated using the Parzen-window and a 10% taper. The program, implemented on the Honeywell 6800, is based on the method of Bloomfield (1976). Also calculated were the auto-correlation and partial auto-correlations of each series and the cross-correlation between series, although not all details are reported here. In addition, the coherency, gain and phase were considered.

RESULTS

Autocorrelation

The autocorrelation and partial autocorrelation functions were calculated for each series to lag 500. The autocorrelation is the correlation between X_i and X_{i+j}, where j is the lag number (j = 0, 1, 2, 3, ...) and the partial autocorrelation is used to investigate the persistence in the dependence between the two series. The partial autocorrelation analysis demonstrated a statistically significant non-zero persistence in the discharge and turbidity record of 26 and 22 days respectively. Closer examination of the partial autocorrelation plot indicated that the effect, from a practical point-of-view, was only notable up to about a four day lag for turbidity, (Fig. 3).

The auto and partial autocorrelations indicated that both series are non-random but may be represented by a low-order Markov model.

Variance spectra

The raw variance spectra for the discharge and turbidity are plotted in Fig. 4 on logarithmic co-ordinates. The exponent of the power function describing the least-squares trend of the spectral signature for discharge is -0.48. The trend-line for the turbidity signature however is less steep -0.37, indicative of a higher proportion of the variance association with high frequencies than is the case for the discharge record.

The raw spectra were smoothed to remove gross spectral fluctuations leaving only the broad-scale features (Fig. 5). The 95% confidence limits, plotted on log-log co-ordinates, are parallel to the smoothed spectrum, so for clarity, the spectrum in each case is not plotted. Significant peaks in the spectrum may suggest separate generating mechanisms. The significance of individual peaks was determined by comparing the 95% C.L. with the spectrum of the fitted Markov 2nd order process (a red noise spectrum) (Munn, 1970, p. 151). Effectively, where the red noise spectrum falls outside the 95% C.L., the fluctuation in the smoothed spectrum is significantly different from red noise. The Nyquist frequency is at 2 days but there should be at least four readings per cycle for the shortest period fluctuation isolated (Rayner, 1971) and so the "significant" frequencies at the high frequency end of the spectrum (period < 4 days) are suspect. In the case of discharge (Fig. 5) it is clear that only the intensity of the annual frequency (f = 2) and the harmonics up to a frequency of 10 (73 days) are significant. Although a wide range of frequencies are present, the range of frequencies up to 10 account for 23% of the total variance. Minor "significant" peaks at the high frequency end of the spectrum account for less than 1% of the total variance of the sample. For the turbidity record frequencies up to 10 account for approximately 14% of the variance, indicating that higher order frequencies are more important than was the case for discharge. The spectrum largely mimics the discharge spectrum and although there are no distinctive periodicities other than an annual cycle it is interesting to consider turbidity as a function of discharge in the time domain.

Coherency

Fig. 6(a) is a plot of the squared coherency between the two series. Squared coherency with limits of 0 and 1 is analogous to the coefficient of determination in regression analysis and measures the proportion of variance in a frequency component of the output series which can be explained by a linear regression on the same frequency component of the input series. There is an even spread in the degree of association of spectrum frequencies across the full spectrum. Two frequencies should be noted in particular. The annual cycle and a broad cycle at a frequency of 34, or about 3 weeks. This latter peak may or may not be a harmonic of the annual cycle.

Gain

The gain (Fig. 6b) is the factor by which a component wave in the input series is amplified in the corresponding wave in the output series. Possibly significant peaks occur at a frequency of 9 (11.6 weeks) and again around 3 weeks. The weak but consistent response indicates that discharge is an important, but not necessarily the major forcing function of turbidity at any time-scale. Other additional controls must be sought.

Phase

Phase, $\phi_{yx}(f)$, represents the time-shift between the component of the two series with the same frequency (Fig. 7). The phase (in radians) is on average zero across the whole spectrum with a number of significant departures. The lead or lag in days may be calculated as the value of the phase shift multiplied by the wave-length, $W = 728/f$, divided by 2π, i.e.

$$\text{phase shift (days)} = \phi_{yx}(f)W/2\pi$$

Other than a seven day lag at a frequency of 15 (6.9 weeks) the other high frequency phase shifts represent lags of turbidity to discharge by less than a day.

DISCUSSION

The variance spectrum analysis demonstrated that for the regulated River Tees the spectrum at high frequencies is not significantly different from a red-noise spectrum. A significant deviation at low frequencies represents the climatic annual cycle and a further possible significant peak at about three weeks is unexplained. This latter peak may be a simple harmonic of the annual cycle or a genuine physical phenomenon.

The flatness of the spectrum is probably typical of regulated flow regimes where regular episodic releases of water are not required within the operational policy. Spectra with significant fluctuations would therefore indicate the probable presence of separate generating processes operating within the catchment in addition to discharge fluctuations. It would be interesting therefore to compare the present results with spectra for unregulated flashy streams and spectra for streams with slow rates of change in discharge. For example, the chalk-streams of Dorset with stable flow regimes would probably have similar spectra to the regulated stream although distinct spikes might be present owing to possible periodic inputs of sediment owing to man's activities within the catchments. These activities include commercial cress-bed operations (Crisp, 1970), weed cutting (Kern-Hansen, 1978) and sediment laiden run-off from M.O.D. tank ranges.

The four day lag in the partial autocorrelation function for turbidity demonstrates the rapid response of the stream suspended sediment load following flood flows and is in broad agreement with the findings of Carling & Douglas (1984) where the memory in the system were estimated to be between one and five days.

ACKNOWLEDGEMENTS

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Figure Captions

Fig. 1. History of the discharge and turbidity levels in the R. Tees, for the water year 1979.

Fig. 2. Summary graphs to establish stationarity or otherwise of time-series. The linear regression lines were fitted to daily data, but only quarterly average values are shown for clarity.

(a) Quarterly average discharge values.

(b) Quarterly average turbidity values. (See text for full details).

Fig. 3. Autocorrelation plots of discharge and turbidity to lag 10. Non-zero 95% confidence limits (shaded) were fitted by the method of Anderson (Kisiel, 1969, p. 76) (a) Discharge, (b) Turbidity.

Fig. 4. Raw variance spectra for discharge and turbidity. The frequency scale (cycles per two years) may be converted to wavelength in days by dividing the frequency division ∿ 728 by the given frequency. (a) Discharge, (b) Turbidity.

Fig. 5. Ninety-five per cent confidence limits for smoothed variance spectra (calculated using a 222 Parzen window and 10% taper) compared with the 2nd order Markov red noise spectrum. (a) Discharge, (b) Turbidity.

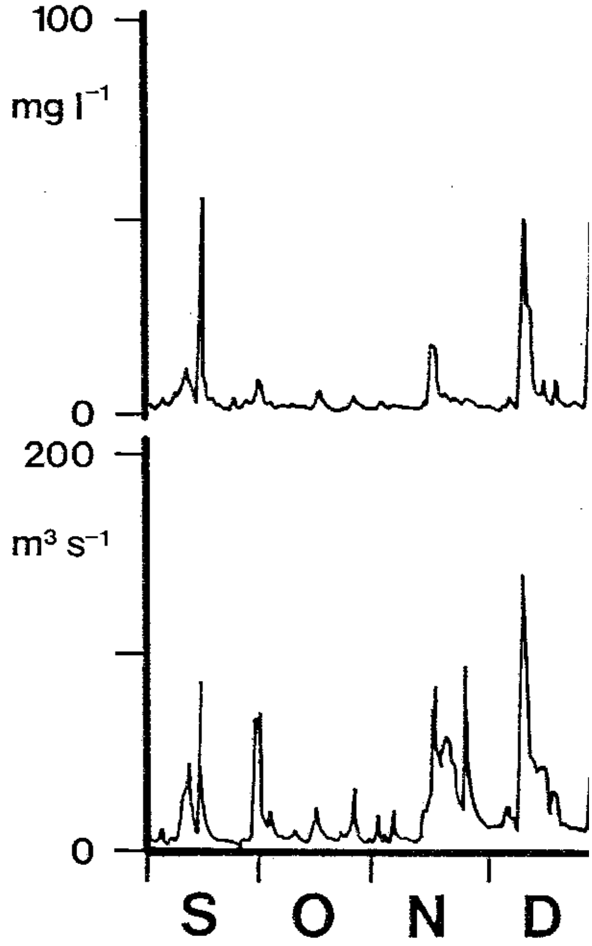
Fig. 6(a) Coherency between the two series indicating the dominance of discharge as the forcing function for turbidity levels across the broad range of frequencies.

(b) The gain function between discharge and turbidity.

Fig. 7. The phase function, representing the lead or lag relationship between the two series. Ninety-five per cent confidence limits are shown.

Table 1. Summary of basic data used in spectrum analysis

	N	Arithmetic mean	s.e.	Geometric mean	Max.	Min.
Discharge ($m^3 s^{-1}$)	4125	16.25	0.43	8.83	370.66	0.74
Turbidity ($mg\ l^{-1}$)	4077	5.02	0.14	3.74	200.00	0.48


100
mg l⁻¹
0
200
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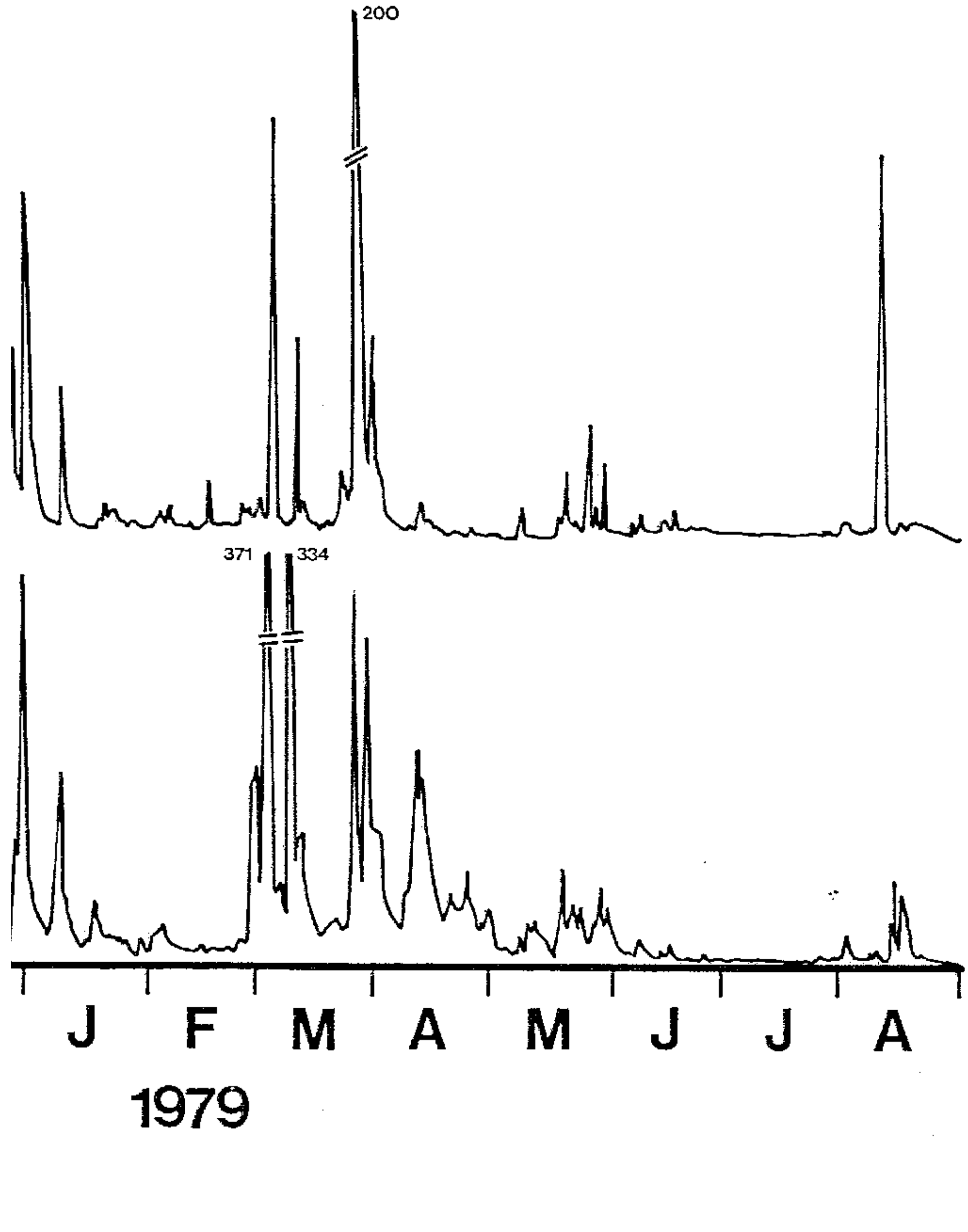
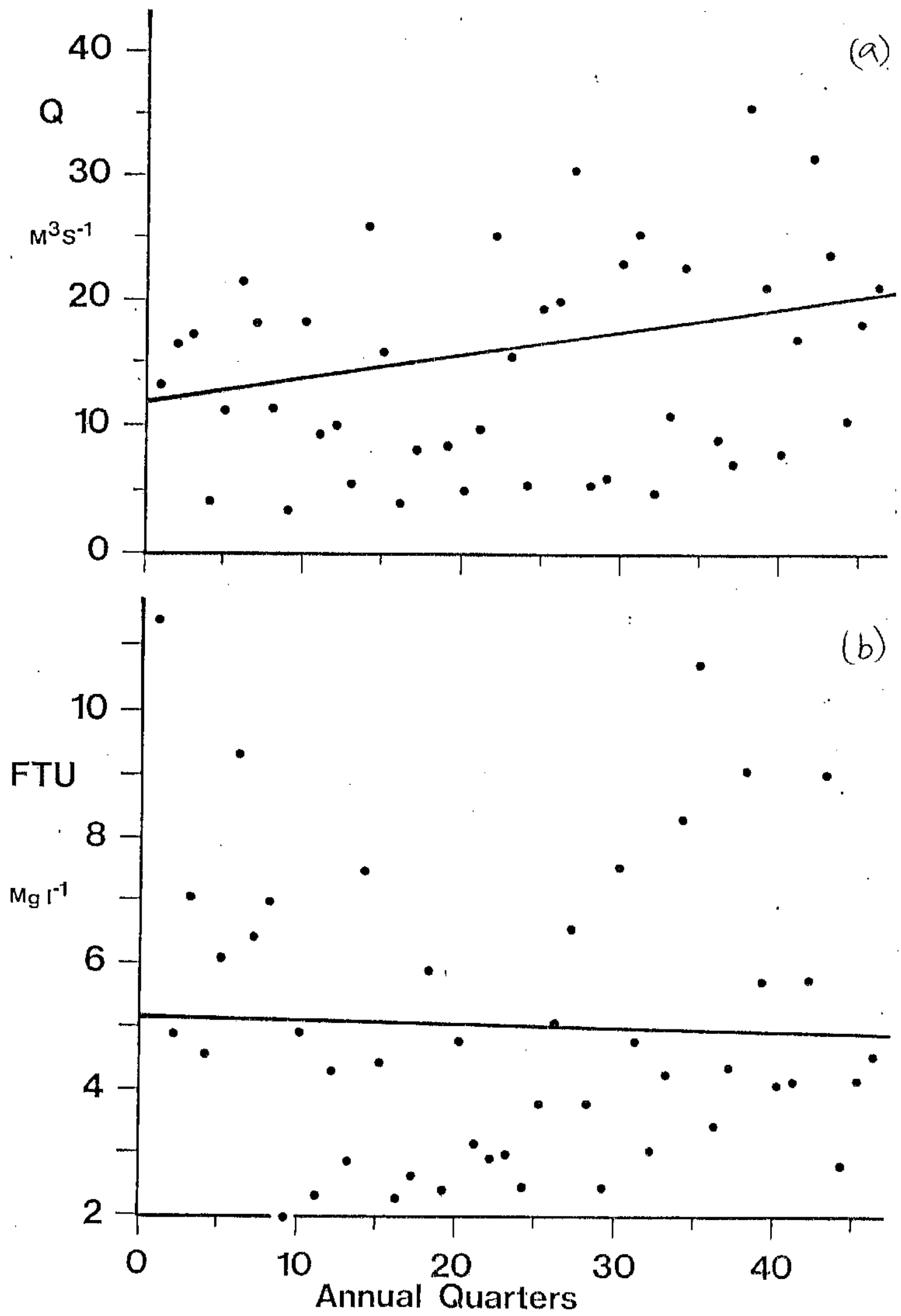


fig 1

Fig 2



(a)
Q
M3S-1
40
30
20
10
0
(b)
FTU
Mg l-1
10
8
6
4
2
0
10
20
30
40
Annual Quarters

Fig 3

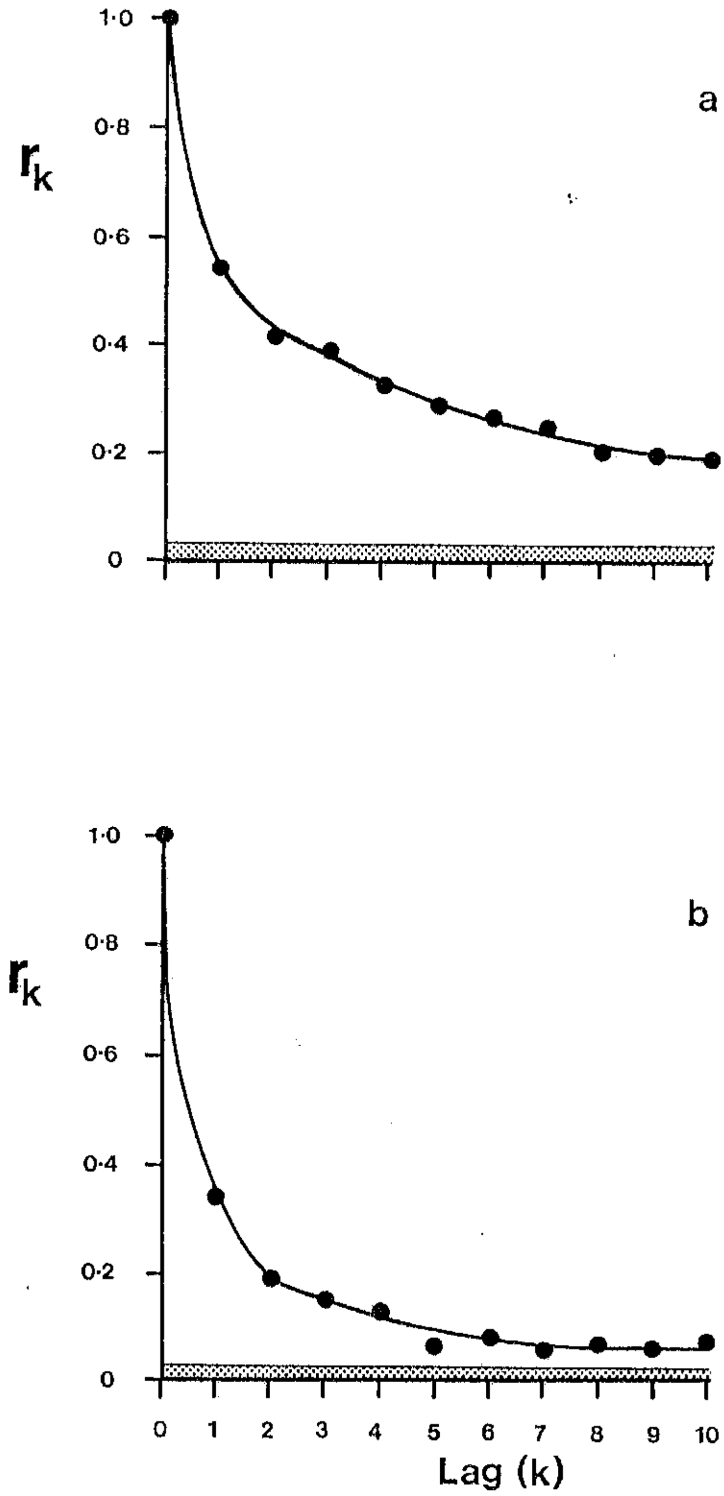
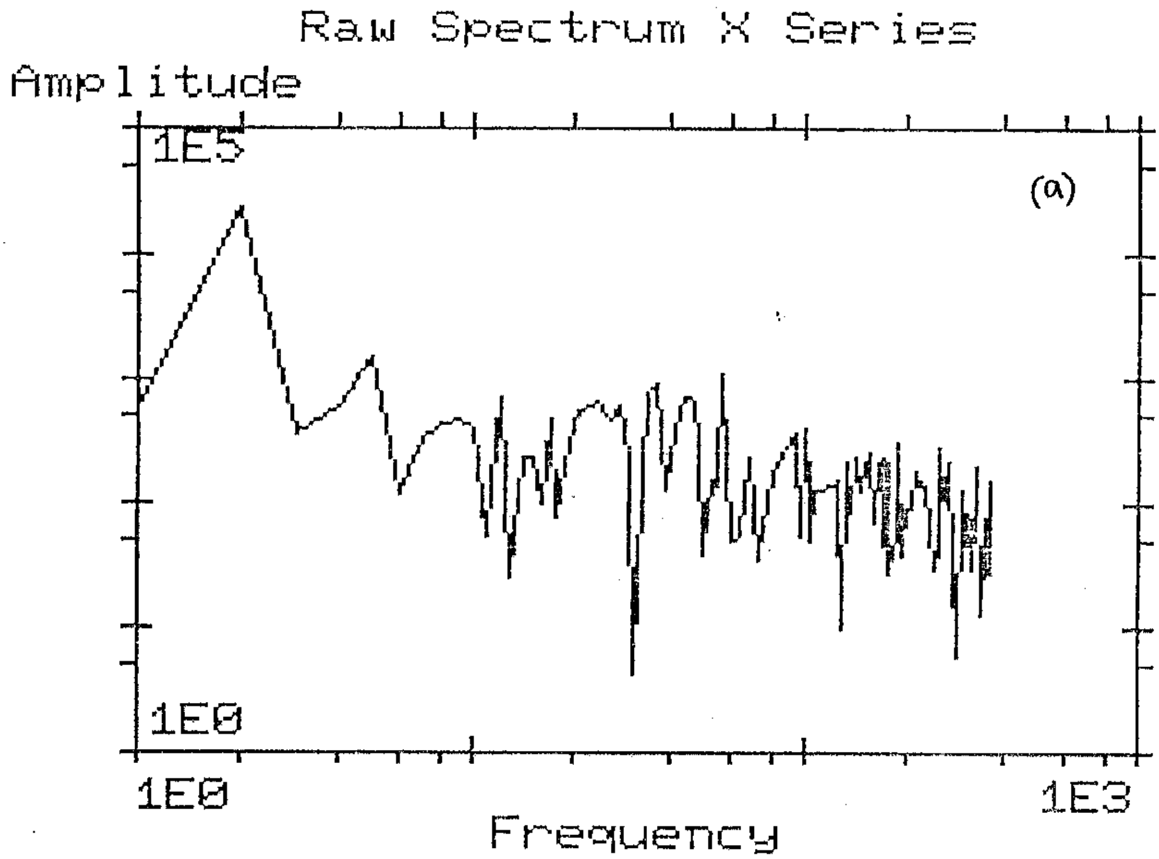


Fig 4


Raw Spectrum X Series
Amplitude
1E5
(a)
1E0
1E0
1E3
Frequency

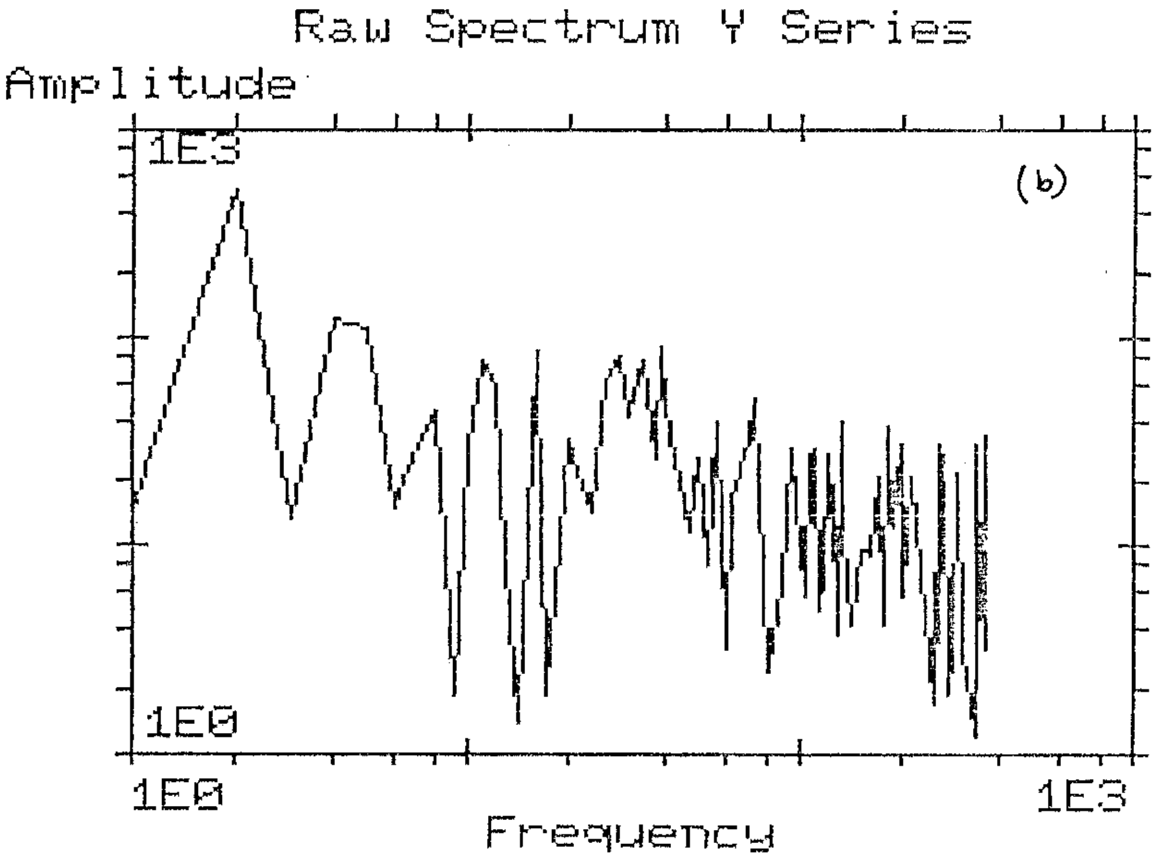
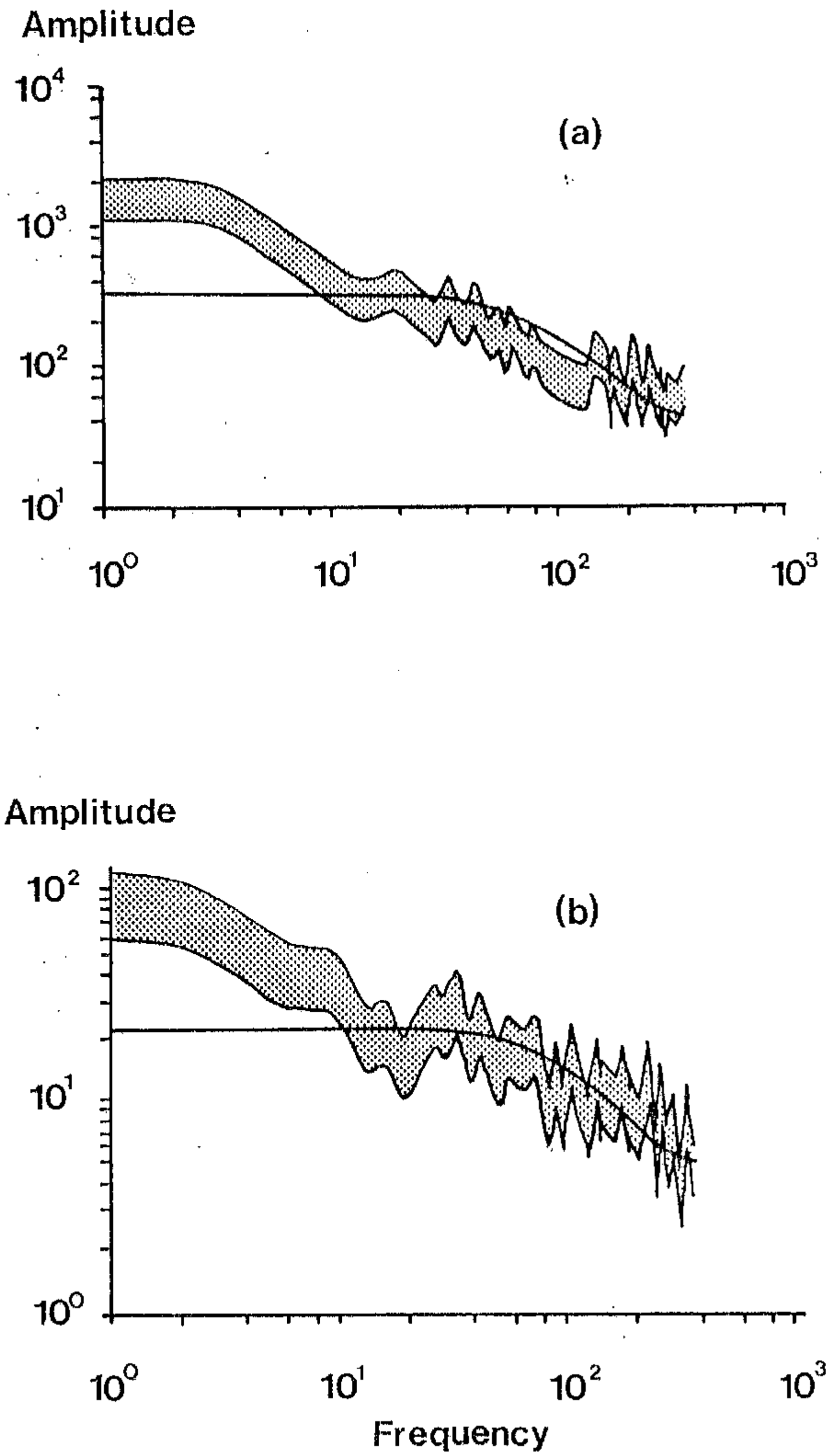
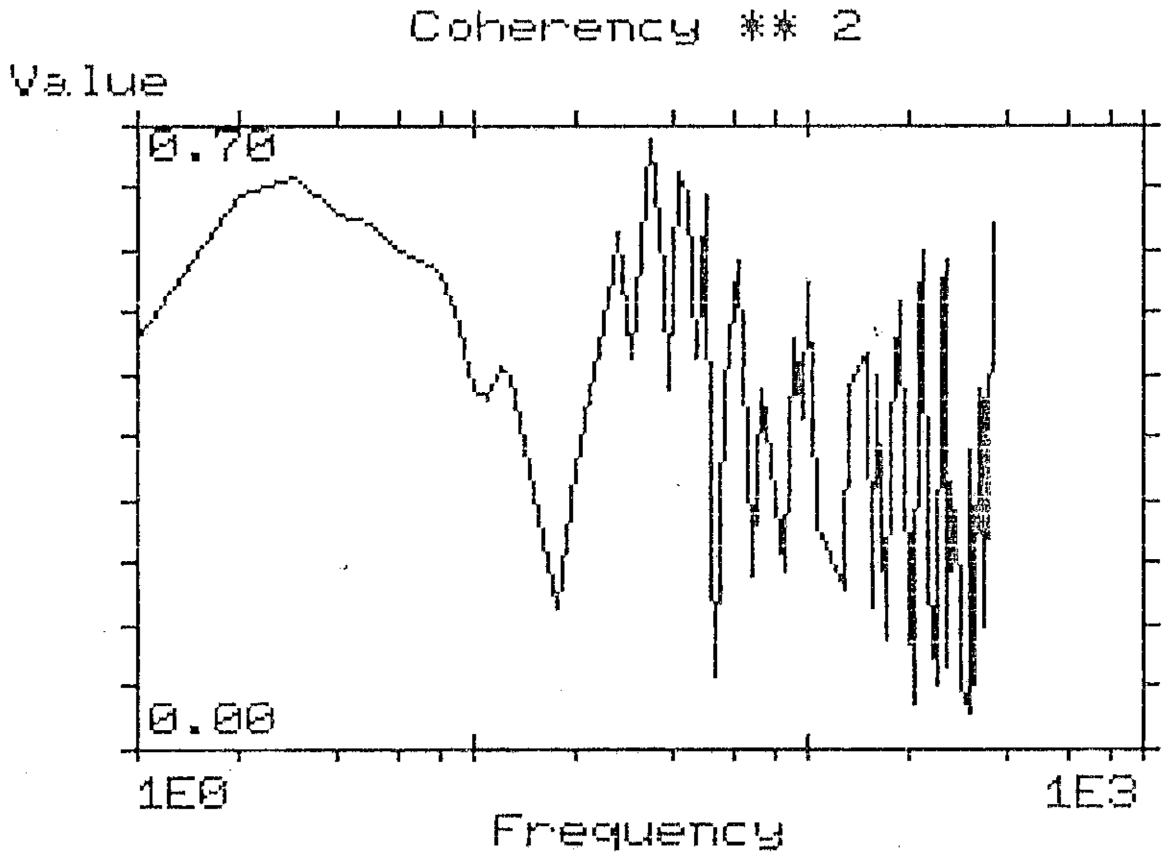

Raw Spectrum Y Series
Amplitude
1E3
(b)
1E0
1E0
1E3
Frequency

fig 5



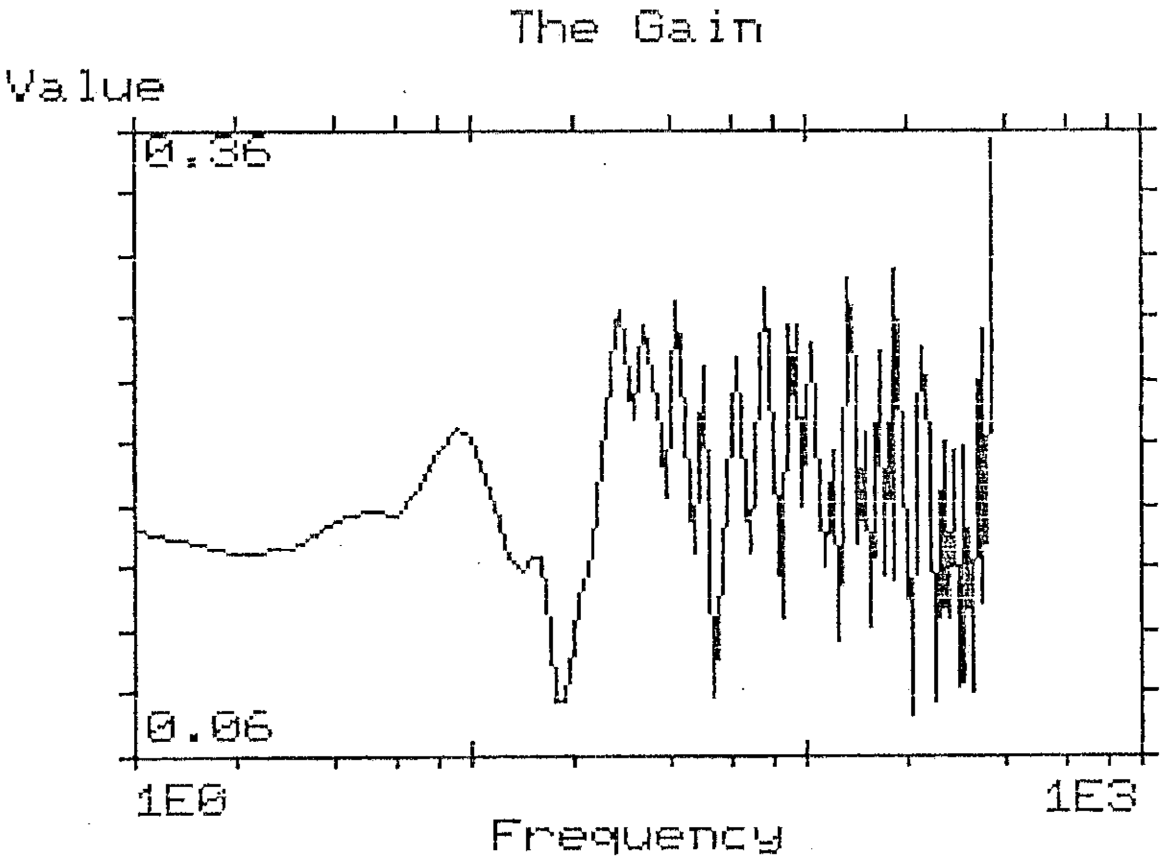
Amplitude
10^4
10^3
10^2
10^1
(a)
10^0
10^1
10^2
10^3
Amplitude
10^2
10^1
10^0
(b)
10^0
10^1
10^2
10^3
Frequency

Fig 6



Coherency ** 2
Value
0.70
0.00
1E0
1E3
Frequency

(a)



The Gain
Value
0.36
0.06
1E0
1E3
Frequency

(b)

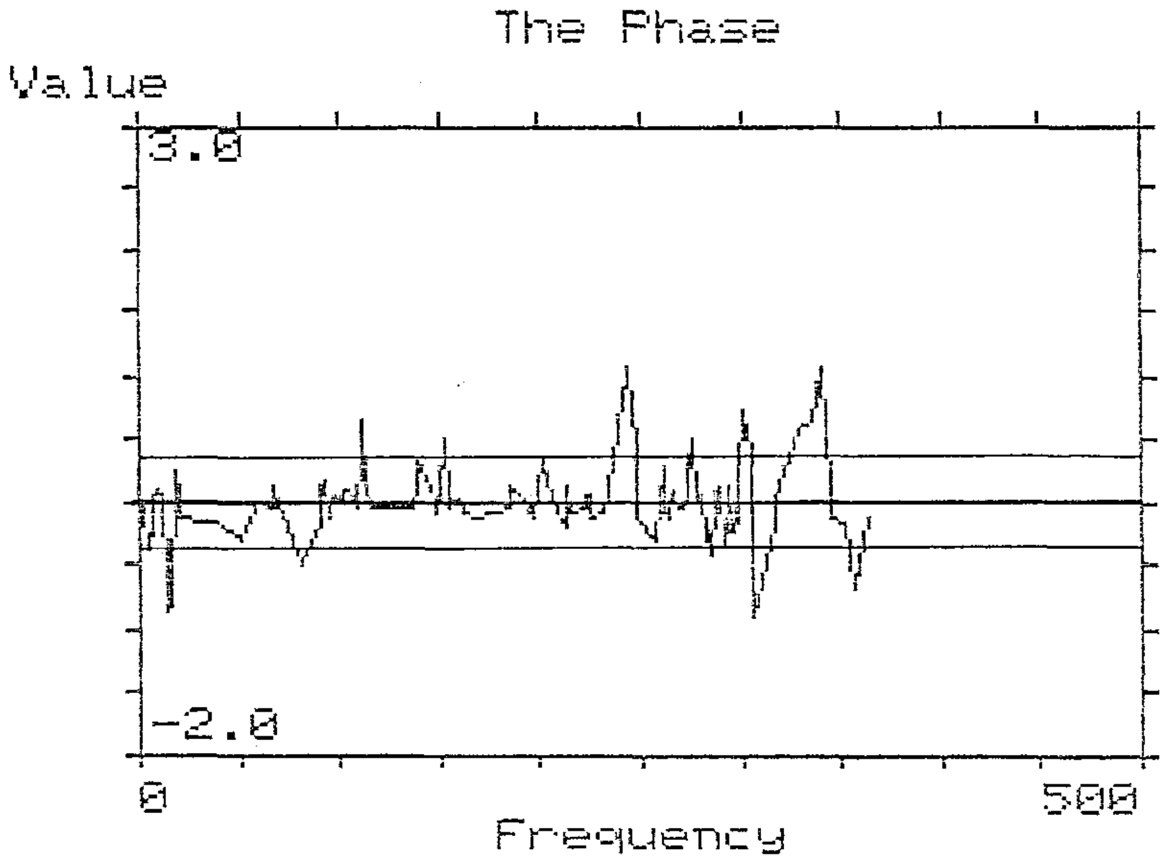


fig 7