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MAGNETOTELLURICS USING LOCK-IN SIGNAL DETECTION

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MAGNETOTELLURICS USING LOCK-IN SIGNAL DETECTION

Wolfgang M. Goubau, Thomas D. Gamble, and John Clarke

Department of Physics, University of California,
and Materials and Molecular Research and Earth Sciences Divisions,
Lawrence Berkeley Laboratory, Berkeley, California 94720

Abstract. Magnetotelluric measurements were performed simultaneously at two sites 4.8 km apart near Hollister, California. The data obtained at each site were analyzed using the two magnetic field measurements at the other site as a remote reference. Even for data for which the E-E predicted coherencies were as low as 0.1, the apparent resistivities obtained using this technique were consistent with resistivities calculated from high coherency data at adjacent periods. Apparent resistivities calculated by a conventional analysis of the same data were biased downward by magnetic noise, sometimes by as much as two orders of magnitude.

Introduction

In magnetotellurics (MT) estimates are obtained for the impedance tensor $\underline{\underline{Z}}$ from the equations

$$E_x(\omega) = Z_{xx}(\omega)\, H_x(\omega) + Z_{xy}(\omega)\, H_y(\omega), \tag{1}$$

$$\text{and} \quad E_y(\omega) = Z_{yx}(\omega)\, H_x(\omega) + Z_{yy}(\omega)\, H_y(\omega). \tag{2}$$

In Equations (1) and (2), $H_x(\omega)$, $H_y(\omega)$, $E_x(\omega)$, and $E_y(\omega)$ are the Fourier

transforms of the fluctuating magnetic and electric fields $H_x(t)$, $H_y(t)$, $E_x(t)$, and $E_y(t)$. In the past, estimates of the impedance tensor elements from Equations (1) and (2) have been based on a least-squares analysis that minimizes the mean square error caused by the noises in two of the four fields [Sims, Bostick, and Smith, 1971]. As is well known, the least-square estimates for $\underline{\underline{Z}}$ contain autopowers of some of the components of electric and magnetic fields, and may therefore be biased by noise in those channels [Swift, 1967, Sims et al., 1971]. These bias errors may be very substantial, as illustrated below. Kao and Rankin [1977] have devised an iterative scheme for eliminating the autopower bias from the various least-squares estimates of $\underline{\underline{Z}}$, but their iteration does not always converge. In another publication [Goubau, Gamble, and Clarke, submitted to Geophysics] we show that estimates of $\underline{\underline{Z}}$ obtained by this method are not always stable. Because of these difficulties, one can usually obtain reliable estimates of $\underline{\underline{Z}}$ only from data for which the E-E predicted coherencies are large (say > 0.95).

In this Letter we describe a field test of a new method of acquiring MT data in which a second magnetometer remote from the MT station is used as a reference to lock-in detect the electric and magnetic signals. This method yields estimates of $\underline{\underline{Z}}$ that are unbiased by noise provided that the noises at the MT station and at the remote magnetometer are uncorrelated. The results obtained were significantly better than those obtained when the same data were analyzed by one of the standard methods. The remote reference technique yielded apparent resistivities that contained no obvious bias even when the coherency was as low as 0.1.

Theory of Remote Reference MT

In the remote reference technique, one simultaneously records the four channels of electric and magnetic fields at the MT station and the two orthogonal horizontal components of the magnetic fields at the remote magnetometer, $H_{xr}(t)$ and $H_{yr}(t)$. We Fourier transform all six fields, multiply Equations (1) and (2) in turn by $H^*_{xr}(\omega)$ and $H^*_{yr}(\omega)$, and average the various crosspowers over a narrow band of frequencies and over all data records to obtain

$$\overline{E_x H^*_{xr}} = Z_{xx} \overline{H_x H^*_{xr}} + Z_{xy} \overline{H_y H^*_{xr}}, \tag{3}$$

$$\overline{E_x H^*_{yr}} = Z_{xx} \overline{H_x H^*_{yr}} + Z_{xy} \overline{H_y H^*_{yr}}, \tag{4}$$

$$\overline{E_y H^*_{xr}} = Z_{yx} \overline{H_x H^*_{xr}} + Z_{yy} \overline{H_y H^*_{xr}}, \tag{5}$$

and $$\overline{E_y H^*_{yr}} = Z_{yx} \overline{H_x H^*_{yr}} + Z_{yy} \overline{H_y H^*_{yr}}. \tag{6}$$

The impedance elements derived from these equations depend only on crosspowers between the MT fields and the reference fields. Thus, they cannot be biased by noise unless the noise in one or more of the MT fields is correlated with the noise in one or both of the reference fields.

Measurements and Signal Processing

To test the remote-reference technique we established two complete MT stations separated by 4.8 km on La Gloria Road in Bear Valley, near Hollister, California (Figure 1). The four MT fields and the vertical component of the magnetic field at Lower La Gloria were transmitted via FM telemetry to Upper La Gloria where they were recorded on a digital

tape recorder, together with the same five fields obtained at Upper La Gloria. We used three dc SQUIDs (Superconducting QUantum Interference Devices) [Clarke, Goubau, and Ketchen, 1976] as a three-axis magnetometer at Lower La Gloria, and three commercial rf SQUIDs as a three-axis magnetometer at Upper La Gloria. The sensitivities were approximately $10^{-5}\,\gamma\,\mathrm{Hz}^{-\frac{1}{2}}$ and $10^{-4}\,\gamma\,\mathrm{Hz}^{-\frac{1}{2}}$ respectively. We used the magnetometer at each site as the reference for the MT signals at the other site.

We recorded data in four overlapping bands that spanned the periods 0.02 to 100 s, and rejected data that were obviously useless because of equipment failure, amplifier saturation, or magnetic interference from passing vehicles. For processing, we grouped the data from each band into segments of equal length in time, subtracted the mean value and linear trend, multiplied the ends of each segment by a cosine taper, and computed the fast Fourier transform. The necessary crosspowers were calculated by averaging crossproducts of the various fields over Fourier harmonics in a window of Q = 3 and over all data segments of a given band.

We computed the impedance tensor at each station and corrected the tensor for the non-orthogonality of the electrode arrays (Figure 1). For comparison, from the same data the impedance tensor (similarly corrected) was also computed from a standard least-squares method [Swift, 1967] in which the local fields H_x^* and H_y^* replace H_{xr}^* and H_{yr}^* in Equations (3) to (6). For this least-squares method the elements of the tensor are biased downwards by noise in the magnetic fields. For each method of analysis we rotated the coordinate axes to maximize $|Z_{xy}|^2 + |Z_{yx}|^2$, thereby aligning one of the axes along the strike direction, if such a direction existed. We computed the apparent resistivities ρ_{xy} and ρ_{yx} for the rotated axes using the expressions

$\rho_{xy} = 0.2\ T\ |Z_{xy}|^2$ and $\rho_{yx} = 0.2\ T\ |Z_{yx}|^2$, where ρ_{xy} and ρ_{yx} are given in Ωm, T is the period in seconds, and Z_{xy} and Z_{yx} are in $(\text{mV/km})\gamma^{-1}$. To obtain a measure of the noise power in our data we computed the coherency

$$C_i = \frac{\overline{E_i\ E_{ip}^*}}{\left(\overline{|E_i|^2}\ \overline{|E_{ip}|^2}\right)^{\frac{1}{2}}} \qquad (i = x, y) \tag{7}$$

where E_{ip} is the electric field predicted from Equations (1) and (2) using the estimates of $\underline{\underline{Z}}$ obtained from the standard analysis.

Results

The apparent resistivities and coherencies at Upper La Gloria for the remote reference and standard analyses are shown in Figures 2 to 4. The corresponding results for Lower La Gloria are shown in Figures 5 to 7. To facilitate a comparison of the results, we have indicated the remote reference apparent resistivities with dashed lines in Figures 3 and 6. All calculated apparent resistivities are included, regardless of the coherency.

It is evident from Figures 2, 3, 5, and 6 that the apparent resistivities for the remote reference analysis lie on much smoother curves than the resistivities for the standard analysis. It is also obvious that the apparent resistivities for the standard analysis are consistently lower than the corresponding values for the remote reference analysis. The systematic discrepancies are consistent with the downward bias that is expected when there is noise in the magnetic fields. The two methods

show the best agreement (within 10%) for ρ_{xy} at Upper La Gloria for periods shorter than 1 s, where the coherency was always above 0.9. On the other hand, at Lower La Gloria near 10 s period, the coherency was as low as 0.1 and ρ_{xy} obtained from the standard analysis was biased downward by more than two orders of magnitude. The corresponding value of ρ_{xy} obtained from the remote reference technique showed no sign of bias.

In a more quantitative analysis [Gamble, Goubau, and Clarke, unpublished] we found that where the bands with the shortest and second shortest periods overlapped (near 0.5 s period), the apparent resistivities agreed to within 1.8%. By comparing apparent resistivities obtained from data collected at different times, we estimated the standard deviation for the apparent resistivities at periods shorter than 3 s to be 1.3%. Furthermore, compared with the standard analysis, the remote reference technique produced significantly improved estimates of the orientation of the apparent strike direction and the skewness.

Summary and Discussion

We have found the remote reference technique to be distinctly superior to the standard MT method. At all periods and for a wide range of coherencies we obtained smooth curves of apparent resistivity that showed no obvious bias due to noise. By contrast, the standard least-squares method yielded apparent resistivities from the same data that were always lower in value, sometimes by more than two orders of magnitude.

We have tested only the use of a remote magnetometer. In principle, a remote telluric array could be used instead for the reference signals. However, we found that the electric measurements often contain more noise

than the magnetic measurements. Furthermore, if the resistivity of the ground is very anisotropic, the electric field response tends to be polarized in the direction of the highest resistivity, and the solutions to Equations (3) to (6) become unstable. Thus, we suspect that, in general, the remote electric reference will be less useful than the magnetic reference.

We have also restricted our tests to the determination of $\underline{\underline{Z}}$. The principle of the remote reference could be used to obtain estimates of the tipper that are not biased by noise in H_x and H_y.

The use of a remote magnetic reference should enable one to carry out a magnetotelluric survey in areas contaminated by cultural noise, provided that the reference is sufficiently far away to ensure that any possible bias errors due to correlated noises are small compared with the random errors. Further, the increased accuracy available with the remote reference technique may enable one to test the validity of the assumptions usually made in magnetotellurics, for example, that the incident magnetic fields are plane waves, and that the electric fields are adequately determined by measurements of the potential difference between widely spaced electrodes. The remote reference technique should also permit the monitoring of long term changes in the apparent resistivity at a given site with greater accuracy than previously possible.

A more detailed account of this work is to be submitted elsewhere.

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Figure Captions

Fig. 1. Magnetotelluric measurement sites in Bear Valley, California. ◎ magnetometer; • electrode.

Fig. 2. Remote reference method apparent resistivities vs. period, Upper La Gloria.

Fig. 3. Standard method apparent resistivities vs. period, Upper La Gloria. --- remote reference results.

Fig. 4. Coherency between measured electric field and the electric field predicted by the standard method of analysis, Upper La Gloria.

Fig. 5. Remote reference method apparent resistivities vs. period, Lower La Gloria.

Fig. 6. Standard method apparent resistivities vs. period, Lower La Gloria. --- remote reference results.

Fig. 7. Coherency between measured electric field and the electric field predicted by the standard method of analysis, Lower La Gloria.

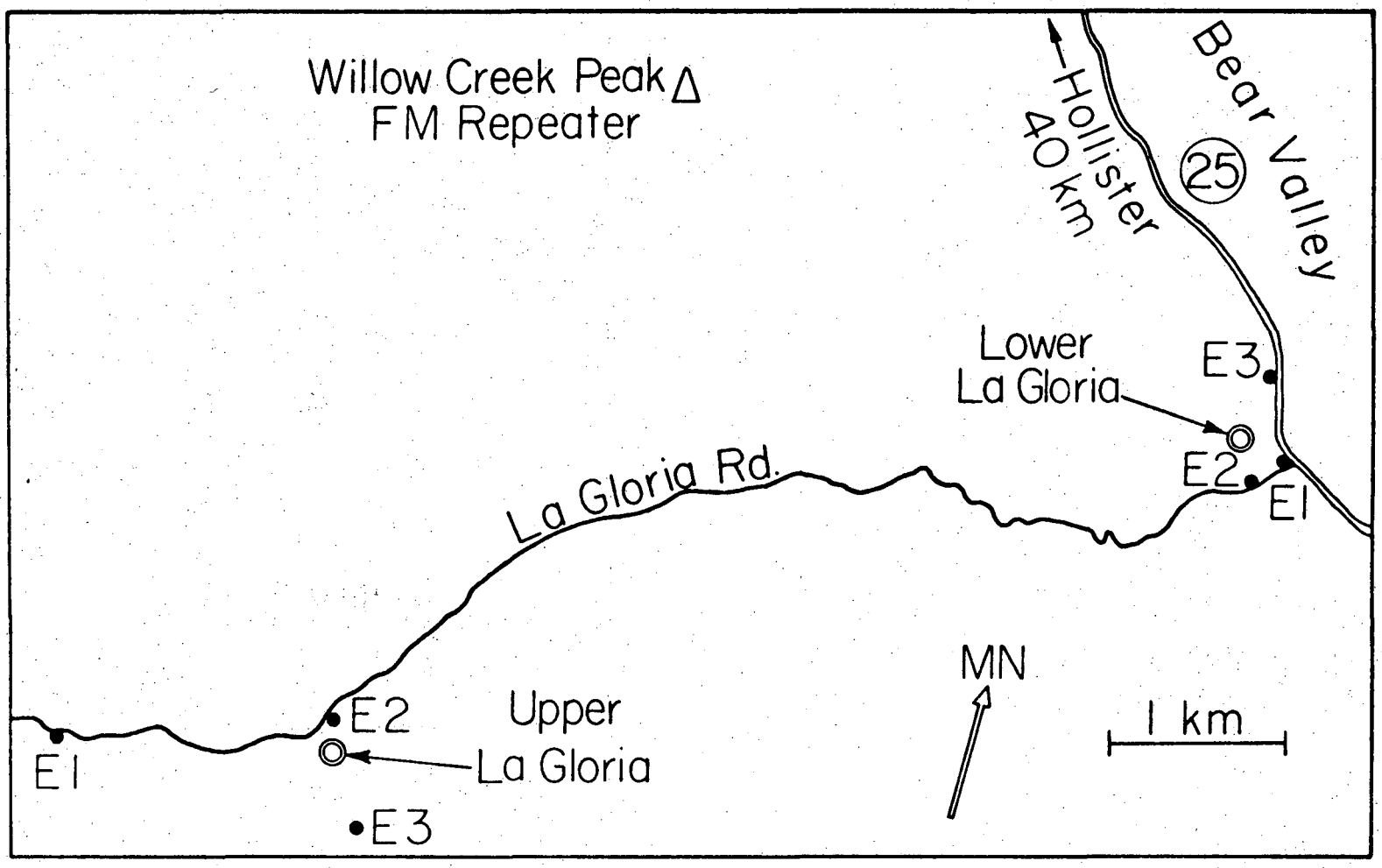

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Fig. 1

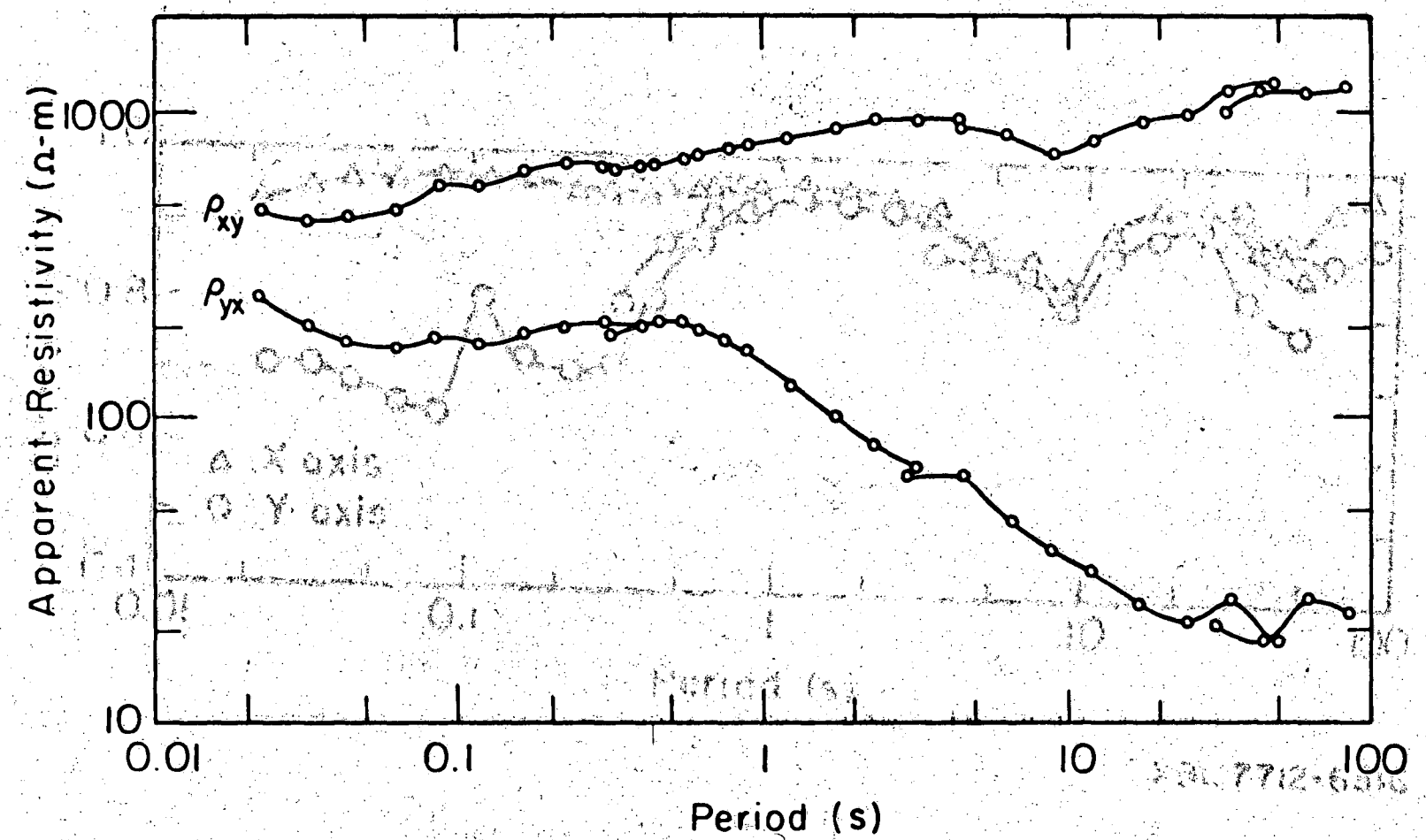

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Fig. 2

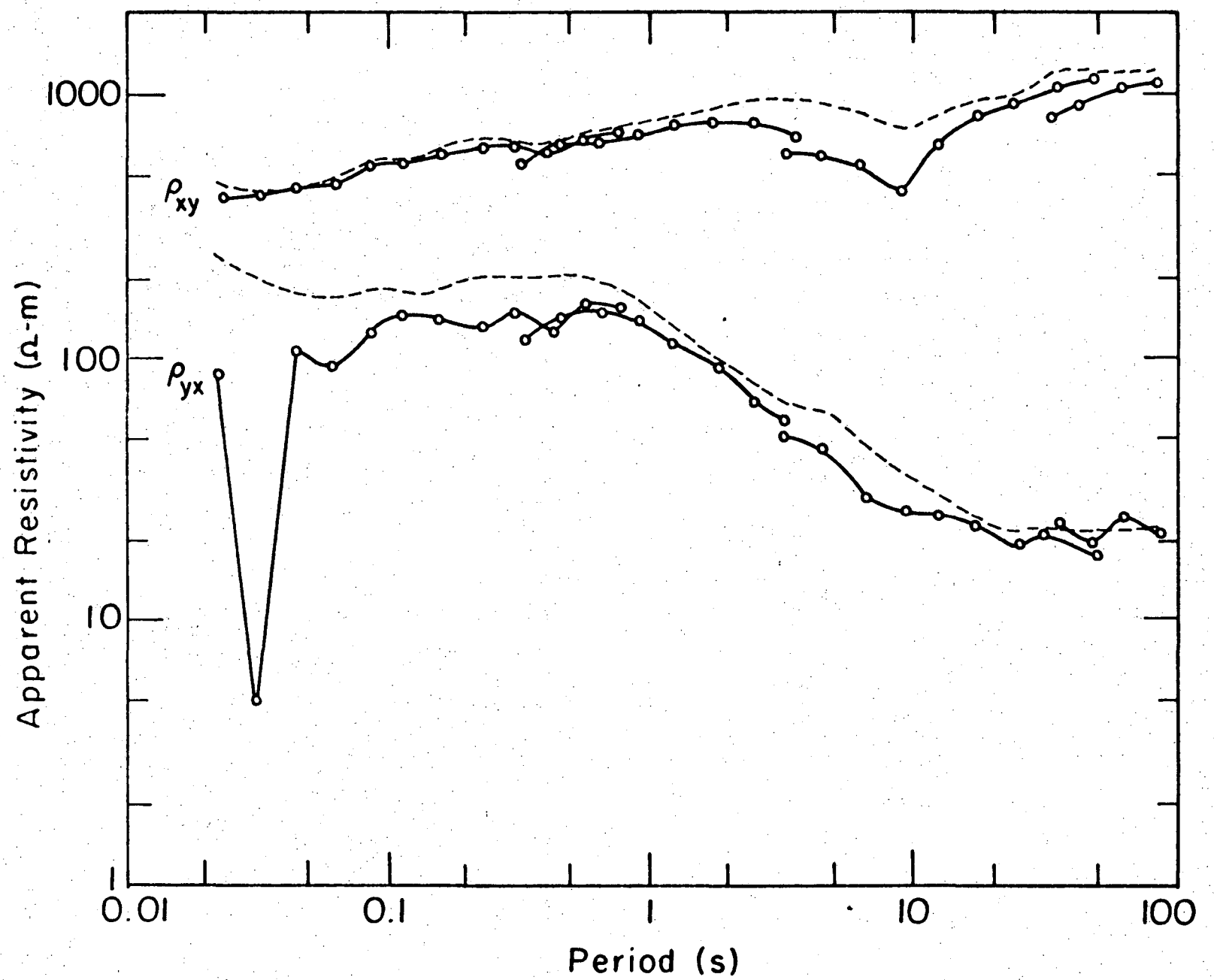

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Fig. 3

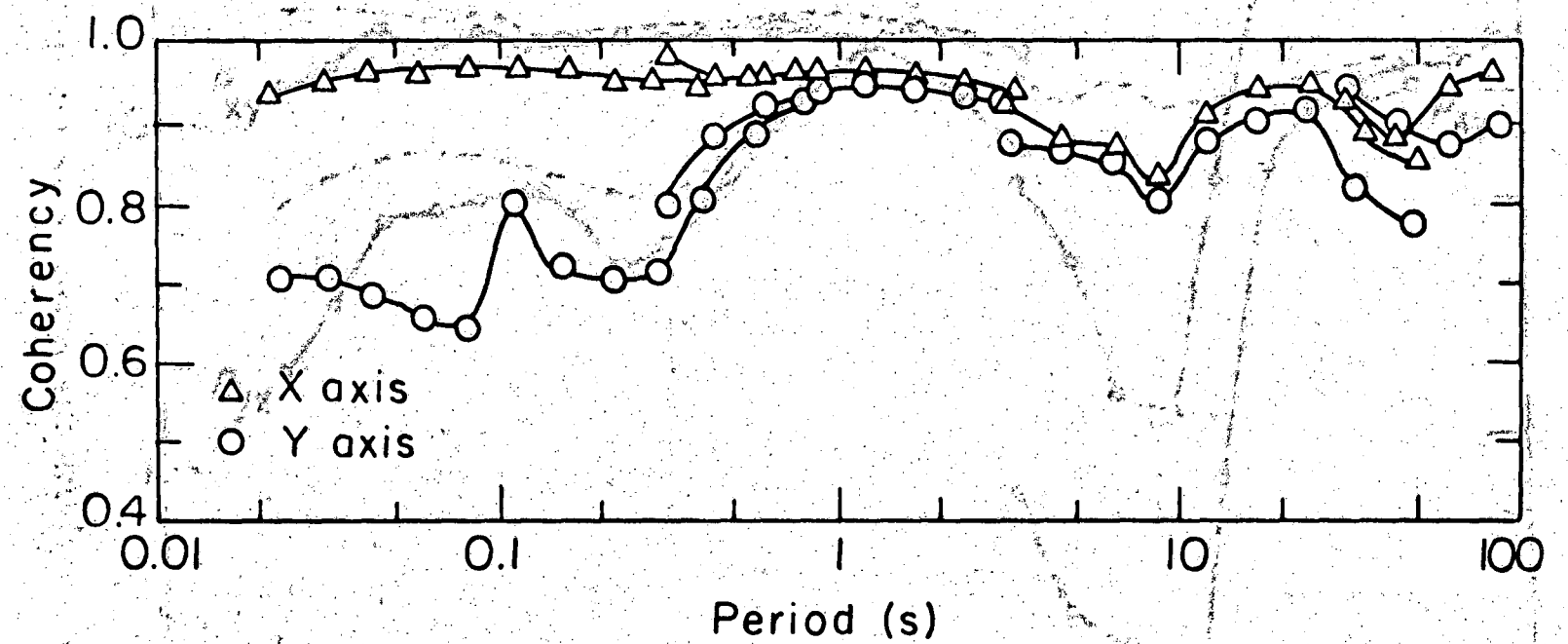

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Fig. 4

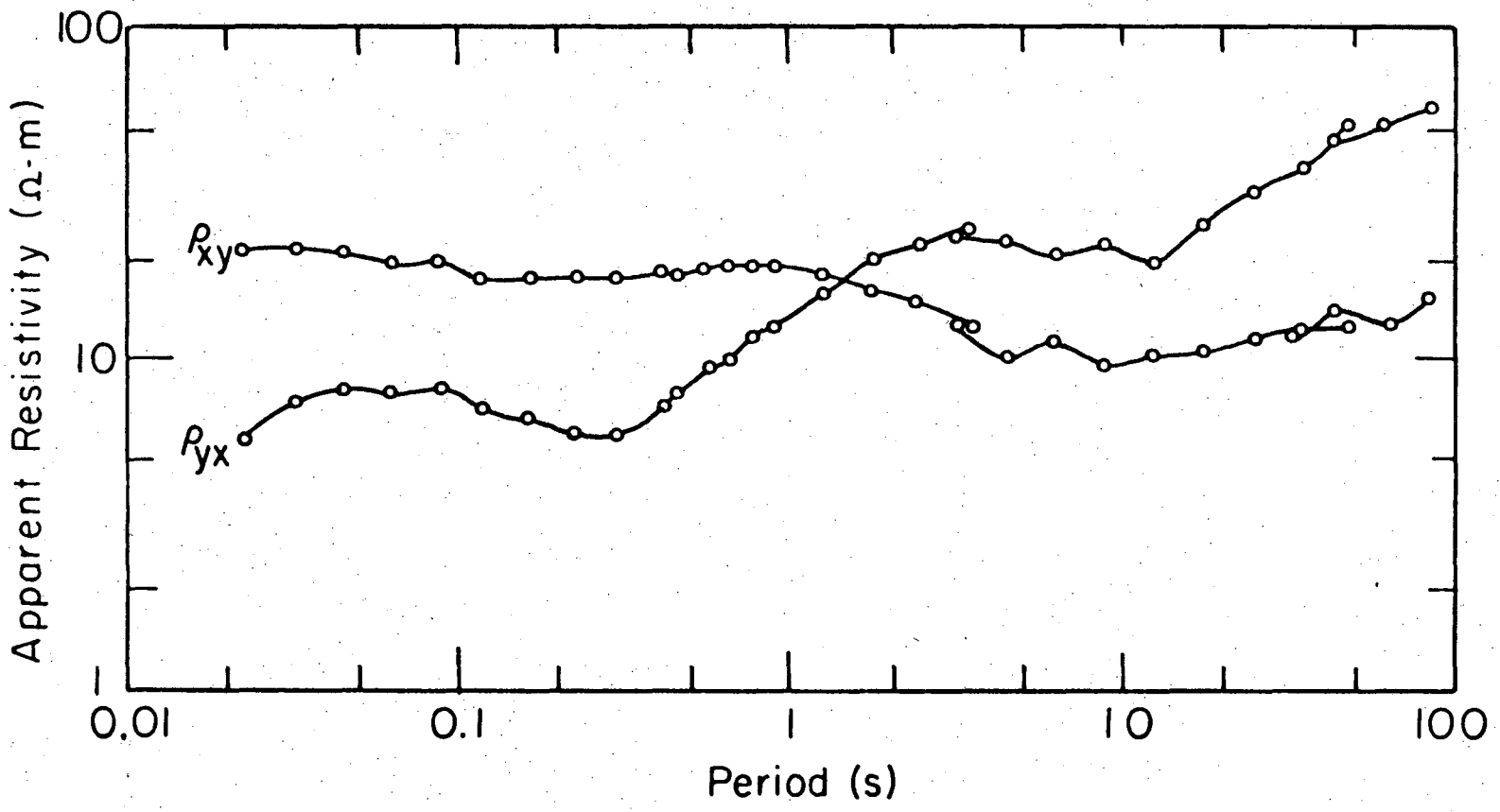

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Fig. 5

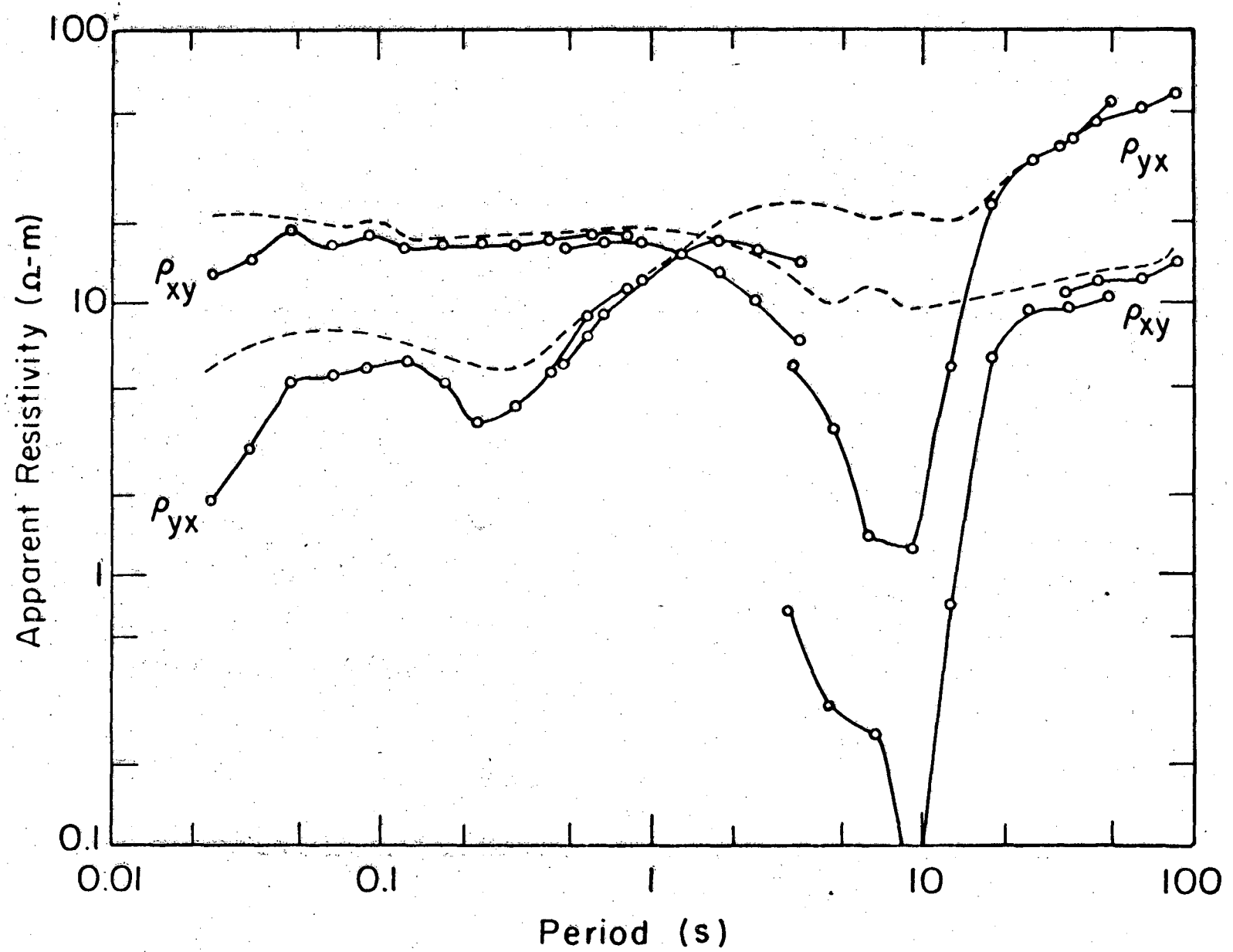

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Fig. 6

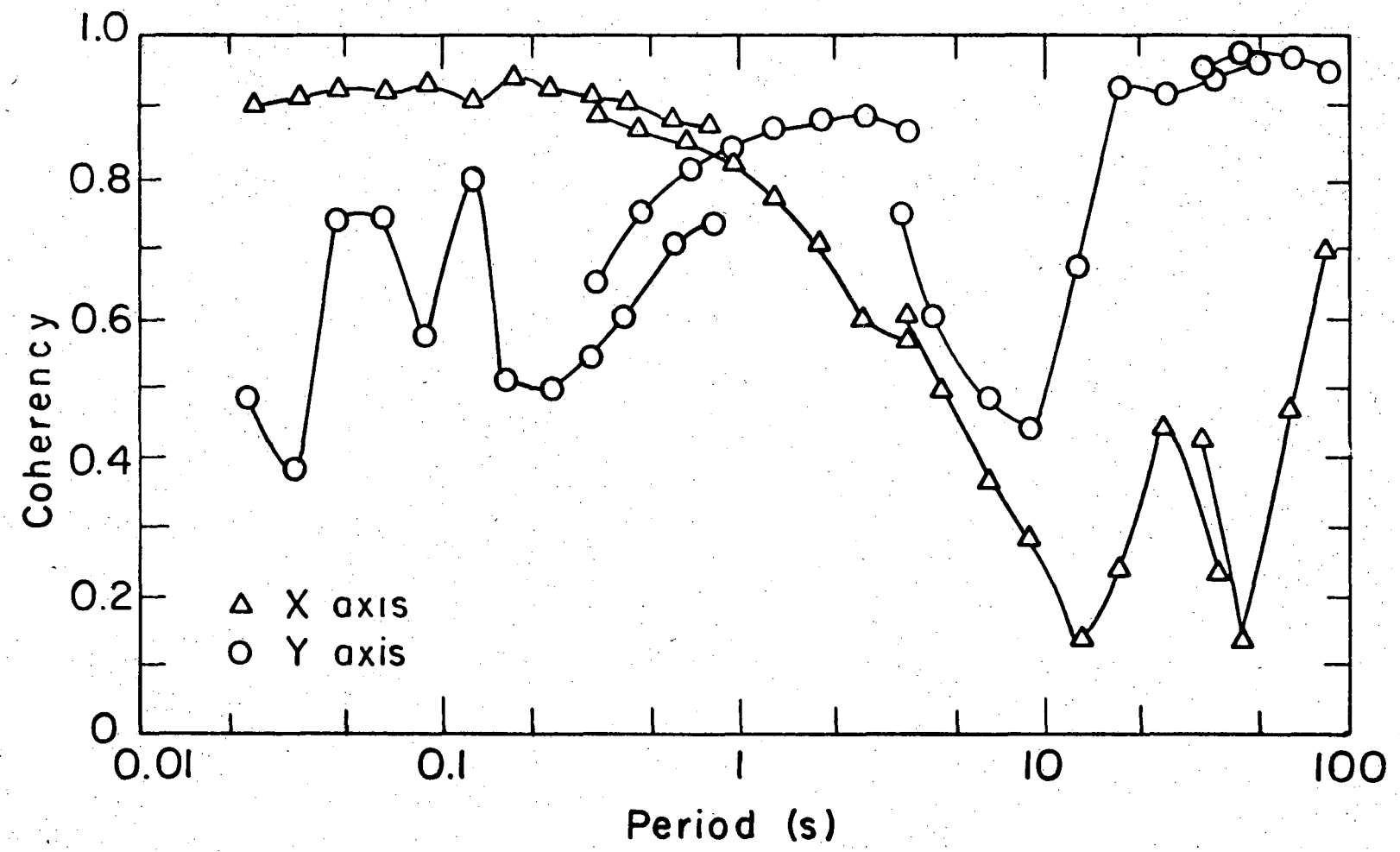

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Fig. 7

0 0 0 0 5 0 0 2 5 8 6

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