NBS TECHNICAL NOTE 689

U.S. DEPARTMENT OF COMMERCE / National Bureau of Standards

A Simulation of the Fluctuations of International Atomic Time

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A simulation of the fluctuations of International Atomic Time

James A. Barnes

In the Annual Report for 1975 the International Time Bureau (BIH) published estimates of noise levels which model the fluctuations in the International Atomic Time Scale (TAI). Based on these noise levels for each type of noise, an Auto Regressive, Integrated, Moving Average (ARIMA) model is constructed. A resulting ARIMA model, which can simulate time fluctuations in TAI, is given by the relation

$$(1 - \phi_1 B - \phi_2 B^2)\ \Delta^2 \chi_t = (1 - \theta_1 B - \theta_2 B^2 - \theta_3 B^3 - \theta_4 B^4) a_t$$

where χ_t represents the time fluctuations in nanoseconds (ns) of TAI measured at successive intervals of ten days; B is the index-lowering operator defined by $B^n \chi_t \equiv \chi_{t-n}$; Δ^2 is the second difference operator equivalent to $(1 - B)^2$; a_t are random, independent variables with a normal distribution, zero mean, and variance of $(147\ \text{ns})^2$; and the coefficients ϕ_i and θ_i are given by

$$\begin{aligned} \phi_1 &= 1.79, & \theta_1 &= 2.93, \\ \phi_2 &= -.795, & \theta_2 &= -3.12, \\ & & \theta_3 &= 1.419, \\ & & \theta_4 &= -0.233. \end{aligned}$$

Key words: Frequency stability; International Atomic Time; models simulation; time scale.

TAI Simulation

In the Annual Report for 1975 [2], the International Time Bureau (BIH) has published the levels of noises thought to perturb the International Atomic Time Scale (TAI). The levels of these noises which were adopted are as follows:

White phase noise	$\sigma_y(\tau = 60\text{d}) =$	0.3×10^{-13}
Flicker frequency noise	$\sigma_y(\tau)\ \ =$	0.5×10^{-13}
Random walk frequency noise	$\sigma_y(\tau = 60\text{d}) =$	0.15×10^{-13}

where $\sigma_y(\tau)$ is the square root of the two-sample (or Allan) variance [3].

For this paper it is specifically assumed that each of these noises is statistically independent of the others, and each is Gaussian in nature. One knows [3] that $\sigma_y^2(\tau) \sim \tau^\mu$ for each of these noises, where $\mu = -2$ for white phase noise; $\mu = 0$ for flicker frequency noise; and $\mu = +1$ for random walk frequency noise. Thus, one can calculate the overall expected, two-sample variance, $\sigma_y^2(\tau)$, for a large range of τ-values by adding the squares of the appropriate functions deduced from the BIH model. Figure 1 provides a graphical representation of this addition.

From the three noise types and the levels given in the BIH Annual Report, one can also determine the estimated power spectral density, $S_x(f)$, of the time fluctuations, $\chi(t)$, of TAI by using the tables in Appendix II of Ref. [3]. That is

White phase noise $S_x(f) = 16{,}124\ (ns)^2/(cycle/10d)$

Flicker frequency noise $S_x(f) = \frac{34.1}{f^3}\ (ns)^2/(cycle/10d)$

Random walk frequency noise $S_x(f) = \frac{0.108}{f^4}\ (ns)^2/(cycle/10d)$,

where, for this paper, f is taken to be measured in cycles per 10 days ($\sim 1.16 \times 10^{-6}$ Hz). Thus, the overall spectrum of $\chi(t)$ for the BIH model is

$$S_x(f) = 16{,}124 + \frac{34.1}{f^3} + \frac{0.108}{f^4}\ (ns)^2/(cycle/10d) \tag{1}$$

For the purpose of graphical display, Figure 2 is a plot of $f^3 S_x(f)$ rather than just $S_x(f)$. From Figure 2, one obtains the two "break frequencies" of 0.128 and 0.0032 cycles/10d. These two frequencies will be needed for the development of an ARIMA model [1] according to the methods given in Appendix B of Ref. [4]. (For convenience of the reader, Appendix B of Ref. [4] is reproduced at the end of this paper.)

Figure 3, then, is a Bode plot of the spectrum which is intended to be modeled (dashed line) with a cascade of ARIMA filters. Superimposed is the Bode plot of the filter cascade (solid line). Following Ref. [4], the filter cascade is just

$$\begin{aligned} \Delta^2\chi'_t &= w_t \\ w_t &= (1 - 0.98\ B)u_t \\ (1 - 0.969\ B)u_t &= v_t \\ v_t &= (1 - 0.92\ B)r_t \\ (1 - 0.82\ B)\ r_t &= s_t \\ s_t &= (1 - 0.6\ \ B)q_t \\ q_t &= (1 - 0.43\ B)a_t, \end{aligned} \tag{2}$$

where B is the index lowering operator defined by $B\chi_t \equiv \chi_{t-1}$; and Δ^2 is the second-difference operator equivalent to $(1 - B)^2$. The coefficients of the B-operators are calculated from the empirical formula [4]

$$\phi \text{ or } \theta = \frac{1 - \pi f_c}{1 + \pi f_c}, \tag{3}$$

where f_c is a "break frequency" in the Bode plot. An autoregressive (AR) operator (ϕ) is used when the Bode plot turns downward in Fig. 3, and a Moving-Average (MA) operator is used when the plot turns upward.

Eliminating the intermediate functions w_t, u_t, v_t, r_t, s_t, and q_t, one obtains

$$(1 - \phi_1 B - \phi_2 B^2)\ \Delta^2\chi'_t = (1 - \theta_1 B - \theta_2 B^2 - \theta_3 B^3 - \theta_4 B^4)a_t \tag{4}$$

where

$$\phi_1 = 1.79,$$
$$\phi_2 = -0.795,$$
$$\theta_1 = 2.93,$$
$$\theta_2 = -3.12,$$
$$\theta_3 = 1.419,$$
$$\theta_4 = -0.233,$$

If the variance of a_t, σ_a^2, takes on the value

$$\sigma_a^2 = (147 \text{ ns})^2, \tag{5}$$

the spectrum of χ_t', $S_x'(f)$, deduced from Equation 3.4.5 of Ref. [2], is a close fit to the intended spectrum of Equation (1), (see. fig. 4).

One can simulate TAI fluctuations by selecting the initial conditions

$$\chi_t' = a_t = 0 \text{ for } t \leq 0,$$

and by letting a_t for $t \geq 1$ be random, normal deviates with zero mean and a variance of $(147 \text{ ns})^2$ (see fig. 5). Of course, such simulations are merely representative of the kinds of fluctuations present in TAI and are in no way estimates of actual TAI errors; that is, they have similar power spectral densities and nothing more. A computer algorithm was written to generate 1,000 χ_t' values (1,000 x 10 days ~ 27.4 years) simulating TAI. The square root of the two-sample variance, $\sigma_y(\tau)$ was computed for various τ-values and is plotted on figure 6 along with the BIH model (solid line). The uncertainties were obtained from Refs. [5, 6, and 7].

Equation (4) can also be used as the optimum predictor for future fluctuations in TAI if one has past values. One simply uses as input to the "filter" represented by (4) the optimum predictions of a_t for future values. Since the a_t are just random, uncorrelated numbers, the optimum prediction for future a_t is just the average value of a_t which has been assumed to be zero. The RMS errors of such a prediction algorithm can be calculated [4], and are plotted on figure 7.

For computational purposes, Equation (4) can be written in a more useful form. In particular, χ_t can be written explicitly as a function of the earlier χ_t and the a_t. That is,

$$\begin{aligned}\chi_t = {} & 3.79\chi_{t-1} - 5.375\chi_{t-2} + 3.38\chi_{t-3} \\ & - 0.795\chi_{t-4} + a_t - 2.93a_{t-1} \\ & + 3.12a_{t-2} - 1.419a_{t-3} + 0.233\, a_{t-4}.\end{aligned} \tag{6}$$

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[1] Box, G.E.P., Jenkins, G. M., Time series analysis, Holden-Day, San Francisco, California (1970).

[2] Rapport Annuel Pour 1975, Bureau International de l'Heure.

[3] Barnes, J. A., et al., Characterization of frequency stability, IEEE Trans. on Instrum. and Meas., IM-20, 105-120 (May 1971).

[4] Barnes, J. A., Models for the interpretation of frequency stability measurements, NBS Technical Note 683 (August 1976).

[5] Lesage, P., Audoin, C., Characterization of frequency stability: uncertainty due to the finite number of measurements, IEEE Trans. on I&M, IM-22, No. 2, 157-161 (June 1973).

[6] Lesage, P., Audoin, C., Correction to: Characterization of frequency stability: uncertainty due to the finite number of measurements, IEEE Trans. on Instrum. & Meas., IM-23, No. 1, 103 (March 1974).

[7] Lesage, P., Audoin, C., Correction to: Characterization of frequency stability: uncertainty due to the finite number of measurements, IEEE Trans. on Instrum. & Meas., IM-25, No. 3, 270 (September 1976).

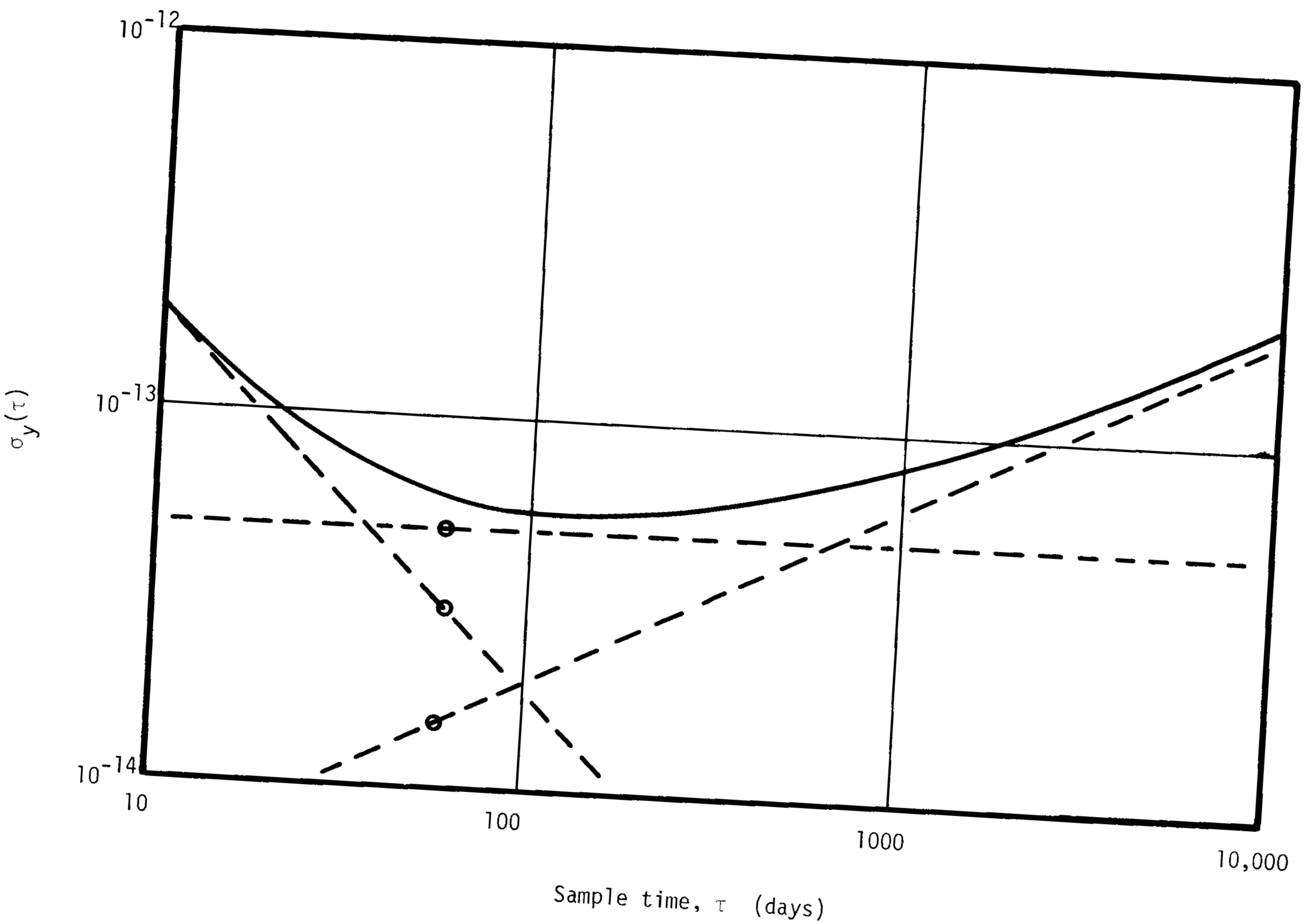

Figure 1. Two-sample variance from BIH model

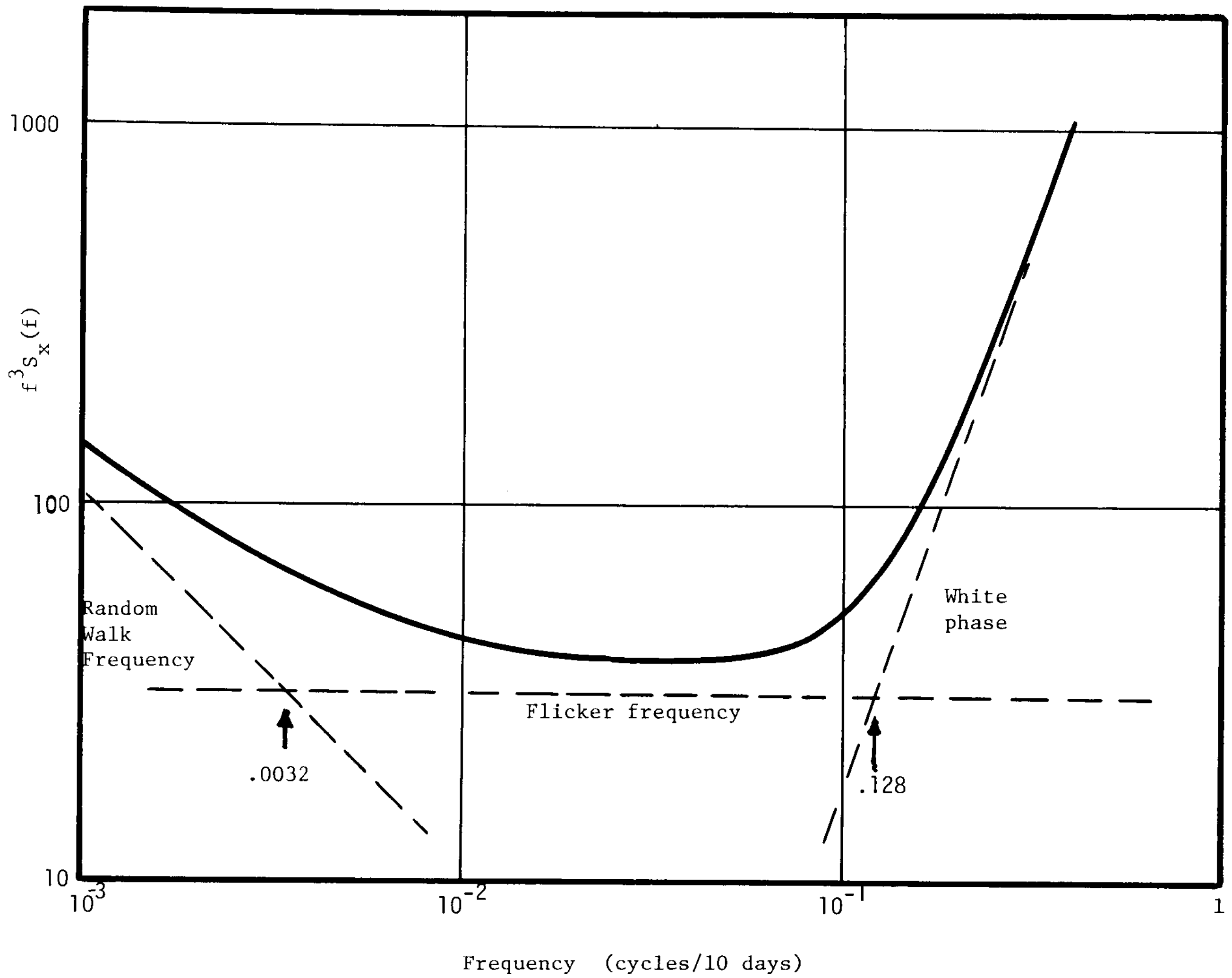

Figure 2. Plot of $f^3\ S_x(f)$ for BIH model

Dashed lines represent individual noise components from BIH model.

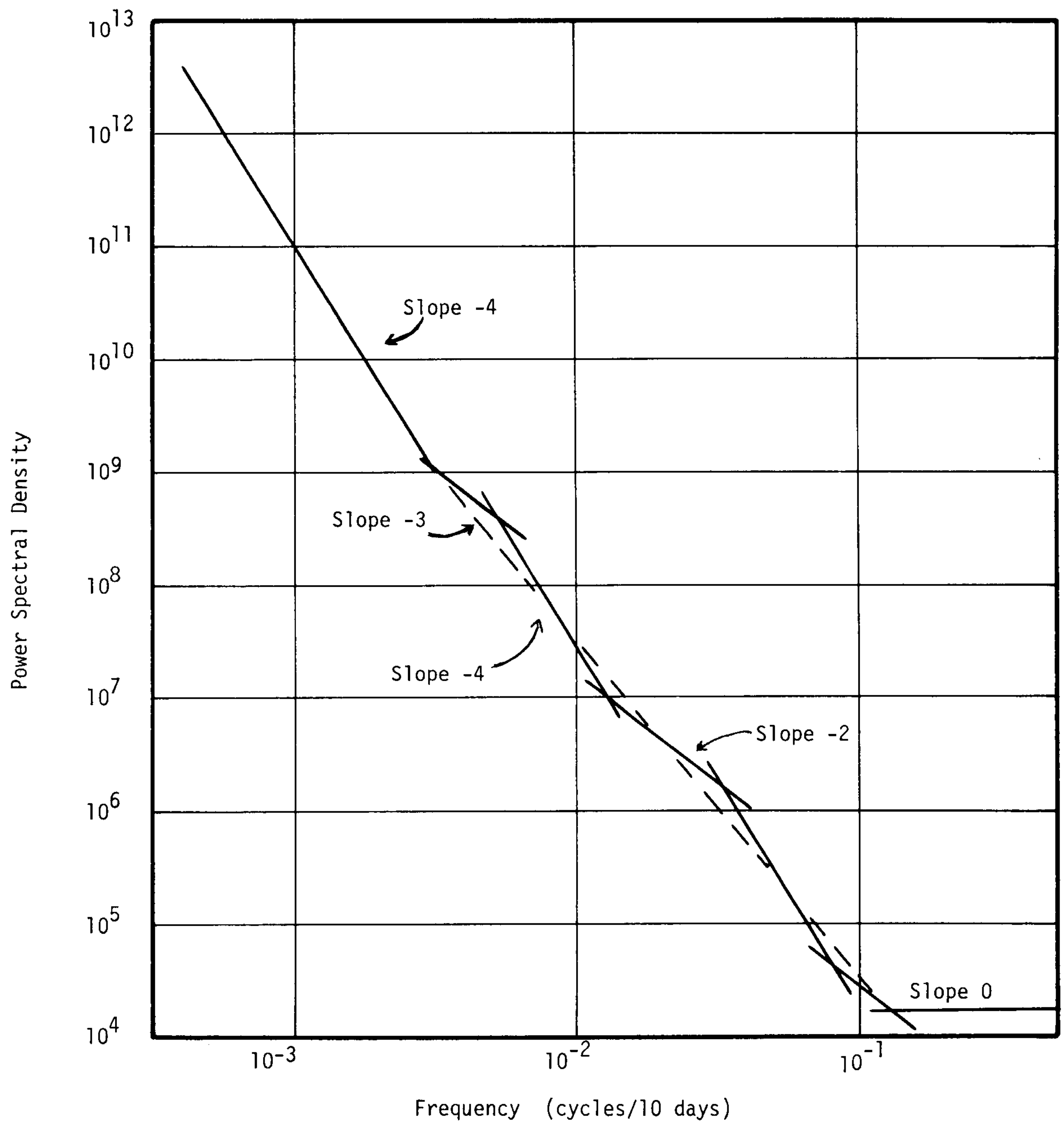

Figure 3. Bode plot of BIH model spectrum (dashed) and ARIMA model spectrum (solid)

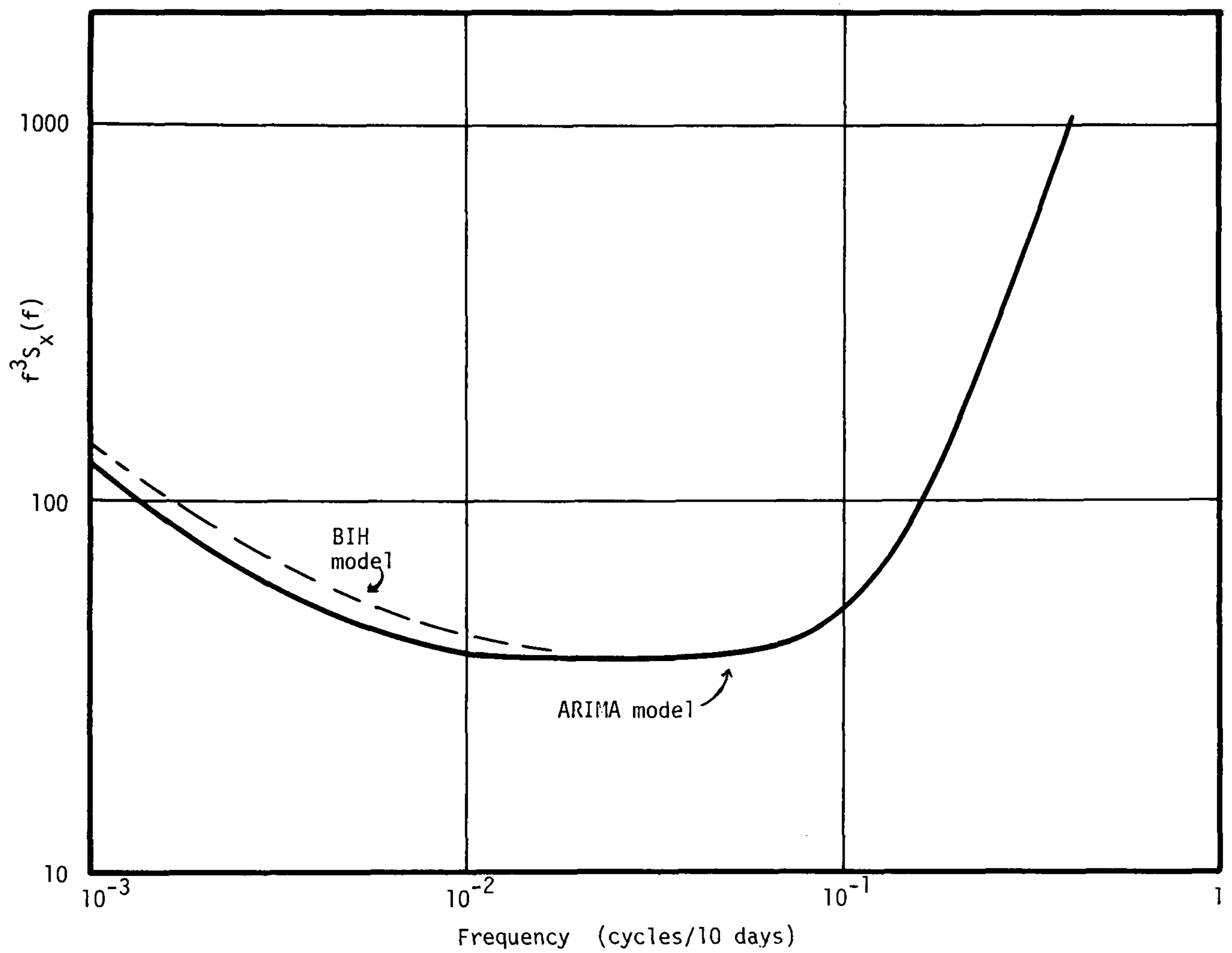

Figure 4. Plot of $f^3S_x'(f)$ for ARIMA model designed to simulate BIH model

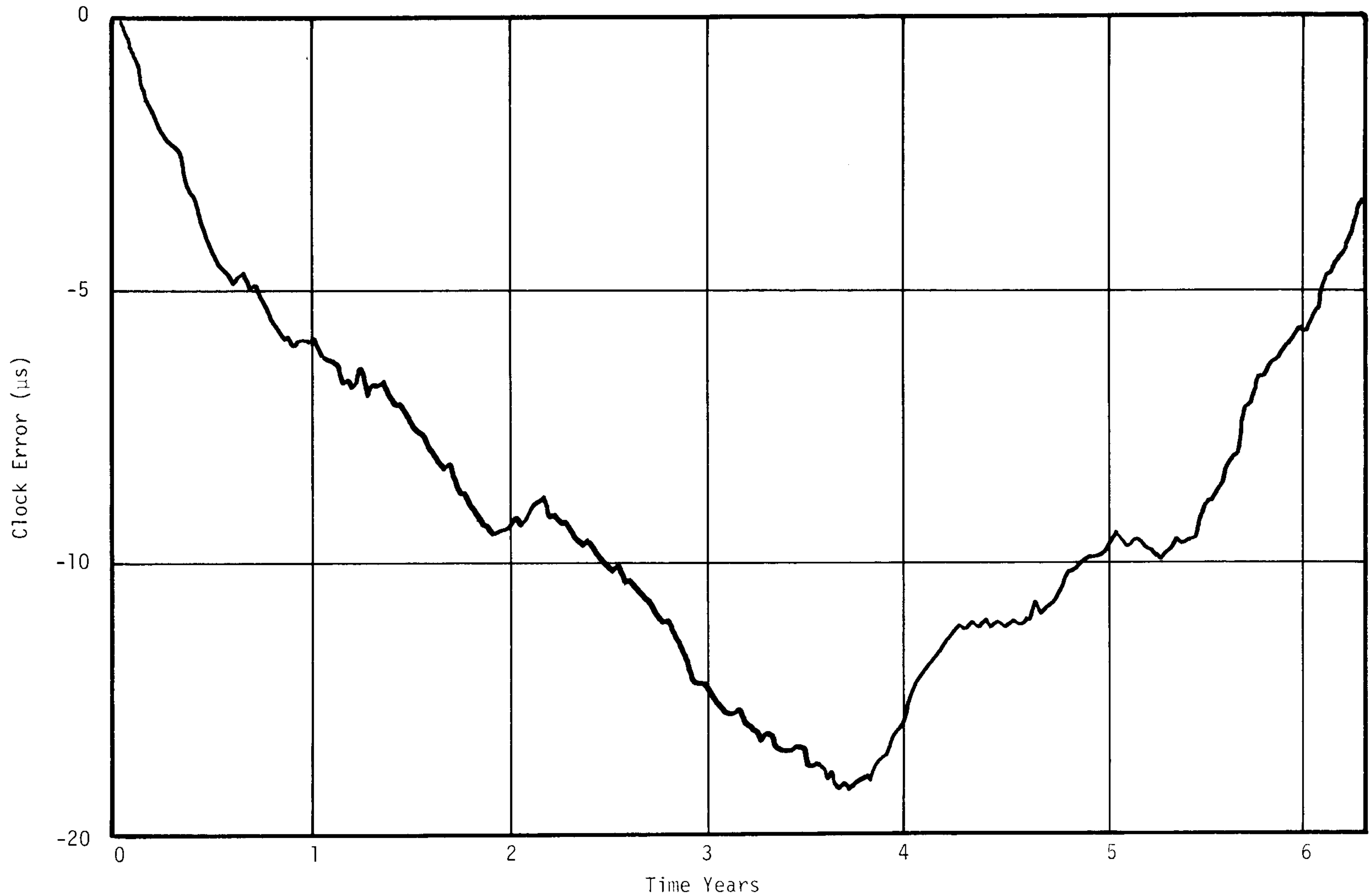

Figure 5. A Simulation of Time Errors for TAI Using ARIMA Model

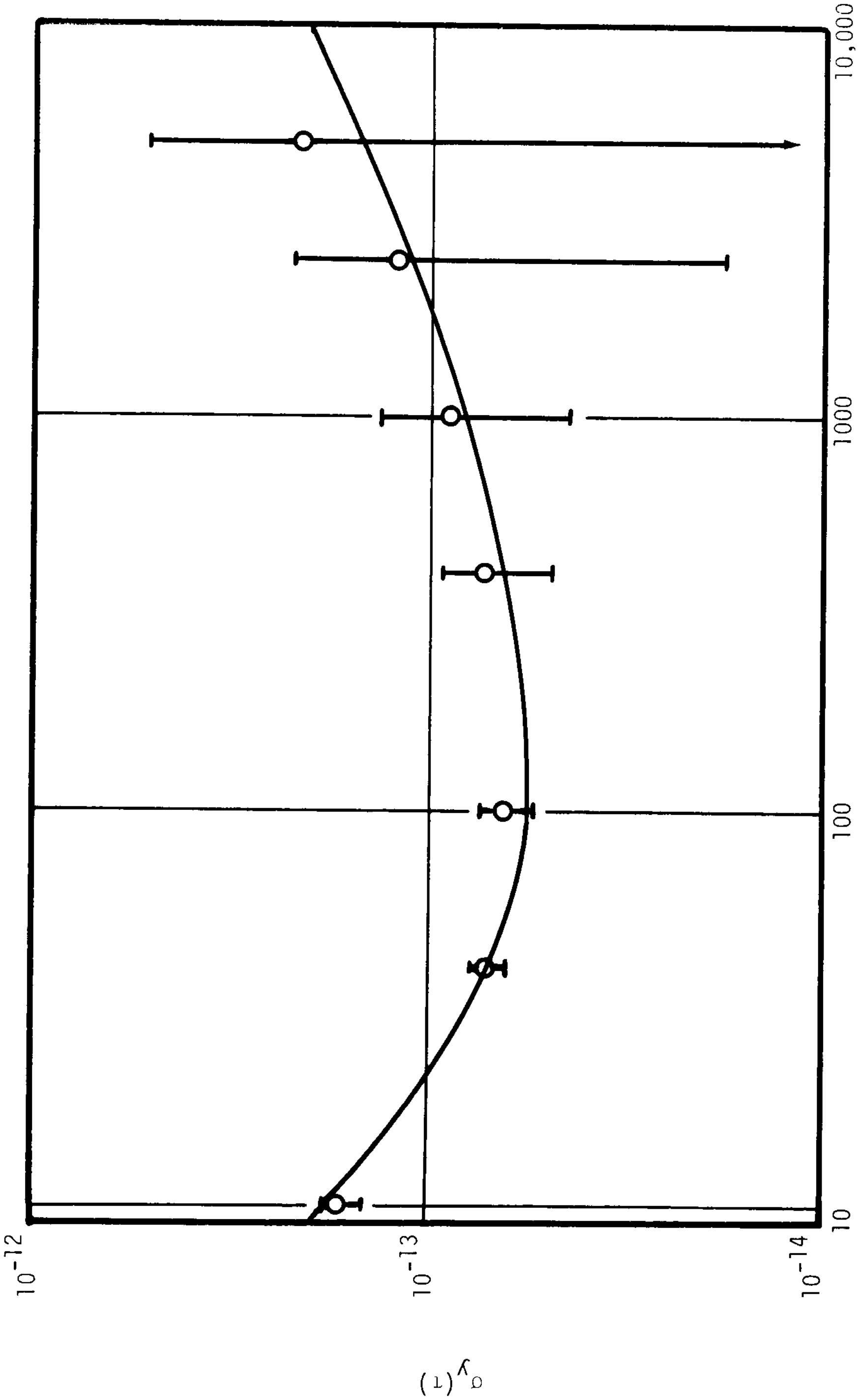

Figure 6. Two-sample variance from simulated data compared to BIH model

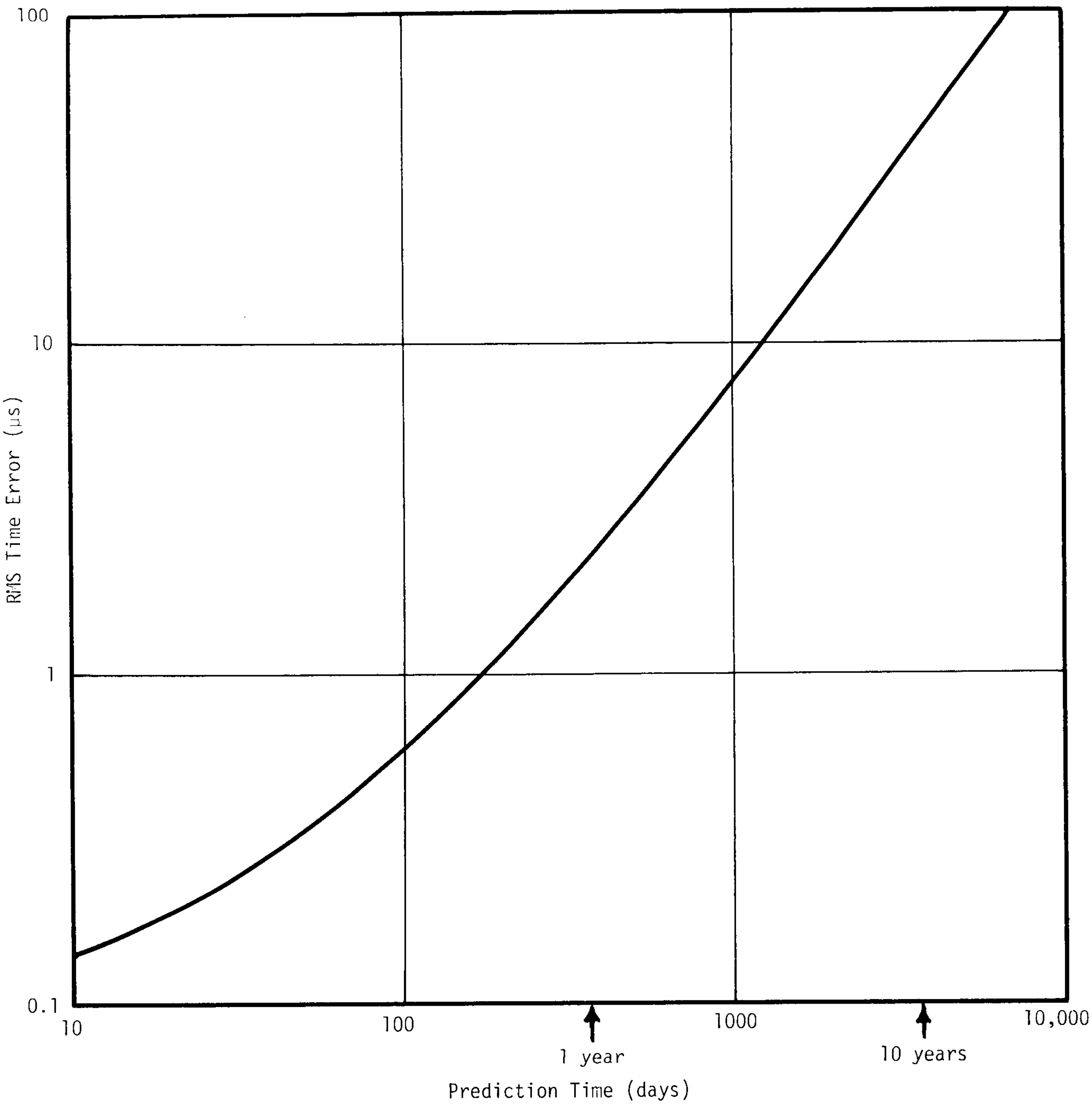

Figure 7. RMS Prediction Errors for ARIMA Model of TAI

The following is an exact reproduction of Appendix B of [4], "Models for the interpretation of frequency stability measurements," NBS Technical Note 682 (August 1976)

Appendix B. Building an ARIMA Model to Fit a Given Spectrum

In general, ARIMA models can approximate a wide range of spectral shapes. This appendix, however, will consider only a rather restricted set of these models. Also, the objective of this appendix is to provide a means of building an ARIMA model to fit a prescribed spectrum. Other techniques [12] emphasize the building of ARIMA models to fit a particular data set regardless of its spectrum.

One method of simulating a flicker noise with ARIMA models has already been published [21]. The treatment here will be a graphical approach using Bode plots.

Consider a random, uncorrelated, Gaussianly distributed, discrete time series, a_t, with mean zero and variance σ_a^2. Also consider a time series ω_t deduced from the a_t by the equation

$$\omega_t - \phi_1\omega_{t-1} - \phi_2\omega_{t-2} - \dots - \phi_p\omega_{t-p} = a_t - \theta_1 a_{t-1} - \theta_2 a_{t-2} - \dots - \theta_q a_{t-q}, \tag{B-1}$$

where the ϕ_i's and θ_i's are constants. We can define the index-lowering operator, B, by the relation

$$B\chi_t \equiv \chi_{t-1}. \tag{B-2}$$

This allows (B-1) to be rewritten in the form

$$(1 - \phi_1 B - \phi_2 B^2 - \dots - \phi_p B^p)\, \omega_t = (1 - \phi_i B - \phi_2 B^2 - \dots - \phi_q B^q) a_t \tag{B-3}$$

The expression in parentheses on the left side of (B-3) is called the Auto Regressive (AR) operator of order p. That on the right is called the Moving Average (MA) operator of order q.

We can further define another time series, Z_t by the relation

$$\Delta^d Z_t = \omega_t, \tag{B-4}$$

where $\Delta Z_t \equiv (1-B)Z_t \equiv Z_t - Z_{t-1}$. That is, Z_t is the d-fold (finite) integral of ω_t. Thus, Z_t is an Auto Regressive, Integrated, Moving Average process defined by the ϕ_i's, θ_i's, σ_a^2, and the d differences of (B-4). In particular it is an ARIMA (p,d,q) process.

In order for ω_t to be stationary and invertible, there are restrictions on the ϕ's and θ's [12]. However, for the present discussions it will suffice to consider only the following two processes

$$\omega_t = (1 - \theta B) a_t \tag{B-5}$$

$$(1 - \phi B)\chi_t = y_t \tag{B-6}$$

For this case it is sufficient that $-1 < \theta < 1$ and $-1 < \phi < 1$.

In these equations one sees that if one sets $\phi = \theta$ and $y_t = \omega_t$, then one obtains $\chi_t = a_t$. That is, if one considers (B-5) and (B-6) to define two digital filters, then (B-5) and (B-6) are inverse filters for each other when $\phi = \theta$. Thus, it is a simple matter to extend any understanding one gains about one filter to the other.

It is of value to consider the effect of a single MA filter of the form (B-5) when θ is further restricted to the interval $0 \leq \theta < 1$. Figure (B-1) shows the general behavior of the transfer function (magnitude squared) of such a filter and the straight-line approximations to this transfer function. The "knee" in the approximation occurs at a frequency f_c which is related to θ by the empirical relationship

$$\theta \approx \frac{1-\pi f_c}{1+\pi f_c}, \tag{B-7}$$

which will not be derived here.

Similarly, Fig. (B-2) is the transfer function of the AR filter with $\phi = \theta = 0.728$ as in Fig. (B-1). Hence, also,

$$\phi \approx \frac{1-\pi f_c}{1+\pi f_c} \tag{B-8}$$

We can now construct an approximation to a process which is a mixture of flicker noise and white noise. Figure (B-3) shows the Bode plot of the desired filter transfer function. The frequency axis of Fig. (B-3) is in terms of cycles per data spacing. Thus, the Nyquist frequency is just 1/2. For the sake of the example, we will assume that it is sufficient to approximate the spectrum to a lower frequency of .002 (cycles per data spacing).

Figure (B-4) superimposes the Bode plot of the filter which will be used onto the spectrum of Fig. (B-3). From each of the "knees" in the approximation one can determine the appropriate ϕ or θ for a filter to be cascaded in series.

Thus, from "knees" at the frequencies of .0233 and .0033, one obtains ϕ's for the AR filters (eq. B-6) of .8636 and .9795, respectively. These numbers have been calculated from eq. (B-8). Similarly, from the "knees" at the frequencies of .062 and .0087, one obtains θ values of .6740 and .9468, respectively, for the MA filters. One decides to use an AR filter if the function turns downward in response with increasing frequency as in Fig. (B-2). Correspondingly, one chooses a MA filter when the function turns upward as in Fig. (B-1).

The final filter can be obtained by cascading the output of one filter to the input of the next in the form

$$\begin{aligned} \omega_t &= (1 - .6740B)a_t \\ (1 - .8636B)\, \chi_t &= \omega_t \\ y_t &= (1 - .9468B)\chi_t \\ (1 - .9795B)\, z_t &= y_t \end{aligned} \tag{B-9}$$

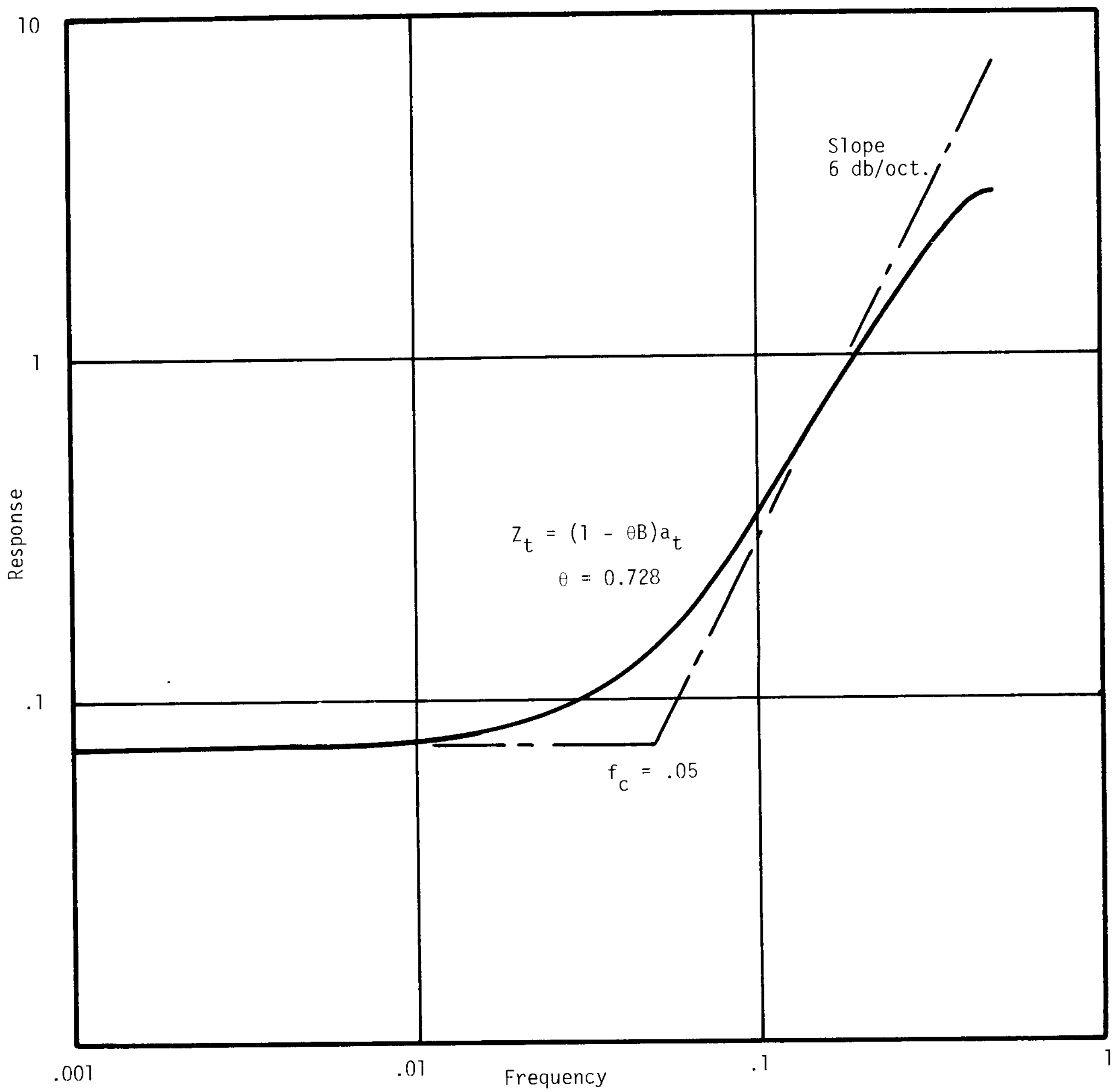

Fig. (B-1) Transfer Function of Simple MA-Filter

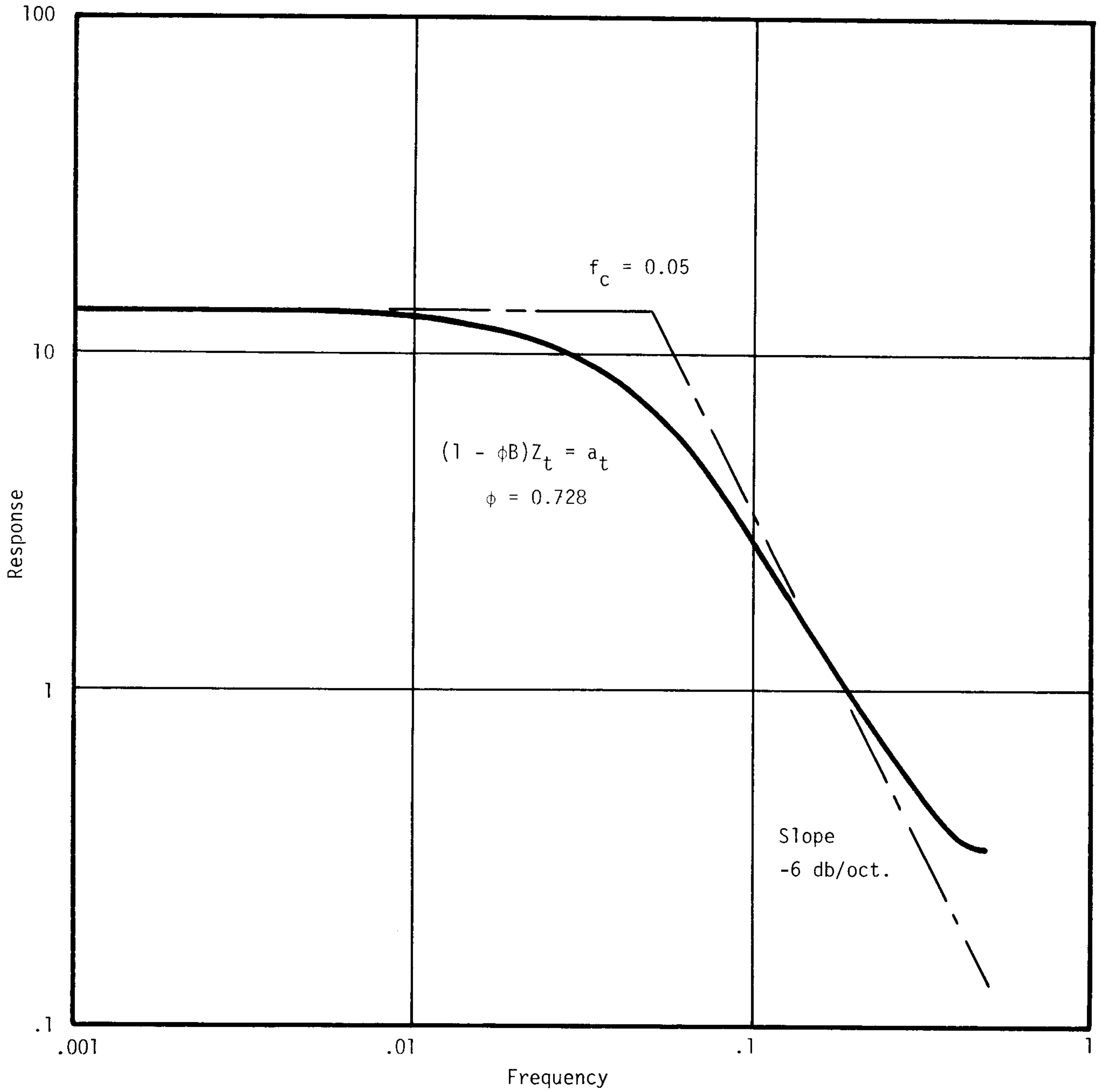

Fig. (B-2) Transfer Function of Simple AR-Filter

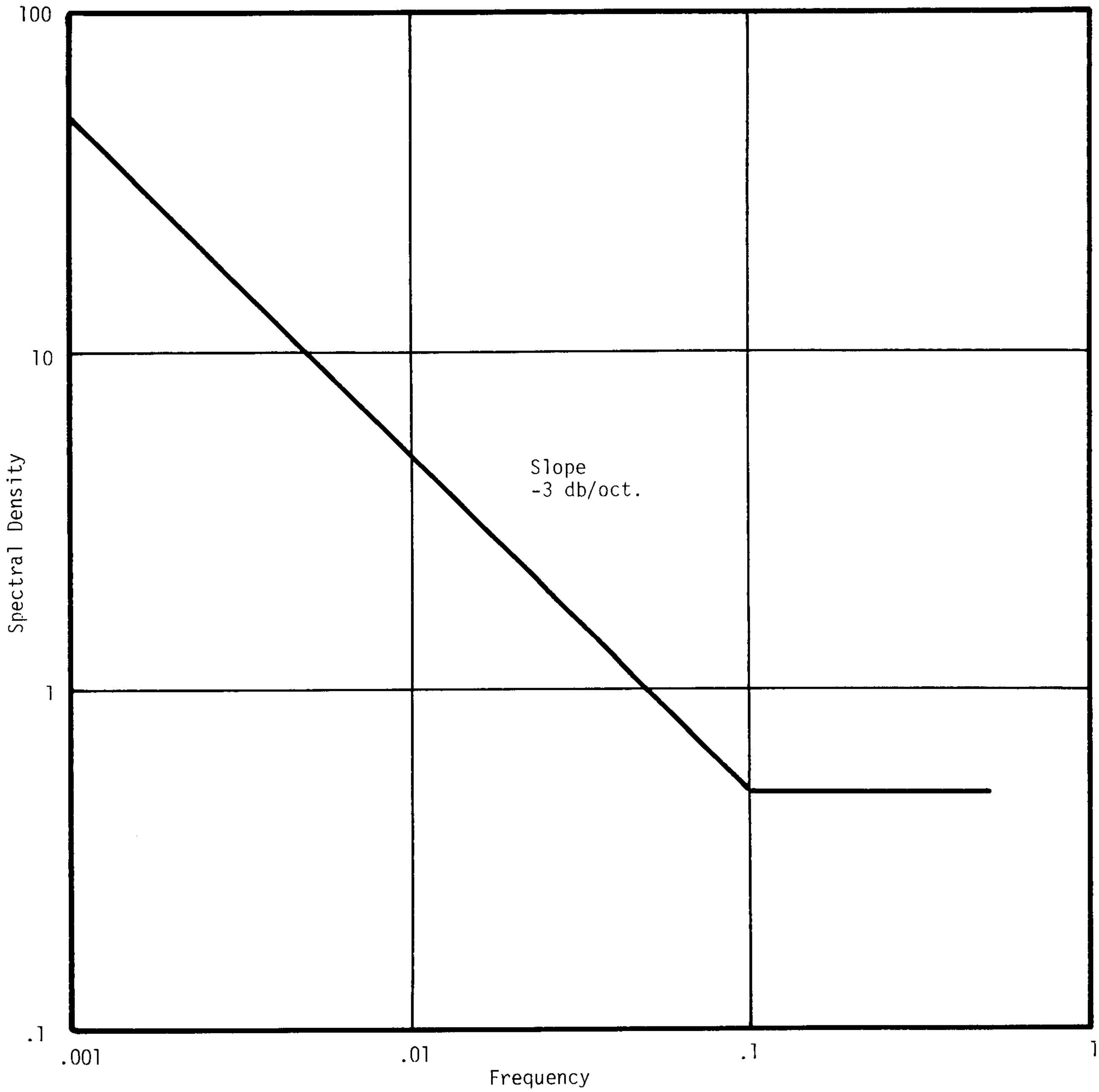

Fig. (B-3) Bode Plot of Desired Spectrum

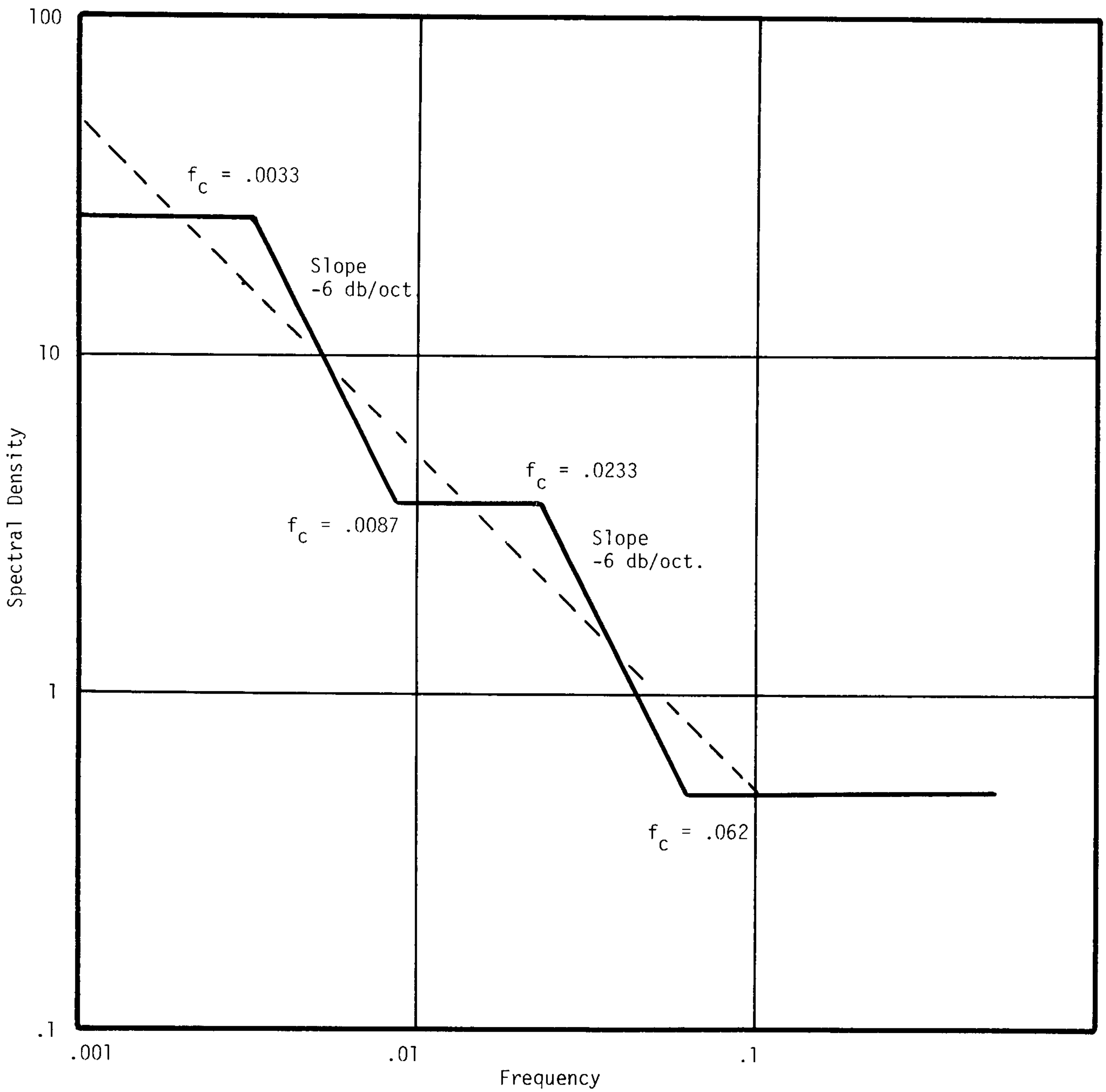

Fig. (B-4) Bode Plot of Filter Cascade

where a_t is the input to the cascade and z_t is the output. One can eliminate ω_t, χ_t and y_t and write an equivalent expression in the form

$$(1 - \phi_1 B - \phi_2 B^2) z_t = (1 - \theta_1 B - \theta_2 B^2) a_t, \tag{B-10}$$

where

$$\begin{aligned} \phi_1 &= 1.8431, & \theta_1 &= 1.6208 \\ \phi_2 &= -.8459, & \theta_2 &= -.6381 \, . \end{aligned} \tag{B-11}$$

Making use of equation (4.2) one can obtain the spectrum corresponding to (B-10). Figure (B-5) is a plot of the spectrum superimposed on the Bode plot of Figure (B-3). The parameter $\sigma_a^2 = 0.319$ was selected to make the spectrum fit the Bode plot in amplitude.

In this example, one could let z_t model the frequency of an oscillator, and it is clearly stationary [12]. To model the phase, one could define a parameter ν_t by the relation

$$(1 - \phi' B) \nu_t = z_t \tag{B-12}$$

where $\frac{1}{1-\phi'}$ is large compared to any data sample to be tested.

In the current example f_ℓ was taken as .002. Thus, one could select $\phi' \simeq .99999$ to be quite adequate. Note that ν_t is also stationary.

By selecting $\phi' = .99999$ one obtains a stationary model for ν_t if one so desires. Of course, for actually generating a data set one could use $\phi' = 1$, since no observational difference in the simulated data would result--that is why ϕ' was chosen as close to unity as it was. Thus, the entire difference between a stationary and a nonstationary model (ν_t) for the phase is centered in whether one chooses .99999 or unity for ϕ'. Further, this choice is totally unobservable for short data sets ($N \sim 1/f_\ell = 500$).

Clearly, these techniques could be used to develop an ARIMA model to simulate data over a much broader range of frequencies than done here. In any event, equations (B-10) and (B-12) allow one to simulate a stationary noise with the desired spectrum.

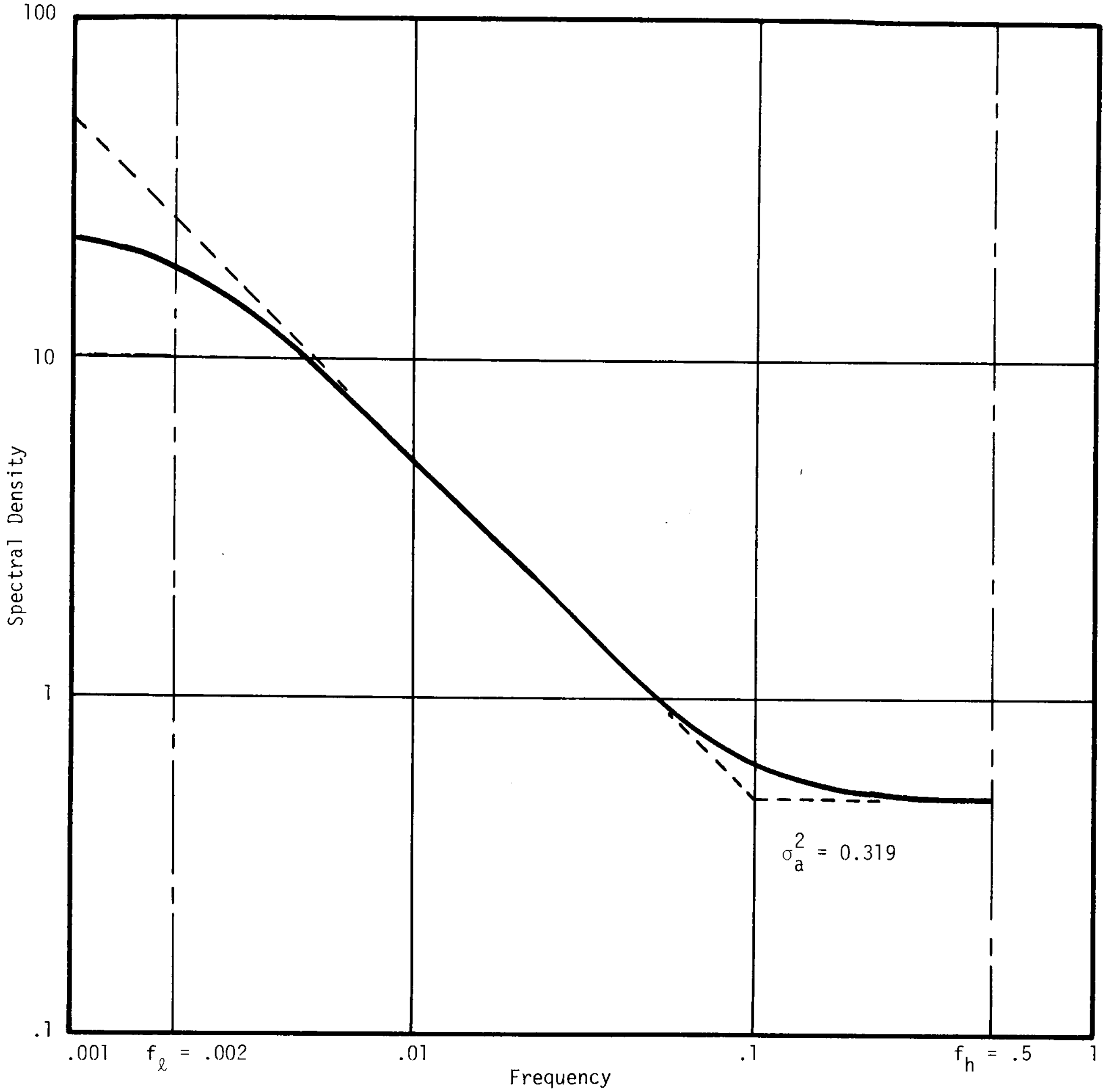

Fig. (B-5) Actual Spectrum of ARIMA (2,0,2) Model

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