# REFERENCE CLOCK PARAMETERS FOR DIGITAL COMMUNICATIONS SYSTEMS APPLICATIONS

Peter Kartaschoff
Swiss Post Office Research and Development Division
Berne, Switzerland

## ABSTRACT

The choice of correctly defined and useful parameters for characterizing the performance of reference clocks used in digital communications systems is a subject of efforts in the CCITT and the CCIR, the consultative technical bodies of the ITU. The operation of the systems depends on timing. Thus the CCITT has chosen in its Recommendation G811, to specify the clock performance requirement by starting a maximum allowable time interval error, i.e. a clocks time departure after initial synchronization.

On the other hand the commonly used characterization of clock performance is based on frequency instability as the basic phenomenon. CCIR Recommendation 538 therefore states the well known polynomial form of the spectral density of random frequency departures. It is now possible to estimate a probable time interval error if the model parameters of the clock are known. This error depends on the initial synchronization error, the frequency drift, the initial frequency setting error and the random frequency instability.

With established relations between the frequency instability of clocks and the timing properties required for the system, the relevant parameters determining the timing properties can be identified.

In a network these parameters are a) the characteristics of the clocks located at the nodes and b) the spectral densities of the delay variations of the links. One important optimization problem is the design of remote control systems for clocks from a master clock over links affected by delay variations and noise. The result depends on the bandwidth of the control loop and the free running stability of the controlled clock.

## 1. INTRODUCTION

The purpose of this paper is to present some definitions, relations and practical data for the planning and design of network timing in digital communications systems. It is based on information which in most cases has already been published in various forms and also provides an update on the current work on recommended performance standards which is going on in the International Telephone and Telegraph Consultative Committee (CCITT) and the International Consultative Commitee on Radiocommunications (CCIR) of the International Telecommunications Union (ITU).

There is a need for clarification of concepts and unification of language among the people working on new devices and systems related to the field of PTTI Applications.

The system planner and designer needs well established theoretical concepts. In addition, he needs a good feeling for the orders of magnitude for the relevant parameters. The data presented in this paper are mainly illustrative and not intended to promote a particular design or product.

In section 2 clock parameters are summarized. Section 3 deals with the concept of Time Interval Error and section 4 with transmission delay variations i.e. the degradation of timing information occurring on communication links. In section 5 the performance of a remote controlled clock is discussed by means of numerical examples.

## 2. CLOCK PARAMETERS

The performance of clocks is described by the following set of parameters.

- Environmental influences:
  - temperature
  - shock
  - acceleration
  - humidity

- Frequency drift or aging

- Random frequency instability

Environmental influences limit the performance of free running clocks. In the case of frequency controlled clocks, the control range will have to be large enough in order to compensate for these effects. Environmental specifications therefore constitute an important set of design parameters which often determine the choice of a system configuration and the requirements on the devices used. The values given in the numerical examples are for a mild environment typical for civilian applications (Temperature +10 to +50°C, Humidity 30 to 80 percent relative, negligible shock and acceleration). Military or civilian mobile and aeronautical applications require other sets of parameters.

Assuming thus that we have environment under control, we can concentrate on the other two parameters, whereby these specifications include some residual environmental effects (e.g. the flicker frequency instability in most operational clocks).

Table 1 contains stability data on the following types of clocks

cesium
rubidium
crystal, oven controlled, high stability types

The aging coefficients are upper limits derived either from manufacturer's specifications or from operational experience. Four different types of crystal oscillators have been considered.

No. 1 is a 5 MHz commercial type in wide use today
No. 2 is a less expensive small oven controlled VCXO
No. 3 is a low noise 10 MHz VCXO
No. 4 is a projection of new designs

The random instability coefficients are those of the well known theoretical model [1-6] recommended by the CCIR [7] and based on the spectral density of normalized random frequency departures:

$$S_y(f) = h_{-2}f^{-2} + h_{-1}f^{-1} + h_0f^0 + h_1f^1 + h_2f^2 \qquad (1)$$

$$\text{with} \quad y(t) = \frac{\nu-\nu_0}{\nu_0}$$

$\nu$ being the actual "instantaneous" value of the frequency, $\nu_0$ the nominal value and f the "Fourier"-frequency. The values in the table are computed from the time-domain data given by the manufacturers as the square root $\sigma_y(\tau)$ of the two-sample Allan-variance, using the relation:

$$\sigma_y^2(\tau) = h_{-2}\frac{4\pi^2\tau}{6} + h_{-1}\,2\ln 2 + h_0\frac{1}{2\tau}$$

$$+ h_1\frac{1}{4\pi^2\tau^2}(4.5 + 3\ln(2\pi f_H\tau) - \ln 2) + h_2\frac{3f_H}{4\pi^2\tau^2} \qquad (2)$$

where $f_H$ is the upper cutoff frequency of the measurement system used to measure $\sigma_y(\tau)$, and $\tau$ the sampling time.

The figures given are all conservative upper limits, usually guaranteed by the manufacturers and not so-called "typical" values which often tend to be optimistic. Only the crystal oscillator example No. 4 constitutes a projection not yet confirmed by large scale operational experience, but prototype results are available [8].

The values missing from the table have not been included because they are either not significant for the applications discussed in this paper (short term, high f fluctuations for Cesium and Rubidium) or small compared to the other terms ($h_0$ for crystal oscillators).

## 3. TIME INTERVAL ERROR

Timing is an essential function in any digital communications system. Therefore, international standards defining the minimum performance of the clocks used for network timing are required in order to achieve world-wide digital communication. The CCITT Study Group XVIII working on standardization of digital networks has issued a Recommendation G811 in 1976 (9). A revised edition will be published in 1981 after the recent 6th General Assembly (Geneva 10-24 November 1980). This document specifies the minimum performance of clocks suitable for plesiochronous operation of international, i.e. border-crossing digital links. Plesiochronous operation between networks means that each network is controlled by a master or reference clock which is free-running with respect to that of the neighbouring network. This requires close tolerance frequency adjustment and high stability in order to keep the rate of occurrence of slips below one in 70 days in any 64 kbit/s channel.

The long term normalized frequency departure must therefore be less than 1 part in $10^{11}$ in normal operation. The probability of degradation to 1 part in $10^9$ shall be less than $10^{-5}$ and that of unavailability less than $10^{-6}$.

The clock performance limits are defined as a maximum allowable Time Interval Error (TIE):

$$\mathrm{TIE}(t) = \Delta T(t+\tau) - \Delta T(t) \qquad (3)$$

where $\Delta T$ is the time difference between the actual timing signal and an ideal timing signal. Using a more familiar notation [2, 3, 4, 6, 7] we have for any time interval $\tau$:

$$\mathrm{TIE}(t_0) = x(t_0+\tau) - x(t_0) = \int_{t_0}^{t_0+\tau} y(t)dt \qquad (4)$$

For a clock which has been adjusted to the nominal frequency and synchronized at t=0, the probable time interval error $\sigma_x(t)$ can be estimated. $\sigma_x(t)$ is the standard deviation of the time departures of an ensemble of identical clocks having random instabilities described by the model of equation 1. The following relation has been demonstrated by means of computer simulations [10];

$$\sigma_x(t) = t \left(\sigma^2_{y_0} + \sigma^2_y (\tau=t)\right)^{1/2} \qquad (5)$$

$\sigma_{y_0}$ is the standard deviation of the initial frequency adjustment and $\sigma_y(\tau)$ the two sample standard deviation (square root of equation 2) describing the random frequency instability. It is assumed that the parameters characterizing the clock do not change with time and that the initial adjustment error and the subsequent random frequency fluctuations are statistically independent. In addition to the random instability and the initial adjustment error, frequency drift has to be considered and this leads to a combined systematic and random estimate of the TIE

$$TIE_{est.} = \frac{a}{2} t^2 + t \left(\sigma^2_{y_0} + \sigma^2_y (\tau=t)\right)^{1/2} \qquad (6)$$

Eventually, significant cyclic environmental effects will have to be included, too. The method of estimating the TIE using equation 6 has been discussed in the CCIR Study Group 7 and included in a draft Report [11].

The allowed limit of the TIE recommended in CCITT G811 is shown in Fig. 1.

On the short term we see different curves which depend on the bit rate of the communications channel considered. This is due to the fact that the limit defined in this range is 100 $\tau$ + 1/8 unit interval, expressed in nanoseconds where the unit interval is the inverse of the bit rate.

In a real situation the random component of the time departure determines a finite probability of violation which can be computed for the model described above. A recommended value will have to be defined after further study.

## 4. TRANSMISSION DELAY VARIATIONS

The systematic and random departures of the timing instants from the ideal periodic timing waveform are designated by the terms of "jitter" and "wander". In the litterature we find these departures referenced either to the signal period (phase jitter) or to a reference time scale (timing jitter). The latter form is to be preferred since it does not depend on the particular bit rate.

The distinction between jitter and wander is at present not very precisely defined. One could treat it as a matter of Fourier Frequency since most specifications of jitter spectral density and jitter transfer functions stop at the low end around about 20 Hz.

In a recent update on synchronization [12] one finds some examples extending the frequency domain to quite lower values for spectral densities having the character of white phase (or timing) noise.

The word "wander" appears in some CCITT documents as a designation for slow systematic and random phase or time fluctuations.

The time fluctuations observed at the receiving end of a transmission link are the sum of the fluctuations originating in the clock at the transmitting end and the path delay fluctuations [13]. The planning and design of a network timing system requires quantitative knowledge of both phenomena. As summarized in sections 2 and 3 we have a fairly complete picture on the modeling of clock performance. Reliable data on path delay variations are more difficult to obtain. This may be due to the large variety of transmission systems in use or under development and to the fact that long term path delay measurements on operational transmission systems are much more difficult to organize than laboratory measurements on oscillators. Therefore, the data given below are neither complete nor definitive but rather an illustration of orders of magnitude to be expected and subject to some revision.

The best known example of jitter accumulation on long transmission links is that occurring on the lowest hierarchy PCM links with a bitrate of 1544 kBit/s (USA and Japan) or 2048 kbit/s (Europe). The basic theory has been established many years ago [14] and recent measurements known to the author [15, 16, 18] appear to confirm the theoretical predictions. The spectral density of the timing jitter has the general approximate form shown in Fig. 2. This figure represents an envelope drawn above the spectrum which is more complex and has maxima and minima depending on the digital word structure or pattern of the signal. Using the envelope for design purposes is a conservative approach. The timing jitter spectral density envelope can be described by

$$S_x(f) = h_{200}\left(1 + \frac{f}{f_B}\right)^{-1} \qquad (7)$$

where $h_{200}$ and $f_B$ are functions of the number N of cascaded regenerators and the bandwidth or Q of the regenerator timing circuit.

Fig. 3 shows this dependence on N for two examples: passive LC circuit regenerators with Q = 80 and PLL-type regenerators with Q = 500.

We see that for Fourier frequencies below $f_B$, the PCM-line jitter has the character of white timing (or phase) noise.

For random, zero mean normally distributed test signals this property appears to be true for arbitrarily low Fourier frequencies. For real voice and data traffic the statistics can be different. However, modern coding techniques tend to approach random or pseudo-random signal statistics. Similar descriptions of transmission delay statistics can be developed for all kinds of digital transmission systems. A complete review is beyond the scope of this paper.

Systematic slow delay variations are mainly caused by environmental influences on the transmission medium. In the case of satellite systems, the dynamics of the system configuration [orbit parameters] play a major role.

Temperature coefficients of metallic and optical fibre cables are summarized in Table 2. These figures are orders of magnitude and may vary depending on the cable type and manufacturer. A published reference [17] has been found only for the optical fibers, the other data have been gathered from various unpublished reports. The temperature variations show a daily and yearly cycle which depends on the climatic conditions. In temperate regions such as Europe an average temperature of +10°C, a peak-to-peak range of 20°C (year) and 2°C (day) can be expected.

For transmission over a geostationary satellite, a 24 hour cyclic variation of the transmission delay is due to imperfect orbital parameters (eccentricity, inclination). Taking into account the necessity of improved stationkeeping due to the increasing population on the geostationary orbit, a peak-to-peak daily delay variation of 600 microseconds should not be exceeded. Long term drift and orbit repositioning will cause additional variations [20]. Terrestrial microwave links over line of sight paths are known to be very stable, probably less than 5 nanoseconds variation due to the radio path itself.

A mostly unknown parameter is the delay variation due to environmental conditions acting on the equipments used in the various transmission systems. Much work remains to be done and it is surprising to note that J.R. Pierce's plea for information on this matter in 1969 [19, p. 629] went almost unnoticed. Whereas theoretical work is abundant and sometimes elaborate in the published literature [12], reliable experimental data on transmission delay variations still remains scarce. It is therefore difficult to see which and what part of the many theoretical approaches are really relevant for operating system design.

For a given transmission system, the quantitative description of delay variations must comprise both random and cyclical components. The random component is conveniently represented in the form of a timing fluctuation spectral density $S_x(f)$. It is at present not known if low frequency divergent terms (flicker or random walk) are significant at very low Fourier Frequencies. If such effects exist, they are probably small compared to the effects caused by temperature cycles. Accumulated statistics on extended systems subject to many temperature cycles with different amplitudes and phases could result in a flicker-like spectrum having significant density down to frequencies of one cycle per year. There is however a fundamental difference between transmission delay and clock time variations: The electrical length of the transmission path is always finite and its variations remain within physically limited bounds, whereas the time departure of any real clock grows without bounds.

## 5. REMOTE CONTROLLED CLOCK

The problem of remote control of the timing properties of a clock over a transmission link arises whatever the type of system organization chosen in practice, i.e. mutual synchronization, hierarchical master-slave (HMS) or any of possible combinations, refinements and self-organization schemes [21, 22]. The basic system elements are always a reference clock, a transmission link and another clock the time and frequency of which is to be controlled by some means in order to obtain the fulfillment of a specification such as CCITT Rec. G811. The reference might be itself a controlled clock or a free running master. The examples discussed in this section are on a quite elementary level compared to those discussed in recent publications [23-26], but include spectral density models of the transmission time jitter and of oscillator instability based on real data.

In most systems currently in operation and under development, the hierarchical master-slave (HMS) type of operation is applied. HMS is straightforward and fits well into the structure of existing public networks at the local and regional level. Compliance with CCITT Recommendation G811 requires that master clocks are accurate in frequency with an uncertainty of less than $\pm$ 1 part in $10^{11}$ and this implies reference to the frequency of UTC. Cesium clocks operated in a reasonable environment are accurate and stable enough to satisfy the requirements with only a minimum of surveillance and very few, if any readjustments. Rubidium and crystal clocks require initial frequency setting and subsequent frequency control from an external reference to compensate for the inherent frequency drift (aging).

Figures 4 and 5 show the time-domain frequency instability $\sigma_y(\tau)$ of typical cesium, rubidium and crystal clocks based on the data of Table 1.

**Fig. 6 shows the estimated time interval error for some clocks (see table 1) operated in the free running mode. It is thereby assumed that each of these clocks has been adjusted in frequency and synchronized** at t=0.

The uncertainty $\sigma_{y0}$ of the initial frequency adjustment for each type of clock is assumed to be minimized, i.e. the averaging time for the measurement used for the readjustment is chosen so that the uncertainty corresponds to the minimum, flat portion ("flicker-floor") of the $\sigma_y(\tau)$ diagram of Fig. 4 and 5 respectively. In some cases, noise in the process of measurement through a transmission link may lead to a higher value of $\sigma_{y0}$ and this must be taken into account in such situations. Figure 6 gives an idea of the possibilities of manual readjustment based on measurements. It allows to determine how long a lower hierarchy clock can be operated in the free-running mode within the specified limits of G811 after interruption of the link to the master clock. It is assumed that the frequency control system memorizes the last valid setting of the oscillator control before the interruption [27, 28]. It turns out that a cesium clock can be operated indefinitely, a rubidium clock ($a = 1 \cdot 10^{-11}$ per month) for 52 days and crystal oscillators No. 1 ($a = 3 \cdot 10^{-11}$ per day) for 1.6 days and No. 4 ($a = 5 \cdot 10^{-12}$ per day) for 5.2 days.

To illustrate further the operation of a remote controlled clock, Figure 7 shows a block diagram comprising a cesium master clock, a PCM link as mentioned in section 4 and a crystal oscillator controlled by the most elementary form of a phase-locked-loop, i.e. a first order PLL having a single pole RC loop filter. The jitter transfer analysis of the PLL is made using the phase-time formalism described in [4, p. 188 ff].

Table 3 shows the formulas used in the computations of $\sigma_{y4}(\tau)$ describing the random frequency instability of the slave oscillator. Then the estimated time interval error of the slave oscillator is computed using the relation:

$$TIE_4(t) = t\,\sigma_{y_4}(\tau=t) + \frac{at}{K_x} \tag{8}$$

The first term is similar to equation 5 and the second term is due to the fact that we use a first order PLL, a is the aging coefficient of the slave oscillator. If the slave oscillator is to be controlled over a noisy link, a low value of $K_x$ ("loose control") is desired but then the second term shows the possible limit of improvement obtainable for a slave oscillator having a given aging coefficient.

The input data for the numerical examples are given in the Tables 4 and 1. The figures which follow show a selection of some typical cases.

Figure 8 shows the spectral density $S_{y_4}(f)$ of the controlled oscillator output for the 4 slave oscillators considered, both values of $K_x$ shown in Table 4 and with and without the PCM line jitter.

Figure 9 shows the corresponding time domain stability $\sigma_{y_4}(\tau)$.

Figure 10 shows the TIE estimate obtained by means of equation 8.

It is to be emphasized that these results do not constitute a design proposal. They are shown to illustrate the relation between reference instability, line timing jitter, control loop parameters and slave oscillator instability using a simple PLL-Control System.

In a practical design, step frequency control with a memory and provided with a fast acquisition mode as described in [27, 28] or perhaps higher order or microprocessor controlled adaptive systems are or will be used. There is not much difference between the loop transfer function $H_x$ in our illustrative example and those used in [27, 28], except for the larger computation effort required for the analysis of these more sophisticated designs.

The difference between the computed TIE estimate and the design limit imposed by Rec. G811 constitutes a margin in which the systematic cyclic delay variations remain to be included. The allowed amplitude of these variations depends on the probability of violation allowed in the design.

In the case of directed control HMS, the type of transmission medium limits the allowable distance between master and slave clocks. Double-ended timing [22] can in principle reduce the effect of slow delay variations but the delays involved in the back and forth transmission of timing information may change the transient response of the control system and careful analysis is required in order to ascertain the stability of the control.

## 6. CONCLUSIONS

The basic parameters relevant to the design of network timing systems describe the random and systematic time departures of the system elements, i.e. master (or reference) clocks, transmission links and other clocks controlled over the links. Using the definitions and notations recommended in CCIR and CCITT texts, the quantitative relations between these parameters have been established and illustrated by means of numerical examples based on available measured data. The examples have been limited to a simple PLL-control system but the analysis can eventually be applied to more sophisticated systems at the cost of increased computational effort.

The author gratefully acknowledges the contribution of Kurt Hilty who did the programming for the computations of the numerical examples.

# REFERENCES

[1] Proc. IEEE, vol. 54, no. 2, Feb. 1966. Special Issue on Frequency Stability.

[2] J.A. Barnes et al., "Characterization of Frequency Stability", IEEE Trans. Instrum. Meas., vol. IM-20, pp. 105-120, May 1971.

[3] B.E. Blair, Ed., "Time and frequency - Theory and fundamentals", NBS Monograph 140 U.S. Gov. Print. Off. SD Catalog C 13:44:140, May 1974.

[4] P. Kartaschoff, Frequency and Time. London, England: Academic Press, 1978.

[5] W.C. Lindsey and C.M. Chie, "Theory of oscillator instability based upon structure functions, "Proc. IEEE, vol. 64, no. 12, pp. 1652-1666, Dec. 1976.

[6] J. Rutman, "Characterization of phase and frequency instabilities in precision frequency sources: Fifteen years of progress, "Proc. IEEE, vol. 66, no. 9. pp. 1048-1075 Sept. 1978.

[7] CCIR Report 580-1 and Recommendation 538, Kyoto 1978, ITU Geneva.

[8] R.J. Besson and D.A. Emmons, "Initial Results on 5 MHz Quartz Oscillators equipped with BVA-Resonators", Proc. 11th PTTI Conference, pp. 457-468, NASA Conference Publication 2129 (1979)

[9] CCITT 6th Plenary Assembly, "Orange Book", Rec. G811, Vol. III-2, pp. 485-468, ITU, Geneva 1977.

[10] P. Kartaschoff, Computer Simulation of the Conventional Clock Model, IEEE Trans. on Instrumentation and Measurement, Vol. IM-28, No. 3, pp. 193-197 (September 1979).

[11] Draft Report AC/7, CCIR Study Group 7 Interim Meeting, Doc. 7/77, ITU Geneva (27 June 1980).

[12] IEEE Transactions on Communications, Special Issue on Synchronization, Vol. COM-28, Nr. 8 (August 1980).

[13] P. Kartaschoff, Frequency Control and Timing Requirements for Communications Systems, Proc. 31st Frequency Control Symposium, U.S. Army Electronics Command Ft. Monmouth, N.J. (1977), pp. 478-482.

[14] C.J. Byrne, B.J. Karafin and D.B. Robinson, "Systematic jitter in a chain of digital regenerators", Bell Syst. Tech. J., vol. 42, No. 6, pp. 2679-2714 (November 1963).

[15] A. Kaeser, "Quelques mesures de taux d'erreur et de gigue en ligne sur les systèmes à 2 Mbit/s sur câbles", Bull. Tech. PTT (Suisse), Vol. 54, No. 11, pp. 428-430 (November 1976).

[16] A. Kaeser, private communication.

[17] L.G. Cohen and J.W. Fleming, Bell Syst. Tech. J., Vol. 58, No. 4, pp. 945-951 (April 1979).

[18] E.P. Graf, private communication.

[19] J.R. Pierce, "Synchronizing Digital Networks" Bell Syst. Tech. J., Vol. 48, No. 3, pp. 615-636 (March 1969).

[20] CCIR Reports 214 and 383, CCIR Vol. IV, ITU Geneva 1978 (revisions to be published).

[21] H.A. Stover, "Suggested attributes for timing in a digital DCS", Proc. 11th PTTI Conference, pp. 15-26, NASA CP-2129 (1979).

[22] H.A. Stover, "Network Timing/Synchronization for Defense Communications", see [12], pp. 1234-1244.

[23] D. Mitra, "Network Synchronization": An Analysis of a Hybrid of Master-Slave and Mutual Synchronization, see [12], pp. 1245-1259.

[24] W.C. Lindsey and A.V. Kantak, "Network Synchronization of Random Signals", see [12], pp. 1260-1266.

[25] A. Kajackas, "On Synchronization of Communication Networks with Varying Channel Delays", see [12], pp. 1267-1268.

[26] W.R. Braun, "Short Term Frequency Instability Effects in Networks of Coupled Oscillators", see [12], pp. 1269-1275.

[27] E.A. Munter "Synchronized Clock for DMS-100 Family", see [12] pp. 1276-1284.

[28] E.P. Graf and B. Walther, "Generation of Base-Band Frequencies for FDM and TDM Telecommunications, Proc. 31st Annual Frequency Control Symposium, pp. 484-488, USAEC. Ft. Monmouth, N.J. 1977.

## TABLE 1

| Type of clock | Aging | Random instability coefficients | | | |
|---|---|---|---|---|---|
| | | $h_{-1}(s)$ | $h_0$ | $h_1(s^{-1})$ | $h_2(s^{-2})$ |
| Cesium | $<5\cdot10^{-13}$/year | $2{,}885\cdot10^{-26}$ | $8\cdot10^{-21}$ | - | - |
| Rubidium | $<1\cdot10^{-11}$/month | $1{,}803\cdot10^{-25}$ | $5\cdot10^{-23}$ | - | - |
| Crystal 1 | $<3\cdot10^{-11}$/day | $7{,}2\cdot10^{-25}$ | - | $9{,}4\cdot10^{-25}$ | $3{,}13\cdot10^{-26}$ |
| " 2 | $<5\cdot10^{-10}$/day | $2{,}89\cdot10^{-22}$ | - | - | $8{,}42\cdot10^{-25}$ |
| " 3 | $<5\cdot10^{-10}$/day | $7{,}23\cdot10^{-23}$ | - | $7{,}88\cdot10^{-25}$ | $7{,}88\cdot10^{-27}$ |
| " 4 | $<5\cdot10^{-12}$/day | $2{,}89\cdot10^{-26}$ | - | $9{,}4\cdot10^{-26}$ | $3{,}13\cdot10^{-27}$ |

TABLE 2

| Type of cable | Temperature coefficient of delay in ns/km x °C |
|---|---|
| Symmetrical pair, wire diameter 0.8 mm paper insulation | 3...5 |
| Symmetrical pair, wire diameter 0.8 mm polyethylene insulation | 0.3...0.75 |
| Coaxial cable polyethylene/air insulation 1,2/4,4 mm 2,6/9,5 mm | 0.03...0.075 |
| Optical fibre $SiO_2$ core [17] | 0.035 |

## TABLE 3

Input data:

| | | | | |
|---|---|---|---|---|
| Source: | ① | ② | ③ | ④ |
| | $S_{y_1}$ | $S_{x_{Line}}$ | $H_x(jw)$ | $S_{y_{40}}$ |
| Derivations: | $S_{x_1}$ | $S_{x_{Line}}$ | | $S_{x_{40}}$ |

$$S_{x_2} = S_{x_1} + S_{x_{Line}}$$

Output:

$$S_{x_4} = S_{x_2} |H_x|^2 + S_{x_{40}} |1 - H_x|^2$$

Transformations:

$$S_{y_4} = 4\pi^2 f^2 \, S_{x_4}$$

$$\sigma_{y_4} = \frac{2}{\pi\tau} \int_o^{u_H} S_{y_4} \left(\frac{u}{\pi\tau}\right) \frac{\sin^4 u}{u^2} \, du$$

with $u = \pi f \tau$

General Relations used:

$$S_{y_i} = 4\pi^2 f^2 \, S_{x_i}$$

TABLE 3 (CONTINUED)

| | |
|---|---|
| PLL-Data: | DC Loop Gain $K_x$ $[s^{-1}]$<br>Single pole RC Filter<br>Time Constant $T_1$ $[s]$<br>Damping ratio: $\zeta = \frac{1}{2\sqrt{K_x T_1}}$<br>natural frequency $f_n = \frac{1}{2\pi} \sqrt{\frac{K_x}{T_1}}$ |
| Loop transfer function: | $\lvert H_x \rvert^2 = \frac{1}{(1-\Omega^2)^2 + 4\Omega^2\zeta^2}$<br>$\lvert 1 - H_x \rvert^2 = \Omega^2 (2\zeta+\Omega)^2 \; \lvert H_x \rvert^2$<br>with $\Omega = \frac{f}{f_n}$ |

# TABLE 4

$S_{y_1} = 2.885\times10^{-26} f^{-1} + 8.0\times10^{-21}$

$S_{x_{Line}} = 2.49 \cdot 10^{-16}$ . max. Jitter  $N = 552$  $Q = 80$

PLL parameters

1) $K_x = 10^{-3} s^{-1}$  $\zeta = \frac{1}{\sqrt{2}}$  $f_n = 2.3\times10^{-4}$ Hz

2) $K_x = 0.1\ s^{-1}$  $\zeta = \frac{1}{\sqrt{2}}$  $f_n = 2.3\times10^{-2}$ Hz

(Crystal Oscillator Parameters see Table 1)

Measurement system cutoff frequency

for time-domain instability $\sigma_y(\tau)$

$f_H = 1000$ Hz for all cases.

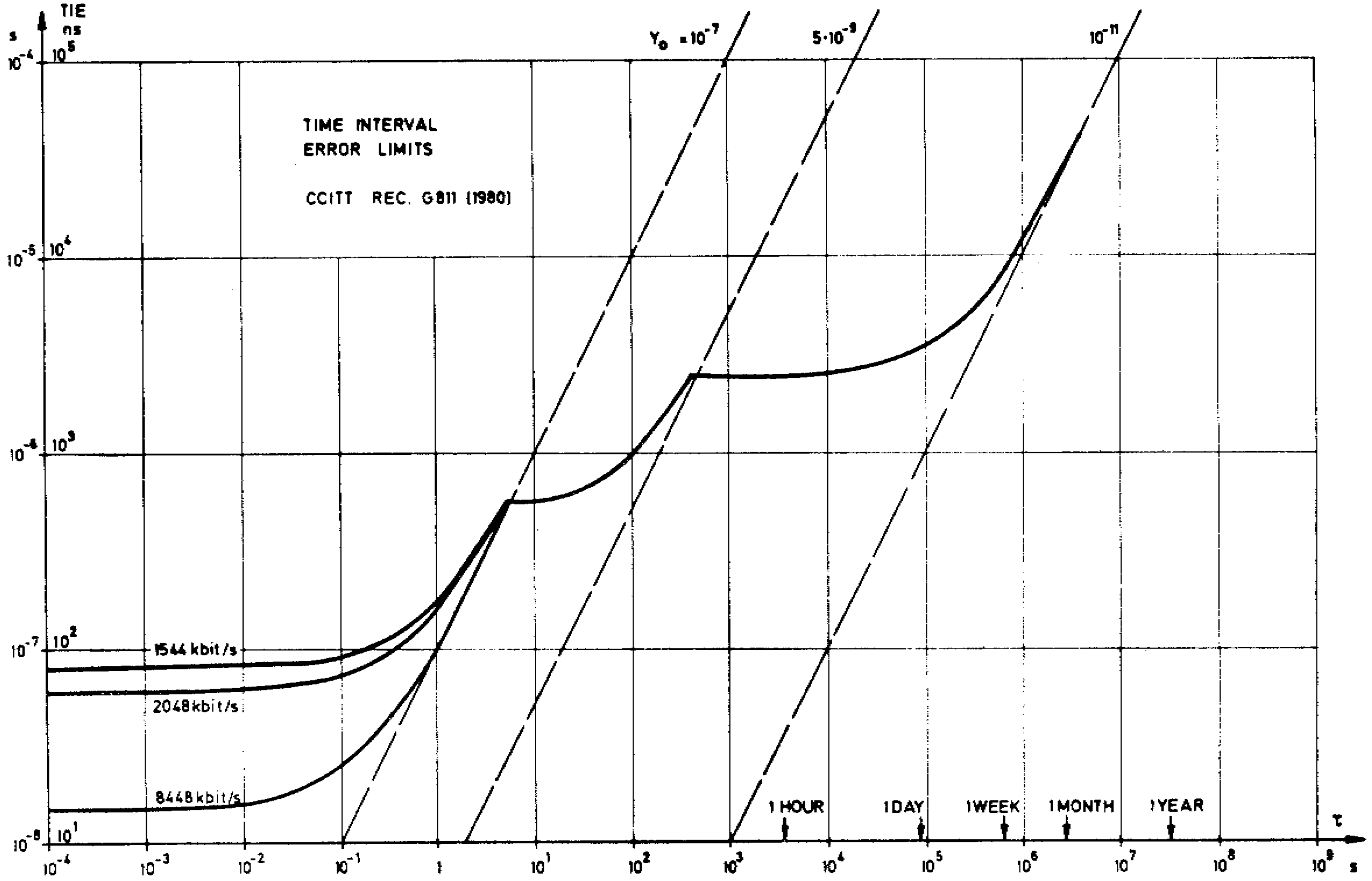


Fig. 1 Time Interval Error Limits, CCITT Rec. G811 (Draft Revision 1980)

**Fig. 2** PCM Timing Jitter Spectral Density

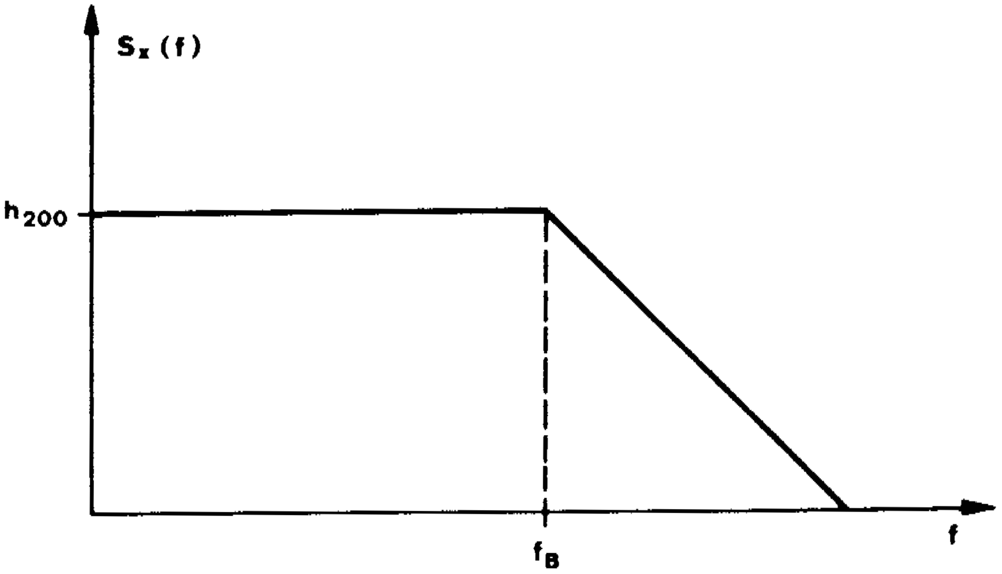


**Fig. 3** PCM Timing Jitter Parameters

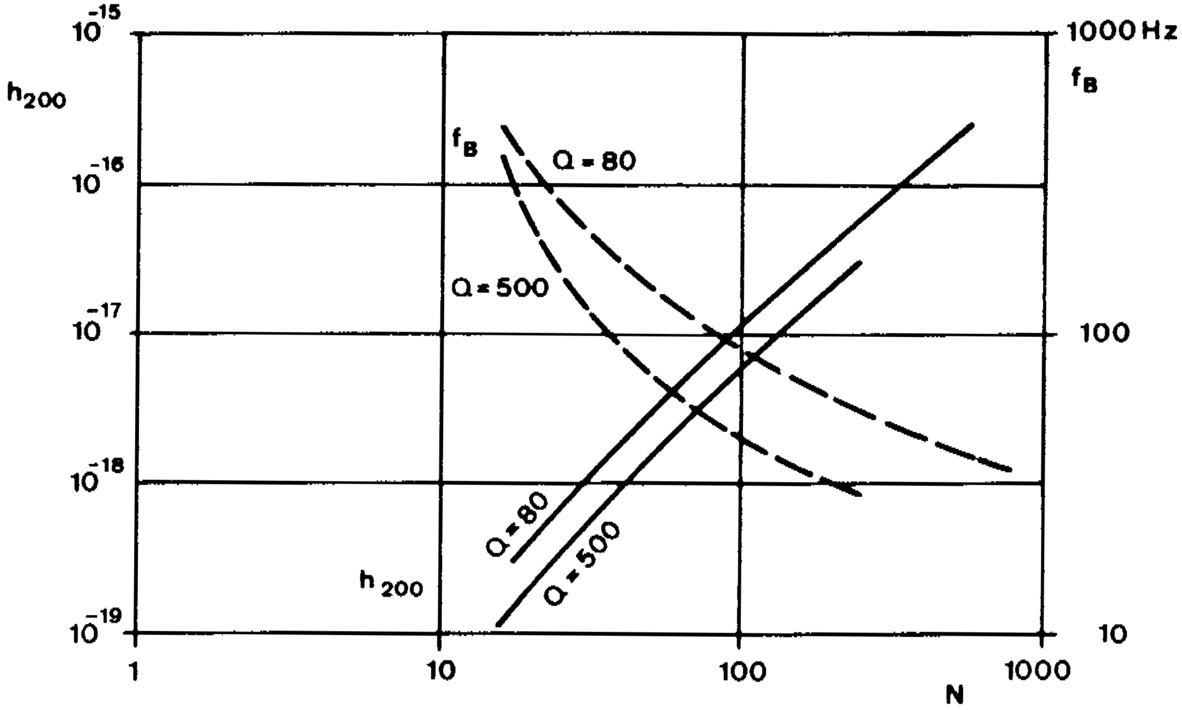


Fig. 4 Cesium and Rubidium clock instability

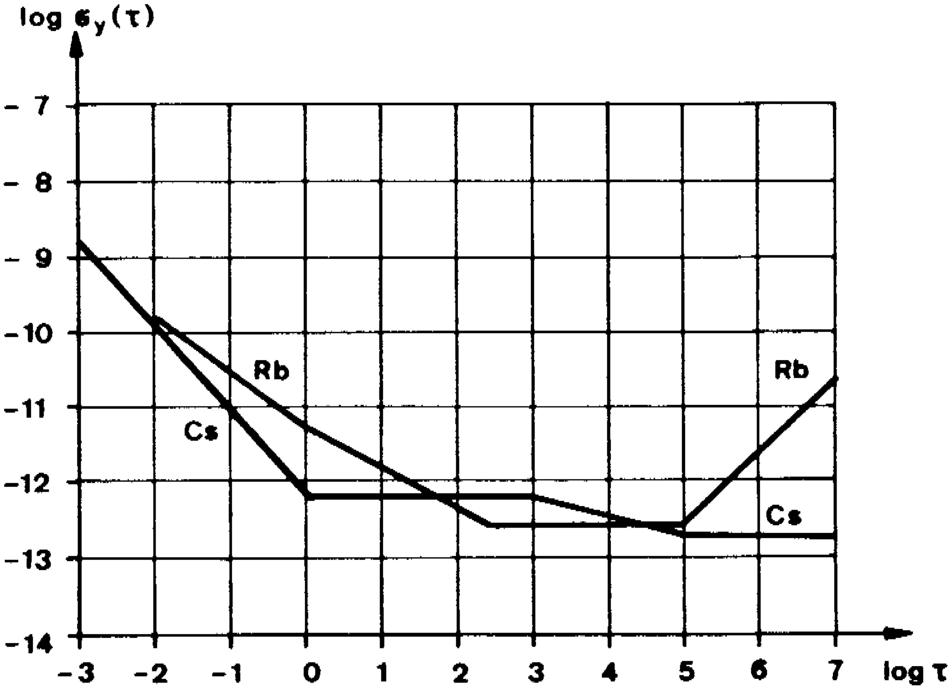
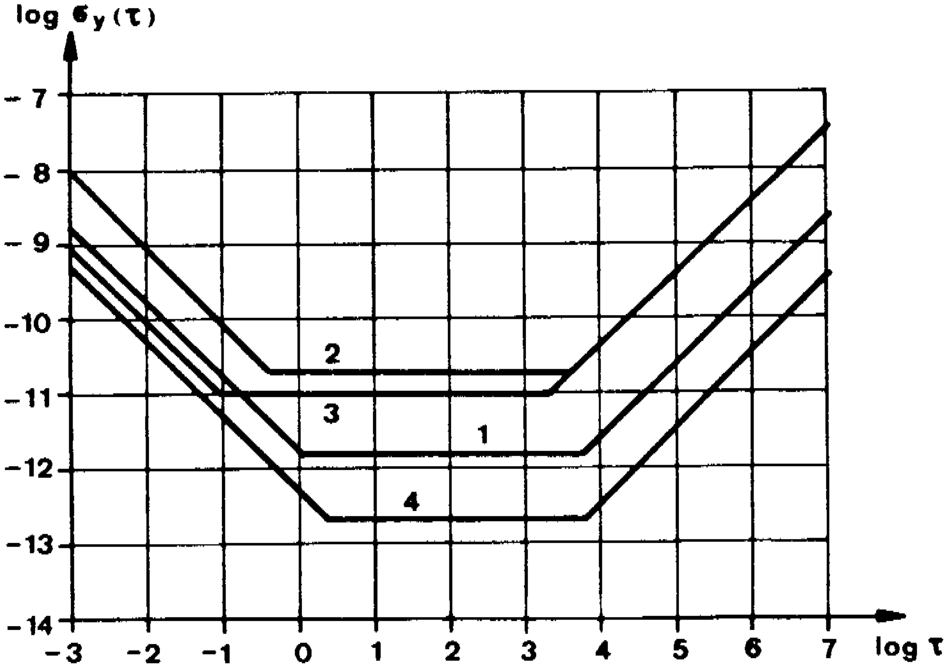


Fig. 5 Crystal clock instability



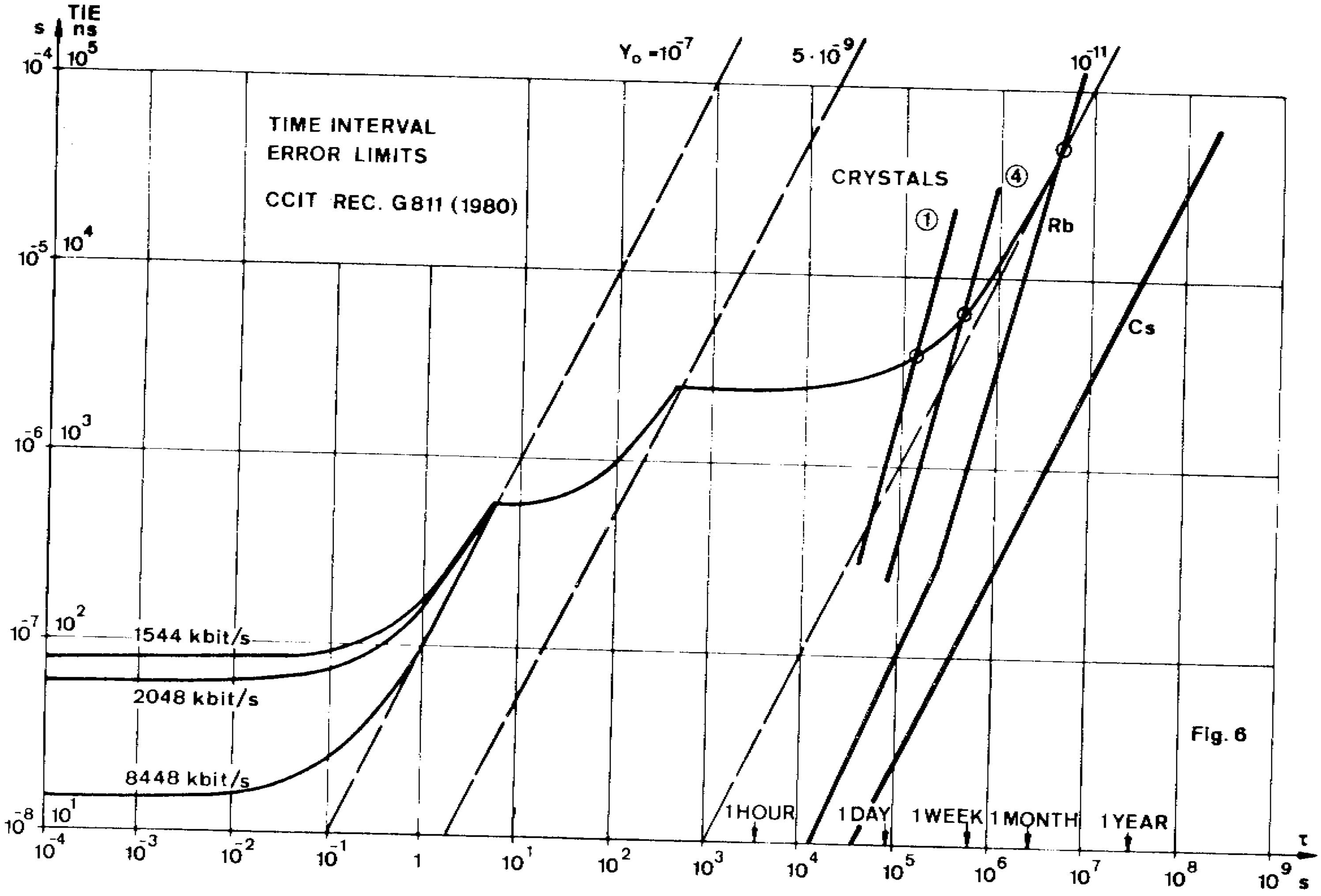


Fig. 6

Fig. 6 TIE for free running clocks

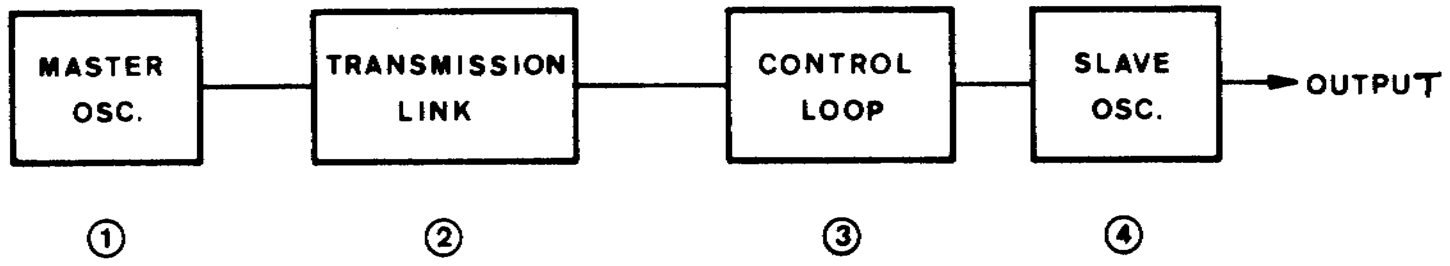


Fig. 7 REMOTE CONTROLLED CLOCK

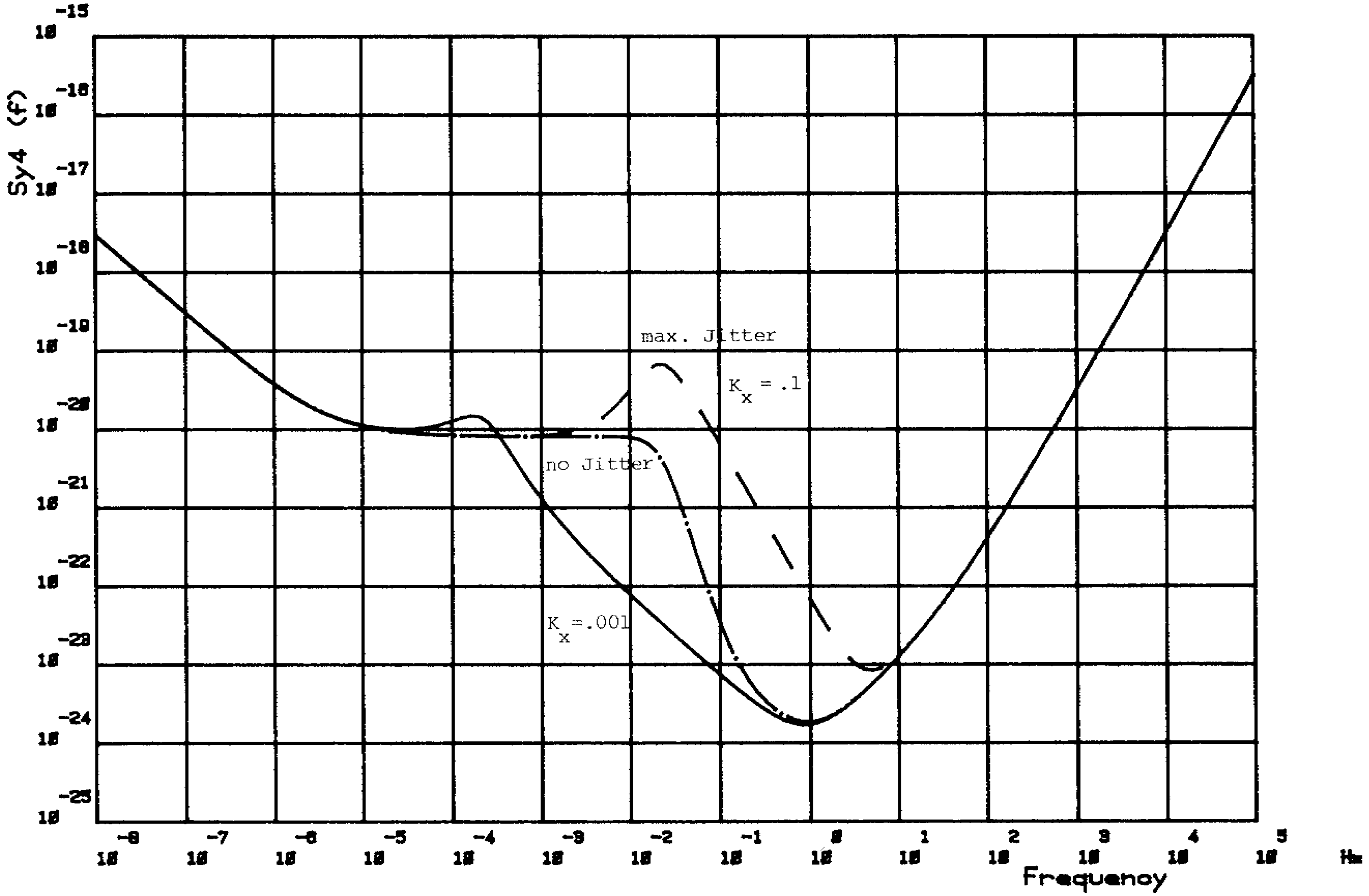


Fig. 8 a) Controlled oscillator frequency domain instability, slave oscillator No. 1

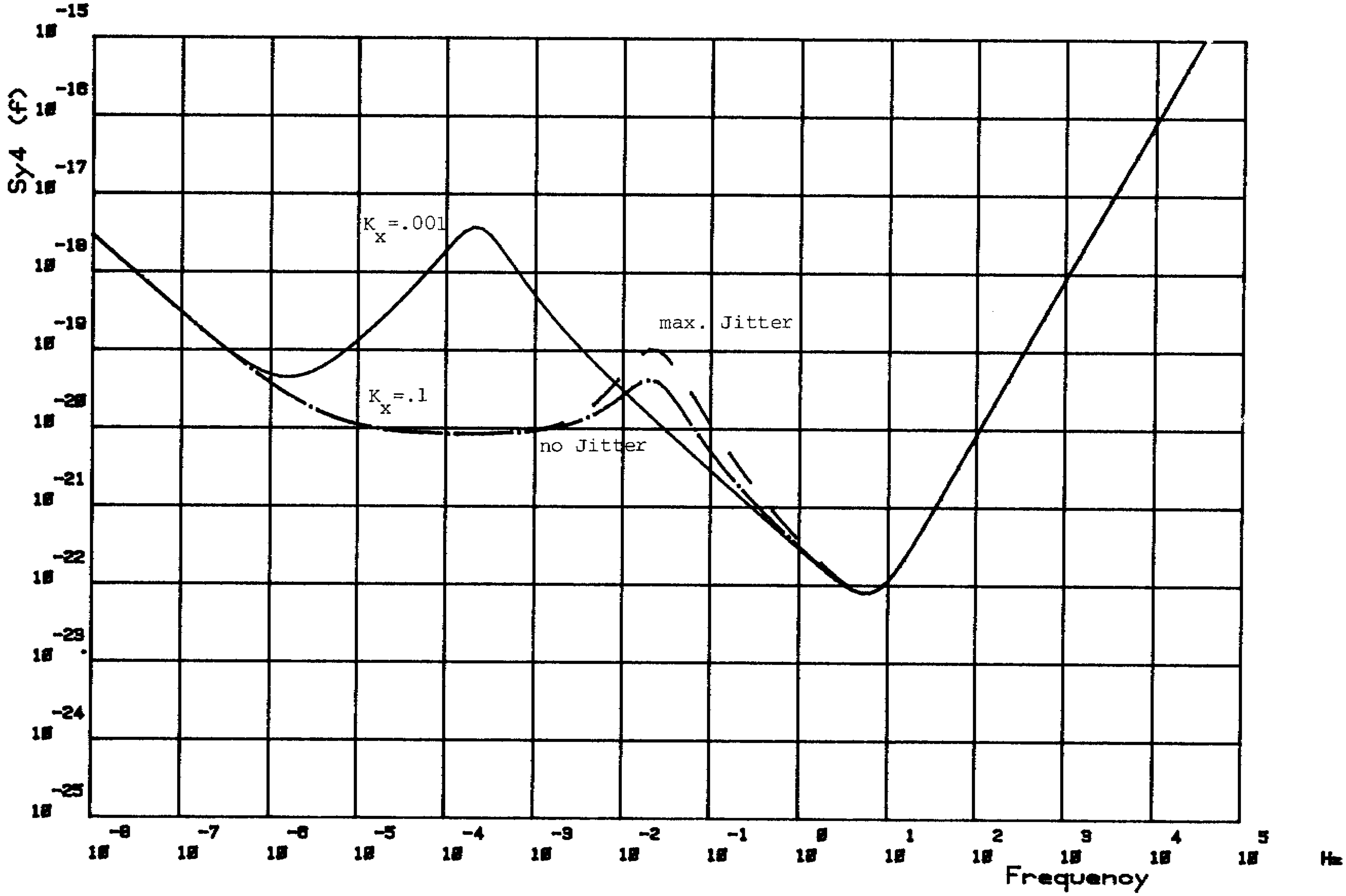


Fig. 8 b) Controlled oscillator frequency domain instability, slave oscillator No. 2

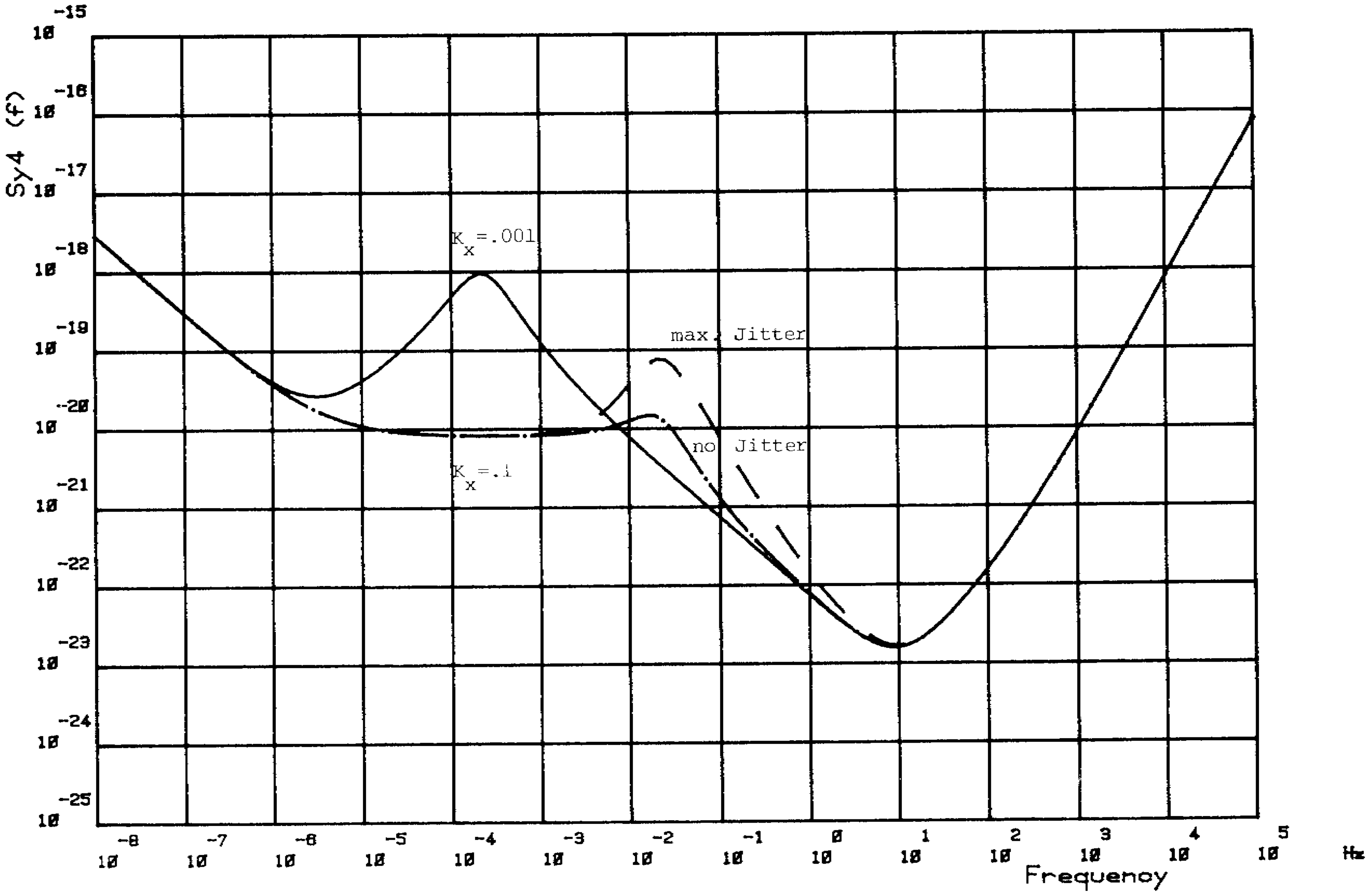


Fig. 8 c) Controlled oscillator frequency domain instability, slave oscillator No. 3

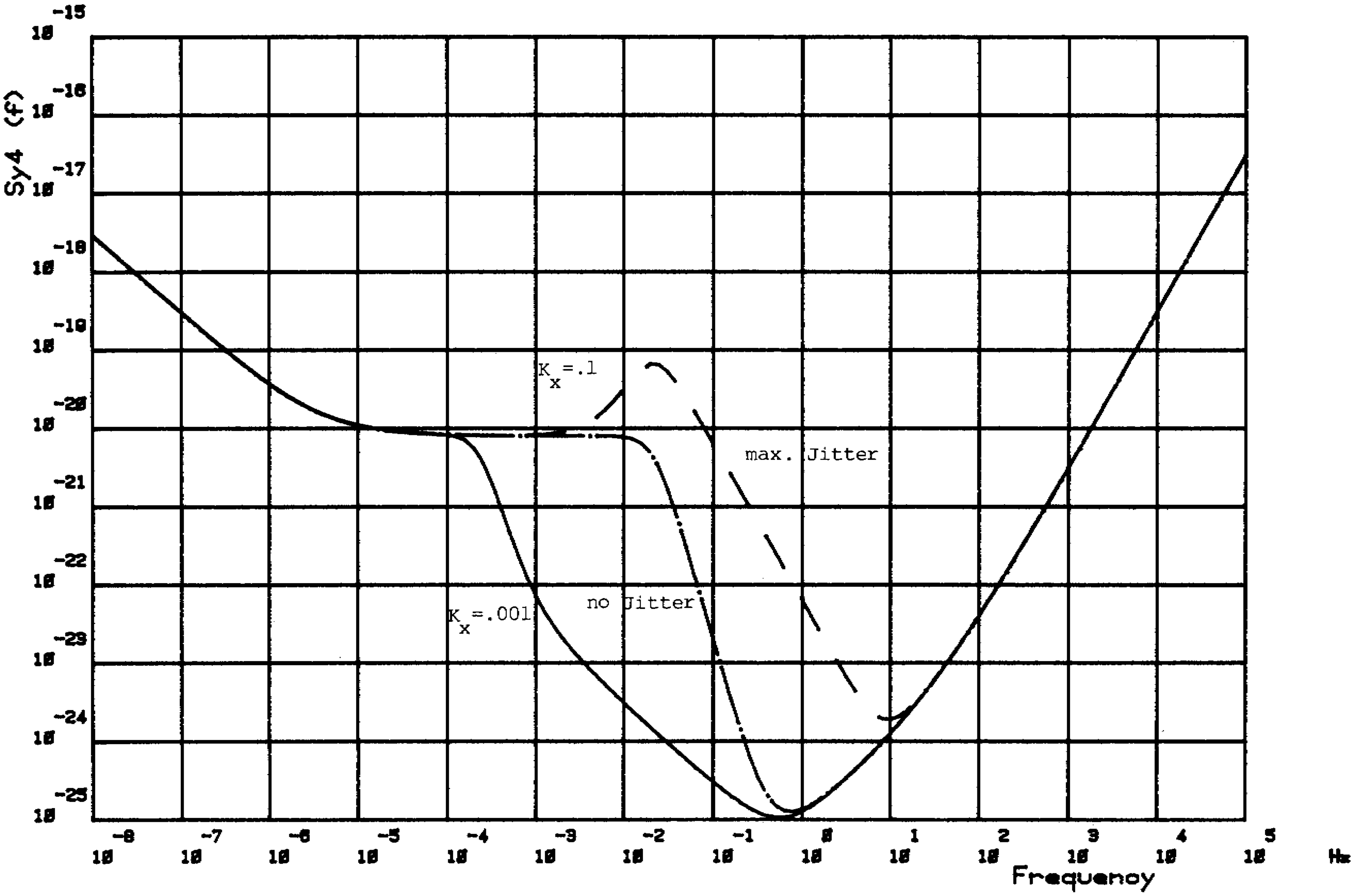


Fig. 8 d) Controlled oscillator frequency domain instability, slave oscillator No. 4

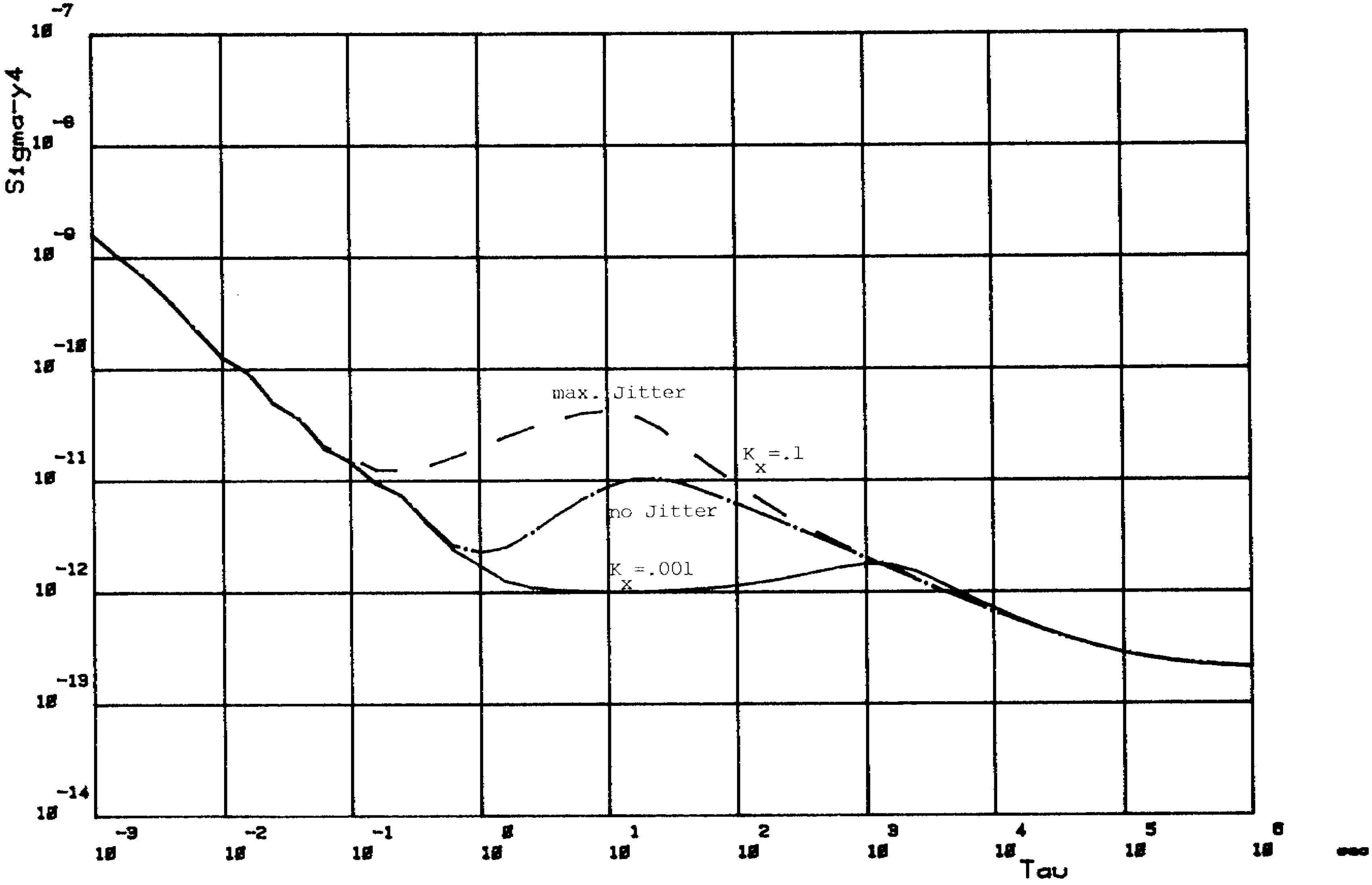


Fig. 9 a) Controlled oscillator time-domain instability, slave oscillator No. 1

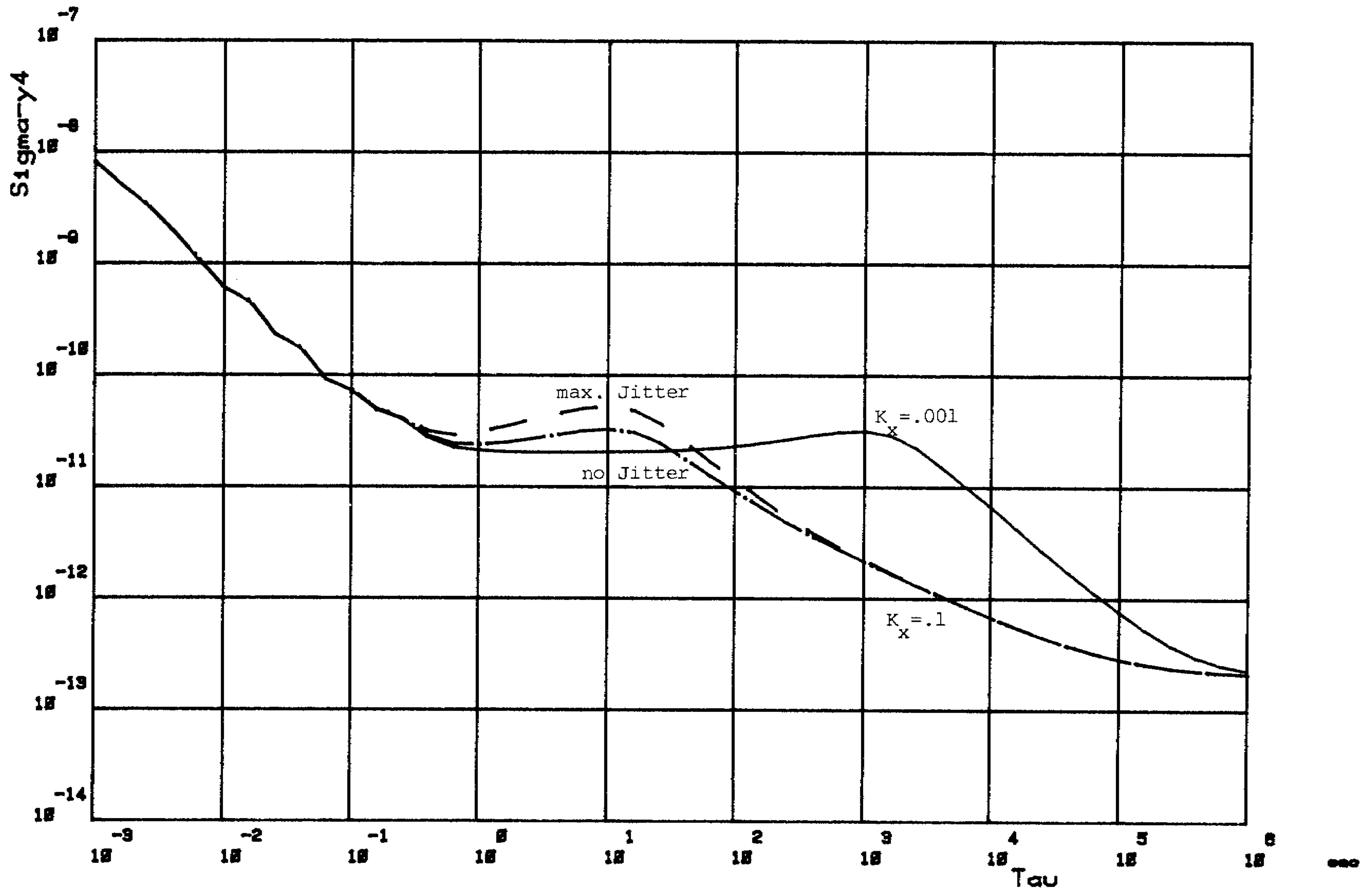


Fig. 9 b) Controlled oscillator time-domain instability, slave oscillator No. 2

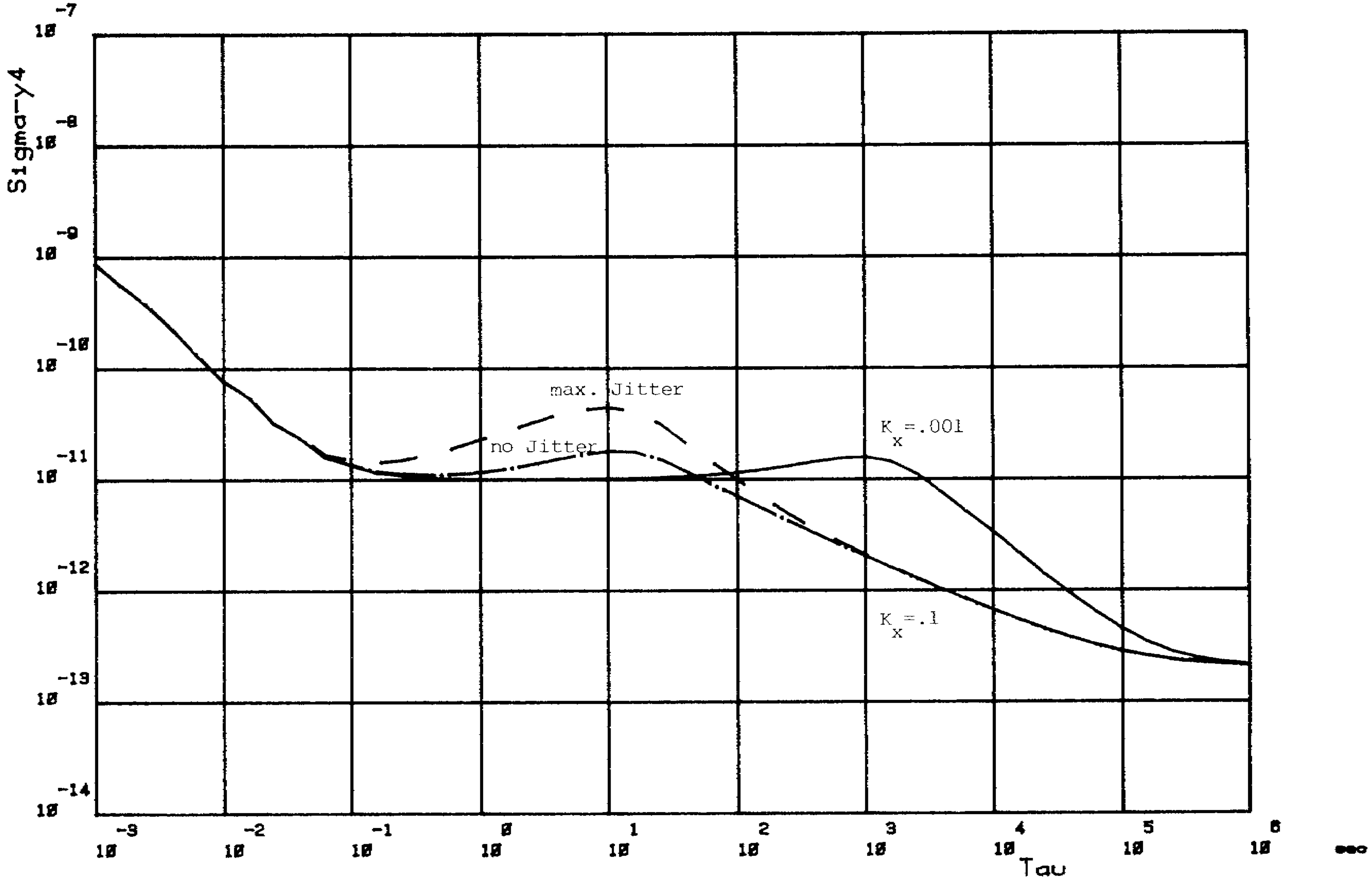


Fig. 9 c) Controlled oscillator time-domain instability, slave oscillator No. 3

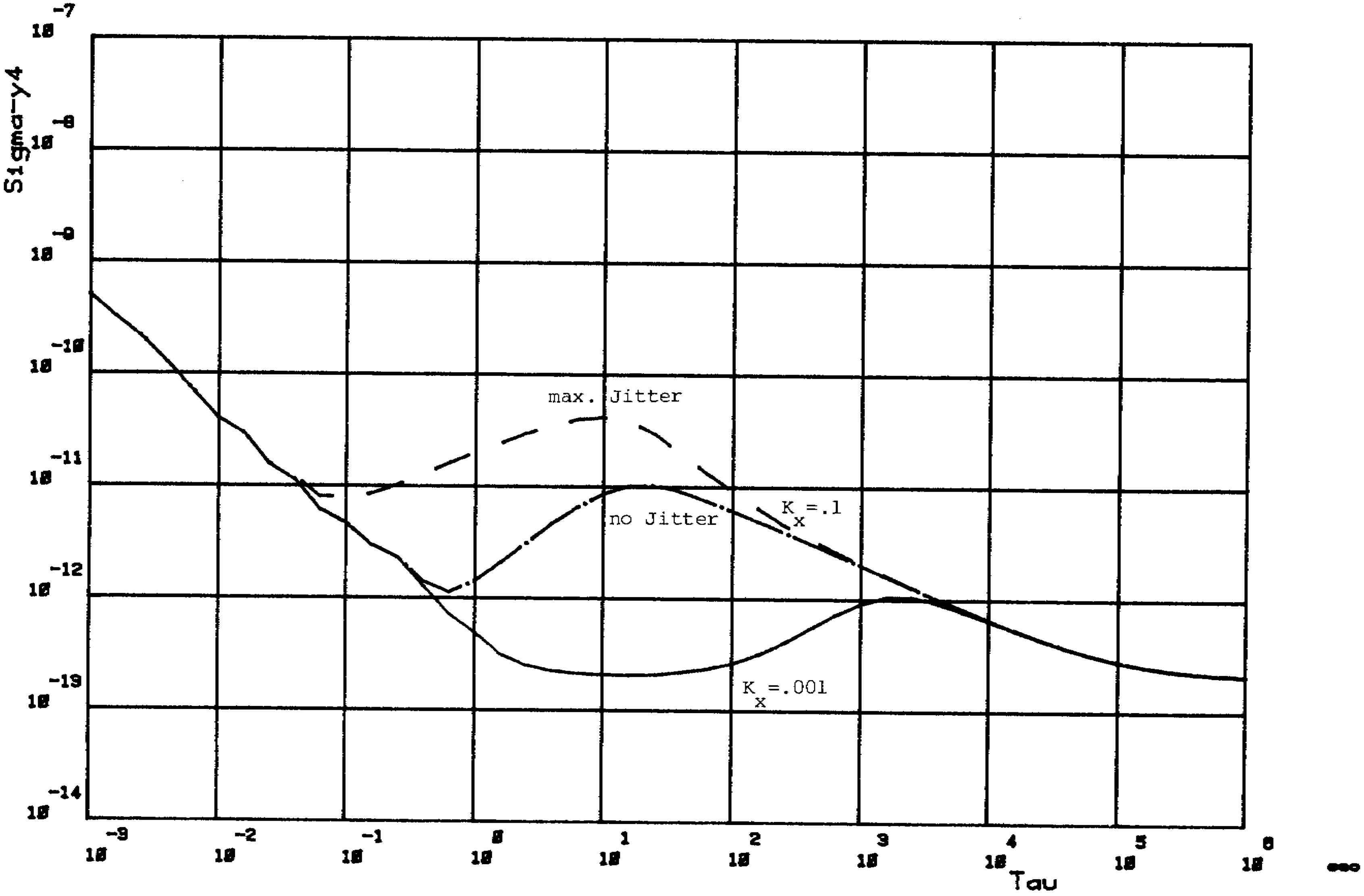


Fig. 9 d) Controlled oscillator time-domain instability, slave oscillator No. 4

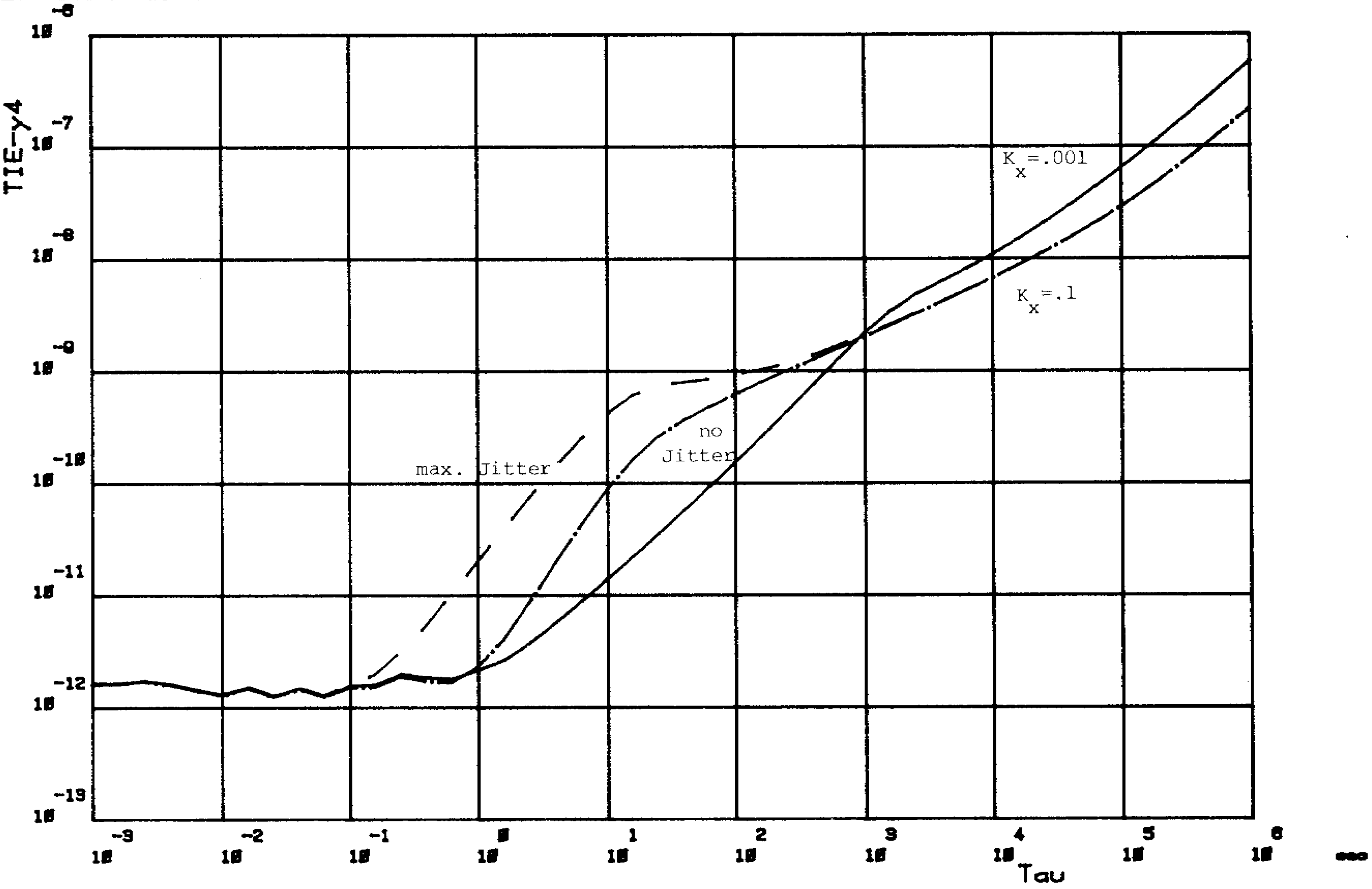


Fig. 10 a) Controlled oscillator time interval error, slave oscillator No. 1

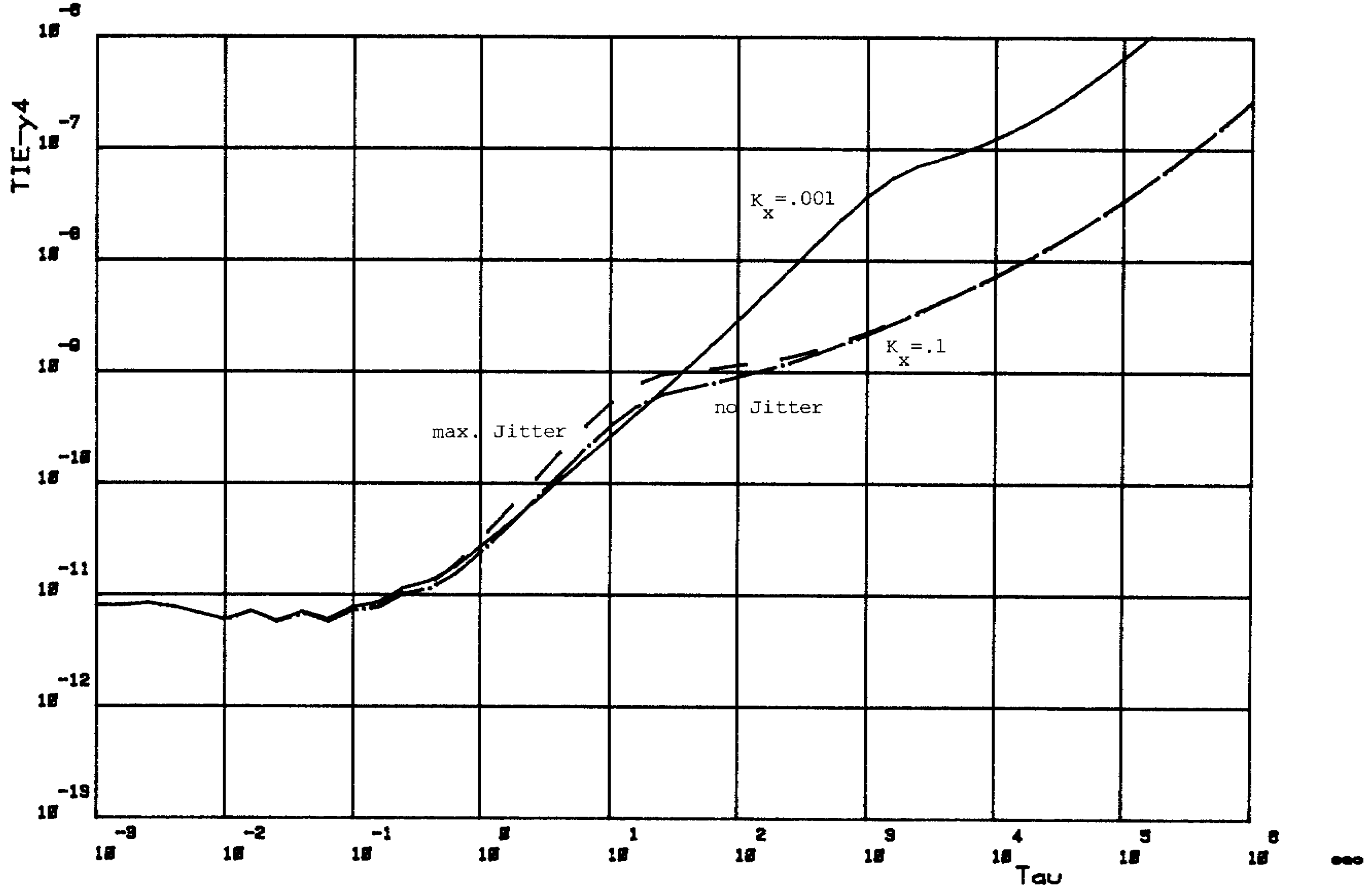


Fig. 10 b) Controlled oscillator time interval error, slave oscillator No. 2

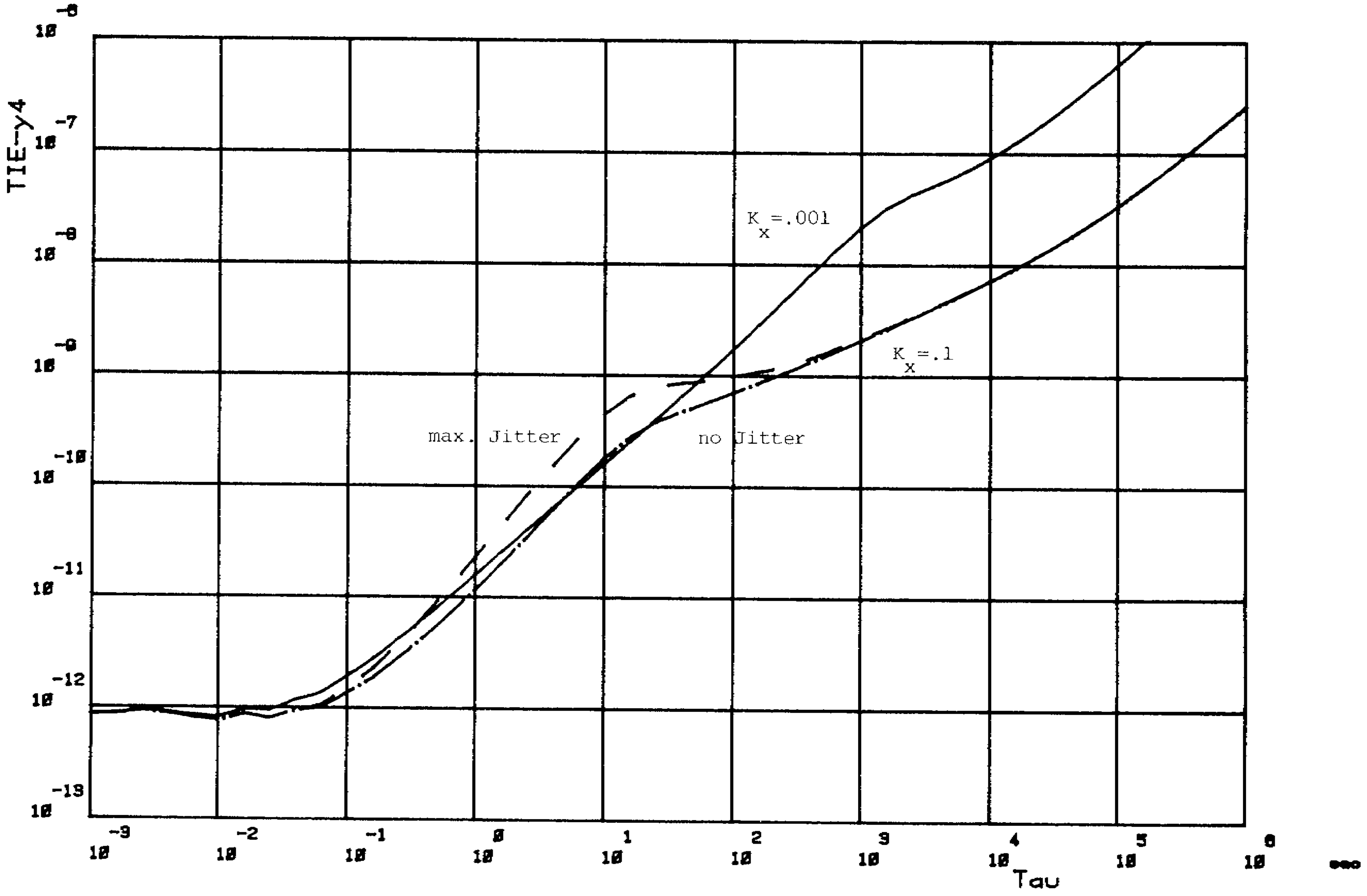


Fig. 10 c) Controlled oscillator time interval error, slave oscillator No. 3

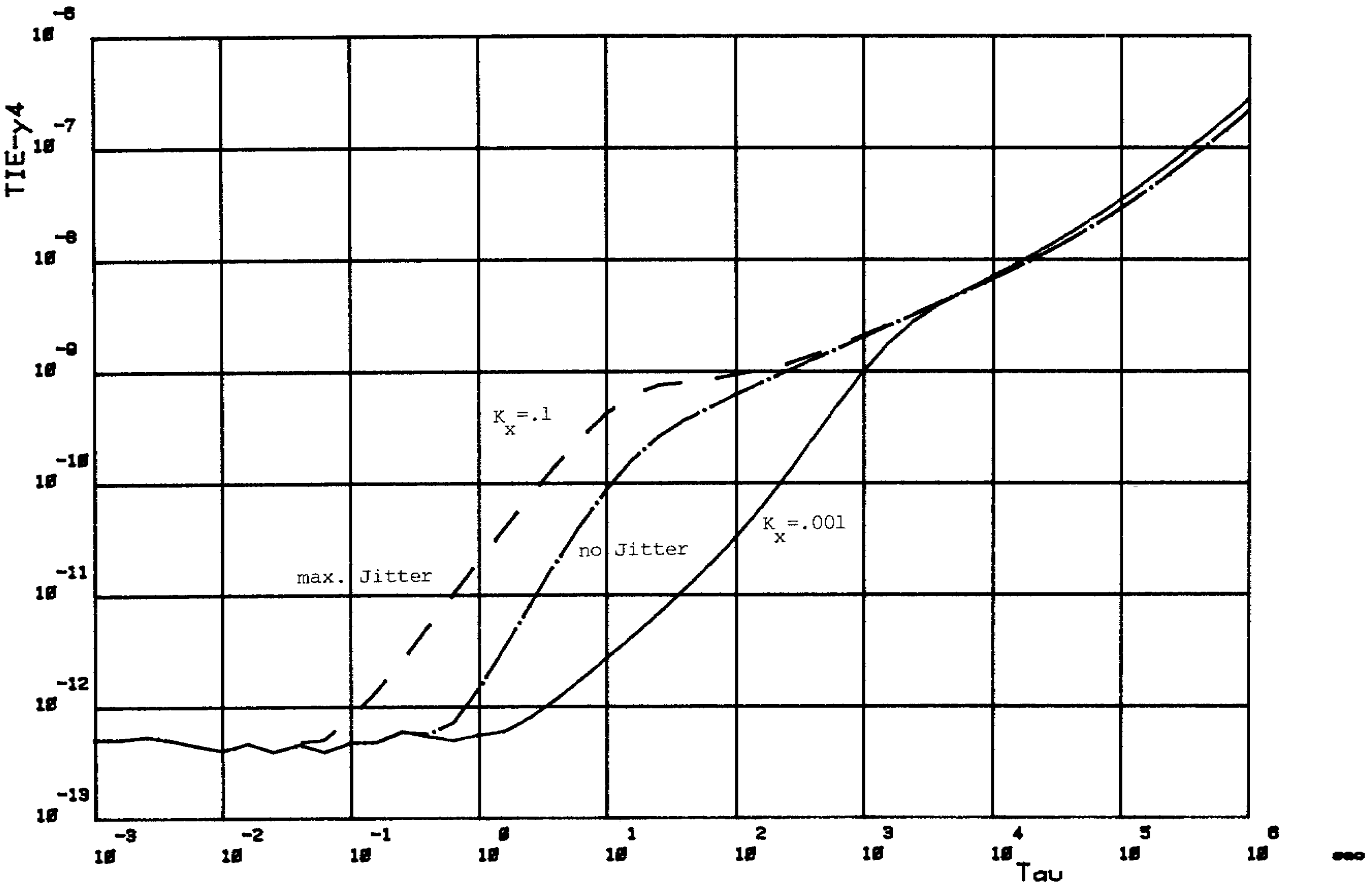


Fig. 10 d) Controlled oscillator time interval error, slave oscillator No. 4

# QUESTIONS AND ANSWERS

MR. GEORGE PRICE:

I have drawn the conclusion that one ought to spend a lot of money to get a very, very good high stability crystal oscillator for a digital communications system, because the requirements of CCIR or CCITT are such that we need that. Is that a wrong conclusion?

DR. KARTASCHOFF:

It is a right conclusion. You can use crystal, or rubidium, or cesium, you can also use very clean links and a lot of crystals.

There are many, many possible solutions. Of course, we would welcome having a little bit better crystals.

MR. PRICE:

I could get by with a very cheap oscillator or I could get by with a real expensive one, and whether I spent the money to get a very expensive one would probably depend upon what? -- accuracy requirements, or slip requirements for the communications? I just don't know why I would spend the money to get a more expensive oscillator, is what I am saying. Is there a communication efficiency advantage in going to a very, very highly stabilized BVA type resonator that you recommended here a bit ago?

DR. KARTASCHOFF:

Well, I do not recommend it, I just have seen that it is a possibility that probably will come on the market, and of course it makes things easier, but the communications system will also work with the present oscillators.