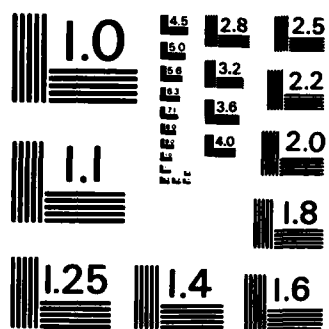END

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NOISE ANALYSIS OF THE COARSE OPTICAL POWER SPECTRUM ESTIMATOR (COPSE) DATA ACQUISITION SYSTEM

by

by

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ABSTRACT

The various components of the COPSE Acquisition System are briefly summarized. The system is theoretically analysed to determine what effect added Gaussian noise will have on its performance. On linear mode, the Gaussian noise was found to negate the quantization effect of the system provided the variance of the noise was high enough. On log mode, the system was found to perform better in the low photo-diode current range.

RÉSUMÉ

Les divers éléments du système de saisie des données COPSE font d'objet d'une brève description. Le système est analysé du point de vue théorique pour déterminer les effets possibles du bruit gaussien ajouté sur son fonctionnement. En mode linéaire, on a constaté que le bruit gaussien annulait l'effet de quantification du système lorsque la variance du bruit était suffisamment élevée. En mode logarithmique, on a constaté que le système avait un meilleur rendement lorsque la photo-diode avait un faible courant.

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v

TABLE OF SYMBOLS

$\rightarrow$	becomes
c	constant
$\cong$	approximately equal to
e_q	quantization error
e_q^N	quantization error with noise
$\overline{e_q^N}$	sample average of e_q^N
$E\{...\}$	expectation value of
G	gain
$>$	greater than
i_k	output current of kth photo-diode
$\|i_k\|$	absolute value of i_k
$\|i_k\|_e$	calculated estimate of $\|i_k\|$
$\Delta\|i_k\|$	incremental change in $\|i_k\|$
k	photo-diode element number (k = 1, 2, 3, ..., 64)
L_k	digital output of A/D converter for k^{th} photo-diode
L_k^N	digital output of A/D converter for k^{th} photo-diode when output of interface is corrupted with noise
ℓ	interger (ℓ = 1, 2, ...)
$<$	less than
$<<$	much less than
$\leqslant$	less than or equal to
ln	natural logarithm
$\log_{10}$	logarithm to the base of 10
N_a	noise voltage added to output of A/D converter

$\overline{N_a}$ sample average of N_a

n_k, σ_k^2 k^{th} photo-diode noise current and its variance

$\overline{n_k}$ sample average of n_k

N_I, σ_I^2 noise voltage added to output of interface and its variance

$\overline{N_I}$ sample average of N_I

N_M, σ_M^2 noise voltage added to output of multiplex and its variance

$\overline{N_M}$ sample average of N_M

S step size of A/D converter

σ_n^2 variance of combined N_a, N_I, n_k noise terms

$\sigma_{n\ell}^2$ variance of combined noise terms as a function of ℓ

$V_I(k)$ output of interface for k^{th} photo-diode

$V_I^N(k)$ $V_I(k)$ corrupted with noise

$\Delta V_I(k)$ incremental change in $V_I(k)$

$V_{Iq}(k)$ quantization estimate of noise-free interface output for k^{th} photo-diode

$V_{Iq}^N(k)$ quantization estimate of noisy interface output for k^{th} photo-diode

$\overline{V_{Ig}^N(k)}$ sample average of $V_{Ig}^N(k)$

$V_m(k)$ multiplex output for k^{th} photo-diode

$V_m^N(k)$ $V_m(k)$ corrupted with noise

$\overline{V_m^N(k)}$ sample average of $V_m^N(k)$

Voff   voltage offset

1.0 <u>INTRODUCTION</u>

The Coarse Optical Power Spectrum Estimator (COPSE) at Defence Research Establishment Ottawa consists of a coherent optical Fourier transform system, a 64 element solid state detector, electronic hardware and software run on a NOVA 1200 and a XEROX Sigma 9 computer (Fig. 1). The signals coming from the 64 photo-diodes in the detector are first multiplexed onto one line. The multiplexed signal is then amplified, biased and amplified again before it is sampled and digitized by an A/D converter. The samples are subsequently stored on magnetic tape.

The various components of the COPSE Data Acquisition System were discussed in depth in an earlier report [1]. Only a brief summary will be presented here. Instead, this report is a continuation of that earlier one. It contains a theoretical analysis of the effect that additive Gaussian noise has on the system.

XEROX SIGMA 9 COMPUTER COPSE DATA PROCESSING PGM.

MAGNETIC TAPE STORAGE

NOVA 1200 MINI-COMPUTER NOVA A/D CONVERTER PGM.

8 Bit A/D CONVERTER

INTERFACE

MULTIPLEX

ELECTRONIC SUBSYSTEM

64 INPUT CHANNELS

WD 6420 RECOGNITION SYSTEMS INC. DETECTOR
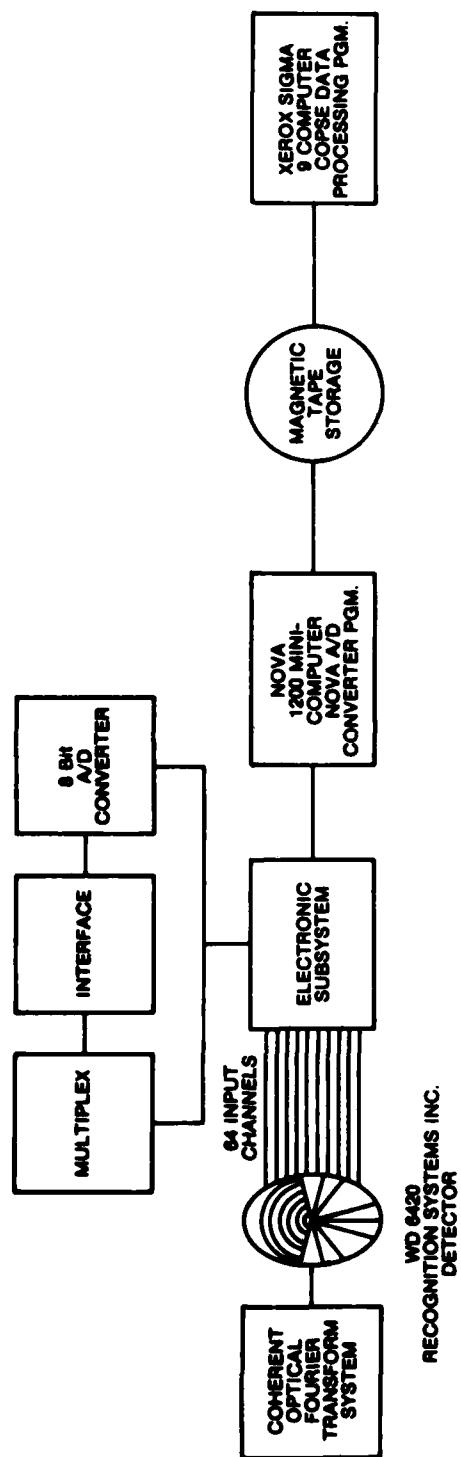
COHERENT OPTICAL FOURIER TRANSFORM SYSTEM

Fig. 1: COPSE System

2.0 COPSE DATA ACQUISITION SYSTEM

The data acquisition segment of the COPSE system consists of a 64 element solid state detector, electronic hardware, software and magnetic tape storage. The electronic hardware is further subdivided into three separate devices: a multiplex, an interface and an 8 bit A/D converter. The signals coming from the 64 photo-diodes of the detector are first switched onto one line by the multiplex. The multiplex allows for either linear or log mode of operation. Letting i_k and $V_m(k)$ represent the output current of the kth photo-diode and its corresponding multiplex output voltage respectively,

$$V_m(k) = - \left| i_k \right| \times 10^4 \text{ volts} \tag{1}$$

on linear mode provided

$$-15 \text{ nanoamps} < i_k < -1.3 \text{ milliamps}$$

and

$$V_m(k) = -10 - 2 \log_{10} \left| i_k \right| \tag{2}$$

on log mode provided

$$-3 \text{ nanoamps} < i_k < -1 \text{ milliamps.}$$

$\left| i_k \right|$ is the absolute value of i_k and k, the photo-diode element number, is an integer between 1 and 64.

The interface next biases and amplifies the multiplexed signal. The device gives the user the choice of several gains (G), scaling factors (M) and voltage offsets (Voff). The interface output voltage takes the form of

$$V_I(k) = - G[M V_m(k) + Voff] \text{ volts} \tag{3}$$

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on linear mode and

$$V_I(k) = - G[V_m(k) + Voff -8] \text{ volts} \tag{4}$$

on log mode when the input voltage is $V_m(k)$.

Substituting equation (1) in (3) and (2) in (4), and solving for $|i_k|$ in terms of $V_I(k)$,

$$|i_k| = \frac{V_I(k)}{GM} \times 10^{-4} + \frac{Voff}{M} \tag{5}$$

and

$$|i_k| = 10^{\frac{V_I(k)}{2G} - 9 + \frac{Voff}{2}} \tag{6}$$

for the two modes. Hence, an incremental change in $|i_k|$ ($\Delta |i_k|$) will result in a corresponding change in $V_I(k)$ of

$$\Delta V_I(k) = GM \times 10^4 \, \Delta |i_k| \tag{7}$$

on linear and

$$\Delta V_I(k) = \frac{2G}{\ln 10} \frac{\Delta |i_k|}{|i_k|} \tag{8}$$

on log. Linear mode gives a constant resolution throughout the photo-diode current range but, on the log mode, resolution depends on $|i_k|$. The two modes have the same resolution in situations where

$$|i_k| = \frac{2 \times 10^{-4}}{\ln 10} \frac{1}{M} . \tag{9}$$
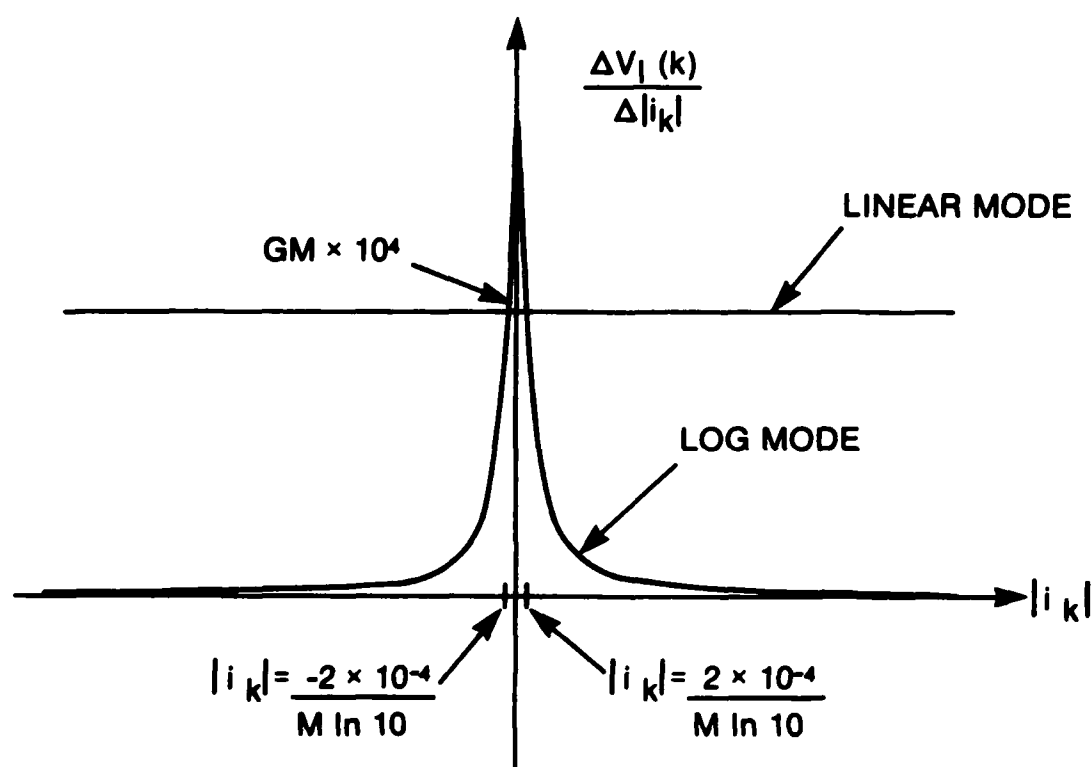
Equations (7) and (8) are plotted in Figure 2.

Fig. 2: Plot of $\frac{\Delta V_I(k)}{\Delta|i_k|}$ Versus $|i_k|$ for Both Modes of Operation

The A/D converter has an input voltage range of 0 to 10 volts. It converts $V_I(k)$ into a binary number whose decimal equivalent L_k satisfies

$$(L_k - 0.5)S < V_I(k) < (L_k + 0.5)S \qquad (10)$$

and is an integer between 0 and 255. The step size of the converter in the COPSE system

$$S = \frac{1}{25.6} . \qquad (11)$$

If the system is noise-free, the COPSE Data Processing program will approximate $V_I(k)$ by

$$V_{Iq}(k) = L_k S \qquad (12)$$

with an error due to quantization of

$$e_q = V_I(k) - V_{Iq}(k). \qquad (13)$$

Note, e_q varies between $+0.5S$ and $-0.5S$.

The program calculates an estimate of $|i_k|$ ($|i_k|_e$) of

$$|i_k|_e = |i_k| - \frac{e_q}{GM} \times 10^{-4} \qquad (14)$$

on linear mode and

$$|i_k|_e = |i_k| \, 10^{e_q/GM} \qquad (15)$$

on log mode.

3.0 NOISE ANALYSIS

To include noise in the analysis, the COPSE Data Acquisition System is assumed to contain a series of strategically-placed current and voltage zero-mean, Gaussian noise generators. Referring to Figure 3, there is a current generator at the output of each of the 64 photo-diodes of the detector and voltage generators at the outputs of the three electronic devices. The noise terms are further assumed to be additive and statistically independent so equations (1) through (4) now take the form of

$$V_M^N(k) = -|i_k| \times 10^4 + n_k \times 10^4 + N_M \quad \text{volts} \tag{16}$$

$$V_M^N(k) = -10 - \log_{10}(n_k + |i_k|) + N_M \quad \text{volts} \tag{17}$$

$$V_I^N(k) = -G[M \; V_M^N(k) + V_{off}] + N_I \quad \text{volts} \tag{18}$$

and

$$V_I^N(k) = -G[V_M^N(k) + V_{off} - 8] + N_I \quad \text{volts} \tag{19}$$

where

n_k, σ_k^2 the kth photo-diode noise current and its variance,

N_M, σ_M^2 noise voltage added to the output of the multiplex and its variance,

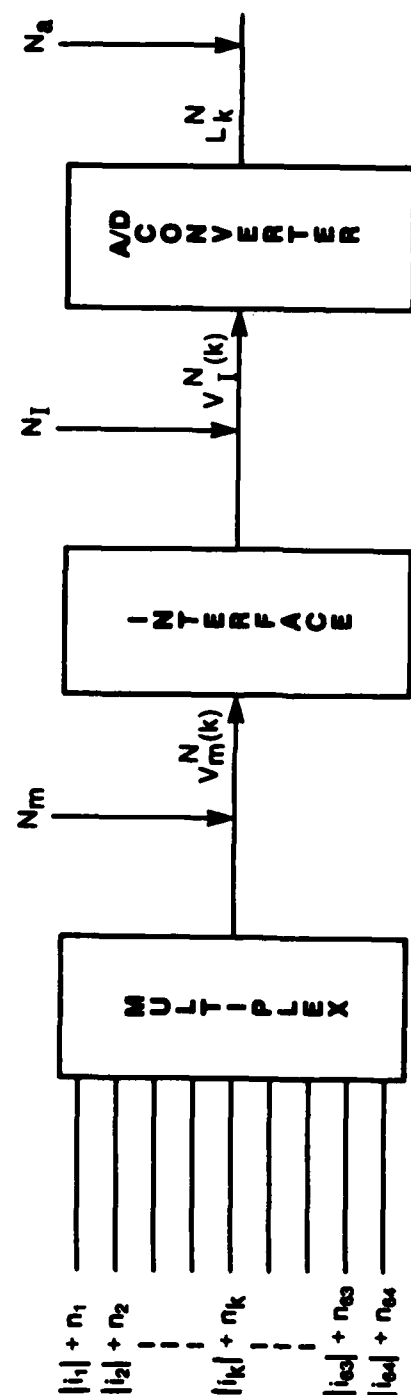N_I, σ_I^2 noise voltage added to the output of the interface and its variance.

Fig. 3: COPSE Electronic Subsystem with Noise Added

The superscript N on $V_I^N(k)$ and on $V_m^N(k)$ denotes a signal which has been corrupted with noise.

The A/D converter converts $V_I^N(n)$ into a binary code whose decimal equivalent, represented now by L_k^N, must satisfy

$$(L_k^N - 0.5)S < V_I^N(k) < (L_k^N + 0.5)S. \tag{20}$$

L_k^N is an integer between 0 and 255. Hence, the error due to quantization is

$$e_q^N = V_I^N(k) - V_{Iq}^N(k) \tag{21}$$

and

$$V_{Iq}^N(k) = L_k^N S . \tag{22}$$

Before the digitized signal is processed, it is once more corrupted with added noise at the output of the interface.

$$L_k^N \rightarrow L_k^N + N_a, \tag{23}$$

N_a being the noise voltage.

The interface output for each photodiode is sampled and digitized 64 times. To average out the noise, the processing program calculates the averages of these samples and estimates $\left| i_k \right|$ to be:

$$\left| i_k \right|_e = \left| i_k \right| - \overline{n_k} - \overline{N_M} \times \frac{10^{-4}}{GM} \left[\overline{N_I} - \overline{e_q^N} + \overline{N_a S} \right] \tag{24}$$

on linear mode and

$$\left| i_k \right|_e = \left| i_k \right| \; 10^{\frac{1}{2G} \overline{(N_a S + N_I - e_q^N)}} \; 10^{-\frac{\overline{N_M}}{2}} \; 10^{\overline{\log_{10}\left[1 + \frac{n_k}{\left| i_k \right|} \right]}} \tag{25}$$

on log mode.

$$n_k, \quad N_M, \quad N_I, \quad e_q^N, \quad \log_{10}\left[1 + \frac{n_k}{|i_k|}\right] \text{ and } N_a$$

are the corresponding sample averages of

$$n_k, \quad N_M, \quad N_I, \quad e_q^N, \quad \log_{10}\left[1 + \frac{n_k}{|i_k|}\right] \text{ and } N_a$$

respectively.

The results of an experiment done with the COPSE system are presented in Figure 4. The detected intensity distribution was that of a collimated Gaussian beam of spot size 16.7mm. Both modes of operation were employed. The shape of the curves are what one would expect from a Gaussian beam which is shifted with respect to the center of the detector.

3.1 Linear Mode of Operation

As the number of samples taken of $V_I^N(k)$ increases, the averages in (24) and (25) approach their ensemble or expectation values. The expectation value of a Gaussian, zero-mean, random variable is zero [2]. Equation 24 therefore reduces to

$$\left|i_n\right|_e = \left|i_n\right| - \frac{E\{e_q^N\} \, 10^{-4}}{GM} . \tag{26}$$

The notation $E\{_n\}$ stands for the operation of ensemble averaging. If all the samples of $V_I^N(k)$ are within the range of the converter, it can be easily proved that

$$e_q + 0.5S < E\{V_{Iq}^N(k)\} - V_{Iq}(k) < e_q - 0.5S \tag{27}$$

where

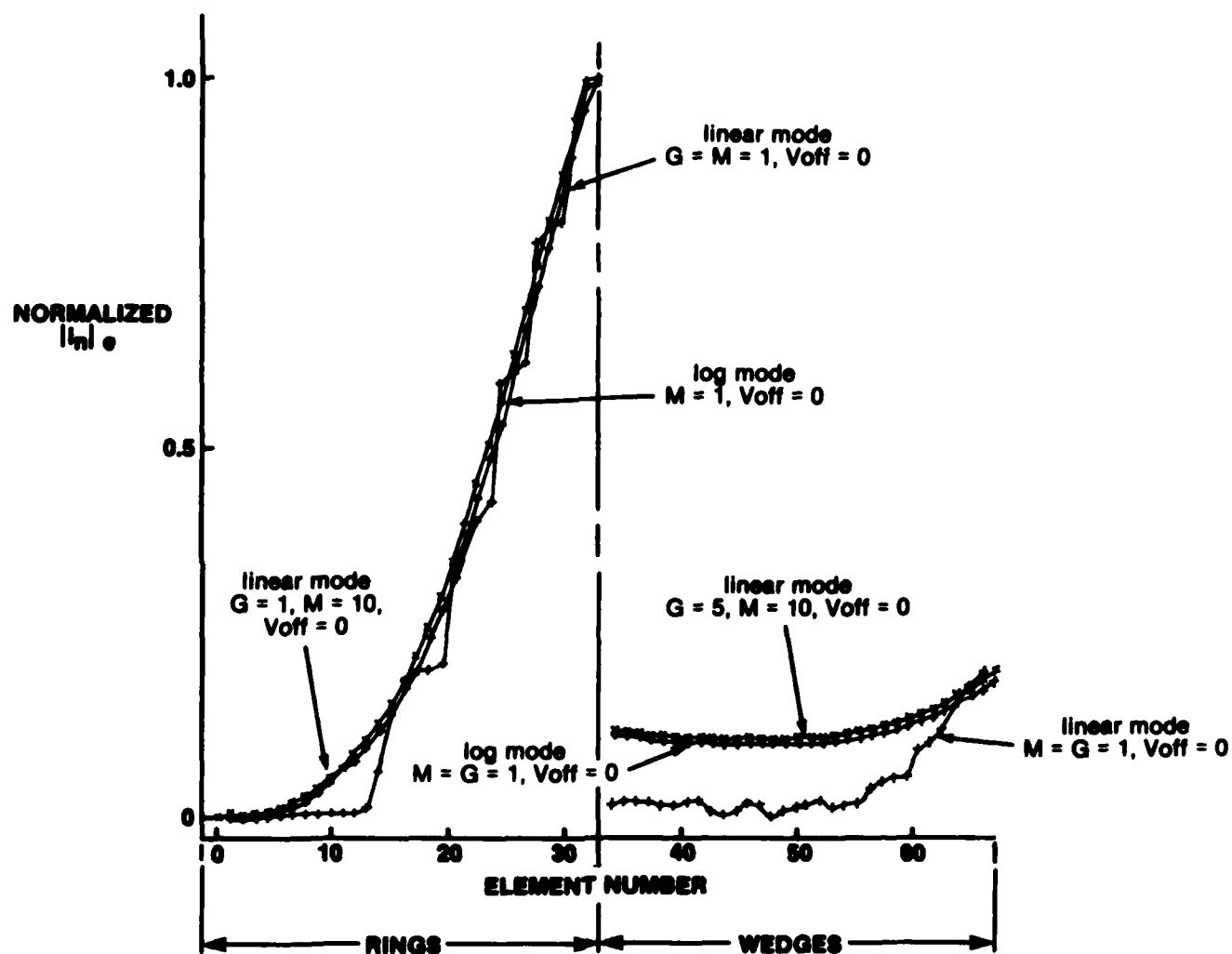$$E\{V_{Iq}^N(k)\} - V_{Iq}(k) = e_q - E\{e_q^N\}. \tag{28}$$

Fig. 4: Estimated Photo-Diode Output Currents
for a Collimated Gaussian Beam
(Spot Size of Collimated Beam = 16.7 mm)

$E\{v_{Iq}^{N}\}$ has the same range of values as e_q; i.e., $\pm 0.5S$. Futhermore, the expectation value of $V_{Iq}^{N}(k)$ is within one step size of its noise-free counterpart. In other words,

$$\left| E\{V_{Iq}^{N}(k)\} - V_{Iq}(k) \right| < S. \tag{29}$$

A more rigorous discussion of the problem is contained in Korn's book [3]. Using his results and after some mathematical manipulation, it can be shown that $E\{e_q^{N}\}$ is given by the sum of weighted sines:

$$E\{e_q^{N}\} = \frac{S}{\pi} \sum_{\ell = 1}^{\infty} \frac{(-1)^{\ell}}{\ell} \sin \left[\frac{\ell e_q \, 2\pi}{S}\right] \times \exp \left\{- \frac{2 \, \sigma_n^2 \pi^2 \ell^2}{S^2}\right\}, \tag{30}$$

Furthermore, since the noise terms are additive and statistically independent,

$$\sigma_n^2 = \sigma_I^2 + G^2 \, M^2 \times 10^8 \, \sigma_k^2 + G^2 M^2 \sigma_M^2. \tag{31}$$

Obviously, $E\{e_q^{N}\}$ depends on the step size of the converter, e_q and the noise statistics. The larger the ratio $\frac{\sigma_n^2}{S^2}$ is, the smaller $E\{e_q^{N}\}$ will be and the better the estimate of $\left| i_k \right|$ will be. Higher gains, scaling factors and noise variances will accomplish that. See Figure 5.

When

$$S < 3\sigma_n, \tag{32}$$

only the first term of the summation in (30) contributes appreciably to the estimate. Equation (30) can be approximated by

$$E\{e_q^{N}\} \cong \frac{S}{\pi} \sin \left\{\frac{2\pi \, e_q}{S}\right\} \exp \left\{\frac{-2\pi^2 \, \sigma_n^2}{S^2}\right\}. \tag{33}$$
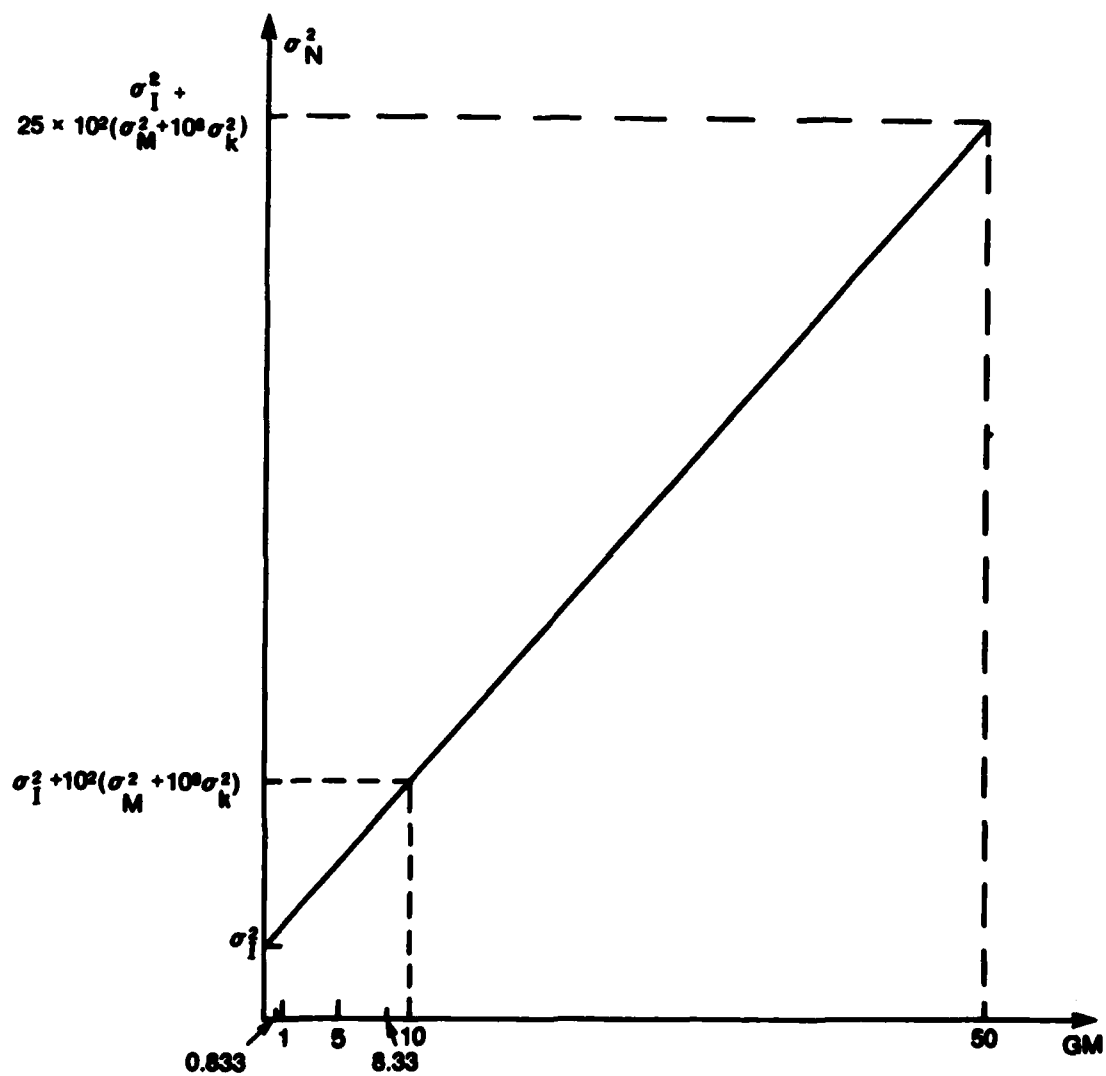
Fig. 5: Plot of $\sigma_N{}^2$ Versus G·M for Linear Mode of Operation
(G = gain, M = scaling factor)

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More terms must be included in the summation if S is larger or σ_n is smaller. Nevertheless, even when

$$S = 4\sigma_n, \tag{34}$$

$E\{e_q^N\}$ is less than its corresponding noise-free value (Table 1). The noise tends to negate the effect of quantization provided the noise variance is high enough. In fact, in situations where e_q is zero or $\pm 0.5S$, it is theoretically possible to recover $|i_k|$ exactly.

Experiments done with the COPSE system indicate that $V_{Iq}^N(k)$ has a range of 1 to 6 step sizes depending on the element number. The higher ring elements, due to their larger areas, have noiser output currents.

It is a common practice in data processing schemes to correct for dark current. In the COPSE system, the correction can only be done when the system is on linear and there is no voltage offset. The correction was found to be insignificant.

3.2 Log Mode of Operation

Equation (25) becomes

$$|i_k|_e = |i_k| \quad 10^{-\dfrac{E\{e_q^N\}}{2G}} \quad 10^{E\{\log_{10}(1 + \dfrac{n_k}{|i_k|})\}} \tag{35}$$

in the limit as the number of samples taken of $V_I^N(k)$ becomes large. Assuming that

$$-1 < \frac{n_k}{|i_k|} < 1, \tag{36}$$

which is a reasonable assumption to make,

TABLE 1

$E\{e_q^N\}$ ESTIMATES

e_q	$S = \sigma_n$	$S = 2\sigma_n$	$S = 3\sigma_n$	$S = 4\sigma_N$
0	0	0	0	0
$\pm$ S/16 ($\pm$ 6.25 x 10^{-2}S)	3.259 x 10^{-10}S	8.761 x 10^{-3}S	1.357 x 10^{-2}S	3.467 x 10^{-2}S
$\pm$ S/8 ($\pm$ 1.25 x 10^{-1}S)	6.022 x 10^{-10}S	1.619 x 10^{-2}S	2.508 x 10^{-2}S	6.44 x 10^{-2}S
$\pm$ 3S/16 ($\pm$ 1.875 x 10^{-1}S)	7.868 x 10^{-10}S	2.115 x 10^{-2}S	3.281 x 10^{-2}S	8.483 x 10^{-2}S
$\pm$ S/4 ($\pm$ 2.5 x 10^{-1}S)	8.516 x 10^{-10}S	2.289 x 10^{-2}S	3.551 x 10^{-2}S	9.269 x 10^{-2}S
$\pm$ 5S/16 ($\pm$ 3.125 x 10^{-1}S)	7.868 x 10^{-10}S	2.115 x 10^{-2}S	3.282 x 10^{-2}S	8.645 x 10^{-2}S
$\pm$ 3S/8 (3.75 x 10^{-1}S)	6.022 x 10^{-10}S	1.619 x 10^{-2}S	2.513 x 10^{-2}S	6.669 x 10^{-2}S
$\pm$ 7S/15 ($\pm$4.375 x 10^{-1}S)	3.259 x 10^{-10}S	8.761 x 10^{-3}S	1.361 x 10^{-2}S	3.628 x 10^{-2}S
$\pm$ S/2 ($\pm$ 5 x 10^{-1}S)	0	0	0	0

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the following approximation can be used:

$$\log_{10}\left(1 + \frac{n_k}{|i_k|}\right) \cong \frac{1}{\ln 10}\left[\frac{n_k}{|i_k|} - \frac{n_k^2}{2|i_k|^2}\right] \tag{37}$$

and, since n_k is a Gaussian, zero-mean, random variable, equation (35) becomes,

$$|i_k|_e \cong |i_k| \; 10^{\displaystyle -\frac{E\{e_q^N\}}{2G} - \frac{1}{2}\frac{\sigma_k^2}{|i_k|^2}\frac{1}{\ln 10}} . \tag{38}$$

$|i_k|_e$ is not only limited by $E\{e_q^N\}$ but also by the statistics of the photo-diode noise current and $|i_k|^2$. The lower the noise-free photo-diode current, the better will be the estimate of $|i_k|$. See Figure 4.

If all the samples of $V_I^N(k)$ are within the range of the A/D converter,

$$-0.5S + \frac{G}{\ln 10}\frac{\sigma_k^2}{|i_k|^2} < V_I(k) - E\{V_{Iq}^N(k)\} < 0.5S + \frac{G}{\ln 10}\frac{\sigma_k^2}{|i_k|^2} . \tag{39}$$

Consequently, $E\{V_{Iq}^N(k)\}$ is within one step size of $V_{Iq}(k)$ even though its range of possible values are biased, i.e.,

$$-S + \frac{G}{\ln 10}\frac{\sigma_k^2}{|i_k|^2} < V_{Iq}(k) - E\{V_{Iq}^N(k)\} < S + \frac{G}{\ln 10}\frac{\sigma_k^2}{|i_k|^2} . \tag{40}$$

Again referring to Korn's book and after a great deal of mathematical manipulation, it was found that

$$E\{e_q^N\} = \frac{S}{\pi}\sum_{\ell=1}^{\infty}\frac{1}{(1 + \ell^2 K^2)^{\frac{1}{4}}}\; \exp\left\{\frac{-2\pi}{S^2}\ell^2\sigma_{n\ell}^2\right\} \times$$

$$\sin\left\{\frac{2\pi\ell}{S}e_q - \tan^{-1}(K\ell) + \frac{2}{S}\frac{G\pi\ell^3}{\ln 10}\frac{K}{1 + K^2\ell^2}\right\} \tag{41}$$

where

$$K = \frac{4G\pi}{S \ln 10} \frac{\sigma_k^2}{|i_k|^2} \tag{42}$$

and

$$\sigma_{n\ell}^2 = G^2 \sigma_M^2 + \sigma_I^2 + \frac{4G^2}{\ln^2 10} \frac{\sigma_k^2}{|i_k|^2} \frac{1}{1 + K^2 \ell^2} . \tag{43}$$

σ_{ne}^2 is plotted in Figure 6 as a function of $\frac{\sigma_k^2}{|i_k|^2}$ and ℓ. Note, $\sigma_{n\ell}^2$ exhibits an exponential-like decay with ℓ and is a maximum at

$$\frac{\sigma_k^2}{|i_k|^2} = \frac{4G\pi\ell}{S \ln 10} . \tag{44}$$

Furthermore, since each term in the summation in (41) is multipled by a function that goes as the inverse of ℓ^2, one would not expect the higher terms in the summation to contribute significantly to $E\{e_q^N\}$.

In the case of very weak photo-diode noise:

$$\frac{n_k^2}{|i_k|^2} \ll 1 , \tag{45}$$

equation (41) reduces to a form similar to that of equation 33:

$$E\{e_q^N\} = \frac{S}{\pi} \sum_{\ell = 1}^{\infty} \sin \{\frac{2\pi\ell}{S} e_q\} \exp \{\frac{-2\pi\ell^2}{S^2} \sigma_n^2\} \tag{46}$$

and (see Figure 6)

$$\sigma_n^2 = G^2 \sigma_M^2 + \sigma_I^2 + \frac{4G^2}{\ln^2 10} \frac{\sigma_k^2}{|i_k|^2} . \tag{47}$$

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$\sigma^2_{n\ell}$

weak noise; slope = $4G^2/\ln^2 10$

$\dfrac{G^2\sigma^2_M + \sigma^2_I + G^3 C_1}{1 + G^4 C_2}$

$C_1 = \dfrac{16\pi I}{S \ln^3 10}$; $C_2 = \dfrac{256\pi^4 I^4}{S^4 \ln^4 10}$

A)

$G^2\sigma^2_M + \sigma^2_I$

0

$\dfrac{4G\pi I}{S \ln 10}$

$\dfrac{\sigma^2_k}{|i_k|^2}$

$\sigma^2_{n\ell}$

B)

$G^2\sigma^2_M + \sigma^2_I + \dfrac{4G^2}{\ln^2 10} \dfrac{\sigma^2_k}{|i_k|^2} \dfrac{1}{1 + K^2}$; $K = \dfrac{4G\pi}{S \ln 10} \dfrac{\sigma^2_k}{|i_k|^2}$
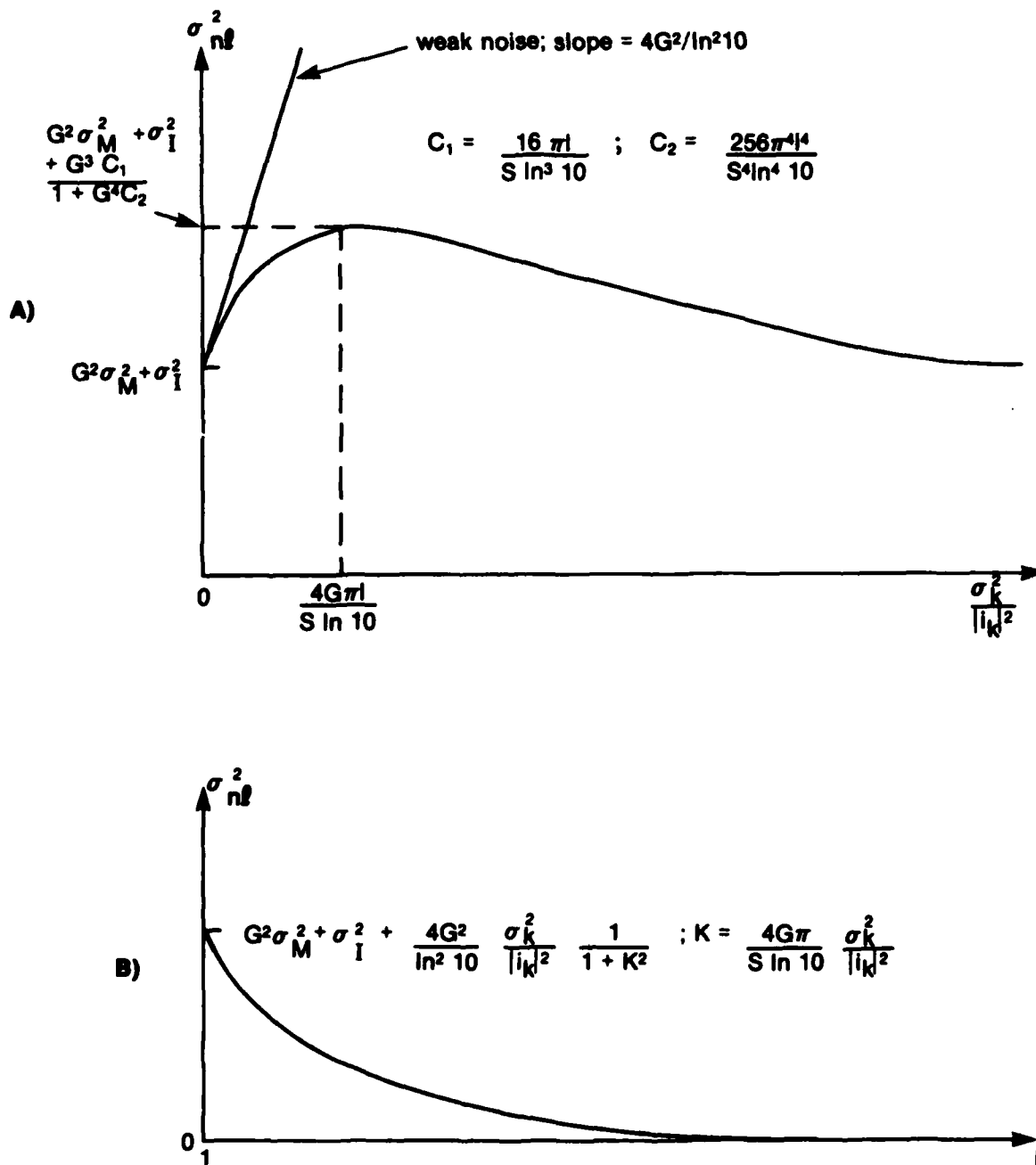
0

1

ℓ

Fig. 6: A) Plot of $\sigma_{n\ell}{}^2$ Versus $\dfrac{\sigma_k{}^2}{|i_k|^2}$

B) Plot of $\sigma_{n\ell}{}^2$ Versus ℓ on Log Mode

(S = step size of converter; G = gain; $\sigma_M{}^2$, $\sigma_I{}^2$, $\sigma_k{}^2$ = noise variances)

If e_g is zero or $\pm 0.5S$, $E\{e_g^N\}$ is zero but, according to equation 38, $|i_k|_e$ is not equal to $|i_k|$. It is

$$|i_k|_e \cong |i_k| \; 10^{-\frac{1}{2} \frac{\sigma_k^2}{|i_k|^2} \frac{1}{\ln 10}}, \qquad (48)$$

The biasing effect of the log mode does not allow for this. Complete recovering of $|i_k|$ occurs only if

$$E\{e_q^N\} = \frac{-G}{\ln 10} \frac{\sigma_k^2}{|i_k|^2} . \qquad (49)$$

Experiments done with the COPSE system on log mode indicated that $V_{Iq}^N(k)$ has a range of values of 1 to 3 step sizes. The lower photo-diode currents have a wider range of sample values as expected.

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13 ABSTRACT

The various components of the COPSE Acquisition System are briefly summarized. The system is theoretically analysed to determine what effect added Gaussian noise will have on its performance. On linear mode, the Gaussian noise was found to negate the quantization effect of the system provided the variance of the noise was high enough. On log mode, the system was found to perform better in the low photo-diode current range.

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KEY WORDS

Gaussian noise

Analysis

Quantization

Linear mode

Log mode

Sample averaging

A/D converter

C.O.P.S.E.

Data acquisition

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