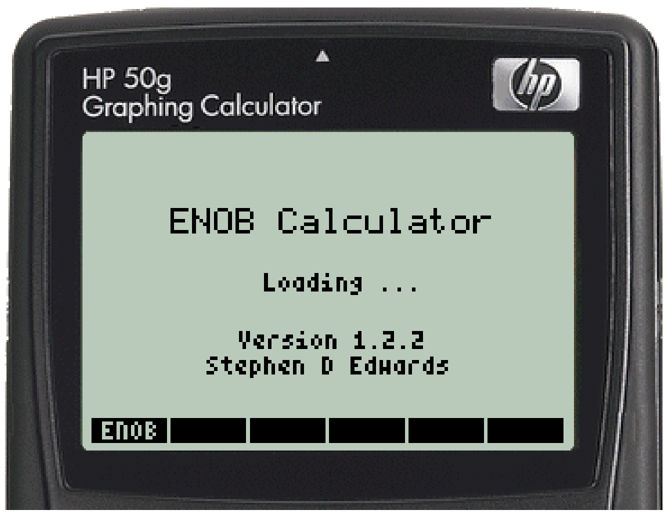
EFFECTIVE NUMBER OF BITS CALCULATOR USER'S GUIDE



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SECTION 1 - INTRODUCTION

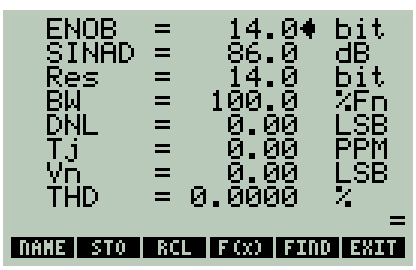
Effective Number Of Bits Calculator (ENOB) is a program for the HP50g calculator that aids in the design and analysis of data converter (ADC and DAC) application circuits. ENOB calculates the effective number of bits of an ideal data convertor. Each parameter can be entered or found. ENOB can also on run on a PC using the free program HPUserEdit 5.4, found at www.hpcalc.org, or the calculator page at www.maximintegrated.com.

Nine parameters can be entered or found,

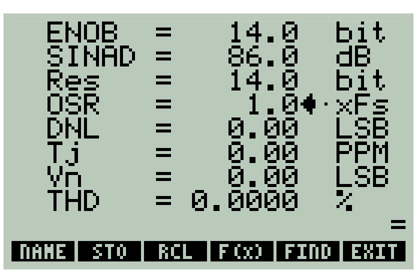
- Effective Number Of Bits, **ENOB,** in bits
- Signal to Noise and Distortion, **SINAD,** in dB
- Resolution, **Res**, in bits
- Bandwidth, **BW**, in % of the Nyquist frequency, or
  Over Sample Ratio, **OSR**, as a multiple of the sample frequency
- Average Differential Nonlinearity, **DNL**, in LSB
- Clock Jitter, **Tj**, in PPM rms
- Analog Referred Noise, **Vn**, in LSB rms
- Total Harmonic Distortion, **THD**, in % or dB.

The ENOB calculator can find any parameter as a function of the others, making it useful for both design and analysis of Analog-to-Digital Convertors (ADC) and Digital-to-Analog Convertors (DACs) applications circuits. It also can plot any two parameter with respect to each other.

These parameters appear in the calculator as shown below:



Two alternative parameters may be displayed: Over Sample Ratio (**OSR**) instead of Bandwidth (**BW**), and/or **THD** in dB instead of **THD** in %.



A small dot to the right of the selection arrow serves as a reminder that an alternative parameter is available. Press the right arrow key, , to select the alternative parameter.

Refer to Section 7 for an explanation of these parameters and how they are calculated.

SECTION 2 - INSTALLATION

ENOB can be installed on the HP50g calculator or a Windows PC.

Installing ENOB on the HP50g Calculator

ENOB may be installed in any one of three ways:

A. Best when installing one calculator:

Copy the executable file ENOB.hp to the home directory or subdirectory of the HP50g calculator. Launch ENOB.hp.

B. Best when installing between two and six calculators:

Copy the executable file ENOB.hp to the root directory of an SD card, and the much smaller file ENOB to the home directory or subdirectory of the HP50g calculator. Launch ENOB.

C. Best when installing six or more calculators:

Install ENOB using the Calculator Launcher (CALC) utility found at www.maximintegrated.com/design/tools/calculators/hp50g/. Refer to the CALC User's Guide for an explanation of this utility.

Refer to the HP50g Graphing Calculator User's Guide for instructions on how to copy files to the calculator.

Installing ENOB on a Windows PC

ENOB can be run on a Windows PC using the free program HPUserEdit 5.4. HPUserEdit is an IDE for the HP50g and contains a suitable emulator.

To install HPUserEdit:

Download and install HPUserEdit 5.4, found at www.hpcalc.org. Search for "HPUserEdit5". The default language is Spanish. However, other languages can be selected as follows,

1. Select 'Opciones' (Options)
2. Select 'Idiomas' (Language)
3. Select the preferred language (English is assumed in this document)

To run ENOB:

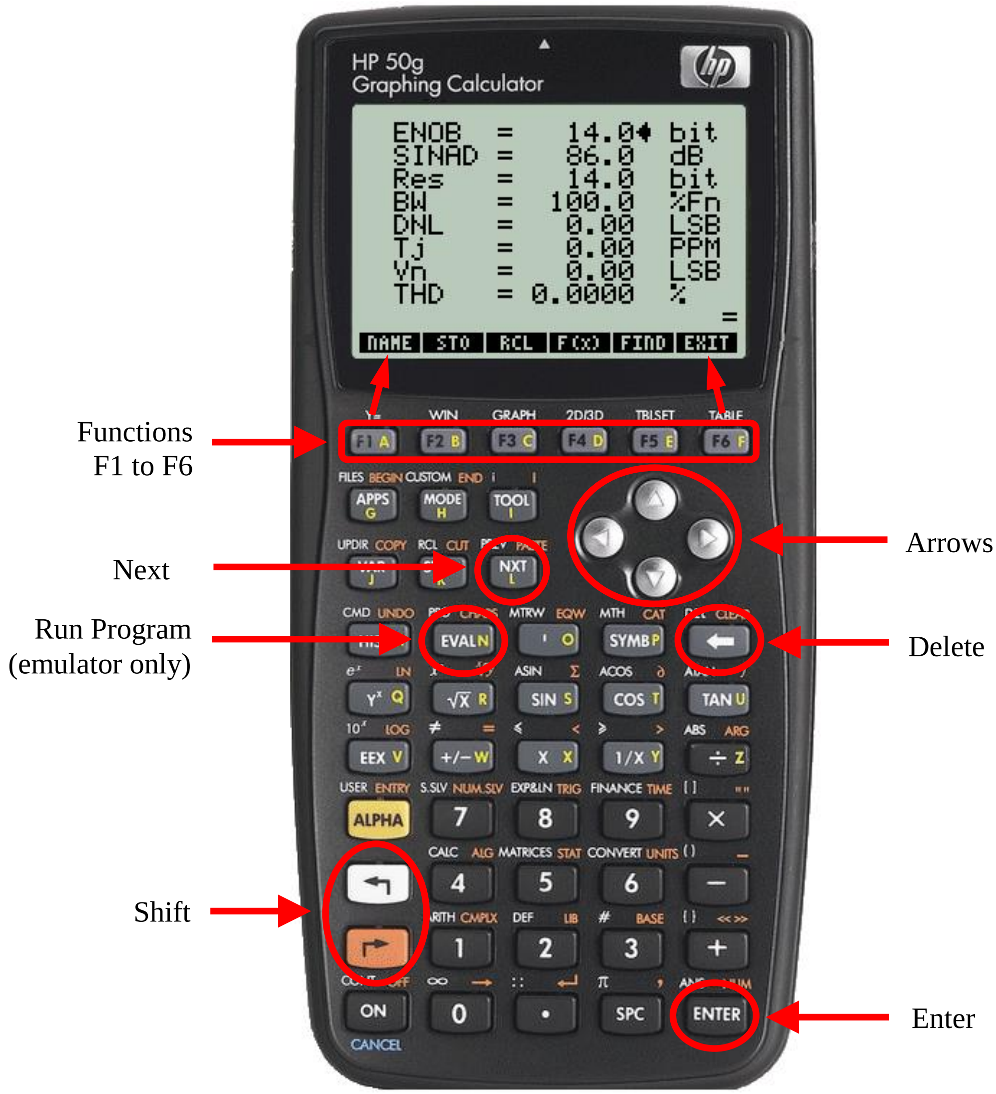
1. Launch HPUserEdit
2. Launch the HP50g emulator by selecting Emulator/Run_the_Emulator from the menu bar. A virtual HP50g appears.
3. Drag and drop ENOB.hp to the calculator screen and click the EVAL key.

The splash screen shown on page 1 of this guide is displayed when the calculator is loading. It appears momentarily, and may not be visible when run on a PC.

ENOB creates a file named 'CalcDB' in the calculator's home directory the first time it is run. 'CalcDB' holds the parametric values used by ENOB when launched, and is used by the STO and RCL commands to store and recall the parameters.

SECTION 3 - KEYBOARD

The following diagram shows the location of all keys used by ENOB:



When using the emulator, the calculator keys map to the PC keyboard as follows:

Calculator Keys	↔	PC Keyboard
Numbers	↔	Numbers
Enter and Delete	↔	Enter and Delete
Yellow Letters	↔	Letters
Arrows	↔	Arrows
Left Shift	↔	Shift
Right Shift	↔	Control

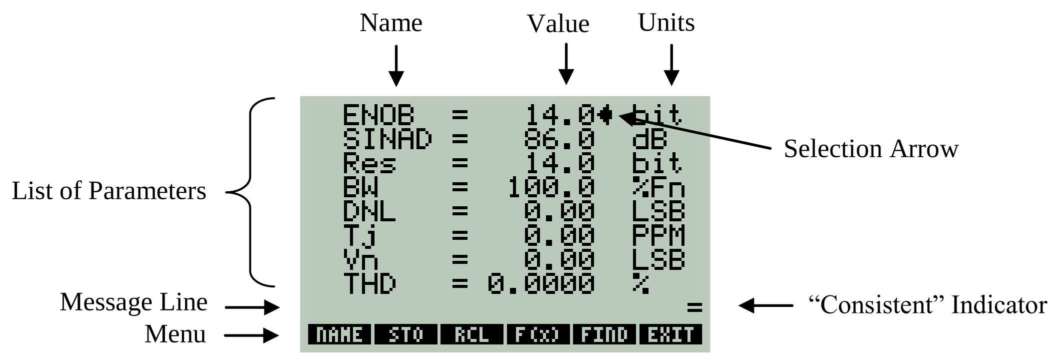
SECTION 4 - COMMANDS

ENOB has three sets of commands:

- Main Menu Commands
- Extended Menu Commands
- Help Commands
- Plot Commands

Main Menu Commands

After launching ENOB for the first time, the following screen appears, listing eight parameters.

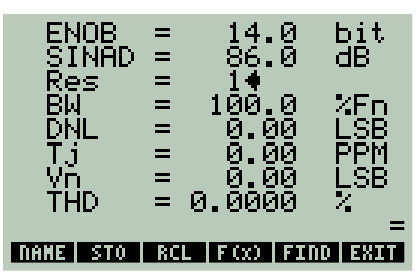


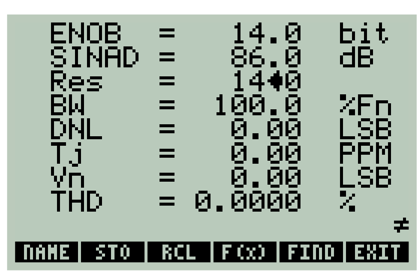
Use the ▽ and △ keys to select a parameter.
Use the ▷ key to display an alternative parameter (**BW** or **OSR**, and **THD** in % or dB only)
Use the ◁ (insert) or ◀ (delete) key to enter or edit a parameter. Press ENTER when finished.

F1 (NAME) displays a description of the selected parameter in the message line
↰ F1 (NAME) displays the full precision of the selected parameter in the message line
F2 (STO) stores all parameters
F3 (RCL) recalls all stored parameters
F4 (F(x)) plots any parameter with respect to any other parameter.
↰ F4 (F(x)) displays a pie chart of all noise and distortion sources
F5 (FIND) finds the selected parameter
F6 (EXIT) or ON (Cancel) exits the program
↰ F6 (EXIT) launches previous run calculator (for physical calculators only - requires CALC)
↱ ON turns off the calculator

Enter or edit a parameter values using the ◀ or ◁ key as shown. Press ENTER when finished.

the delete key (◀), and the left arrow (insert) key (◁)

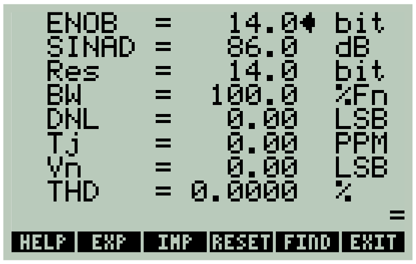




The equal sign (=), in the lower right hand corner of the display, indicates that all the parameters are consistent with each other. That is to say, **ENOB** and **SINAD** result from the values of **Res**, **BW** (or **OSR**), **DNL**, **Tj**, **Vn**, and **THD** entered. The parameters are always consistent immediately following a F5 (FIND) command, and the "=" will appear. Any entry of a parameter value will show the "≠" sign, indicating that the parameters may no longer be consistent.

Extended Menu Commands

Press the NXT key to display the Extended Menu showing four additional commands. Press NXT again to return to the Main Menu.



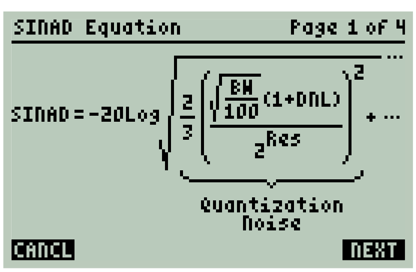
← The Extended Menu

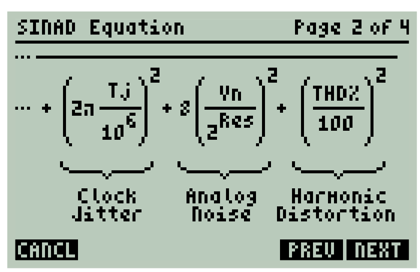
F1 (HELP) displays the equations used by ENOB
F2 (EXP) exports the selected parameter to the stack upon exiting
F3 (IMP) imports a number present in level 1 of the stack when ENOB was launched, to the selected parameter.
F4 (RESET) restores all default parameter values. Parameters are not stored until STO is executed.

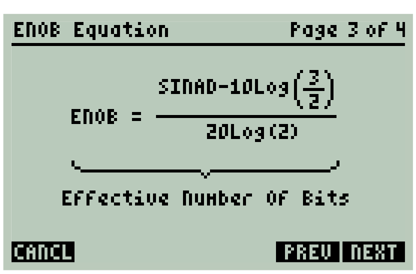
The Main Menu reappears after executing an extended menu command.

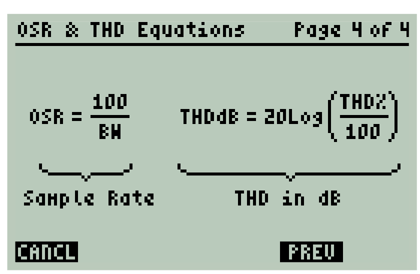
Help Command

Press F1 (HELP) to display the help screen, and F5 (PREV) and F6 (NEXT) to view pages 1 through 4 shown below. Press F1 (CANCL) to return to the parameter display.









Plot Commands

(F4 in the Main Menu) plots any two parameters with respect to each other.

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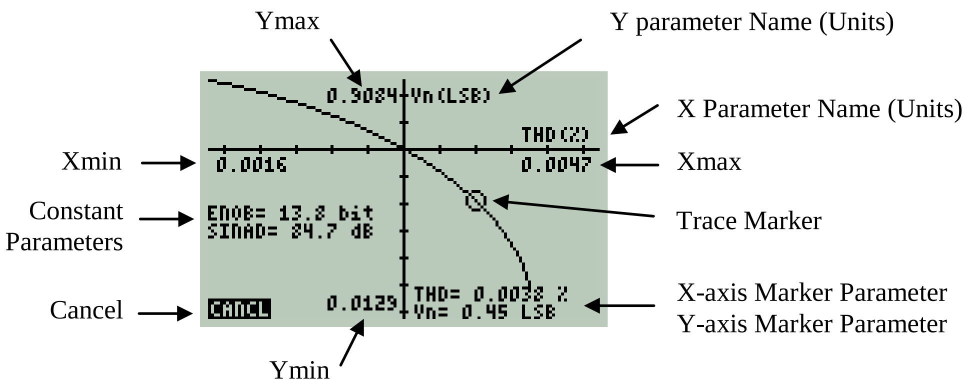
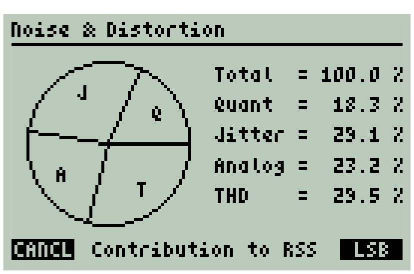
The key elements of the plot display are show below:

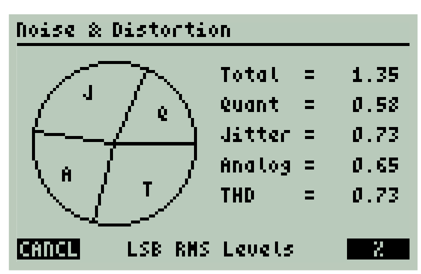


The following keys are active when a plot is displayed:

	▲	Zoom out
	▼	Zoom in
↱	◄	Move trace marker left by 1 pixel
	◄	Move trace marker left by ½ division
↰	◄	Move trace marker left by 2 divisions
↱	►	Move trace marker right by 1 pixel
	►	Move trace marker right by ½ division
↰	►	Move trace marker right by 2 divisions
F1	(CANCL)	Return to the parameter display

↰ (F4 in the Main Menu) displays a pie chart of four noise and distortion components, as a percentage of the root sum square (RSS) total, or their magnitudes in LSB RMS.





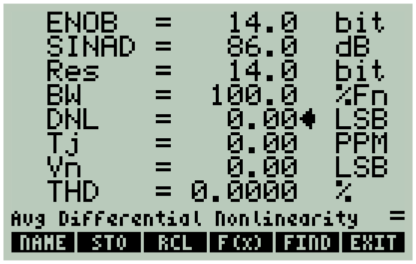
The following keys are active when this plot is displayed:

F6 (LSB) displays the noise and distortion components in LSB RMS.
F6 (%) displays the noise and distortion components as a percentage of the RSS total.

SECTION 5 - MESSAGES

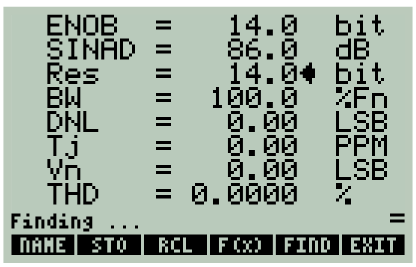
The calculator displays five types of messages on the message line:

1. Name Messages



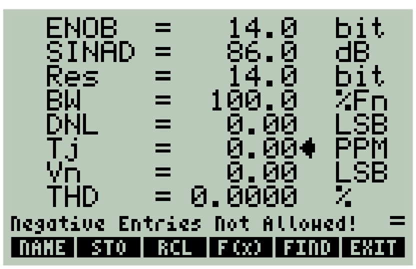
Name messages describe the selected parameter when NAME is active.

2. Busy Messages



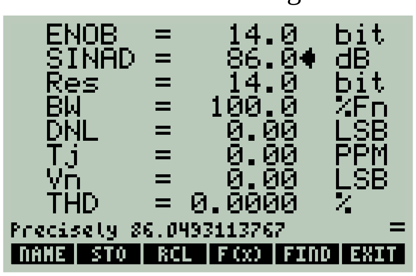
Busy messages explain what the program its doing.

3. Error Messages



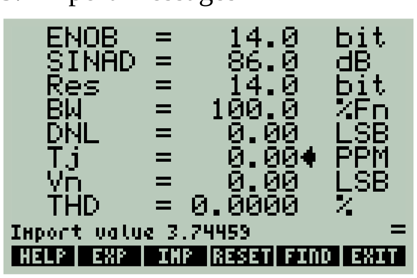
Error messages warn of an illegal entry, command, or result.

4. Full Precision Messages



Full Precision messages show the full precision of the selected parameter, when ↰ NAME is active.

5. Import Messages



Import messages show the value to be imported.

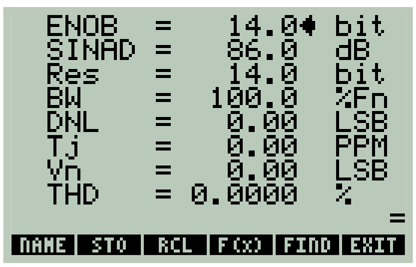
SECTION 6 - EXAMPLES

The ENOB calculator can find any parameter as a function of the others, and plot any parameter with respect to another. This makes it useful for both design and analysis. The following two example are used to demonstrate how to use the ENOB calculator.

Entering (,) and Finding (F5)

This example illustrates how to use ENOB to select an appropriate ADC (**Res**, **DNL**, **THD**, and Aperture Jitter, **Tj**) given a system requirement of ≥80dB **SINAD**, and the large signal bandwidth of 0 to 100KHz.

Using the rule of thumb equation for an ideal data convertor, SNR = 6*Res + 1.76dB, we start by looking look at 14-bit ADCs (SNR = 86dB)



Step 1:

Start with the default parameter values. **Res** is 14 bits by default. The display shows that an ideal (noiseless) 14 bit ADC has a **SINAD** of 86dB. Real ADCs will have a lower **SINAD** because **DNL**, **Tj**, **Vn**, and **THD** are always greater then zero.

Step 2:

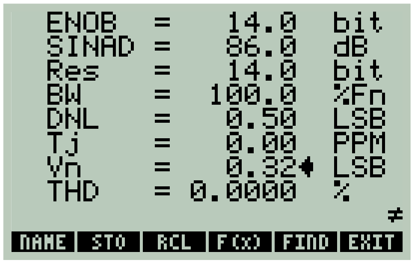
Find a 14 bit ADC that will accept a 0 to 100KHz input signal. A quick search of the Maxim ADC Parametric Table, at www.maximintegrated.com/products/data_converters/, yields many 14-bit candidates. For this example the MAX1062 will be used.

ELECTRICAL CHARACTERISTICS

($AV_{DD} = DV_{DD}$ = +4.75V to +5.25V, f_{SCLK} = 4.8MHz (50% duty cycle), 24 clocks/conversion (200ksps), V_{REF} = +4.096V, $T_A = T_{MIN}$ to T_{MAX}, unless otherwise noted. Typical values are at T_A = +25°C.)

PARAMETER	SYMBOL	CONDITIONS	MIN	TYP	MAX	UNITS
DC ACCURACY (NOTE 1)						
Resolution			14			Bits
Relative Accuracy (Note 2)	INL	MAX1062A			±1	LSB
		MAX1062B			±2	
		MAX1062C			±3	
Differential Nonlinearity	DNL	No missing codes over temperature		±0.5	±1	LSB
Transition Noise		RMS noise		±0.32		LSB_{RMS}
Total Harmonic Distortion	THD			-99	-86	dB
Aperture Jitter				<50		ps
Sample Rate	f_S	f_{SCLK} / 24			200	ksps

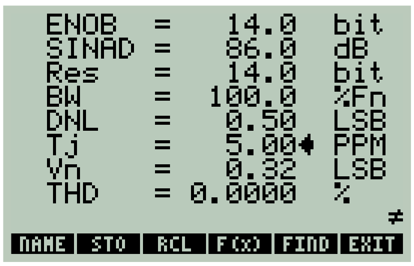
The data sheet indicates it has a typical **DNL** of ±0.5 LSB, a typical transition noise **Vn** of 0.32 LSB RMS, a typical **THD** of -99dB, and a typical aperture jitter **Tj** of 50ps.



Step 3:

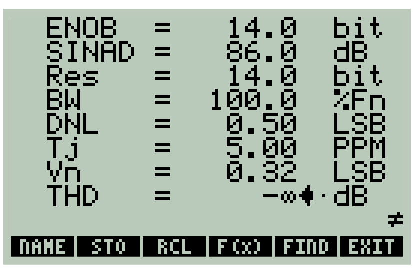
Enter **DNL** by using the up or down arrow keys to move the selection arrow () from **ENOB** to **DNL.** Use the or key to enter 0.5. Next, enter a **Vn** of 0.32 LSB RMS. Note that the consistency indicator has changed from "=" to "≠" indicating that all the parameters are now no longer consistent.

In this program **Tj** is defined as the ratio of the RMS jitter of the sample clock to the period of a full scale sine wave, in PPM. In this case, the worst case **Tj** is found by taking the ratio of 50ps to the shortest input signal period of 1/100KHz and multiplying by 1E6; Therefore, **Tj** = (50E-12/10E-6)*1E6 PPM = 5 PPM.



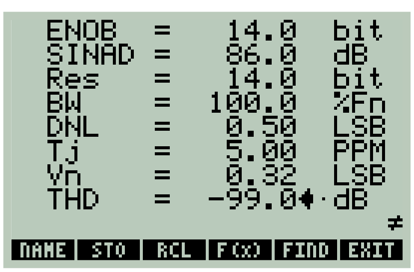
Step 4:

Enter **Tj** by using the down arrow key to move the selection arrow () to **Tj.** Use the or key to enter 5.



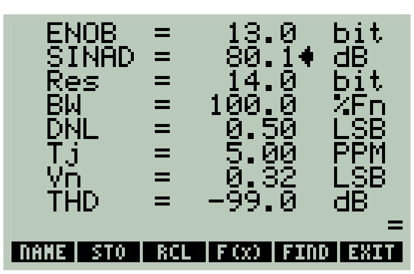
Step 5:

Before entering a THD of -99dB, first move the selection arrow to **THD** and press the right arrow key once, to change the units from % to dB.



Step 6:

Enter a **THD** of -99dB.

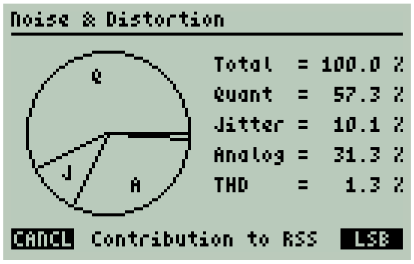


Step 7:

Find **SINAD** by moving the selection arrow to **SINAD** and press the F5 (FIND) menu key. It is found that, for this application, the MAX1062 has a typical **SINAD** of 80.1dB. Note that the consistency indicator has changed from "≠" to "=" indicating that all the parameters are now consistent.

The MAX1062 will met our target SINAD of 80 dB, with a 0.1 dB margin. However, in practice, additional margin is needed because we have used the typical values rather then the maximum, and have not accounted for the presence of additional noise sources.

Examine the noise and distortions levels to see where improvements can be made.



Step 8:

Press ↰ F4 ( ) to see the relative magnitudes of each noise and distortions source. It is seen that the quantization noise is the largest contributor to the total noise and distortion. Quantization noise can be reduced by increasing the resolution.

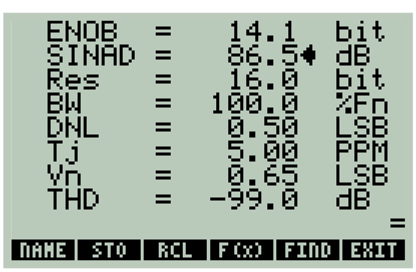
Therefore, additional margin can be achieved by selecting the 16-bit version of the same device, the MAX1162.

ELECTRICAL CHARACTERISTICS

(AV_{DD} = DV_{DD} = +4.75V to +5.25V, f_{SCLK} = 4.8MHz (50% duty cycle), 24 clocks/conversion (200ksps), V_{REF} = +4.096V, C_{REF} = 4.7µF, T_A = T_{MIN} to T_{MAX}, unless otherwise noted. Typical values are at T_A = +25°C.)

PARAMETER	SYMBOL	CONDITIONS		MIN	TYP	MAX	UNITS
DC ACCURACY (NOTE 1)							
Resolution				16			Bits
Relative Accuracy (Note 2)	INL	MAX1162A				±2	LSB
		MAX1162B				±2	
		MAX1162C				±4	
Differential Nonlinearity	DNL	No missing codes over temperature	MAX1162A		± 0.5	±1	LSB
			MAX1162B	-1		±1.75	
		MAX1162C				±2	
Transition Noise		RMS noise			±0.65		LSB_{RMS}
Total Harmonic Distortion	THD				- 99	-90	dB
Aperture Jitter	t_{AJ}				<50		ps
Sample Rate	f_S	f_{SCLK} / 24				200	ksps

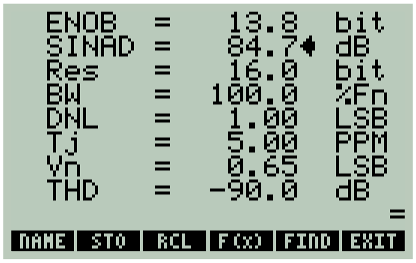
When not given, the typical values are estimated from the 14-bit device, the MAX1062.



Step 9:

Enter a **Res** of 16 and **Vn** of 0.65 LSB RMS, and find **SINAD**. It is found that there is a 6.4dB increase in **SINAD** over the 14-bit device. This is primarily do to a reduction in quantization noise.

We find that the MAX1162 meets our target SINAD of 80 dB, with a 6.5 dB margin.

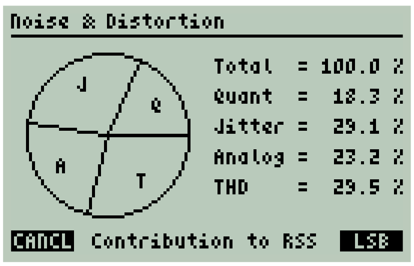


Step 10:

Find out if the 16-bit MAX1162 will meet our 80dB **SINAD** requirement using the worst case **DNL** and **THD**. The data sheet indicates a worst case **DNL** of ±1 LSB (Max) and worst case **THD** of -90dB (Max). Entering these values, **SINAD** is found to be 84.7 dB.

We conclude that the MAX1162 meets our target SINAD of 80 dB, with a 4.7dB margin.

Reexamine the worst case noise and distortions levels.

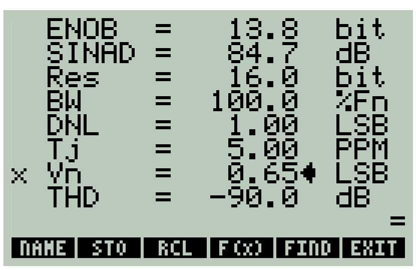


Step 11:

Press ↰ F4 (F(x)) again to see the relative magnitudes of each noise and distortions source. It is seen that quantization noise is no longer the dominate source of noise.

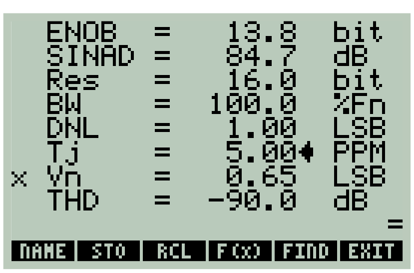
Plotting (F4)

The ENOB calculator can plot any two parameters with respect to each other. The following example demonstrates how to use the F(x) (F4) function to show the trade-off between clock jitter, (**Tj**) and input noise (**Vn**) such that **SINAD** remains unchanged.



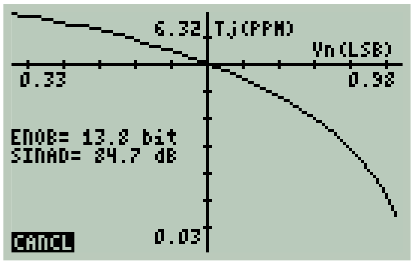
Step 1:

Select the independent (x-axis) parameter by moving the selection arrow to **Vn** and pressing the F4 key. An 'x' appears to the left of the independent (x-axis) parameter.

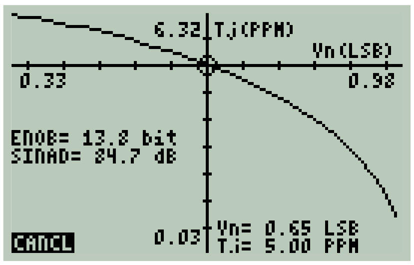


Step 2:

Move the selection arrow to the dependent (y-axis) parameter **Tj** and press the F4 again.

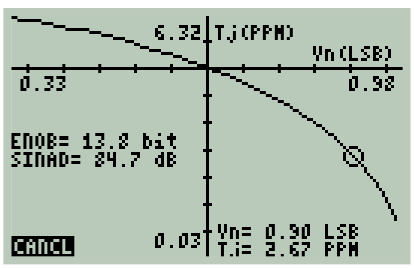


The following plot appears. This plot shows the trade-offs between clock jitter (**Tj**) and input noise (**Vn**), such that **SINAD** remains unchanged.



Step 3:

Press the left or right arrow key (◄ ►) to display a circular marker at the origin with the x-axis and y-axis values in the lower right corner of the display.



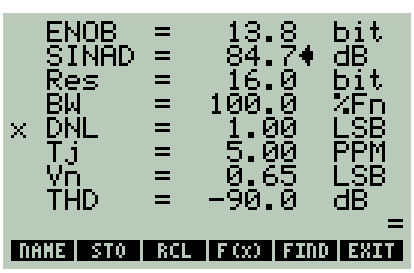
Step 4:

Use the left and right arrow keys to move the marker left and right along the curve. The x-axis and y-axis parameter values of the marker's position appear on the lower right corner of the display.

This marker position indicates the trade-offs between **Vn** and **Tj** that maintain a **SINAD** of 84.7dB. The position above indicates that if **Vn** is increased to 0.9 LSB then the clock jitter must be decreased to 2.67 PPM to maintain the same **SINAD** of 84.7dB.

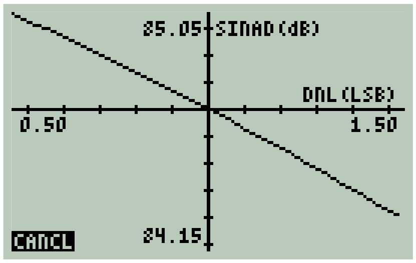
Zooming (▲ , ▼)

This example illustrates how to use the zoom function by analyzing the sensitivity of **SINAD** to changes in **DNL**.



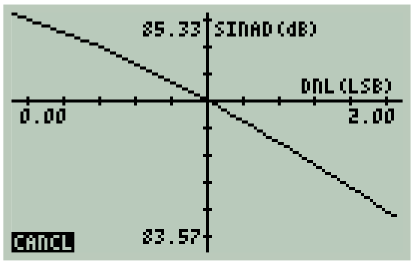
Step 1:

Select the independent (x-axis) parameter by moving the selection arrow to **DNL** and pressing the F4 key. An 'x' appears to the left of the parameter. Then move the selection arrow to the dependent (y-axis) parameter **SINAD** and press F4 again to plot the selected parameters.



Step 2:

The following plot appears, showing how **SINAD** decreases as **DNL** increase.



Step 3:

Zoom out by pressing the up arrow key (▲) twice. The span of the x-axis increases by 2X.

Each press of the up or down arrow key increases or decreases the span of the x-axis by a factor of the square root of 2.

SECTION 7 - BACKGROUND

ENOB and How it is Calculated

Effective Number of Bits (**ENOB**) is a measure of an Analog-to-Digital Converters' (ADCs) or Digital-to-Analog Converters' (DACs) ability to convert a signal between the analog and digital domains. **ENOB** is an AC specification and is synonymous with Signal to Noise and Distortion (SINAD). **SINAD** is the ratio of the full scale rms signal to the rms sum of all other noise and distortion components. **ENOB** says that a data converter has a level of noise and distortion equivalent to an ideal (i.e., noise and distortion free) data convertor of **ENOB** bits and full bandwidth. **ENOB** is always less then or equal to the resolution (**Res**) of the device. **ENOB** should not be confused with DC accuracy which is based on the resolution (**Res**) and linearity (INL) of a data convertor.

The calculator accounts for four sources of noise and distortion in a data convertor, they are:

- Quantization Noise (**Res**, **BW** or **OSR,** and **DNL**)
- Clock Jitter Noise (**Tj**)
- Analog Referred Noise (**Vn**)
- Total Harmonic Distortion (**THD**)

The equations used in this program for **ENOB** and **SINAD** are,

$$ENOB = \frac{SINAD - 10 \cdot Log\left(\frac{3}{2}\right)}{20 \cdot Log(2)}$$

and

$$SINAD = -20\log\sqrt{\underbrace{\frac{2}{3}\left(\frac{\sqrt{\frac{BW}{100}}(1+DNL)}{2^{\mathrm{Res}}}\right)^2}_{\text{Quantization Noise}} + \underbrace{\left(2\pi\frac{Tj}{10^6}\right)^2}_{\text{Clock Jitter Noise}} + \underbrace{\left(\frac{2\cdot\sqrt{2}\cdot Vn}{2^{\mathrm{Res}}}\right)^2}_{\text{Analog Noise}} + \underbrace{\left(\frac{THD_{\%}}{100}\right)^2}_{\text{THD}}}$$

SINAD reduces to the familiar,

$$SNR = 6.02N + 1.76dB$$

when **SINAD** = SNR dB, **Res** = N bits , **BW** = 100 %, **DNL** = 0 LSB,
Tj = 0 PPM RMS, **Vn** = 0 LSB rms , and **THD** = 0%. In this case **ENOB** = N bits.

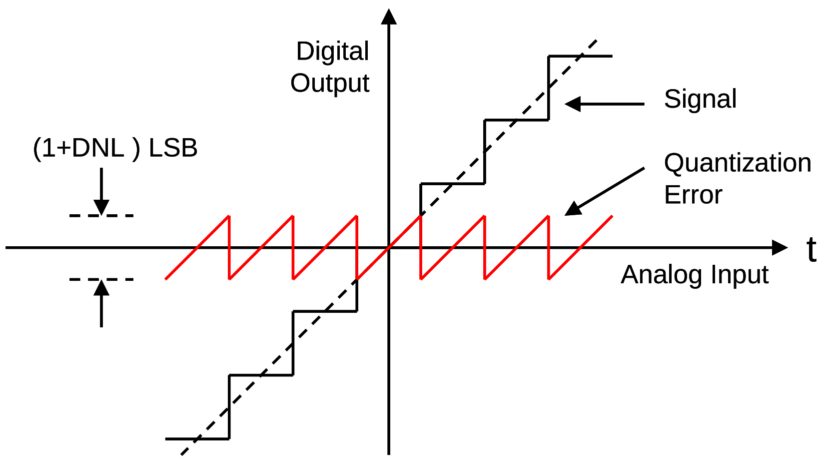
Together, these parameter values describe the "ideal" data convertor where the only noise source is the full bandwidth quantization noise inherent in the sampling processes.

Quantization Noise

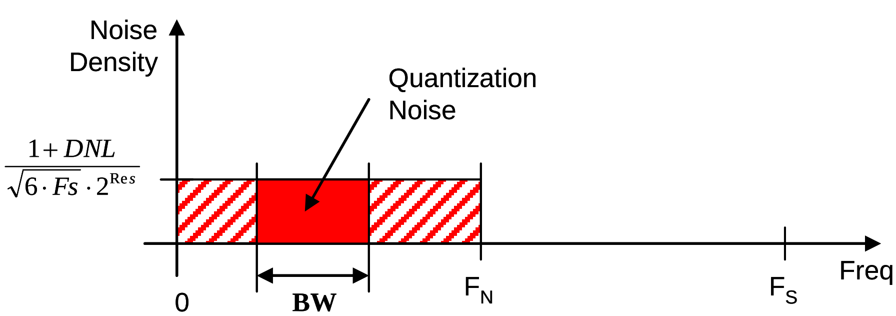
The first term in the **SINAD** equation is the SNR due to quantization noise,

$$\sqrt{\frac{2}{3}}\left(\frac{\sqrt{\frac{BW}{100}}(1+DNL)}{2^{\text{Res}}}\right)$$

Quantization noise is a direct result of the errors inherent in the sampling and quantization process used by data convertors. The quantization error for an ADC is shown below,



If the sample frequency (Fs) and the input signal are harmonically uncorrelated then the quantization noise is Gaussian and is distributed between DC and the Nyquist frequency, Fn. The sample frequency (Fs) is always twice the Nyquist frequency (Fn). This noise density spectrum is shown below,



The quantization noise, in LSB RMS, is

$$n_q = \frac{\sqrt{\frac{BW}{100}}(1+DNL)}{\sqrt{12}}$$

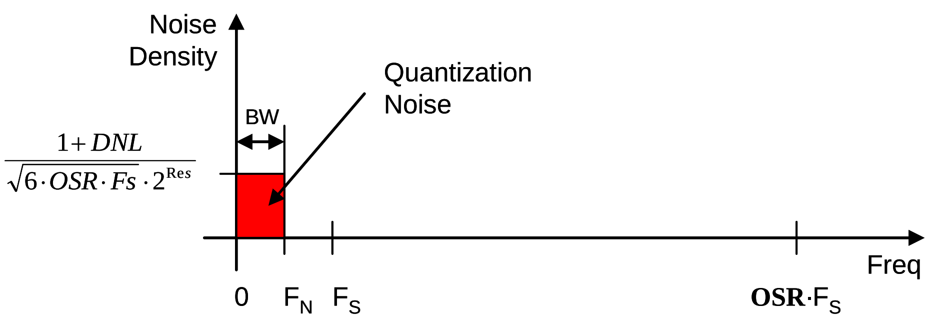
LSB size decreases with increasing **Res**. Therefore, quantization noise decreases with an increase in resolution (**Res**), decreases with Bandwidth (**BW**), and decreases with average **DNL**. **BW** is in units of percentage of Nyquist frequency (%Fn), and **DNL** is the average deviation, between any two adjacent codes, from an ideal 1 LSB step.

This program assumes *all* out-of-band noise has been removed by filtering using an ideal brick wall filter in the out-of-band regions. It assumes no noise shaping is used. In practice, not all out-of-band noise can be entirely removed so the noise predicted by the program will be somewhat lower then expected. A further reduction of in-band quantization noise is possible using noise shaping filters.

Alternatively, Over Sample Ratio (**OSR**) can be used in place of **BW**. With OSR, the SNR due to quantization noise becomes,

$$\sqrt{\frac{2}{3}}\left(\frac{\sqrt{\frac{1}{OSR}}\left(1+DNL\right)}{2^{\mathrm{Res}}}\right)$$

OSR is the ratio of some higher sample rate **OSR**·Fs to the original sample rate Fs. **OSR** assumes that the original bandwidth remains unchanged, 0 to Fn, where Fn = Fs/2. This noise density spectrum is shown below,



As defined, **BW** and **OSR** are related by,

$$OSR = \frac{100}{BW}$$

The quantization noise, in LSB RMS, is

$$n_q = \frac{\sqrt{\frac{1}{OSR}}\left(1+DNL\right)}{\sqrt{12}}$$

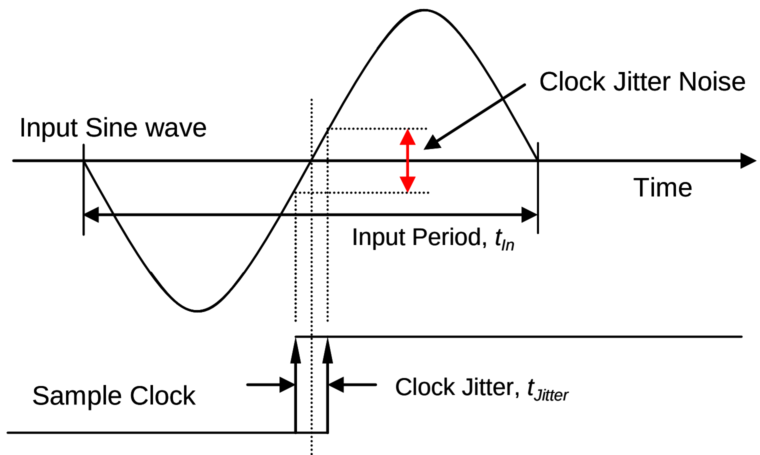
Sample Clock Jitter Noise

The second term in the **SINAD** equation is SNR due to sample clock jitter,

$$2\pi \frac{Tj}{10^6}$$

Sample clock jitter introduces noise when sampling a time varying signal, by producing unwanted variations in sampled values. Clock jitter can result from sources internal and external to the data converter.

This term assumes the signal is a full scale sine wave and that **Tj** is the ratio of the RMS jitter of the sample clock to the period of the sine wave, in PPM. This is shown below,



Where **Tj** is,

$$Tj = \frac{t_{Jitter}}{t_{In}} \cdot 10^6$$

The clock jitter noise, in LSB RMS, is

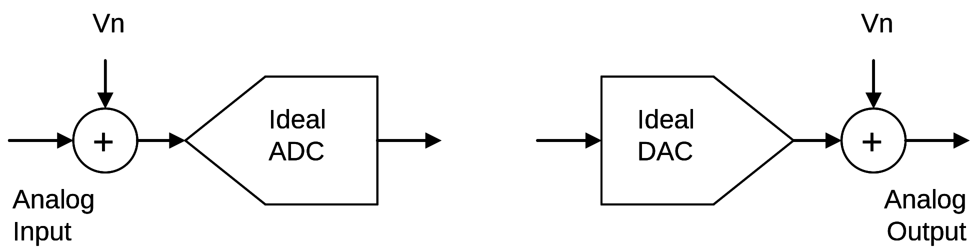
$$n_j = \frac{2\pi}{\sqrt{8}} \frac{Tj \cdot 2^{Res}}{10^6}$$

Analog Referred Noise

The third term in the **SINAD** equation is the SNR of the analog referred noise,

$$\frac{2 \cdot \sqrt{2} \cdot Vn}{2^{\mathrm{Res}}}$$

Vn is the effective RMS noise referred to the input of an ADC or the output of a DAC, and is given in units of LSB RMS. **Vn** can be from internal or external sources and is assumed to be Gaussian.



The analog referred noise, in LSB RMS, is

$$n_A = Vn$$

Total Harmonic Distortion

The last term in the **SINAD** equation is **THD**,

$$\frac{THD_{\%}}{100}$$

Total Harmonic Distortion (THD) is the ratio of the root sum square of all harmonic distortion components relative to full scale RMS. **THD$_{\%}$** is given in percentage relative to 100% full scale, or **THD$_{dB}$** is given in dB relative to 0dB full scale

Alternatively, the **THD** term of the SINAD equation can be expressed in dB (**THD$_{dB}$**) as,

$$10^{\frac{THD_{dB}}{20}}$$

The noise due to harmonic distortion, in LSB RMS, is

$$n_{THD} = \frac{2^{\mathrm{Res}} THD_{\%}}{100\sqrt{8}} \quad \text{or} \quad n_{THD} = \frac{2^{\mathrm{Res}}}{\sqrt{8}} \cdot 10^{\frac{THD_{dB}}{20}}$$

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