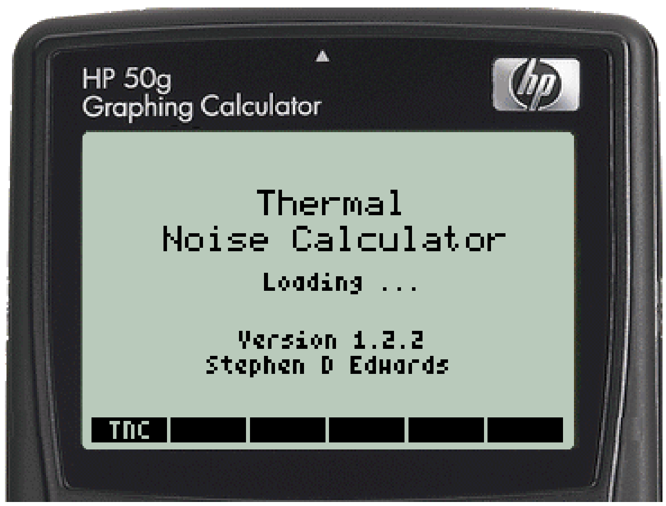
THERMAL NOISE CALCULATOR USER'S GUIDE



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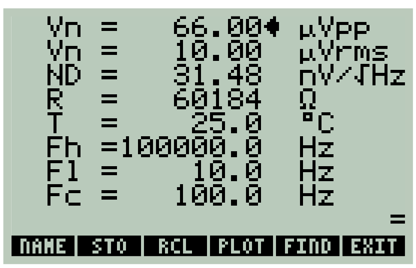
SECTION 1 - INTRODUCTION

Thermal Noise Calculator (TNC) is a program written for the HP50g calculator that aids in the analysis of thermal noise found in resistors and other noise sources. TNC finds the noise voltage generated by any device if its white noise spectral density and 1/f corner frequency are known. Each parameter can be entered or found. TNC can also be run on a PC using the free program HPUserEdit 5.4, found at www.hpcalc.org, or the calculator page at www.maximintegrated.com.

Seven parameters can be entered or found,

- Noise Voltage, **Vn,** in µVpp or µVrms
- White Noise Spectral Density, **ND,** in nV/√Hz
- Johnson Resistance, **R**, in Ω
- Temperature, **T**, in °C
- Upper Frequency, **Fh**, in Hz
- Lower frequency, **Fl**, in Hz
- 1/f Corner Frequency, **Fc**, in Hz

TNC finds any parameter as a function of the others, making it useful for both design and analysis. These parameters appear in TNC as shown below:



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

SECTION 2 - INSTALLATION

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

Installing TNC on the HP50g Calculator

TNC may be installed in any one of three ways:

A. Best when installing one calculator:

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

B. Best when installing between two and six calculators:

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

C. Best when installing six or more calculators:

Install TNC 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 TNC on a Windows PC

TNC 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 TNC:

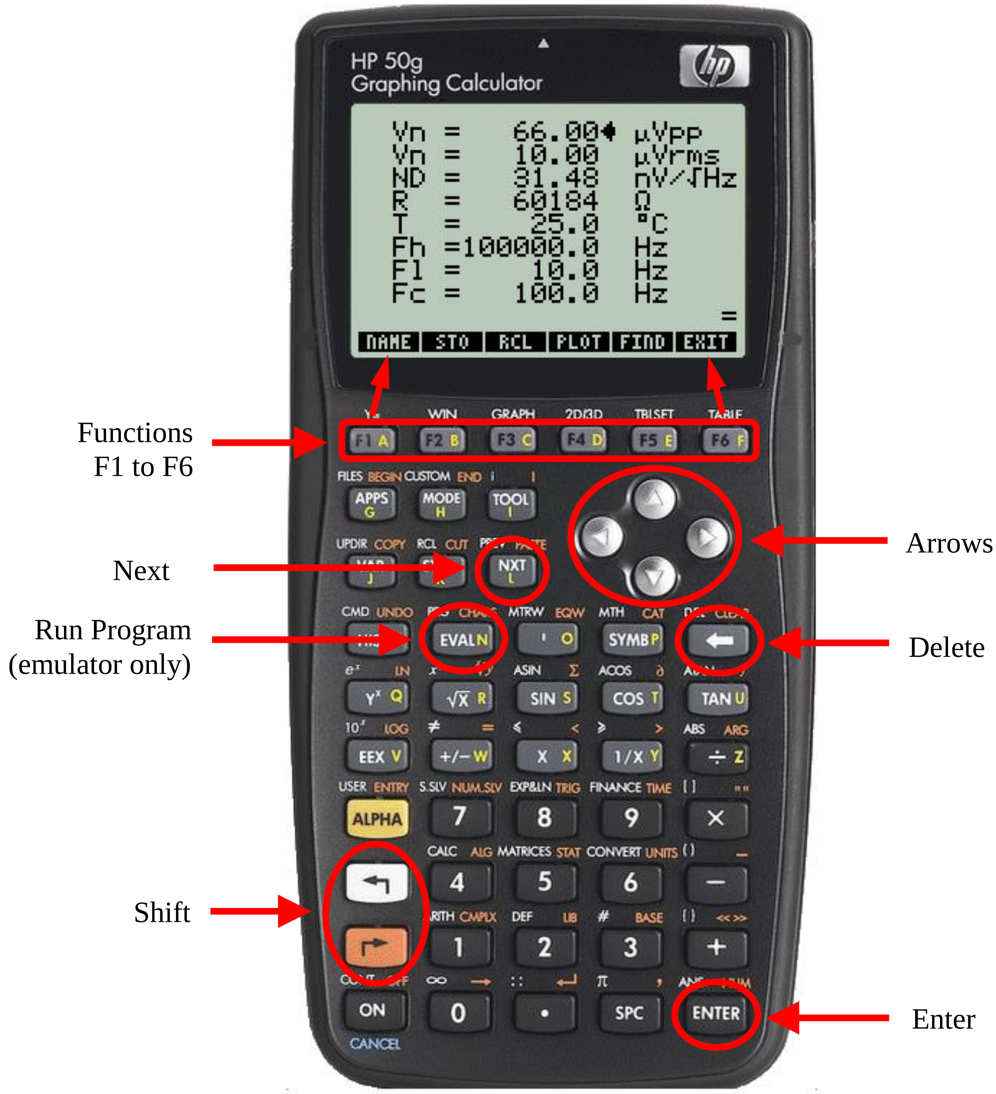
1. Launch HPUserEdit
2. Launch the HP50g emulator by selecting Emulator/Run_the_Emulator from the menu bar. A virtual HP50g appears.
3. Drag and drop TNC.hp to the calculator screen and click the EVAL key.

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.

TNC creates a file named 'CalcDB' in the calculator's home directory the first time it is run. 'CalcDB' holds the parametric values used by TNC 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 TNC:



For convenience, 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

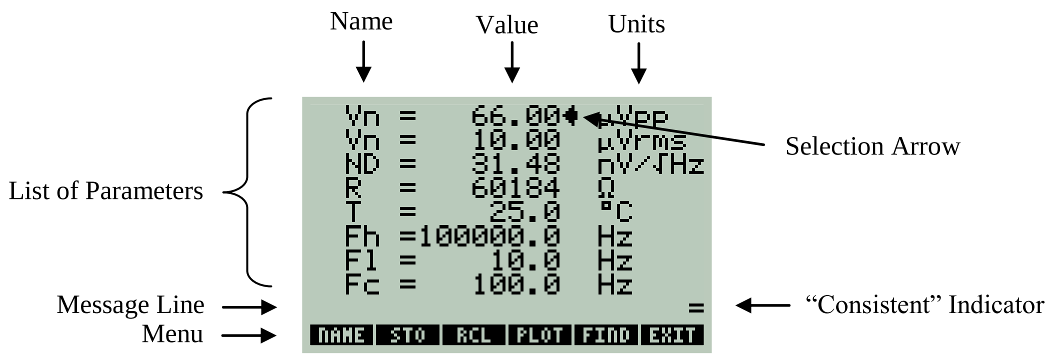
SECTION 4 - COMMANDS

TNC has two sets of commands:

- Main Menu Commands
- Extended Menu Commands
- Help Commands

Main Menu Commands

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

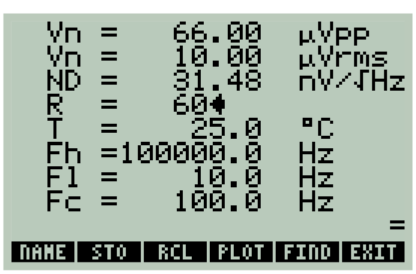


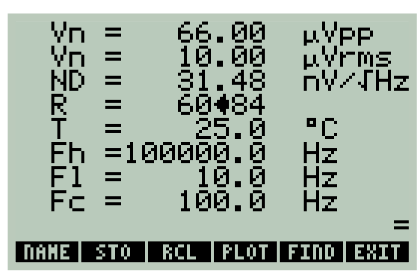
Use the ▼ and ▲ keys to select a parameter.
Use the ◄ (insert) or ◄ (delete) key to enter or edit a parameter. Press ENTER when finished.

- F1 (NAME) displays the name 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 (PLOT) plots the noise density spectrum
- 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 value by using one of the following keys:

the delete key (◄), and the left arrow (insert) key (◄)



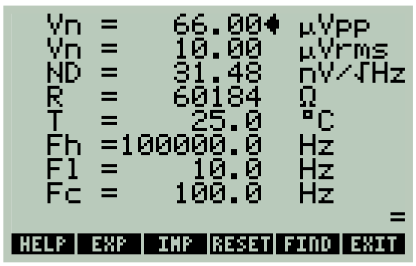


Press ENTER when finished.

The equal sign (=), in the lower right hand corner of the display, indicates that all the parameters are consistent with each other. The noise **Vn** (in µVpp and µVrms) is the noise that comes from a resistor of resistance **R**, at temperature **T**, between frequencies **Fl** and **Fh**, having a 1/f corner frequency of **Fc**. 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.



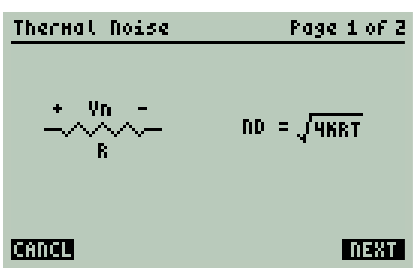
← The Extended Menu

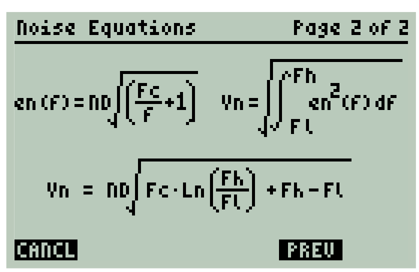
F1 (HELP) displays the thermal noise equations used by TNC
F2 (EXP) exports the selected parameter to the stack upon exiting
F3 (IMP) imports a number present in level 1 of the stack when TNC was launched, to the selected parameter.
F4 (RESET) enters all default parameter values. Parameters are not stored 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 and 2 shown below. Press F1 (CANCL) to return to the parameter display.

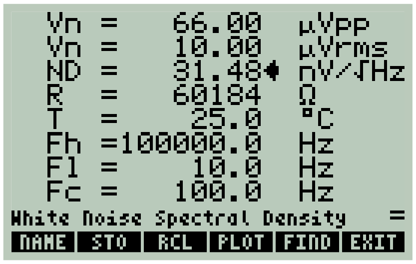




SECTION 5 - MESSAGES

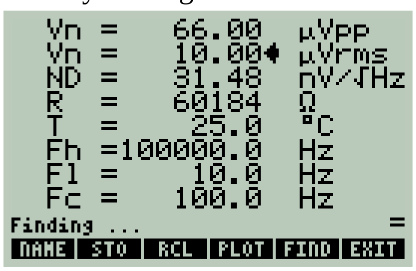
TNC displays five types of messages on the message line:

1. Name Messages



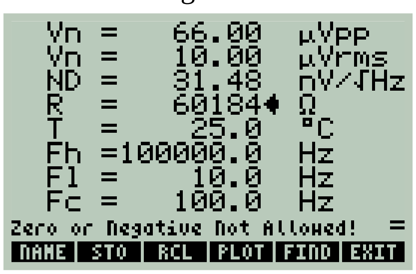
Name messages describe the selected parameter when NAME is active.

2. Busy Messages



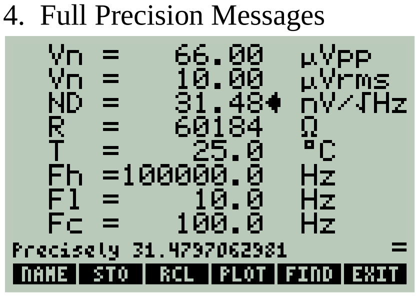
Busy messages explain what the program its doing.

3. Error Messages



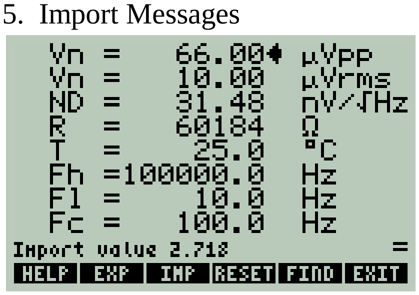
Error messages warn of an illegal entry, command, or result.

4. Full Precision Messages



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

5. Import Messages



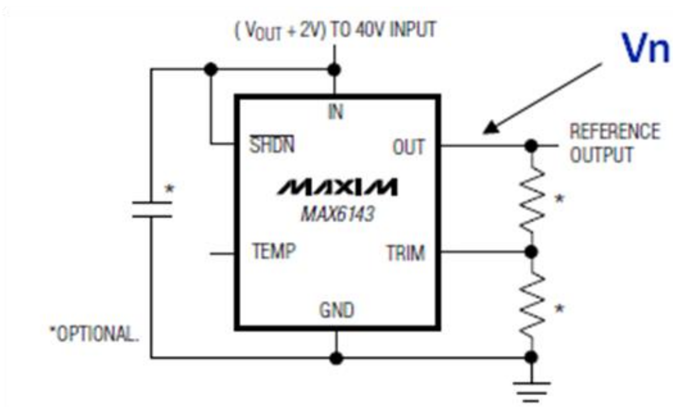
Import messages show the value to be imported.

SECTION 6 - EXAMPLES

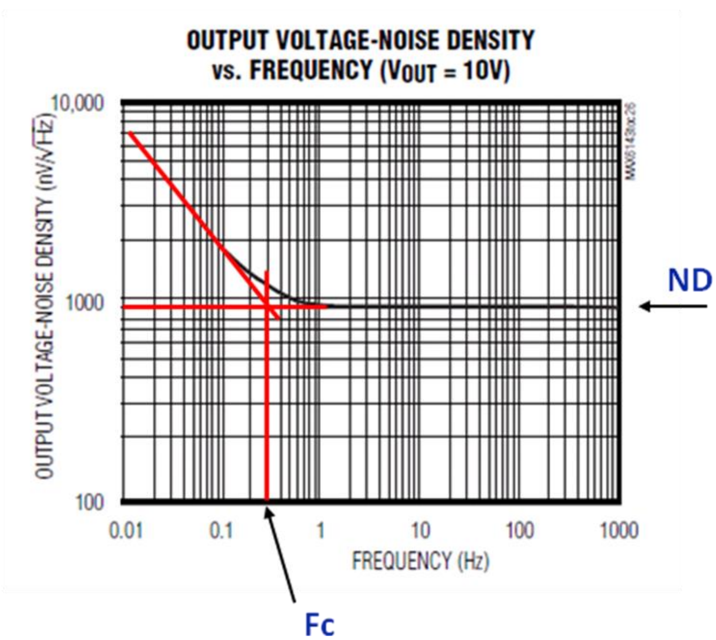
TNC enable all parameters to be entered or found.

Entering (,) and Finding (F5)

In this example, uses TNC to estimate the output noise voltage of the MAX6143 10V series voltage reference for use in an audio application. Find the noise over the low frequency band of 0.1Hz to 10Hz and the full audio band of 20Hz to 20KHz. Determine if the output noise meets a noise budget of < 112uVrms over the voice band of 0 to 8KHz.

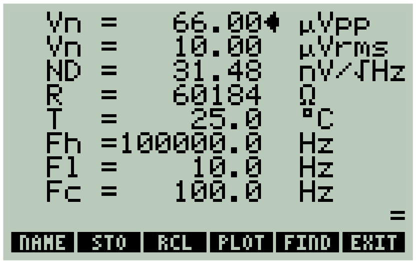


Start by referring to the Noise Density plot in the Typical Operating Characteristics section of the data sheet. Find the white noise spectral density (**ND**) and the 1/f corner frequency (**Fc**) from the plot.



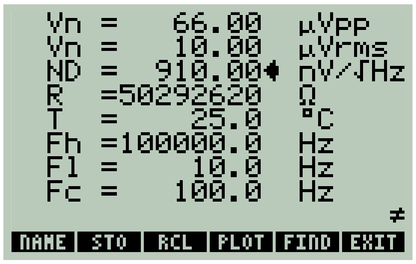
Fc is found at intersection of the ND line and the 1/f line when plotted in a log-log scale. These lines are shown in red.

The white noise density is ~ 910nV√Hz and the corner frequency is ~ 0.3 Hz.



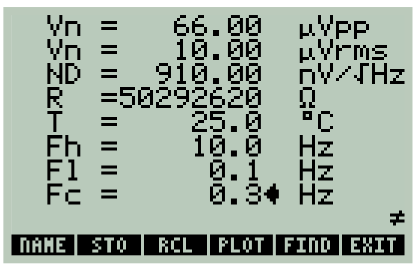
Step 1:

Starting with TNC's default parameter values, first enter the spectral density, **ND**, found from the data sheet. Use the up or down arrow keys to move the selection arrow (◄) from **Vn** to **ND.**



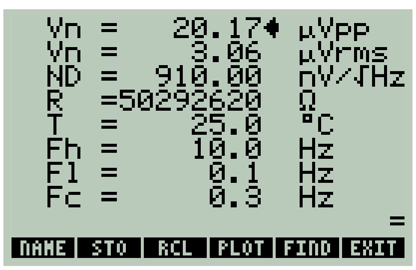
Step 2:

Us the ◄ or ◄ key to enter 910nV√Hz. Note that the resistance (**R**) changes automatically. **R** is the resistance necessary to produce a 910nV√Hz white noise density at 25°C. The consistency indicator changes from = to ≠ indicating that all parameters are no longer consistent.



Step 3:

Find the low frequency noise by first entering 10Hz into **Fh**, 0.1Hz into **Fl**, and 0.3Hz into **Fc**.

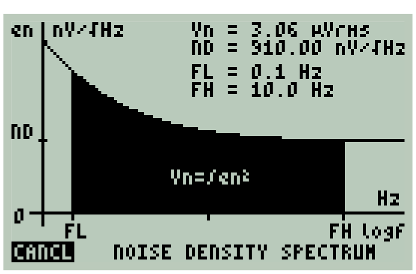


Step 4:

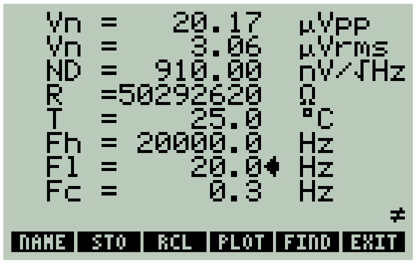
Find the low frequency noise by moving the arrow to **Vn** (in µVrms), and pressing the F5 (FIND) menu key. The answer is 20.17µVpp which closely agrees with the Electrical Characteristics Table (18µVpp) . The equivalent noise in µVrms automatically updates, and the consistency indicator changes from ≠ to = indicating that all parameters are consistent.

Plotting (F4)

Press F4 to plot the noise spectral density of the entered parameters. The parameters must be consistent to be plotted.

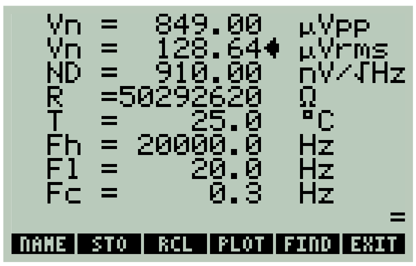


This is the plot of the low frequency noise of the MAX6143, from Step 4 above. The noise, Vn, is the area under the square of the noise density spectrum curve, en(f).



Step 5:

Find the noise over the audio frequency band by entering 20000Hz into **Fh**, 20Hz into **Fl**, and keeping **Fc** at 0.3Hz.

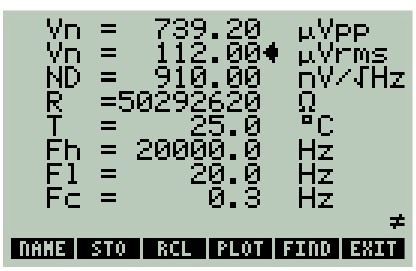


Step 6:

Find the audio band noise by moving the arrow back up to **Vn** (in µVrms), and pressing the F5 (FIND) menu key. The noise produced is 128µVrms.

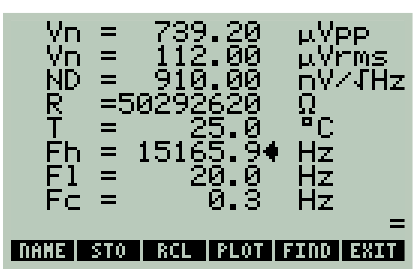
Note that **Vn** is a prediction of the noise over a band that does not appear in the Electrical Characteristics Table but is derived from information on the datasheet.

Find the upper frequency where Vn equals our noise error budget of 112 µVrms. 112 µVrms represents a SNR of -90 dB of a 10 Vpp audio signal.



Step 1:

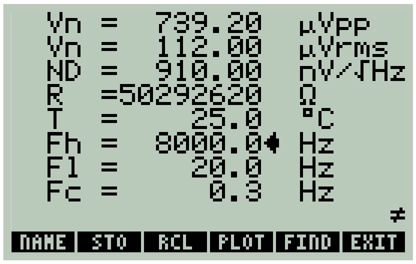
Enter 112µVrms into **Vn.**



Step 2:

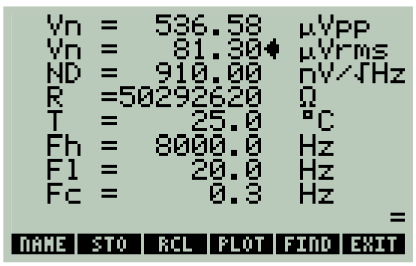
Find the upper frequency by moving the arrow to **Fh**, and press F5 (FIND). It is found that **Vn** exceeds 112µVrms when **Fh** exceeds 15.2 KHz.

The MAX6043CAUT10 will meet our noise budget of < 112 µVrms over the voice band of 20 Hz to 8 KHz. But by how much?



Step 1:

Enter 8 KHz into **Fh.**



Step 2:

Find the RMS Noise Voltage by moving the arrow to **Fh**, and pressing F5 (FIND). It is found that **Vn** is 81.3 µVrms.

Vn of 81.3 µVrms is a 27.4% margin below the 112 µVrms noise budget.

SECTION 7 - BACKGROUND

Types of Noise

Noise comes from many sources can be placed in one of two categories depending on its spectral density. All noise sources discussed in this guide are random and have a Gaussian (Normal) distribution.

White Noise
White noise is characterized by a uniform spectral density. It is present in all active and passive devices. Examples of white noise are:

- *Thermal Noise* also called *Johnson Noise*, is present in all passive resistive elements and is caused by random thermal motion of electrons. It does *not* require the flow of current.
- *Shot Noise*, also called *Schottky Noise*, is generated in active devices whenever charge crosses a potential barrier. Shot noise is proportional to current.
- *Avalanche Noise* which is found in pn junctions operating in reverse breakdown mode. Avalanche noise requires the flow of current.

Pink Noise
Pink noise is characterized by a spectral density that increases with decreasing frequency. It is present in all active and some passive devices. Examples of pink noise are:

- *Flicker Noise* (also called *1/f Noise* or *Contact Noise*), which is generated by random fluctuations in current due to defects in semiconductor materials and increases with DC current.
- *Popcorn Noise* (also called *Burst Noise*), is a modulation of current caused by the capture and emission of a channel carrier. Its cause is related to heavy metal ion contamination in semiconductor materials and increases with DC current.

Integrated circuit noise is always some combination of white and pink noise. Each internal noise sources may have a different white noise density and corner frequency. These will combine to yield a net white noise density (**ND**) and corner frequency (**Fc**).

TNC can be used to estimate the noise level from any source if its white noise density (**ND**) and 1/f corner frequency (**Fc**) are known. In these cases **R** and **T** are not use.

How Thermal Noise is Calculated

Thermal Noise, also called Johnson Noise, is present in all passive resistive elements and is caused by random thermal motion of electrons. All passive resistive elements generate thermal noise, whether discrete or integrated. Thermal noise has a uniform spectral density and is called “white”. It increases with temperature and resistance. The thermal noise level is unaffected by DC current. Resistors always generate noise, even when floating outside of a closed circuit.

In addition to white noise TNC models 1/f noise found in semiconductor devices. 1/f noise is characterized by a spectral density that increases with decreasing frequency. It has the property of having the same power in each frequency decade (or octave). It is present in all active and some passive devices.

Vn is the thermal noise voltage found across a resistor. It is expressed in both µVpp and µVrms, and are related by,

$$Vn_{pp} = 6.6 \cdot Vn_{rms}$$

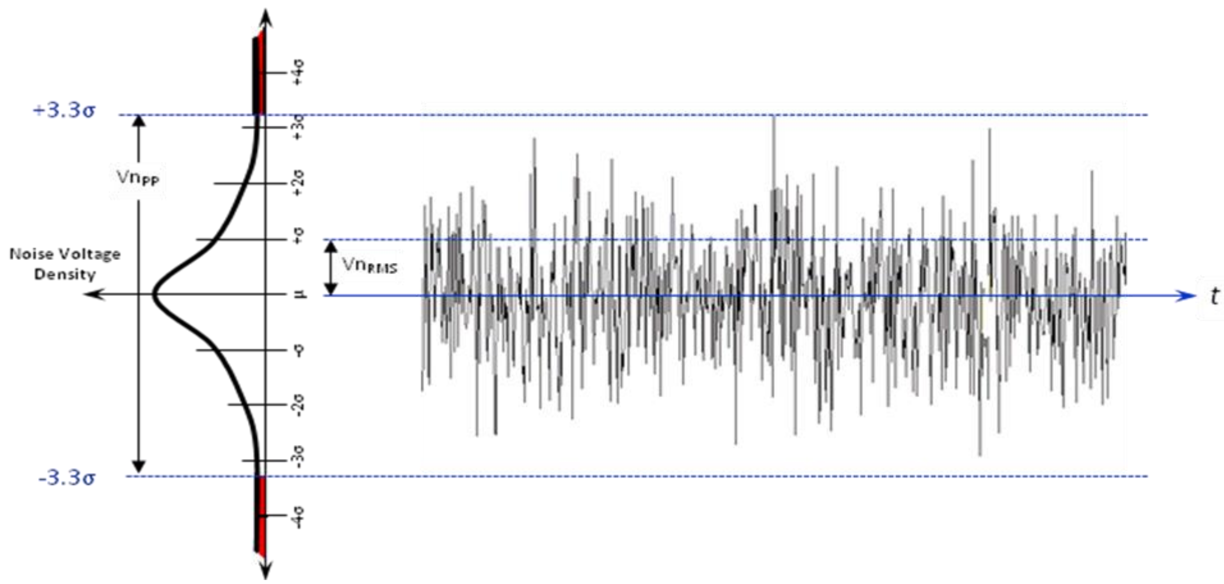
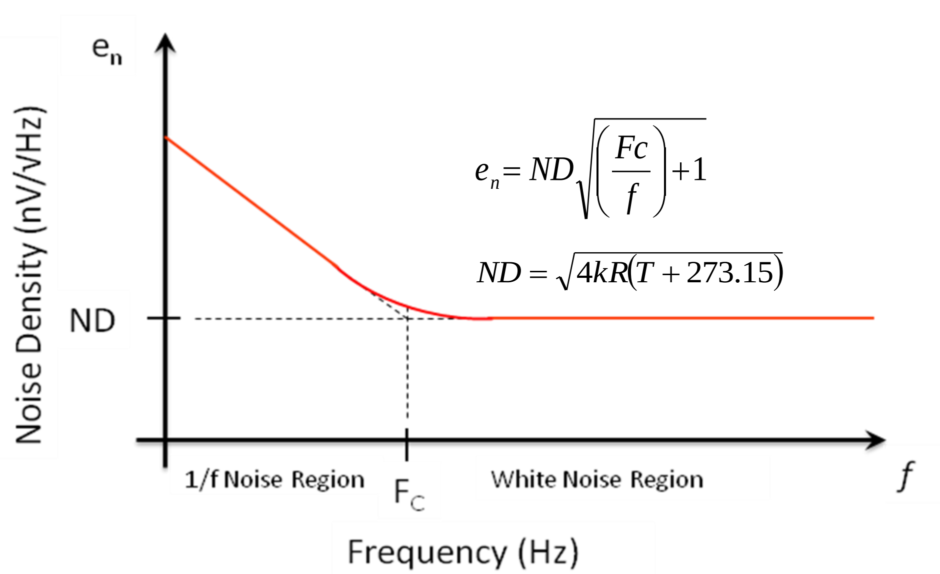


Figure 1: Gaussian Amplitude Distribution

The 6.6 is a commonly used crest factor, and comes from the fact that, statistically, a Gaussian noise source produces a peak-to-peak voltage 6.6 times the rms voltage 0.10% of the time. This is the shaded area under the Noise Voltage Density curve shown in Figure 1 where the probability of exceeding ±3.3σ is 0.001.

TNC models the Noise Spectral Density as shown in Figure 2.



$$e_n = ND\sqrt{\left(\frac{Fc}{f}\right)+1}$$

$$ND = \sqrt{4kR(T+273.15)}$$

Figure 2: Noise Spectral Density

Semiconductor noise sources are made of both white noise which dominates at high frequencies, and 1/f noise which dominates at low frequencies. **ND** is the white noise spectral density and is related to **R** and **T** by,

$$ND = \sqrt{4kR(T + 273.15)}$$

where k is the Boltsmann constant, **R** is the Johnson resistance in ohms, and **T** is the temperature in centigrade.

Vn (μVrms) is the root sum square of the noise density over the frequency band of interest,

$$Vn_{rms} = \sqrt{\int_{Fl}^{Fh} \left(ND \sqrt{\left(\frac{Fc}{f} \right) + 1} \right)^2 df}$$

where **Fh** and **Fl** are the upper and lower limits of the frequency band. **ND** is the white noise spectral density, **Fc** is the 1/f corner frequency, and **f** is frequency. **Fc** is the corner frequency dividing these two regions. See Figure 3.

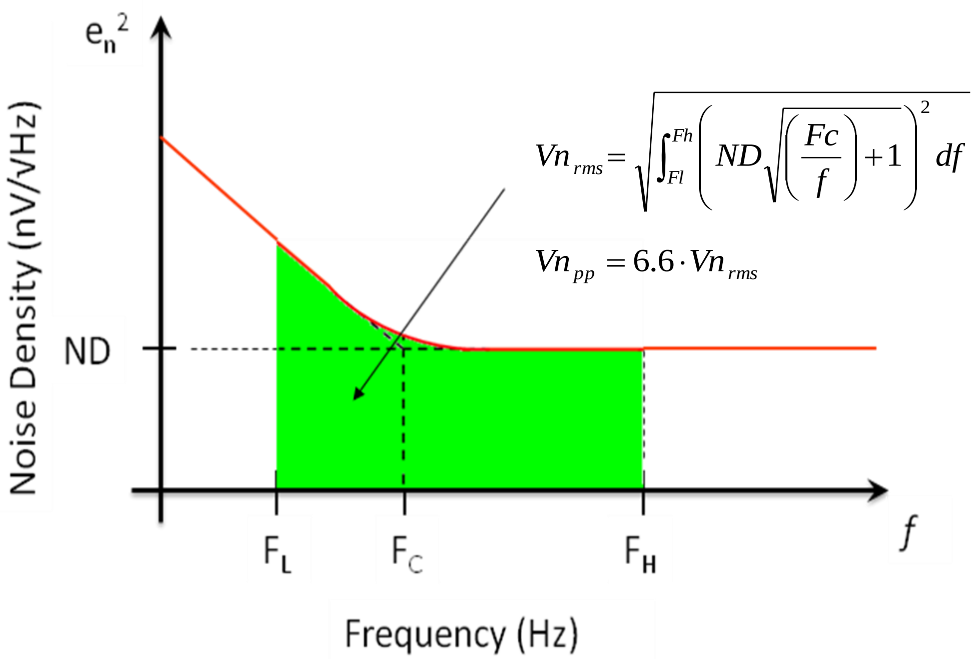


Figure 3: Noise Voltage

Integration yields,

$$Vn_{rms} = ND \sqrt{Fc \cdot Ln\left(\frac{Fh}{Fl} \right) + Fh - Fl}$$

SECTION 8 - TOOLS, MODELS, AND SOFTWARE NOTICE