SETTLING TIME CALCULATOR USER'S GUIDE

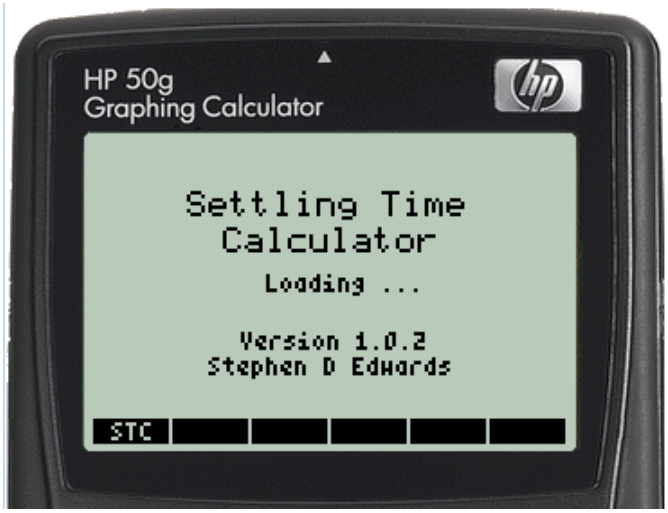

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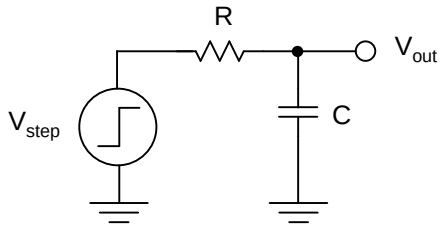
TABLE OF CONTENTS

SECTION 1 - INTRODUCTION

Settling Time Calculator (STC) is a program written for the HP50g calculator that aids in the analysis and design of the step response of a single pole RC filter. STC finds the time it takes (**ts**) for the output voltage to respond to a step input voltage (**Vstep**) and settle to within a specified fraction (**Accu**) of the final value.



Each parameter can be entered or found. STC 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.

Ten parameters can be entered or found,

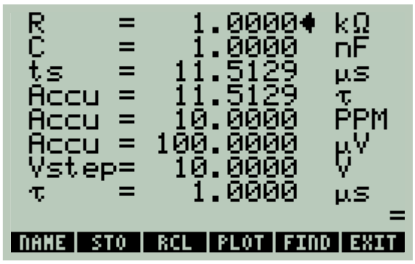
- Resistance, **R,** in kΩ
- Capacitance, **C,** in nF
- Settling Time, **ts**, in µs
- Accuracy, **Accu**, in τ
- Accuracy, **Accu**, in PPM
- Accuracy, **Accu**, in %
- Accuracy, **Accu**, in µV
- Accuracy, **Accu**, in LSB
- Voltage Step Size, **Vstep**, in V
- Resolution, **Res**, in bits

STC can find any of these parameters as a function of the others, making it useful for both design and analysis.

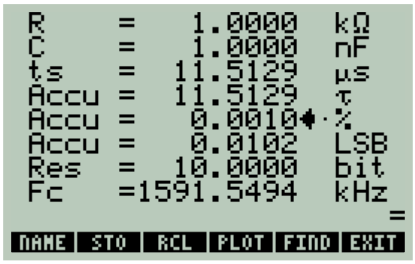
Three additional circuit parameters are found,

- Time Constant, **τ**, in µs
- Cutoff Frequency, **Fc**, in kHz
- Rise Time, **tr**, in µs

These parameters appear in STC as shown below:



with alternative parameters,



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

SECTION 2 - INSTALLATION

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

Installing STC on the HP50g Calculator

STC may be installed in any one of three ways:

A. Best when installing one calculator:

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

B. Best when installing two to six calculators:

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

C. Best when installing six or more calculators:

Install STC 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 STC on a Windows PC

STC 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 STC:

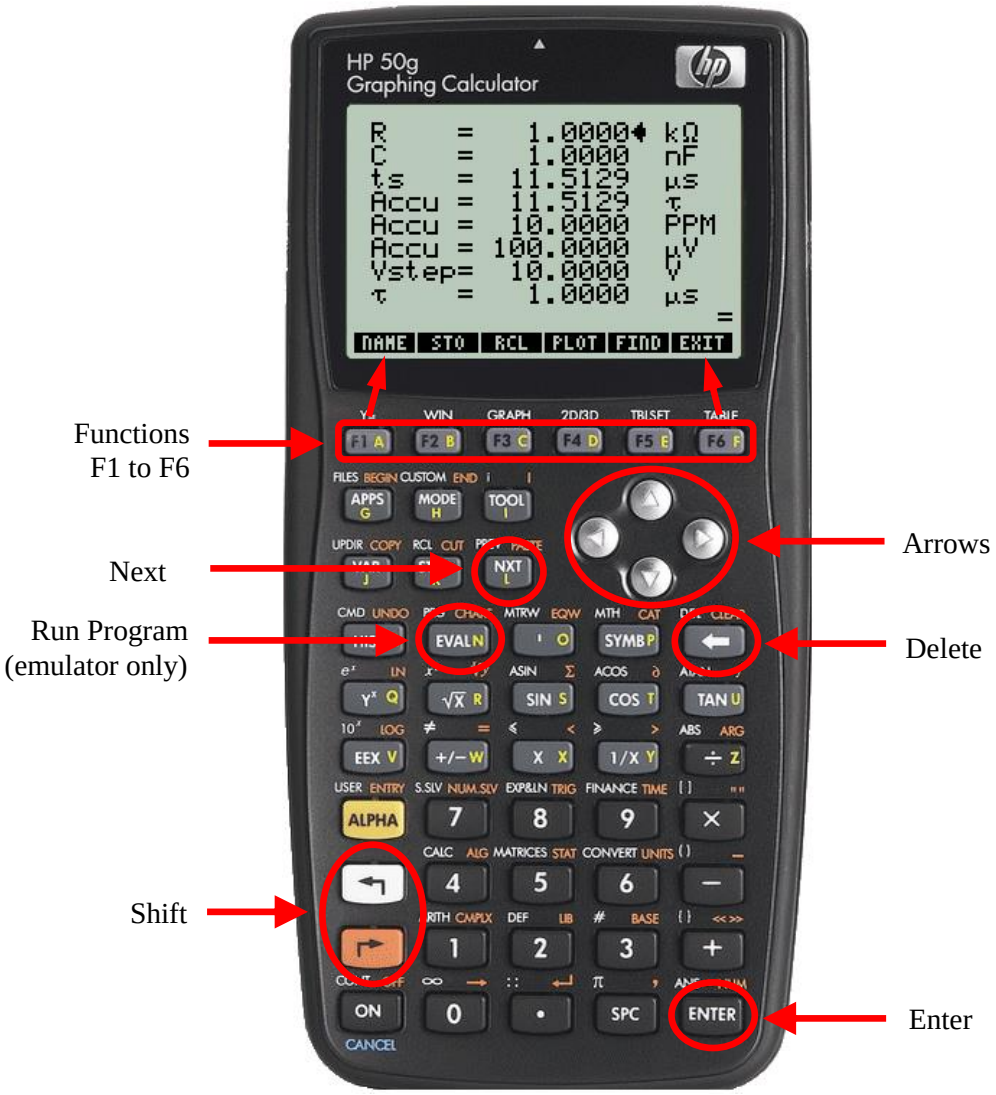
1. Launch HPUserEdit
2. Launch the HP50g emulator by selecting Emulator/Run_the_Emulator from the menu bar. A virtual HP50g appears.
3. Drag and drop STC.hp from an *unzipped* folder to the calculator screen and click the EVAL key.

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.

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



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

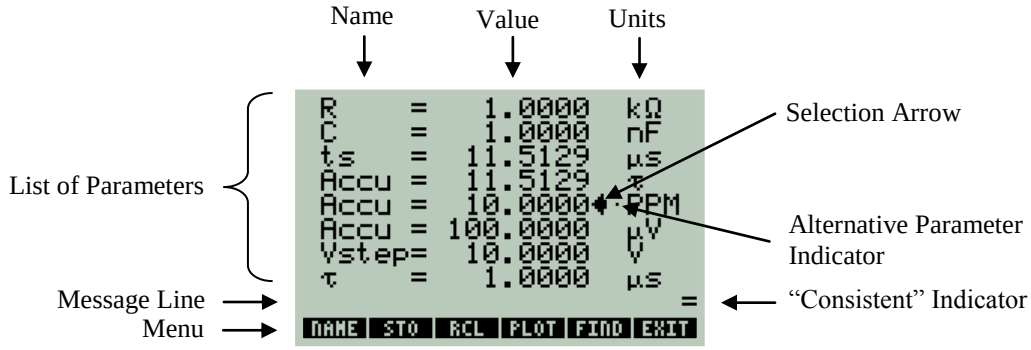
SECTION 4 - COMMANDS

STC has four sets of commands:

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

Main Menu Commands

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

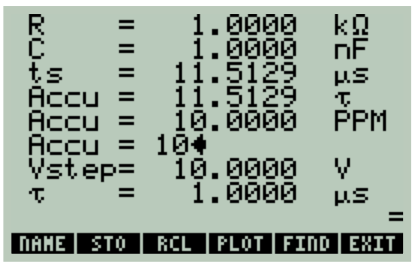


Use the ▼ and ▲ keys to select a parameter.
Use the ▶ key to display an alternative parameter where a "·" appears right of the selection arrow.
Use the ◀ (insert) or ◀ (delete) key to enter or edit a parameter. Press ENTER when finished.

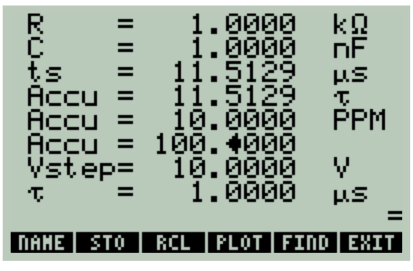
F1 (NAME) Display the name of the selected parameter in the message line
↰ F1 (NAME) Display the full precision of the selected parameter in the message line
F2 (STO) Store all parameters
F3 (RCL) Recall all stored parameters
F4 (PLOT) Plot the step response
F5 (FIND) Find the selected parameter
F6 (EXIT) Exit the program
ON (Cancel) Exit the program
↰ F6 (EXIT) Launch previous run calculator (for physical calculators only - requires CALC)
↱ ON Turn 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 (◀)

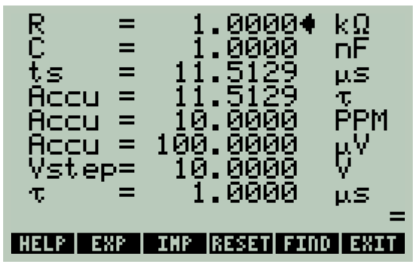


Press ENTER when finished.

The equal sign (=), in the lower right hand corner of the display, indicates that all the parameters are consistent with each other. That is, an RC filter with component values **R** kiloohms and **C** nanofarads will settle to an accuracy of **Accu** (in PPM, %, uV, LSB, or τ) in **ts** microseconds, and have a time constant of **τ** microseconds, a cutoff frequency of **Fc** kilohertz, and a rise time of **tr** microseconds. 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.



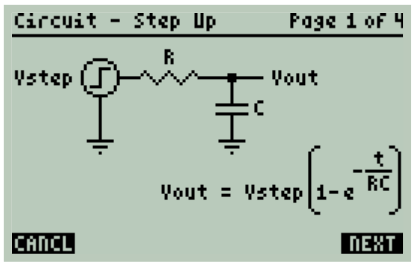
← The Extended Menu

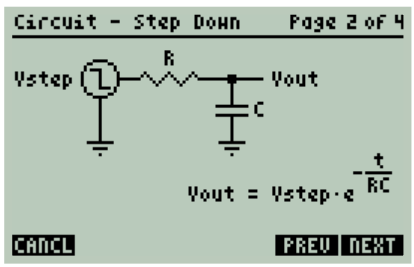
F1 (HELP) Display the settling time equations used by STC
F2 (EXP) Export the selected parameter to the stack upon exiting
F3 (IMP) Import the number present in level 1 of the stack when STC was launched to the selected parameter
F4 (RESET) Enter all default parameter values

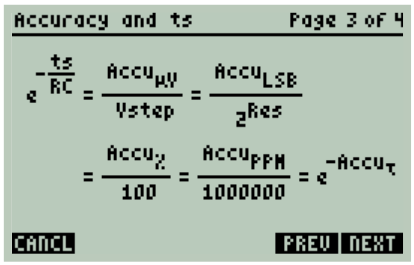
The Main Menu reappears after executing an extended menu command.

Help Command

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



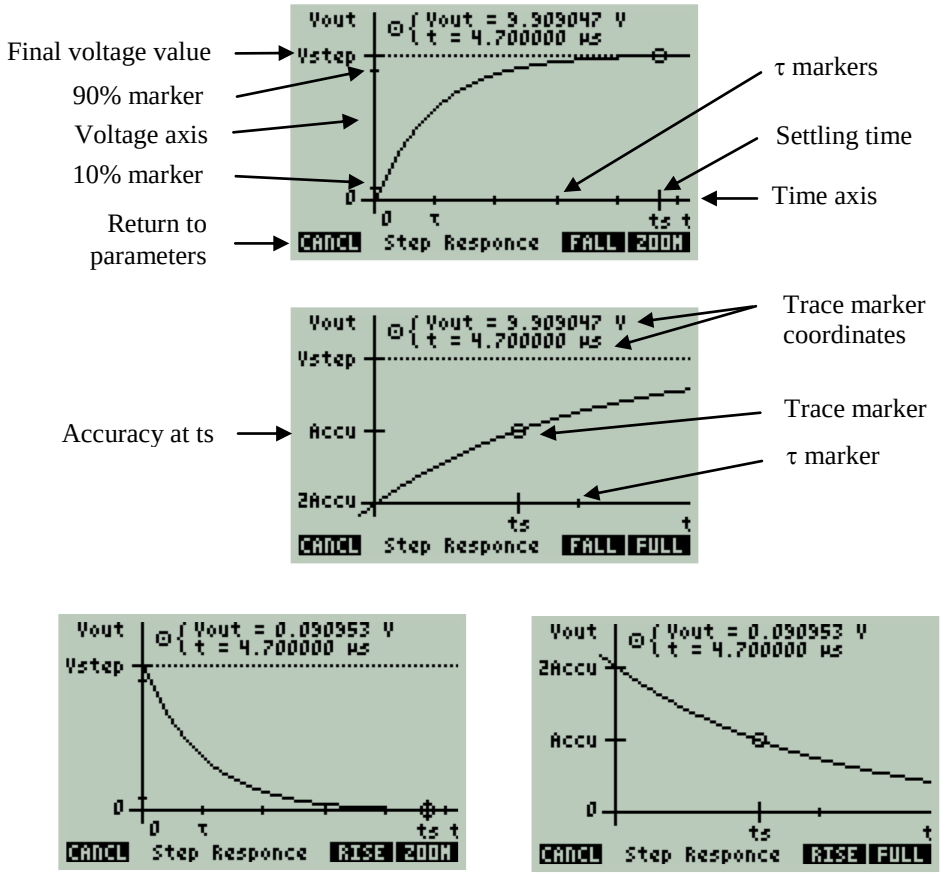




Plot Commands

[PLOT] ([F4] in the Main Menu) plots the step response of an RC filter.

The key elements of the plot display are show below:



The following keys are active when a plot is displayed:

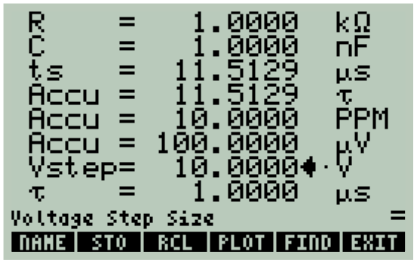
[F1] ([EDIT]) Return to the parameter display
[F5] ([FALL]) Display a falling step
[F5] ([RISE]) Display a rising step
[F6] ([FULL]) Plot the full settling time (0 to ts)
[F6] ([ZOOM]) Plot the time range between ½·**Accu** and 2·**Accu**

[→] [◀] Move trace marker left by 1 pixel
[◀] Move trace marker left by 10 pixel
[←] [◀] Move trace marker left to the closest marker
[→] [▶] Move trace marker right by **1** pixel
[▶] Move trace marker right by 10 pixel
[←] [▶] Move trace marker right to the closest marker

SECTION 5 - MESSAGES

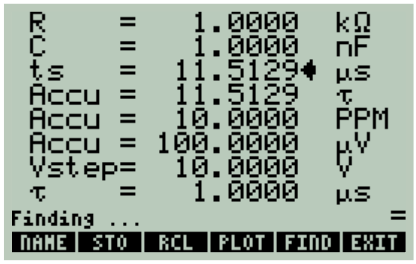
STC displays five types of messages on the message line:

1. Name Messages



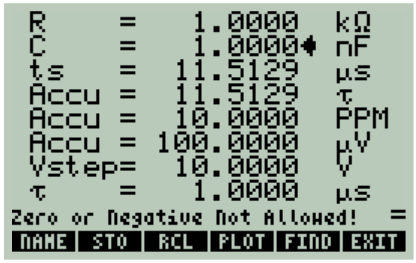
Name messages describe the selected parameter when [ALPHA] is active.

2. Busy Messages



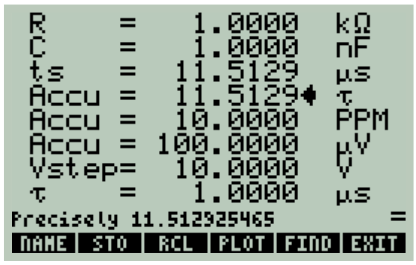
Busy messages explain what the program its doing.

3. Error Messages



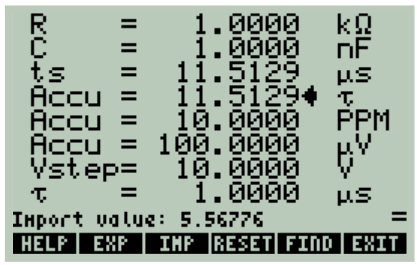
Error messages warn of an illegal entry, command, or result.

4. Full Precision Messages



Full Precision messages show the full precision of the selected parameter value, when [↰] [ALPHA] is active.

5. Import Messages



Import messages show the value to be imported.

SECTION 6 - EXAMPLES

This section demonstrates how to use STC by solving a real world problem.

Entering (,) and Finding (F5)

STC enables parameters to be entered or found.

In this example, STC is used to predict the settling time of the output voltage of a precision digital to analog convertor (DAC) under different load conditions. Trade-offs between settling time, accuracy, and load are examined. The MAX542A precision DAC is used as an example. The application circuit is shown below,

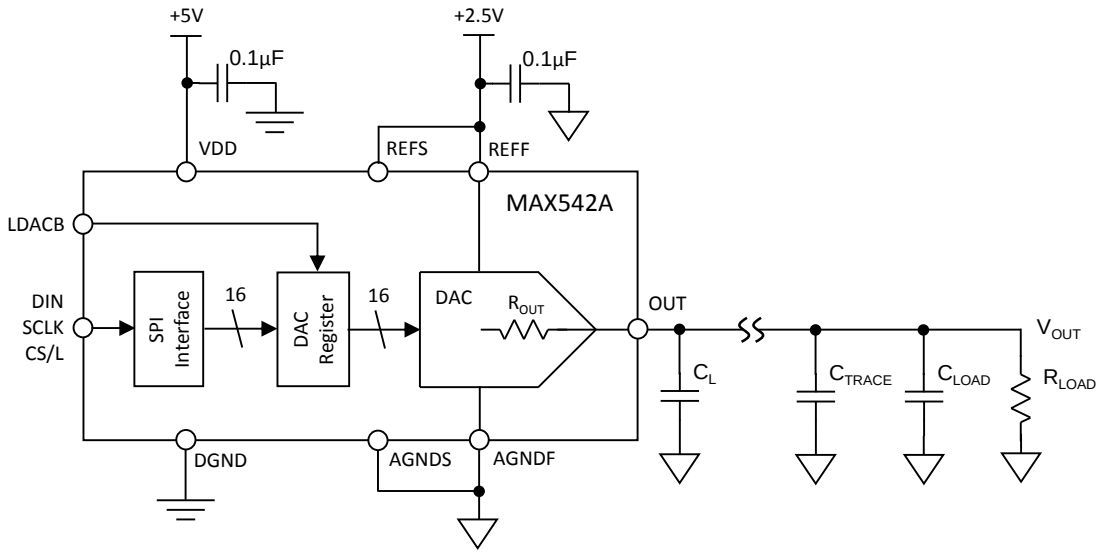


Figure 1

In this circuit, the output voltage (V_{OUT}) settles to a final value defined by the equation,

$$V_{OUT} = V_{REF} \cdot \frac{DIN[15:0]}{2^N}$$

Where,

V_{REF} is the full scale reference voltage, 2.5V
N is the DAC resolution, 16 bits
DIN[15:0] is a user supplied digital code ranging from 0 to 65,635.
R_{OUT} is the DACs output impedance, 6.25kΩ
C_L is the load capacitance specified as the test condition in the data sheet, 10pF
C_{TRACE} is the capacitance due to circuit board trace, vias, connectors, etc.
C_{LOAD} is the load capacitance (i.e., opamp input capacitance
R_{LOAD} is the load resistance to ground

The falling edge of LDACB ("Load DAC Bar") initiates an output voltage change and is the time zero reference point (t_0) when measuring the settling time ($\mathbf{t_s}$). See Figure 2 below.

Graphically,

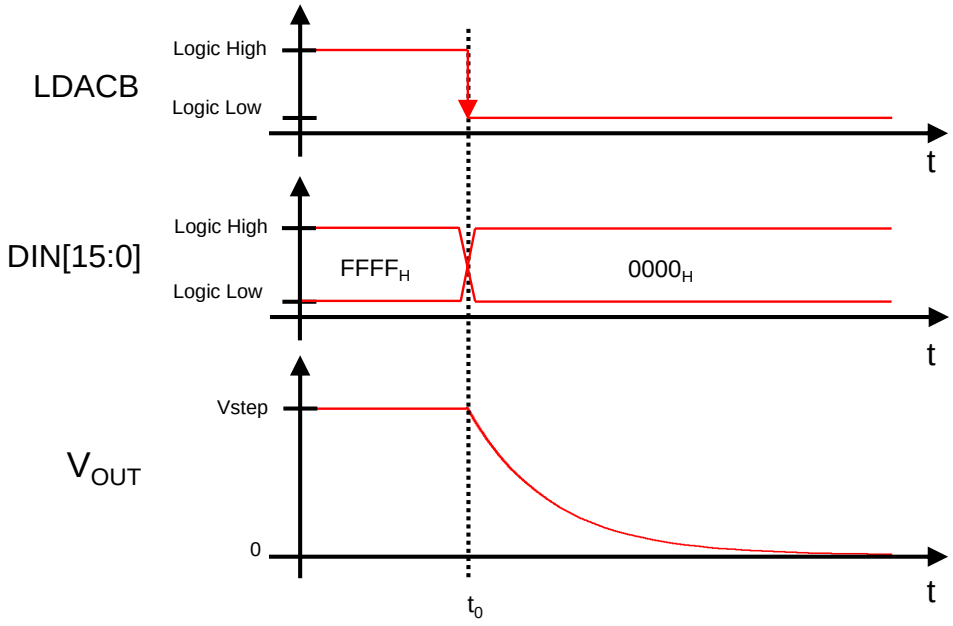
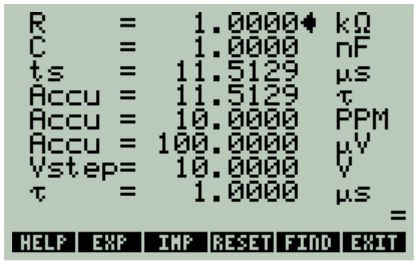


Figure 2

1. Finding the Settling Time Under Device Test Conditions

First, calculate the settling time of MAX542A DAC under the test conditions given in the data sheet.



Step 1:

Start with STC's default parameter values as shown.

The MAX542A datasheet gives the following device parameters used in this example,

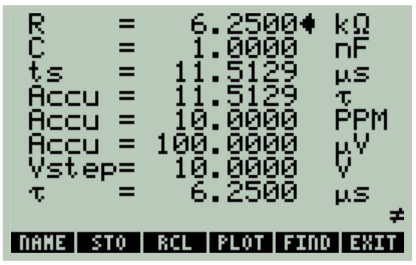
ELECTRICAL CHARACTERISTICS

(V_{DD} = +5V ±5%, V_{REF} = +2.5V, AGND = DGND = 0, T_A = T_{MIN} to T_{MAX}, unless otherwise noted.)

PARAMETER	SYMBOL	CONDITIONS	MIN	TYP	MAX	UNITS
STATIC PERFORMANCE—ANALOG SECTION (R_L = ∞)						
Resolution	N		16			Bits
DAC Output Resistance	R_{OUT}	(Note 2)		6.25		kΩ
DYNAMIC PERFORMANCE—ANALOG SECTION (R_L = ∞, unipolar mode)						
Output Settling Time		to ±½LSB of FS, C_L = 10pF		1		µs

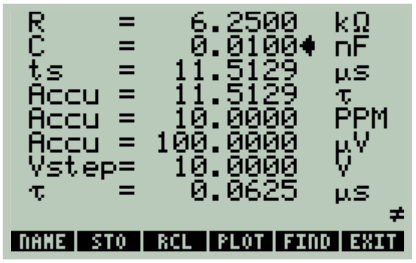
Note 2: R_{OUT} tolerance is typically ±20%.

This test condition assumes, in Figure 1, that C_{TRACE} and C_{LOAD} are zero, and R_{LOAD} is infinite.



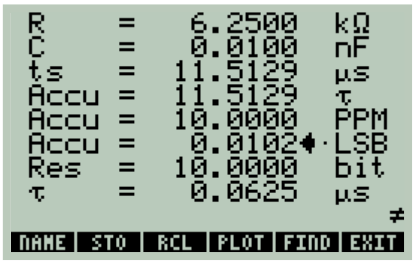
Step 2:

With the selection arrow (☛) pointing to **R**, use the ◀ or ◀ key to enter the DAC's output resistance, R_{OUT}, into **R**. From the Electrical characteristics table R_{OUT} is 6.25kΩ. Note that the consistency indicator changes from = to ≠ indicating that all parameters are no longer consistent.



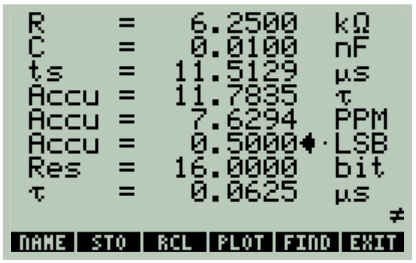
Step 3:

Use the up and down arrow keys (▼ and ▲) to move the selection arrow (☛) to **C.** Enter the load capacitance, C_L, from the data sheet of 10pF (0.010nF)

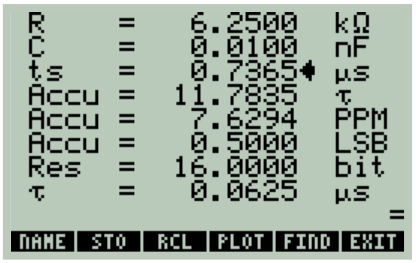


Step 4:

Enter the DAC resolution of 16 bits and the specified settling time accuracy of 0.5 LSB. Move the selection arrow (☛) to any of the accuracy (**Accu**) parameters and press the right arrow key (▶) to display **Accu** in LSBs and resolution (**Res**) in bits.



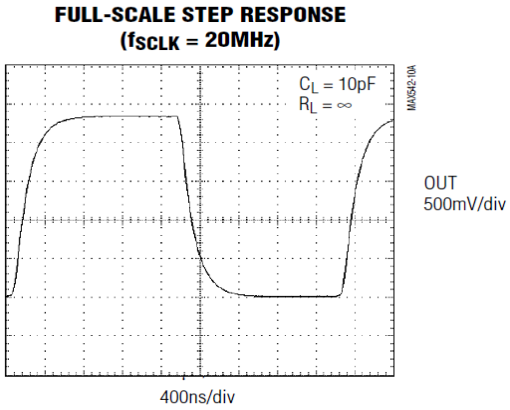
Step 5:
First, select **Res** and enter the DAC resolution of 16 bit. Next, select the **Accu** parameter in LSB and enter 0.5. Note that the equivalent accuracies in τ and PPM are automatically updated.



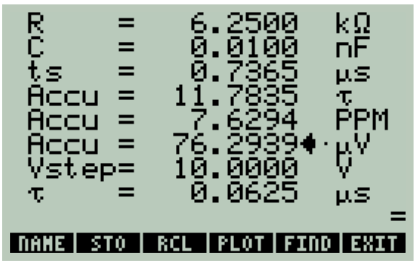
Step 6:
Find the settling time by selecting parameter **ts** and pressing the F5 ( ) key. Parameter **ts** changes showing a settling time of 0.74µs. Note that the consistency indicator changed from ≠ to = indicating that all parameters are consistent.

We find that V_{OUT} settles to 0.5 LSB of its final value in 0.74µs. Observe that this is less than the 1µs typical settling time specified in the data sheet. This difference is because the 1µs specification is a conservative estimate accounting for typical process variations (e.g., R_{OUT} +/-20%)

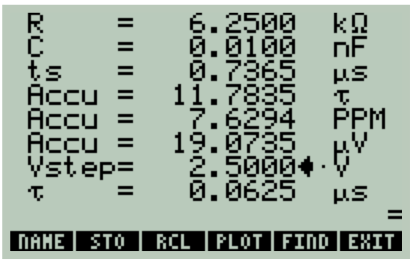
The predicted settling time of 0.74µs is in close agreement with the step response found in the Typical Operating Conditions (TOC) section of the data sheet,



Next, for the same circuit, find the accuracy in µV, given a full scale step of 2.5V.



Step 7:
Display **Accu** in µV and **Vstep** in volts. Move the up and down arrow keys (▽ and △) to move the selection arrow (☛) to any of the accuracy (**Accu**) parameters and press the right arrow key (▷).



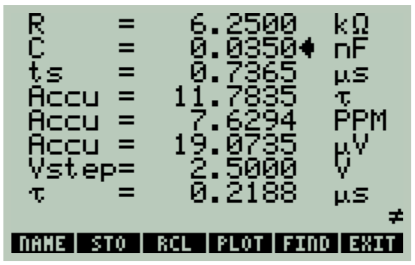
Step 8:
Enter the full scale step voltage of 2.5V in **Vstep**. Note that **Accu** in µV automatically changed to 19.07µV.

We find that V_{OUT} settles to within 19µV of its final value in 0.74µs.

2. Finding the Settling Time Under Real World Conditions

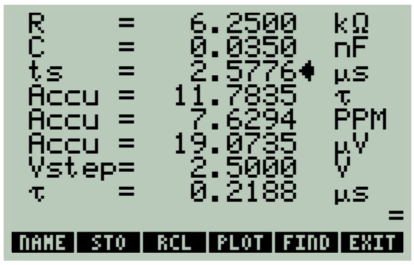
In real application circuits (see Figure 1), the DAC output will see additional capacitance due to the (C_{TRACE}) and load (C_{LOAD}), and additional load resistance (R_{LOAD}). The presence of these will affect the settling time. R_{LOAD} appears in parallel to R_{OUT} effectively reducing R_{OUT}, and C_{TRACE} and C_{LOAD} add to C_L increasing the effective load capacitance (Figure 3).

In this second example, find the settling time of the MAX542A DAC when driving a high impedance input of an OpAmp ($R_{LOAD} = \infty$) having 5pF input capacitance ($C_{LOAD} = 5pF$) and a trace capacitance of 20 pF ($C_{TRACE} = 20pF$).



Step 9:

Use the up and down arrow keys (▼ and ▲) to move the selection arrow (◆) to **C.** Enter the total load capacitance of 35pF (0.035nF), $C = C_L + C_{TRACE} + C_{LOAD} = 10pF + 20pF + 5\ pF$.



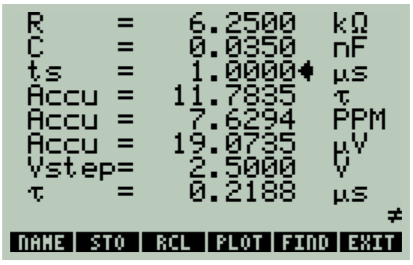
Step 10:

Find the settling time by moving the selection arrow (◆) to **ts**. and pressing the F5 (FIND) key. The settling time has more than tripled to 2.6µs.

It is seen that, although the MAX542A data sheet specifies a typical settling time of 1µs, it can be much longer under the load conditions found in a typical application circuit.

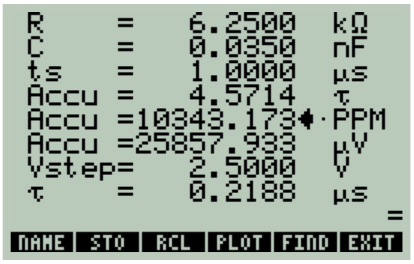
3. Finding the Output Accuracy Under Load

Find the accuracy, in uV and LSB, to which the application circuit will settle in 1µs.



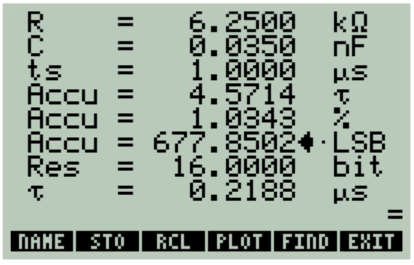
Step 11:

Enter 1µs in **ts**.



Step 12:

Find **Accu** in PPM.

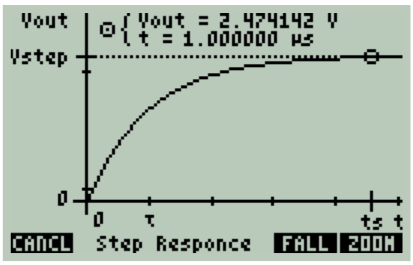


Step 13:

Display **Accu** in % and LSB by pressing the right arrow key (▶) at PPM (to display %) and again at **Accu** in µV to display **Accu** in LSB.

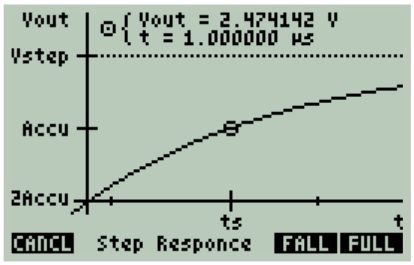
Settling time can be very sensitive to load capacitance. Here, it is found that tripling the load capacitance (10pF to 35pF) reduces the accuracy at 1µs by over a factor of 1000 (0.5LSB to 677 LSB)!

Plotting (F4)



Step 14:

Press F4 to plot the step response. The parameters must be consistent (i.e., "=" displayed) to be plotted.

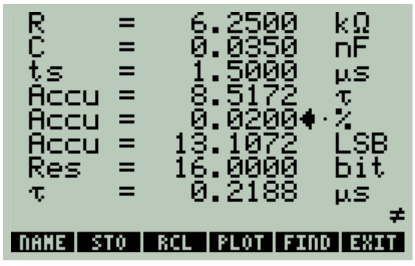


Step 15:

Press F6 (ZOOM) to zoom in around **ts**.

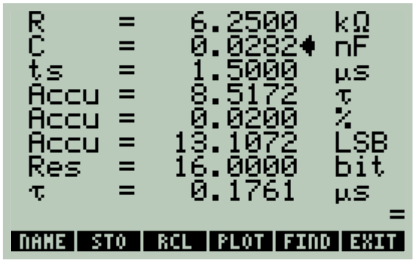
4. Finding the Maximum Load Capacitance

Finally, find the maximum load capacitance that can be driven and achieve an accuracy of 0.02% in 1.5µs.



Step 16:

Enter 1.5µs in **ts** and 0.02% in **Accu**,



Step 17:

Find **C**.

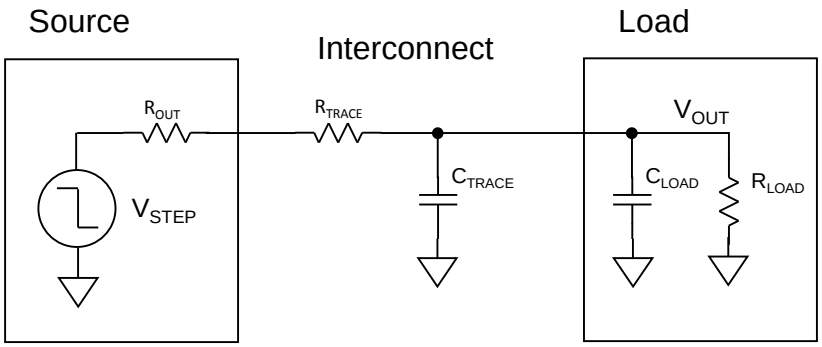
It is found that to settle within 1.5µs the total load capacitance must be less than or equal to 28pF.

SECTION 7 - BACKGROUND

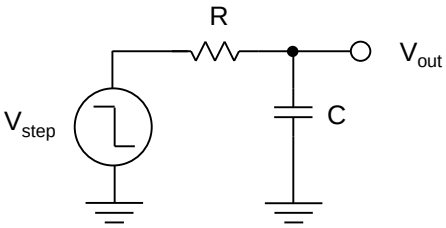
All electrical circuits suffer from some degree of time delay between input excitation and output response. This delay limits both the speed of digital circuits and the precision of analog circuits. This delay is often measured as the time it takes for the output voltage to respond to a step change in input voltage.

The RC Network

Common causes of signal delay are the RC networks found in every circuit. They are made from the various resistances and capacitances found in all signal sources, interconnections, and loads. For example,



These resistances and capacitances can be combined, and the circuit reduced to a simplified RC network as shown,



Where,

$$R = \frac{R_{OUT} \cdot (R_{TRACE} + R_{LOAD})}{R_{OUT} + R_{TRACE} + R_{LOAD}}$$

and, $C = C_{TRACE} + C_{LOAD}$

Figure 3

The step response of this circuit is an exponentially declining output voltage, given by the equation,

$$V_{OUT} = V_{STEP} \cdot e^{-\frac{t}{\tau}}$$

Where τ is the time constant, $\tau = R \cdot C$. The settling time increases with R and C.

Accuracy vs. Settling Time

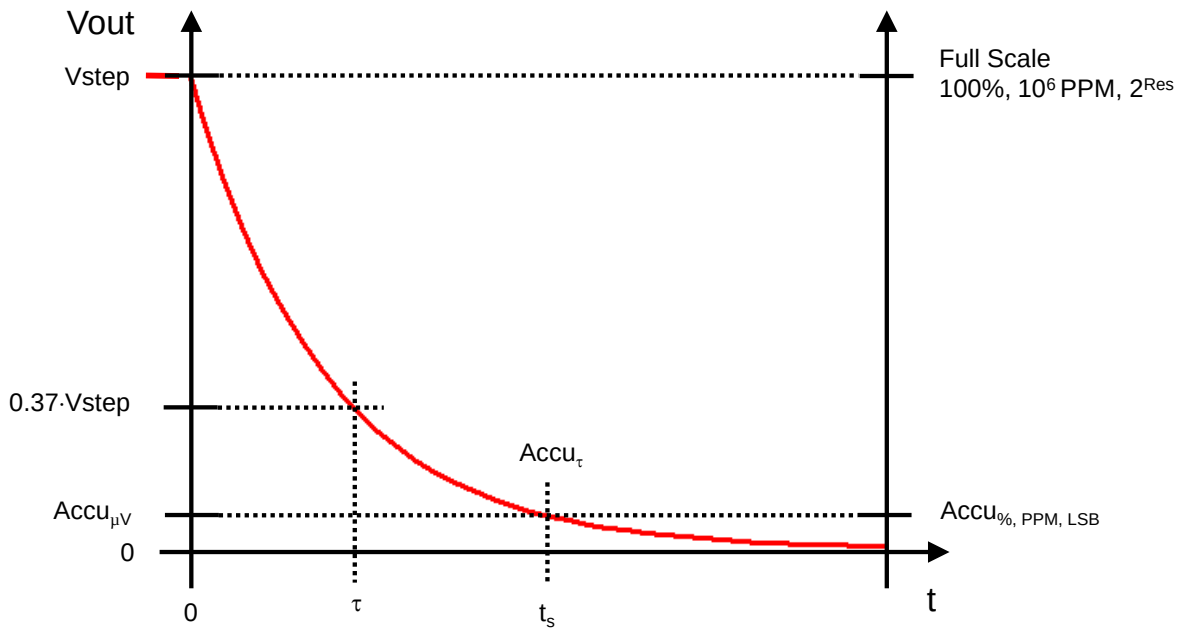
How close V_{OUT} comes to its final value (0V) is a measure of accuracy, and is specified at a particular time, t_s. Accuracy is usually measured as a fraction of the step size, V_{STEP}.

$$\frac{V_{OUT}}{V_{STEP}} = e^{-\frac{t_s}{RC}} = \frac{Accu_{\mu V}}{V_{STEP}}$$

Accuracy may be expressed in several of ways. STC uses five: μV, LSB, %, PPM, or number of τs. These parameters are related by the equation,

$$e^{-\frac{t_s}{RC}} = e^{-Accu_\tau} = \frac{Accu_{\mu V}}{V_{STEP}} = \frac{Accu_{\%}}{100} = \frac{Accu_{PPM}}{1000000} = \frac{Accu_{LSB}}{2^{Res}}$$

Graphically,



As can be seen, the greater the accuracy the longer it takes to settle.

The settling time of an RC network is commonly defined to be 5τ, where V_{OUT} settles to less than 1% of its final value. However, settling time can be two or three times longer than this for high accuracy circuits such as 12 to 20 bit precision DACs. This can be seen in the following table that shows equivalent measures of accuracy.

Table of Equivalent Accuracy

Equivalent Accuracy				
τ	%	PPM	μV *	bits **
0.0	100.0000000	1000000.000	4096000.0000	0.0
0.7	50.0000000	500000.000	2048000.0000	1.0
1.0	36.7879441	367879.441	1506834.1910	1.4
2.0	13.5335283	135335.283	554333.3201	2.9
3.0	4.9787068	49787.068	203927.8320	4.3
4.0	1.8315639	18315.639	75020.8569	5.8
4.6	1.0000000	10000.000	40960.0000	6.6
5.0	0.6737947	6737.947	27598.6309	7.2
5.5	0.3906250	3906.250	16000.0000	8.0
6.0	0.2478752	2478.752	10152.9689	8.7
6.9	0.0976563	976.563	4000.0000	10.0
7.0	0.0911882	911.882	3735.0685	10.1
8.0	0.0335463	335.463	1374.0549	11.5
8.3	0.0244141	244.141	1000.0000	12.0
9.0	0.0123410	123.410	505.4866	13.0
9.7	0.0061035	61.035	250.0000	14.0
10.0	0.0045400	45.400	185.9581	14.4
11.0	0.0016702	16.702	68.4102	15.9
11.1	0.0015259	15.259	62.5000	16.0
12.0	0.0006144	6.144	25.1667	17.3
12.5	0.0003815	3.815	15.6250	18.0
13.0	0.0002260	2.260	9.2583	18.8
13.9	0.0000954	0.954	3.9063	20.0
14.0	0.0000832	0.832	3.4059	20.2
15.0	0.0000306	0.306	1.2530	21.6
15.2	0.0000238	0.238	0.9766	22.0
16.0	0.0000113	0.113	0.4609	23.1
16.6	0.0000060	0.060	0.2441	24.0
17.0	0.0000041	0.041	0.1696	24.5

* V_{STEP} = 4.096V ** 1 LSB accuracy

Rise Time

Rise time, t_r, is commonly defined as the time it takes V_{OUT} to move from 10% to 90% of V_{STEP}. It is calculated by,

$$t_r = \ln(9)RC$$

Bandwidth

The RC network forms a single-pole low-pass filter with a 3dB cut-off frequency, Fc. Where,

$$F_c = \frac{1}{2\pi RC}$$

SECTION 8 - TOOLS, MODELS, AND SOFTWARE NOTICE

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