RFdude.com IP3/P1dB "Linearity Tester" Introduction and instructions

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Request:

Please read this document before trying to use the program or asking me questions about it. If it does not answer your questions, I would like to know so that I can improve it. Thanks!

Please see the "**hints**" section at the end of this document for some important tips

Changes from software version 0.2 to 0.4

1. some tweaks in the IP3 measurement code that should help to handle devices with larger gain slope variations over the frequency range (still not ideal, but this should be better):
    a. allowing more iterations in the power control routine
    b. ratcheting the level down further if the measurement is off the screen
    c. bombing out if either of the generators are set to their upper limit more than a couple times
2. Adding preliminary support (i.e. untested or only partially tested at this point) for different spectrum analyzers (HP8568B/66B, HP8591)
3. Adding P1dB measurement (still requires two generators to be connected, and uses the same calibration as the IP3 tests and probably will for the foreseeable future). This is slow, 45-60 seconds on my setup per frequency. Typically gets compression within +/-0.1 dB though and provides all the data.
4. Rearranged the dialog box, adding spectrum analyzer select dialog, adding "file prefix" edit box (note: you need to use good file naming syntax for this to work properly)
5. The signal generator types are now written to the output files as well for completeness.

Introduction

Testing P1dB, IIP3, or OIP3 of circuits or modules can be very tedious and prone to human error. The software described in this document was designed to automate the process, allowing engineers to obtain more consistent and detailed data in a shorter period of time with a minimum of manual steps. It also gives you more time to surf the web or answer nature's calls while the measurements are running.

Features:

- Testing of Gain/IIP3/OIP3 at constant output power level per tone across frequency
- Testing of Gain/IIP3/OIP3 at constant input power level per tone across frequency
- Testing of P1dB across frequency, including detailed level sweeps in the output around the P1dB point.
- Testing of Gain/IIP3/OIP3/P1dB for mixers/converters:
  - Fixed input frequency, swept LO, swept output frequency (TX Upconverter as an example)
  - Fixed output frequency, swept LO, swept input frequency (RX Downconverter as an example)
  - Fixed external LO, swept input, swept output (block converter or testing of a product with an internal LO)
- **User parameters:**
  - Type of test (described above)
  - Test and calibration description text
  - Instrument GPIB addresses and instrument model types
  - Power input/output per tone (IP3 measurements)
  - Estimated minimum output compression point (P1dB measurements)
  - Power output per tone Tolerance / On screen leveling tolerance for constant input power case (this is odd, feel free to ask me about this one)
  - Maximum DUT gain
  - Tone spacing
  - Start frequency, stop frequency
  - # of points (2-100 valid)
  - Calibration info (described later)
  - **There is only a very basic level of error checking on the inputs, so think about how you would run a manual test when specifying sweep ranges, etc.**
- **File input /output**
  - The main output report is in a Comma Separated Values (CSV) format which is easy to read into excel and other applications. A template for graphing the results is provided, simply copy all the report output and paste it into the template. The output also captures the user's description, the test specifications, and the spectrum analyzer model/revision/serial number, the signal generator types, and is time stamped.
  - The "snapshot" output is a capture of the final spectrum analyzer screen shot at each frequency in the sweep, i.e. the one that measurements are derived from. This was originally included for debugging, but it may be useful for identifying other odd behavior such as identifying poorly

  - behaved nonlinearities or spurious signals in the DUT or setup. This is also written in “CSV” format and a graphing template is provided.
  - In the case of P1dB measurements, the “snapshot” concept is replaced with a file that provides all of the compression data measured that could be plotted as power input/output curves. The data for the curves are generated out of order, sorted at the end, and available in the output file. Thus, there may actually be redundant measurements, but plotting in an X-Y graph in excel will yield decent graphs. Unfortunately, I see no easy method for plotting the compression curves in a simple template format.
  - All test settings and calibration info can be stored in a configuration file so that tests can be repeated exactly by simply reopening the file.
- **Calibration:**
  - “Manual”
    - “Gain” between Generator 1/Generator 2 and the input to the DUT [1]are specified by the user (typically this is a loss, but in some cases it could be a gain. **To avoid confusion, “gain” is always used in specifying these quantities)**
    - “Gain” between the DUT output and the spectrum analyzer input.
  - “Automatic” (only available in the “Normal” mode, i.e. no mixer measurements allow automatic calibration)
    - For this mode, the Spectrum analyzer is considered the “trusted” entity. All measurements and calculations assume that the spectrum analyzer is accurately reporting power levels.
    - The starting point for this mode is the manual calibration constants used for the “manual mode”, hence they should be set first to get the system into the ballpark.
    - The automatic calibration mode can handle up to +/- 4-5 dB of gain slope across the sweep range in the current implementation because the analyzer is put in 1 dB/ Vertical division mode for best accuracy of measuring the tone levels.
    - The calibration process involves two steps:
      1. The user connects the cable that normally goes to the DUT input directly to the spectrum analyzer input. The software sweeps the generators across the whole frequency range of the test to be run in order to determine the “gains” in the power combiner and the cables[2], and for any offset in the signal generator output levels. See Figure 5.
      2. The user next connects the spectrum analyzer input “network” which will consist of a cable and perhaps an attenuator or directional coupler. The software again sweeps the generators across the frequency range of interest (at this point they’ve been calibrated to be approximately equal), measuring the “gain” of the path between the DUT output and the spectrum analyzer. See Figure 6

[1] DUT stands for “Device Under Test”, an amplifier, mixer, attenuator, anything that an IP3 test is meaningful for.

[2] It is perfectly reasonable to insert gain between the generators and the power combiner or the power combiner and the DUT input, just make sure of two things: First, make sure you adequately estimate the gain of the network (more later in the automatic calibration section of this document). Second, make sure that at the power levels that the amplifier is operating that it does not contribute significant intermodulation distortion or compression to the system.

Compatibility

The software runs under Windows 2000 and Windows XP (and perhaps other windows operating systems) using National Instruments GPIB interfaces (PCMCIA, USB, others have been tested). The software (including all instrument drivers) was written completely from scratch in Microsoft Visual C++, the low level GPIB interface routines from the National instruments Language Interface /DLL for Microsoft C were used. Other than this software package, you will only need to have a National Instruments hardware interface product and drivers installed. Microsoft Excel is also recommended for using the graph templates.

The initial releases of the software, while rough around the edges, are functional and support the following test equipment:

Spectrum analyzer: HP856x series (tested with HP8562A, 8563E, 8565E). HP859x and HP8566B/68B Support has been added in version 0.4, but it has not yet been tested.
Signal generators: HP8656A/B (I believe HP8657's are compatible but I have not yet fully tested them), HP8648 series, HP 83711/712 series, Anritsu 3631/3632 series.

Disclaimer:

This software is provided totally "as is". Use at your own risk. If you do have problems with the software, I would like to hear about it but I make no guarantee that it will be fixed if I do not have access to the same type of equipment or I cannot duplicate the problem. Noting that it has taken me over a year and a half to release the 2nd version of this software, realize that spare time is not plentiful.

Users may wish to use this software to test high power equipment. It is **YOUR** responsibility to ensure that your equipment (such as the spectrum analyzer or the DUT) is protected from damage. Always assume that the signal generators could be set to maximum or the wrong frequency and that the spectrum analyzer could be set to an inappropriate level of attenuation. Facilities for easily incorporating attenuators/couplers in the setup are provided for this reason.

Walkthrough for a simple amplifier measurement

For more advanced tests, it is suggested that the user experiment with the program themselves.

We will progress from the upper left of the program window (See Figure 1) across and then down through the settings like text is normally read on a page.

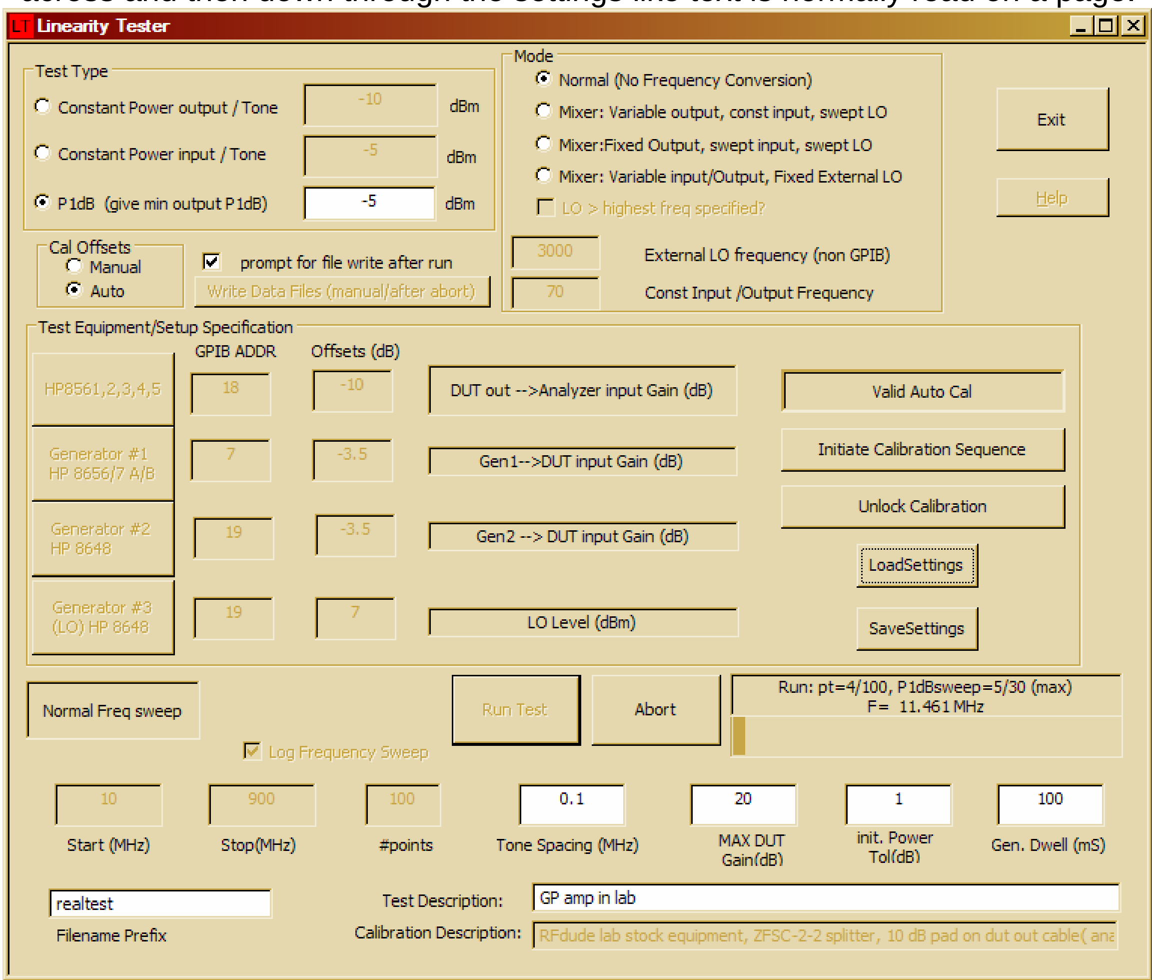

Figure 1: Main application window

1. Select the test type and set the power level parameter (note this is at the DUT input/output, the calibration offsets take care of delivering/setting the power level to this point). You should know what you're testing in the sense that you need to select this power level based on knowing that 3rd order intermodulation distortion can actually be observed on the screen. Beware, the software does manipulate the "Maximum Mixer Level" setting in the spectrum analyzer to achieve the best strong signal handling capability, so the noise level may appear higher than you are used to, masking the intermodulation you are trying to see.
2. Select the test mode (leave it in "Normal" mode for an amplifier test)
3. Select Manual Calibration in the "Cal/Offsets" group
4. Select the instrument types you have available on your GPIB bus and set the addresses correctly. The instrument model is selected by clicking on the button for the spectrum analyzer and each generator (note in the figure these buttons are greyed out since a calibration has been performed and the user cannot change the equipment and have the calibration remain valid). If you do not know the GPIB addresses, consult the equipment documentation, there is normally a button sequence that will read out the address.
5. Set the offsets. See Figure 2 for a typical setup. *The Cal offsets represent the items in the boxes.* I recommend using an attenuator at the spectrum analyzer input if you are measuring a device capable of damaging the spectrum analyzer. If you had a 10 dB pad installed at the analyzer input you would put "-10" in the box under "Offsets" in the same row with the spectrum analyzer settings Figure 1. I typically use a mini-circuits ZFSC-2-5 power splitter/combiner in my setup and the "gain" of this from each generator to the DUT input is typically -3 to -4 dB. For future use: note that when using an automatic calibration these values need to be entered as the nominal values for the setup – the "automatic" calibration starts with these as guesses and moves on from there, correcting the actual values at each frequency. If you do not tell the software that you had put a 20 dB pad inline and tried to do the 2nd step of the calibration, it will fail (and you might not know that until later). This will be described in more detail later.
6. Skip over the next few buttons and set the Start, Stop frequency, the number of points and the tone spacing. I recommend Tone spacings of 0.1 MHz to 10 MHz as they will execute in a reasonable amount of time (larger tone spacings will equate to larger resolution bandwidths, spans, and faster sweep times). Version 0.4 adds the option for a log frequency sweep. I had spent my career working on narrowband equipment until recently and the value of a log sweep became obvious.
7. Set the maximum DUT gain. This just helps the software to estimate the appropriate drive level on the first pass to get the desired output (for constant output power cases) or to set the reference level appropriately (for constant input power cases). The software will always adapt to what the DUT actually has for gain (currently this loops a number times to do this), but it will save time to have this estimate either exact (at the starting frequency), or to have the estimate a little high for gain. In IP3 modes, the gain is carried from one frequency to the next (i.e. the 2nd frequency will use the gain measured at the 1st frequency as the first guess and adapt). For P1dB measurements, the starting point is always the same based on the calibration and Min output P1dB parameters, as well as the max DUT gain, i.e. the gain is not carried from one measurement to the next.
8. Set Pout tolerance. For constant output power cases I do not recommend setting this much below 0.5 dB, certainly not much below 0.25 dB as the spectrum analyzer resolution is not much better than this in the normal sweep mode (we could change settings for the leveling, but this adds little value and would take longer). For constant input power cases I recommend setting this to >1 dB (3dB would probably be fine and may make some measurements run considerably faster). The leveling that is done here is similar, but it simply tries to get the two main output tones at roughly the same point on the spectrum analyzer screen so that the detector is operating in the same region.
9. Set the generator dwell time. This is the time in milliseconds that the software waits between setting the generators on the new frequency/level and taking a picture of (measuring) the output with the spectrum analyzer. Different generator types take

different amounts of time to switch frequency and level (such as when mechanical attenuators kick in and synthesizers settle).

10. Write text descriptions in the Test and Cal boxes, and in the filename prefix box. Note that the filename prefix will be the beginning of the file: “lance” in the file prefix box will mean the files will start with “lance_”. The prefix needs to be in proper filename syntax – i.e. I would recommend avoiding random punctuation that is illegal in filenames and such. Stick to a name/number, use underscores instead of spaces (although spaces will probably work). Note: an underscore will automatically be added after the prefix.
11. If you think you may want to repeat this test or save the equipment settings, click the “save settings” box and you will be prompted with a dialog box that helps you to select the location and name of the settings file. The “Load settings” button does the opposite.
12. Hook up the DUT and run the test! If you have the “Prompt for write after run” box checked (upper right of the program window), you will be prompted for the file name and location of the output when the test is done. If you feel that the test is going wrong in any way, you can hit the “abort” button at any time. Avoid the temptation to exit the program right away, let it finish. It will abort relatively shortly after you hit it. A progress bar and text description are provided while the sweep is running(in the lower middle of the screen next to the run button), but I think it’s more fun to watch the equipment. The “Write data files” button is there if you don’t want to be prompted at the end of the test and would prefer to initiate this yourself (but beware, the data is gone when you exit the program).
13. The report files (report and snapshot) can be opened to review the output. For graphs, just select all the text of the report and paste them into the Excel templates provided in the installation directory (shortcuts are made to these). I typically get into a routine: I click on the data file, hit CTRL-A (select all), then CTRL-C (copy), then I close the file (when prompted I say, yes – I want to keep this data on the clipboard), then I open the template, click on cell A1 in the “paste data here” tab and hit CTRL-V (paste). The templates can be found as shortcuts in the programs menu where the software was installed – just make sure you save them somewhere else once you’ve pasted the data. The resulting graphs for (an old, outdated) this sweep can be found in Figure 3 and Figure 4 . Note that if the leveling loop fails, an ERROR term is shown in the output report and on the output graph labeled “Error_chart”. The leveling works well, but still fails occasionally for some reason. A flaky DUT will definitely cause it to fail, as will specifying levels which cannot be achieved (such as levels above which the generators can supply). OIP3H/L are the OIP3 based on the high tone/IM3 product and Low tone and IM3 product. Significant imbalance in these should raise a warning flag.

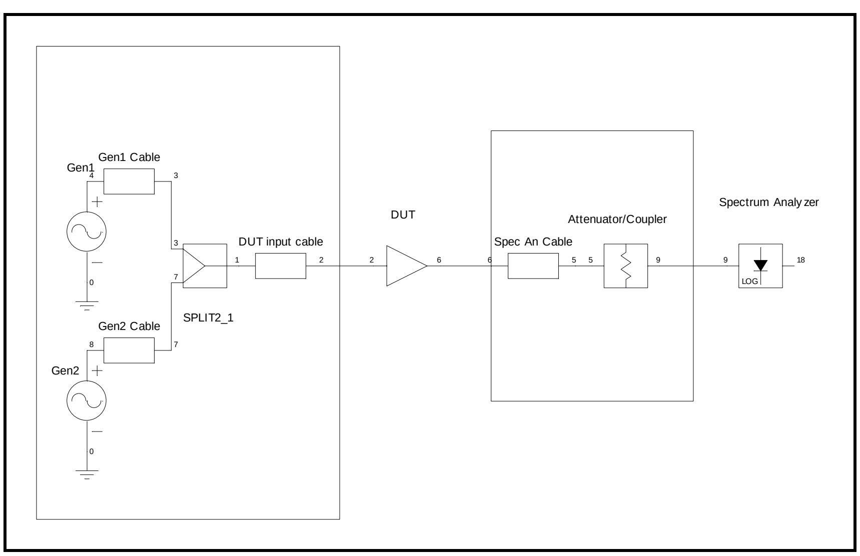

Figure 2: Basic two-tone linearity test setup

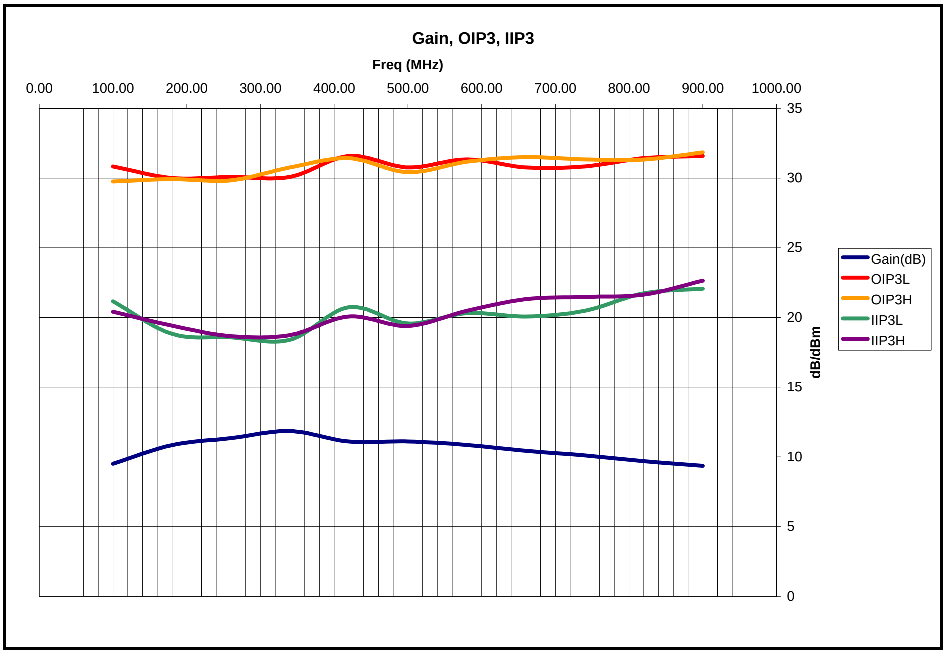

Figure 3: 11 point sweep of an AH1 amplifier prototype

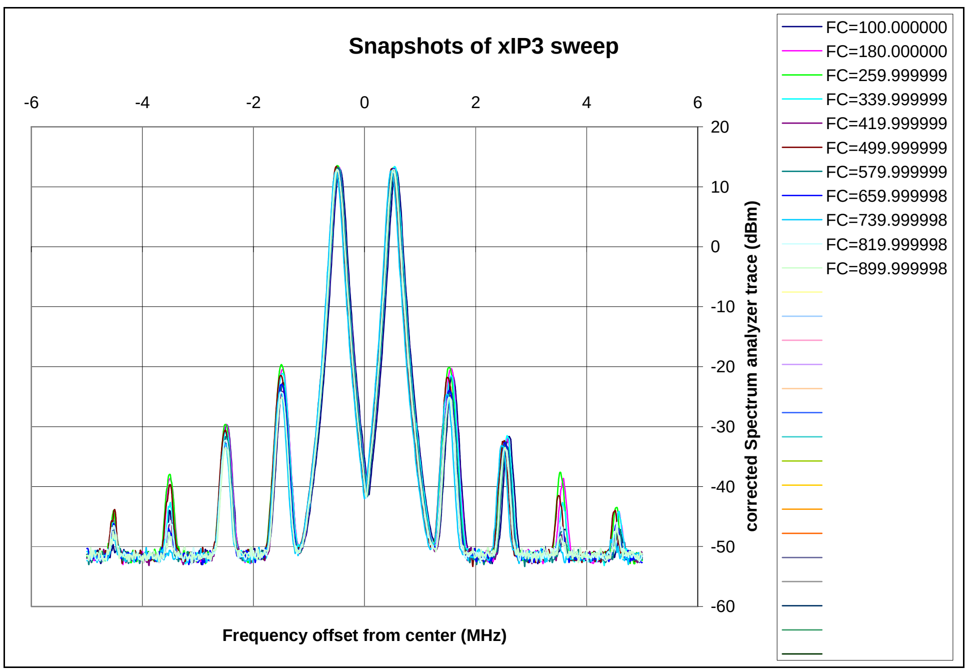

Figure 4: "Snapshots" taken during the sweep

Automatic calibration

The Automatic calibration mode, described above, is handy for higher accuracy measurements or measurements where the setup has a frequency response which is not flat over the sweep range. As mentioned earlier, the P1dB mode doesn't have it's own calibration routine. Simply run a calibration with a two-tone test setup and then do the P1dB measurement – the same calibration will be used. Two generators will still be required for the P1dB test even though one will just get initialized then left dormant for the duration of the test.

To enter the calibration mode, follow the following steps:

1. click "Auto" in Cal Offsets.
2. Write an updated description of the test setup in the Cal description string (this will get locked in and can't be written after the calibration is saved).
3. Hit "Initiate Calibration sequence" on the right portion of the screen.
4. Follow the prompts, connecting the equipment as specified BEFORE hitting "OK". The setup connections for the first and second prompts are shown in Figure 5 and Figure 6 respectively (they are also described in the dialogs**). Important note: as of the time that this document was written, the power level that is used for calibration (delivered to the spectrum analyzer input) is hard coded to -20 dBm. This was chosen as a compromise. Specifically most generators + splitter losses + attenuators at the input of the analyzer would still allow – 20 dBm to be delivered without hitting the upper limit of most signal generators output power range. This may be made an option later, but to keep things simple and accommodate most cases, this level was chosen.**
5. Once done, if you have the "prompt for write after run" box checked, you will be prompted to save the calibration and sweep information in a settings file. This is highly recommended because as long as you don't change your cables/attenuators/etc, this calibration should be reasonably valid.
6. As a sanity check you can verify the calibration (or see how good it is) by leaving the setup configured as is shown in Figure 6, then running a test (with an appropriate power level set, perhaps much less than you intend to run with a high gain DUT). There certainly shouldn't be any distortion, but you can see how flat the gain is. I did this in my setup while preparing this document; the results are shown in Figure 9. It is impossible to replace a network analyzer (easily) with a spectrum analyzer and generator setup like this, but having the gain measurements and a calibration capability helps to better capture the context of the measurements and will improve consistency.
7. To keep users from mistakenly invalidating their calibrations, once a successful auto calibration is done, the start/stop frequencies and the number of points are locked out (grayed out, but still visible). I am assuming that tone spacing and power levels are still safe to change after calibration. You can always go to manual cal mode, but if you want to change your auto cal calibration, you must hit the "Unlock Calibration" button which will blow away the current cal after you are prompted to make sure that's what you want to do. The calibration will always remain for previous saved configurations in the ".cfg" files unless you overwrite them.

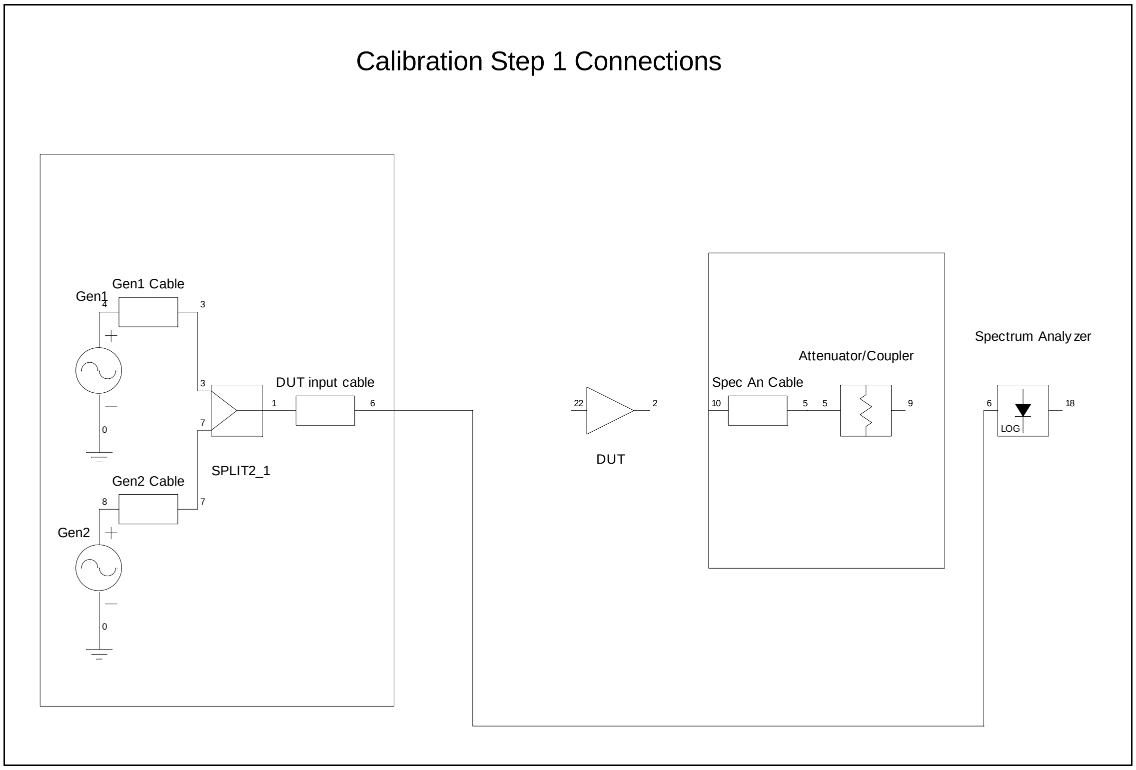

Figure 5: calibration step 1

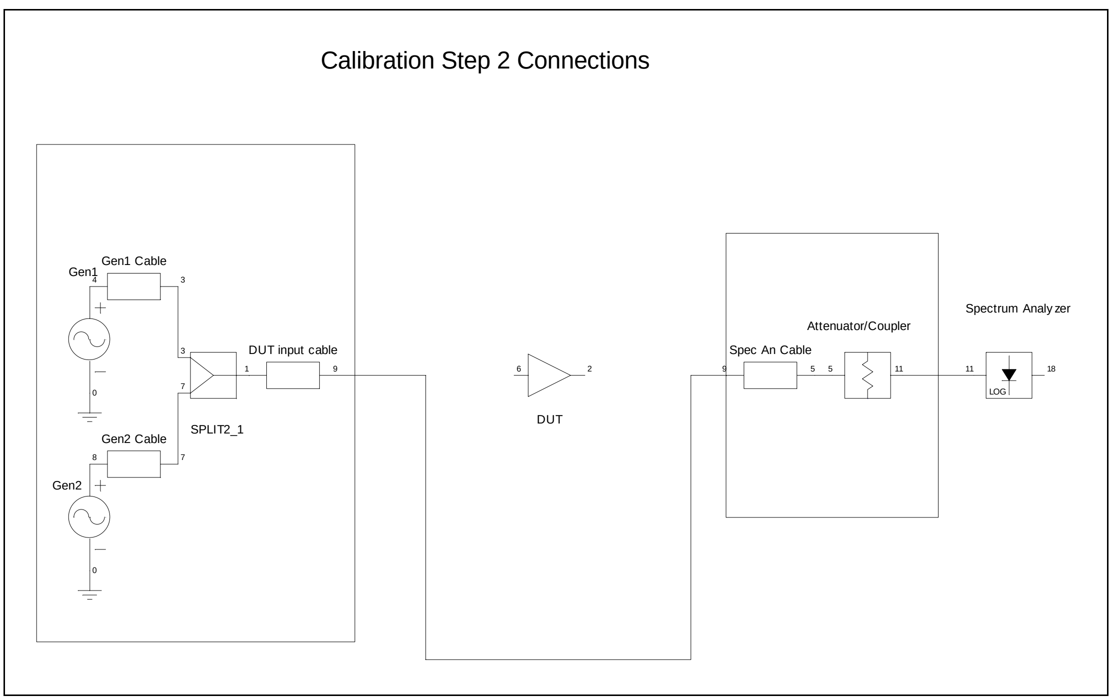

Figure 6: calibration step 2

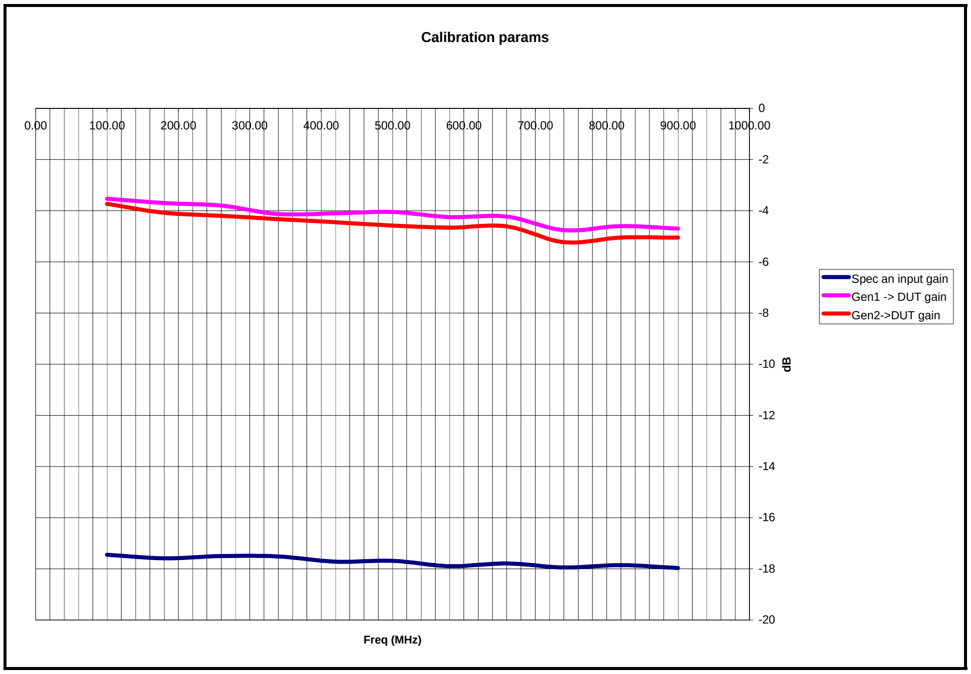

Figure 7: Auto calibration Cal values written to the report. Note, one of my generators has a rear panel connector so I need a longer cable for it to reach the splitter, explaining the increasing loss vs. frequency when compared to the other.

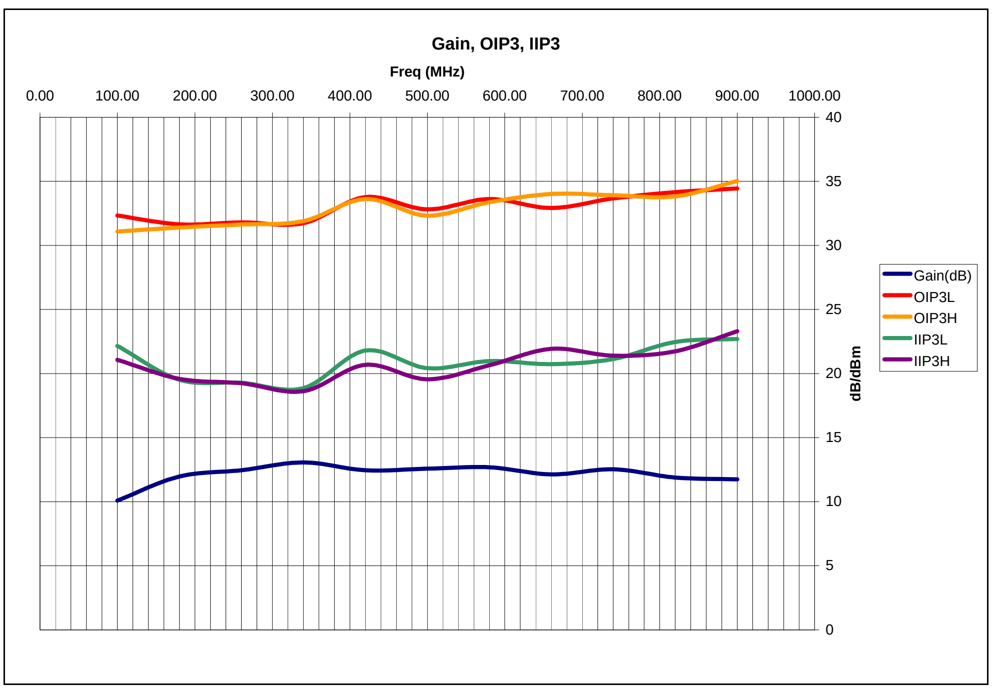

Figure 8: Test case with Auto Calibrated setup. Note that the gain is shown to be more flat than that in Figure 3 because of the variable correction applied.

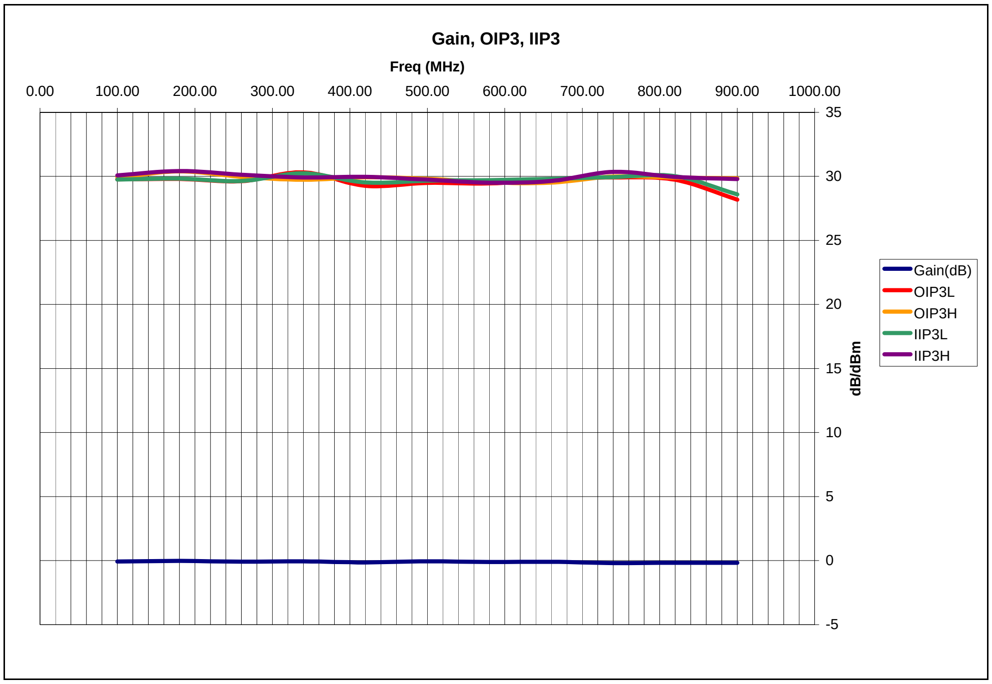

Figure 9: Auto calibration verification with a barrel connector and Pout/Tone set to 0 dBm. The gain is flat, as we hope. In my setup the gain error was about -0.2 dB maximum. Your luck may vary depending on the equipment and various settings.

Mixer modes

(this section is very rough)

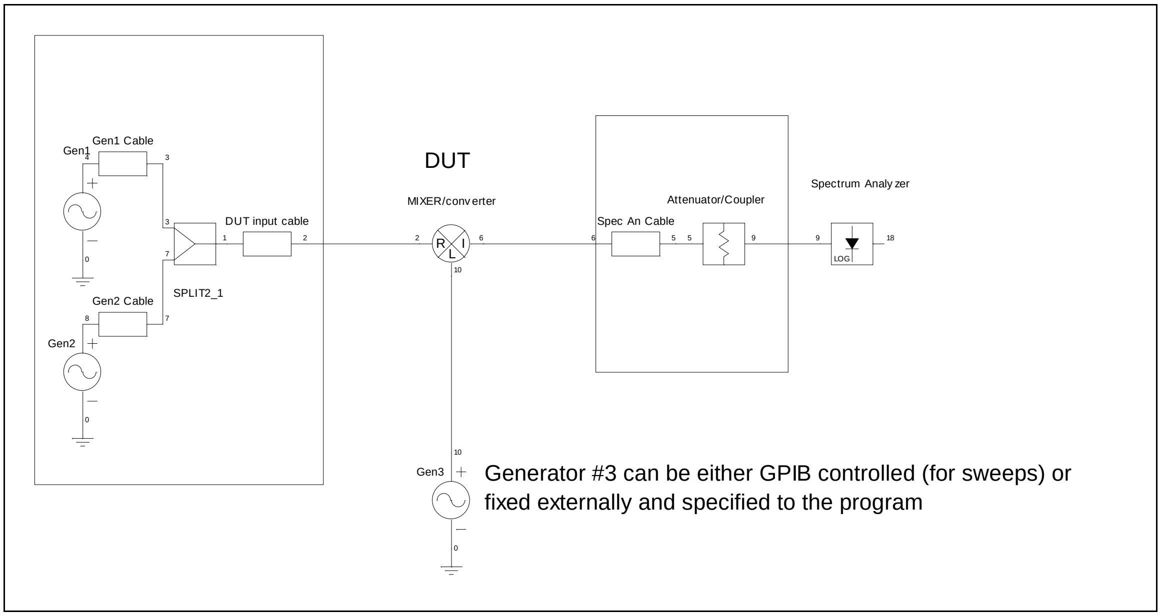

Figure 10: measurement setup with frequency translation

The mixer/converter modes can be a little bit confusing. There are a number of nuances to the operation that may be best clarified by simply providing a table of examples. As previously stated, there is very little error checking on all of the various inputs to the program, so please think about the settings as you enter them (using Table 1 as a template guide).

Also realize that some features of the main program window (Figure 1) change as buttons are clicked, i.e. in the case of the mixer modes various parameters are locked out, and description text changes (such as the text next to the frequency sweep parameters).

Note: in the case of the external LO that is GPIB controlled, the “level” setting is exactly what the signal generator is set to, no calibration or offset is available.

Table 1: Mixer / Converter example summary

Test example Description	Linearity Tester Mode	User specifies range	User specifies constant input/output frequency	LO > Highest frequency specified box checked?	LO frequency	Input frequency	Comments
Upconverter with fixed IF and swept LO Fin = 100 MHz Fout= 500-550 MHz LO = low side injection	"Mixer: Variable output, constant input, swept LO"	Mixer output frequency (500-550 MHz)	Input (100 MHz)	No, the highest frequency specified is the output	400-450 MHz	100MHz +/- Tone spacing /2	
Upconverter with fixed IF and swept LO Fin = 100 MHz Fout= 500-550 MHz LO = high side injection	"Mixer: Variable output, constant input, swept LO"	Mixer output frequency (500-550 MHz)	Input (100 MHz)	Yes, the highest frequency specified is the LO	600-650 MHz	100MHz +/- Tone spacing /2	

Test example Description	Linearity Tester Mode	User specifies range	User specifies constant input/output frequency	LO > Highest frequency specified box checked?	LO frequency	Input frequency	Comments
Downconverter with fixed IF output, swept LO Fin=500-550 IF out = 100 MHz LO= Low side injection	"Mixer: fixed output, swept input, swept LO"	Mixer input frequency (500-550 MHz)	Output frequency (100 MHz)	No, input frequency is highest specified	400-450 MHz	500-550 MHz	
Downconverter with fixed IF output, swept LO Fin=500-550 IF out = 100 MHz LO= High side injection	"Mixer: fixed output, swept input, swept LO"	Mixer input frequency (500-550 MHz)	Output frequency (100 MHz)	Yes, LO frequency is highest specified	600-650 MHz	500-550 MHz	

Test example Description	Linearity Tester Mode	User specifies range	User specifies constant input/output frequency	LO > Highest frequency specified box checked?	LO frequency	Input frequency	Comments
Upconverter with fixed external LO (1000 MHz), variable input/output. Desired output 1200-1300 MHz Input below LO.	"Mixer: Variable input/output, Fixed external LO"	Mixer output frequency (1200-1300 MHz)	User specifies fixed LO frequency = 1000 MHz (box is enabled for this mode)	(Note: in this case the box description reads "input frequency > external LO") No, the input is below the external LO.	Fixed external	200-300 MHz	
Upconverter with fixed external LO (1000 MHz), variable input/output. Desired output 1200-1300 MHz Input above LO.	"Mixer: Variable input/output, Fixed external LO"	Mixer output frequency (1200-1300 MHz)	User specifies fixed LO frequency = 1000 MHz (box is enabled for this mode)	(Note: in this case the box description reads "input frequency > external LO") Yes, the input is above the external LO.	Fixed external	2200-2300 MHz	

Test example Description	Linearity Tester Mode	User specifies range	User specifies constant input/output frequency	LO > Highest frequency specified box checked?	LO frequency	Input frequency	Comments
Downconverter with fixed external LO (1000 MHz), variable input/output. Desired output 200-300 MHz Input above LO.	"Mixer: Variable input/output, Fixed external LO"	Mixer output frequency (200-300 MHz)	User specifies fixed LO frequency = 1000 MHz (box is enabled for this mode)	(Note: in this case the box description reads "input frequency > external LO") Yes, the input is above the external LO.	Fixed external	1200-1300 MHz	
Downconverter with fixed external LO (1000 MHz), variable input/output. Desired output 200-300 MHz Input below LO.	"Mixer: Variable input/output, Fixed external LO"	Mixer output frequency (200-300 MHz)	User specifies fixed LO frequency = 1000 MHz (box is enabled for this mode)	(Note: in this case the box description reads "input frequency > external LO") No, the input is below the external LO.	Fixed external	800-700 MHz	

Hints

1. To be safe, always estimate a little high for "Max DUT gain" – this will make sure the measurement doesn't overshoot on the initial passes and is absolutely critical for P1dB measurements. This may actually make the measurement go faster in some cases, slower in others.
2. for P1dB measurements, always estimate a little low for the minimum output P1dB. If the initial measurements are made at too high a level, the gain will not be accurately known (since the DUT will already be compressing). The initial measurement is made at some offset (a hard coded value) below the minimum P1dB to ensure that the gain is measured at an uncompressed point – so this initial guess is important.
3. When first starting out with the software (or with a new circuit that you've not measured before), do a coupe things to get acquainted: 1) Manually get a feel for the circuit so you know the numbers to plug into the program. 2) run a test with only 2-3 points to see that the software is well behaved – watch the instruments and look at the output files. Make adjustments **before** you end up running a long test and finding an error at the last point!
4. When using calibrated modes, the maximum slope with frequency (of the elements of the test setup) is on the order of +/- 5dB. The calibration will likely fail if your power splitter or cable/pad/coupler has significant slope across the band. The main reason for why a calibration would fail is that the analyzer is setup for 1dB/division during this measurement and the measurements may end up off the screen.
5. Don't measure DUT's with really high gain slopes. The software should accommodate these to a degree, it is not a good idea to try and measure an amplifier/filter cascade for instance.
6. (repeat from above) **Set Pout tolerance**. For constant output power cases I do not recommend setting this much below 0.5 dB, certainly not much below 0.25 dB as the spectrum analyzer resolution is not much better than this in the normal sweep mode (we could change settings for the leveling, but this adds little value and would take longer). For constant input power cases I recommend setting this to >1 dB (3dB would probably be fine and may make some measurements run considerably faster). The leveling that is done here is similar, but it merely tries to get the two main output tones at the same point on the spectrum analyzer screen so that the detector is operating in the same region. For P1dB measurements this is simply the tolerance for getting the initial power to the right point and is not terribly important. Setting this to 1 dB for P1dB measurements is more than adequate.
7. If you do think the software is causing you problems, please send me the configuration and data files from the failed tests. Even if you abort a test after only one measurement you can hit the "write data files" button and it will write out the data (calibration and otherwise) that has been collected.

Some technical details as of the initial release of version 0.4 (subject to change)

IP3 measurements:

- Power control is given 25 iterations max to level the tones on the screen
- The "maximum mixer level" in the spectrum analyzer is set to -30 dBm
- Span is set to 10x the tone spacing
- RBW is set to 1% of the span for measurements, 3% for calibration (to speed it up, big signals are being measured)
- VBW is set to 1% of the RBW
- The software tries to keep the tones about 3 dB below the top of the screen (the reference level)
- IP3 measurements (not calibration) are done at 10 dB/division

P1dB measurements

- Initial minimum P1dB (out) is targeted for 15 dB below the reference level. The initial measurement point is set to 4 dB below the minimum estimated output P1dB.
- Initial P1dB steps are 10 dB, "middle" steps are 0.5 dB, starting a little below the estimated 1dB compression point. "final" steps are 0.3 dB each over a 3dB span centered on the point nearest to p1dB measured thus far (since the level goes up and down, the data are searched for the nearest point then the "final" sweep just runs open-loop through this region). The initial dB's per division are 5, then they drop to 1 when the detail sweep is done.
- In the end of the P1dB sweep the data are sorted and the nearest point to P1dB is reported (after searching the data). Multiple measurements at the same input power level might be present in the output and may actually give different results – measurement variation and the fact that different dBs per division were used can contribute to the discrepancy. There will always be some variation…
- If the measurement is greater than the RL minus 2 dB, the reference level is increased by 4 dB.