VNWA3E – A Low Cost Vector Network Analyzer not only for Education

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Part C: Monitoring and automated long time measurements

Introduction:

This third article part focuses on automation of VNWA measurements. Several tools will be demonstrated that allow for component monitoring and data logging. In section 1 this is done with a quartz crystal micro balance (QCM) as test object. Section 2 shows, that the VNWA3E can quite unexpectedly be used for measuring oscillator frequencies with extreme precision. Finally, the VNWA remote control interface is introduced in section 3.

1. Measuring and monitoring resonators

1.1 Quartz crystal microbalances (QCMs)

A quartz crystal microbalance (QCM) is a quartz crystal resonator that can be exposed to environments like gases or liquids. The resonance frequency and Q-value of such resonators react very sensitively to adsorption of molecules from the gas or liquid phase. Particularly, resonant frequencies can be measured with high accuracy. Therefore, QCMs can be used to detect very small amounts of adsorbed matter. Figure 1 shows two commercial QCMs from [1].

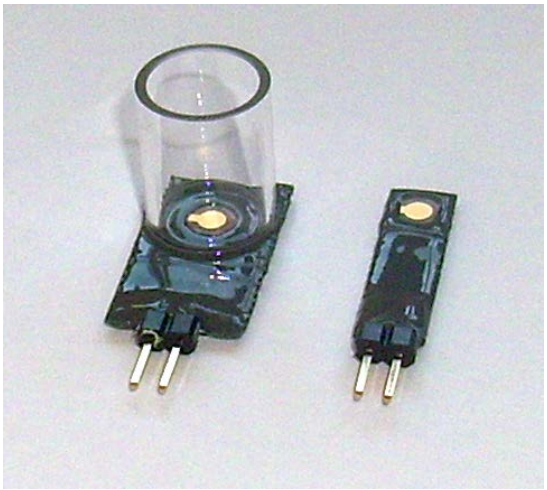

Figure 1: Two commercial quartz crystal microbalances from [1]. The left one is a flow cell type, while the one on the right is a regular one.

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The left one has a tubular flange attached for easy system integration. The exposed bright top metallization of the quartz crystal resonator can clearly be seen in both devices. Electrically, the resonator is a disk capacitor with a crystal dielectric that can resonate. The visible two contact pins connect to both sides of the crystal disk. Normally, the impedance of the resonator is rather high. Only when the series resonant frequency is applied, the impedance can become quite low. Therefore, such a device is favorably evaluated with a transmission measurement as shown in figure 2. With this configuration impedances in the 1Ω range can be measured but accuracy improves with increasing DUT impedance.

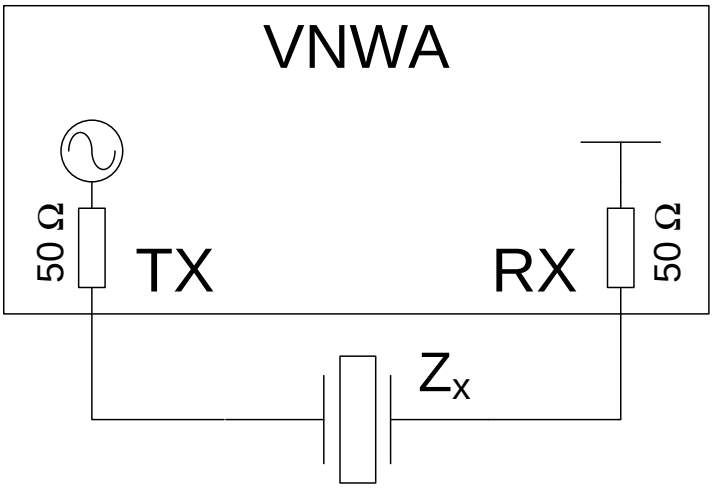


Figure 2: The mostly high impedance Z_x of a quartz crystal resonator is most accurately evaluated with a transmission measurement.

Figure 3 shows a time series of measurements in 4s intervals on the flow cell QCM of figure 1, where moist air had been blown into the QCM container before the first measurement. As the condensed moisture slowly dries away from the resonator, the resonance frequency slowly shifts up due to decreasing mass loading and the resonance peak narrows as the resonator Q increases due to decreasing friction. The red curve is the dry performance measured before the time series. The time series was visualized using the VNWA storage screen facility. This facility is also useful when tuning filters for comparing the current tuning status to all previous ones.

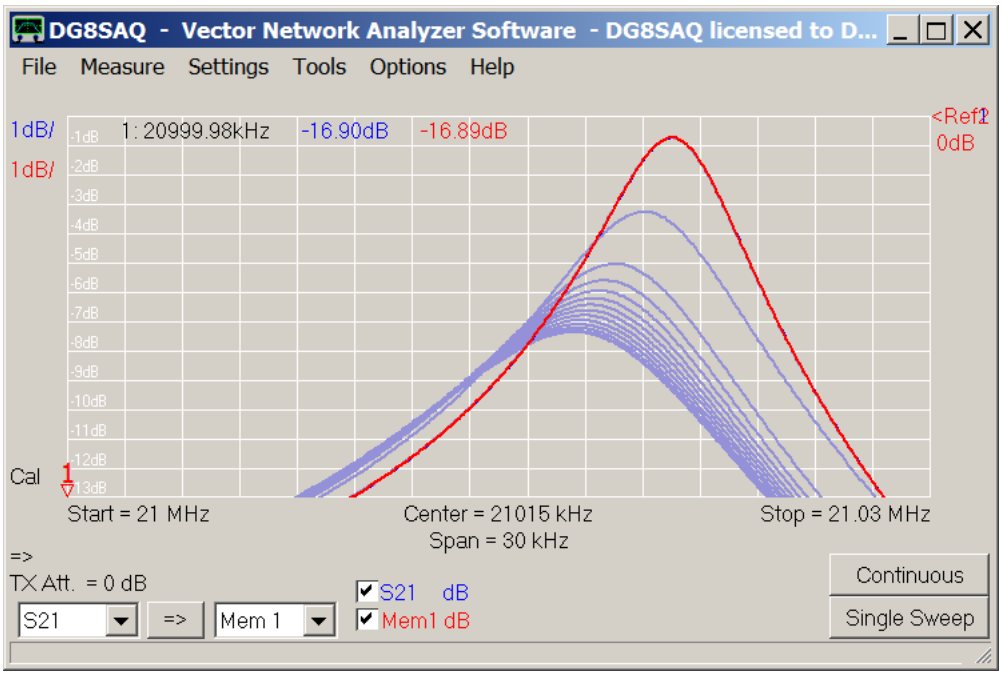


Figure 3: Consecutive sweeps of 4s duration of the flow cell type QCM after moist air had been blown in. The resonance curve slowly changes back to the red “dry” performance as the moisture on the resonator evaporates. The time series was visualized using the VNWA storage screen facility.

1.2 The VNWA Crystal Analyzer

Figure 3 only gives a qualitative indication of the dynamics taking place on the drying resonator. In order to obtain quantitative results, every measurement curve has to be analyzed in detail, preferably in real time right after it has been measured. This can be achieved using the VNWA “Crystal Analyzer” tool shown in figure 4. This is a highly specialized and thus fast model fitting tool tailored to analyze crystal resonators. It can either be used in single sweep mode to evaluate one resonator after the other or in continuous sweep mode to monitor the same resonator over an extended period of time. After every sweep the equivalent circuit model shown on top left is fitted to the measurement data and the parameters derived from the model fit are being logged to a new line on the Excel style data grid on the bottom. This way, time dependent parameters like the QCM peak frequency can easily be tracked. Using a model fit to find the peak frequency considerably improves the accuracy as all measurement points enter the model fit. Figure 5 demonstrates the high quality of the model fit. It shows a typical transmission measurement of the clean flow cell QCM (S21) in terms of attenuation (top) and phase (bottom). The model fit as obtained with the VNWA “Crystal Tool” is overlaid (s_21). The simulation matches the measurement very well.

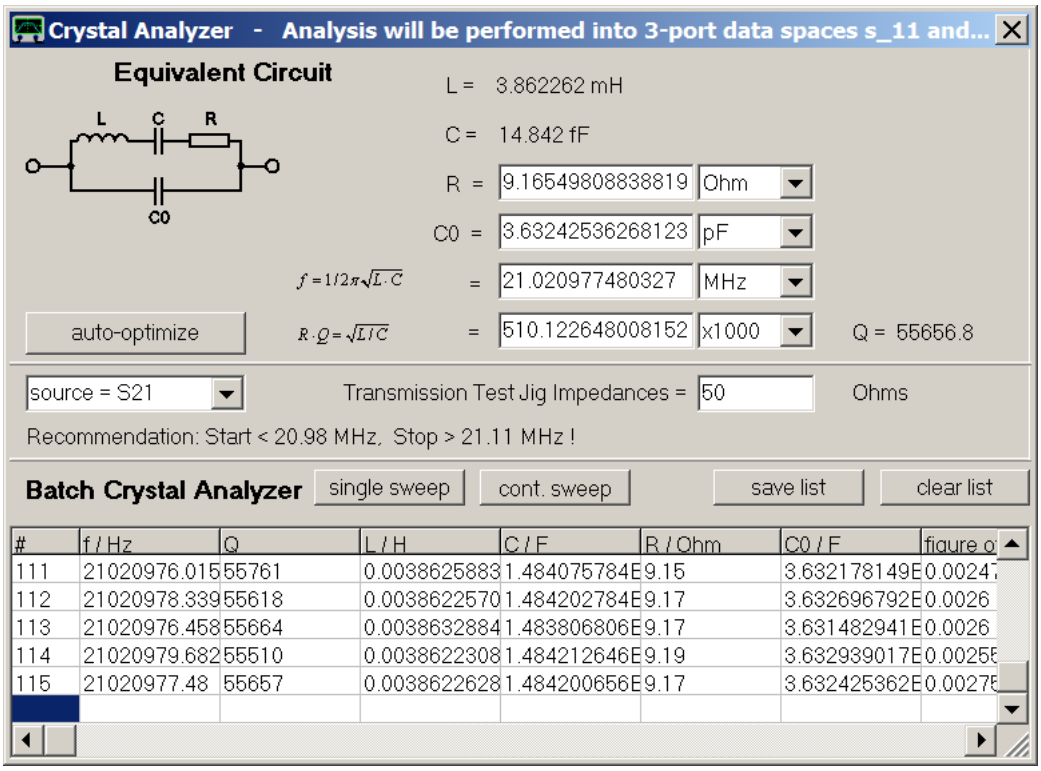


Figure 4: VNWA “Crystal Analyzer” tool. This is an automatic model fitting and documentation tool to evaluate resonators. The data grid shows the end of a time series obtained on the moistened flow cell type QCM.

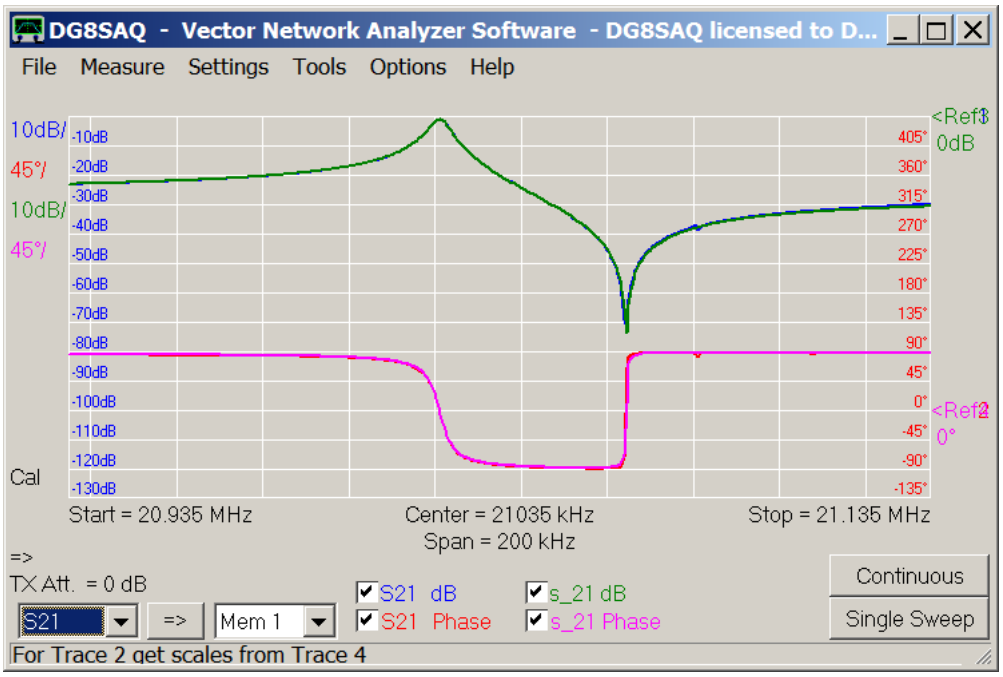


Figure 5: Typical transfer characteristic of a QCM resonator (S21, blue and red) showing the series resonance (maximum) and parallel resonance (notch). Overlaid is the model fit obtained with the

VNWA “Crystal Analyzer” (s_21, green and pink). Measurement and model simulation are almost indistinguishable.

The time series of the drying flow cell QCM obtained using the crystal tool as shown in figure 4 was saved into an ASCII file to be visualized by standard plotting software. Besides the fitting parameters, the file contains a timestamp for each measurement. Therefore one can plot the QCM parameters depending on time. This has been done for the series resonance frequency and for the resonator Q in figure 6.

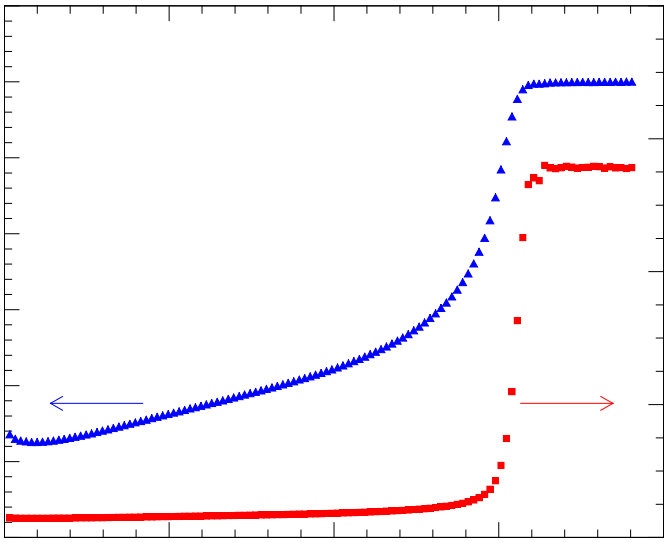


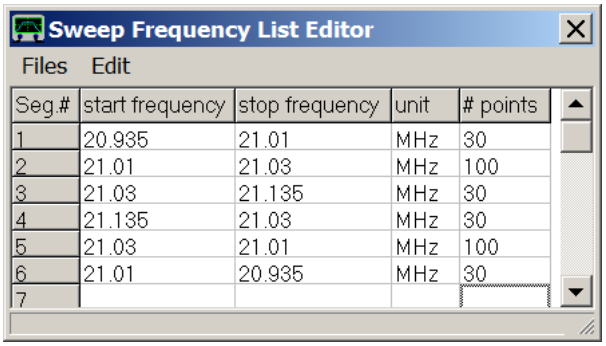
Figure 6: Analysis of the time series on the moistened and drying flow cell type QCM from figure 4.

The quantitative effect of the reduction of mass loading and friction as the moisture dries away is apparent. The QCM reacts particularly sensitive in the low contamination range. It is thus a highly sensitive device for detecting very small masses.

1.3 Using listed sweeps

One problem encountered when measuring high Q crystal resonators lies in the fact that the measured peak resonance position depends on the sweep speed. As the resonator requires time to settle to a changed frequency stimulus, the resonance peak is slightly shifted to later times, i.e. to higher frequencies in the case of the sweep being performed from low to high frequencies. This effect may well matter for high precision measurements that are to be swept fast. As sweeping slowly is not an option by definition, one may use the VNWA listed sweep capability instead. Here, the sweep frequency grid is customized by user definition of several concatenated linear sub-grids. This way one can sweep the resonance in both frequency directions within one single sweep such that the just discussed frequency shifts cancel out during the fitting process. Also, it is possible to place the frequency points more densely around the peak frequency and thus slow down the sweep

locally and also increase the statistic weight of this area during the fitting process. Figure 7 shows the VNWA “Sweep Frequency List Editor”. Here the sub-grids are defined by specifying the frequency boundaries and the number of frequency points. Note, that the end of one sub-grid has been chosen here as the start of the next sub-grid. This need not necessarily be the case. One may also sweep intermittent frequency ranges. Figure 8 shows the dry flow cell QCM as measured with the listed frequency sweep defined in figure 7 (S21, blue) together with a model fit obtained with the Crystal Analyzer tool (s_21, red).



Seg.#	start frequency	stop frequency	unit	# points
1	20.935	21.01	MHz	30
2	21.01	21.03	MHz	100
3	21.03	21.135	MHz	30
4	21.135	21.03	MHz	30
5	21.03	21.01	MHz	100
6	21.01	20.935	MHz	30
7				

Figure 7: A listed sweep is defined using the “Sweep Frequency List Editor”.

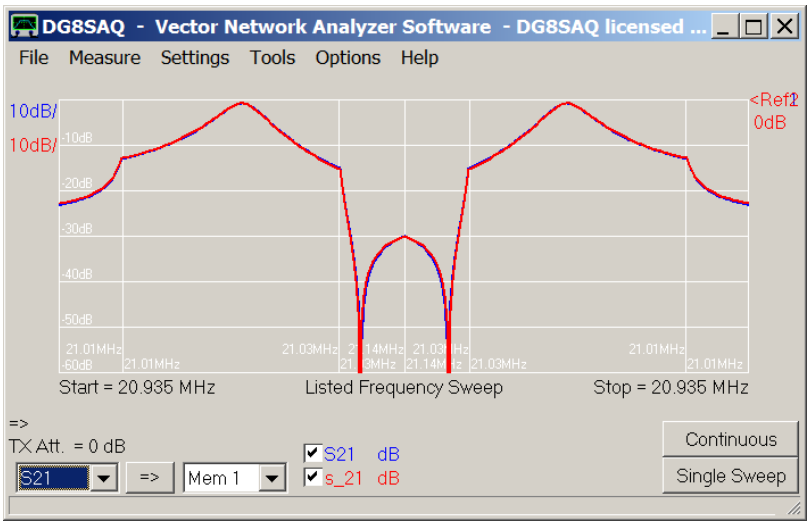


Figure 8: Listed sweep measurement of the dry flow cell QCM (S21, blue) together with a model fit obtained with the Crystal Analyzer tool (s_21, red). Note, that the resonator is measured twice in opposite frequency sweep directions. The vertical grid lines denote the sub-grid boundaries.

Again, an almost perfect match between measurement and the Crystal Analyzer model fit is achieved. Note, that the highest frequency is reached in the center of the plot. Thus, the resonator is measured twice in opposite frequency sweep directions. This way, the Crystal Analyzer tool can yield more accurate results for the resonance frequencies as discussed above.

2. Precision frequency measurement

2.1 Principle

The VNWA can also be used to very precisely measure the output frequency of fairly stable oscillators. The measurement principle rests on the fact that the VNWA can measure the phase offset of any signal fed into the VNWA RX port with respect to the internally generated reference signal as a function of time. Thus, the signal to be analyzed has to be fed into the VNWA RX port as shown in Figure 9.

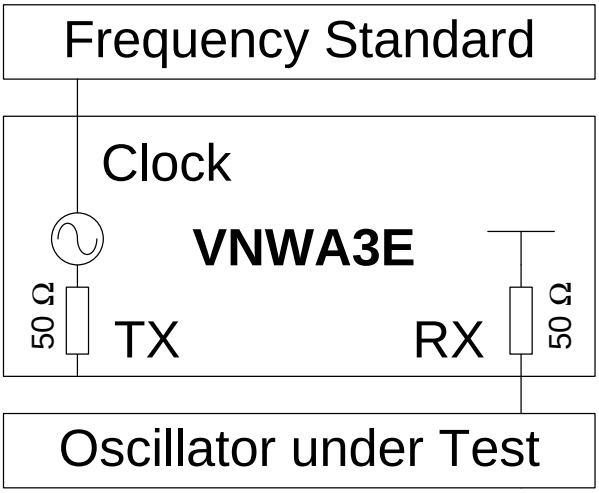


Figure 9: Setup for performing a precision frequency measurement using the VNWA3E. For highest precision an external frequency standard like a Rubidium frequency reference standard or a GPSDO is to be connected to the external clock input.

The momentary frequency offset *Δf(t)* can then be calculated from the time dependent phase difference *φ(t)* in radians by calculating the time derivative:

$$\Delta f(t) = \frac{1}{2\pi}\frac{d\phi(\mathrm{t})}{dt} \ .$$

This is a very sensitive and accurate method to measure a frequency for the following reason: A simple frequency counter with a time gate can only count integer numbers of signal periods. Therefore, a gate time of 1s will yield a frequency counter accuracy of 1Hz. Since the VNWA can measure phases with an accuracy much better than 1°, it can measure small fractions of a signal period. Thus, it is possible to determine a frequency with an accuracy of about 0.0001Hz within a measurement interval of 1s (!) as we will see.

2.2 Example FOX924 TCXO

Figure 10 shows a measurement result on the FOX924 TCXO by FOXElectronics [2]. Here the horizontal diagram axis denotes time as the frequency span is chosen to be zero. Since the TCXO frequency is lower than the nominal frequency defined by an external Rubidium standard here, the signal phase decreases with increasing time in a more or less linear fashion (red trace, c.phase). The frequency offset calculated from the phase difference (blue trace, dF) reveals a quite dramatic and unexpected behavior, though. While there is a slow overall up-drift in frequency, the up-drift is digitally compensated by switching the TCXO frequency in approximate 1Hz steps. While these 1Hz or 0.08ppm jumps are well inside the manufacturer's stability specification, they might be quite

disturbing when the TCXO is multiplied into the microwave range for use in narrowband applications. Multiplied to 10GHz the jumps amount to 1kHz frequency jumps! On the other hand, when evaluating the TCXO with a scope, a frequency counter or an RF spectrum analyzer, these 1Hz jumps will most likely escape observation. Note, that the frequency could be measured with an approximate accuracy of 0.1Hz (visible dF noise amplitude) within a measurement time of 2ms per data point, which makes the small but steep 1Hz steps dramatically visible. This could not be detected with a normal frequency counter.

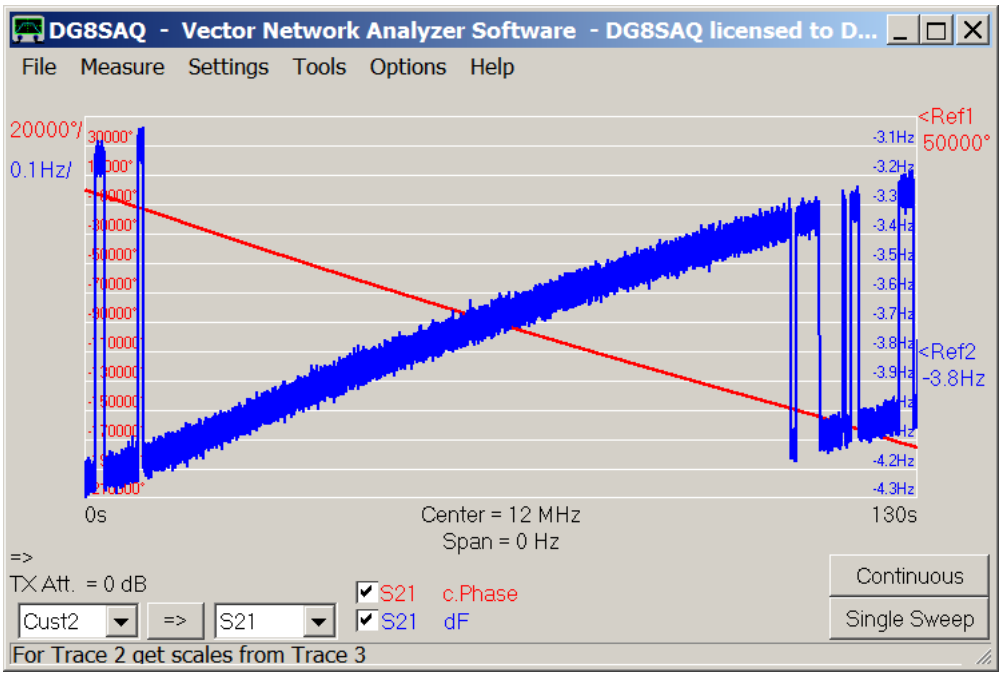


Figure 10: Continuous phase and frequency measurement on a FOX924 TCXO [2] against a DATUM LPRO-101 Rubidium frequency standard. The time resolution is 2ms. The total measurement time is 130s. Note, that the continuous phase does not jump at 360° intervals.

2.3 Evaluation of a GPS controlled oscillator

The time resolution of the frequency measurement can be increased up to 160µs allowing to investigate rapid transient frequency corrections of a low cost GPS controlled oscillator. The very low cost NEO-7M GPS module by u-blox [3] offers the possibility to reconfigure the 1pps output pin to produce any GPS locked frequency between 1Hz and more than 10MHz in 1Hz steps. The signal is produced by digital means and is thus expected to show a large jitter. This can indeed be measured with the VNWA3E as demonstrated in figure 11.

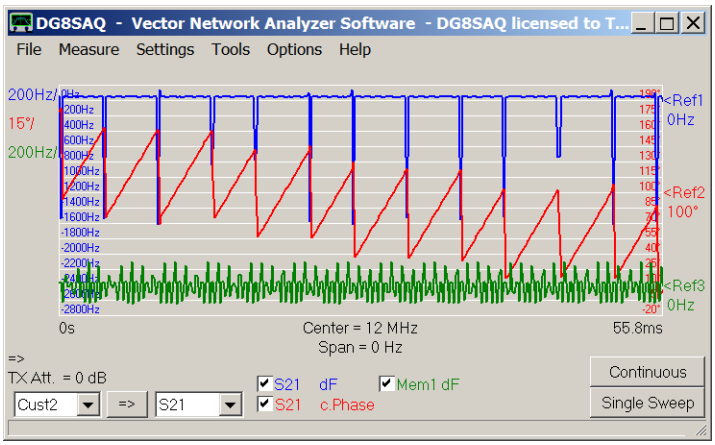


Figure 11: Output signal of the NEO-7M GPS module [3] configured to produce 12MHz (S21, blue red) or 10MHz (Mem1, green) compared to a DATUM LPRO-101 Rubidium frequency standard.

Note, that during the measurement time of about 56ms, the signal phase of the 12MHz signal and thus the frequency jumps many times. While for 10MHz the corrections are less severe, they are more frequent. In any case, these signals are not suitable for direct use in communications or as reference clock for a VNWA3E. Figure 12 shows a measurement of the GPS module set to produce 10MHz over an extended time period of 6500s with a resolution of 0.1s.

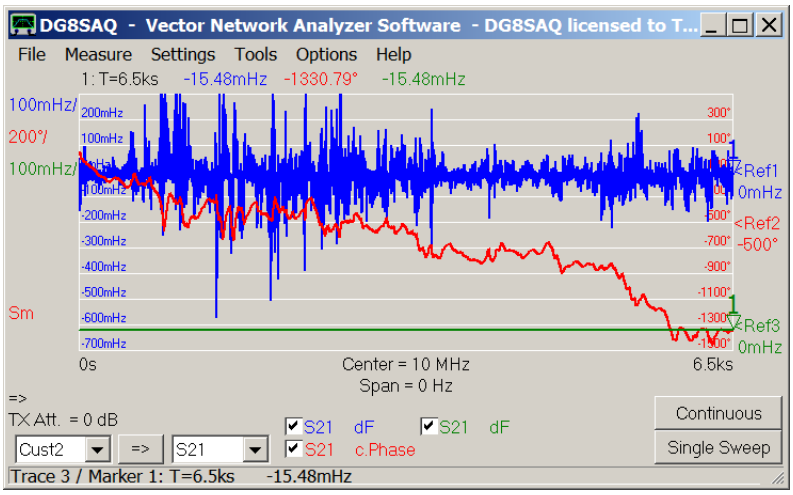


Figure 12: Output frequency (blue) and phase (red) of the NEO-7M GPS module [3] configured to produce 10MHz compared to a DATUM LPRO-101 Rubidium frequency standard. The green trace is the average of the blue trace obtained with the VNWA smoothing functionality.

Since the smallest analysis interval or resolution is 0.1s, the rapid frequency jumps from figure 11 are no longer visible. Instead, slower frequency variations (blue trace) and phase drift (red trace) become visible. The average of the blue frequency deviation trace yields the green one. Thus, an average frequency deviation of -15mHz or $1.5*10^{-9}$ between the GPS oscillator and the Rubidium reference over the full time range of 6500s can be read off from the marker values.

Summarizing, the module seems very well suited to serve as a reference signal for a frequency counter. For use in communications, the signal should be cleaned up by locking a low phase noise crystal oscillator to it with a rather large time constant.

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2.4 Comparison of two Rubidium frequency standards

The discussed measurement method is even accurate enough to compare and thus evaluate two highly stable Rubidium frequency standards. Figure 13 shows a measurement, where two identical 10MHz Rubidium frequency standards (DATUM LPRO-101) are measured against each other (S21, blue trace). The time resolution has been chosen to be 0.1ms. The 65000 points correspond to a measurement time interval of 6500s or about 1.75h. The VNWA “Precision Frequency Meter” facility (top panel) calculates a frequency offset of about -2.5mHz over the full measurement time span. As shown in the meter the allowed input frequency range is only ±4Hz. This limitation comes from the fact that the measurement point to point phase change must be less than 180° such that the direction of the phase change can unambiguously be determined. For the fastest sweep rate of 0.16ms/point the allowed frequency range increases to ±2.5kHz. Thus, this measurement method does not replace a frequency counter, but allows very precise frequency measurements in a narrow frequency range.

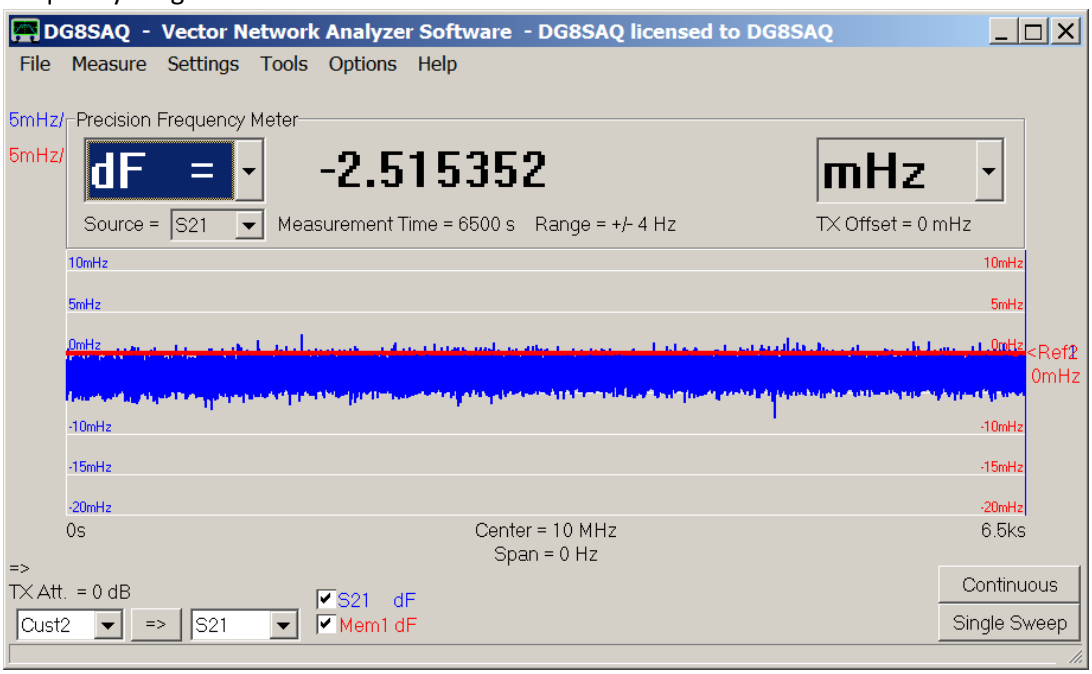

Figure 13: Frequency measurements on a DATUM LPRO-101 Rubidium 10MHz frequency standard against a second identical one (S21, blue) and against itself (Mem1, red). The time resolution is 0.1s. The total measurement time is 6500s. The VNWA “Precision Frequency Meter” facility indicates an average frequency offset of -2.5mHz of the two Rubidium standards over the full measurement time.

Note, that the vertical scale in figure 13 is only 5mHz (5 Milli-Hertz!) per division. Thus a frequency variation of about 5mHz is observed for the Rubidium standards. Here, the question arises if this is caused by the measuring instrument or if this is real drift. This can easily be investigated by measuring an oscillator against itself as demonstrated with the red trace (figure 13, Mem1). The instrument noise is apparently much less than the noise observed in the comparison of the two Rubidium standards. Thus, the frequency variation is real.

2.5 Allan deviation analysis

The output frequency of oscillators may fluctuate on many largely different time scales. This can best be evaluated and visualized by means of an Allan deviation analysis [4]. The VNWA software can compute Allan deviations corresponding to performed frequency measurements and save the data to ASCII files, which can then be read and visualized by standard plotting software. This has been done in figure 14. The blue trace shows the Allan deviation of the two Rubidium standards against each other. The shape of curve is to be expected as is discussed in [4]. Both, blue and red traces have been calculated from the corresponding measured data in figure 13. Thus, the red trace demonstrates the instrument's detection limit. As indicated with the dashed lines, at 1s measurement time, a relative measurement accuracy of about 10^{-12} can be achieved, which amounts to an error of 10µHz for a frequency of 10MHz.
The green trace shows the behavior of the NEO-7M GPS module as measured in figure 12. Clearly, the module's output frequency stability is not very good over short time periods, but becomes comparable to that of the Rubidium standards for a time interval of the order of an hour. Thus, when locking a crystal oscillator to the GPS module, a time constant of at least 1h should be used.

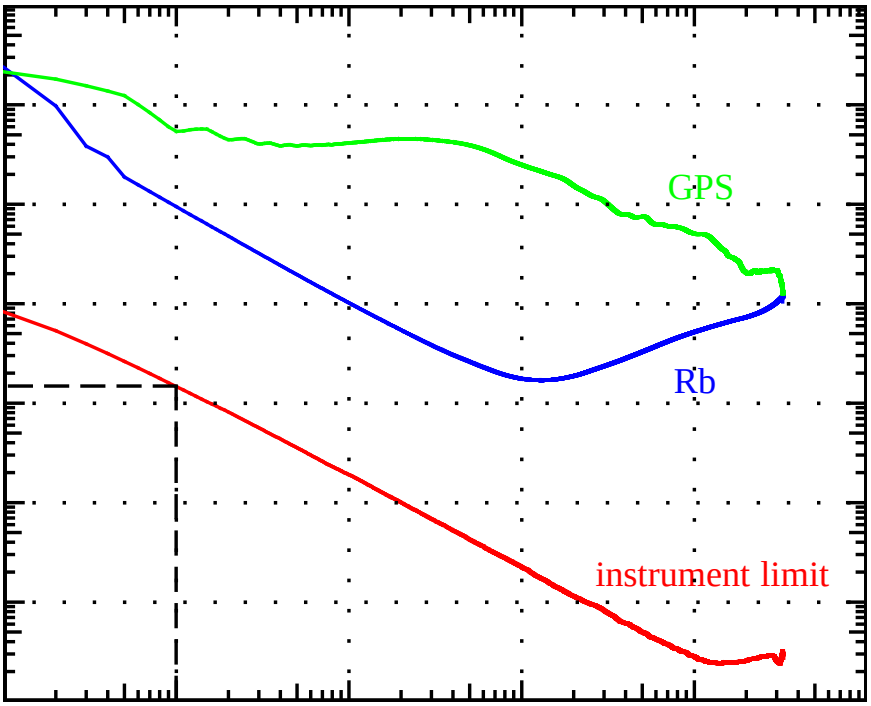

Figure 14: Allan deviation [4] as calculated from the measured data shown in figures 12 and 13. The blue trace corresponds to the measurement of two DATUM LPRO-101 Rubidium frequency standards against each other, while the red one shows a measurement of one frequency standard against itself. The red curve thus represents the instrument noise limit. The green curve represents the NEO-7M GPS module at 10MHz output frequency as measured against a Rubidium standard.

3. Automation of measurements

3.1 VNWA "Specification Tool"

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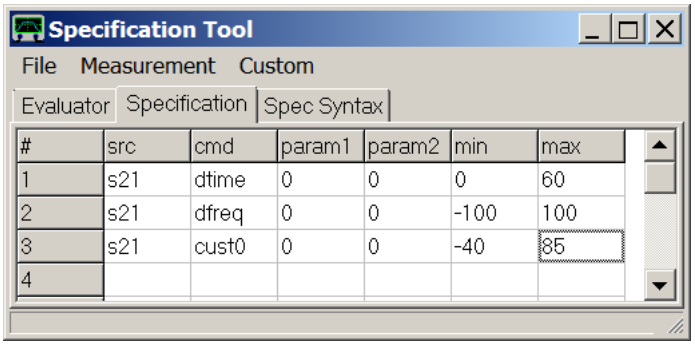
The VNWA “Specification Tool” allows to define a specification, perform a measurement and test the measurement against the specification’s minimum/maximum values. The specification is defined in an excel style table as shown in figure 15. Many analysis commands are predefined like attenuations, amplitude ripples, group delay ripples, impedances and many more. Two optional parameters define frequency intervals and the min/max values denote the specification limits. There are two possible modes of operation: Single sweep operation is useful to test a lot of identical components one after the other. Timed sweep operation is useful to monitor the behavior of a single component over an extended period of time e.g. under varying environmental conditions. An application of the latter is being demonstrated in the following.



#	src	cmd	param1	param2	min	max
1	s21	dtime	0	0	0	60
2	s21	dfreq	0	0	-100	100
3	s21	cust0	0	0	-40	85
4						

Figure 15: Definition of a specification in the VNWA “Specification Tool”.

The specification in figure 15 has only got three entries. The first line entry “dtime” returns the elapsed time in seconds between initiation of the timed sweep sequence and the end of the current sweep. This serves as a timestamp. Note, that timed sweep sequence may be chosen to terminate when a Fail condition is encountered. In this case, the measurement process would automatically stop latest after 60s with above specification as the “dtime” max parameter is set to 60 for example. The second line entry “dfreq” returns the precision frequency meter value deviation from the nominal frequency in Hz. Thus, the specification is set up to monitor an oscillator’s frequency with high precision over an extended period of time. The third line entry is a custom specification check to be provided by the user in the form of a dynamic link library (dll). The VNWA software allows to load a user written dll, where up to 10 user defined specifications can be tested and results returned to the VNWA software. The user has full software access to the current measurement data and may implement any analysis desired. Instead of returning a measurement analysis result, the dll may be used to return environmental parameters like ambient temperature or voltage readings. In this example “cust0” returns the current DUT temperature as measured by the user dll which controls an external thermometer in this case. Thus, automatic temperature measurements may be implemented. In a similar fashion the C(V) characteristic of a varactor diode might be measured. A source code example for such a custom dll may be downloaded from [5].

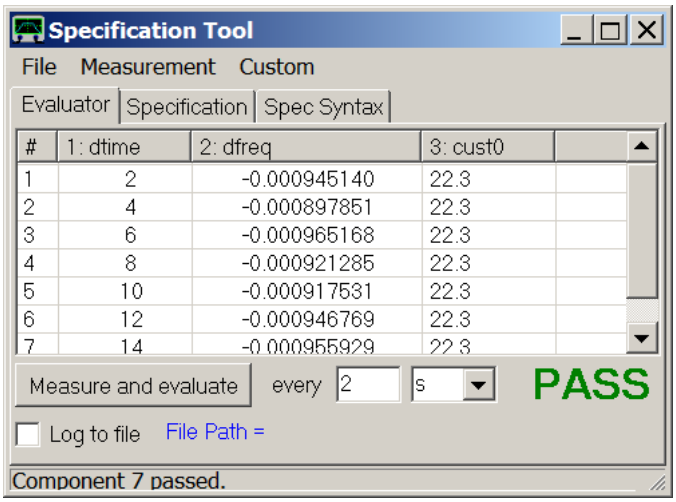


Figure 16: A timed series of measurements in the VNWA “Specification Tool” tested against the specification of figure 15.

Figure 16 shows part of a timed series of measurements against the specification of figure 15. The measurement results are being displayed in a data grid as well as logged to an ASCII file for documentation. The actual measurement data may be chosen to be time stamped and saved as well, so individual sweeps e.g. of failures may be retrieved for later inspection. The pass/fail information is being displayed optically and acoustically and it is logged together with the analysis data. After the time series has completed, the logged data may be analyzed and e.g. visualized with any plotting software as shown in figure 17.

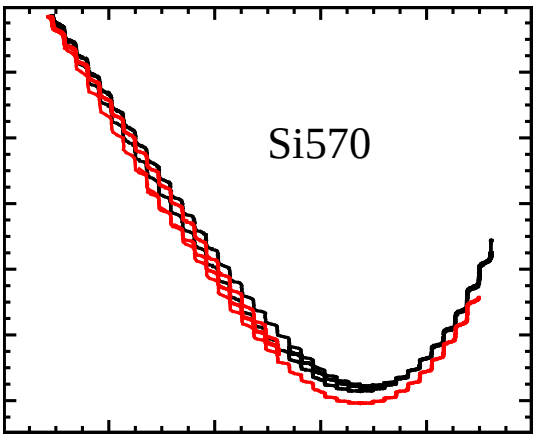


Figure 17: Frequency deviation vs. temperature of a SILICON LABS Si570 clock generator [6] inside a FA-SY N°1 module [7] as measured automatically using the VNWA “Specification Tool” over several automatic sweep sequences (black, red). During the measurement sequences the ambient temperature was varied.

Here, the output frequency of a FA-SY N°1 module [7] containing an Si570 PLL clock generator chip [6] and a microcontroller serving as USB interface for setting the generator frequency was monitored. For simplicity, the custom dll was used to directly connect to the microcontroller’s internal temperature sensor via its USB interface and read out the controller chip temperature. As the

controller is right next to the Si570 chip, the controller temperature is a reasonable approximation of the Si570 temperature. Note, that the step like curves in figure 17 are caused by the fact that the on chip temperature sensor has a resolution of only about 1°C. Nevertheless, the parabolic temperature dependence of the Si570 chip could well be determined for later software temperature compensation [8].

3.2 Remotely controlling the VNWA soft- and hardware

As the VNWA3 is intricately linked with PC hardware like the audio CODECS used for data acquisition, there is no way around using the VNWA software to control the instrument hardware and to perform measurements. Nevertheless, the instrument may be controlled by user defined software if the VNWA software is used as intermediate communication layer. Communication between the custom software and the VNWA software takes place by means of Windows messages, which can be used to send small amounts of data (actually two integer numbers) from one Microsoft Windows application to another. Every application has a handle, which is a number serving as destination address. The Windows message consists of this handle and two 4 byte integers (wparam and lparam). A typical communication flow from a custom software to VNWA may look as follows.

a) Custom program launches the VNWA software with the custom program handle as start parameter.
b) VNWA software sends back its own handle to the custom program by means of a Windows message in acknowledgement. Now the communication channel is established as both programs know each other's handle.
c) Custom program sends commands to load a calibration file and waits for acknowledgement. This will at the same time set the frequency grid.
d) Custom program sends the command to set the measurement time per data point and waits for acknowledgement.
e) Custom program sends the command to start a measurement and waits for acknowledgement that the sweep has successfully completed.
f) Custom program sends commands to save measurement data to a file and waits for acknowledgement.
g) Custom program sends command to terminate VNWA software and waits for acknowledgement.

An example source code for such a custom program may be downloaded from [10]. Figure 18 shows an example run of the demo program, where a measurement is performed and the measurement data is retrieved by the demo program.

In step a) the VNWA software may be started with several options. The "-silent" option lets the VNWA software start such that the VNWA main software window remains invisible. This may be desirable for automatic measurement systems. The "-debug" option lets a debug window become visible where the commands received by the VNWA software may be monitored. This option is useful during software development. Note, that the transfer of file names requires multiple Windows messages as only one letter is transferred at a time. The implemented interface is very simple and robust.

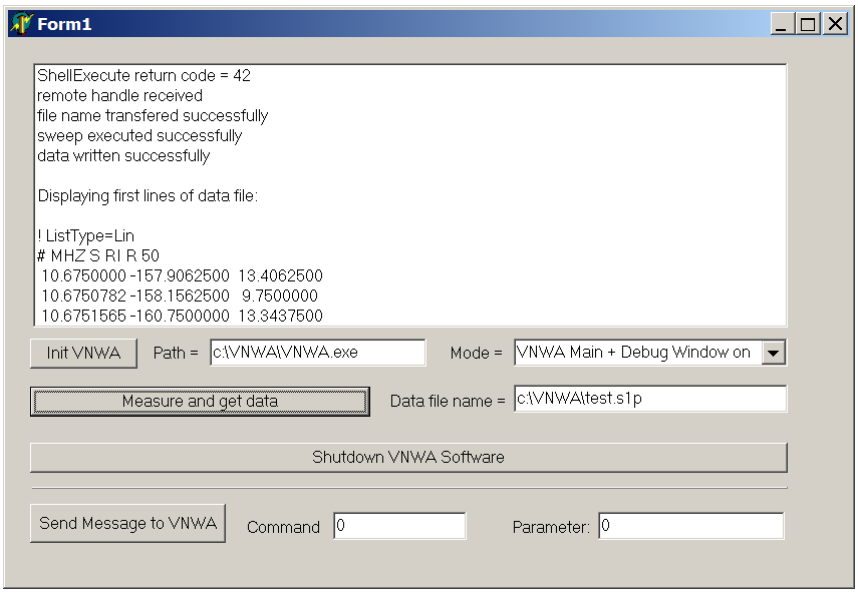


Figure 18: Example run of the demo program for remote-controlling the VNWA. A remote-controlled measurement has been performed and the first three data points have been retrieved.

Summary:

Several methods for performing automated measurement with the VNWA like the “Crystal Analyzer”, the “Specification Tool” and the remote control interface have been demonstrated. The VNWA is very well suited to evaluate resonators and to monitor QCMs. A very unusual application for a VNA is performing high precision oscillator frequency measurements. While most VNAs cannot do this, it was demonstrated that the VNWA3E is excellently suited for this task.

References

1. QCMs from Sunrise Industrial Co., Ltd.: QBS-01 (regular type), QBS-02FC (flow cell type).
2. TCXO by FOXElectronics, datasheet: http://www.foxonline.com/pdfs/fox924.pdf
3. NEO-7M by u-blox, http://www.u-blox.com .
4. See e.g. http://tf.nist.gov/general/glossary.htm
5. Specdll.zip currently in https://groups.yahoo.com/neo/groups/VNWA/files/A1%20DG8SAQ/Drivers_DLLs_Firmware/
6. https://www.silabs.com/Support%20Documents/TechnicalDocs/si570.pdf
7. FA-SY N°1 module available at http://www.box73.de .
8. T. Baier, "FA-SY als temperaturkompensierter Kanaloszillator", FUNKAMATEUR 12/2012, S. 1291-1293.
9. https://msdn.microsoft.com , see also VNWA software documentation.
10. DelphiRC_VNWA.zip currently in https://groups.yahoo.com/neo/groups/VNWA/files/A1%20DG8SAQ/

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