THE PENNSYLVANIA STATE UNIVERSITY
SCHREYER HONORS COLLEGE

DEPARTMENT OF ELECTRICAL ENGINEERING

ICE-PENETRATING RADAR SYSTEM BASED ON VECTOR NETWORK ANALYZER TECHNOLOGY

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SPRING 2019

A thesis
submitted in partial fulfillment
of the requirements
for a baccalaureate degree
in Electrical Engineering
with honors in Electrical Engineering

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ABSTRACT

This thesis explores a vector network analyzer-based ice-penetrating radar to measure ice thickness in polar regions. The harsh operating environment requires the vector network analyzers to be low-cost and portable. In this project ,three vector network analyzers were tested. The first was the SDR-Kits VNA, which had its internal oscillator modified to reduce the system's temperature sensitivity and improve measurement accuracy in 2012. Since then, new generations of portable vector network analyzers have been introduced on the market, and these vector network analyzers are of interest to determine if they can improve performance. This thesis compares the performance of the SDR-Kits VNA with two candidates, the Tektronix TTE506A VNA and the Keysight P5004A VNA.

To determine the effectiveness of the new Tektronix and Keysight vector network analyzers, the performances of the SDR-Kits VNA, the TTR506A VNA, and the P5004A VNA are compared. Data for frequency stability, phase noise, and delay-line depth test were collected from all three vector network analyzers under varying thermal conditions. The tests show that a candidate network analyzer satisfies requirements for use in the ice penetrating radar system, and that its improved performance and compact size make it suitable as a replacement.

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ACKNOWLEDGMENTS

In the completion of my honors thesis, I would like to give a special thank you to my honors advisor, Dr. Sven Bilén, who generously provided me with this opportunity to work on this project and guided me to complete all the honors requirements. During my undergraduate time at Penn State, Dr. Sven Bilén mentored and inspired me not only in academic but also in life. I would also like to thank Dr. Sridhar Anandakrishnan, who served as faculty reader of my thesis and provided confirmation of my work and gave me the chance to explore the Ice Radar system. I wish to thank Mr. Peng Liu and Mr. Hanxiong Hu who inspired me to find solutions to the problems I encountered while working on the project, and I appreciate all my colleagues in the Systems Design Lab who provided me with valuable suggestions and helped me overcome the difficulties I encountered.

Chapter 1

Introduction

The melting of polar ice is one of the primary concerns related to global climate change. To measure changes in ice thickness at high resolution, researchers within the Systems Design Lab (SDL) at Penn State have, over the past several years, been developing low-cost radar instrumentation based on a vector network analyzer (VNA) architecture. Although high-end benchtop VNAs have the required accuracy and resolution, their size, cost, and power consumption present limitations for use by glaciologists in the field measuring ice sheet thicknesses. The temperatures of the harsh polar environment require a VNA to be encased in a temperature-controlled case, which are additional drivers for small size and low power consumption.

To address these issues, in 2013, an ice-penetrating radar system derived from a modified, low-cost, portable SDR-Kits VNA was designed and validated to take accurate measurements of very shallow ice-sheet depths [Herrold, 2013]. The SDR-Kits VNA was first sold in 2009 and at that time represented a new class of low-cost VNAs available to the hobbyist. In recent years, however, traditional test-equipment manufacturers and several new companies have begun to release versions of portable VNAs that perform as well as benchtop equipment but at a lower cost, with lower power, and in a smaller form factor. This study seeks to evaluate these newer VNAs for consideration in improving the technology of the VNA-based ice-radar system. The Tektronix TTR 506A, released in 2018, and Keysight P5004A, released in 2019, are two of these new portable high-resolution devices that are considered as candidates for an updated ice-penetrating radar system.

1.1 Project Scope and Requirements

The SDR-Kits Vector Network Analyzer, shown in *Figure 1*, was developed by Baier [2009]. To increase its functionality for the ice-radar application, Tim [2012] changed the oscillator to a temperature-compensated crystal oscillator (TCXO), which improved the oscillator's stability and accuracy. The VNA uses a Universal Serial Bus (USB) port as its power source. It also uses the USB port to communicate with a computer using developer-specified software for operation.

Figure 1. Axotron. (2014). SDR-Kits Vector Network Analyzer. Retrieved from: http://axotron.se/blog/vector-network-analyzer-a-christmas-present-to-myself/

The Tektronix TTR506A, shown in *Figure 2*, is a new compact two-port VNA that offers a measurement frequency range of 100 kHz–6 GHz. Compared to benchtop VNAs, the TTR506A uses a tightly integrated single-board electronics assembly and communicates with a computer using a USB port [Tektronix, 2018]. The TTR 506A was selected for evaluation because of its small size, which makes it easy to transport to an ice sheet for field measurements.

Figure 2. TTR506A Vector Network Analyzer [Tektronix, 2018].

The Keysight P5004A, shown in *Figure 3*, has a frequency range of 9 kHz–20 GHz within a compact form factor. The two-port Keysight VNA provides benchtop-equivalent VNA measurement accuracy. It uses a USB port to provide an interactive front panel interface for the user on a PC [Keysight, 2019]. The compact chassis and powerful data processing capability make the Keysight VNA a solid candidate for the ice-penetrating radar system.

Figure 3. P5004A USB Vector Network Analyzer [Keysight, 2019].

If it is used to replace the SDR-Kits VNA in the ice-penetrating radar system, the ideal candidate (e.g., TTR506A or P5004A) must provide the same or better accuracy, frequency stability, phase stability, resolution, and delay-line test results over a range of temperatures and over significant periods of time. The detailed project requirements are listed in *Table 1* [Tim, 2012].

Table 1. Project Requirements for the Candidate VNA and SDR-Kits VNA

Number	Name	Requirement	Rationale
1	Frequency Range	VNA shall maintain a resolution within 200 to 400 MHz	This frequency range is the expected spectrum of the ice penetrating radar application
2	Resolution	VNA shall resolve the thickness of a 1-km-thick ice sheet with < 1 cm of error between visits	Slow melting requires a high resolution to make an accurate prediction of the rate
3	Thermal Stability	VNA shall maintain its resolution over a temperature range of 0 °C to −25 °C	This is the typical thermal environment for ice measurements
4	Power Supply	VNA shall run on DC power	Available power is derived from a battery or an AC-to-DC power adapter

1.2 Thesis Overview

This thesis provides an overview of the test development and all the tests that were performed to evaluate the feasibility of the candidate VNAs for replacing the existing SDR-Kits VNA used in the ice-penetrating radar system. Chapter 1 introduces the project's goals and the existing and candidate devices that underwent evaluation. Chapter 2 provides background information about ice-penetrating radar systems and the principles of VNAs and oscillators. Chapter 3 discusses differences between the architectures of the SDR-Kits VNA, the TTR506A Tektronix VNA, and the Keysight P5004A VNA. Chapter 4 discusses the system testing of the

SDR-Kits VNA and all other candidates. Chapter 5 discusses the performance of the system, draws conclusions, and makes recommendations for future work.

Chapter 2

Background

2.1 Ice-Penetrating Radar

Radar systems work by emitting electromagnetic waves that carry energy from the antenna to their interaction point(s) with targets. Some of this energy is reflected by the target (e.g., subsurface boundaries in the case of ice radars), whose electrical properties are different from those of the background media. Some portion of this energy travels back to the radar receiver. The signals allow the radar to detect the depth, conductivity, permittivity, density, and location of subsurface objects by comparing the strength, phase, and time delay between the emitted and the received signals. The characteristics of the target can be inferred from the amount of time between when the wave is emitted from the transmitter and when the scattered signal is received by the receiver.

The depth of a sheet of ice can be determined based on the amplitude and phase of emitted and received signals. The distance a wave travels can be found by calculating the phase velocity of the wave through a medium and the time a signal takes to reflect and return to the emitter. The actual depth of an ice sheet is calculated using half of the signal's travel time.

The ice melting rate is determined by comparing return signal patterns over time [Corr, 2002]. The depth of an ice sheet decreases as the ice sheet melts. Therefore, a wave will take less time to travel through the ice sheet, and the amplitude pattern will contain information about the ice sheet. The amount of melting can be calculated by comparing the phase difference between the return signal and the reference signal [Corr, 2002].

2.2 Vector Network Analyzers

Vector network analyzers (VNAs) are used to characterize the response of a linear circuit with respect to frequency. A VNA's signal port consists of a source, a test set to separate signals, a receiver to detect signals, and a processing stage [Herrold, 2013]. A VNA measures both the magnitude and phase of the network's response by down-converting the RF (radio frequency) signal to an intermediate frequency (IF). The signal is further sampled directly using a tuned receiver. The VNA compares the returned IF signal to a reference signal to provide phase information [Anritsu, 2009].

2.2.1 Scattering parameters and devices under test

It is challenging to measure total voltage and current at a device port at high frequencies. Due to the probe impedance and the difficulty of placing probes at their desired positions, a voltmeter or current probe cannot be used to take accurate reference measurements. Another challenge is that active devices may oscillate or self-destruct due to shorts or open circuits [Agilent, 2004]. Transmission-line effects may also influence the RF signal since the wavelength of an RF signal can be shorter than the length of the probe's cable at very high frequencies.

S-parameters, defined in terms of the voltage of traveling waves, are generally used for high-frequency analysis [Agilent, 2004]. S-parameters are calculated based on the magnitude and phase of the incident, transmitted, and reflected voltage waves. *Figure 4* shows the two-port device under test (DUT) along with the four waves and corresponding S-parameters [National Instruments, n.d.]. The complete set of S-parameters measurements is defined by setting the incident waves at Port 1 and Port 2 to zero and observing the responses of the system in each case of a stimulus at only one port. Forward signals are introduced at Port 1, and the signals at Port 2 are reversed signals. Reflection is defined as when a signal emerges from the port where it was introduced. Transmission is defined as when a signal passes through two different ports.

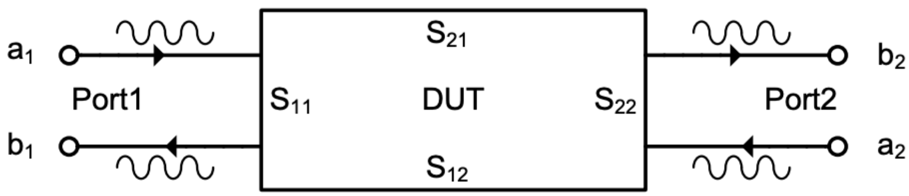


Figure 4. Two-port system [National Instruments, n.d.]

The subscripts of the S-parameters are determined by port i at which the response is observed and port j at which the stimulus is introduced in the form S_{ij}. To extract the individual S-parameters, the specific load with a characteristic impedance (Z_0) is used to terminate the DUT. In most cases, this impedance is 50 Ω. When the characteristic impedance is presented at Port 2, a_2 is equal to zero; thus, the equations for S_{11} and S_{21} are defined as the ratio of the corresponding b and a parameters. The reverse of this principle can be applied by setting a_1 to zero in S_{22} and S_{12}. The four completed S-parameters are presented in *Figure 5* [National Instrument, n.d.] and summarized in *Table 2*.

$$\boldsymbol{S_{11} = \frac{b_1}{a_1}\bigg|_{a_2=0}} \qquad \boldsymbol{S_{12} = \frac{b_1}{a_2}\bigg|_{a_1=0}}$$

$$\boldsymbol{S_{21} = \frac{b_2}{a_1}\bigg|_{a_2=0}} \qquad \boldsymbol{S_{22} = \frac{b_2}{a_2}\bigg|_{a_1=0}}$$

Figure 5. S-parameters definition [National Instruments, n.d.].

Table 2. S-parameter Summary

S_{11}= forward reflection coefficient
S_{22}= reverse reflection coefficient
S_{21}= forward transmission coefficient
S_{12}= reverse transmission coefficient

In applications such as the ice-penetrating radar, this conventional method for determining the S-parameters by placing characteristic impedance across opposing terminals is not available. The VNA needs to be calibrated to account for this. This calibration is achieved by connecting a known load to the transmission port and recording the information. The three impedances typically used are short, open, and 50-Ω load. Generally, six error terms in the forward direction and six error terms in the reverse direction can be resolved using calibration [Anritsu, 2009].

Since ice-penetrating radar operates on the surface of ice sheets (*Figure 6*), $S_{11}$and S_{21} are the only available S-parameters. S_{11} is measured from the transmitted and reflected signals at Port 1. S_{21} is measured from the signal transmitted from Port 1 that reflects from the ground below the ice sheet and returns to the receiver's antenna. The depth of the ice can be inferred based on the time delay and phase shift of these two signals.

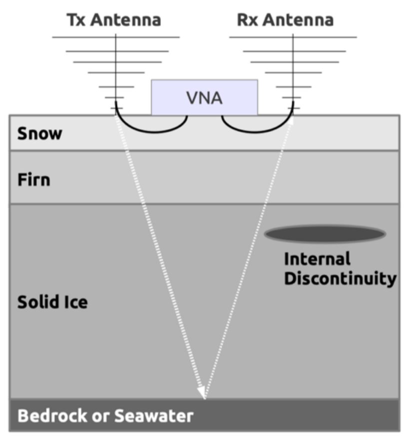


Figure 6. VNA-based radar system [Herrold, 2013].

2.3 Oscillators

The oscillator is one of the most significant components of a VNA. It generates the RF signals and provides the reference signals that are used for comparison with the return signals. The quality of the oscillator greatly affects the accuracy of the VNA’s measurements. Therefore, factors influencing oscillator quality and some of the types of oscillators are briefly reviewed below.

2.3.1 Oscillator quality and accuracy

An oscillator’s quality is determined based on three factors: accuracy, stability, and precision (*Figure 7*). Accuracy is used to describe the degree of “correctness” of a measurement. The average of a set of measurements from a sample should agree with the definition of the quantity being measured. Stability is used to calculate the derivation of changes as a function of parameters like time and temperature. Precision is the extent to which the average of a set of measurements agrees with the given set of measurements for a particular sample [Vig, 2004]. All three factors are relevant to the quality of an oscillator.

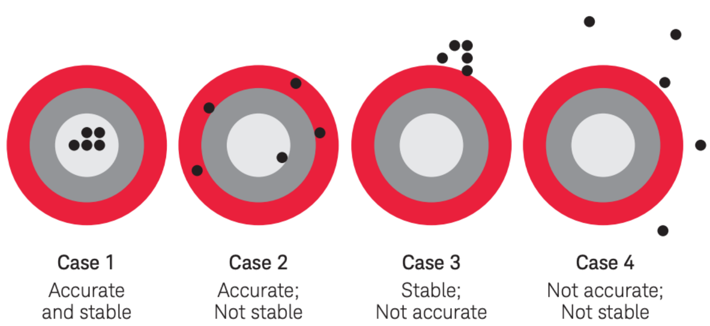


Figure 7. XO frequency, stability, and accuracy [Keysight, n.d.].

Reproducibility is another factor that determines the quality of an oscillator. Reproducibility measures how likely an oscillator is to output the same frequency with each use without user adjustments. The calibration of the VNA should compensate for reproducibility issues. A suitable oscillator for high-precision measurements should maintain stability between calibrations. *Table 2* provides a list of all influences on oscillator stability.

Table 2. Influences on Oscillator Frequency [Vig, 2004].

Influences on Oscillator Frequency	
I.	Time • Short term (noise) • Intermediate term (e.g., due to oven fluctuations) • Long term (aging)
II.	Temperature • Static frequency vs. temperature • Dynamic frequency vs. temperature (warm-up, thermal shock) • Thermal history ("hysteresis", "retrace")
III.	Acceleration • Gravity (2-g tipover) • Acoustic noise • Vibration • Shock
IV.	Ionizing radiation • Steady state • Photons (X-rays, γ-rays) • Pulsed • Particles (neutrons, protons, electrons)
V.	Other • Power supply voltage • Humidity • Magnetic field • Atmospheric pressure (altitude) • Load impedance

In theory, the output voltage of an ideal oscillator is a perfect sine wave. In practice, however, the output of the oscillator deviates from a sine wave. This deviation represents the stability of the oscillator and can be separated into short-term and long-term values (*Figure 8*).

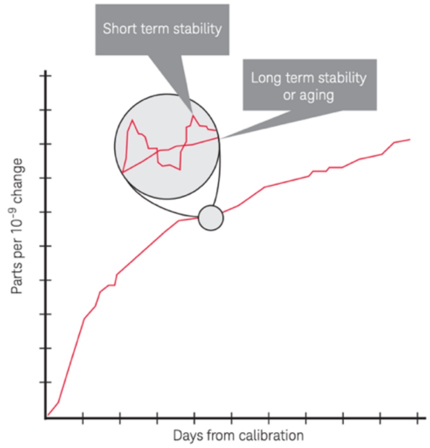


Figure 8. Short- and long-term stability [Keysight, n.d.].

Table 3 below lists the causes of short-term instabilities. Of these causes, Johnson noise, also known as thermal noise, is the limiting factor for an oscillator. Thermally-induced charges fluctuate within the physical components to generate Johnson noise.

Table 3. Causes of Short-Term Instabilities [Vig, 2004]

Causes of Short-Term Instabilities
• Johnson noise (thermally-induced charge fluctuations; i.e., "thermal *emf*" in resistive elements) • Phonon scattering by defects and quantum fluctuations (related to *Q*) • Noise due to oscillator circuitry (active and passive components) • Temperature fluctuations, thermal transient effects, activity dips at oven set-point • Random vibration • Fluctuations in the number of adsorbed molecules • Stress relief, fluctuations at interfaces (quartz, electrode, mount, bond) • Shot noise in atomic frequency standards

The Allan deviation is used for characterizing short-term instability in samples taken at short intervals. The fundamental idea is to eliminate the influence of long-term drift due to aging, temperature, or wander. Adjacent samples are compared consecutively rather than with the entire population of data. The Allan deviation is widely used because it is relatively easy and fast to calculate, converges for all noise processes observed in a precision oscillator, and has a straightforward relationship with power-law spectral density [Vig, 2004]. The Allan deviation is given as

$$\sigma_y^2(\tau, m) = \frac{1}{m}\sum_{k=1}^{m}\frac{1}{2}(y_{k+1} - y_k)^2 \ , \tag{1}$$

where τ is the time interval of the measurement, m is the number of samples, y is the fractional frequency measurement, and k denotes successive fractional frequencies.

With reference to *Figure 9*, long-term instability of an oscillator is defined as slow changes in the oscillator frequency over time (e.g., minutes, hours, or days). Noise also changes the output frequency. However, only low-frequency noise can be considered over the long term. Both temperature changes and oscillator aging can cause drifts in frequency that affect long-term stability. For high-quality oscillators, this instability is measured in parts per million (ppm). Using ppm to describe instability is akin to using the percentage change in the oscillator frequency. However, instead of expressing this change relative to one-hundredth of the oscillator frequency ω_0 (i.e., 1% of the oscillator frequency), we represent this change as relative to one one-millionth of the oscillator frequency ω_0 [Stiles, 2005].

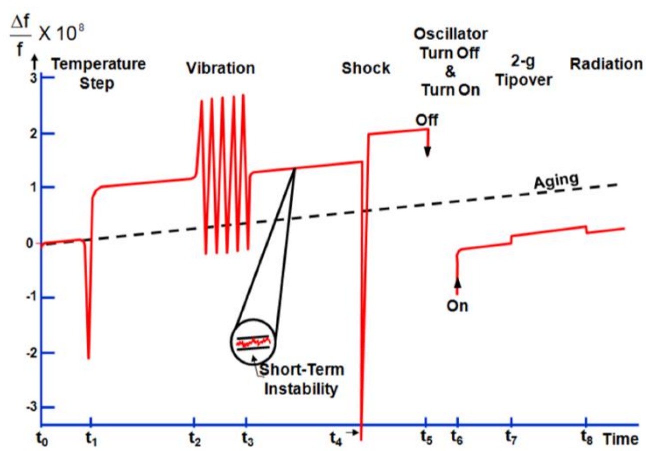


Figure 9. Major types of oscillator frequency instabilities [Vig, 2004].

2.4 VNA Candidates and Selection

Due to the special operating environment of the ice-penetrating radar system, a VNA candidate for replacing the SDR-Kits VNA is required to be small, highly thermally stable, and covers the 200-to-400-MHz frequency range. All VNAs considered for evaluation are listed in *Table 4.* All of the VNAs listed have a relatively compact size compared with benchtop VNAs and all cover the required frequency range. A host computer is required to provide the user with the VNA interactive interfaces that display the measured data and analysis results. We selected the Tektronix TTR506A and Keysight P5004A VNAs for evaluation due to existing relationships with the product vendors and similar total cost and power draws.

Table 4. List of VNA Candidates

One-port VNAs:
Copper Mountain R54
Copper Mountain R60
Copper Mountain R140
Copper Mountain R180
Two-ports VNAs:
PicoVNA 106
Tektronix TTR506A
Planar TR1300
Copper Mountain TR5048
Copper Mountain S5065
xaVNA
mRS Mini VNA
PocketVNA
Keysight P5004A

Chapter 3

VNA Architectures

3.1 SDR-Kits VNA

Figure 10 shows a block diagram of the SDR-Kits VNA. The VNA uses the computer's USB port as its power source, and the VNA is registered as an audio device by the computer. Both direct digital synthesizers (DDS) are driven by the oscillator. An SWR bridge separates the incident and reflected waves. A splitter is used to sample the incoming reference signal. The output signal from the bridge is then mixed, passes through the amplifier, and finally into the left channel of the computer's sound card line-in. Since standard sound cards only have a stereo line-in channel, the switch multiplies the reflected signal using the signal from mixer M3. The mixed signal from the LO (local oscillator) and RF DDS is fed into the right channel of the sound card line-in to obtain phase measurements [Baier, 2009]. The computer uses these data for digital signal processing, leading to the final output of the radar.

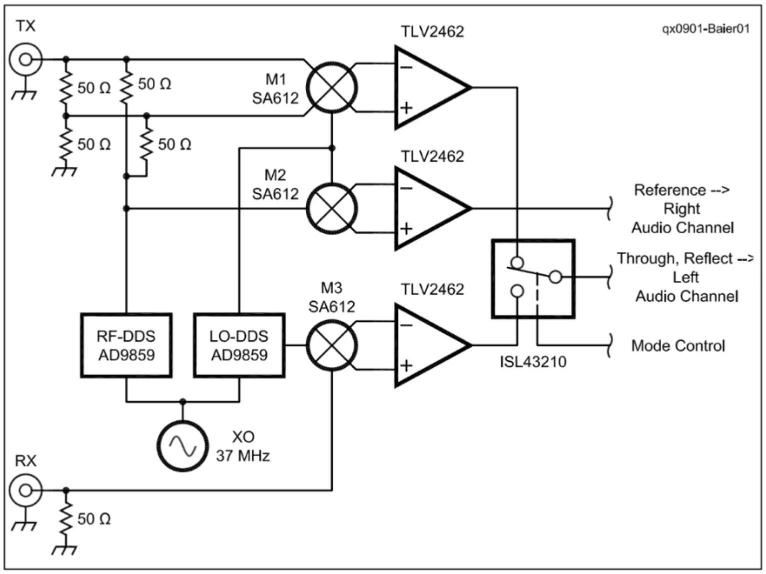


Figure 10. SDR-Kits VNA block diagram [Baier, 2009].

The 37-MHz source oscillator was verified to be not accurate or precise enough for use in the ice-penetrating system. Therefore, it was replaced with a 20-MHz Connor Winfield TCXO D53G. This oscillator has a minimum temperature below −25 °C with temperature stability of ±5 ppm and −80 dB of phase noise at the center frequency. It reaches 0.5 ppm stability in 5 ms [Tim, 2012].

3.2 Tektronix TTR506A VNA

The Tektronix TTR506A VNA uses a custom ASIC (application-specific integrated circuit) as its central processor (*Figure 11*). The system generates a stimulus signal that is stepped through a range of measurement frequencies. The ASIC collects the stimulus signal (r_1, r_2), the signals reflected from the DUT (a_1, a_2), and the signals transmitted through the DUT (b_1, b_2). Four S-parameters are calculated using the equations in Figure 4. All six receivers can measure both the magnitude and phase of a signal. Directional couplers separate the signal into forward and reverse directions. The RF sources are phase-locked to 10 MHz and can synthesize signals from 100 kHz to 6 GHz [Tektronix, 2018]. Compared with benchtop VNAs, the TTR506A has no internal computer, display, or physical inputs. Therefore, the system consumes less energy and has a more compact size, lower component stresses, and higher reliability than benchtop VNAs. It is also quiet, as it does not require a fan. The entire VNA is powered by a 4.75–5.25-V DC supply with less than 20 W. Data are collected over a USB 2.0 port and displayed via the specified PC software.

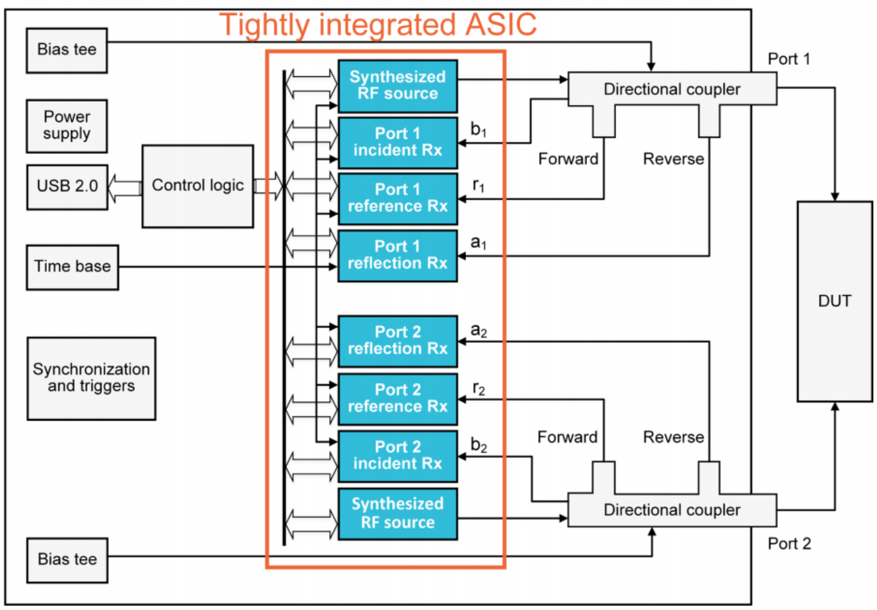


Figure 11. TTR506A VNA block diagram [Tektronix, 2018].

3.3 Keysight P5004A VNA

The block diagram of Keysight P5004A VNA is shown in *Figure 12*. The source stimuli are synthesized over the frequency range from 9 kHz to 20 GHz. Two couplers, two receivers, and one attenuator are built into each of the ports. The internal LO provides a 10-MHz signal with ±7 ppm. However, Keysight offered limited information about the type of LO used. The P5004A VNA is controlled by the user via a host computer with USB 3.0 port. The system is powered by a 15-V, 58-W DC power supply through an adaptor.

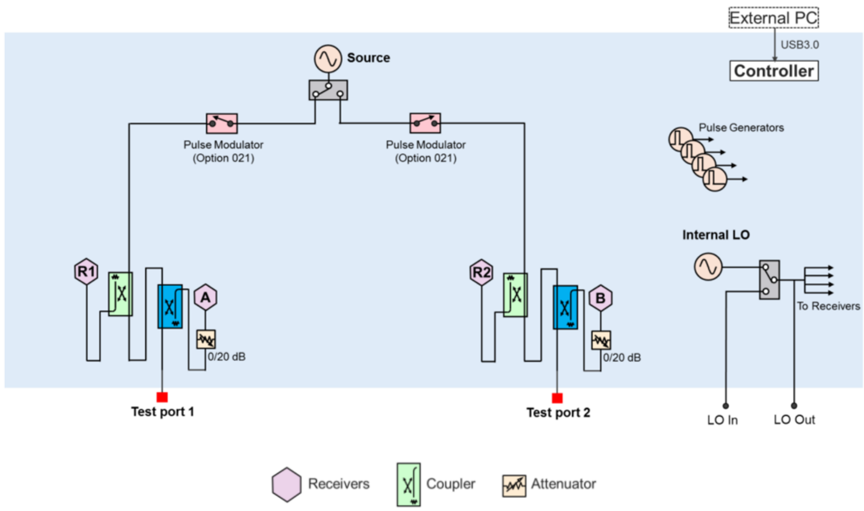


Figure 12. P5004A Keysight VNA block diagram [Keysight, 2019].

Chapter 4

VNA System Evaluations

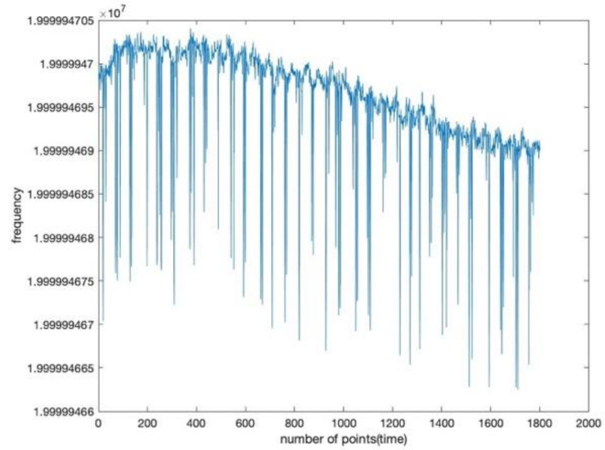
To ensure that updating the ice-radar system with a newer VNA will meet the system requirements, a series of tests were run to evaluate and compare the performance of the three candidates VNAs. Due to the limited measurement equipment and VNA factors that we can test, the testing procedure is based on that developed by Tim [2012] with modifications. The tests used the SDR-Kits and candidate VNAs, a Hewlett Packard 53153A Frequency Counter, a Hewlett Packard 58503A GPS-trained OCXO, an Agilent E4408B Spectrum Analyzer, and a Testequity 1007C Thermal Chamber. The VNAs being evaluated emitted incident signals and collected return signals. The frequency counter was used to measure the frequency changes over time and over changes in temperature. The GPS-trained OCXO provided an external reference for the frequency counter, and the high-precision signal was assumed to provide the reference without introducing any instability or noise. The spectrum analyzer was used to determine the TX phase noise of the system, and the temperature chamber was used to simulate the arctic environment. Given the difficulty of obtaining measurements with the temperature chamber (after the development of the test procedure, the cooling capability of the chamber broke), the functionality of the ice-penetrating radar, and the availability of the measurement instrument, the tests were focused on frequency stability over time and stability at different frequencies.

4.1 SDR-Kits VNA at Room Temperature

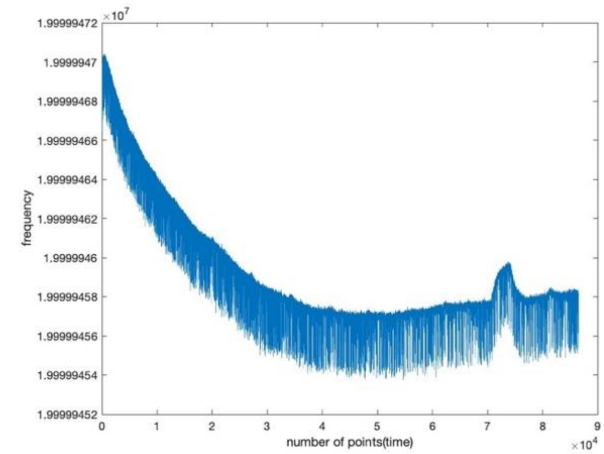
Room-temperature operating conditions were used to collect a comparative dataset to determine deviations in the VNA's operation. The oscillator inside the VNA was assumed to function ideally at room temperature. Short-, medium-, and long-term frequency stability data were collected using the frequency counter and plotted. The TCXO's 20-MHz TX signal was examined by the spectrum analyzer to determine the phase noise. The phase noise over the entire range of working frequencies was measured using the spectrum analyzer. Finally, a delay-line test was used to determine whether the VNA-based ice radar could accurately detect the delay in signal transmission for calculating the depth of ice.

4.1.1 Frequency stability over time

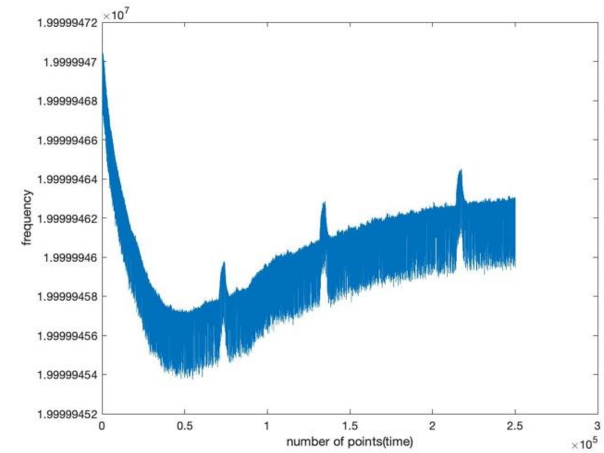
The VNA was powered by a USB port on a MacBook Pro and was calibrated to the center frequency of the Connor Winfield TCXO at 20 MHz. The TX port of the VNA was connected to the Hewlett Packard 53132A with a BMA cable. The frequency counter used the GPS-trained OCXO as its external reference frequency. The short-, medium-, and long-term frequency plots are shown in *Figure 13*. As the operating time of the VNA increases, the disparity between the maximum and minimum output increases, which indicates that there is some instability. The disparity between the highest and lowest observed frequencies over three days was only 1.662 Hz (0.0831 ppm). To achieve the measurement of a 1-km thick ice with 1-cm accuracy, the source of the VNA needs to have a frequency stability with 0.5 ppm [Tim, 2012]. Therefore, the system meets stability requirements.



(a) 30 minutes



(b) One day



(c) Three days

Figure 13. SDR-Kits VNA room temperature frequency stability plots.

Table 5. SDR-Kits VNA Room Temperature Frequency Stability Summary

Parameter	Frequency	Unit
30 Min Short Term		
Mean	19,999,946.956 998 3	Hz
Disparity	0.415 624 499 320 984	Hz
Variance	0.004 249 774 903 256	Hz
Standard derivation	0.065 190 297 615 950	Hz
One Day Medium Term		
Mean	19,999,945.931 143 9	Hz
Disparity	1.662 647 496 908 90	Hz
Variance	0.100 485 314 441 410	Hz
Standard derivation	0.316 994 186 762 802	Hz
Three Day Long Term		
Mean	19,999,946.064 433 0	Hz
Disparity	1.662 647 496 908 90	Hz
Variance	0.056 267 069 476 975	Hz
Standard derivation	0.237 206 807 400 157	Hz

4.1.2 Phase noise of the TCXO

Phase noise also indicates the stability of an oscillator, with a frequency-domain representation of the fluctuation in the phase. The phase noise of an internal oscillator affects the quality of the output signal at the TX port. *Figure 14* shows the phase noise of this study's oscillator with a center frequency of 20 MHz. The sharp peak indicates that the oscillator provided an acceptable phase noise factor; phase noise is less than −68 dBc/Hz at 5 kHz.

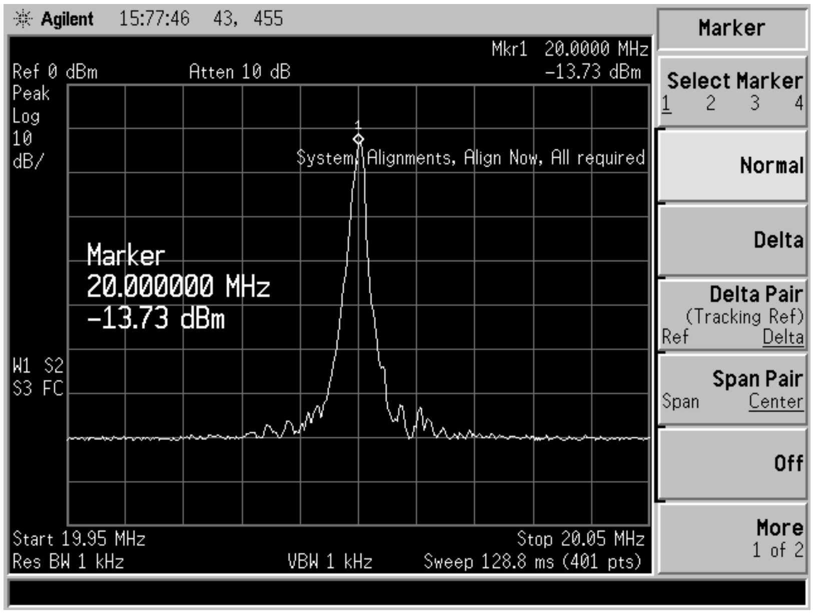


Figure 14. Room temperature TCXO phase noise.

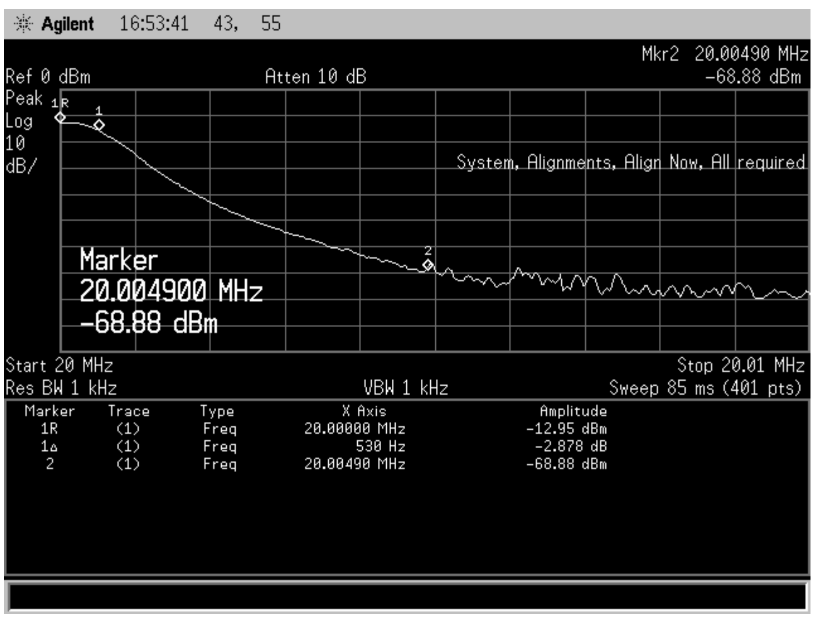
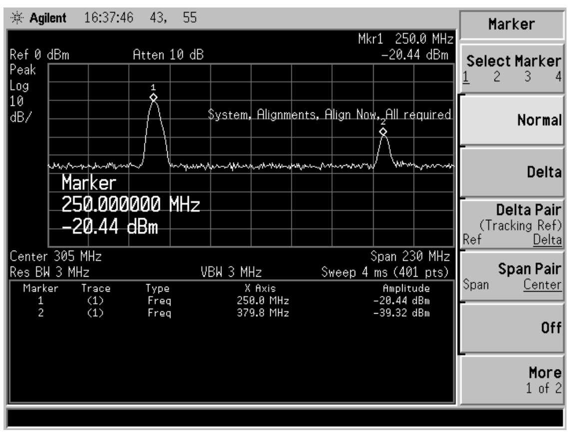


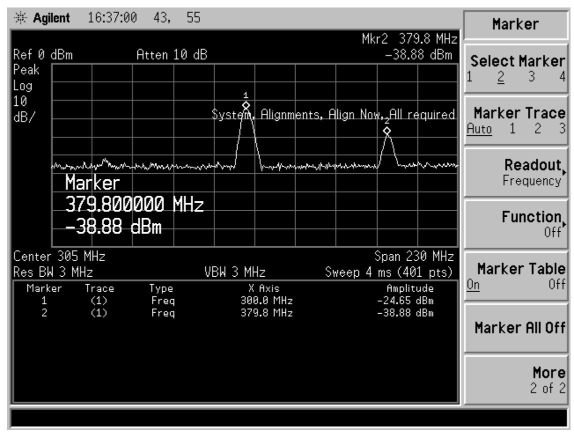
Figure 15. Room temperature TCXO phase noise (for measurement).

4.1.3 Phase noise of the TX

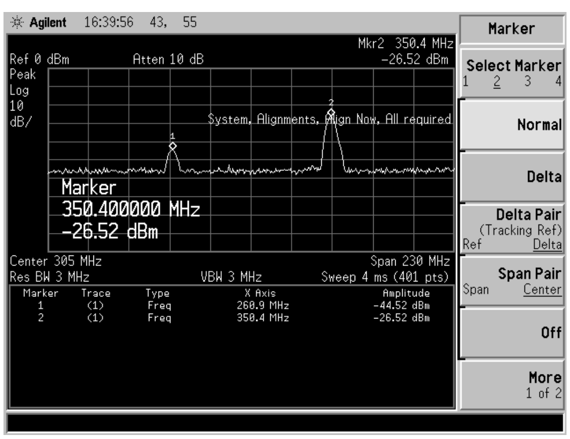
The output signal at the TX port directly affects the data used for depth calculations. The TX output over the entire frequency range is shown in *Figure 16*. The software for the SDR-Kits VNA allows the multiplication of the DDS clock signals to be changed. To increase accuracy, the multiplication was set to be as high as possible. The two DDSs also have two different multiplication factors. The static multiplication factors used for DDS1 and DDS2 were 19 and 20, respectively. This caused a noise peak at the clock frequency of the DDS in the TX port around 380 MHz.



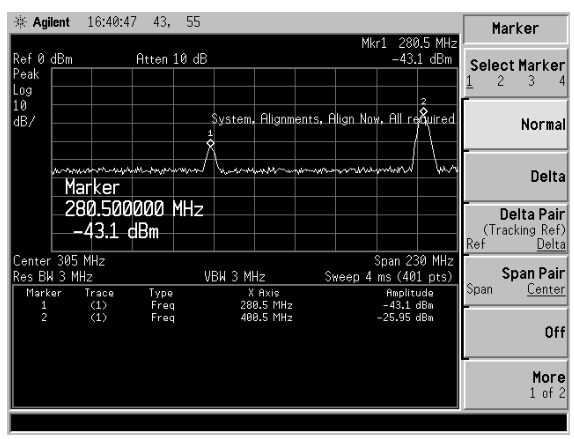
(a) TX phase noise 250 MHz



(b) TX phase noise 300 MHz



(c) TX phase noise 350 MHz



(d) TX phase noise 400 MHz

Figure 16. SDR-Kits VNA TX phase noise at room temperature.

4.1.4 Room-temperature delay-line test

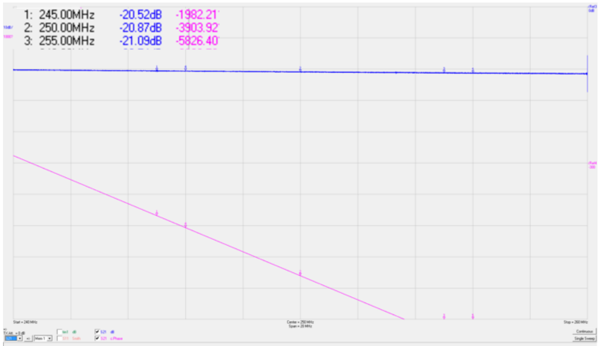
Delay-line tests are used to simulate the detection of the depth of an ice sheet. An RFC400 coaxial cable was used for signal transmission. The RX and TX ports of the SDR-Kits VNA were connected to this coaxial cable. The S_{21} parameter was then used to calculate the delay time. Setting the unwrapped phase in the VNA-supported software enabled the network analyzer to display traces of the data without limitation between 0 to 360 degrees. In this manner, the phase change was able to be measured over thousands of degrees instead of being restricted to ±180 degrees. The signal transmission velocity of the coaxial cable was $0.85c$. Since the coaxial cable has a constant electrical delay over the frequency range, the trace is a straight line, and the delay is calculated as

$$\text{Delta phase} = \frac{(\text{electrical delay (s)} \bullet 360 \text{ (degrees/period)})}{(\text{period of the waveform (s/period)})} \quad (2)$$

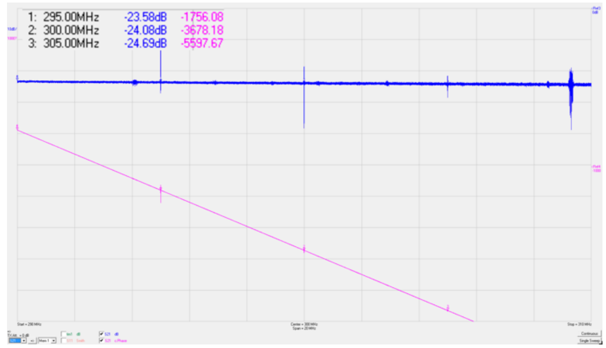
$$\text{Delay phase} = \text{Electrical Delay} \bullet \text{Frequency} \bullet 360 \quad (3)$$

$$\text{Slope} = \text{electrical delay} \bullet 360 \quad (4)$$

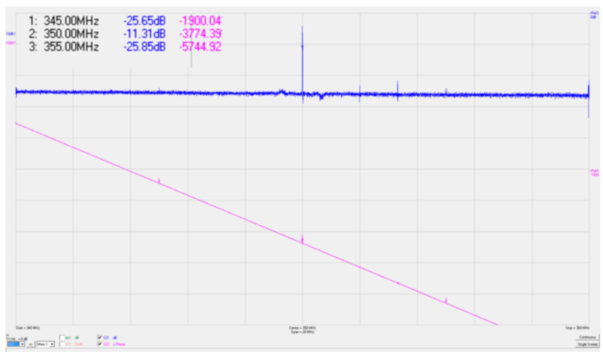
The delay line length was calculated at room temperature using Equation 4. *Figure 17* shows the unwrapped phase plot from the VNA output. S_{21} shows the phase at three frequencies. The ultimate length of the delay line is the average of these three measurements, as shown in *Table 6*.



(a) Delay line test 250 MHz



(b) Delay line test 300 MHz



(c) Delay line test 350 MHz

Figure 17. SDR-Kits VNA room temperature delay line tests.

Table 6. Room-Temperature Delay-Line Test for SDR-Kits VNA

Temperature (°C)	Measured Length (m)
Room Temperature	272.2967

4.2 SDR-Kits VNA Low Temperature

Low-temperature tests simulate the operating environment when using an ice-penetrating radar in the field. To compare datasets and testing results, all factors were kept the same except for the temperature. A thermal chamber was used to reduce the temperature surrounding the test devices. The VNA was cooled in the chamber for 5 hours to make sure its internal temperature matched the chamber temperature.

4.2.1 Frequency stability over dynamic temperature change

Dynamic temperature tests are used to simulate actual weather conditions in the field. With reference to *Figure 18*, the chamber was programmed to start at +23 °C. The chamber held at +23 °C for two hours. After that, the temperature was cooled down to −25 °C over two hours. The chamber held this temperature for two hours. After that, over ten hours the temperature in the chamber was increased back to +23 °C. This progression was intended to simulate one day of the more severe temperature changes that usually take place in an arctic environment in order to test the frequency stability of the VNA. The VNA remained connected to the frequency counter using the GPS OCXO external reference signal. *Figure 19* reports the frequency stability over the temperature changes, and the measurements are summarized in *Table 7*.

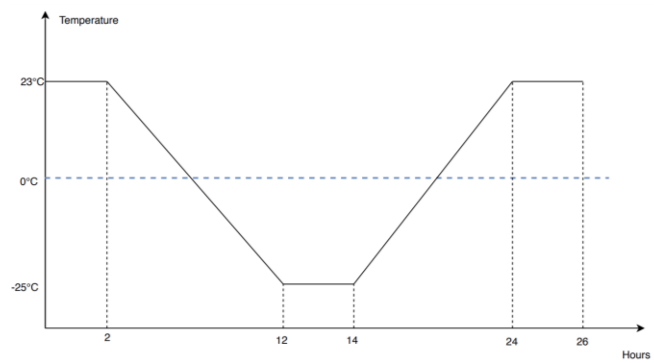


Figure 18. Chamber temperature settings.

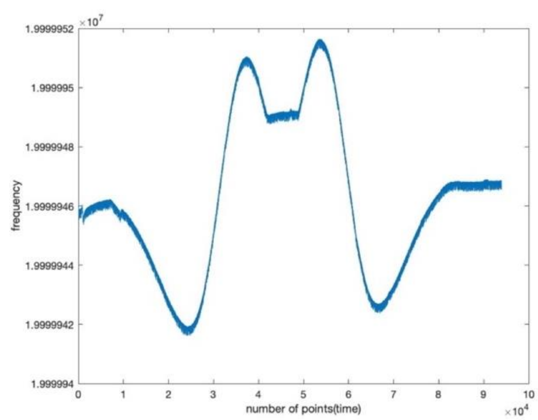


Figure 19. Frequency stability over dynamic temperature changes for the SDK-Kits VNA.

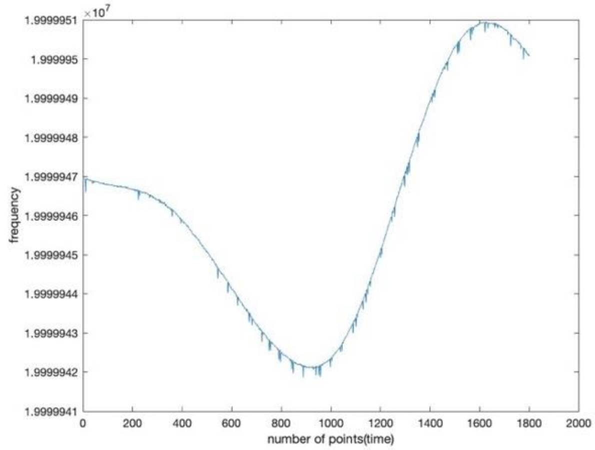
Table 7. Summary of Frequency Stability over Dynamic Temperature Changes for the SDR-Kits VNA.

Parameter	**Frequency**	**Unit**
Max	19,999,951. 641	Hz
Min	19,999,941.612	Hz
Average	19,999,946.398 1	Hz
Disparity	10.028 521 098 1	Hz
Standard Deviation	2.695 965 411 98	Hz

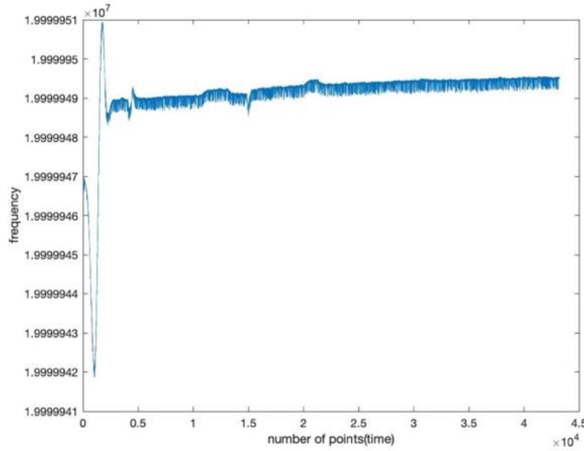
The TCXO uses a compensating network to maintain the frequency stability. As shown in Table 7 above, the frequency disparity of the oscillator was much larger than it was at room temperature. The change of frequency output is symmetric with respect to the temperature change. The approximate curve for the temperature frequency can be expressed as a third-order polynomial or a fifth-order polynomial and the curve in *Figure 19* matches the theoretical result [“TCXO, Temperature Compensated Crystal Oscillator”, n.d.].

4.2.2 Frequency stability with static temperature

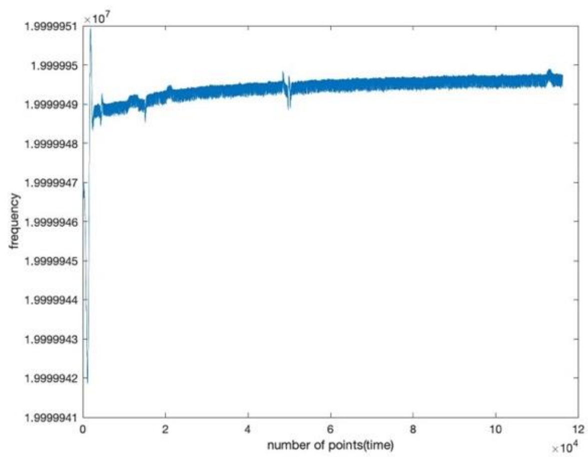
Static temperature tests use the same method as the room temperature tests, but the VNA is in the thermal chamber. To test the VNA under the harshest possible conditions, short-, medium-, and long-term stability tests were performed at −25 °C. The phase noise of the TCXO and TX was measured at −25 °C as well. The delay-line test was implemented at temperatures ranging from 0 °C to −25 °C.



(a) 30 minutes



(b) One day



c) Three days

Figure 20. SDR-Kits VNA low Temperature frequency stability plot.

Table 8. SDR-Kits VNA Low-Temperature Frequency Stability Summary

Parameter	Frequency	Unit
30 Min Short Term		
Mean	19,999,946.113 2924	Hz
Disparity	9.088 458 299 636 84	Hz
Variance	8.080 912 669 740 48	Hz
Standard derivation	2.842 694 614 224 41	Hz
One Day Medium Term		
Mean	19,999,949.133 741 4	Hz
Disparity	9.088 458 299 636 84	Hz
Variance	0.786 711 313 914 211	Hz
Standard derivation	0.886 967 481 880 937	Hz
Three Day Long Term		
Mean	19,999,949.442 509 6	Hz
Disparity	9.088 458 299 636 84	Hz
Variance	0.360 359 944 897 180	Hz
Standard derivation	0.600 299 879 141 401	Hz

The most substantial variation was seen at the beginning of the tests. The primary factor affecting stability is the internal heating of the circuit when the circuit first powers up. During long-term stability testing, the stability was approximately 0.27 ppm. As the operating time increased, the stability was largely improved so that the curve became smoother and the frequencies settled around 19.999949 MHz.

4.2.3 TCXO low-temperature phase noise

For a clear comparison of the internal oscillator stability, testing was performed at −25 °C. *Figure 21* and *Figure 22* show no noticeable deviation in the phase noise. Therefore, the TCXO is a reliable signal source for the ice-penetrating radar system at low temperatures.

Figure 21. SDR-Kits VNA low temperature phase noise.

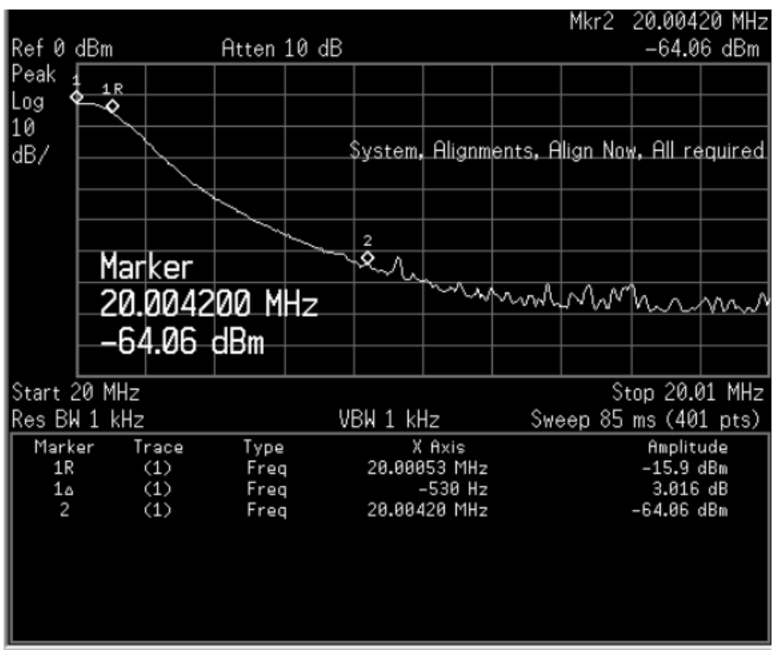
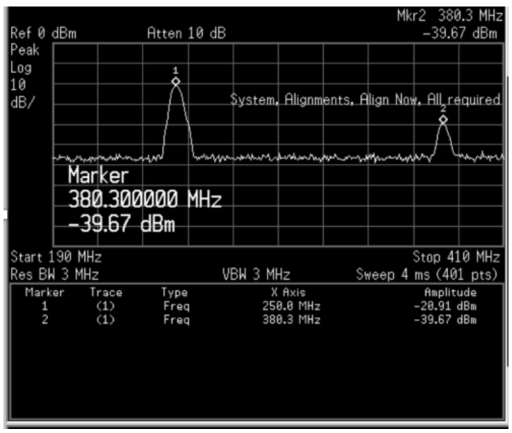


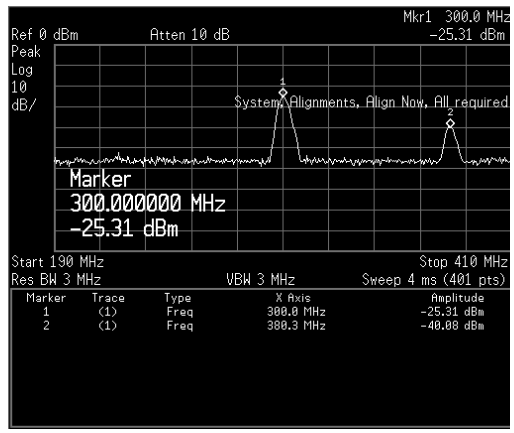
Figure 22. SDR-Kits VNA low temperature phase noise (for measurement).

4.2.4 TX low temperature phase

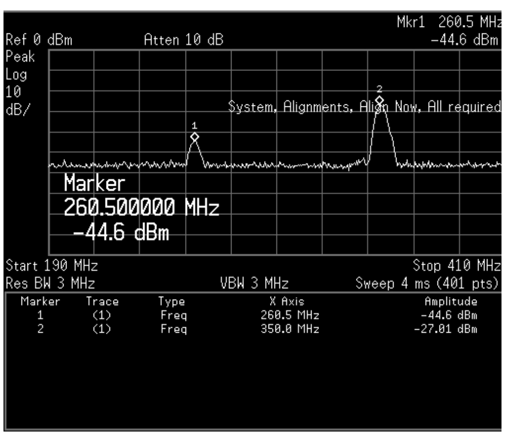
The TX phase noise spectrum at −25 °C is shown in *Figure 23*. The 380-MHz peak appeared when the frequency was below 300 MHz, just as it did at room temperature. The frequency output is roughly the same at room temperature and at low temperature. The trouble peak still appears and no noticeable change can be observed compared with room temperature.



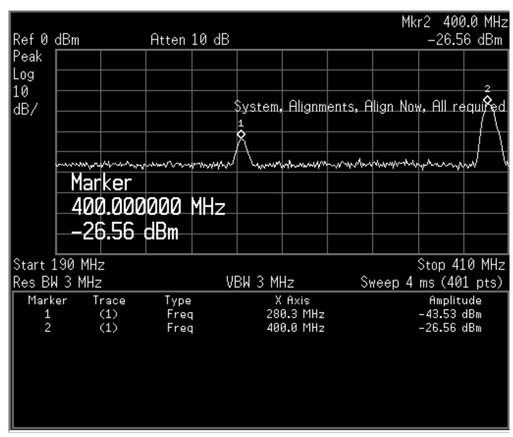
(a) 250 MHz



(b) 300 MHz



(c) 350 MHz



(d) 400 MHz

Figure 23. SDR-Kits VNA TX low temperature phase noise tests.

4.2.5 Low-temperature delay-line tests

The delay line tests were performed at temperatures ranging from 0 °C to −25 °C. At each temperature setting, the VNA was initially held at that temperature for 5 hours so that the entire device reached temperature equilibrium. The final calculated length represents the average of three measurements taken at the same temperature. From 0 °C to −25 °C, the length, as measured by the disparity in radar signals, changed by about 2.1 cm. While this is larger than the 1-cm error requirement, it is still a very small effect.

Table 9. Delay-Line Test Under Various Temperatures for the SDR-Kits VNA Summary

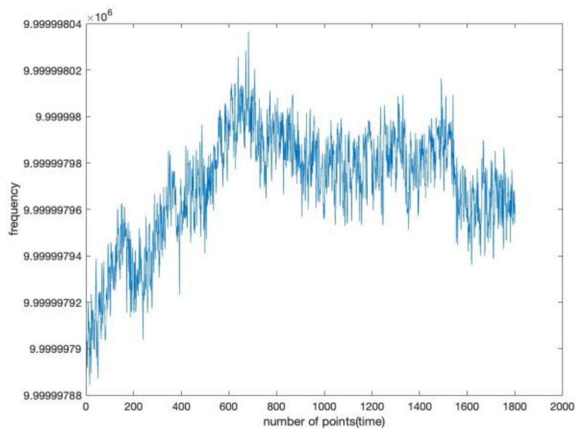
Temperature (°C)	Measured Length (m)
Room Temperature	272.297
0	272.298
−5	272.298
−10	272.283
−15	272.300
−20	272.276
−25	272.318

4.3 TTR506 VNA Room Temperature

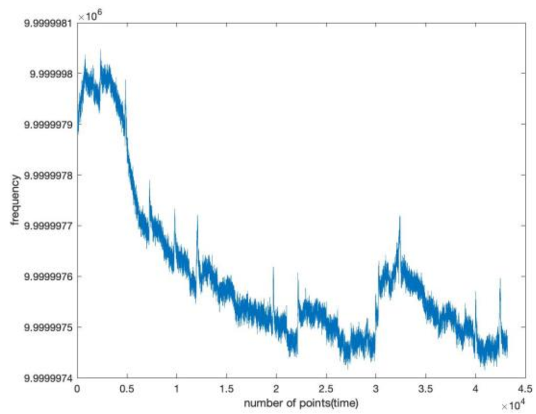
To examine the performance of the TTR506A VNA and create a comparison set, it is necessary that the test system remains the same apart from the replacement of the VNA. Unfortunately, as mentioned above, the cryo-oven experienced an issue (perhaps related to the solenoid valve SV1 that may be defective) such that the cooling apparatus of the chamber was no longer operational. Several alternative cooling methods were tried, but none could satisfy the testing requirements. For this reason, only room temperature testing could be performed on the candidate VNAs. Room-temperature testing was implemented as it was for testing with the SDR-Kits VNA to reduce other noise factors. The resulting data were used to compare the performance of the VNAs. Room-temperature tests included measurements of frequency stability, internal oscillator phase noise, and TX port phase noise. The same test equipment as that described in above was used in the following tests.

4.3.1 Frequency stability over time

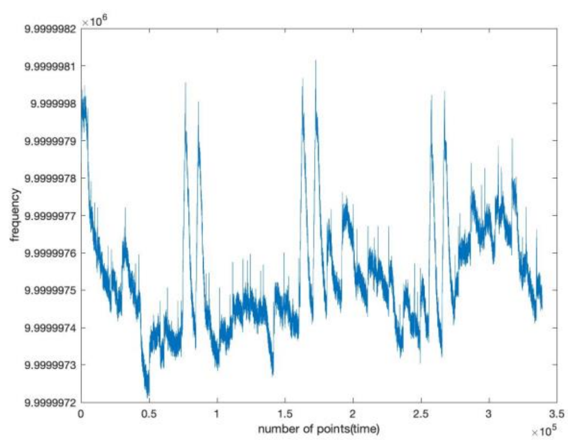
The TTR506A uses a 10-MHz internal reference clock instead of a 20-MHz clock. The output of the TTR506A's 10-MHz clock was measured by the frequency counter with a highly precise, GPS-trained signal. The short-term, medium-term, and long-term frequency outputs are plotted in *Figure 24* summarizes the output frequencies. Compared with the SDR-Kits VNA, the TTR506A internal reference was found to be much more stable. Over long-term testing, the output of the internal clock deviated by about 2 Hz around the desired 10-MHz target value, and the difference in the max and min over three days was less than 1 Hz. Overall, the TTR506A internal reference was closer to the desired 10-MHz target value than the SDR-Kits TCXO and showed less deviation.



(a) 30 minutes



(b) One day



(c) Three days

Figure 24. TTR506A VNA room-temperature frequency stability plots.

Table 10. TTR506A VNA Room Temperature Frequency Stability Summary

Parameter	Frequency	Unit
30 Min Short Term		
Mean	9,999,997.970 217	Hz
Disparity	0.152 036 609 128	Hz
Variance	0.000 589 567 274	Hz
Standard derivation	0.024 281 006 464	Hz
One Day Medium Term		
Mean	9,999,997.601 928	Hz
Disparity	0.632 416 300 475	Hz
Variance	0.022 742 555 760	Hz
Standard derivation	0.150 806 351 858	Hz
Three Day Long Term		
Mean	9,999,997.537 575	Hz
Disparity	0.904 175 391 420	Hz
Variance	0.022 387 422 500	Hz
Standard derivation	0.149 623 439 372	Hz

4.3.2 Phase noise of TTR506A internal reference

The phase spectrum of the TTR506A internal reference signal is shown in *Figure 25*. The 10-MHz frequency of the TTR506A had a sharper peak than the SDR-Kits VNA output under the same testing conditions. The phase noise is less than -38 dBc/Hz at 5 kHz (*Figure 26*). The TTR506A output phase noise is slightly larger than that of SDR-Kits VNA.

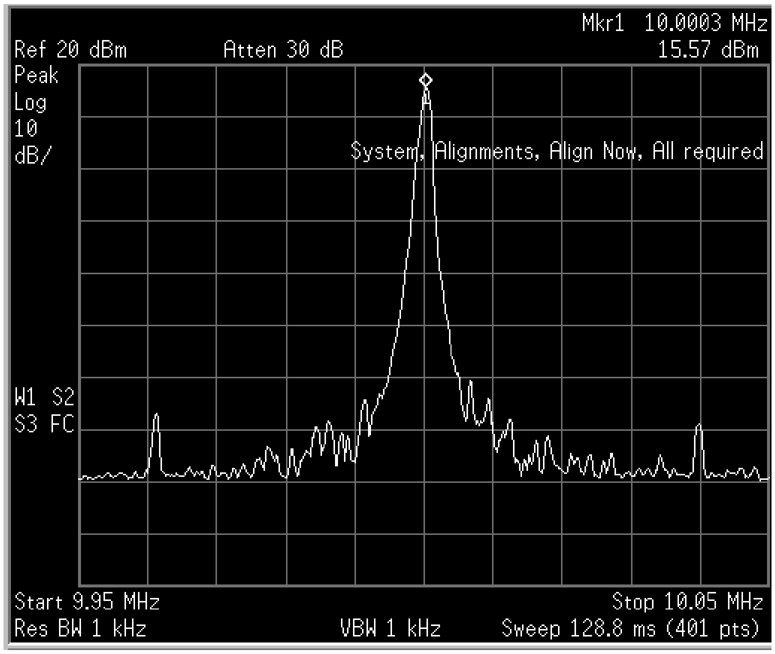


Figure 25. TTR506A phase noise under room temperature.

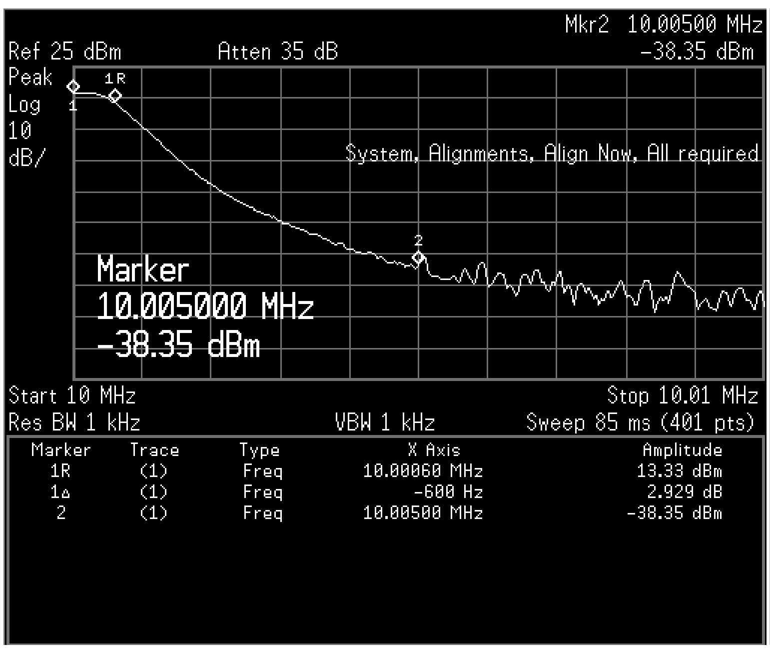
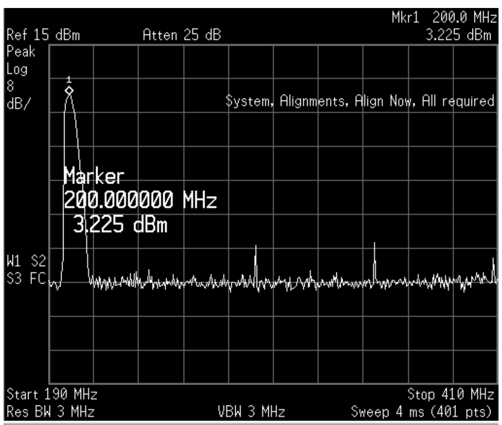


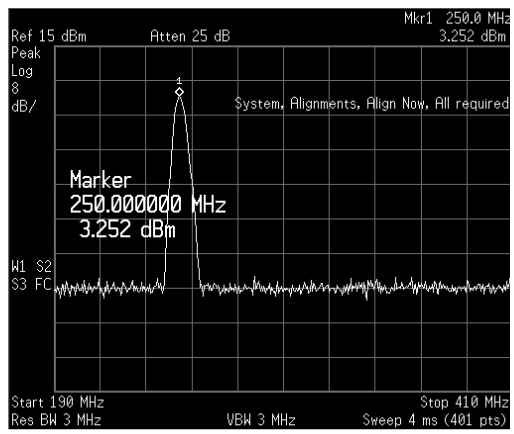
Figure 26. TTR506A phase noise under room temperature (for measurement).

4.3.3 TX phase noise of TTR506A

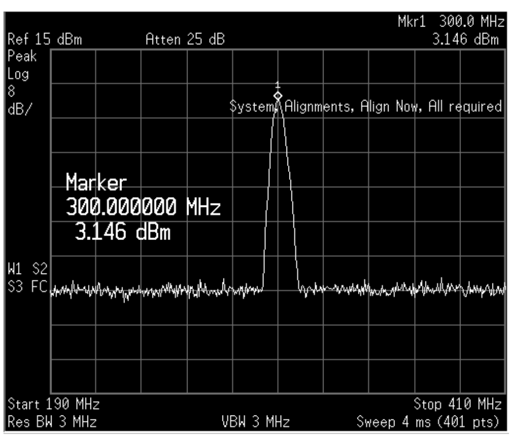
The signal from the TX port was the critical factor that affected our measurements. A clear output signal with less phase noise would increase the accuracy of the depth measurements and improve the field test results. *Figure 27* shows the output of the TX port signal over the frequency range of 200 to 400 MHz. Compared with the SDR-Kits VNA TX output, the TTR506A output signal was much clearer. Over the entire frequency range, no noticeable phase noise was introduced.



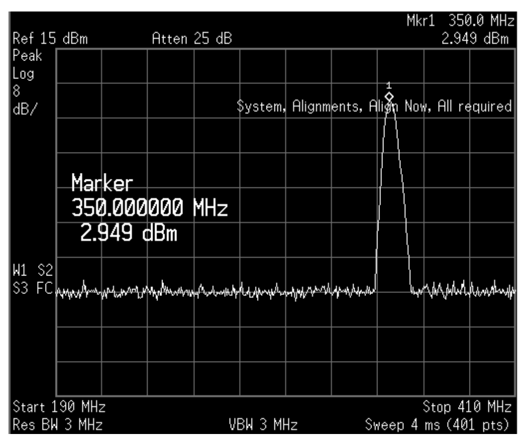
(a) TTR506A TX output at 200 MHz



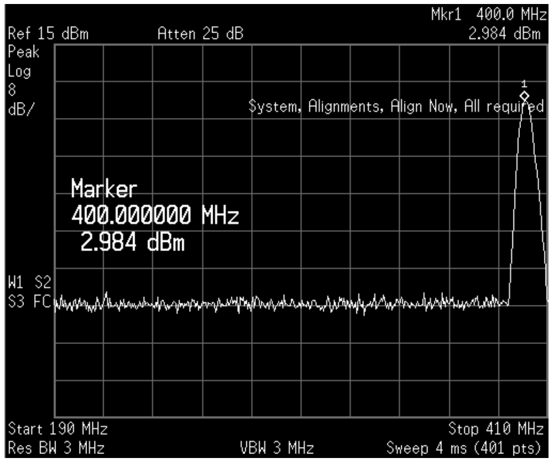
(b) TTR506A TX output at 250 MHz



(c) TTR506A TX output at 300 MHz



(d) TTR506A TX output at 350 MHz

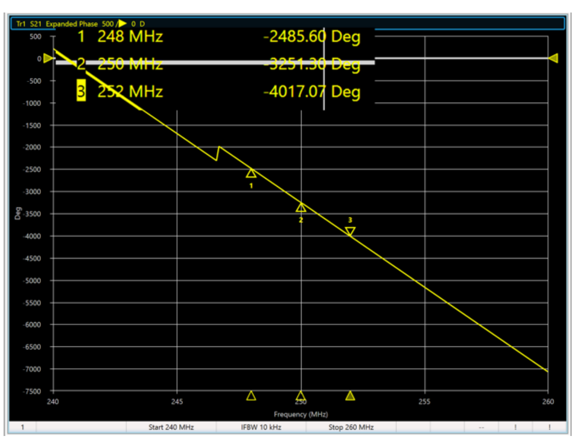


(e) TTR506A TX output at 400 MHz

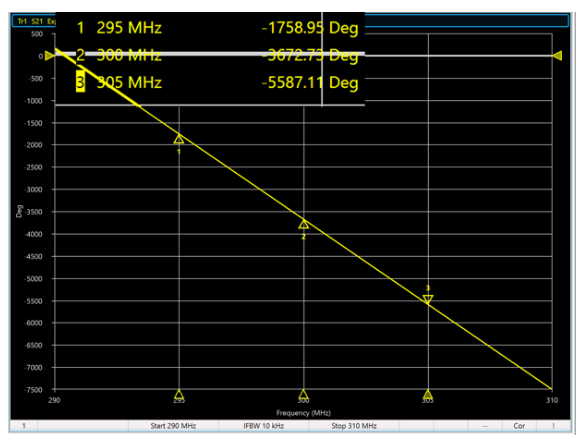
Figure 27. TTR506A TX spectrum at room temperature tests.

4.3.4 TTR506A delay-line test

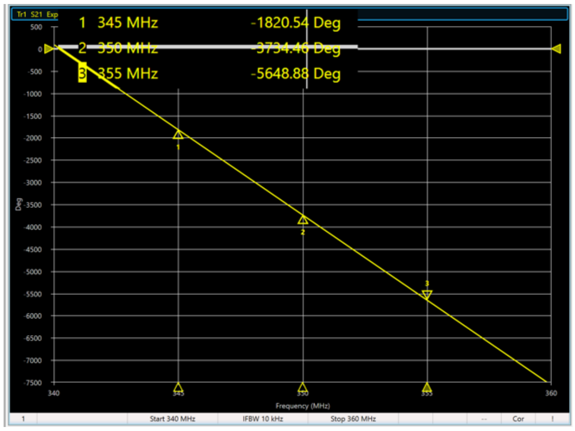
The delay-line test for the TTR506A VNA was conducted using the same method as the delay line test for the SDR-Kits VNA. The output phase is shown in unwrapped plots, and the delay time is calculated by using Equations 2, 3, and 4. To reduce the error, the result is given as the average of three measurements taken at different frequencies, shown in *Figure 28* (note, these plots look different than *Figure 17* as each VNA uses different display software).



(a) Delay line test at 250 MHz



(b) Delay line test at 300 MHz



(c) Delay line test at 350 MHz

Figure 28. TTR506A VNA delay-line test at room temperature plots.

Table 11. TTR506A Room-Temperature Delay-Line Test

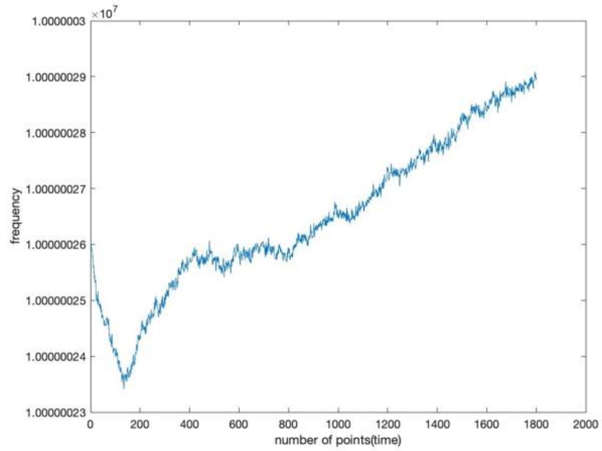
Temperature (°C)	Measured Length (m)
Room Temperature	272.179

4.4 Keysight P5004A VNA Room Temperature

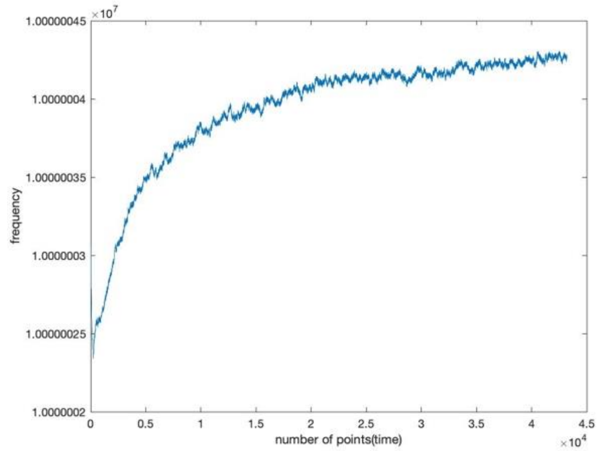
The Keysight P5004A VNA was also a candidate for the ice-penetrating radar system. The frequency stability, phase noise, and TX port phase noise were examined at room temperature. An additional frequency stability test over temperature increase was also discussed. The collected data were compared to the other two VNAs.

4.4.1 P5004A VNA frequency stability over time

The Keysight P5004A VNA used a 10-MHz internal reference with ±7 ppm. Due to the limited time available, the frequency output was only collected for 30 minutes short term and one-day medium term. The P5004A VNA is the only one that has a fan. The frequency stability is shown in *Figure 29*. With increasing operating time, the stability decreased, but the rate of change also reduced.



(a) 30 minutes



(b) One day

Figure 29. P5004A room temperature frequency stability plots

Table 12. P5004A VNA Room Temperature Frequency Stability Summary

Parameter	Frequency	Unit
30 Min Short Term		
Mean	10,000,002.647 824	Hz
Disparity	0.566 831 501 200	Hz
Variance	0.019 074 650 734	Hz
Standard derivation	0.138 111 008 737	Hz
One Day Medium Term		
Mean	10,000,003.930 114	Hz
Disparity	1.965 974 900 871	Hz

Variance	0.154 948 100 059	Hz
Standard derivation	0.393 634 475 192	Hz

4.4.2 P5004A phase noise at room temperature

The P5004A's phase spectrum is shown in *Figure 29* below. Compared with the TTR506A, the amplitude of the peak is around 10 dBm smaller. The phase noise is less than -48 dBc/Hz at approximately 5 kHz(*Figure 30*). The overall phase noise plot of P5004A VNA is slightly better than that of TTR506A VNA.

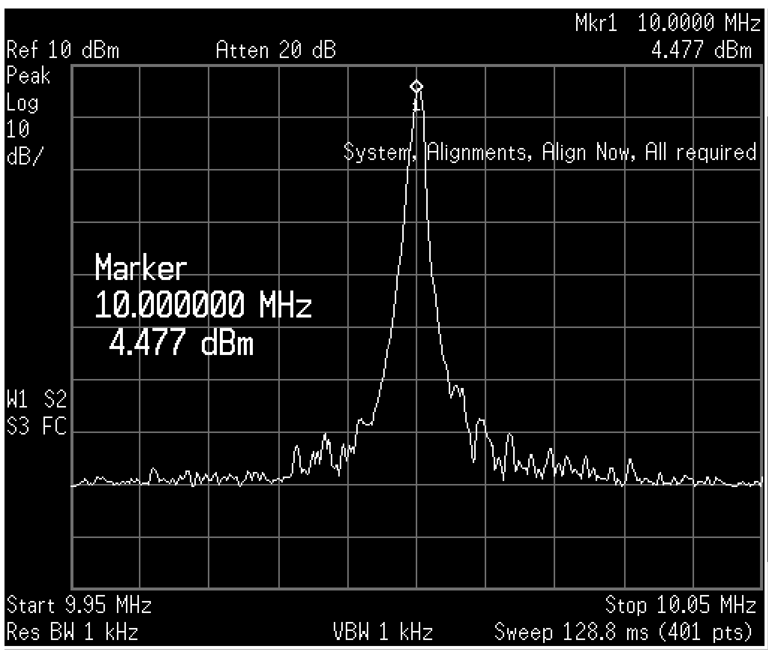


Figure 29. P5004A VNA phase noise

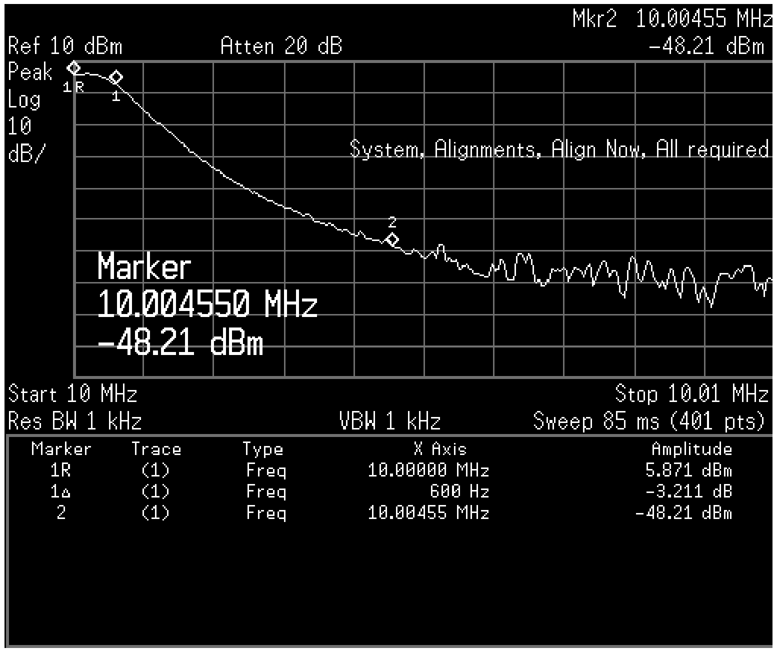
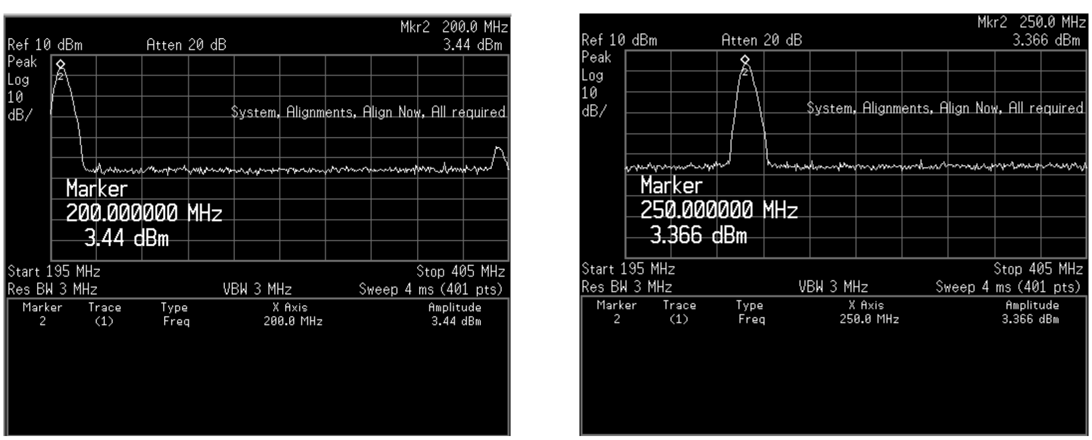


Figure 30. P5004A VNA phase noise (for measurement).

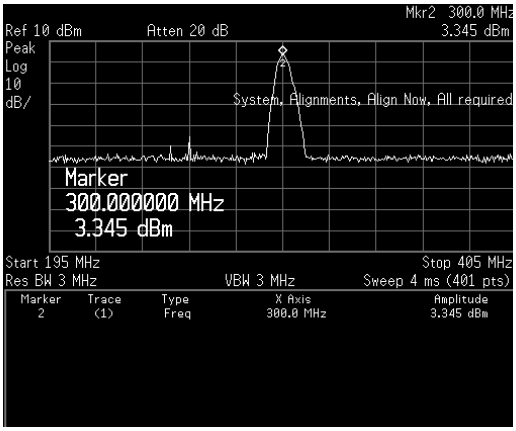
4.4.3 P5004A TX phase noise at room temperature

The TX port outputs over interested frequency range as shown in *Figure 31*. Compared with the SDR-Kits VNA, the peak of the spectrum only appears at user set values. The amplitude of the peak is similar to TTR 506A VNA and no significant phase noise peak appears over the frequency range.

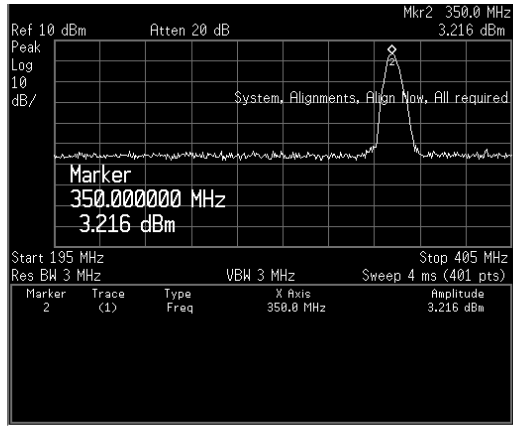


(a) TX at 200 MHz

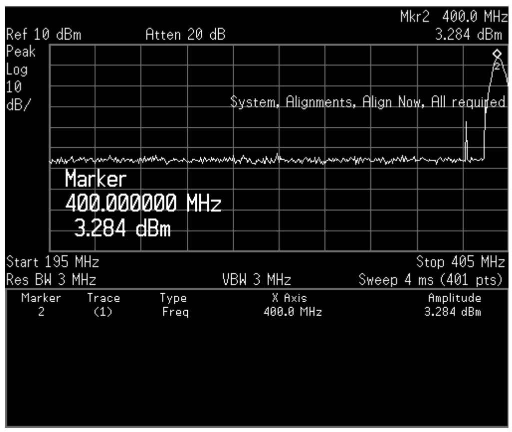
(b) TX at 250 MHz



(c) TX at 300 MHz



(d) TX at 350 MHz



(e) TX at 400 MHz

Figure 31. P5004A TX phase noise plots

4.4.4 P5004 Frequency stability over temperature change

To explore the frequency stability over temperature change, the P5004 VNA was tested under a dynamic temperature curve. The outside environmental temperature of the VNA increased from room temperature (23 °C) to 45 °C and then dropped back to room temperature (23 °C) over 8 hours. The observed frequency curve is shown in *Figure 32* below. The disparity of the maximum and minimum dramatically increased to 30.141Hz. The internal reference output frequency is 10 MHz ± 7 ppm; therefore, a 30-Hz deviation is within the 7 ppm (70 Hz) specification. Keysight suggests the user put the device at a stable surrounding temperature environment for 60 minutes before turning on [Keysight, 2019]. Therefore, a larger frequency output deviation over dynamic temperature change is expected.

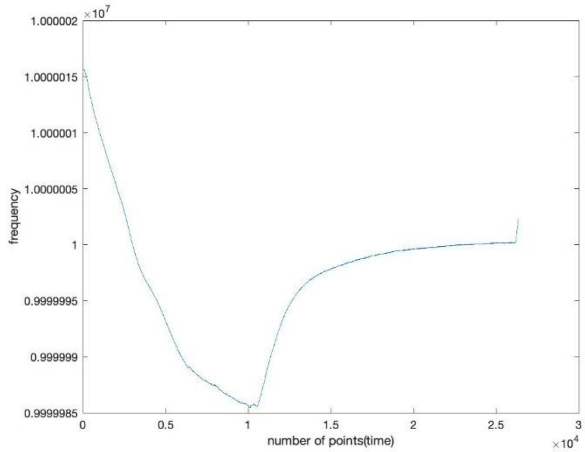


Figure 32. P5004A Frequency stability over dynamic temperature change

Table 13. P5004A VNA Dynamic temp frequency stability summary

Parameter	**Frequency**	**Unit**
Max	10,000,015.608	Hz
Min	9,999,985.467	Hz
Average	9,999,996.854	Hz
Disparity	30.141 522 621	Hz
Standard Deviation	6.369 846 265 78	Hz

Chapter 5

Conclusions

This thesis evaluated several VNA candidates for an ice-penetrating radar system. The internal reference frequency stability, phase noise, TX port frequency stability, and delay-line tests were performed for three VNAs. Due to a mechanical issue with the chamber and the availability of time, the Tektronix TTR506A VNA and Keysight P5004A VNA were tested primarily at room temperature.

During system tests, the TTR506A VNA had a highly stable performance among all other VNAs at room temperature. The internal short-term, medium-term, and long-term stability of the TTR506A VNA were 0.015 ppm, 0.0632 ppm, and 0.0904 ppm, respectively; the SDR-Kits VNA had stabilities of 0.0416 ppm, 0.1663 ppm, and 0.1663 ppm, respectively; and the P5004A VNA were 0.0567 ppm and 0.1996 ppm with respect to short-term and medium-term. Furthermore, the internal reference oscillator and the TX phase noise of the TTR506A was lower than that of P5004A VNA. Observing the TX output signal over the entire required 200 MHz to 400 MHz frequency span, there was no noticeable spurious peak for the TTR506A VNA and the P5004A VNA, unlike for the SDR-Kits VNA. Overall, the Tektronix TTR506A proved more accurate and reliable in all testing factors, suggesting that it is a good candidate for replacing the SDR-Kits VNA in the radar system.

However, all the tests described in this project were performed in a laboratory setting with fewer environmental factors than would be seen in a field test. Furthermore, low-temperature testing was not examined due to the issue with the chamber. To evaluate the feasibility of replacement, it is necessary to test all three of these VNAs under actual low-temperature operating conditions. Furthermore, an entire ice-penetrating radar that includes the antenna and amplifier design needs to be developed by researchers. Since both Keysight P5004A VNA and Tektronix TTR506A VNA requires the addition DC power supply, a low-noise power source needs to be designed to improve the portability of the device and increase the device’s convenience for researchers.

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Appendix

VNA Testing Procedure

For low-temperature testing, please read the user manual of the environmental chamber from the manufacturer to correctly set chamber operating mode and temperature point or range.

Please read the operating and storage temperature requirements of the VNA to avoid damaging the devices.

1) Frequency stability test
   Device needed: VNA
   Frequency Counter
   External GPS Signal
   Hewlett Packard 58503A GPS-trained OCXO
   BMA Cable
   Host Computer
   (Environmental Chamber)
   Procedure:
   a) Connect frequency counter external reference port with the GPS-trained OCXO signal.
   b) Power up the VNA with USB or manufacturer-specified power adapter.
   c) Connect VNA to the host computer and enable the reference out via software.
   d) Connect VNA reference out port to frequency counter with BMA cable and set specific reading requirement on the frequency counter.
   e) Save data or trending plot to external Flash Drive.

2) Internal phase noise measurement
   Device needed: VNA
   Spectrum analyzer
   BMA Cable
   Host Computer
   (Environmental Chamber)
   Procedure:
   a) Power up the VNA with USB or manufacturer-specified power adapter.
   b) Connect VNA to the host computer and enable the reference out function via software.
   c) Connect VNA reference out port to spectrum analyzer input.
   d) Scale the plot and add markers to the points of interest.
   e) Save plots to external Flash Drive.

3) TX phase noise measurement
   Device needed: VNA
   Spectrum analyzer
   BMA Cable
   Host Computer
   (Environmental Chamber)
   Procedure:
   a) Power up the VNA with USB or manufacturer-specified power adapter.
   b) Connect VNA to the host computer and set frequency out.
   c) Calibrate the VNA!
   d) Connect VNA TX port to spectrum analyzer input.
   e) Scale the plot and add markers to the points of interest.
   f) Save plots to external Flash Drive.

4) Delay line tests
   Device needed: VNA
   Delay line
   Host computer
   (Environmental Chamber)
   Procedure:
   a) Power up the VNA with USB or manufacturer-specified power adapter.
   b) Connect VNA to the host computer and set frequency range.
   c) Calibrate the VNA!
   d) Connect VNA TX and RX ports to the delay line.
   e) Read S_{12} or S_{21} expanded phase plot and add markers
   f) Calculate the delay time and delay line length using Equation 2, 3 and 4

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EDUCATION:

Pennsylvania State University Aug 2015-May 2019

Major: B.S. in Electrical Engineering| Schreyer Honor Student

Minor: Mathematics

AWARDS & CERTIFICATES:

- NI Certified LabVIEW Associate Developer (CLAD) PSU, University Park, Nov 2017
- Academic Achievement Award PSU, Greater Allegheny, Apr 2017
- Faculty Award for Academic Excellence in Engineering/Earth & Mineral Science PSU, Greater Allegheny, Apr 2017
- Kieffer Scholarship $2900 PSU, University Park, 2017, 2019
- Dean's List PSU 2015, 2016, 2017, 2018

EXPERIENCE HIGHLIGHTS:

Robomaster Robotics Competition | Co-founder of PSU Robo X PSU, University Park, PA May 2017-Mar. 2019

- Participated in mechanical design and electrical control system design of 2 robots for competition.
- Recruited 40 members, organized training lectures concerning automatic drive, machine learning.
- Organized workshops for engineering freshmen to develop new robots to prepare for the new robotic competition.

System Design Lab | Undergraduate Research Assistant PSU, University Park, PA Jan 2017-April 2019

- Used vector networking analyzer to simulate ice penetrating radar system.
- Designed low temperature VNA radar testing protocol.
- Acquired oscillator operating stability data in short-term and long-term simulated testing

Honeywell Shanghai, Honeywell Process Solution Department | Testing Engineer Shanghai, China May 2018-July 2018

- Tested remote terminal units (RTU) and programmable logic controller (PLC).
- Developed a program to trace bug frequency.
- Developed an automation system to verify end to end scenarios and perform configurations.

PROJECTS:

Object Detection PSU, University Park, PA Oct 2018

- Used correlation to score the similarity of the template to the image with rotation and scaling; Used non-maximal suppression to locate and enumerate template matches; Used graphic overlays to enumerate each detection with accuracy higher than 80%

Microwave Amplifier PSU, University Park, PA Nov 2018

- Designed and built amplifiers and oscillators and characterize their stability and performance in DC biasing, impedance matching, noise matching; Used Agilent Advanced Design System (ADS) to simulate and analyze RF circuit design;

3D Model Printing Independent Study | Assistant PSU, Greater Allegheny, PA Jan 2017-May 2017

- Decomposed complex geometric models into simple parts and manipulated their mathematical expressions' parameters for efficient programming.
- Used Mathematica to print hyperboloids, hyperbolic paraboloids, spheroids, neural cells and atomic structures as teaching tools, and print paw-print-shape keychains with PSU Nittany Lion face as souvenirs for perspective students.

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