CONSTRUCTION OF AN EXPERIMENTAL RADAR SYSTEM

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ABSTRACT

CONSTRUCTION OF AN EXPERIMENTAL RADAR SYSTEM

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In this thesis, an Experimental Radar System is designed and constructed for use in experimental radar studies such as clutter measurement and target detection, both in the laboratory and outdoor. COTS laboratory equipments are utilized as hardware elements of the radar and MATLAB is used as signal processing and user interface software tool. Vector signal generator (as transmitter), spectrum analyzer with vector signal analysis (as receiver), a high power amplifier, a low noise amplifier, horn antennas and a computer are the hardware units of the system. Various transmit signals are generated and pulse Doppler processing is performed at the receiver side. The system is controlled through the user interface which runs on a PC.

Keywords: Radar Design, Radar Elements, Signal Generator, Spectrum Analyzer, Pulse Doppler Processing

ÖZ

DENEYSEL AMAÇLI BİR RADAR GERÇEKLEŞTİRİLMESİ

KILIÇOĞLU, Nezaket
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Bu tezde, laboratuvar ortamında veya dış ortamlarda, kargaşa ölçümü ve hedef tespiti gibi amaçlarla deneysel olarak kullanılmak üzere bir Deneysel Radar Sistemi tasarlanmış ve gerçekleştirilmiştir. Radar donanımında ticari laboratuvar cihazları kullanılmıştır. Radar arayüzü ve sinyal işleme bölümleri MATLAB ile oluşturulmuştur. Vektör sinyal üreteci (göndermeç olarak), vector sinyal analizi yazılımı ile çalışan spektrum analizör (almaç olarak), bilgisayar, huni antenler, bir yüksek güçlü yükselteç ve bir düşük gürültülü yükselteç donanım elemanlarını oluşturmaktadır. Çeşitli sıkıştırılmış ve modülesiz yayın sinyalleri oluşturulmuş ve almaç tarafında darbe Doppler analizi gerçekleştirilmiştir. Radar sistemi, bilgisayarda koşan arayüz üzerinden kontrol edilebilmektedir.

Anahtar Kelimeler: Radar Tasarımı, Radar Birimleri, Sinyal Üreteci, Spektrum Analizör, Darbe Doppler İşleme

To my parents

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LIST OF ABBREVIATIONS

3D	3 Dimensional
ALC	Automatic Level Control
BNC	Bayonet Neill-Concelman
BW	Bandwidth or Beamwidth
COTS	Commercial On The Shelf
CW	Continuous Wave
DAC	Digital to Analog Converter
DANL	Displayed Noise Level
FFT	Fast Fourier Transform
GPIB	General Purpose Interface Bus
GUI	Graphical User Interface
I/Q	In Phase / Quadrature Phase
LAN	Local Area Network
LNA	Low Noise Amplifier
LO	Local Oscillator
METU	Middle East Technical University
PC	Personal Computer
PRF	Pulse Repetition Frequency
PRI	Pulse Repetition Interval
PSA	Performance Spectrum Analysis
PW	Pulse Width
REF IN/OUT	Reference Input/Output
RF	Radio Frequency
RX	Receiver
SCPI	Standard Commands for Programmable Instrumentation
SNR	Signal to Noise Ratio
T/R	Transmit/Receive
TCP/IP	Transmission Control Protocol / Internet Protocol
TX	Transmitter
USB	Universal Serial Bus
VSG	Vector Signal Generator
YIG	Yttrium-Iron-Garnet

CHAPTER 1

INTRODUCTION

RADAR (**RA**dio **D**etection **A**nd **R**anging) is an important electromagnetic system which is used for detection and ranging of objects by using electromagnetic energy. Radar radiates electromagnetic energy, a portion of which is intercepted by a reflecting object (target) and is reradiated in all directions and the reradiated signal is received and processed by the same radar for detection. The distance of the target is measured by observing the time delay between the transmitted and the received signal and the velocity of the target can be measured by the frequency shift in carrier frequency of the received signal, [1].

The word "radar" was originally an acronym, RADAR, for "radio detection and ranging" but today it has been a standard English noun since the technology is so common, [3].

Considering the major components and subsystems that make up a radar, as well as how they fit together, constructing a radar in the laboratory with COTS test equipments is the main concern of this thesis. Some COTS test equipments were present in the METU Telecommunications Laboratory which were bought for a project that has been conducted between METU and ASELSAN Inc. . The COTS equipments present are as following;

- Agilent E8267D Vector Signal Generator
- Agilent E4446A PSA Spectrum Analyzer
- AML218L1502 Low Noise Amplifier
- Agilent N6030A Arbitrary Waveform Generator

These COTS equipments were evaluated according to their capabilities and technical specifications whether a radar system could be constructed by utilizing them or not. The constructed radar was planned to be used for clutter measurements and analysis. Examining the major components and subsystems making up a radar, decisions are made on the COTS equipments to utilize as radar blocks. In consequence of these considerations, it is decided that a radar system would be constructed by these equipments and vector signal generator, spectrum analyzer and low noise amplifier are chosen to be used as radar blocks. However, these units are not enough to construct a radar and in addition to these equipments, computer, high power amplifier, DC power supply, antennas are also added to the system. The reason for not choosing the N6030A arbitrary waveform generator is that vector signal generator covers the capabilities of it since it has an internal arbitrary waveform generator that lets the user create various waveforms by defining their I/Q data. In addition to these available COTS equipments, by the end of this thesis a newer version of PSA E4446A which is Agilent's EXA N9010A Signal Analyzer, has been available to be used. It has also been utilized in the system as substitute of PSA.

The system is designed as generic as possible to provide opportunity to derive different types of radars from the same design by making small changes. The hardware is chosen from COTS equipments as mentioned, on the other hand the radar processing and defining the transmit signals are in the scope of this thesis. MATLAB is used as the receiver processing and graphical user interface preparation tool. This radar is planned to be used for experimental studies so it is named as "Experimental Radar System".

The capabilities and the possible measurements that could be performed by experimental radar system are told under Chapter 3 and technical specifications of each equipment that affect the experimental radar system are given in relevant chapters.

The purpose of this work is to provide a radar system in the laboratory so that various studies and measurements with that radar can be performed to develop and improve the subjects related to radar systems. For instance, clutter measurements can be performed or performances of different transmit signals and receiver algorithms can be analyzed in the environment. The system has been used for land and cloud clutter measurements. Using the received signal results, clutter is studied statistically. These studies are described in [12].

The experimental radar system is used both in the laboratory and on the roof of METU Electrical and Electronics Department's Building D. In Fig.1, the system is shown when it is being used on the roof. Radar measurements are performed in the environment seen from the roof; moreover, echoes returning from the clouds are also examined.

Figure 1. Experimental Radar System

Main blocks constituting the experimental radar system are the transmitter, receiver, RX and TX antennas, high power amplifier, low noise amplifier and a PC. A graphical user interface is prepared and the transmit signal definitions, received signal analyses, power analyses are conducted via this GUI which runs on the PC. Transmitter and the receiver are connected to the PC via Ethernet and USB, respectively, and they are controlled and programmed via these interfaces.

Operation of the experimental radar system is as follows:

i. The transmit signal’s type and parameters are defined on the PC via the user interface by the user and downloaded to the transmitter to be generated.
ii. The received echoes are captured and saved as “.mat” file on the PC, the saved received signal is in complex I/Q data format.
iii. The saved received signal and corresponding transmit signal is chosen via the user interface and analyzed to generate the 3D graphs of the results showing the Doppler and range information of the received signal. These graphs are presented to the user on the PC’s monitor. The

user examines the results; an automatic detection algorithm has not been implemented yet.

The system is designed as a pulsed radar; unmodulated pulse, Barker 7 coded, P4 type phase coded and random phase coded pulses can be chosen to be generated via GUI, however it is possible to add different transmit signal types to this list. On the receiver side, pulse Doppler analysis is implemented. Transmit signal generation and receiver algorithm will be discussed in the related chapters.

1. Organization of the Thesis

The thesis is organized as follows:

Chapter 2 gives a background on radars and radar types, describes the general block diagram of a radar and discusses every unit in this diagram.

Chapter 3 explains the experimental radar system constructed by means of its block diagram, the equipments and software tools used, general operation and the specifications of the system.

Chapter 4 explains the RX and TX antennas used in the system by giving their radiation patterns, gain values and describing other properties of them.

Chapter 5 explains the instrument used as the transmitter of the system, generation of transmit signals, and the properties of the transmitter.

Chapter 6 explains the specifications of high power RF amplifier and the low noise amplifier used in the system.

Chapter 7 describes the units making up the receiver and discusses every unit's specifications and function. Receiver processing is also described in this chapter.

Chapter 8 describes the functions and usage of the graphical user interface prepared to control the system.

Chapter 9 gives the measurement results of the system and comments on these results.

Chapter 10 describes the problems of the experimental radar system and presents possible improvements for the system.

Chapter 11 gives a brief conclusion of the thesis.

CHAPTER 2

RADAR AND RADAR TYPES

2.1 Description and History of Radar

Radar is an electromagnetic sensor for the detection and location of reflecting objects, [5]. The history of radar extends to the early days of modern electromagnetic theory, [1], [4]. It starts with the Hertz's demonstration of the reflection of radio waves in 1886. Tesla described a concept for electromagnetic detection and velocity measurement in an interview in 1900. In 1903 and 1904, the German engineer Hülsmeyer experimented with ship detection by radio wave reflection and this idea was advocated by Marconi in 1922. Albert H. Taylor and Leo C. Young of the U.S. Naval Research Laboratory (NRL) demonstrated a wooden ship detection in that same year and in 1930 Hyland, also of NRL, first detected aircraft by radar, setting off a more substantial investigation that led to a U.S. patent for what would now be called a continuous wave radar in 1934, [3].

The development of radar accelerated after 1930 and independent studies took places mostly in U.S., Britain, France, Russia, Germany, Italy, and Japan. Efforts began to develop pulsed radar with the first successful demonstration in 1936 by R.M. Page of NRL and by British in 1935. In 1938 British established the Chain Home surveillance radar network that remained active until the end of World War II. In this same year, U.S. demonstrated its first operational system SCR-268 antiaircraft fire control system and in 1939 the SCR-270 early warning system which is used in Pearl Harbor, [3]. After 1940s, radar development has continued to increase by the development of different radar equipments. Although its development was driven by military use, radar now has an increasing range of applications some of which are the police traffic radars, meteorological radars, air traffic control radars.

The operation of radar can be summarized as follows, [5]:

- The radar radiates electromagnetic energy from an antenna, transmit antenna, to propagate in space,
- Some of the radiated energy is intercepted by a reflecting object, a target, located at a distance from the radar,
- The energy intercepted by the target is reradiated in many directions,
- Some of the reradiated energy, echo, is returned to and received by the radar antenna, receive antenna,
- After amplification by the receiver and with the aid of proper signal processing, a decision can be made at the output of the receiver as to whether or not a target echo signal is present. At that time the target location and other information is also acquired.

The transmit and receive antennas of the radar can be separate or a single antenna can be used for both functions together with a duplexer. The transmit signal could be CW or pulsed. Although the operation logic of the radar is the same, it can be grouped into different types according to some major features of it. There are many ways to group radars considering different features, some of which are listed in Fig.2 as a chart.

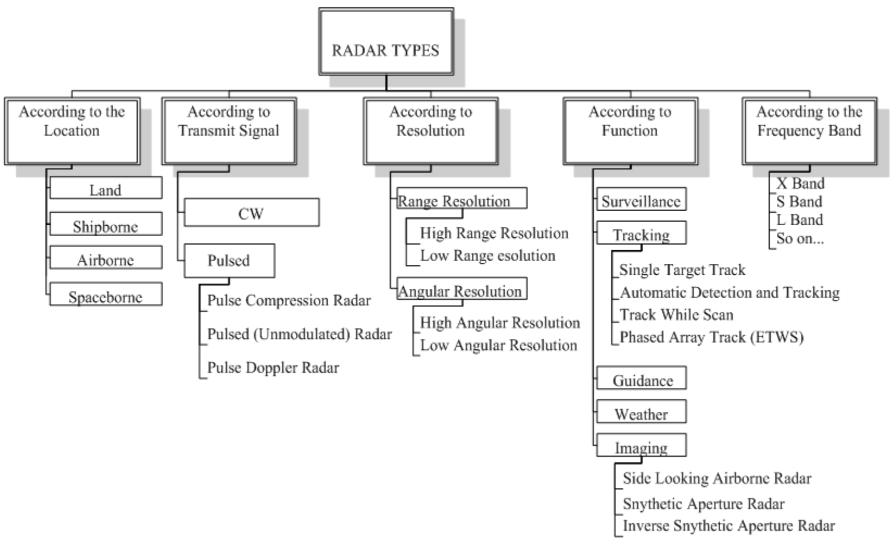


Figure 2. Radar Types

The chart in Fig.2 can be organized differently or it can be expanded by adding various branches. In this figure, radar types according to its location, transmit signal, function, range resolution and frequency band are given.

Common terms to define the features and capabilities of a radar are as follows:

- *Function:* It defines the application area of the radar and the role of the radar. For example, the function of the radar could be air surveillance, guidance of a missile or traffic control. According to the function of it, the capabilities required are designated and the radar is designed according to these requirements. The range resolution requirement of a tracking radar and a surveillance radar are different in a way that the tracking radar needs far better range resolution than the surveillance radar.
- *Operating Frequency:* It is the carrier frequency of the transmitted signal. Radar systems have been operated at frequencies as low as 2 MHz and as high as 220 GHz, [1]. However, most radars operate in the microwave frequency region of about 200 MHz to about 95 GHz.
- *Average Output Power:* It is the average power radiated through the transmit antenna of the radar. Average output power is a better indication of the radar performance than the peak power of the radar.
- *Pulse Width:* It is the duration of the transmit pulse in pulsed radars. Pulse width determines the range resolution and the bandwidth of the radar. For radars using modulated/coded pulses, range resolution and bandwidth are determined by the chip width of the radar.

$$\text{Range Resolution} = \frac{\text{Pulse Width (sec)} * \text{Speed of Light} \left(\frac{\text{m}}{\text{sec}}\right)}{2}$$
$$= \text{Pulse Width}(\mu\text{s}) * 150 \text{ m}$$

$$\text{Bandwidth} = 1/\text{Pulse Width} \quad \text{for a simple pulse of sine wave}$$

- *Pulse Repetition Frequency (Hz):* It is the number of pulses per second. The reciprocal of the PRF is the Pulse Repetition Interval which is the time elapsed from the beginning of a pulse to the beginning of the next pulse. PRF determines the maximum unambiguous range and the maximum Doppler frequency that can be determined by the radar.

$$\text{Max Unambiguous Range(m)} = \frac{(\text{PRI} - \text{PW})(\text{sec}) * \text{Speed of Light (m/sec)}}{2}$$

$$\text{Max Doppler Frequency(Hz)} = \frac{1}{\text{PRI(sec)}} = \text{PRF}$$

- *Range Resolution:* It shows the ability of the radar in distinguishing close targets. The radar can distinguish two separate targets that are placed at least range resolution apart. Range resolution is determined by the band width of the radar.
- *Angular Resolution:* When two targets are placed at the same range but at different azimuth (or elevation) angles, angular resolution of the radar determines if the radar is able to distinguish these targets. Angular resolution of the radar in the azimuth and elevation dimensions is determined by the antenna beamwidths in the respective planes. Fig.3 describes how angular resolution of a radar is found with respect to the 3 dB beamwidth of the antenna in corresponding axis (azimuth or elevation) and the range. Angular resolution changes with respect to the distance from the radar.

$$\text{Angular Resolution} = 2\text{R} \sin\frac{\theta}{2}$$

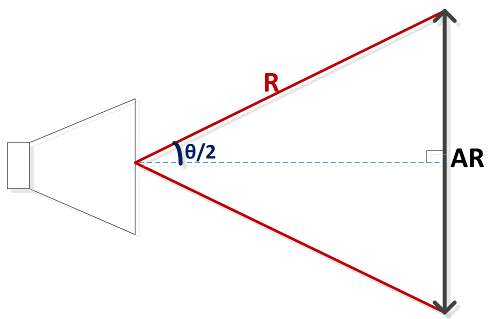


Figure 3. Angular Resolution of Radar

- *Doppler Resolution:* It shows the ability of radar to distinguish the Doppler frequencies of two targets. It is determined by the time length that is processed by pulse Doppler processing, Coherent Processing Interval,CPI,

$$\text{Doppler Resolution(Hz)} = \frac{1}{\text{PRI(sec)} * \text{Number of Pulses (to be processed)}}$$

- *Bandwidth:* It is the signal bandwidth that is determined by the signal pulse width or by any internal modulation of the pulse. Bandwidth and range resolution has a close relationship since they are both determined by the same parameter. Good range resolution requires large bandwidth.
- *Antenna Beamwidth:* It is the 3-dB beam width of the antennas in azimuth and elevation. This is an important parameter since it determines the angular resolution of the radar.
- *Receiver Sensitivity:* The sensitivity is defined as the lowest signal a receiver can receive and still do its jobs, [6]. High sensitivity means that the receiver can receive very low signals.

$$\begin{aligned}\text{Receiver Sensitivity(dBm)}&\\ &= \text{Thermal Noise in Receiver (kTB)(dBm)}\\ &+ \text{ Receiver Noise Figure (dB)}\\ &+ \text{Radar's Required Signal to Noise Ratio(dB)}\end{aligned}$$

Required SNR is determined by the probability of detection desired.

This list can be surely extended and detailed since the radar system application area is very wide.

2.2 General Block Diagram of a Radar System

Fig.4 shows a possible block diagram for a pulsed monostatic radar. This diagram shows the basic radar elements and how they are connected to each other. Experimental radar system's elements are determined according to this block diagram however, there are some differences.

Consider the block diagram elements shown in Fig.4. Following the operation order of the radar, waveform generator is the first unit that should be examined since transmit signal definition starts here. *Waveform generator* is the element where the desired pulse waveform is generated and its output is sent to the *transmitter* in order to be modulated to the desired RF frequency and amplified to a useful power level for detection.

The signal at RF frequency is routed to the *antenna* through a *duplexer,* also called *circulator* or *T/R switch,* to be radiated to propagate in space. Antenna is the device that allows the transmitted energy to propagate into space and collects the echo energy on receive, [5]. Duplexer permits the receiver and transmitter to share the same antenna by playing a switch role between them. The returning echoes are captured by the antenna and routed to the receiver again through the duplexer. The first stage of the receiver is usually a *low noise amplifier* in order to amplify the received echo while adding as low noise as possible. The receiver is usually a superheterodyne receiver, in which the received RF signal is down converted first to IF and ultimately to baseband. These down conversions are done by *mixers* and *oscillators*. The down conversion could be analog or digital. Down conversion to IF is achieved by analog means and the output is sent to analog to digital converter to digitize the signal. The digitized signal is sent to digital down conversion block to be converted to baseband. The baseband signal is sent to the *signal processor*, which performs variety of functions such as matched filtering, Doppler processing. The output of the signal processor varies depending on the purpose of the radar. The results are shown on a *display*.

This block diagram is not unique. For instance, signal processing can be achieved at IF or, instead of using a duplexer separate antennas can be used for transmit and receive. The point where the digitization is performed can differ between radars.

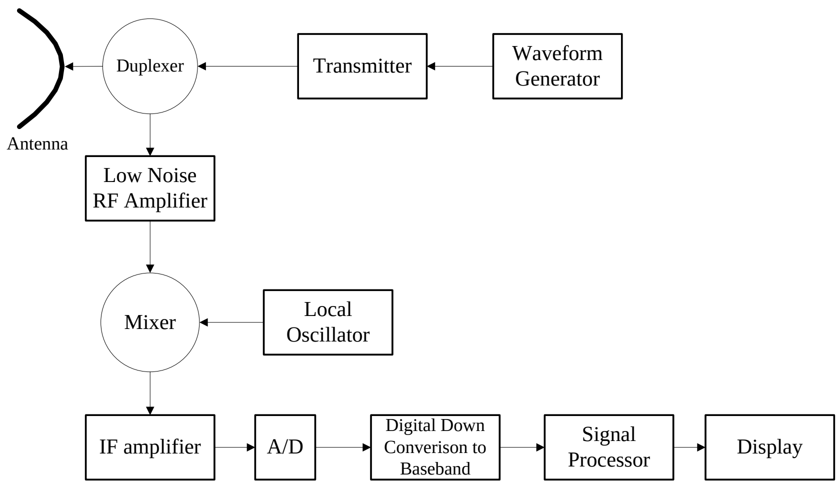


Figure 4. Block Diagram of a Pulsed Monostatic Radar

The choice of the hardware elements is also a major subject in designing a radar system. According to the required parameters of the radar system and the location that it is planned to be used, suitable equipments should be chosen considering both the capabilities and environmental conditions.

CHAPTER 3

THE EXPERIMENTAL RADAR SYSTEM

3.1. Description and Block Diagram of the System

In this thesis work, an Experimental Radar System is configured for laboratory use by utilizing COTS test equipments as hardware and MATLAB is used as signal processing and user interface software tool as described in the introduction. The COTS hardware equipments and software tools building up the experimental RADAR system are Agilent E8267D Vector Signal Generator as transmitter, Agilent E4446A PSA Spectrum Analyzer as receiver, HP8348A Amplifier, AML218L1502 Low Noise Amplifier (LNA), computer, DC Power Supply, Agilent Vector Signal Analysis Software Tool and MATLAB. Overall block diagram is shown in Fig.5.

Having radar in the laboratory makes practical studies, tests, measurements possible. This experimental radar system can be considered as a generic system as it is possible to construct different types of radar by making changes on the hardware or software of the system designed. For instance, signals with different waveforms, carrier frequencies can be generated and used as transmit signal; a CW or pulse Doppler radar can be configured with the same hardware. Phased array antennas can be used instead of horn antennas, or a duplexer can be utilized to use a single antenna for both transmission and reception. Range resolution can be changed by utilizing pulses with narrow pulse widths, or the Doppler resolution for the pulse Doppler radar can be changed by changing the length of the acquired data in time.

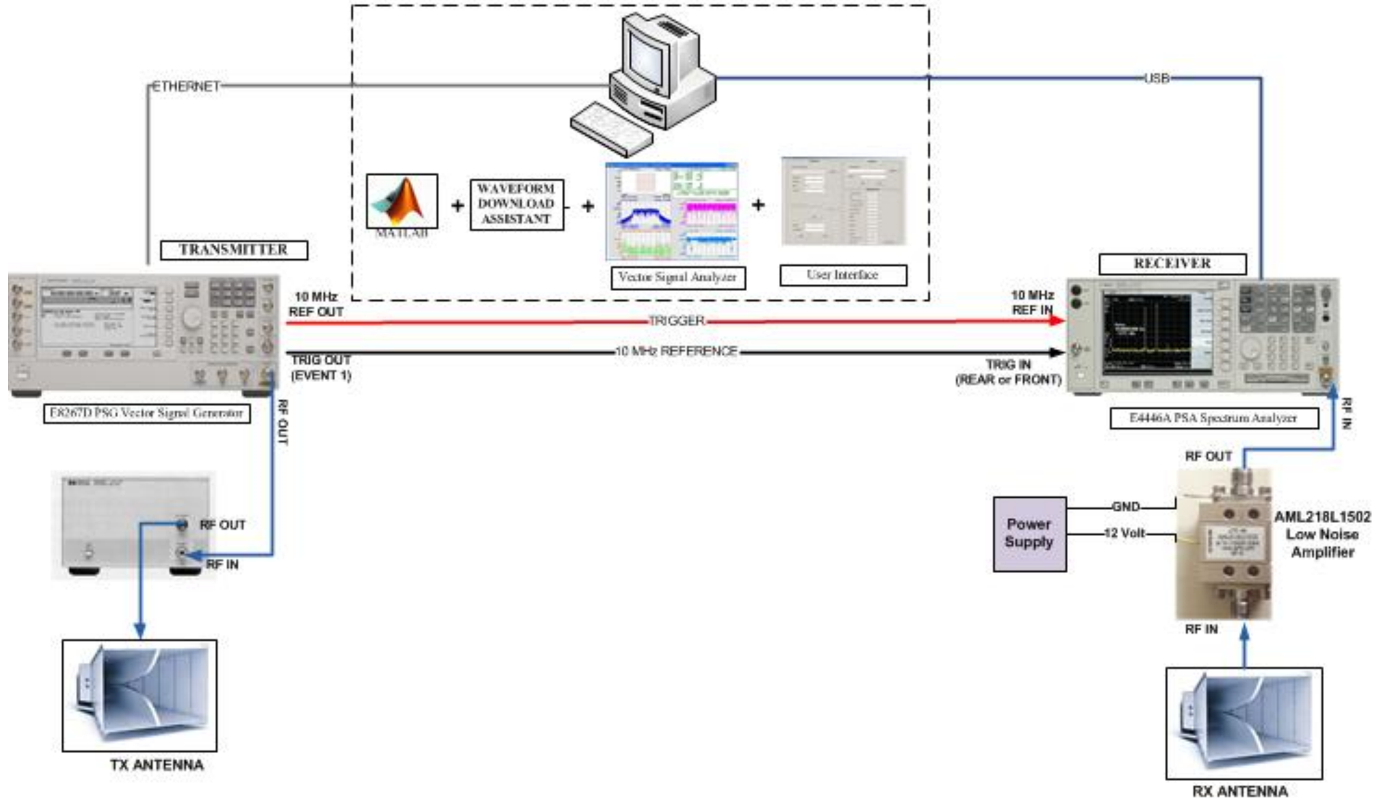


Figure 5. Block Diagram of Experimental Radar System

Consider the experimental radar system whose overall block diagram is shown in Fig.5. This system is constructed by seven hardware equipments, which are;

- Agilent E8267D Vector Signal Generator (VSG) – Transmitter
- Agilent E4446A PSA Spectrum Analyzer (PSA) –Receiver
- HP8348A Amplifier – Power Amplifier
- AML218L1502 Low Noise Amplifier (LNA)
- Computer – MATLAB, Agilent Vector Signal Analysis (VSA), User Interface (designed by MATLAB GUI) and Agilent Waveform Download Assistant are installed on this computer.
- Horn Antennas – RX/TX Antennas
- DC Power Supply – Supplies 12 V for LNA

The connection between these equipments are described clearly in Fig.5. By explaining the need for each unit and describing their functions in depth, the general structure of radar system will be studied through the thesis. In this chapter, brief explanation about the function of each unit and their role in the radar system will be told; their detailed characteristics will be discussed in subsequent chapters.

General block diagram of radar system is given in Chapter 3. Transmitter, receiver, antennas and amplifiers are the main blocks that build up a radar. Experimental radar system is also constructed by these blocks, in addition a control PC, on which MATLAB, user interface, COTS equipments' control interfaces and VSA are installed. Instruments constituting these radar blocks of experimental radar system are as follows:

- The *waveform generator and transmitter* of the radar system is the E8267D Vector Signal Generator. Transmit signal is defined by the user via user interface which is prepared by MATLAB GUI and runs on PC. User defines the main parameters of the signals and transmit signals are formed by their I/Q values, sampling frequency, RF value and output power using MATLAB and downloaded to VSG via Ethernet. I/Q data of the waveform, sampling frequency, RF value and output power are the parameters that VSG needs to form the transmit signal. VSG has an internal arbitrary waveform generator and is capable of generating both modulated/unmodulated pulsed and CW signals. Defining the transmit signal by its I/Q data brings freedom for choosing transmit signal. Although VSG is very manageable in terms of the types of the waveforms that can be defined, it does not have a high output power.

Its maximum output power changes according to the generated signal's parameters and properties. For instance, maximum output peak power changes whether the signal is CW or pulsed, and for the pulsed signals it changes according to the pulse width and pulse repetition interval of the signal. The maximum output power available is 25 dBm, but for many signals, this power level cannot be reached. For this reason, the generated signal is amplified via HP8348A amplifier and routed to TX antenna.

- The *power amplifier* of the radar system is the HP8348A high power amplifier which has a wide operating frequency range of 2 to 26.5 GHz. Amplified transmit signals are sent through the transmit antenna.
- The *receive and transmit antennas* of the radar system are horn antennas which operate in X-Band. Radiation patterns and gains of the antennas will be described in Chapter 5. Reflected echoes are captured by the receive antenna and sent through the low noise amplifier.
- The *low noise amplifier* of the radar system is AML218L1502 LNA. Received signal is amplified by LNA and in addition to amplifying the received signal, LNA also changes the noise figure of the system. Noise level of LNA is much less than the noise level of spectrum analyzer and since it is the first stage of the receiver side, LNA improves the noise level of the system.
- The *receiver* of the radar system is E4446A Spectrum Analyzer and 89601A Vector Signal Analysis Software Tool together with the PC and LNA. Spectrum analyzer is a hardware unit of the receiver block, which is used to acquire RF echoes and together with the VSA, I/Q data of the received echo is obtained. I/Q data is saved on PC and receiver processing is implemented by MATLAB which is also installed on the same PC. Spectrum analyzer is connected to the PC via USB and VSA, which is also installed on the PC, has a connection with spectrum analyzer over the PC. Spectrum analyzer gets the RF signal, which is captured by the RX antenna, down converts it to IF, and the signal at IF is digitized by spectrum analyzer. VSA software uses spectrum analyzer as hardware, it acquires the digitized signal at IF from spectrum analyzer through the USB line and it down converts the digital IF signal to baseband by digital down conversion method. VSA further processes the raw data to generate some time related graphs or demodulate the

signal. In the experimental radar system, VSA is used to get the I/Q data of the received signal. I/Q data acquired by VSA can be saved as ".mat" file. This saved file contains the I/Q data of the received signal and a header containing the settings of the spectrum analyzer and VSA when the signal is saved. I/Q data is processed in MATLAB to generate the "Range vs. Doppler vs. Amplitude" graphs regarding the received echoes. Pulse Doppler processing is implemented using MATLAB for the receiver side.

- The *user interface* of the radar system is running on the PC and implemented by MATLAB GUI. Transmit signal parameters and type are defined by the user via the user interface. The saved received file corresponding to the defined transmit signal, is chosen by the user via the same user interface and the analysis is achieved by the receiver analysis program. There are push buttons on the user interface, which let the user to save and send the defined transmit signal parameters to the vector signal generator to generate the RF signal, analyze the received signal by browsing the saved received signal files and generate the 3D graphs of the results after processing. Screenshot of user interface is shown in Fig.6.

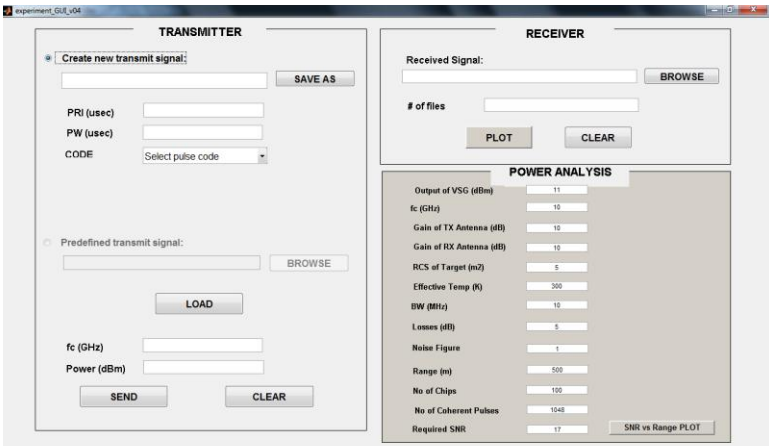
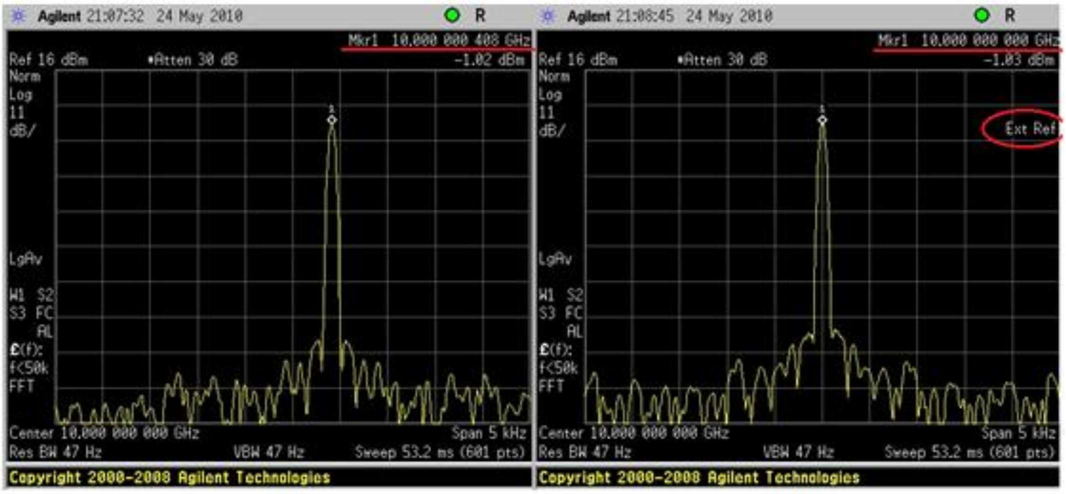


Figure 6. User Interface

There are two important points for the radar system setup; the first one is that the 10 MHz reference signals of the vector signal generator and the spectrum analyzer should be locked, in other words both units should use the same reference. This is done by connecting one of the unit's 10 MHz REF OUT signal to the other unit's REF IN input connector via a BNC cable. Unless the units use the same reference, there is a frequency reading error. These two cases are shown in Fig.7.



(a) (b)

Figure 7. (a) VSG and SA Using Their Internal 10 MHz Reference (b) 10 MHz Reference of VSG and SA are Same

The screenshots shown in Fig.7 are from spectrum analyzer. "10 MHz RF Out" connector of VSG is connected directly to spectrum analyzer, and the signal generated on VSG is a CW signal at 10 GHz and 0 dBm output power. When the two devices use their internal 10 MHz references, there is a frequency reading error, which is 408 Hz for the example shown in Fig.7(a). This error is not constant; it changes from measurement to measurement. When the devices use the same reference, there is no frequency reading error. For the example shown in Fig.7, spectrum analyzer uses the 10 MHz reference signal of VSG, i.e. 10 MHz reference output of VSG is connected to 10 MHz reference input connector of spectrum analyzer. This case is shown in Fig.7(b); observe the "Ext Ref" annotation on spectrum analyzer's display at the right. Both connectors reside at the rear panel of the devices.

The second important point is that the SA should be triggered by the transmit signal when the transmit signal is a pulsed signal. VSG generates a trigger pulse at the start of the transmit signal and VSG's "TRIGGER OUT" is connected to the "TRIGGER IN" connecter of the spectrum analyzer. The trigger pulse is defined at the beginning of the transmit pulse, thus the spectrum analyzer is triggered at the beginning of the transmit signal and after it is triggered, it fills the acquisition time defined. This provides synchronization of time. The received signal's time zero reference becomes the start of the transmit signal, in other words the start of measurement by spectrum analyzer is the start of the transmit signal, thus the time of arrival values of the received pulses with respect to the transmit pulse start can be calculated easily. VSG's trigger out connecter is named as "EVENT 1" connector and it is located at the rear panel of the instrument. The generation time of the trigger pulse is programmable; its position in time is defined by utilizing markers, which will be discussed in 5.1.3 Waveform Markers section under Chapter 5.

3.2. Specifications of Experimental Radar System

This design is considered as a radar system and important system specifications can be listed as;

1. Frequency Range = 250 kHz – 44 GHz (if appropriate antenna is chosen)
2. Time Resolution (min) = Transmitter : 10 ns/sample (100 Msample/sec)
   Receiver : i. PSA+VSA: 100 ns/sample
   ii. PSA : 66.67 nsec/sample
   iii. EXA: 66.67 nsec/sample
3. Range Resolution (min) = 10 m (PSA or EXA), 15 m (PSA+VSA)
4. Receiver's Noise Figure at 10 GHz = 9.185 dB if one LNA is used,
   3.244 dB if two LNAs are used successively (NF of LNA = 3 dB, Gain of LNA = 18 dB, NF of PSA = 26 dB)
5. TX Antenna : 3 dB azimuth BW = 30°
   Gain = 15.3 dB at 10 GHz
6. RX Antenna : 3 dB azimuth BW = 30°
   Gain = 11.8 dB at 10 GHZ
7. Maximum Time Record Length (Receiver) = Depends on the time resolution chosen and the equipment used. Time resolutions is determined by the frequency span set on VSA and, by the IF filter BW set on PSA and

EXA spectrum analyzers. VSA is able to record I/Q data of signals up to 26.5 GHz, PSA lets up to 3 GHZ and EXA lets up to 13.6 GHz.

The relation between maximum time length and time resolution for different configurations is given in Table 1. Corresponding Doppler resolutions are also added to this table.

Table 1. Time Resolution vs. Total Time Record Length of the System

VSA 89601A (up to 26.5 GHz)			PSA E4446A (up to 3 GHz)			EXA N9010A (up to 13.6 GHz)		
Time Res (nsec)	Max Time Length (msec)	Doppler Res (Hz)	Time Res (nsec)	Max Time Length (msec)	Doppler Res (Hz)	Time Res (nsec)	Max Time Length (msec)	Doppler Res (Hz)
781.25	179.70	5.56	1470.00	1470.00	0.68	1470.00	5880.00	0.17
390.32	59.90	16.69	1000.00	1000.00	1.00	1000.00	4000.00	0.25
260.42	59.90	16.69	733.33	733.34	1.36	733.33	2933.32	0.34
195.31	59.90	16.69	533.33	533.34	1.88	533.33	2133.32	0.47
156.25	59.90	16.69	400.00	401.00	2.50	400.00	1600.00	0.63
130.21	59.90	16.69	266.67	266.68	3.75	266.67	1066.68	0.94
111.61	58.50	17.09	200.00	201.00	5.00	200.00	800.00	1.25
97.66	51.20	19.53	133.33	133.33	7.50	133.33	533.32	1.88
			66.67	66.67	15.00	66.67	266.68	3.75

The system has been described in general in this chapter; detailed information about the instruments and the process will be discussed in the subsequent chapters starting with the antennas.

3.3. Maximum Detectable Range of the Experimental Radar System

Maximum detectable range is the range at which a target’s echo can be received with a desired echo. This value gives information about the radar’s capability of range detection. The maximum unambigious range is defined by the PRI of the transmit signal but maximum range that can be detected may delimit this value. Maximum detectable range is derived from the radar range equation which is as follows;

$$P_r = \frac{P_t * G_t}{4\pi R^2} * \frac{\sigma}{4\pi R^2} * A_e \text{ (Watts)}$$

where P_t = Radiated Peak Power from Transmit Antenna,

G_t = Gain of TX Antenna,

σ = Radar Cross Section of Target, A_e = Effective Area of RX Antenna

The relationship between the gain of an antenna and the effective aperture is;

$$G_t = \frac{4\pi A_e}{\lambda^2} \quad \text{where } \lambda = \text{wavelength}$$

P_t is the peak power of a radar pulse. P_{avg}, average power, gives a better idea for detection capability of the radar. Thus, P_{avg} will be used instead of peak power. Average power is given by;

$$P_{avg} = P_t * \frac{PW}{PRI}$$

The transmit signal is a repetitive series of pulses whether modulated or not. The received signal is not composed of a single pulse; a number of pulses are collected and integrated before a detection desicion is made. To take the improvement due this integration into account, an integration factor is added to the numerator of the radar equation. In addition, if the transmit pulse is compressed, number of chips making up the pulse also brings an integration factor which is also inserted to the numerator of the radar equation.

$$\text{Integration Factor of Pulse Integration} = nE_i(n)$$

$$\text{where } n = \text{number of pulses}, E_i(n) = \text{Efficiency in adding together n pulses}$$

$$E_i(n) = \frac{SNR_1}{n * SNR_n} \quad \text{where } SNR_1 \text{ is the SNR of one pulse}, SNR_n \text{ is SNR of n pulses.}$$

$$E_i(n) = 1 \text{ when integration is performed before processing}$$
$$- \text{the case in the system} -$$

$$\text{Processing Gain due to Pulse Compression} = m$$

$$\text{where } m = \text{number of subpulses(chips) in the waveform}$$

The improvements are good for the system's max range capability; on the other hand the system has losses like cable losses, mismatch losses, polarization loss, and atmospheric loss. When these improvement factors and loss factor (L) are inserted in the range equation, the equation becomes;

$$P_r = \frac{P_t * G_t}{4\pi R^2} * \frac{\sigma}{4\pi R^2} * \frac{G_r * \lambda^2}{4\pi} * n * m * \frac{1}{L} \text{ (Watts)}$$

Maximum detectable range is found when the received signal power is the minimum signal power that the radar can detect.

$$S_{min} = \text{Thermal Noise} * \text{NoiseFigure}_{receiver} * \text{SNR}_{required} \text{ (Watts)}$$

$$\text{Thermal Noise} = kTB$$

where $k = \text{Boltzman's Constant}, T = \text{Temperature in Kelvin and}$

$B = \text{Receiver Bandwidth}$

When $P_r = S_{min}$, maximum detectable range is ;

$$R_{max} = \sqrt[4]{\frac{P_t * G_t * G_r * \lambda^2 * \sigma * n * m}{(4\pi)^3 * S_{min} * L}} \text{ (m)}$$

Using this formula, maximum detectable range calculations for the experimental radar system is performed for two different waveforms in order to give an idea about the range performance of the system.

The temperature is 290 K. The receiver noise figure is 3.244 dB which is calculated in Chapter 6. Cable losses are approximately 6 dB at 10 GHz and the gain of the LNA is 18 dB. Gain of the high power amplifier is added to the output power of the vector signal generator and defined as peak transmit power. Gains of the antennas are given in Table 2 which are 15.3757 dBi and 11.8457 dBi at 10 GHz.

Max Detectable Range at corresponding SNR graphics are presented for the following waveforms.

i. Unmodulated Pulsed Signal
   PW=1 µsec, PRI=100 µsec, f_c = 10 GHz, BW=1 MHz
   Average Transmit Power = Peak Transmit Power – (PRI/PW) dB

= 30 dBm -20 dB=10 dBm

The output of VSG is 24 dBm but the maximum input power of the high power amplifier could be 22 dBm and it operates in saturation region with that input power value, thus the output peak power is 30 dBm.

Number of PRIs integrated, in other words received time length changes with respect to the time resolution chosen on VSA, PSA or EXA depending on the chosen equipment to be used as receiver. When EXA is used, Time Res=400 nsec → Time Length = 1600 msec, Number of PRIs = 16000

ii. Compressed Pulsed Signal (P4 Phase Coded)

a. PW=4 usec, PRI=100 usec, f_c = 10 GHz, BW=10 MHz
   Number of Chips / Chip Width = 100 nsec = 40, Number of PRIs = 266msec/100usec=2660 (66.67 nsec time resolution should be chosen as the chip width is 100 nsec and corresponding max time length is 266 msec for EXA)

b. PW=4 usec, PRI=500 usec, f_c = 10 GHz, BW=10 MHz
   Number of Chips = 40 / Chip Width = 100 nsec, Number of PRIs = 532

The Max. Detactable Range vs SNR graphs of these waveforms are given in the figures below when RCS = 200 m^2 and 1 m^2. It is obvious that the maximum range the system can detect changes abruptly when compressed signals are used and when number of PRIs integrated changes. For target detection, required SNR is determined by Probability of Detection and Probability of False Alarm.

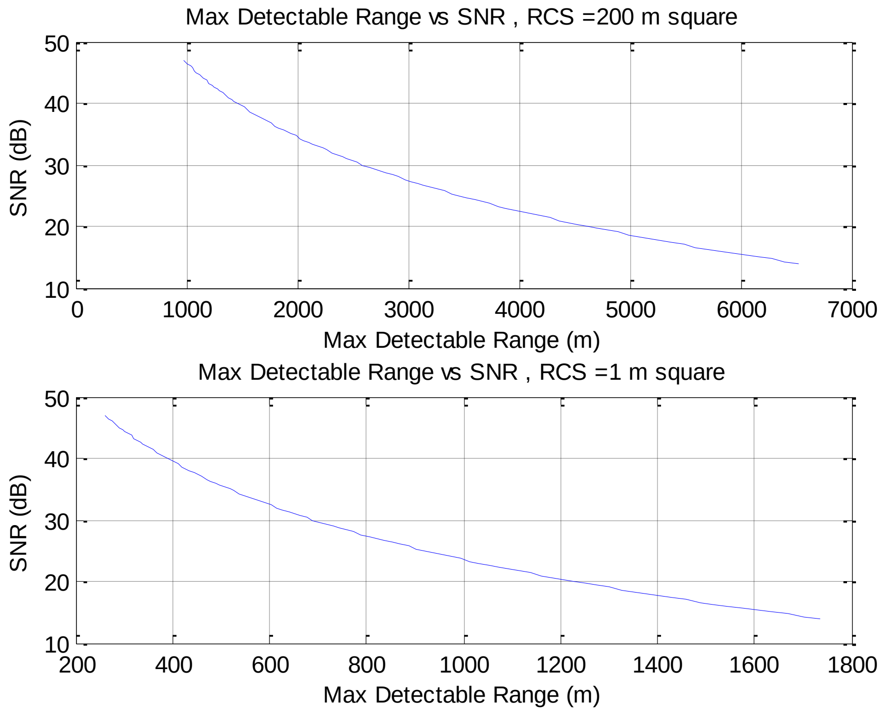


Figure 8. Max. Detectable Range vs. SNR for Unmodulated Pulsed Signal(i)

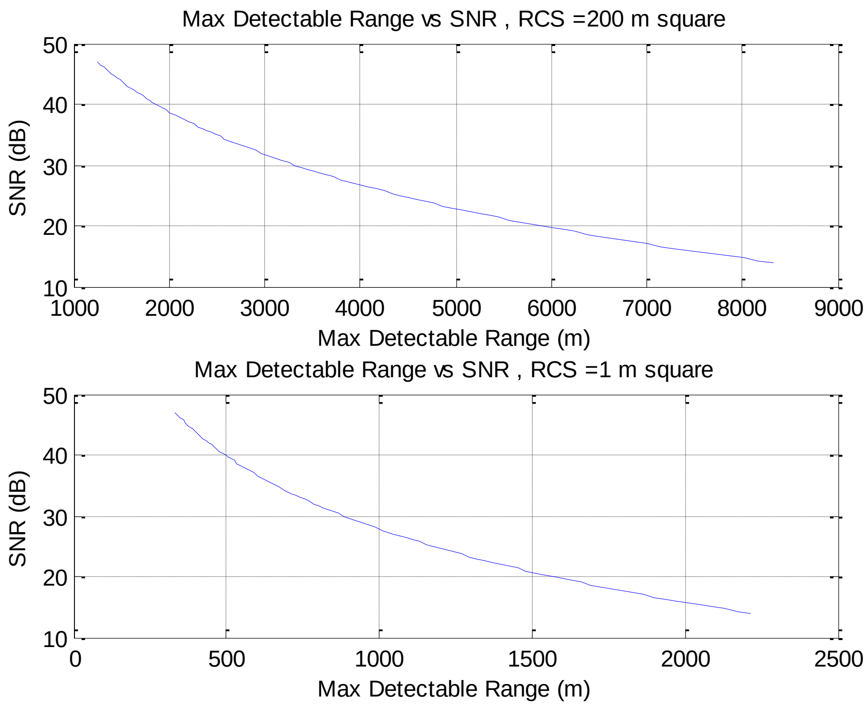


Figure 9. Max. Detectable Range vs. SNR for Modulated Pulsed Signal (ii-a)

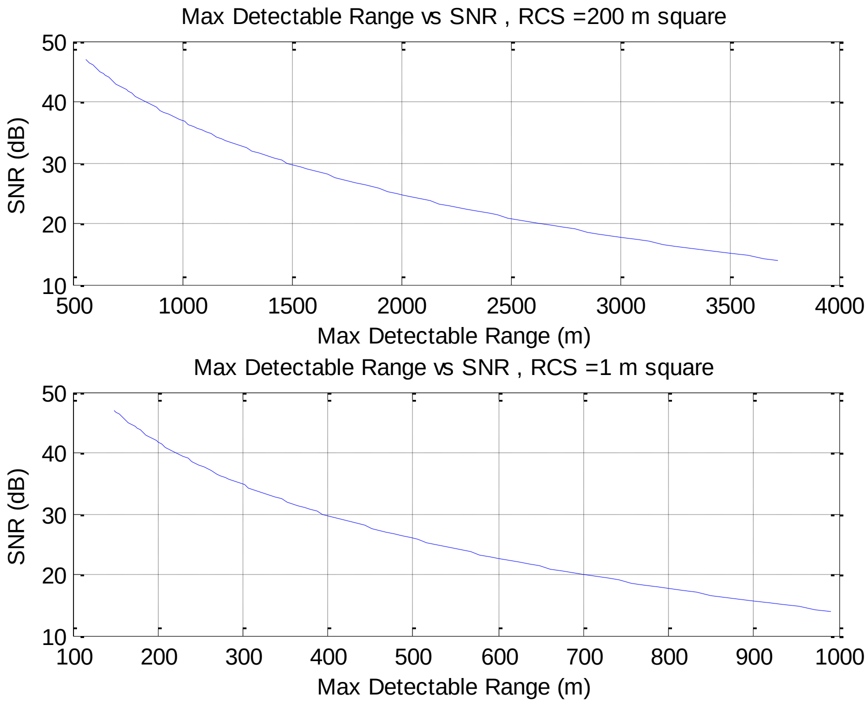


Figure 10. Max. Detectable Range vs. SNR for modulated Pulsed Signal (ii-b)

CHAPTER 4

ANTENNAS

Antenna is a fundamental component of radar systems. By definition, the basic role of an antenna is to provide a transducer between the free space propagation and the guided wave propagation of electromagnetic waves, [1].

The specific function of an antenna during transmission is to concentrate the radiated energy into a shaped directive beam, which illuminates the targets in a desired direction. During reception, the antenna collects the energy contained in the reflected target echo signals and delivers it to the receiver.

In the experimental radar system, two antennas are used; one for transmitting and the other for receiving. Two double ridged horn antennas, GAH-1042 and DRH-412, have been utilized as transmit and receive antennas of the radar system. They are directed in the same direction, but located at sufficient distance to provide necessary isolation. Besides, they are not rotating, i.e. they are placed at a fixed position during the measurements. Transmit antenna is connected to RF output of the power amplifier, and receive antenna is connected to RF input of the low noise amplifier.

In the experimental radar system, transmit and receive units are separate as described in Chapter 3. Separate antennas are used for transmit and receive in this system, so there is no need for a T/R switch to switch between the transmit and receive units. On the other hand, when two antennas are used, the type of antennas, the physical spacing and the orientation of the antennas to one another are also major concerns. Isolation between the transmit and receive antennas are required for two main reasons which are;

- The receiver can be damaged if high level RF signals, like those directly from a transmitter output, is applied to the receiver antenna

- The receiver may become desensitized and not receive weak signals due to its dynamic range when there is a high level signal near the receive frequency

In the experimental radar system, receive and transmit antennas are placed next to each other and receive antenna receives both the transmit signal and the echoes returning from targets. They are placed at least one meter apart in order to increase isolation and decrease the received power level of transmit signal. However, although they are placed apart from each other, receiving the transmit signal is unavoidable for this radar setup. The solution to this problem would be using extra hardware such as a T/R switch or isolator between the antennas, or discarding the transmit signal samples in received signal data. The latter solution which is used in this radar system will be examined in detail in Chapter 7. Briefly, samples of one transmit pulse duration are discarded in every pulse repetition interval of the saved received signal. Since the received signal measurement starts at the beginning of a transmit pulse by means of the trigger pulse generated at the beginning of the transmit pulse, transmit pulse duration of every PRI's beginning is occupied by the transmit pulse. Thus, discarding the pulse duration of every PRI's beginning can be considered as silencing the receiver while transmit pulses are being sent. This solution is a software-based solution, since it is performed by a simple step in the software; no extra hardware is required.

Antennas of the radar system are not rotating. They are placed at a fixed position, thus the environment that they cover does not change during measurements.

These two antennas will be examined considering the basic parameters of antennas, which are:

i. Reciprocity

Antennas demonstrate a property known as reciprocity that is an antenna will maintain the same characteristics (gain, pattern, impedance) regardless if it is transmitting or receiving. However, not all antenna types are reciprocal, examples of nonreciprocal antennas are phased arrays using nonreciprocal ferrite components, active arrays with amplifiers in the transmit/receive modules, [1].

Antennas of experimental radar system are reciprocal. Their gain values and radiation pattern graphs are given under the next two titles.

It is advantageous to have reciprocal antennas since they can be interchanged or instead of using both of them, one of them can be used for both functions; this brings flexibility to the radar system for further development.

ii. Gain

The ability of an antenna to concentrate energy in a narrow angular region (a directive beam) is described in terms of antenna gain. "Directive Gain (Directivity)" and "Power Gain (Gain)" are the two different definitions for antenna gain.

Directivity is the ability of an antenna to focus energy in a particular direction when transmitting or to receive energy better from a particular direction when receiving. Mathematically, it is defined as the maximum radiation intensity (watts/steradian[1]) relative to the average radiation intensity

$$D = \text{maximum radiation intensity / average radiation intensity}$$

$$= \text{maximum power per steradian/(total power radiated}/4\pi)$$

$$= \text{maximum power density/(total power radiated}/4\pi R^2)$$

In other words, directivity expresses how much stronger the actual power density is than the case if the radiated power were distributed isotropically.

Gain involves antenna losses and it is related to the power accepted by the antenna at its input port. Gain is given by;

$$G = \frac{\text{maximum power density}}{\frac{\text{total power accepted}}{4\pi R^2}}$$

Gain is closely related to directivity, if the total power radiated is equal to the total input power than the antenna is said to be 100% efficient.

$$G = \eta * \text{Directivity where } \eta \text{ is the efficiency}$$

[1] The steradian (symbol: sr) is the SI unit of solid angle.

Gain measurements of the experimental radar system were carried out in the anechoic chamber which is a room designed to absorb the electromagnetic waves to stop reflections from the walls of the room. Two standard gain horn antennas are used as reference antennas. The gain of the reference antenna, which is used as receive antenna, is known. Test setup is shown in Fig.11. The test is completed in two steps. At the first step, these two standard gain antennas are placed facing each other with a constant distance between them in the anechoic chamber, the power measurement at the receiver side is held by the network analyzer, and the results are noted down. At the second step, the standard gain RX antenna, whose gain is known, is replaced with the antenna of the radar system that will be tested. For each antenna, same power measurement is done and the results are again noted down. Since the RX antenna in the setup is the only unit that is replaced, conditions that affect measurement (transmit signal, cable losses, space loss, mismatch at TX antenna port, amplifier gain...) in the setup are same for both cases. The gain of the antenna under test can be found by comparing the power measurement results of itself and the standard gain antenna whose gain is known since the test environment is not changed.

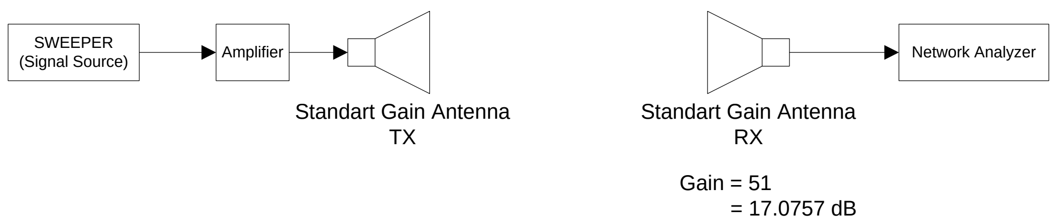


Figure 11. Setup for Antenna Gain Measurement

The measurements are performed as described above and the gains of the both antennas used in the system are calculated. The results are tabulated and given in Table 2.

Table 2. Gain of the Experimental Radar System's Antennas

	f = 9 GHz	f = 10 GHz
Antenna 1 (GAH-1042)	15.5257 dBi	15.3757 dBi
Antenna 2 (DRH-412)	11.1457 dBi	11.8457 dBi

iii. Radiation Pattern

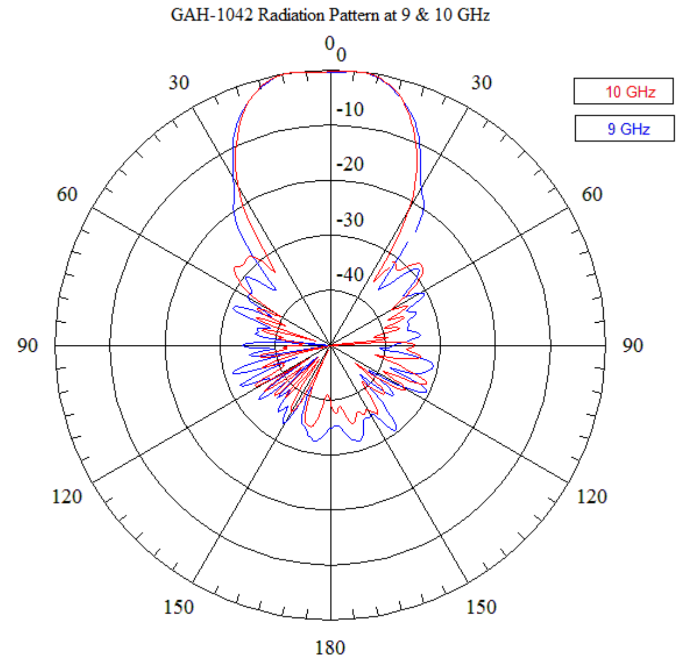
Radiation pattern is the distribution of electromagnetic energy transmitted from or received by the antenna in three-dimensional angular space. Radiation patterns of the antennas of the system at 9 GHz and 10 GHz are shown in Fig.12. Radiation patterns are obtained experimentally. The experiments are performed again in anechoic chamber. The antenna that is under test is rotated 360° with 1° resolution and at every angle power measurement is performed and saved. This rotation and saving the results are done automatically. At the end of the experiment, the power values corresponding to angle values are obtained and radiation patterns are plotted in polar coordinates.

Azimuthal 3dB beamwidths of the antennas are nearly 30 degrees. Depending on the function of the radar, antenna with suitable beamwidth can be chosen. For example, narrower beamwidth is suitable for track systems, wide beamwidths cannot support focusing on a region. If covering a wide region is preferred, then an antenna with a wide beamwidth should be chosen.

i. Polarization

Polarization describes the electric field orientation of the antenna; the direction of polarization is defined as the direction of the electric field vector of the antenna. Polarization can be linear (vertically or horizontally), circular (right hand or left hand) or elliptical.

Antennas used in the system have vertical linear polarizations when the reference is the planar earth. The polarization of a linearly polarized horn antenna can be directly determined by the orientation of the feed probe, which is in the direction of the E-field.



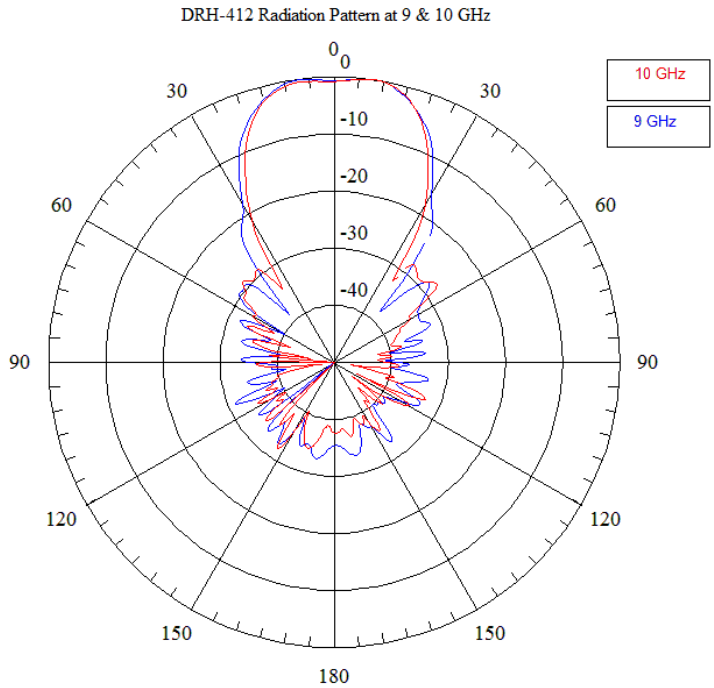


Figure 12. Radiation Patterns of Antennas (E- Plane)

CHAPTER 5

WAVEFORM GENERATOR AND TRANSMITTER

Waveform generator and the transmitter of a radar system are the main units to generate the desired pulse waveform and modulate this waveform to the desired radio frequency (RF). Generated RF signal is amplified to a power level, which is required for detection before sending to the antenna for transmit. This amplification process can be considered as a part of transmitter. After the desired signal is generated at the desired power level, it is routed to the transmit antenna.

In the radar system of this thesis, E8267D Agilent PSG Vector Signal Generator (VSG) is used as the waveform generator and the transmitter units. Amplification is achieved using a high power amplifier, which will be described in the following chapter.

The Agilent E8267D is a fully synthesized signal generator, which has the following properties[2];

i. Frequency range of 250 kHz to 44 GHz (0.001 Hz resolution)
ii. Power range of -130 dBm to +18 dBm(typical) for 10 GHz- 20 GHz frequency range(With I/Q modulation on, maximum power specification is typically reduced by 3 dB.) Measured power levels for the frequency range available are shown in Fig.13.

[2] Properties listed here are filtered according to the usage of the VSG in this thesis's radar system

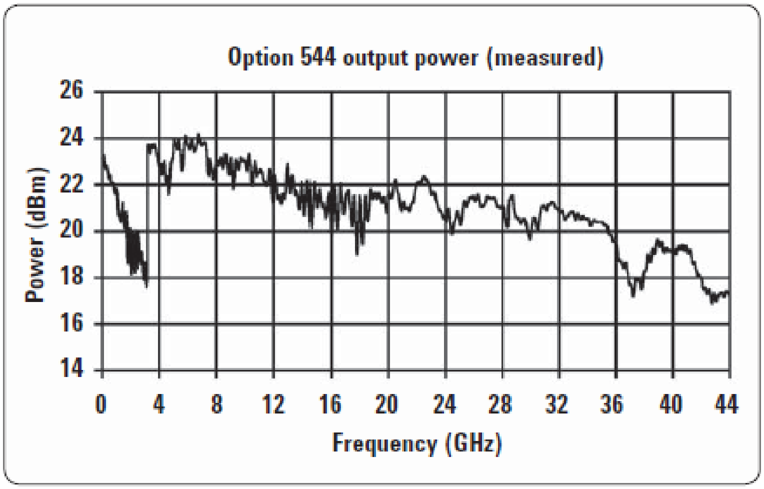


Figure 13. Measured Maximum Available Power of VSG in CW Mode, [8]

iii. 50 Ω output resistance

iv. Harmonics : -55 dBc (for 2 GHz to 20 GHz frequency range)

Subharmonics: < –60 dBc (for 2 GHz to 20 GHz frequency range)

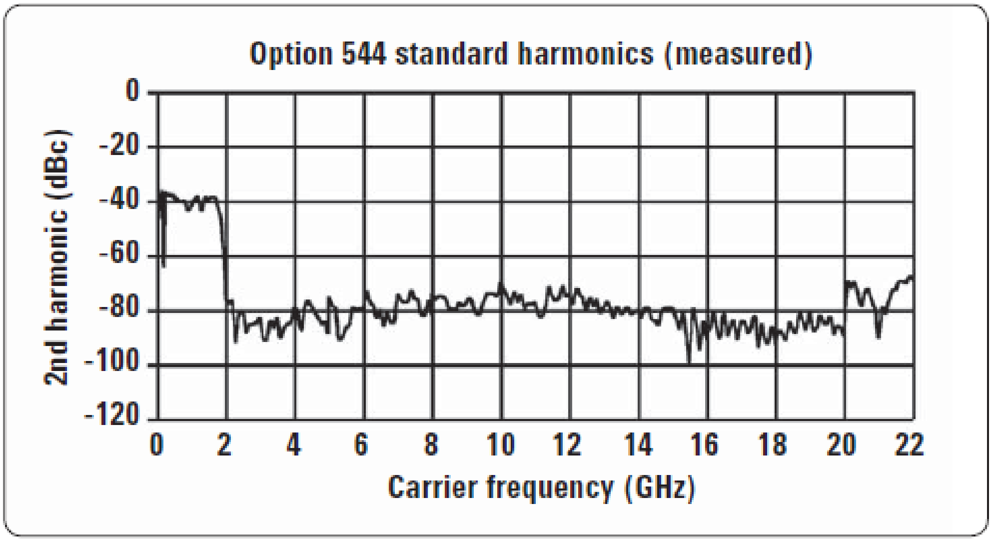


Figure 14. Measured Harmonics, [8]

v. Internal baseband generator (Arbitrary Waveform Mode)

a. 2 Channels [I and Q]
b. Resolution = 16 bits [1/65,536]
c. Baseband waveform memory length (playback) = 64 Megasamples (MSa/channel)
d. Clock = 1 Hz to 100 MHz (0.001 Hz resolution)

vi. Remote control

vii. Interfaces with GPIB (IEEE-488.2,1987) with listen and talk, RS-232, and 10BaseT LAN

viii. Waveforms(I/Q Data) can be downloaded from PC to E8267D VSG

E8267D VSG has an internal baseband modulator and, waveforms that are created by MATLAB, C/C++, C#, Basic, Perl, can be downloaded to the instrument. Agilent Waveform Download Assistant software toolkit is used with MATLAB for downloading waveforms. This toolkit includes MATLAB ".m" files each of which is a MATLAB function that performs different tasks. For instance, "agt_newconnection.m" file includes the function that generates connection structures according to the different interface types such as TCPIP or GPIB, and "agt_sendcommand.m" file includes the function that sends SCPI commands to the instrument. These m files should be added to a directory and its path should be added to the start up file of MATLAB.

Basic block diagram of E8267D is shown in Fig.15. The parameters of the signal that will be generated could be defined by three different ways. First way is to use the menu buttons which are placed on the front panel of the instrument; second way is to define the digital I/Q waveform data on PC and send it to the instrument via LAN or GPIB and the third way is to use external analog I/Q inputs through the I and Q input connectors placed on the front panel of the instrument.

In the experimental radar system, digital I/Q data is defined on PC and sent to vector signal generator via Ethernet, therefore the RF path of this case will be examined. All RF signals originate from the YIG Oscillator (YO) output frequencies of 3.2 GHz to 10 GHz. RF output frequencies below 3.2 GHz are generated by dividing the YO signal; RF output frequencies between 10 to 20 GHz are generated by doubling the 5 to 10 GHz YO signal in the 20 GHz Doubler, and RF output frequencies above 20 GHz are generated by the 40 GHz doubler and 44 GHz upconverter. There are actually two separate RF chains, one for carrier frequencies below 3.2 GHz and the other for carrier frequencies above 3.2 GHz. Each RF chain consists of an I/Q modulator, RF gain, ALC and pulse modulators, output amplification, and filtering.

User defined waveforms are downloaded to the waveform memory and data is sequenced from waveform memory by the field programmable gate array block, passed on to the format builder block, and finally to the output section. I and Q DACs at the output convert the digital waveform data to analog. The I and Q output DACs are driven by a sample clock generated by an on–board VCO. These operations take place in "Baseband Generation" block. Analog I and Q output of baseband generator are fed into the I/Q modulator. For the RF output above 3.2 GHz, 3-10 GHz I/Q modulator is used and the output is sent to 40 GHz doubler and 44 GHz upconverter if the output RF is above 20 GHz. The upconverter frequency-translates the I/Q-modulated signal by a factor of 3 (between 20 and 28.5 GHz) or 5 (between 28.5 and 44 GHz). Finally at the output section the signal is amplified and fed into ALC circuitry through a coupler and detector. The coupler couples off a portion of the RF signal which is then detected and used to monitor the RF output power level. The detector converts the coupled RF signal to a dc voltage that is routed to the ALC, where it is compared to a reference voltage and integrated. The ALC loop maintains power level control and power level accuracy. Level accuracy is achieved by comparing the measured dc voltage to a reference dc voltage, integrating the difference, and using the integrated output to drive the ALC modulation diode. Level control is achieved by adjusting the reference voltage. At the end of this RF chain, 115 dB step attenuator exists right before the RF output.

General operation logic of vector signal generator is described up to here, and a basic block diagram of this RF path is given in Fig.15. Having been discussed how the RF signal is generated by the vector signal generator, the parameters that should be defined and downloaded to the instrument in order to generate RF signals will be discussed in subsequent titles of this chapter.

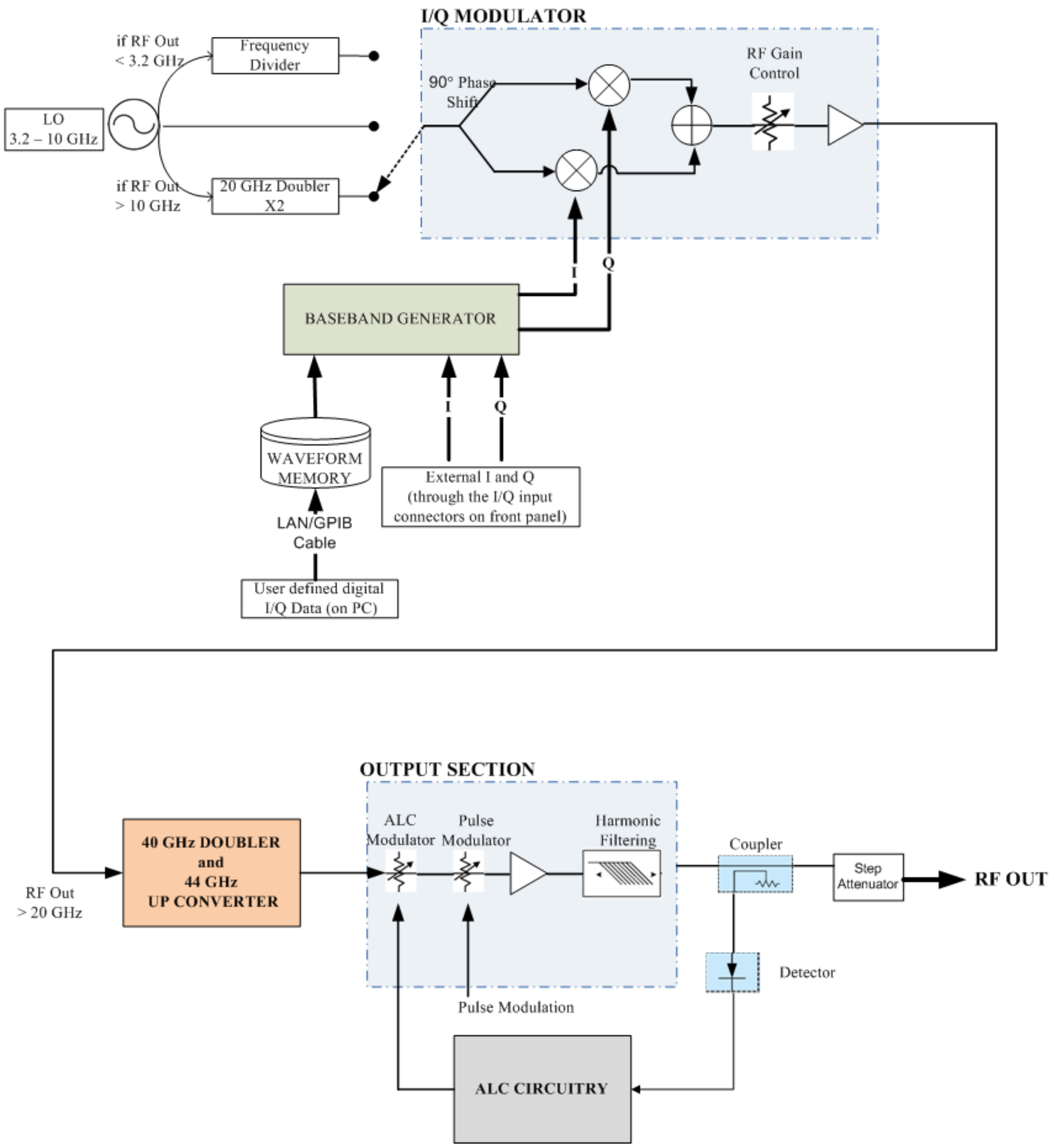


Figure 15. Basic Block Diagram of VSG E8267D

5.1 Generating Waveforms

MATLAB is chosen for creating and downloading waveforms to VSG in this thesis's radar system. A waveform is defined by three main parameters which are the I/Q data (complex array) forming it, the sampling rate and the waveform markers.

5.2 I/Q Data

I/Q data of the desired waveform should be generated using at least 60 complex samples per waveform (60 samples for I and 60 samples for Q). To be successful for downloading the waveform, the data should be created in the required format;

- 2–byte integer values
- Input data range of −32768 to 32767
- Minimum of 60 samples per waveform (60 I and 60 Q data points)
- Interleaved I and Q data
- Big endian byte order
- The same name for the marker, header, and I/Q file

For I and Q data, the signal generator uses two bytes to represent an integer value. The signal generator uses a 16–bit digital to analog converter (DAC) to process each of the 2–byte integer values for the I and Q data points. The DAC determines the range of input values required from the I/Q data. Remember that with 16 bits we have a range of 0–65535, but the signal generator divides this range between positive and negative values:
Because the DAC's range uses both positive and negative values, the signal generator requires signed input values.
It is quite easy to define and form the I/Q data in MATLAB. In phase(I) and Quadrature phase (Q) parts of a waveform are created by defining a phase array and an amplitude array;

$$\text{Phase Array} = P = [\theta_1\ \theta_2\ \theta_3\ .\ .\ .\ \theta_N\ ]$$

$$\text{Amplitude Array} = A=[a_1\ a_2\ a_3\ .\ .\ .\ a_N]$$

$$\text{I Data} = A*\cos(P)$$

$$\text{Q Data} = A*\sin(P)$$

and then I/Q data -a complex array- is obtained by

$$\text{IQ Data}=I + j*Q$$

Any kind of waveforms (single pulse, modulated pulse, pulse bursts,...etc) can be formed and downloaded to VSG. The waveform is created at baseband and while downloading it to VSG, the desired carrier frequency information is also sent. The advantage of forming the waveform at baseband is that memory is used efficiently as much larger memory would be required for defining the signal at the carrier frequency.

Fig.16 shows the connection diagram used for downloading the waveform. When the waveform is downloaded to VSG, it is written on its memory and the VSG repeats the waveform continuously until a new waveform is downloaded.

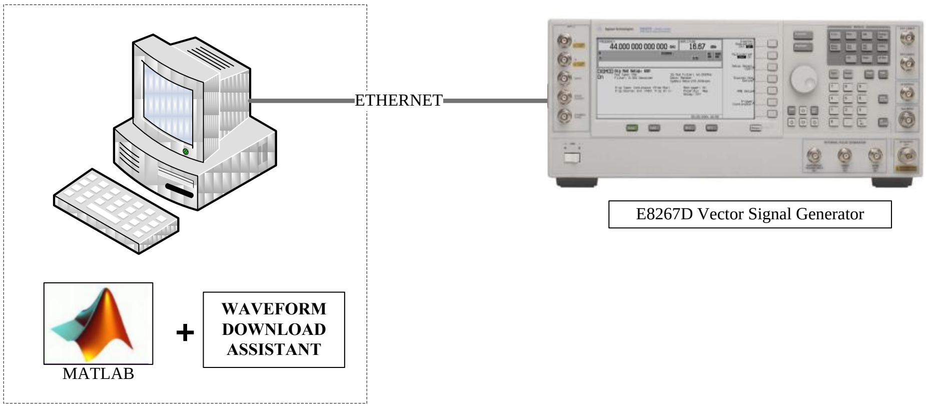


Figure 16. Connection Between PC and VSG

Downloading the waveform is achieved by the MATLAB function "agt_waveformload", which is included in the Agilent Waveform Download Assistant Toolkit's function archive. There is no need for any manual intervention; the instrument goes to remote mode and all settings are done automatically. When the instrument is in remote mode, the "R" annotation on the display of the instrument turns on, and all the front panel buttons are disabled except for the "LOCAL" push button. It is possible to change the operation mode of the instrument to local while it is repeating the waveform by pressing that button. When the instrument is in local mode, it enables the menu buttons on front panel and changes could be made to the signal that is being repeated such as changing the carrier frequency, output power or adding modulation.

While downloading the I/Q Data to VSG, the carrier frequency and the output power of the signal are also defined. Fig.17 shows the VSG's I/Q Modulator stage. First, consider an ideal I/Q modulator. A CW signal (at the carrier frequency) is fed into a quadrature power splitter, producing two signals, which differ in phase by 90 degrees. These signals are fed to the LO ports of two identical mixers. The IF ports (or low-frequency/DC ports) of these mixers are fed by the I and Q inputs respectively. The RF outputs of the two mixers are summed together, with, ideally, no phase shift between them. The resulting output from this structure is an I/Q modulated signal at the same carrier frequency as the LO.

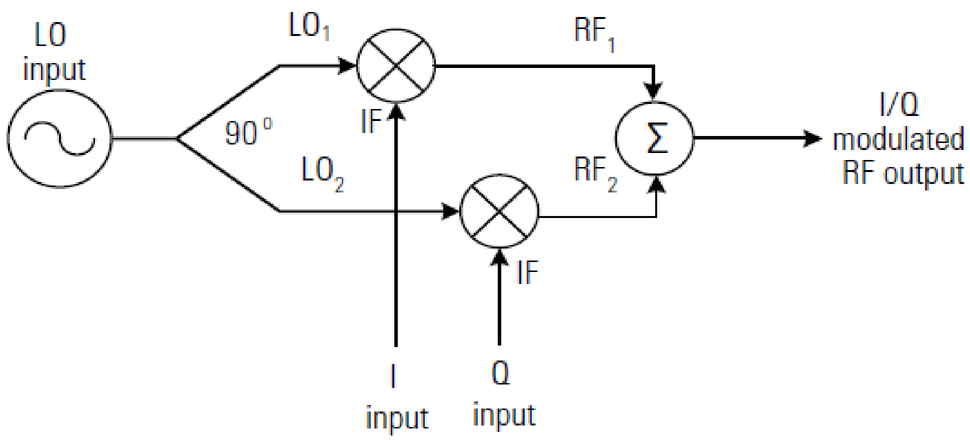


Figure 17. VSG's I/Q Modulator Block Diagram

As an example, assume that the LO signals are described by

$$LO_1 = \sin(\omega_c t), \text{ and}$$
$$LO_2 = \cos(\omega_c t)$$
$$I = A\sin(\omega_m t), \text{ and}$$
$$Q = A\cos(\omega_m t)$$

Since the mixers are assumed to be ideal multipliers for the ideal I/Q modulator case, the mixer outputs will be:

$$RF_1 = \sin(\omega_c t) * A\sin(\omega_m t) = A/2 * \cos((\omega_c - \omega_m)t) - A/2 * \cos((\omega_c + \omega_m)t)$$

$$RF_2 = \cos(\omega_c t) * A\cos(\omega_m t) = A/2 * \cos((\omega_c - \omega_m)t) + A/2 * \cos((\omega_c + \omega_m)t)$$

The output will be RF1 + RF2 = $A \cos((\omega_c - \omega_m)t)$ for the ideal case.

However, I/Q modulator is of course not ideal and have some imperfections. These imperfections are;

1. LO or Carrier feedthrough, sometimes called Origin Offset: This can be caused by:
   - The two mixers not being identically matched and balanced, resulting in LO leakage which is dependent on carrier frequency.
   - DC offset at the I and/or Q inputs, resulting in LO leakage which is independent of carrier frequency. VSG provides adjustable I and Q DC offsets for the internal baseband generator, [14].
2. LO quadrature error results if the two LO signals are not exactly 90 degrees apart. This can be caused by LO splitter phase error, or phase matching imperfections in the mixers. This has the effect of producing an undesired image which does not depend on I/Q modulating frequency, [14].

   For example, assume that

   $LO_1 = \sin(\omega_c t)$ and

   $LO_2 = \cos(\omega_c t + \alpha)$, where α is the quadrature error.

   The mixer outputs will be:

   $RF_1 = \sin(\omega_c t) * A\sin(\omega_m t) = A/2 * \cos((\omega_c - \omega_m)t) - A/2*\cos((\omega_c + \omega_m)t)$

   $RF_2 = \cos(\omega_c t) *A\cos(\omega_m t + \alpha) = A/2 * \cos((\omega_c - \omega_m)t - \alpha) + A/2 * \cos((\omega_c + \omega_m)t + \alpha)$

   The output will be

   $RF_1 + RF_2 = A \cos(\alpha/2) \cos((\omega_c - \omega_m)t - \alpha/2) - A \sin(\alpha/2) \sin((\omega_c + \omega_m)t + \alpha/2)$ (the latter component is the unwanted image)
3. I/Q mismatch errors also result in unwanted images. These errors are caused by differences between the I and Q signals, due to baseband hardware limitations. These errors can be:
   - Amplitude mismatch. For example, in the ideal case above, a 0.1 dB difference results in an undesired image level of −45 dBc, [14]. The vector signal generator has adjustable I/Q gain balance for the internal baseband generator .
   - Phase mismatch. For example, in the ideal case above, a 1 degree difference results in an undesired image level of −41 dBc, [14]. Phase mismatch can be adjusted using the internal quadrature adjustment in the vector signal generator.

- Group delay mismatch (skew), which is more predominant at higher modulation rates. For example, in the ideal case above, a 1-degree error (resulting in a −41 dBc image) can be caused by a 2.8-nanosecond delay mismatch at a 1 MHz modulating rate, or by only a 5.5-picosecond delay mismatch at a 500 MHz modulating rate, [14]. The vector signal generator has adjustable skew correction for the internal baseband generator.

For experimental radar system, I/Q data that constitute phase coded pulsed waveforms, unmodulated pulses with different chip widths, pulse widths and pulse repetition intervals are created and downloaded to the vector signal generator in order to use as transmit signals.

5.2.1 Sampling Rate

After creating the complex I/Q data for the desired waveform, sampling rate should be defined. The clock range of the VSG is 1 Hz to 100MHz, thus the sampling rate could be set between 1 sa/sec to 100 Msa/sec. The minimum pulse width that can be achieved is 10 nsec which could be obtained with 100Msa/s sampling rate. Pulse widths, pulse repetitions intervals are defined by the sampling rate. Sampling rate information is sent from the PC to the vector signal generator while downloading the IQ data of the waveform. Sampling rate is an input of the function "agt_waveformload".

5.2.2 Waveform Markers

The VSG provides four waveform markers to mark specific points on a waveform segment. These four markers are used to create trigger signals, to initiate ALC (Automatic Level Control) hold, or RF Blanking (which includes ALC hold). When a waveform file is created, a marker file is also created. The marker file includes the marker's position in the waveform, polarity and function. The markers can be placed anywhere during the waveform, their width are defined by indicating their start and stop samples. Their polarity can be negative or positive. Their function can be creating trigger signals, Pulse/RF Blanking or ALC Hold.

The marker file uses one byte per I/Q waveform point to set the state of the four markers either on (1) or off (0) for each I/Q point. When a marker is active (on), it provides an output trigger signal to the rear panel EVENT 1 connector (Marker 1 only) or/ and the AUX IO, EVENT 2 connector pin (Markers 1, 2, 3, or 4), that corresponds to the active marker number.

Because markers are set at each waveform point, the marker file contains the same number of bytes, as there are waveform points. For example, for 200 waveform points, the marker file contains 200 bytes. The following example shows a marker byte;

$$\begin{array}{lll} & & 4\ \ 3\ \ 2\ \ 1\ \ \rightarrow \text{Marker Number Position} \\ \text{Marker Byte} & \underbrace{0\ \ 0\ \ 0\ \ 0}_{\text{reserved}} & 1\ \ 0\ \ 1\ \ 1 \end{array}$$

This example sets markers 4, 2 and 1 on. When VSG encounters this example (when the marker function is not Pulse/RF Blank or ALC Hold), it sends a trigger signal which is ~3.3 V if the marker has positive polarity, and 0 V if it has negative polarity to the EVENT 1 connector (BNC connector) at the rear panel and to the AUXILIARY connector's EVENT 2 pin which is also at the rear panel. The width of the trigger pulses depends on the sampling rate and the number of samples that they are defined.

Each marker's polarity and marker points (on a single sample point or over a range of sample points) can be set. Each marker can also perform ALC (Automatic Level Control) hold or RF Blanking and ALC hold. Fig.18 shows marker usage path in the VSG.

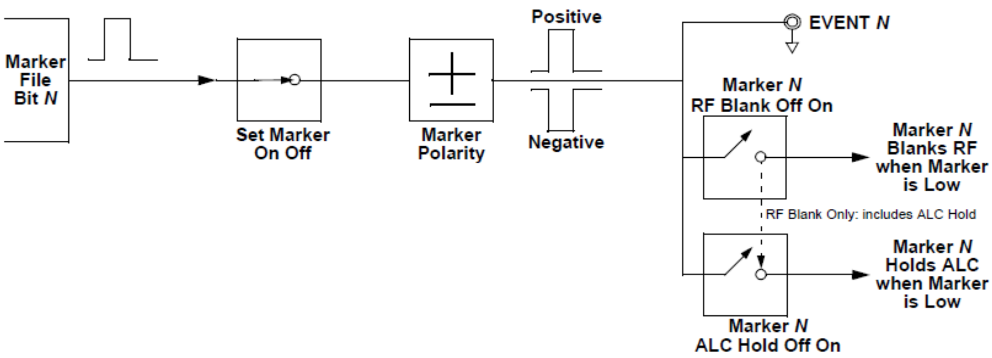


Figure 18. Waveform Markers

In the radar system of this thesis, two markers are used. The first marker, Marker 1, is used for creating a trigger signal. EVENT 1 connector at the rear panel of the VSG is used as the trigger out connector. Marker 1 is placed at the first sample of the transmit pulse, positive polarity is chosen. So, a trigger pulse which is a sample duration long and ~3.3 V is provided at the EVENT 1 connector. The marker can be checked on VSG's monitor. Fig.19 shows the marker at the first sample of the waveform.

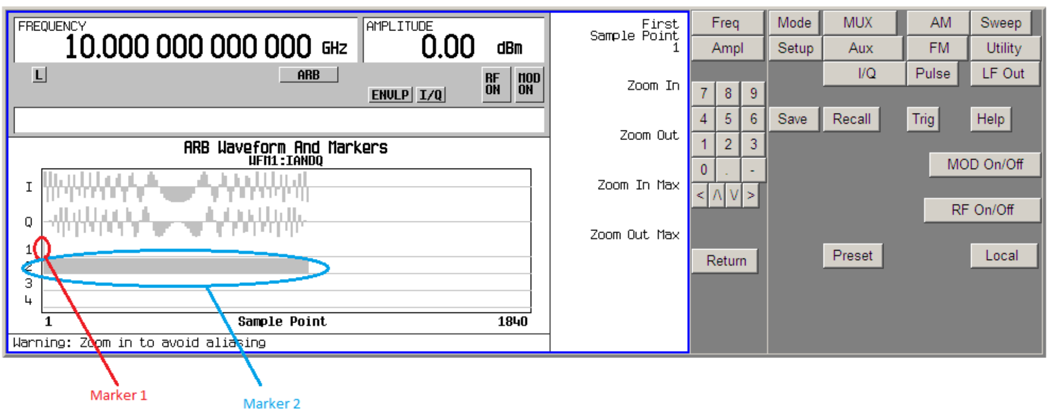


Figure 19.Viewing Marker Position

The second marker, Marker 2, is used for Pulse/RF Blanking. When waveforms are formed of pulses, the off time between pulses are denoted by

I Data = 0 and,

Q Data = 0.

For the waveforms having idle times, VSG may be unable to maintain the correct output level for the on time of the pulse and may cause a DC level for the off time of the pulse instead of 0 Volts. In order to maintain the output level ALC should be used and to blank the RF during the off time of the pulse RF Blanking should be used. Thus, the function for the second marker is Pulse/RF Blank which also includes the ALC Hold.

Fig.20 explains the usage of Pulse/RF Blank Marker. If the marker polarity is chosen as positive, then the marker should be defined during the on time of the waveform because the RF output is blanked during the samples where the marker is off. If the marker polarity is chosen as negative, then the marker should be defined during the off time of the waveform because the RF output is blanked during the samples where the marker is on.

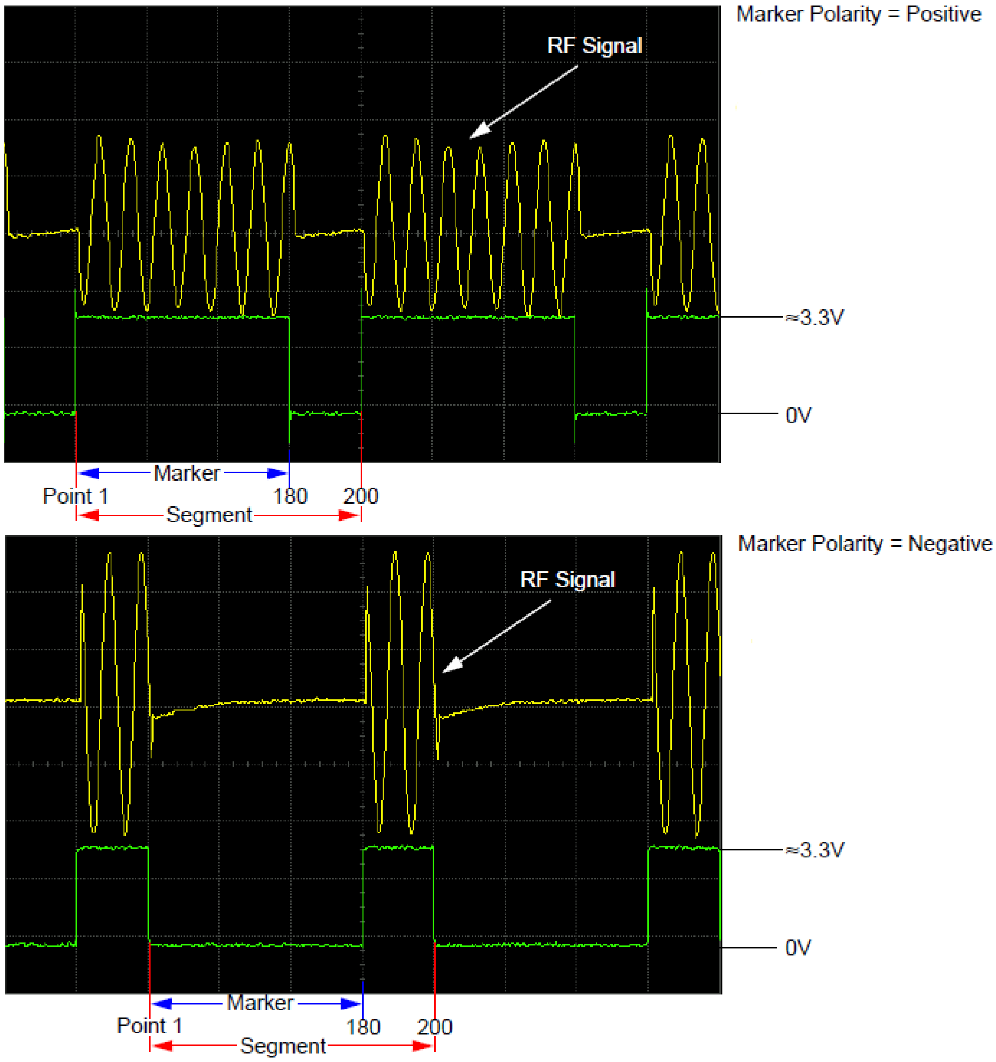


Figure 20. Pulse/RF Blank Marker Description

When the marker function is chosen as Pulse/RF Blank, it also includes the ALC Hold function. As mentioned above, with ALC Hold function the output level of the signal is maintained. When the output level cannot be maintained, an annotation "UNLEVEL" appears on the VSG's screen indicating that the output power level cannot be maintained correctly. In order to solve this, ALC circuitry should be set. This is again done by markers. The ALC samples the waveform portion where the marker is defined, and uses the average of the sampled waveform to set the ALC circuitry. This is described in Fig.21; the ALC should sample only during the top portion of the envelope, not during the rise/fall times.

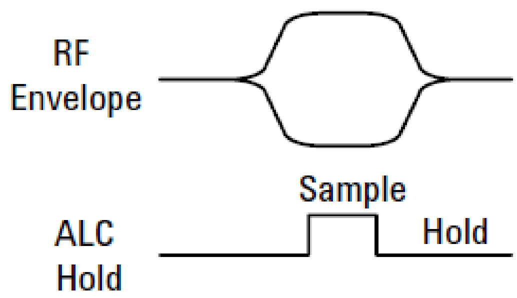


Figure 21. ALC Sampling

Fig.22 shows an example to describe how this marker function works. This example shows a marker set to sample the waveform's region of highest amplitude. The marker is set well before the waveform's region of lowest amplitude. This takes into account the response difference between the marker and the waveform signal. The ALC samples the waveform when the marker signal goes high, and uses the average of the sampled waveform to set the ALC circuitry as mentioned before. The correct sample/hold signal must be routed to the ALC integrator so that the circuitry is set correctly. For correct setting, the rise and fall times of the waveform should not be included in the marker. In this example, the ALC samples the waveform during the on marker points, as the marker polarity is positive.

Pulse/RF Blank marker can also be checked on VSG's monitor. This is shown in Fig.19; Marker 2 is the Pulse/RF Blank marker, which is defined during the pulse duration since there is no rise or fall times defined.

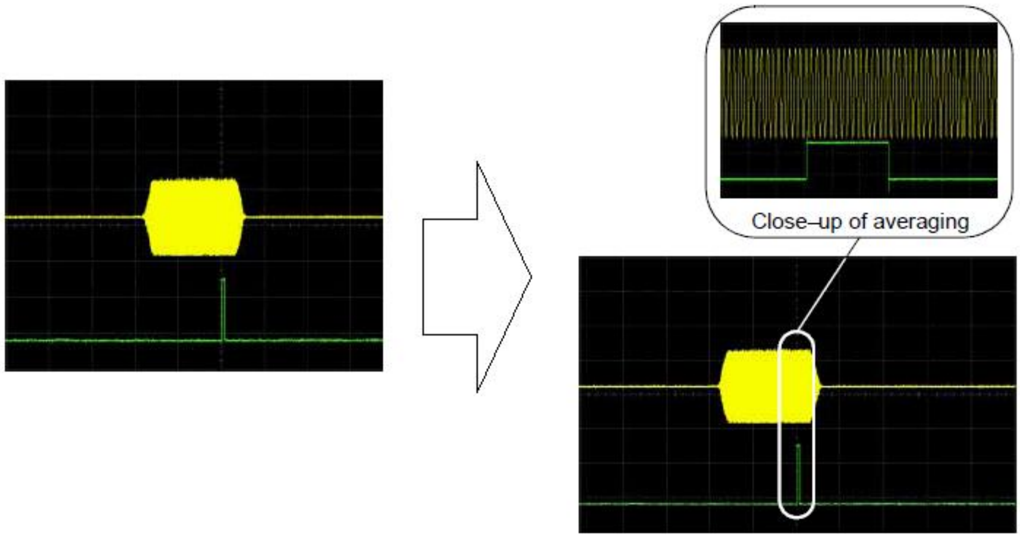


Figure 22. ALC Hold Marker Description

Up to this point, three main parameters required for generating waveforms are examined. After these parameters' values are determined, the carrier frequency and the output power of the signal are decided and all this information is loaded to VSG to be transmitted via Ethernet.

5.3 Transmit Signals

The transmit signals are formed by defining their I/Q Data. This gives flexibility to generate a wide range of signals. CW or pulsed - modulated (frequency, phase, amplitude), unmodulated or coded- signals can be generated easily. Besides for the pulsed signals, pulse widths and pulse repetition intervals can be set easily with a resolution of 10 nsec.

Thus, any kind of signal can be used as transmit signal of this thesis's radar system with a transmit frequency in the range 250 kHz to 44 GHz (0.001 Hz resolution).

According to the function of the radar the most suitable transmit signal can be decided and generated. The flexibility for defining the transmit signal makes this radar system manageable.

Many signals have been generated as this experimental radar's transmit signal and transmitted to the environment for observation. Mostly used transmit signals are;

- Phase Coded Pulses
    - Barker
    - P4
- Single Pulse

Different pulse widths, chip widths, chip numbers, pulse repetition intervals have been used. X-Band frequency values have been chosen as transmit frequency since the antennas of this system support X-Band.

Barker code can be defined for maximum 13 phases, thus maximum 13 chips can be defined for a Barker coded pulse. On the other hand, P4 code can be defined for any number of phases, [2].

5.4 Problems Caused by VSG

5.4.1 Amplitude Variation on Phase Transitions

When phase coded compressed pulses are chosen as transmit signals, power reduction is observed on phase transitions. Fig.23 shows an example of this case. The screenshot shows the pulse, which is received by PSG E4446A, on Vector Signal Analysis window. The signal shown in Fig.23 is a Barker 7 coded pulse 50 μsec PRI and 7μsec PW at 10 GHz. There are three phase transitions and change in amplitude can be seen easily on these transitions. The signal is constituted as described in preceding parts of this chapter. Chip duration is 1 μsec and the sampling rate is 100Msa/sec, thus one chip is composed of 100 samples. However, time resolution on receiver side is 100nsec.

Amplitude variation occurs when the phase changes abruptly in chip transitions. The more the phase difference is between two chips, the more the band extends. The phase discontinuity between transitions creates high frequency terms and requires a relatively large percentage of the power to occur outside of the intended band. The signal generator filters these high frequency terms. When these abrupt changes are smoothed by defining rise and fall times for the phase transitions, amplitude variations decrease.

There is no rise or fall time defined at phase transitions in the example above. To get rid of this amplitude variation, defining a certain number of samples at the beginning of the chips as rise time and at the end of the chips as fall time decreases the amplitude variation as it provides smooth phase transition instead of an abrupt transition. Fig.24 shows an example of the same signal but this time 20 samples at the beginning of the pulse constitute rise time, 20 samples at the end of the pulse constitute fall time and 20 samples constitute rise and fall times at transitions. When the pulse is formed in that manner, it is seen that the amplitude variation decreases. Yet, this improvement is possible when there are enough samples for chip duration. When 100nsec is chosen as chip/pulse duration, this solution cannot be applied.

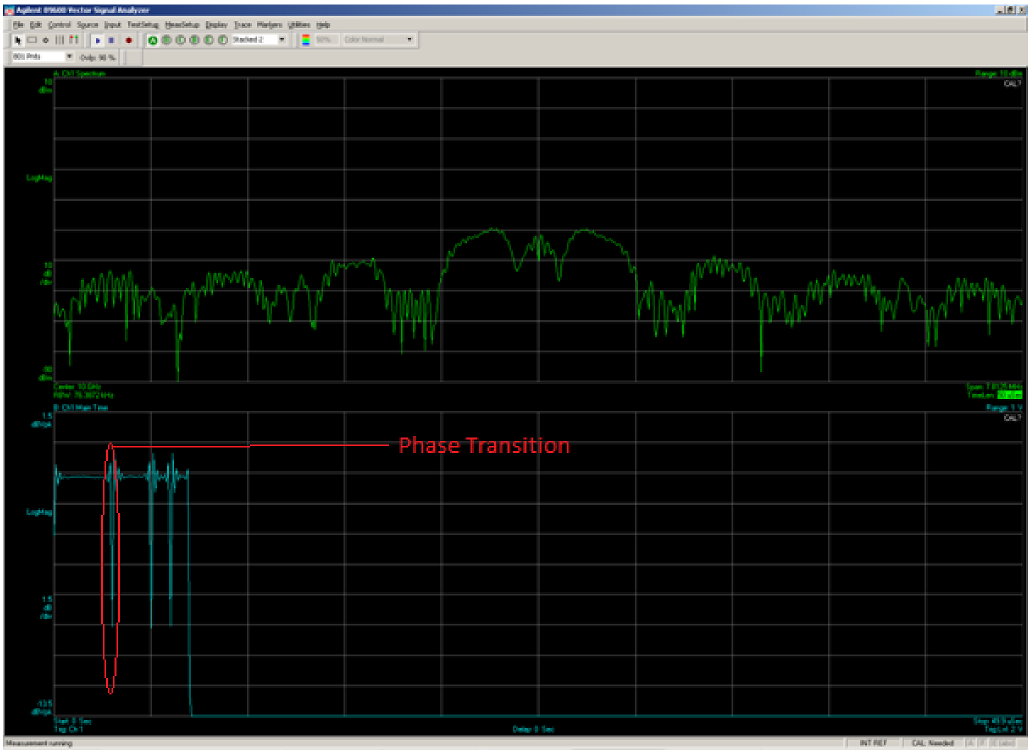


Figure 23. Power Reduction on Phase Transitions

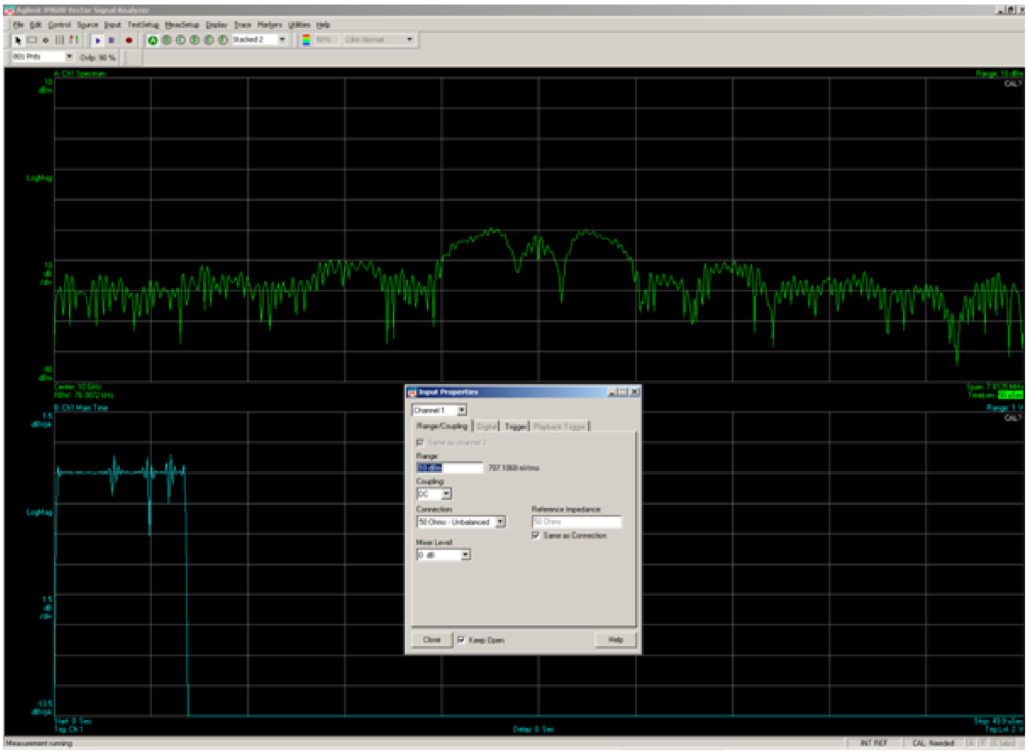


Figure 24. Power Reduction on Phase Transitions-Rise and Fall Time Defined

CHAPTER 6

AMPLIFIERS

6.1 High Power Amplifier

A high gain RF amplifier, HP 8348A, is used to increase transmit power. Agilent E8267D Vector Signal Generator is used as transmitter, and the amplifier is connected to its RF output. Vector signal generator's output power depends on the frequency of the signal and type of the signal. Fig.25 shows the output power values of the vector signal generator for CW signals. For pulsed signals, the output power level is considerably less than the CW signals.

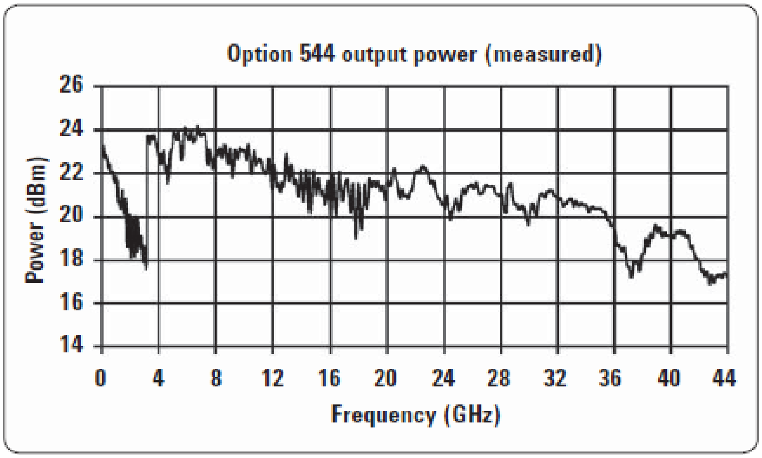


Figure 25. Maximum Available Power of VSG E8267D in CW mode

Choosing compressed pulsed signals and utilizing pulse integration, power can be improved. On the other hand, when compressed pulses are chosen as transmit pulses, the power output of the VSG drops to 0 – 10 dBm.

An amplifier is necessary to increase the output power. Detection of targets depends on the received power which is directly proportional to transmit power. For these reasons, an amplifier is added to the system.

Features of the RF amplifier HP 8348A are as follows;

- Frequency range of 2 to 26.5 GHz
- Maximum continuous input power = 22 dBm
- Maximum output power is shown in Fig.26 at 0 dBm input
- Input and output impedance = 50 Ω
- Input SWR < 3:1
- Output SWR <4.5:1 (2 -20 GHz)
- Noise Figure < 10 dB (1-20 GHz)
- Pulse Transmission Capability : Rise/Fall Time < 5ns, Delay Time < 5ns

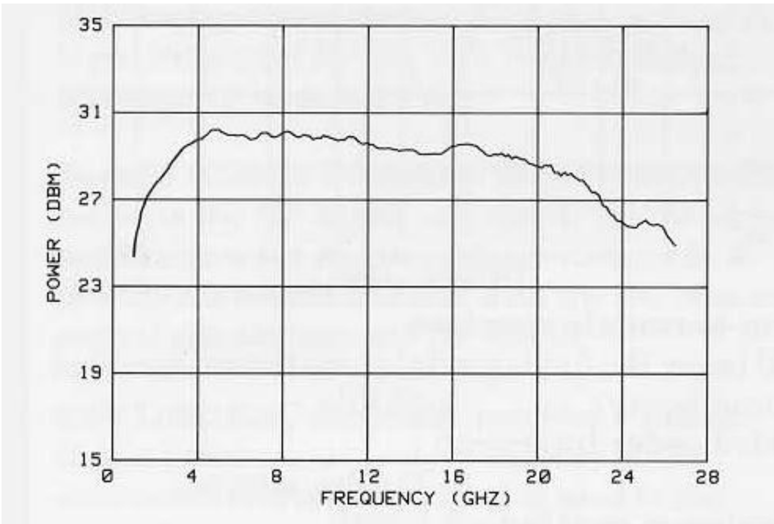


Figure 26. Typical Maximum Output Power of HP8348A at 0 dBm Input

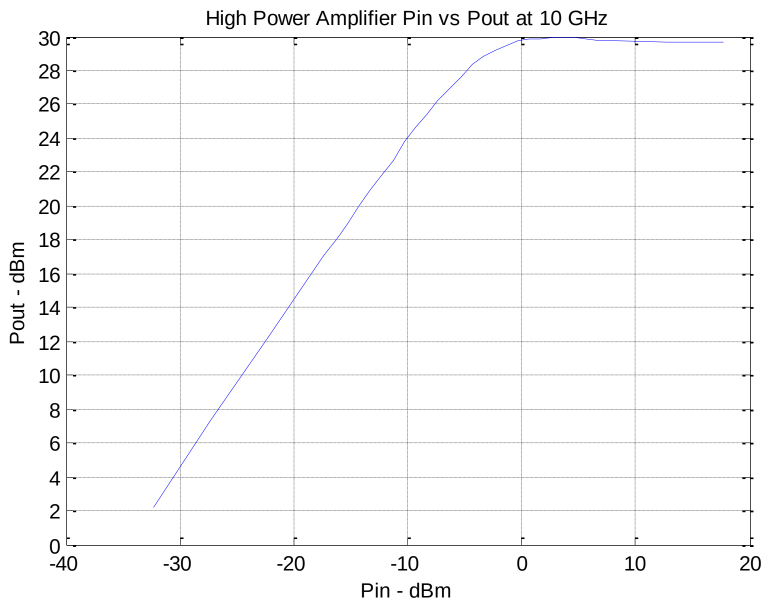


Figure 27. Input Power vs. Output Power of HP8348A at 10 GHz

In Fig.27, input and output power characteristics of the amplifier are given at 10 GHz. The amplifier enters saturation at 0 dBm input and maximum available power is approximately 30 dBm. The gain of the amplifier is 33 dB in linear region.

It is good to have high output power for good detection. Cable losses, space loss, mismatch decreases power. Radars use very high power amplifiers such as Travelling Wave Tube Amplifiers, Solid State Amplifiers.

6.2 Low Noise Amplifier

Low Noise Amplifier is a key element used between the receive antenna and the spectrum analyzer, which amplifies the received signal and has relatively low noise figure. LNA is an element of the receiver block of the system.

The noise level of the receiver sets the fundamental limit to the signal that the system can measure. While amplifying the signal, noise and distortion are added by the amplifiers. According to Friis' Noise Figure Formula (1) overall noise figure of cascaded stages of system is as follows:

$$\text{Overall NF} = NF_1 + \frac{NF_2 - 1}{Gain_1} + \frac{NF_3 - 1}{Gain_1 Gain_2} + \cdots + \frac{NF_N - 1}{Gain_1 Gain_2 \ldots Gain_{N-1}}$$

When Friis' Equation is examined, it is obvious that the first amplifier contributes most to the system noise level, so if the first amplifier is chosen to be a low noise amplifier, the overall noise figure of the system is reduced most.

For experimental radar system's receiver part Friis formula becomes;

$$\text{Overall NF} = NF_{LNA} + \frac{NF_{PSA} - 1}{Gain_{LNA}} \qquad \text{when one LNA is used}$$

$$\text{Overall NF} = NF_1 + \frac{NF_2 - 1}{Gain_1} + \frac{NF_3 - 1}{Gain_1 Gain_2} \qquad \text{when two LNAs are used}$$

Noise figure of the receiver part becomes 9.185 dB when one LNA is used and it becomes 3.244 dB when two LNAs are used successively. The configuration with one LNA is described in Fig.28.

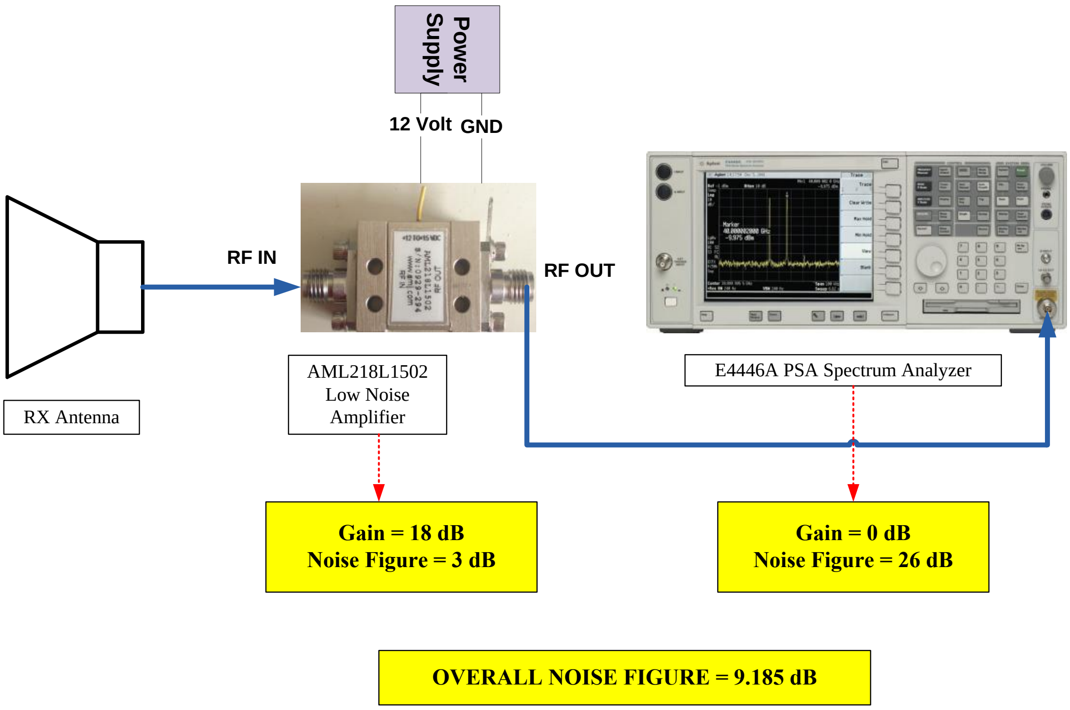


Figure 28. Noise Figure of Radar System with one LNA Inserted

AML218L1502 is chosen as the system's low noise amplifier which has the following characteristics;

- Frequency Range : 2 – 18 GHz
- Noise Figure 3 dB (max)
- Gain 15 dB (min) –Fig.29 shows the gain of LNA over its frequency range
- Input VSWR 2.0:1 (Nominal), 2.5:1 (Max)
- Output VSWR 2.0:1 (Nominal), 2.5:1 (Max)

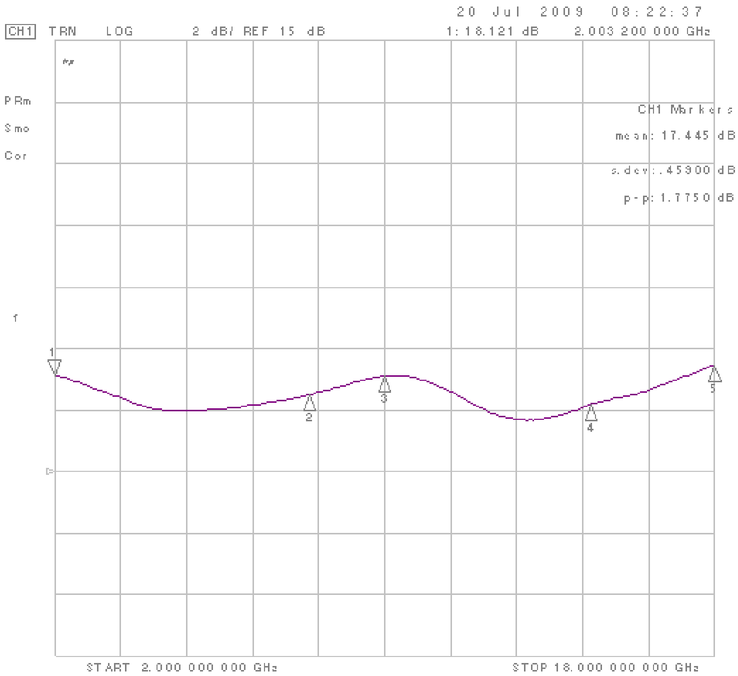


Figure 29. Gain Characteristics of LNA

AML218L1502 is a distributed low noise amplifier with the gates grounded via 50 Ω resistors.

In conclusion, an amplifier added to a system changes the overall noise level of the system and the first amplifier in the system's chain affects the noise level most, thus it is best to choose an LNA as the first amplifier. LNA improved the noise figure of the system's receiver part by a value of nearly 17 dB as the noise figure of the system is nearly 26 dB without the LNA. In addition, LNA amplified the received signal by nearly 17 dB at 10 GHz which made the weak echoes distinctive.

CHAPTER 7

RECEIVER

Receiver of radar is the unit, where the received echoes captured by the receiving antenna sent to, in order to separate the desired signal from the ever-present noise and other interfering signals. The output of the receiver may be presented on a display to an operator who makes the decision as to whether or not a target is present, or the receiver output can be processed by electronic means to automatically recognize the presence of a target and to establish a track of the target from detections made over a period of time, [1].

The receiver of experimental radar system can be classified as a super heterodyne type receiver. It is considered to have four main blocks which are LNA, Agilent's PSA E4446A Spectrum Analyzer, Agilent's Vector Signal Analysis Software that runs on a PC and the receiver signal processing block which is written in MATLAB. Spectrum analyzer along with the LNA forms the hardware of the system's receiver; basically the received echo is transferred to spectrum analyzer through its RF IN port and it down converts the received RF echo to IF frequency where the digitization of the signal is performed. Digitized signal at IF frequency is digitally down converted to baseband and I/Q components of the signal is obtained. The super heterodyne architecture of spectrum analyzer is the reason why the receiver is classified as super heterodyne receiver. Vector signal analysis software runs on the PC; it uses the spectrum analyzer as hardware and I/Q data of the signal is transferred to the PC with the help of this software. I/Q data of received signal is loaded in MATLAB to be processed. Depending on the transmit signal type, appropriate receiver processing should be implemented. Pulse Doppler processing algorithm is coded via MATLAB in the scope of this thesis which will be described later in this chapter. The results of the processing are presented to the operator graphically on the monitor of the

PC. The graphics have the range, Doppler frequency and amplitude information of the received echo. No detection decision is made automatically.

The practical and functional property of this structure is that I/Q data is acquired from the COTS equipments and processing the I/Q data is left to the user. Thus, the user can choose any kind of transmit signal and design the corresponding receiver signal processing blocks. This feature makes the radar system flexible by means of choosing the transmit signal.

The parts constituting the receiver of the system, that are mentioned above, are discussed under three main titles which are Agilent E4446A Spectrum Analyzer, Agilent 89601A Vector Analysis Software and Receiver Processing.

7.1 Agilent E4446A Spectrum Analyzer

E4446A is a Performance Spectrum Analysis (PSA) spectrum analyzer, which very basically depicts a window in frequency domain. Its basic block diagram is shown in Fig.30, [11]. This spectrum analyzer down converts the RF signal to IF and it has an all-digital IF section. After the input signal is down converted to IF which is 321.4 MHz, it is immediately digitized, and all processing is performed digitally.

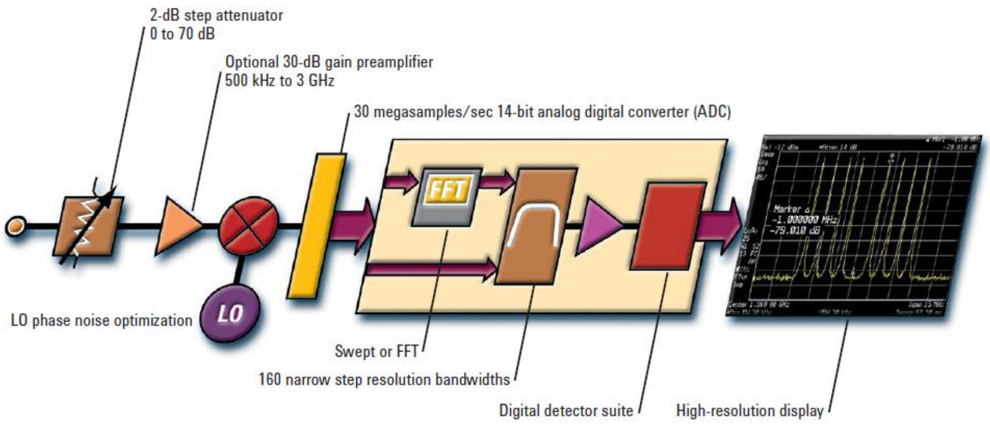


Figure 30. Basic Block Diagram of E4446A

Main properties of spectrum analyzer are;

- Frequency Range : 3 Hz to 44 GHz
- Frequency Span : 0 Hz (Zero span), 10 Hz – 44 GHz
- Trigger : Free run, line, video, RF burst, external front, external rear, frame (basic mode)
- Resolution Bandwidth Range : 1 Hz to 3 MHz (10% steps), 4, 5, 6, 8 MHz
- Analysis Bandwidth : 10 MHz
- IF output : 321.4 MHz
- Video Bandwidth Range : 1 Hz to 3 MHz (10% steps), 4, 5, 6, 8 MHz
- Measurement range : Displayed average noise level (DANL) to maximum safe input level (30 dBm)
- Input attenuator range (3 Hz to 44 GHz) : 0 to 70 dB in 2 dB steps
- Displayed Average Noise Level : 1.2 GHz to 3 GHz ~ –166 dBm (when the PreAmplifier is ON)

  3 GHz to 6.6 GHz ~ –151 dBm

  6.6 GHz to 13.2 GHz ~ –146 dBm

  13.2 GHz to 20 GHz ~ –144 dBm
- Dynamic Range : ~81 dB
- Memory : 1 M complex samples

In the experimental radar system, spectrum analyzer is the second hardware used in receiver part of the system after the LNA. Spectrum analyzer has a wide frequency range, which is listed above, and it covers the frequency range of the signal generator that is used as transmitter. This feature makes the system flexible for choosing the transmit frequency when an appropriate antenna for the chosen frequency is utilized. Noise level values of the spectrum analyzer are reasonable, however the instrument has two preamplifier options that improve the actual noise level but these hardware options should be chosen to be added to the instrument, they are not included in the base system of the instrument. The preamplifier that has a frequency range of 100 kHz to 3 GHz is added by the Option 1DS, and it improves the noise level by approximately 13 dB with respect to the noise level of the spectrum analyzer without the preamplifier in its operating range; on the other hand the preamplifier with a frequency range of 10 MHz to 26.5 GHz is added by the Option 110 and similarly it improves the noise level approximately 16 dB in its operating range. The spectrum analyzer used in the radar system has Option 1DS, however it does not have Option 110.

The noise level of the spectrum analyzer can be measured by utilizing markers and the results can be read on the display of the instrument. The important point is that the measured noise level depends on the Noise Figure, Resolution Bandwidth and noise bandwidth. This relation is given by the following equation;

$$\text{Measured Noise Level (dBm)} = \text{kTB(dBm)} + \text{NF(dB)} + 10\log_{10}\left(\frac{\text{RBW(Hz)}}{\text{B(Hz)}}\right) \quad (3)$$

where k= Boltzman's Constant, T = Temperature (Kelvin), B= Noise Bandwidth

NF= Noise Figure of Spectrum Analyzer,

RBW = Resolution Bandwidth of Spectrum Analyzer

For instance, consider Fig.31. A CW signal at 10 GHz frequency and -30 dBm power is connected to the RF input of spectrum analyzer. Marker 1 is placed on the noise level of the spectrum analyzer and it reads -89.688 dBm. However, it is known that the noise level should be approximately -174 dBm from the noise power formula "Noise Power = kTB" when the temperature is 20°Celcius and the bandwidth is 1 Hz. From equation (3), it is known that the noise level reading on the spectrum analyzer is dependent to RBW and NF of spectrum analyzer. If the parameter values are placed in this equation, then;

Measured Noise Level = kTB (-174 dBm) + NF (25 dB at 10 GHz) + $10\log_{10}$ (910KHz/1Hz)

= -174 dBm + 25 dB + 59.59 dB

= -89.41 dBm

The measured noise level is -89.688 dBm, which is closely equal to the result found above. Hence, the measured noise level should not mislead the user.

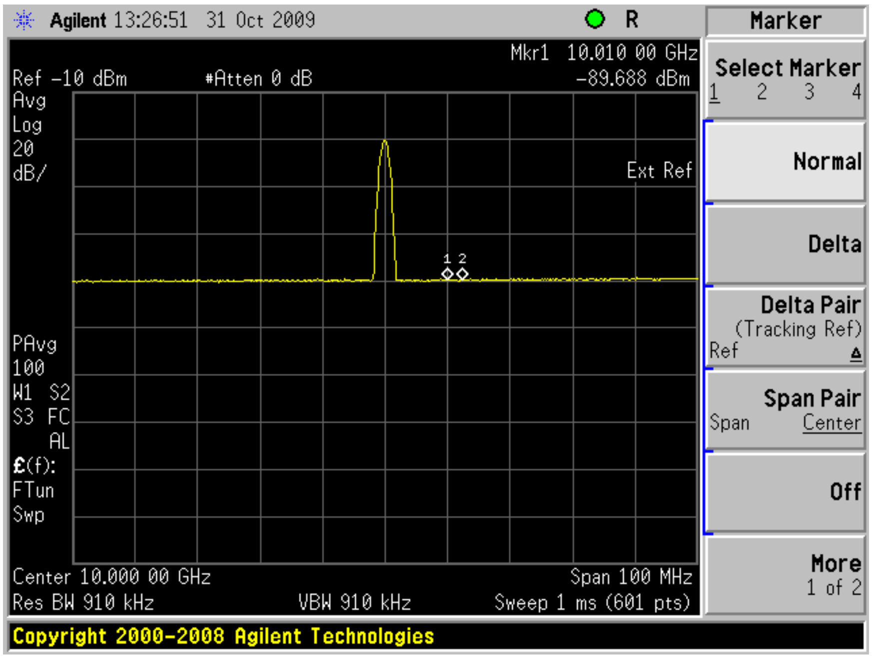


Figure 31. Noise Level Measurement of Spectrum Analyzer

Analysis bandwidth of the spectrum analyzer is the instantaneous bandwidth available about a center frequency over which the input signal can be digitized for further analysis or processing in the time, frequency, or modulation domain. This spectrum analyzer's analysis bandwidth is 10 MHz, but it can be improved to 40 MHz or 80 MHz with options 140 or 122. These options are not included in the used spectrum analyzer, thus the maximum analysis bandwidth available is 10 MHz.

This spectrum analyzer works like a super heterodyne receiver. It captures the RF signal and down converts it to IF frequency which is 321.4 MHz. It has two operating modes, which are spectrum mode and basic mode. Mainly, in spectrum mode, frequency domain analysis is performed and spectrum of the input signal is displayed. On the other hand, in basic mode, time domain analysis is performed and I/Q data of the input signal is displayed.

When using spectrum mode, spectrum trace of the RF signal is observed, many power measurements such as channel power, peak power, and integration band power can be achieved easily. When basic mode is chosen, I/Q Data vs. Time, RF Envelope vs. Time and again spectrum traces are present. I/Q Data vs. Time trace shows I and Q data of the input signal with different colours and magnitude of input signal (magnitude (I + jQ)) is shown on RF Envelope vs. Time trace.

It is good to see baseband signal time domain traces on Spectrum Analyzer; it is possible to export complex data of the input signal to PC via USB, GPIB or Ethernet. In the experimental radar system, PC and spectrum analyzer are connected via USB. The vector signal generator is connected via Ethernet, thus an Ethernet switch is required if the connection of spectrum analyzer is also preferred to be via Ethernet. On the other hand, if GBIP is chosen GPIB card and cable is required which are not included in the instrument’s package, thus USB connection seemed to be the easiest way.

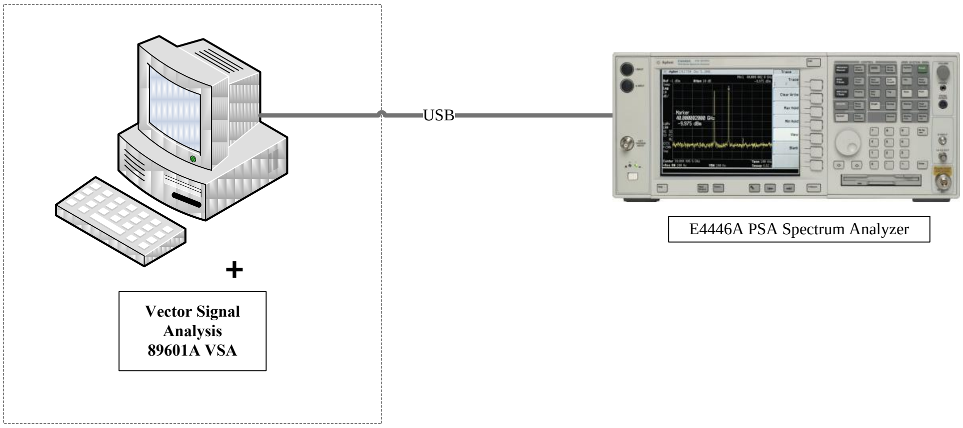


Figure 32. Connection Between Spectrum Analyzer and PC

The frequency and time analysis results shown on the traces of spectrum and basic mode can be downloaded to PC as data arrays by SCPI commands or their screenshots can be captured by Intuilink program which is again Agilent’s software tool. In addition, setup of the instrument can also be saved by Intuilink and the saved file can be used to recall the same setup state later. These are the properties that make the instrument manageable but there is a limitation of the instrument for the basic mode, which makes the usage of Vector Signal Analysis software necessary. The instrument lets basic mode analysis up to 3 GHz frequency. Although, spectrums of signals at frequencies up to 44 GHz are analyzed and displayed on instruments monitor, time domain analyses of signals at frequencies higher than 3 GHz are not performed. In other words, maximum center frequency that is allowed in basic mode is 3 GHz.

If the received signal has center frequency below 3 GHz, it is possible to transfer its acquired complex I/Q data from spectrum analyzer to PC directly via USB. The spectrum analyzer acquires 1 M complex samples, and it is possible to get these samples by using SCPI commands. The time resolution for the received signal is defined by setting "IF Filter BW" parameter of the spectrum analyzer. Regardless of the time resolution set, maximum acquired samples number does not change which is always 1 M. Consequently, maximum time length is designated by the time resolution chosen. Table 3 lists the relation between time resolution and IF filter BW for possible settable values of IF filter BW.

Table 3. Time Resolution vs. IF Filter BW on PSA and EXA

IF Filter BW (kHz)	Time Res (nsec)	Max Time Length PSA (msec)	Max Time Length EXA (msec)
50	1470	1470	5880
75	1000	1000	4000
100	733.33	733.34	2933.36
150	533.33	533.34	2133.36
200	400	401	1604
300	266.67	266.68	1066.72
500	200	201	804
750	133.33	133.33	533.32
1000	133.33	133.33	533.32
1500	66.67	66.67	266.68
2000	66.67	66.67	266.68
3000	66.67	66.67	266.68
5000	66.67	66.67	266.68
7500	66.67	66.67	266.68
8000	66.67	66.67	266.68

I/Q data of signals with frequency higher than 3 GHz cannot be obtained by E4446A. This is the point where Vector Signal Analysis software is needed because this tool performs time domain analyses up to 26.5 GHz when it is used together with E4446A. Time resolution and corresponding maximum time length values are different than PSA when VSA is used. These values are also given in Table 5.

At the end of this thesis, EXA N9010A Signal Analyzer is used as substitute of PSA. EXA is a newer version of PSA series spectrum analyzers. It has mainly the same technical specifications except two important capabilities that PSA does not have. First difference is that it can analyze signals with frequencies up to 13.6 GHz in basic mode. Second difference is that it acquires 4 M complex samples in basic mode which is 4 times better than the maximum acquired samples in PSA. Similarly, time resolution is set by the IF filter BW on EXA and the relation between IF filter BW and time resolution is exactly same with PSA which is given in Table 3. Thus, maximum time length is four times better than PSA as listed in Table 3.

It is also possible to transfer the complex I/Q data from EXA to PC via USB. Another advantage of the EXA is that, when it eliminates the need for VSA. Since it performs time domain analysis up to 13.6 GHz in basic mode, it eliminates the 3 GHz limit of the PSA. Measurements are performed when EXA is used as the receiver of the system and the results of these measurements are also studied.

7.2 Agilent 89601A Vector Analysis Software

The 89600 Vector Signal Analysis (VSA) software is a tool designed to measure, evaluate and troubleshoot complex (I/Q) modulated signals. It is fundamentally a digital system that uses DSP to perform spectrum analysis with FFTs, and uses demodulator algorithms to perform vector-modulation analysis.
This software runs on a PC and works with a variety of hardware measurement platforms. These platforms include Agilent's 89600S VXI based vector signal analysis systems, the 89650S wideband vector signal analysis system, the PSA high performance spectrum analyzers, the ESA general-purpose spectrum analyzers, the X-Series signal analyzers, Infiniium and InfiniiVision 6000 and 7000 Series oscilloscopes, many Agilent Acqiris digitizer modules, and several Agilent logic analyzers. Common features of these platforms are that they down convert and digitize the signal, provide signal capture capability, and move the data to the PC in a sequential stream of data blocks. The 89600 software processes the data in the time, frequency and modulation domains, [7].
89600 is the number code used for the VSA group, 89601A is the one used with PSA E4446A Spectrum Analyzer and it is installed on PC. E4446A Spectrum Analyzer is the hardware section of this combination and it is designated as

analog to digital converter module for the VSA 89601A. This designation is done through the path Utilities > Hardware >ADC1 tab on VSA which is shown on Fig.33.

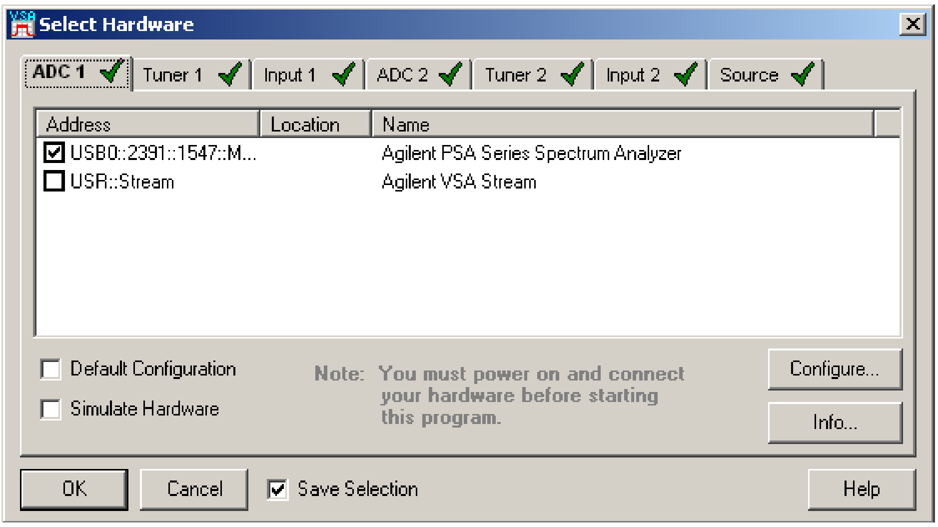


Figure 33. Designation of Spectrum Analyzer as ADC on VSA

The specifications of PSA E4446A Spectrum Analyzer when used with VSA are as follows:

- Frequency
    - Range 3 Hz – 44 GHz
    - Center frequency tuning resolution : 1 mHz
    - Frequency span : < 10 Hz to 8 MHz
    - Frequency points per span : 51 to 524,288
- RBW Range : 1 Hz to 2.3 MHz

  The range of available RBW choices is a function of the selected frequency span and the number of frequency points. User may step through the available range in a 1-3-10 sequence or directly enter an arbitrarily chosen bandwidth by choosing the RBW mode as arbitrary.
- Input

  Input value combines attenuator setting and ADC gain. PSA ADC gain is set to 6 dB and attenuator is set to [89601A range (in dBm) + 18] dB. Attenuation values of PSA corresponding to the input range values of VSA are given in Table 4.

Table 4. PSA Attenuation vs. VSA Input Range

Attenuation(dB)	Input
54	30
44	20
34	10
24	0
14	-10
4	-20
0	-30

- Input Range : −30 dBm to +30 dBm in 2 dB steps

The input range must be set correctly to obtain accurate measurements. Input ranges that are too low overload the analyzer's ADC. Input ranges that are too high increase noise. There is not an optimum value for input range, it should be designated according to the peak power of the input RF signal and it should be chosen higher than the input signal's peak power. The frequency spectrum of the input signal is distorted when appropriate input range is not chosen. This situation is described in Fig.34.

The input signal used in the example of Fig.33 is a pulsed signal at 10 GHz and has 1μsec pulse width, 50 μsec pulse repetition interval and 0 dBm output power. When the input range is chosen as 30 dBm, there is no distortion. Distortion starts when the input range is 0 dBm and it gets worse when it is chosen smaller. Three cases are shown in Fig.34, there is no distortion in the first case, the second case shows the situation when distortion starts and the distortion is very distinctive in the third case.

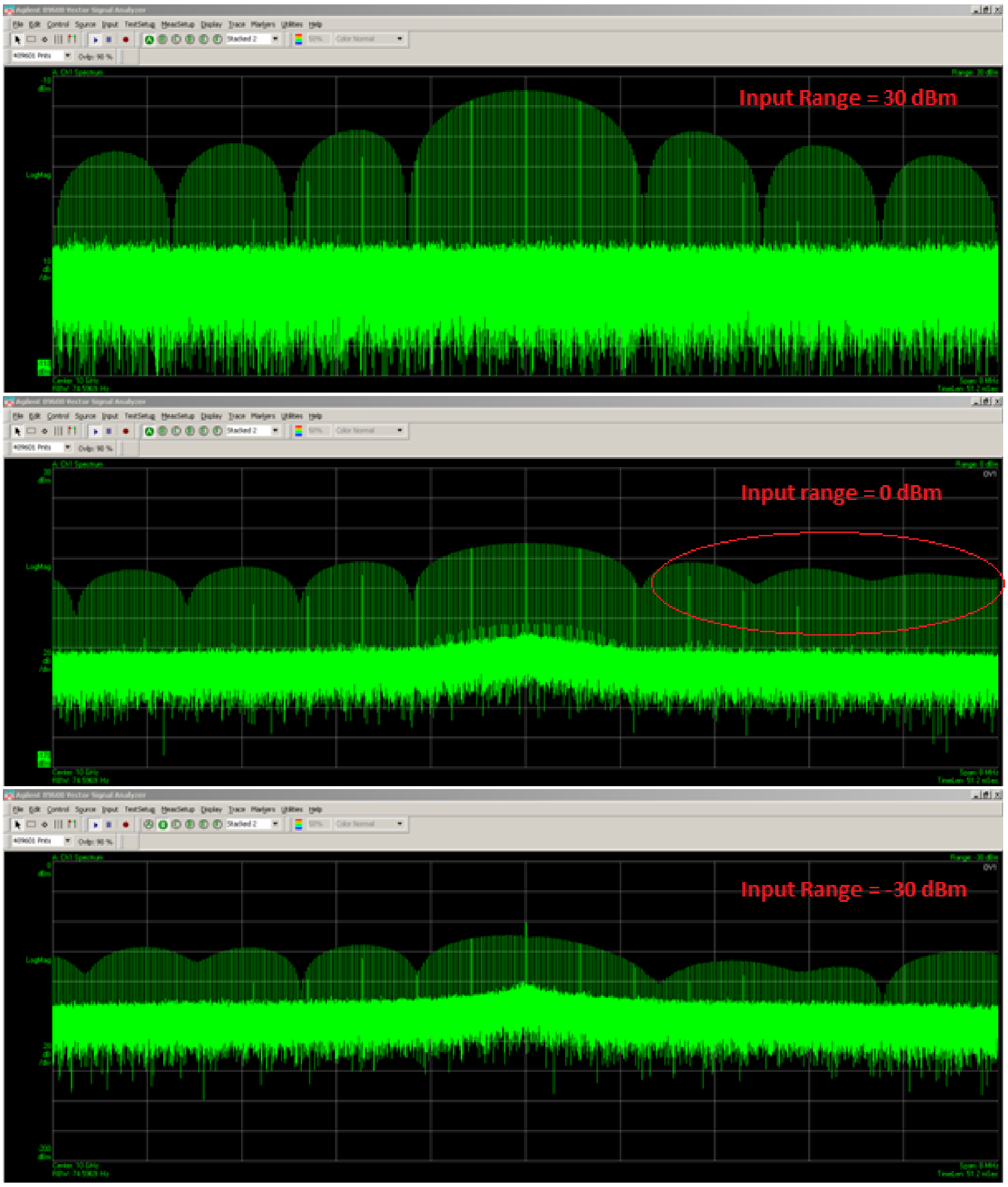


Figure 34. Input Range Choice

Consider the block diagram of the VSA 89601A shown in Fig.35. The operation theory and VSA measurement concepts will be discussed by examining the block diagram shown in that figure.

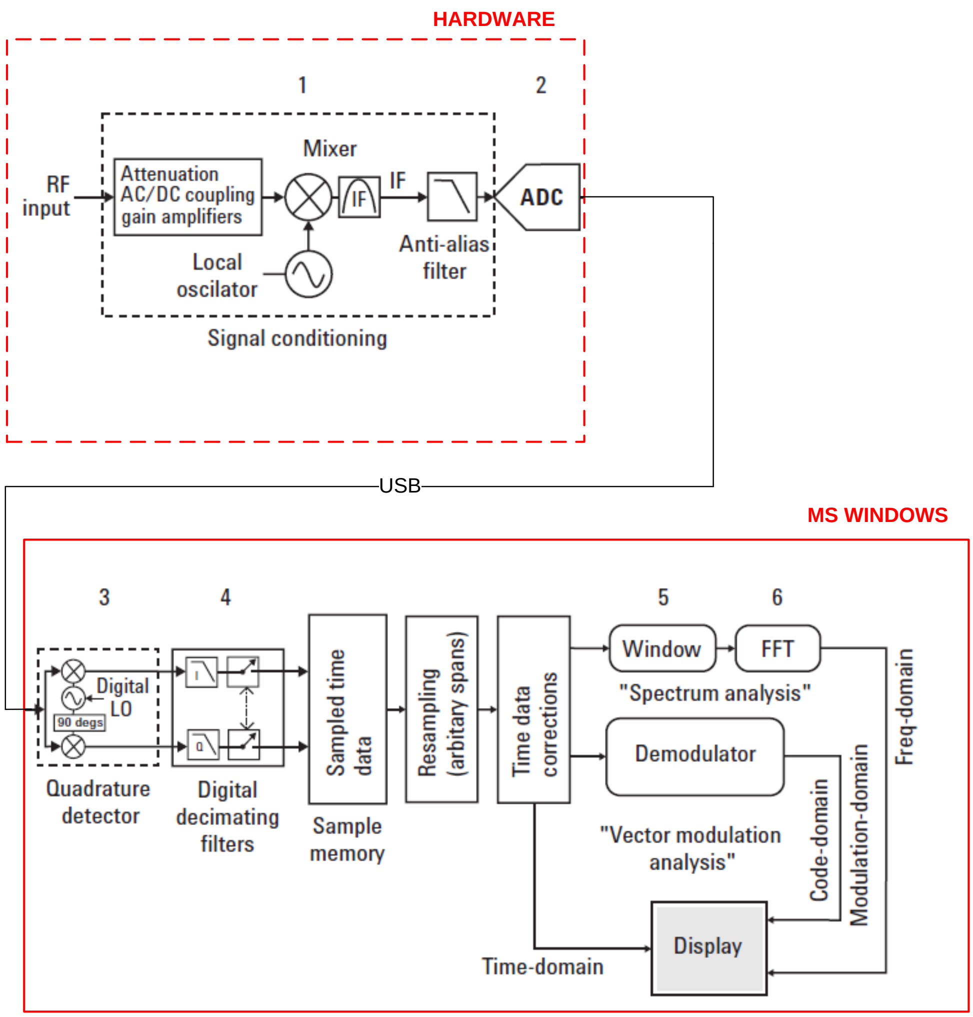


Figure 35. VSA Block Diagram

This is the general block diagram of the VSA; it may show some differences according to the hardware it is used with. For the case of VSA 89601A, the RF signal enters the hardware which is E4446A spectrum analyzer and it is down converted to IF and the signal at IF frequency is passed through the ADC. The process until the end of digitization takes place in the hardware. The digitized signal data is sent to the PC in a sequential stream of data blocks. This data is recorded by VSA. This recorded data is down converted to baseband by digital down conversion and decimated by digital filters. The sample rate into the decimating digital filter is *f*s; the sample rate out of the filter is *f*s/n, where "n" is the decimation factor and is an integer value. Similarly, the bandwidth at the input filter is "*BW*," and the bandwidth at the output of the filter is "*BW*/n". The output of the digital decimating filters represent a bandlimited, digital version of the analog input signal in time-domain. Digital decimating filter performs binary decimation (divide-by-2 sample rate reduction), which means that the sample rate is changed by integer powers of 2, in $1/(2^n)$ steps (1/2, 1/4, 1/8...etc). Frequency spans that result from "divide by 2^n" are called cardinal spans. Measurements performed at cardinal spans are typically faster than measurements performed at arbitrary spans due to reduced DSP operations [10].

This digital data stream is captured in sample memory. The *sample memory* is a circular FIFO (first in, first out) buffer that collects individual data samples into blocks of data called time records, to be used by the DSP for further data processing. The time data collected in sample memory is the fundamental data used to produce all measurement results, whether in the frequency domain, time domain, or modulation domain [10].

To provide more accurate data results, VSA implements time data correction capability through an equalization filter. In vector analysis, the accuracy of the time data is very important. Not only is it the basis for all of the demodulation measurements, but it is also used directly for measurements such as instantaneous power as a function of time. Correcting the time data is the last step in creating a nearly ideal bandlimiting signal path. While the digital filters and resampling algorithms provide for arbitrary bandwidths (sample rates and spans), the time-domain corrections determine the final passband characteristic of the signal path. Time-domain corrections would be unnecessary if the analog and digital signal paths could be made ideal. Time-domain corrections function as an equalization filter to compensate for passband imperfections. These imperfections come from many sources. The IF filters in the RF section, the analog anti-aliasing filter, the decimating filters, and the resampling filters all contribute to passband ripple and phase nonlinearities within the selected span. The design of the equalization filter begins by extracting information about the analog signal path from the self-calibration data based on the instrument's configuration. This is the data used to produce the frequency-domain correction output display. Once the analog correction vector has been computed, it is modified to include the effects of the decimating and resampling filters. The final frequency response computations cannot be performed until after the span is selected, because that determines the number of decimating filter stages and resampling ratio. The composite correction vector serves as the basis for the design of the digital equalization filter that is applied to the time data, [10].

In the experimental radar system, time domain trace data, in other words main time data is used. The time domain display will be examined in details, however spectrum analysis and demodulation capabilities of VSA will not be discussed because they are out of the scope of this thesis and the corresponding data is not used in radar system.

The time-domain display shows the time-data just before FFT processing as shown in Fig.35. VSA provides two measurement modes, baseband and zoom(or band selectable). The mesaurement mode is determined according to the start frequency. If the start frequency is set to 0 Hz, the measurement mode is the baseband mode. If the start frequency is set to a non-zero value than the VSA operates in zoom mode. Baseband mode provides real-valued time data referenced to 0 time and 0 Hz (DC).

The input signal is directly digitized and the waveform display shows the entire signal (carrier plus modulation), very much as an oscilloscope would.

In zoom (or band selectable) mode, which is typically the default mode for VSA, the time waveform after it has been mixed and quadrature demodulated is viewed. Specifically, the time data viewed is the product of analog down conversion, IF filtering, digital quadrature mixing, and digital filtering/resampling, based on the specified center frequency and span. The result is a band-limited complex waveform that contains real and imaginary components. The digital LO and quadrature detector perform the *zoom* measurement function. In zoomed measurements, the selected frequency span is mixed down to baseband at the specified center frequency (f_{center}). To accomplish this, first the digital LO frequency is assigned the f_{center} value. Then the input signal is quadrature detected; it is multiplied or mixed with the sine and cosine (quadrature) of the center frequency of the measurement span. The result is a complex (real and imaginary) time-domain waveform that is now referenced to f_{center}, while the phase is still relative to the zero time trigger. Remember, the products of the mixing process are the sum and difference frequencies (signal – f_{center} and signal + f_{center}). So the data is further processed by the low-pass filters to select only the difference frequencies. If the carrier frequency (f_{carrier}) is equal to f_{center}, the modulation results are the positive and negative frequency sidebands centered about 0 Hz. However, the spectrum displays of the analyzer are annotated to show the correct center frequency and sideband frequency values, [10].

The zoom mode is described in Fig.36. Broadband time- domain signal is shown in (a). The center frequency and the span is chosen by the user (b), so the zoom span and zoom span center frequency are assigned by VSA according to the inputs of user (c). Digital LO spectrum is designated at zoom center frequency (d). Frequency span is mixed down to baseband and frequency axis is adjusted to show the correct span and center frequency, [10].

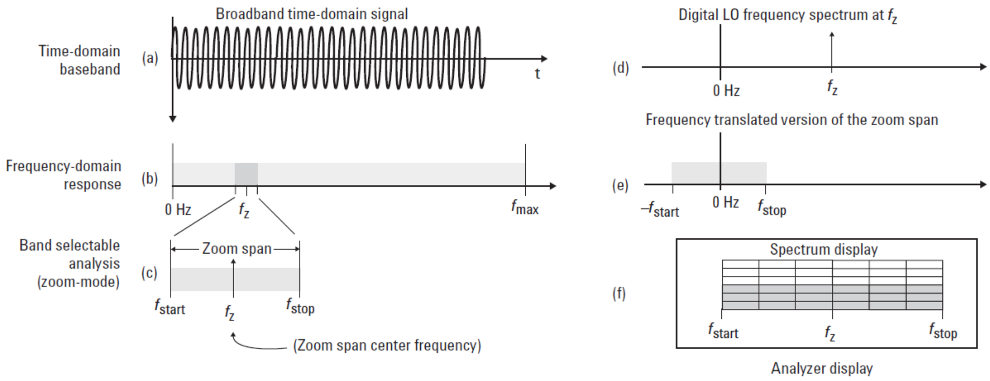


Figure 36. Zoom (Band Selectable) Mode of VSA [10]

It is possible to save the trace data as ".mat" file. The saved file contains the setup parameter values when the trace is saved and the data displayed on the chosen trace. In the experimental radar system, the time domain trace data is saved and opened in MATLAB for further analysis.

Important time record characteristics of VSA 89601A are;

i. $$\text{Time Record Length(sec)} = \frac{\text{Number of Frequency Points} - 1}{\text{Span with RBW mode set to arbitrary,auto} - \text{coupled}}$$

"Number of Frequency Points" is chosen by the user through the menu path MeasSetup > ResBW > Frequency Points . "Frequency Points" can be chosen from 51, 101, 201, 401, 801, 1601, 3201, 6401, 12801, 24601, 51201, 102401, 204801, 409601 choices.

Maximum allowable time record lengths are listed in Table 1 on page 18.

Table 5. Time Resolution vs. Total Time Record Length on VSA

Span (MHz)	Time Resolution XDelta (ns) (1/(1.28*Span))	Total Length (ms)
1	781.25	179.7
2	390.32	59.9
3	260.42	59.9
4	195.31	59.9
5	156.25	59.9
6	130.21	59.9
7	111.61	58.5
8	97.66	51.2

ii. Time Sample Resolution = 1/(k x span) where: k = 2.56 baseband mode
k = 1.28 zoom mode
Span = frequency span

Operation theory, main specifications and block diagram of VSA 89601A have been discussed. VSA is considered as the second unit that constitutes the receiver of radar system. The third unit, which performs the processing of the IQ data, will be discussed in the following part.

7.3 Receiver Processing

The receiver of radar system constitutes of three main blocks. E4446A and VSA8961A are discussed; the third part of the receiver is the "Receiver Processing" block which is a code written in MATLAB, processing the I/Q data acquired by VSA. The receiver processing should be implemented according to the transmit signal; processing algorithm is not the same for pulsed and CW signals, or a phase modulated pulsed signal and a frequency modulated pulsed signal. The receiver of experimental radar system performs pulse Doppler processing. General block diagram of this processing is shown in Fig.37. The operation that is performed is written inside the blocks. The block diagram also shows the flow of the process.

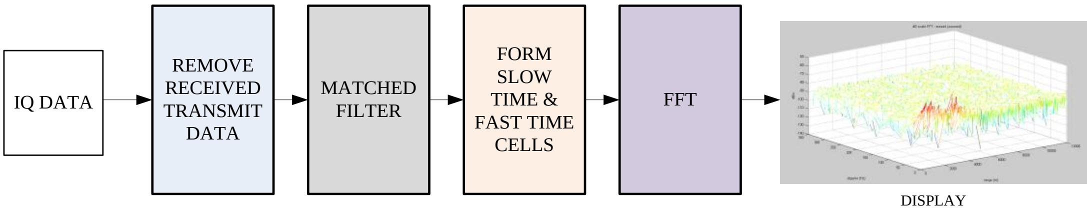


Figure 37. Receiver Processing Blocks

The receiver processing is explained in detail in [12]. Here, a brief description will be given. The process could be summarized as;

1. The I/Q data of received signal is saved by VSA in ".mat" file format. This file includes the amplitude (V), time resolution (sec), number of data points, time scale (sec) and all the other settings when the data is saved. The user should know the transmit signal corresponding to the saved received signal file as transmit and received signal files are chosen by the user via user interface. The code reads both files and gets the information required for processing.

2. The purpose of the second block is to get rid of the transmit signal which is added to the received echoes due to the reason that the antennas are placed next to each other. As described in Chapter 4, transmit signal is also received by the RX antenna. The received signal measurement starts according to the trigger pulse which is generated at the beginning of every transmit pulse. After the spectrum analyzer is triggered, the time length defined in VSA is filled. The PRI of the transmit signal is chosen as constant, thus the beginning of every pulse repetition interval is occupied by the transmit signal. Transmit pulse duration of every pulse repetition interval's start is erased. This is equivalent to turning off the receiver during transmission.

3. The I/Q data of received echoes which is cleared of the transmit signal is filtered by the matched filter to maximize the signal to noise ratio. Matched filter is formed by the transmit signal, actually it is the conjugated time reversed form of transmit pulse. The transmit signal's I/Q data which is sent to VSG to be generated is present because the parameters of transmit signal is also defined by the user

and that data is formed for VSG. Matched filtering is achieved by convolving the conjugated time reversed transmit pulse and the received signal that is cleared of the transmit signal. Fig.38 shows an example for the input and output of the matched filter. The left graph shows the input time domain signal to the matched filter. The signal is a P4 phase coded signal with 40 chips, 4 μsec pulse duration and 100 μsec pulse repetition interval. The right graph is the output of the matched filter, arising peaks are observed at the output.

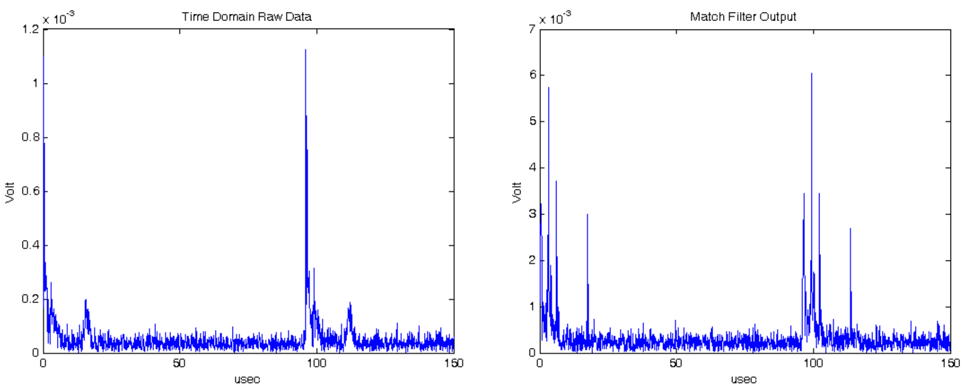


Figure 38. Input and Output of Matched Filter

4. After filtering the raw data by the matched filter, a two dimensional matrix is formed by arranging the output of the matched filter. Each row of this matrix corresponds to one pulse repetition interval of received signal and each column corresponds to samples received from the same range. The dimension of this array is MxN where;

M=Number of PRIs Captured = Received Time Length (sec) / PRI (sec)

N=(Number of samples in one PRI – Number of samples in one transmit pulse)) = (PRI (sec) – Pulse Width (sec)) / Time Resolution(sec)

Each row corresponds to one (PRI (sec) – Transmit Pulse Width (sec)) duration and successive rows are occupied by the successive PRIs. The sampling interval of the vertical dimension is the PRI, on the other hand the sampling interval of the horizontal dimension is the range samples. The horizontal dimension is called the “fast time” while the vertical dimension is called the “slow time” due to the large difference in their sampling intervals. Each cell of the matrix is occupied by one couple I/Q sample. This matrix is described in Fig.39.

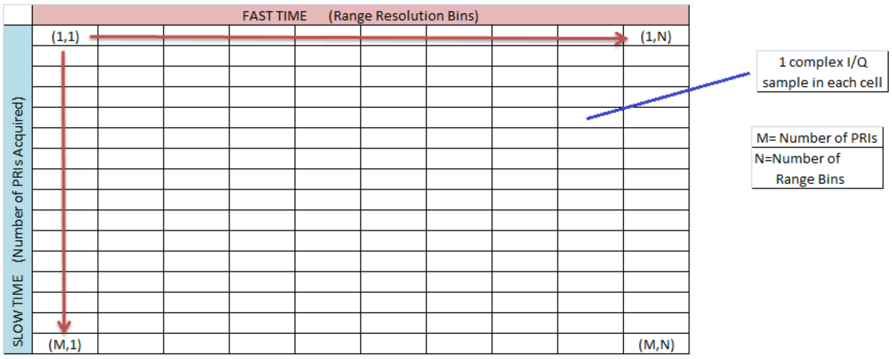


Figure 39. Two Dimensional Data Matrix

5. Received signal is cleared of the transmit signal, filtered and arranged to form a two dimensional data matrix having the pulse repetition interval samples of received signal in successive rows. Final step for determining Range (m), Doppler (Hz) vs. Amplitude (dBm) characteristics of received signal is to take FFT through the columns of the formed radar data matrix. Since each column of this data matrix is occupied with the samples of returned signal from the same range, taking column wise FFT of this matrix determines the frequency spectrum of the data in that column. Since each column corresponds to a range bin and FFT of that column gives the frequency spectrum analysis of that range, both the range and Doppler analysis are performed with this algorithm.

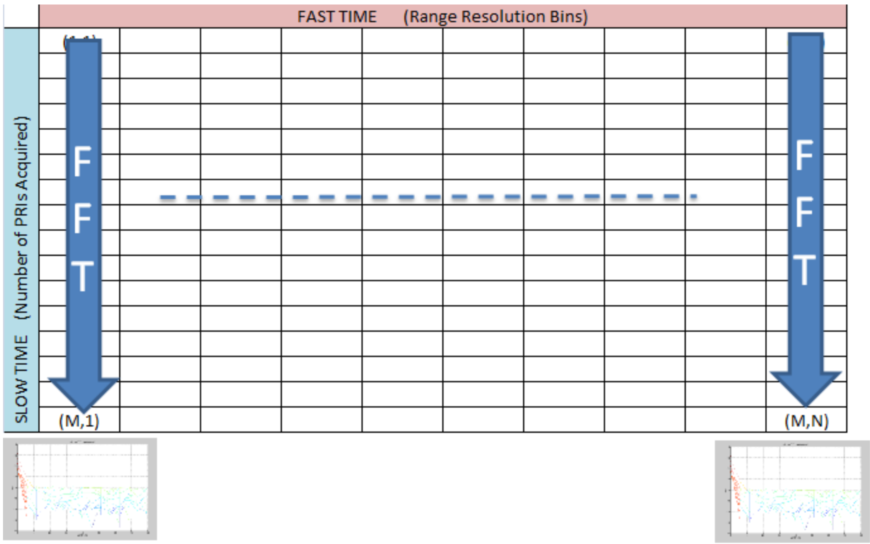


Figure 40. Column Wise FFT

6. Range (m), Doppler (Hz) vs. Amplitude (dBm) characteristics of received signal is determined by the process described above; the result is presented to the user by a 3D graph which is shown in Fig.41.

The X-axis is the range axis and its unit is in meters. Since the range is determined by the delay of the pulses with respect to transmit pulse, the unit of the delay is in seconds and it is converted to meters by the following equation;

$$\text{Range (m)} = \frac{\text{Time Delay (sec)} * \text{Speed of Light (m/sec)}}{2}$$

Consider also the equations given below; they formulate the range resolution, unambiguous range of the radar and the number of range bins present in range axis.

$$\text{Range Resolution (m)} = \frac{\text{Chip Width (sec)} * \text{Speed of Light (m/sec)}}{2}$$

where Chip Width = Pulse Width for unmodulated and uncompressed pulse,

$$\text{Number of Range Bins} = \frac{\text{PRI (sec)} - \text{PW(sec)}}{\text{Range Resolution}}$$

$$\text{Unambiguous Range} = \frac{\big(\text{PRI (sec)} - \text{PW(sec)}\big) * \text{Speed of Light (m/sec)}}{2}$$

The range axis lies between "0" and "Unambiguous Range".

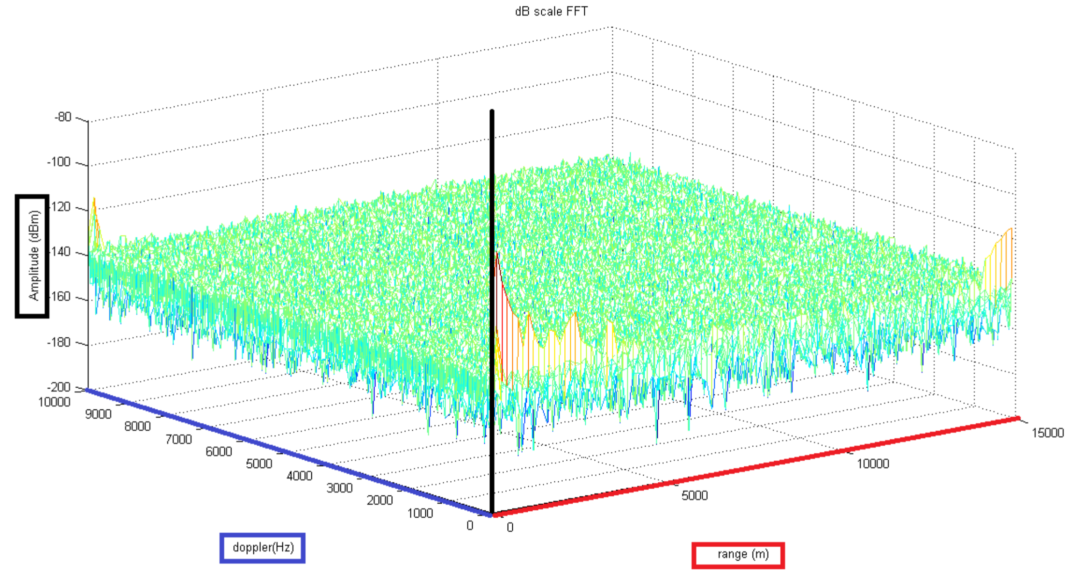


Figure 41. Range (m) vs. Doppler (Hz) vs. Amplitude (dBm) Graph

The Y-axis is the Doppler axis, which shows the Doppler Spectrum; and its unit is in Hertz. The FFT is taken column wise and the sampling rate is the PRF, thus the principal period of Doppler spectrum for stationary radar is PRF, which equals to 1/PRI. The Doppler axis is between [-1/2PRI, 1/2PRI]. If it is known that all the targets are approaching the radar, the axis can be defined between [0, 1/PRI]; on the contrary if it is known that all the targets are moving away from the radar, the axis can be defined between [1/PRI, 0]. In Fig.41, the Doppler axis range is defined as [0, 1/PRI].

The Z-axis is the amplitude axis, which shows the received power from the targets in dBm. The main time raw data is saved by VSA as described in 7.2 Agilent 89601A Vector Analysis Software section, this data is given by Volt (RMS) vs. Seconds units. This amplitude value is converted to power in dBm by the following equations;

$$\text{Power (Watt)} = \frac{(\text{Volts(rms)}/\sqrt{2})^2}{\text{R}} * \text{Duty Ratio, where Duty Ratio} = \frac{\text{PW}}{\text{PRI}} \text{ and R} = 50\Omega$$

$$\text{Power (dBm)} = 10 \log(\text{Power in Watts}) + 30$$

There are two important corrections while deducing the received power. First correction is that the FFT function of MATLAB does not perform any normalization, the output of FFT function should be divided by FFT size. The second correction is that the attenuation value of the spectrum analyzer should be added to output of the FFT function after normalization. The attenuator value is related to the "Input Range" of VSA, which is set by the user. This relation is given by Table 3 on page 58.

The radar process is completed by presenting the 3D graphs of results to user. The system does not make a decision about the existences of targets, in other words there is no automatic detection algorithm. This feature can be a future work and added to the system.

CHAPTER 8

GUI OF THE EXPERIMENTAL RADAR

GUI of the system is the interface between the user and the system which lets the user enter the parameters for the transmit signal, or recall a saved transmit signal; choose the saved received signal file to be analyzed and perform power analysis of radar. It is prepared by MATLAB. The user determines the parameters where necessary through edit boxes and presses the push buttons for the operation intended. The interface has three main parts which are the "TRANSMITTER", "RECEIVER" and "POWER ANALYSIS" and all parts are presented in a single window. "TRANSMITTER" is the part where the transmit signal's parameters are entered by the user and saved, or a previous saved transmit signal file is recalled and loaded. The order of operations is as follows:

1. Create a new transmit signal by entering the parameters of the signal, write a name for the transmit signal file and a folder for it to be saved in and press LOAD to save the transmit signal file in the defined folder. The program saves the file in ".mat" format.
2. If a previous transmit signal is intended to be chosen, check the "Predefined transmit signal:" radio button, choose the file by browsing and press the "LOAD" button to load the file.
3. When "LOAD" button is pressed, I Data vs. Time, Q Data vs. Time and Magnitude of IQ Data vs. Time are presented to the user.
4. Enter the carrier frequency and the output power of the transmit signal and press "SEND" push button to download the signal to the signal generator in order to be transmitted. Pressing the "SEND" button is enough for transmitting the signal, the signal generator's RF output is made on automatically.

5. If a new transmit signal file is wanted to be chosen or a new one is wanted to be created, all the edit boxes related to the transmit signal can be cleared by pressing the "CLEAR" push button.
6. Received signal file is chosen by browsing the saved received signal files and number of files that is wanted to be analyzed is defined by entering the number to the related edit box. A transmit signal should be loaded to perform analysis.
7. Press the "PLOT" push button to analyze the received signal as described in 7.3 Receiver Processing. The 3D graphs of the results are presented to user.
8. The chosen received signal is cleared by the "CLEAR" push button in receiver part and a new received file can be chosen.
9. Power analysis is not related to transmit or received signals. The user enters the required parameter values in the edit boxes and SNR vs. Range graph is presented to the user according to these values. Radar equation is used for power analysis, it is added to the user interface to inform user about the SNR values corresponding to a range interval.

Fig.42 and Fig.43 show two different screen shots of user interface. Fig.42 shows the case of creating a new transmit signal. Transmit signal type is chosen from the "CODE" menu. Available types are Barker 7, P4, single pulse, random phase code and P4 with obstacles. This menu can be extended and new types can be added as a future work. "Single pulse" choice means the transmit pulse is neither coded nor modulated.

Fig.43 shows the case of recalling a saved transmit signal file. When a new signal is created, it is saved as .mat file automatically in defined folder and this file includes all the information needed to provide the VSG generate the signal.

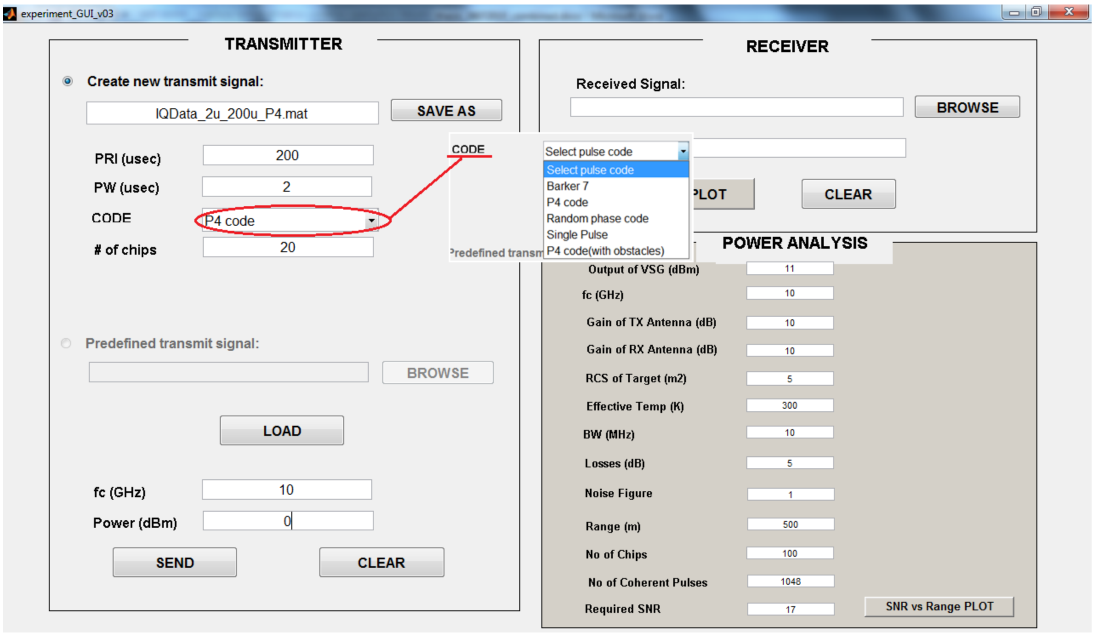


Figure 42. GUI of the Experimental Radar System-1

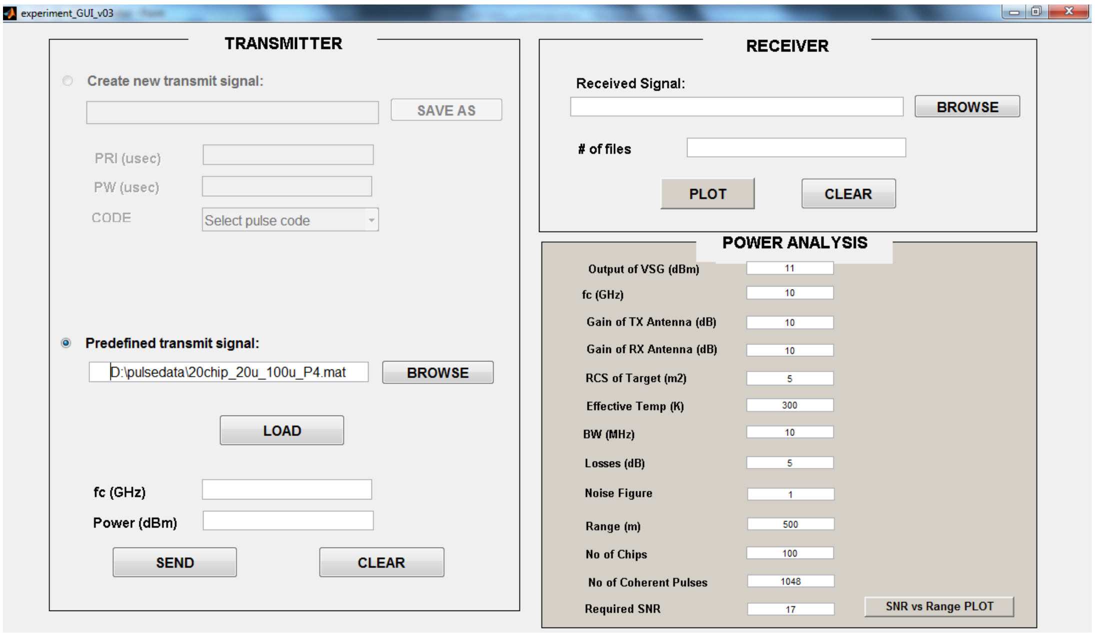


Figure 43. GUI of the Experimental Radar System-2

CHAPTER 9

MEASUREMENTS AND COMMENTS ON RESULTS

Experimental radar system is placed on the roof of METU EEE Department’s Building D and measurements are held from different observation environments. Range and Doppler characteristics of these measurements are examined.

Examinations and comments of the measurement results from two different observation areas, Observation Area-1 and Observation Area-2, are given in this study. Same transmit signal and same setup are used for both observations. The transmit signal used has;

- P4 coded pulsed waveform with PW=5.32 μsec, PRI=133 μsec, Number of Chips=40, Chip Width=133 nsec (Range Resolution = 19.95 m)
- Frequency = 10 GHz
- Average Output Power =7.5 dBm

The EXA N9010A is used at the receiver side and the I/Q data of the received signal is acquired directly from the EXA Signal Analyzer. Two LNAs are used successively before the RF input of the signal analyzer. The received signal has;

- Time Resolution = 66.67 nsec
- Acquired Time Length (Observation Time)=266 msec (which leads Doppler Resolution=3.8 Hz)

Thus, each acquisition contains 266 msec/133 μsec =2000 PRIs.

9.1 Observation Area -1

The first observation area is shown in Fig.44. This picture is taken on the day of the measurements made. There are many buildings both near the experimental radar and far from it. There is a dense grove area near the experimental radar. Some of the buildings are marked in order to make comparisons. Top view of this area is also taken using Google Earth application which is also shown in Fig.45. Same marking names are used for both views. Top view covers the first nearly 3000 m from the observation point.

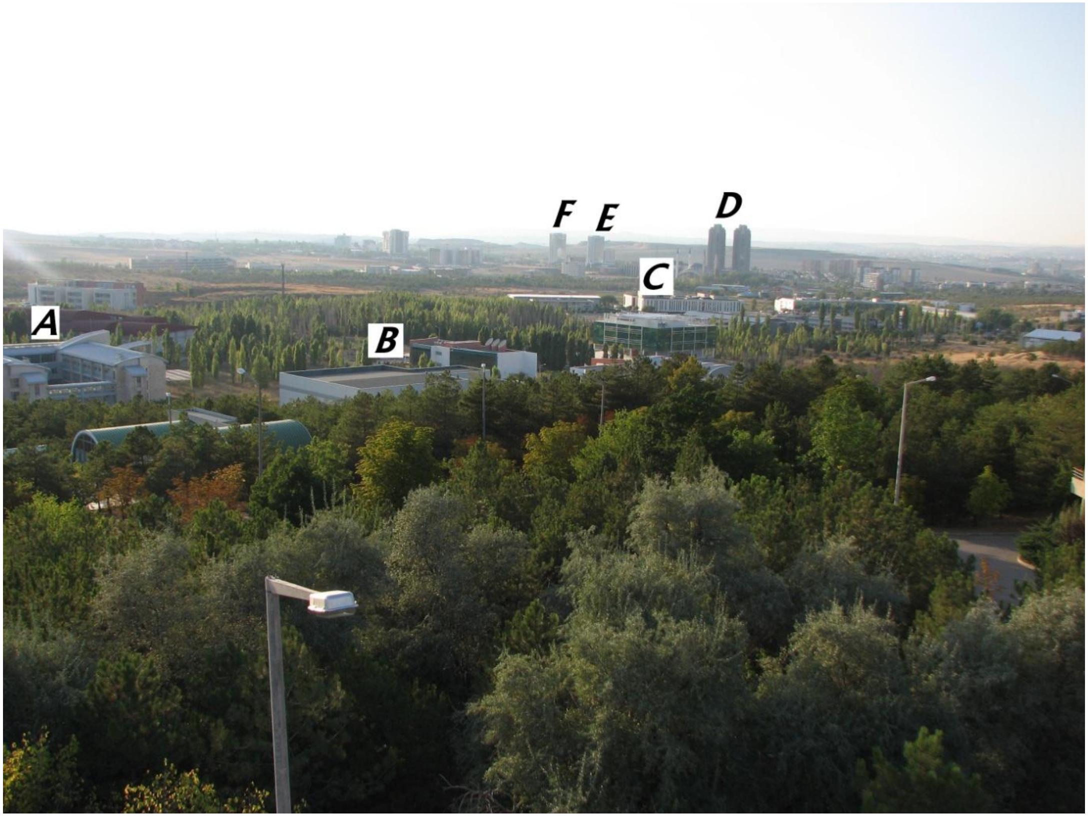


Figure 44. View of Observation Area -1 from Observation Point

Figure 45. Top View of Observation Area-1

Distances of high buildings are measured using Google Earth application; Building A: 340 m, Building B: 300 m, Building C: 480 m, Building D: 2620 m, Building E:3690 m , Building F: 3856m. These values are used for comparison with the radar analysis results.

Fig.46 shows the range characteristics of that observation area for full range which is obtained by range analysis. Following comments could be made examining these results;

- There is a crowded area through the first 4 km range.
- There does not seem any detected objects between 6 km and 11 km
- There are objects with reasonable SNRs beyond 11 km.

Actually, the first 4 km range is really crowded with many buildings with various heights and there is a dense grove field. Between 6 km and 11 km, there are relatively flat field crops; moreover the buildings which are nearer may be shadowing this region because they are high compared to the buildings behind them.

The objects beyond 11 km are also thought to be buildings but it is difficult to comment on these objects because the transmit antenna has 3 dB BW of 30° at azimuth which brings a coverage of 5.7 km horizontally.

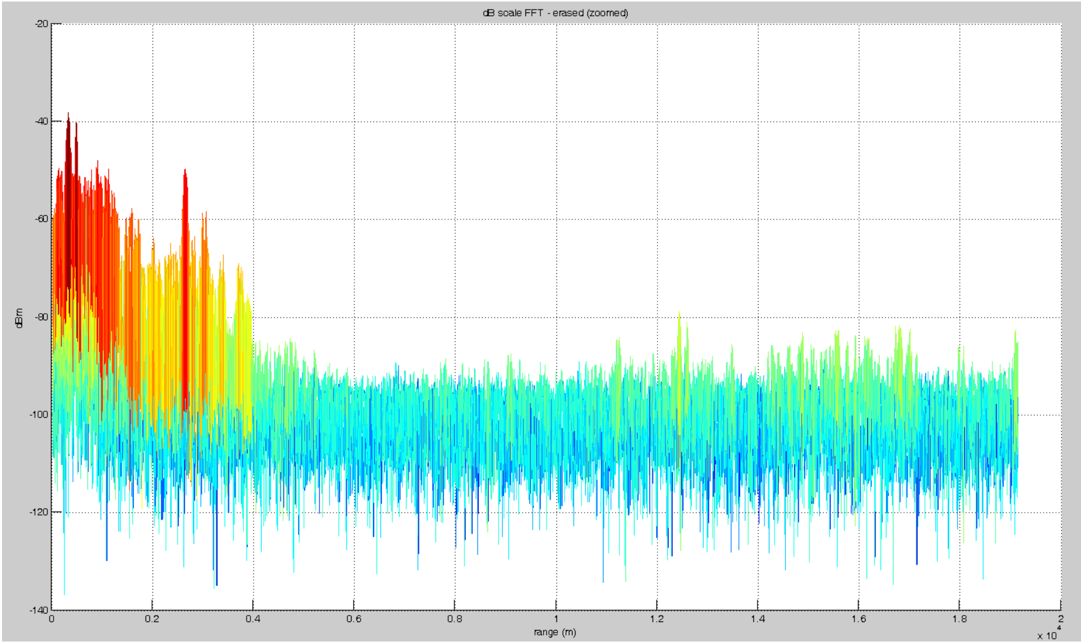


Figure 46. Range Characteristics of Observation Area-1, Full Scale

Fig.47 shows the range characteristics of the area zoomed into 0 – 5 km region. Following interpretetations could be made;

- Peak at 330 m → Building A
- Peak at 490 m → Building C
- Peak at 2650 m → Building D
- Peak at 3680 m →Building E
- Peak at 3870 m →Building F
- The first 1300 m region is very crowded, this may be due to the grove area which is full of trees.

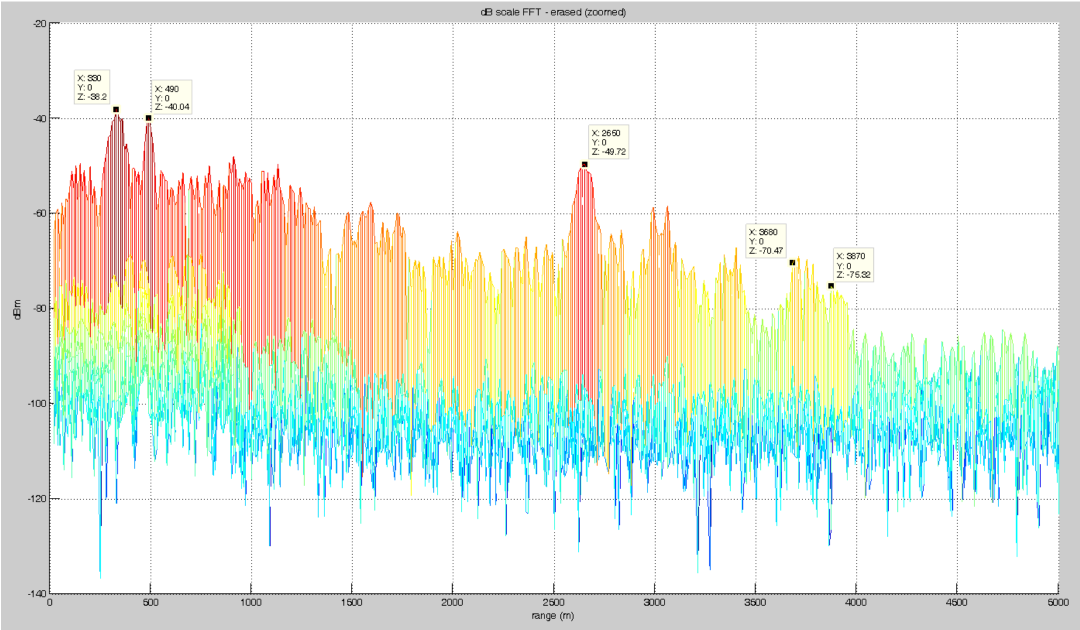


Figure 47. Range Characteristics of Observation Area-1, 0 – 5 km

9.2 Observation Area -2

The second observation area is shown in Fig.48. Similar to first observation area, there is also a dense grove area for the first 500 m. The buildings in this area have approximately equal heights compared to each other and there are groups of buildings close to each other. In Fig.49, the top view of this area is shown which is taken from Google Earth application. Besides, in Fig.50 a path is shown as a red line starting from the observation point to a point at nearly 13.3 km and the altitude profile of this path is shown in the same figure. It is observed that the altitude increases until 5 km and after that distance it remains nearly flat for 2.5 km and then the altitude decreases.

Some locations are marked on both views with the same names. In the first observation area, relatively high and standing alone buildings were marked, in this case the marked locations are occupied by many buildings with similar characteristics.

Figure 48. View of Observation Area -2 from Observation Point

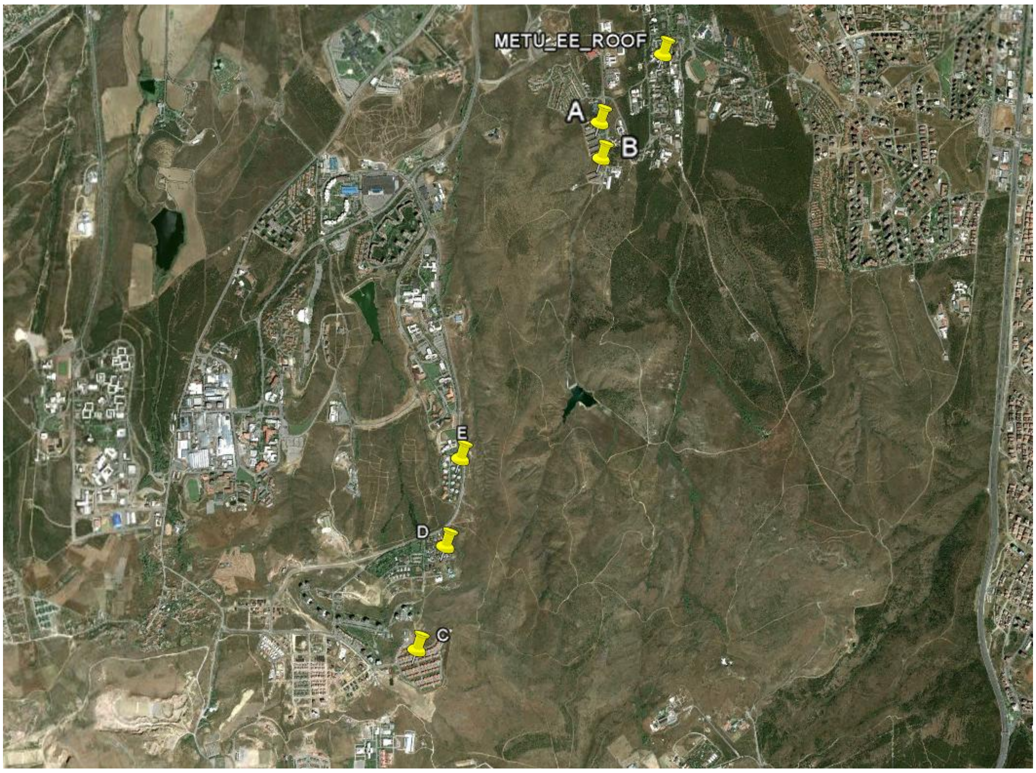


Figure 49. Top View of Observation Area -2 from Observation Point

Distances of locations marked are measured using Google Earth application; There is a building at location A which is 650 m away from the radar, location B is also occupied by a building which is 870-900 m away from the radar. Location C is occupied by a group of buildings and their distances are between 4.3 – 4.6 km. Similarly, location D and E are occupied by group of buildings with distances 3.8 – 4 km and 3.1 – 3.3 km respectively. These values are used for comparison with the radar analysis results.

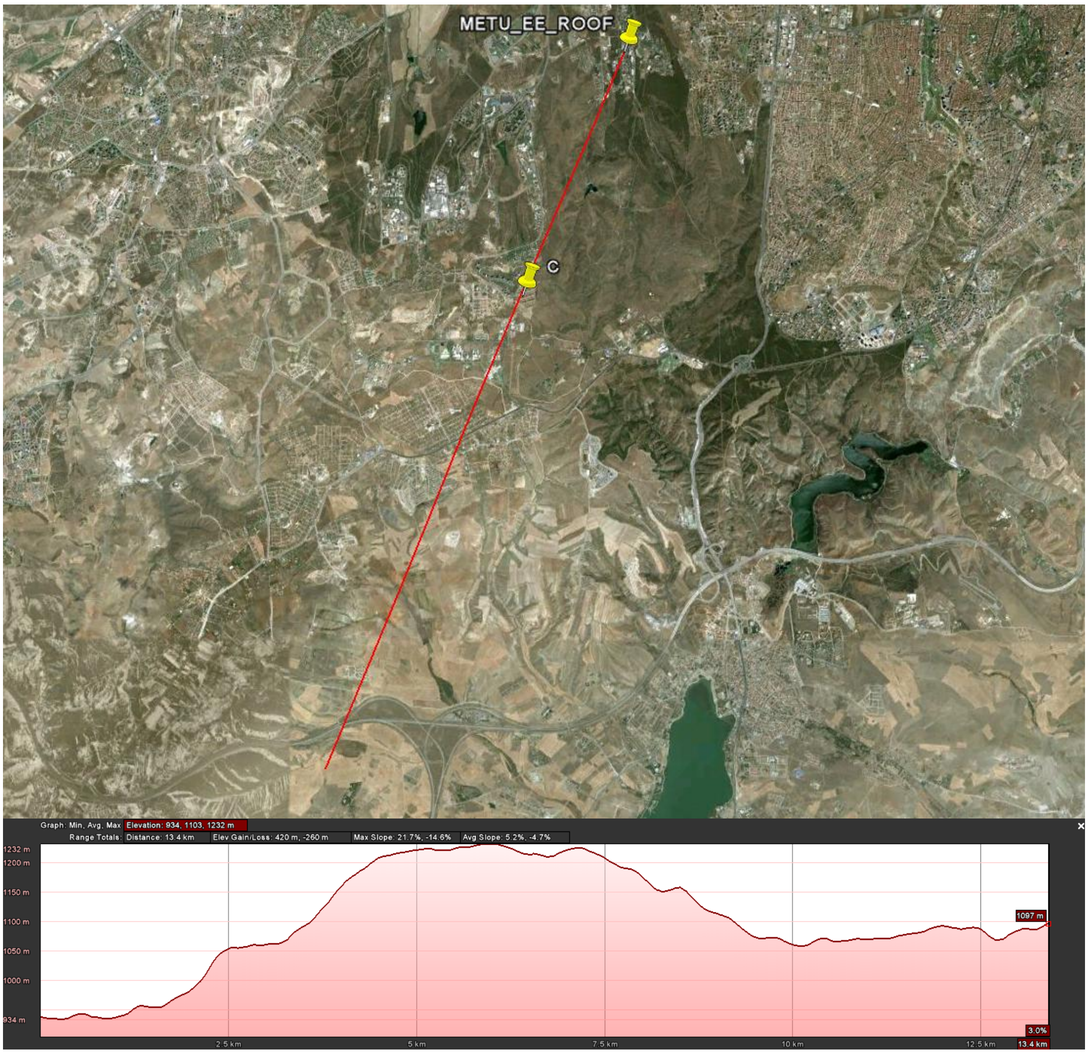


Figure 50. Altitude Graph of the Path from Observation Point

Fig.51 shows the range characteristics of this area which is obtained by analysis. Following comments could be made by examining this result;

- First 900 m is very crowded, it is occupied by many objects.
- After 5 km, it can be said that there is no detection. Actually, 5 km is the horizon line for this area. This claim is consolidated with the altitude characteristics of this area. Since 5 km from the observation point is the distance where an uphill is reached, the bacwards are shadowed.

Fig.52 shows the range characteristics of the area zoomed into 0 – 6 km region. Following interpretetations could be made;

- Crowded region until 880 m could be due to the grove and the buildings at A and B
- Peaks around 3120 m → Buildings at location E
- Peaks around 3900 m → Buildings at location D
- Peaks around 4470 m → Buildings at location C

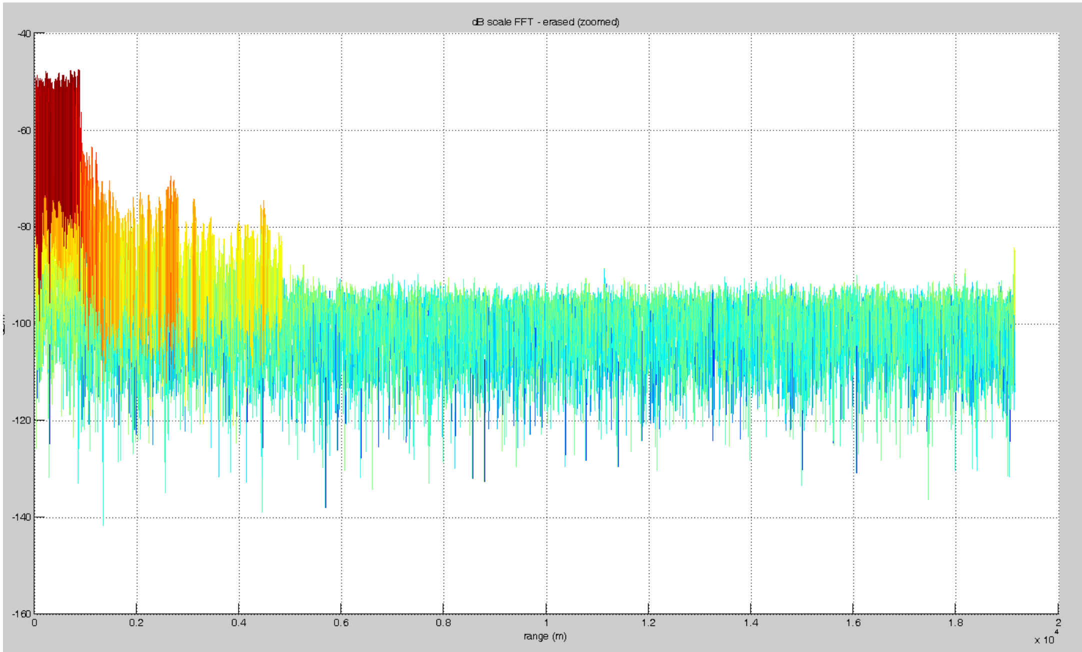


Figure 51. Range Characteristics of Observation Area-2, Full Scale

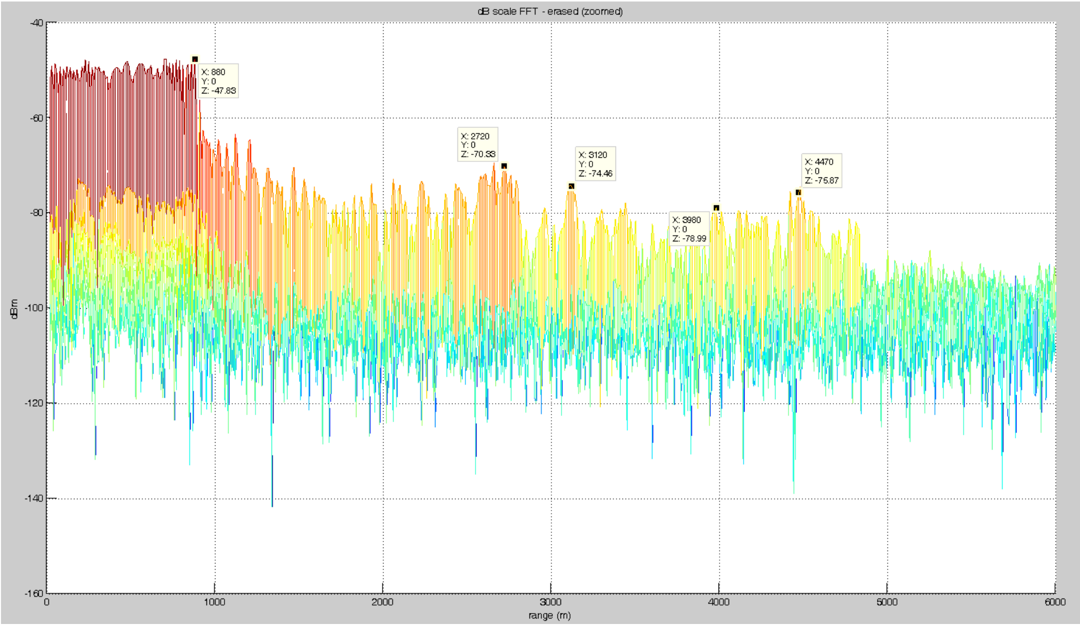


Figure 52. Range Characteristics of Observation Area-2, 0-6 km

CHAPTER 10

PROBLEMS OF THE SYSTEM AND POSSIBLE IMPROVEMENTS

The main aim of constructing the experimental radar system is to measure clutter. The return signal of the radar is composed of the direct path return from the target, multipath returns,echoes from other objects, thermal noise, and jammer if present. Anything except the target, jammer and noise can be considered as clutter. In other words, clutter is the unwanted echoes returning from objects like buildings, vehicles, rain, snow, trees, animals, ground, sea, clouds etc..

Clutter can be characterized in time or in space which by performing respectively temporal analysis or spatial analysis. Considering the measurement requirements for examining the clutter temporally or spatially, some specifications of the experimental radar system should be improved further. Clutter measurements performed with the present constructed experimental radar system is described in [12] including the results of the analyses. The clutter measurements are performed in the observation areas described in Chapter 9. These measurements regard all received echoes as clutter.

The requirements for the clutter measurement setup are dependent on many parameters, some of which can be listed as;

- Analysis type of clutter
    - Temporal Analysis
    - Spatial Analysis
- The terrain (land, sea, forest, etc.)
- Weather conditions (rain, snow, wind, etc.)
- Vehicle Activity
- Bird Activity
- Cloud Density

According to the analysis type of the clutter, the measurement zone should be examined and the parameters affecting the measurement zone's stability in time and space should be listed. The parameters could be descriptive like bird activity in the zone, or numerical like the speed of wind. In order to perform controlled clutter measurement experiments, list of affecting parameters should be prepared and the descriptions or numerical values of the parameters should be filled in this list before every measurement.

According to these parameters, the requirements for the experimental radar setup are designated. For example, consider the observation areas presented in Chapter 9. When clutter measurements for these areas are held for spatial analysis, the parameters affecting this analysis could be defined by considering the differences between two range cells. Buildings, trees, high ways or hills are the parameters that change the spatial structure of these zones. In addition, wind, snow fall, rain, bird activity, vehicle activity, cloud density, moisture and humidity are also the parameters affecting the structure of these zones. The spatial analysis of clutter is performed by correlating two distinct range cells in order to see the change of difference between them. Thus, the size of the range cells should be defined by considering how closely the spatial structures of these zones differ for spatial analysis. On the other hand, temporal analysis of clutter is performed by considering the change in one range cell with time. Thus, if temporal analysis is wanted to be performed, then the observation time should be defined long enough to observe the change in time.

A similar clutter measurement study was held by MIT Lincoln Laboratory and the comparison between their setup and experimental radar system is given in [12] in details.

Consequently, considering the needs of the experiment case, some specifications of the experimental radar system are not sufficient for the measurement of clutter. These specifications and the possible improvements for them are listed as;

1. **Improvement of the Received Signal Size (Time Length)**

The maximum time length of the system is the maximum continuous time that can be stored at once. It determines the Doppler resolution and it is an important parameter for temporal analysis of clutter. The measurement from a terrain should be saved until it reaches a stable state. Examining the terrain and the parameters affecting the terrain in time, maximum required time length could be designated. For example, consider a measurement zone where is windy with changing speed through time and the clutter of this region is desired to be analyzed temporally. Then, continuous measurement in time should be saved from this zone in order to see the effect of wind until the wind reaches to a stable speed. This could take minutes or days.

The Doppler resolution is inversely proportional to maximum time length analyzed. The Doppler bins should be small enough to analyze the spread of the clutter.

For the present case, the memory of the receiver is limited to a value which is determined by the instrument used in the receiver block.

E4446A PSA Spectrum Analyzer with VSA is used as the receiver of this system. Table 1 on page 18 tabulates the maximum allowable storable time lengths corresponding to the chosen time resolution on relevant equipment. VSA is needed to get the I/Q data of the received signal when the carrier frequency of the transmit signal is above 3 GHz as described in Chapter 8 and for the frequencies below 3 GHz maximum 1 million complex samples can be saved with PSA. Actually VSA limits the number of points that can be saved in a record and the number of points that it stores differs with the time resolution chosen; number of points that can be saved is not constant.

Saving two or more consecutive measurements and appending them could be considered as a solution for obtaining longer measurements. However, the instrument cannot capture signal during its process time thus it cannot capture exactly consecutive signals. Due to this, the phase is not continuous between two records. Hence, this is not a solution for increasing the time length of a record.

There are two solutions to increase the maximum time length which are both based on hardware revisions.

2. Replacing Agilent E4446A PSA Spectrum Analyzer

The first solution is to replace the PSA E4446A with another spectrum analyzer that has a larger acquisition memory and allows to transfer the I/Q data to a computer. Agilent's EXA and PXA series spectrum analyzers are the newer versions of the PSA and have larger memories. For example, EXA N9010A Signal Analyzer is also present in METU EEE microwave laboratory, which was available to be used at the end of this thesis, has 4 million complex samples acquisition memory. This is 4 times larger than PSA and at least 8 times larger than VSA's memory. In addition, Tektronix has Real Time Spectrum Analyzers which have 256 million complex samples acquisition memory with 6.7 nsec time resolution. Depending on the time resolution chosen, maximum recordable time length is designated.

Definitely, there are other COTS spectrum analyzers or receivers that can be purchased to replace PSA E4446A but this solution is not feasible since these instruments are expensive units.

3. Digitizing the IF Output of PSA E4446A

The second solution is to digitize and record the IF output of the spectrum analyzer. PSA E4446A has an output for the down converted to the IF signal of the input signal. The specifications of this IF output of the PSA are as follows;

- IF Center Frequency = 321.4 MHz
- 3-dB IF Filter BW :
  - Low band (3 Hz to 3.05 GHz) 40 MHz
  - High band (2.85 to 26.5 GHz) 35 to 70 MHz (monotonically increasing)
  - mm band (26.5 to 44 GHz) 40 MHz
- Conversion Gain :
  - Low band (3 Hz to 3.05 GHz) +2 to +4 dB (nominal)
  - High / mm band (2.85 GHz to 44 GHz) –6 to –8 dB (nominal)

The IF output of the PSA E4446A is connected to another spectrum analyzer to observe the IF filter characteristics of PSA E4446A. Two different signals are used which has different bandwidths. Fig.53 shows the IF output of the PSA when the input signal is a pulsed signal with PW = 50 nsec, PRI = 100 usec at 10 GHz an thus its bandwidth is 20 MHz. Since the bandwidth of the signal is narrower than the bandwidth of the IF filter, the signal is not filtered as shown in Fig.53. When the input signal is again a pulsed signal with PW = 10 nsec, PRI = 100 usec at 10 GHz, it is filtered since it has a bandwidth of 100 MHz which is wider than the bandwidth of the IF filter. This case is shown in Fig.54. For both cases the center frequency is 321.4 MHz and the 3-dB points are marked with Markers 2 and 3 . For the second case, the bandwidth of the IF signal is 44.5 MHz since it is filtered.

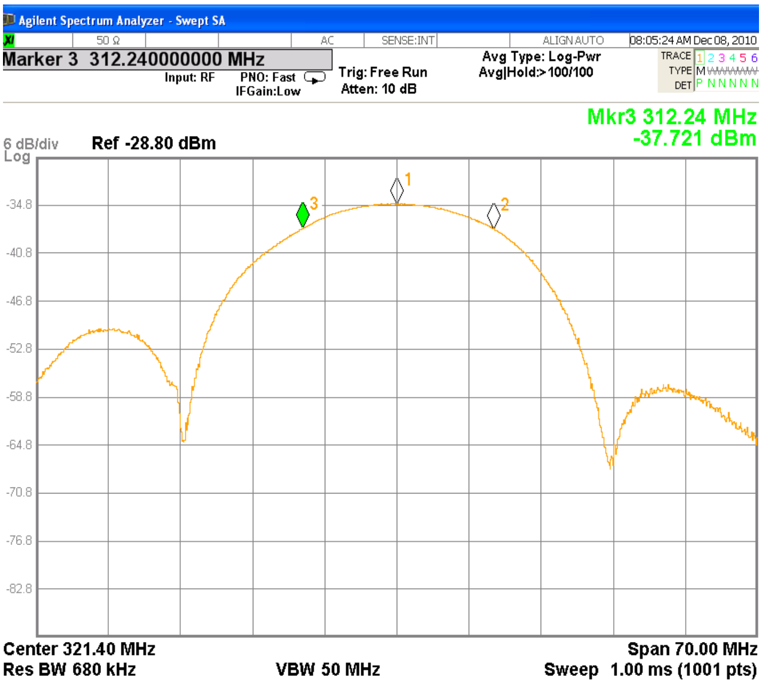


Figure 53. IF Output of E4446A for Pulsed Signal with 20 MHz BW

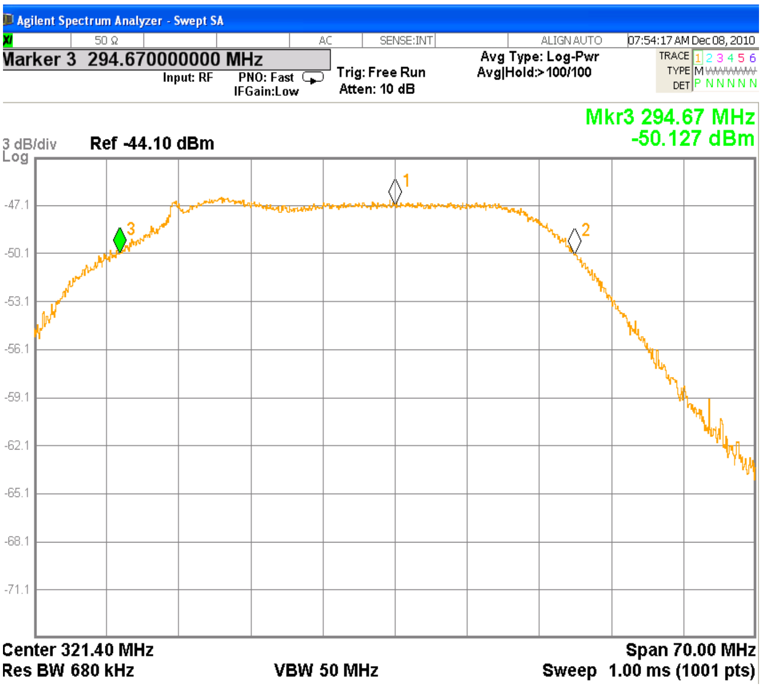


Figure 54. IF Output of E4446A for Pulsed Signal with 100 MHz BW

Instead of being bounded to the acquisition memory of the spectrum analyzer, this IF output can be digitized and stored. The IF output of the PSA is uninterrupted, in other words it outputs the IF signal of the RF input continuously. The digitized and stored IF signal can then be down converted to baseband digitally and analyzed to get range and Doppler characteristics of the received signal.

The requirements for IF Digitizer could be listed as;

- At least 2*40 MHz = 80 MS/s sampling rate and at least 321.4 MHz input band if band pass sampling is used,
- At least 2*321.4 MHz = 642.8 MS/s sampling rate if band pass sampling is not used.

Different IF digitizers have been searched and three alternatives are distinguished as can be used in experimental radar system. These alternatives are;

a. IF Digitizers Compatible with PCI/PCI Express Slot of PCs

There are A/D converters which are placed in the PCI/PCI Express slots of PCs with an onboard memory. The advantages of these A/D converters are that they are easy to use together with a computer. There are variety of these converters according to their sampling rates and onboard memory sizes. Since the bandwidth of the IF output of the PSA is 40 MHz, an A/D with at least 80 MS/s according to Nyquist would be enough. On the other hand, the center frequency of the IF output is 321.4 MHz which brings at least 321.4 MHz input band requirement to the A/D converter. However, these A/D converters do not perform bandpass sampling and their input bands are nearly half of their sampling rates. When this alternative is chosen, then a card with at least 643 MS/s sampling rate should be chosen. Many companies, some of which are Strategic Test, National Instruments, Acqiris manufacture these A/D cards. For example, Strategic Test's UF3e-2130 numbered part 8-bit A/D converter has 1 GS/s sampling rate and 4 GS onboard memory which provides 4 sec recording. Since the IF signal is digitized with a high sampling rate, the onboard memory is not used efficiently.

b. External Wideband Recorders

The second alternative is using a wideband recorder which is an external unit that gets the analog IF signal as input to digitize and record. Since it is an external unit, it has many disk drives supplying storage capacity at Terabyte orders. These instruments generally have programmable input band and sampling rate and they are set by the user through user interface.

Pentek, Eonic and Curtiss Wright are some of the companies manufacturing such recorders. Pentek's 2706-012 numbered model wideband recorder is one example for this group of recorders. It has programmable IF center frequency up to 600 MHz and programmable input bandwidth up to 80 MHz. Its A/D has 16 bit resolution and it has 6 TB storage capacity configured as three 2 TB RAID 0 arrays, thus it can store digitized data a couple of hours duration. Considering the technical properties, these units seem to be good solutions if they are affordable. This is an expensive alternative compared to other two alternatives.

c. Designing and Constructing the Required IF Digitizer

The third alternative is to construct the IF digitizer since the requirements are defined. There are many A/D converters with variety of sampling rates and input bandwidths from which the most appropriate one can be designated. This alternative requires time and non-recurring engineering. Evaluation boards of ADCs could be used to accelerate the engineering process. Analog Devices Inc. has a wide range of A/D converter evaluation boards. The company also has FIFO based data capture kits which are used together with A/D converter evaluation boards. Data capture kits capture the digitized data via FIFO based buffers and enables real time data analysis via its analysis program running on a PC which is connected to the board through USB. Using these two evaluation boards would be a good solution but the data is transferred to the PC after the FIFO is filled and data is lost during this transfer. The buffer size is 256 kB maximum. If the output of the data capture kit is connected to hard disks and the captured data is transferred to hard disks without losing any data through an appropriate interface, a good solution would have been achieved.

Apart from the alternatives for digitizing the IF output, there is also an option for PSA to change the IF output characteristics. The center frequency of the IF output could be changed to 80 MHz with an extra option. Then 160 MS/s sampling rate would be enough to digitize the output without band pass sampling property requirement.

4. Improvement of the Receiver Noise Figure

The maximum detectable signal power depends on the noise figure of the receiver and the required SNR. For target detection, required SNR is determined by the probability of false alarm and probability of detection. For clutter analysis, relatively high SNRs are required. For example, in the clutter measurements held by MIT Lincoln Laboratory, clutter is examined at power levels 70 dB below the zero-Doppler peak. Both the noise figure and the maximum transmitted power determine if it is possible or not to measure 70 dB below the zero-Doppler peak level.

Noise level values of E4446A Spectrum Analyzer at different frequency ranges are given in Chapter 7. The noise figure of the instrument is 26 dB at X Band; however this value can be decreased by 16 dB when a preamplifier that operates between 10 to 26.5 GHz is added by the Option 110. Two LNAs are available for using in the system, thus they can be used cascaded or only one LNA could be used. Noise figure values are given for different configurations. Considering these values, configuration with two LNA can be considered as a good solution because it can be configured easily since the amplifiers are available and the noise figure values of the configuration with two LNAs and the one with extra preamplifier in the PSA are very close.

Table 6. Noise Figures for Different Configurations

Configuration	Noise Figure (dB)
1 LNA + PSA	9.18
2 LNA + PSA	3.24
1 LNA + PSA with preamplifier	3.30
2 LNA + PSA with preamplifier	3.03

5. Improvement of the Receiver Sampling Rate

The highest sampling rate of the receiver is 10 MHz, thus time resolution is 100 nsec. On the other hand, the transmitter has 100 MHz sampling rate. If the sampling rate of the receiver is improved, pulses with shorter widths could be generated as transmit signal.

Range resolution of the system gets better by choosing narrower pulse/chip widths which is possible only with high sampling rates. The required range resolution can be determined according to the heterogeneity of the range bins in the measurement zone. For the current case, the range resolution is 15 m and it is considered to be enough for the observation areas described in Chapter 9 for clutter measurement. If the measurement zone is very heterogenic and changes very rapidly through a path, than better range resolutions are required. For low range resolution the spatial behavior of clutter is Gaussian distributed, however for high range resolutions the distribution of clutter deviates from Gaussian, [12]. Thus, to be able to observe this deviation high range resolutions are required and 15 m can be considered as high resolution. But it can be improved to 1.5 m since the transmitter generates 10 nsec width pulses when an appropriate spectrum analyzer is used.

6. Solving the Carrier Feedthrough Problem on the Receiver Side

Carrier feedthrough is the leakage of the LO to the IF output of the mixer. The received signal is mixed with LO by the analog mixer of the spectrum analyzer, to be down converted to IF as described in Chapter 8 through the block diagram of the instrument. However the LO may leak to the output signal and this LO leakage causes a DC like signal and it is observed at the Range vs. Amplitude plot of the system and on the spectrum trace of the VSA. It is observed when the RF input power is weak.

A test has been conducted to observe the carrier leakage and find a solution. The antennas are removed from the system and the transmitter's RF output is connected directly to the input of the receiver which is the RF input of the LNA. The setup is shown in Fig.55. The spectrum analyzer uses the 10 MHz reference of the vector signal generator. Pulsed waveform with 1 μsec pulse width and 100 μsec PRI at 10 GHz is defined and sent to the receiver through the RF cable. The output peak power of the transmit signal is changed to observe the carrier leakage on the spectrum trace of the VSA.

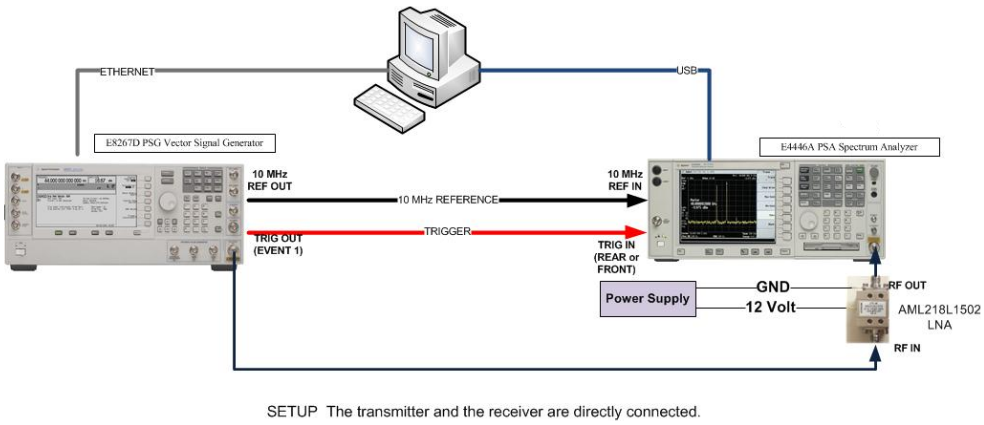


Figure 55. Set Up for LO Leakage Test

There is only cable loss on the way of the transmit signal since the equipments are connected directly through a cable. When the output power, thus the received power, is high enough there is no carrier observed on the spectrum trace which is shown in Fig.56. On the other hand, when the output peak power is -80 dBm or lower, the carrier is observed on the spectrum trace which is shown in Fig.57.

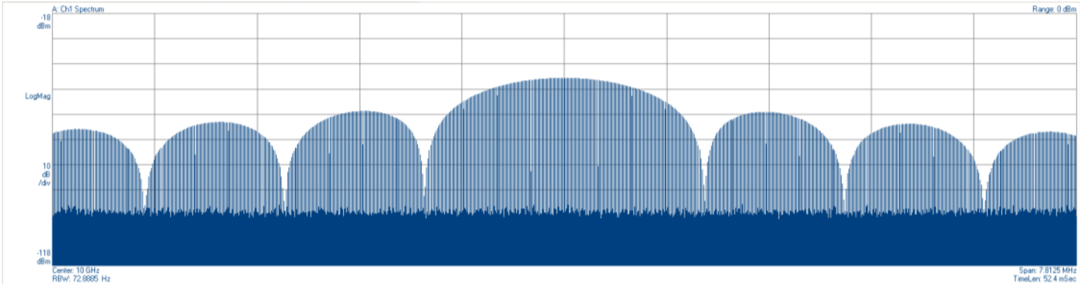


Figure 56. Spectrum Trace of Pulsed Waveform with -20 dBm Output Peak Power

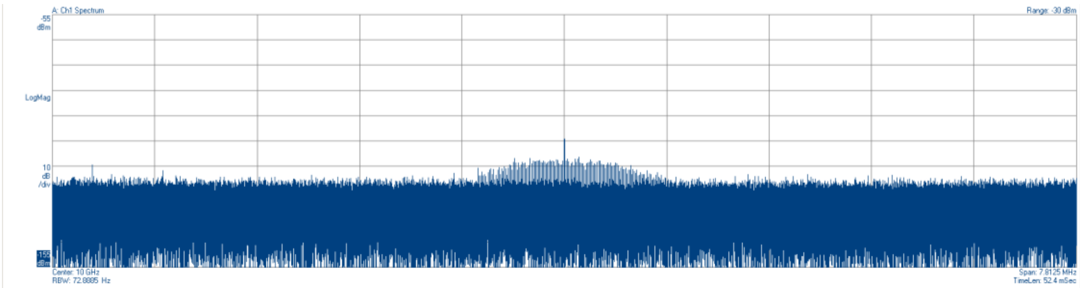


Figure 57. Spectrum Trace of Pulsed Waveform with -90 dBm Output Peak Power

The peak output power of the signal is set to -20 dBm first whose spectrum is shown in Fig.56. Then it is set to -90 dBm whose spectrum is shown in Fig.57. For both cases the received signals are analyzed and the resulted Range vs. Amplitude graphs are shown in Fig.58.

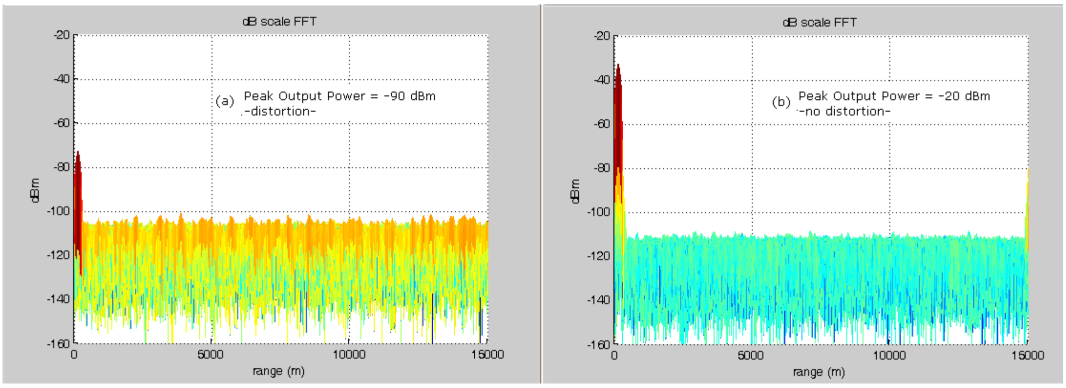


Figure 58. Range vs. Amplitude Graphs after Processing

Due to the carrier leakage at the mixer, in addition to the target's echo which is the transmit signal itself in this test case, it is obvious that another signal leaks to the output which is observed as a level shift changing the noise floor.

When an offset is added to the transmit signal's carrier frequency, this effect diminishes. 1 kHz offset is added to test signal's carrier frequency and it is again transmitted with -90 dBm peak power. The Doppler and Range graphs are shown in Fig.59. There is no distortion on range axis and 1 kHz offset is shown in Doppler axis. Thus sending the signal with a frequency offset could be a solution, since the power of received signal will be much lower than -90 dBm which causes certainly an LO leakage.

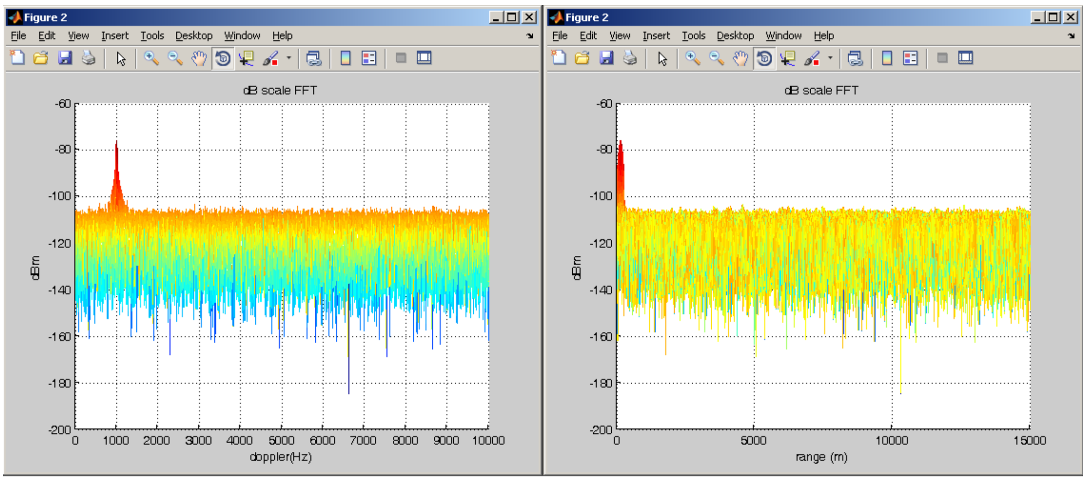


Figure 59. Doppler and Range vs. Amplitude Graphs for the Test Signal with 1 kHz Offset

7. Improvement of the Antenna 3 dB Beamwidths

Azimuthal 3 dB beamwidth values of the antennas are given in Chapter 4 which are nearly 30° for both antennas in azimuth. The angular resolution is defined by the 3 dB beamwidths of the antennas as a distance at a given range. For the experimental radar system, the angular resolution values are not very narrow at further ranges. For example, it is 2588 m in azimuth at 5000 m for experimental radar system. Range resolution, elevation and azimuth beamwidths of the radar define its resolution cell which is shown in Fig.60. Volume of resolution cell increases while moving away from the radar.

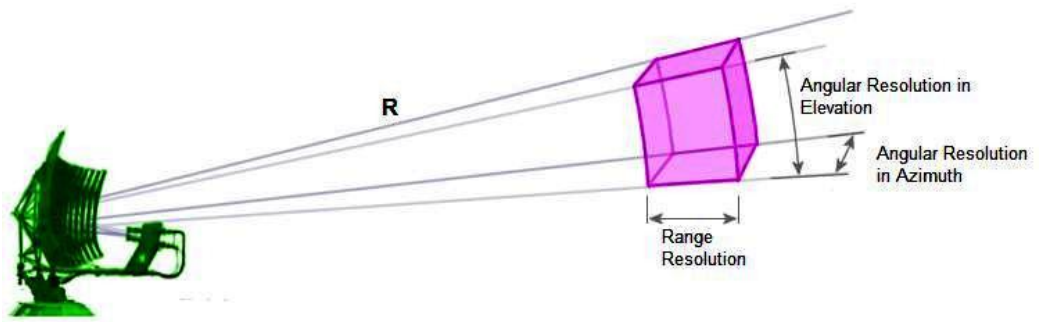


Figure 60. Range Cell of Radar at Distance R

Clutter can be characterized spatially in two different ways according to the antenna being fixed or spinning. If the antenna is spinning, the relation between range cells at the same range but at different azimuth angles can be analyzed. If the antenna position is fixed, then the relation between successive range cells at the same azimuth angle can be analyzed. The antennas of the experimental radar system are fixed, thus clutter can be measured at a fixed angle. Definitely different azimuth angles can be analyzed by changing the antenna position.

When radar resolution cell gets very wide so that many different objects fall in the same cell, the spatial analysis of clutter does not give accurate information.

The resolution cell should be narrow enough to distinct the objects that causes differences in space. Consider the observation areas given in Chapter 9. They both have regions occupied by trees, buildings or empty space. It would be better for spatial clutter analysis when a resolution cell includes only one kind of these textures. In experimental radar system, range resolution is narrow but angular resolution is very wide causing large volume resolution cells. MIT Lincoln Laboratory has performed clutter measurements and the antenna used in their study has 1° of 3-dB beamwidth in azimuth and 3° in elevation.

The required 3-dB beamwidth of the antenna can be calculated by defining the required resolution cell dimension at a distance R.

In addition, narrower beamwidths increase the directivity and the gain of the antenna.

If high angular resolution is not needed depending on the measurement zone, current antennas are not required to be replaced.

8. Adding a Duplexer (T/R Switch) to the System

In the current system, two separate antennas are utilized as RX and TX antennas. As described in Chapter 4 and 7, the receiver antenna also captures the transmit signal and the captured transmit signal is erased from the received signal before processing.

If a high power amplifier with higher output power than the present one was used, there would be two main problems in using two separate antennas. First one is that the receiver may be damaged because of the transmit signal since it is also captured. The second problem would be the improper adjustment of the reference level and the dynamic range of the receiver. The reference level is adjusted considering the highest signal entering the receiver, the spectrum analyzer gives the warning “Input Overload” if the highest signal power is greater than the input reference level. The instrument’s upper limit is the input reference level and the lower limit is the input reference level minus the dynamic range. When the transmit signal is captured by the receiver, the reference level is set by considering its power since it has a relatively higher power than the echoes returning from the targets. Adjusting the input reference level according to the transmit signal’s power may obscure the weak echoes since they may be out of the dynamic range.

Adding a duplexer to the system can solve this problem, since the receiver and transmitter does not operate at the same time instance when a duplexer is used.

9. Improving Maximum Output Power of the System

The high power amplifier used in the experimental radar system supplies 30 dBm maximum peak output power. To increase the maximum detectable range, and choose a reference for clutter analysis with respect to the zero-Doppler peak, obviously the output power of the radar system should be increased.

In order to determine the maximum transmit power required, maximum unambiguous range, range of the horizon line and SNR required for clutter analysis should be defined.

This amplifier would be replaced with a TWTA or Solid State Amplifier that have higher output power.

CHAPTER 11

CONCLUSION

In this thesis, a radar system is constructed for experimental uses in the laboratory and outdoor. It is designed to be as generic as possible to give the opportunity to be used for different purposes and its design can be improved further by changing both the hardware and the software.In this construction study, COTS equipments are chosen as radar hardware units and MATLAB is used as software tool. It is easy to reach COTS products and they can be replaced with upgraded versions in the future.

The experimental radar system is composed of seven hardware units which are the Vector Signal Generator, Spectrum Analyzer, Power Amplifier, Low Noise Amplifier, Computer, Horn Antennas and DC Supply. The system is controlled through a user interface which runs on the computer. The transmit signal definition and the corresponding received signal file selection is done via the user interface. The Doppler and Range vs. Amplitude graphs are presented to the user after the user chooses to analyze the received signal file.

It is possible to define various transmit signals such as frequency or phase modulated, compressed pulses. The transmit signal is defined by the I/Q data forming the desired waveform and it is downloaded to the VSG, thus the user is free to create any type of signal. Pulse Doppler processing is performed on the receiver side but it can be developed and different algorithms can be used. The received signal is saved and the saved file includes the I/Q data of the received signal and a header that contains other parameters like the sampling rate, center frequency, time length and date of the recording. The transmit signal is sent through the TX antenna and received by the RX antenna which are both horn antennas operating at X-Band.

The system is designed to make radar measurements and studies possible in the laboratory and outdoor. It has already been used for clutter measurements and the spectral and statistical analyses of the measurements are described in [12]. The system is placed on the roof of the department and received signals are saved. Having recorded received signals make such studies possible.

However, some specifications of the system should be improved for better performance. For future work, there may be made some changes in the hardware and the software of the system for better performance. The upgrades in the hardware would make remarkable changes in the performance of the radar. The specifications and the performances of the transmitter and the LNA are good, the antennas and the spectrum analyzer could be replaced with better performance ones.

The antennas could be replaced with ones that have higher gain and narrower beam widths. Angular resolution would get better with narrower beamwidths. A duplexer would be added to the system so that a single antenna would be used for both TX and RX functions.

The changes that would be made in the spectrum analyzer that resides in the receiver side will affect the experimental radar system performance comparably to the changes in other units because the limitations of the system are mostly caused by the receiver. Two different spectrum analyzers are used during the thesis. The maximum record length of the spectrum analyzer should be increased. For the present configurations , maximum time record lengths and corresponding Doppler resolutions are given in Table.1. For the clutter spread measurements 19 Hz Doppler resolution and even 3.75 Hz resolution are not enough because the Doppler spread of clutter might as low as 2 Hz[13]. In addition, minimum time resolution of the transmitter is 10 nsec whereas it is 97.66 nsec or 66.67 nsec for the receiver depending on the configuration used. Narrower pulses could be generated and received if the time resolution of the spectrum analyzer was better. Another specification of the spectrum analyzer that can be improved is the noise level. It would be pulled down to lower values by adding extra preamplifiers with lower noise figures. The system's structure is open to be developed and different types of radars can be constructed.

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