DESIGN, ANALYSIS AND PERFORMANCE OF AN ULTRA-WIDE
S-BAND, THROUGH-WALL NOISE RADAR

A Thesis in
Electrical Engineering
by
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Abstract

Through-wall surveillance and detection technology became an area of interest, and subsequently, intense research after the advent of microwave radar systems in the 1980s designed to search for survivors post natural disasters and catastrophes. The ability to detect and monitor targets through barriers is useful not only for search and rescue operations but also military combat situations. This thesis proposes the design, architecture and analysis of an ultra-wide band (UWB) random noise radar operating in the S-band. The waveform consists of a band-limited chaotic signal with an embedded continuous wave tone. Our research work hinges on the use of such a unique system for performing range detection (up to several feet) and tracking of targets through various barriers and lossy media (with a standoff distance from the wall of at least 6 feet). The aforementioned functionality is achieved via the noise component of the waveform. Moreover, as a result of the embedded tone in the waveform and certain signal processing approaches, we find that this radar is also capable of human activity classification based on the micro-Doppler induced signals from moving human targets. Ultimately, this thesis addresses key principles of the noise radar system, correlation concepts and techniques as well as the design and development of helical (end-fire) antennas used by the system.
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Do thy duty that is best; leave unto the Lord the rest. Godspeed.
Dedication

...my thoughts in this piece of work are dedicated to Denise Smith, my mother - a compassionate lady beyond all measure and imagination. She is the perpetual light and everlasting love in my moments of darkness; she is my greatest teacher and number one fan. I love you mommy...
Chapter 1

Introduction

In the late 1880’s, Heinrich Hertz, a physicist, demonstrated that radio waves (i.e. electromagnetic energy) could be reflected from metallic objects. This would lead to a chain of scientific discovery for the use of systems which took advantage of the aforementioned principle. Nearly a century later, such technologies would be employed by emergency, military, law enforcement and even civilian personnel.

Fundamentally, the objective of a “radar” (radio detection and ranging) system is target detection and range determination. [1] Developed clandestinely by several nations circa World War II, radars, initially, were used to detect objects such as aircraft and ships. However, over the past several decades, modern radars have evolved to include the capabilities of target tracking, imaging, and classification.

1.1 Motivation

1.1.1 Through-wall Surveillance Technology

Through-wall sensing technology gained headwind in the late 1980’s after pioneering research in [2]. These researchers developed an X-band microwave detection system to identify human subjects located behind certain obscurments. Potential applications for such a system were for search and rescue missions after large scale catastrophes. In the years following, progressive development increased in through-wall sensing technology [3]; and, the need to create cutting edge and advanced systems became the priority of many industries, in particular, the Department
of Defense. Therefore, prevailing and revolutionary radars, like ultra-wide band (UWB) noise radars \[4, 5, 6\], were explored to meet the needs and requirements of the military and law enforcement organizations.

To detect and locate targets behind walls necessitates a radar system in which the radio frequency (RF) signals can penetrate the impediment. Furthermore, there must be a certain level of sophistication within the architecture of the radar to enable the signal processing and the extraction of meaningful information (in the given through-wall environment). Thus, an integrated system with high resolution in range and a broad frequency response ought to be considered.\[7\]

1.1.2 Considerations for Overall System

The scope of the project, which this thesis addresses, was to design and develop a covert and portable RF radar system for through-wall detection, ranging, and human activity recognition. The sensor system would enable an operator to be at a certain standoff distance and detect targets behind barriers, thereby extending his or her situational awareness. Our work expands upon the existing research by the US army \[8\] which scrutinized many of the design challenges with sensing through different wall materials at various standoff distances.

The S-band radar presented transmits a composite signal comprised of an ultra wideband noise waveform with an embedded continuous wave tone. The composite signal is still noise-like and thus exhibits characteristics such as immunity from detection and anti-jamming. Furthermore, noise waveforms have relatively flat power spectra and hence the total power transmitted is effectively low. Ultimately, the noise component of the waveform is responsible for the detection, ranging, and tracking of a target, while the single tone is used to capture micro-Doppler induced signals from a target’s movements.

The background and theory on basic radar principles as well as a brief introduction of noise radars with relevant mathematical concepts are presented in Chapter 2. The design and implementation of our S-band noise radar architecture is discussed in Chapter 3. Chapter 4 delves into the antenna considerations for the system. The feasibility of characterization of human activity based on micro-Doppler signals is explored briefly in Chapter 5. Experimental work and results are
examined and explained in Chapter 6. At last, the thesis concludes with Chapter 7 providing a succinct summary and directions for future work.
Chapter 2

Background and Theory

2.1 Elementary Radar Principles

A radar system consists of a transmitter that generates an electromagnetic signal that is radiated into space by an antenna. When such a signal is intercepted by a target, a portion of that transmitted energy gets re-radiated in many directions. The signal that comes back toward the radar is collected by a receiving antenna and processed to detect the presence of the target.

2.1.1 Radar Range Equation

The radar range equation in [1] is given by:

\[
R_{\text{max}} = \left[ \frac{P_t G A_e \sigma}{(4\pi)^2 P_r} \right]^{\frac{1}{4}}
\]  

(2.1)

where \(P_t\) is the power transmitted, \(G\) is the gain of the transmit antenna, \(A_e\) is the effective area of the receiving antenna, \(\sigma\) is the radar cross section of the target and \(P_r\) is the minimal detectable signal.

The aforementioned equation (2.1) is a simplified version of the radar range equation as it does not adequately detail the real performance of a radar system because it does not include system and environment losses. Nevertheless, important to note, if the equation is rearranged to solve for received power, then the formula indicates that received signal strength declines as the fourth power of the
range. Therefore, return power is small from targets at a far range.

### 2.1.2 Doppler Effect

In short, the Doppler effect is a phenomenon that discusses the frequency shift caused by a target that is in motion with respect to the source. This occurrence reveals information about the target velocity and aids in the detection effort. For an active radar, the Doppler frequency is given by the following expression found in [1]:

\[ f_d = \frac{2f_t \nu_r}{c} \]  

where \( f_d \) is the Doppler frequency, \( f_t \) is the transmit frequency, \( \nu_r \) is the radial velocity of the target’s movement, and \( c \) is the speed of light.

Radial movement is the only relevant component of the target’s speed and the maximum Doppler frequency shift occurs when movement is directly toward or away from the radar system.

### 2.2 Random Noise Radar

“Noise radars” transmit a random, or chaotic, signal and are finding applications because of the inherent attributes of noise waveforms. Given the non-deterministic nature of noise, when used by radar systems, there are no ambiguities in the measurement of range and/or velocity.

Generally, noise radars offer the following advantages (which include but not limited to): (a) noise waveforms have low-probability of intercept/low-probability of detection (LPI/LPD) characteristics and are thus covert; (b) noise waveforms are inherently anti-jamming; and finally, (c) these waveforms can share the frequency spectrum without mutual interference.
2.3 Mathematical Formulation of Random Noise Processes

The aperiodic characteristic of noise only allows the random process to be described in terms of its statistical attributes. Moreover, authors in [10] explain that the information or data for a variety of random physical phenomena are approximated by the Normal probability density function (pdf):

$$f_X(x) = \frac{1}{\phi \sqrt{2\pi}} \exp\left(\frac{-(x - \mu)^2}{2\phi^2}\right)$$  \hspace{1cm} (2.3)

where $p(x)$ is the probability of finding $x$ (e.g. noise voltage) on some given interval and $\phi$ is the mean square value of $x$ (i.e. the power of signal $x$).

2.3.1 Theory of the Expectation of Random Processes

To understand how a correlation detector functions with inputs such as noise signals, the discussion begins with a comprehension of the expectation operator in probability theory. Reference [11] provides this background knowledge. Without loss of generality, the expected value for a continuous random variable is given by the following expression (this formula can be extended to a random process and, more importantly, to more than one random variable or process):

$$E[X] = \int_{-\infty}^{+\infty} xf_X \, dx$$  \hspace{1cm} (2.4)

The expected value is a weighted average of the possible outcomes a random variable or process can have. With this basis and the extension to stochastic processes, the definition of the correlation (or cross correlation) between two random processes ($X(t)$ and $Y(t)$) is observed as:

$$R_{XY}(t, \tau) = E[X(t)Y(t + \tau)]$$  \hspace{1cm} (2.5)

The above expression is a useful tool for analyzing a pair of processes to obtain information regarding the relationship between the random (and possibly independent) processes. As is well known, the properties of the cross correlation function are such that for wide sense stationary processes, like White Gaussian noise, the
correlation depends only on the time difference between the two random processes. Hence, in noise radars, we correlate a copy of the transmit signal with the delayed return signal to determine the time delay (i.e. distance) between the two signals.

2.3.2 Ultra-Wideband Signals

An UWB signal describes waveforms that have instantaneous fractional bandwidths greater than 25 % with respect to the center frequency. These signals are normally very low power with fine resolution (since range resolution is inversely proportional to the bandwidth) and well-suited for short-range applications. Coupled with the features of noise, such an intelligent system (i.e. an UWB noise radar) finds applicability in through-wall sensor technology.
Chapter 3

Design and Implementation of the Noise Radar System

3.1 Basic Principle of Noise Radar Operation

Over nearly half a century ago, Billy Horton established the precept of noise radars. Again, noise radar technology uses a random waveform as the transmitting signal. Detection is achieved via correlation, which is inherently a coherent signal processing technique. The radar system uses a reference copy of the transmit signal and compares that with the returned reflected waveform.

3.1.1 The Cross-Correlation Technique

The correlation process enables one to measure the degree of similarity or “match” between two sequences or signals. As previously indicated, a duplication of the transmitted waveform is directed to the receiver chain. Here, the reference signal and the delayed returned signal are multiplied together and averaged. In hardware, this is accomplished via a mixer and low pass filter. Nevertheless, at the output of the correlation, the various (amplitude) peaks indicate the portion of the waveforms that displayed high levels of agreement, while the lag values at those peaks correspond to the delay between transmitted and reflected signal. After a mathematical transformation, the delay (i.e. a returned echo) can be equivalently interpreted as the distance between the radar system and the reflections from a
target in the scene of interest.

Following from the statistical correlation between random processes (see Chapter 2), the cross-correlation function is an expression of the temporal (i.e. lag) distance between two points. Equation 3.1 denotes the cross correlation (⊗) between two signals:

\[
\phi_{xy}(\tau) = x(t) \otimes y(t + \tau).
\]  

Here, \( x(t) \) is taken as the transmit signal and \( y(t) \) is the received signal. “\( \tau \)” signifies the delay of the return signal.

### 3.2 Noise Radar System Design

To select the appropriate frequency of operation for the through-wall radar system, the following: range resolution; the beamwidth of the antennas; and losses of the system and from the environment ought to be scrutinized. Given these denominators, frequencies within the S-band for the through-wall system were considered. A higher frequency was desired for better Doppler resolution, while a lower frequency was preferred for propagation through media. Also, from a cost and development perspective, many of the components were found to operate either in a range from 2 - 4 GHz or 4 - 8 GHz; thus, we looked at center frequencies of the respective band.

The down-range resolution is critical for discriminating objects certain distances apart in a given locality. Typically, the desire is to have a very fine resolution. Related to bandwidth, the range resolution is given by:

\[
\Delta R = \frac{c}{2BW}.
\]  

where \( c \) is the speed of light and \( BW \) is the bandwidth. To achieve a range resolution of 1 foot (necessitated to localize an individual target, such as a human), the \( BW \) must be approximately 500 MHz.
3.2.1 System Description

A wideband noise signal is used to detect the range to the target; while a single continuous tone signal is required to detect induced Doppler from human activity. This tone will be chosen within the frequency band of the noise source. In previous iterations of the radar system design, the noise and the single tone were combined and transmitted as a composite waveform. However, in the most recent layout, a switch is used to operate either source. To maximize the human activity classification algorithm (as originally coded), the option of transmitting just the continuous tone was preferred (since the combination of the noise signal with the tone would become too noisy as the signal propagated through the dispersive media causing issues for the sensitive classifier). Nonetheless, below (Figure 3.1) is the block diagram for the S-band noise radar system:

Figure 3.1: Block diagram of S-band noise radar architecture.
Figure 3.2 illustrates an original draft layout of the S-band noise radar system (including the barrier strips and 4 modular power switching supplies) prior to housing it in its respective enclosure. The following sections discuss (in general) the main operating principles of the different sections of the noise radar. For a complete description, access to the technical report for the project is needed.

### 3.2.2 Transmit Chain

The noise source is from NoiseWave and produces an approximate ultra-wideband noise waveform with a specified frequency range from 100 Hz (as close to DC as possible) to 500 MHz. The rated power output is +10 dBm. The noise signal is then filtered through two different low pass filters from Mini-Circuits to accentuate the cutoff frequency of about 500 MHz and obtain a smooth roll-off. After filtering, the waveform passes through a power splitter (suffering a 3 dB loss at each exiting port) where one output terminates to channel one (of the Digitizer) and serves as a reference signal, and the other output goes to a switch (SPDT RF Switch) awaiting to be up-converted (or combiner to be merged with the single tone - in a previous schematic). Figure 3.3 shows preliminary testing results of the noise
source and of the filtering effects.

![Power Spectrum of Noise Source (Unfiltered)](a)
![Power Spectrum of Noise Source (Filtered Once)](b)

Figure 3.3: (a) Power spectrum of noise source, and (b) Power spectrum of noise source after passing through a low pass filter (VLF-530).

The single tone is generated by a voltage controlled oscillator (VCO) purchased from Mini-Circuits. The VCO ($VCO_1$) produces an output of about +6 dBm at a desired frequency (and though it was not a phase-locked oscillator to mitigate against issues of jitter or phase noise, it performed satisfactorily for the system requirements). This signal is split (similar to the noise source) where one output leads to a low pass filter and then to the switch awaiting to be up-converted (like the noise source), and the other terminal goes to an amplifier ($PowerAmp_2$), filter, and finally to a mixer ($Mixer_2$) (in the receiver chain).

At the switch, depending on user preference, either the noise signal or single tone is sent to the 90° Hybrid to split the waveform into in-phase and out of-phase components. From there, the outputs of the 90° Hybrid pass to the I/Q Modulator. Then, the upper-side band of the radar is selected and passed through a power amplifier ($PowerAmp_0$) and two bandpass filters before terminating at the input to the transmit antenna.

The output power of the transmit chain can be determined by exploring gains and losses in the signal strength as the signal passes through the various components prior to reaching the transmitting antenna. It is valuable to note that noise power (e.g. in units of dBm) is measured per bandwidth. Nevertheless, the theoretical value of output power for the transmit signal (in the latest iteration of the
architecture) before reaching the antenna is less than 20 dBm (i.e. 100 milliwatts).

3.2.3 Receiver Chain

The receiver chain begins at the output of the received antenna and continues onto the low noise amplifier and into the mixer (Mixer). Another VCO (VCO₂), responsible for the up-conversion, is also used in down converting the signal. This VCO is amplified by another power amplifier (PowerAmp₁), filtered twice and then sent to a power splitter. From here, the signal is connected to I/Q Modulator for up-conversion and connected (after passing through an attenuator) to the mixer (Mixer) for down-conversion. Ultimately, at the output of that mixer, the baseband signal is filtered twice and sent to another power splitter. One terminal (of the power splitter) goes into the Digitizer as channel two (for range detection). The other output is filtered twice again with even lower cutoff frequency filters before entering another mixer (Mixer₂). The signal is mixed with the original VCO (VCO₁) and then the output is filtered twice again before terminating at the National Instrument’s multifunction data acquisition (DAQ) unit (for target activity detection).

3.2.4 Antennas

Several antennas were examined for the radar system. The log periodic printed circuit board antennas (shown in Figure 3.4) with an average gain of 6 dBi and a typical half-power beamwidth that ranges from 40° to 60° (for the E-plane) were the initial choice in the early design phase. These antennas have a broadband frequency range from 2.1 to 11 GHz. As the design progressed, the antennas of choice were the dual quad horns (also shown in Figure 3.4) with an operating frequency range from 2 to 18 GHz and a reported gain of about 10 dBi (in the S-band). The normal half-power beamwidth of such antennas (in the same band) varied from 60° to 31° (for the E-plane).

Ultimately, the focus shifted to designing custom (helical) antennas to meet the project requirements. Given size and shape constraints, one critical objective was to increase the gain of the antennas (and in effect, narrowing the beamwidth and allowing the radiation to concentrate on a smaller region of interest). Chapter
4 delves further into this matter.

![Log Periodic PCB antenna](a) and ![Dual Polarization Horn antenna](b)

Figure 3.4: (a) Log Periodic PCB antenna, and (b) Dual Polarization Horn antenna.

### 3.2.5 System Integration

#### 3.2.5.1 Power Consumption

Table 3.1 indicates the power consumption for the major active components of the prototype radar system. Such information proved to be useful when choosing the appropriate power rated modular power supplies.

Table 3.1: Table showing the power consumption for the major active components of the radar system.

<table>
<thead>
<tr>
<th>Type</th>
<th>Quantity</th>
<th>Input Voltage [V]</th>
<th>Current Drawn [Amps]</th>
<th>Power [Watts]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Noise Source</td>
<td>1</td>
<td>24</td>
<td>0.16</td>
<td>3.84</td>
</tr>
<tr>
<td>VCO₁</td>
<td>1</td>
<td>5</td>
<td>0.03</td>
<td>0.15</td>
</tr>
<tr>
<td>VCO₂</td>
<td>1</td>
<td>5</td>
<td>0.04</td>
<td>0.2</td>
</tr>
<tr>
<td>SPDT RF Switch</td>
<td>1</td>
<td>5</td>
<td>0.001</td>
<td>0.005</td>
</tr>
<tr>
<td>PowerAmp₀</td>
<td>1</td>
<td>12</td>
<td>0.4</td>
<td>4.8</td>
</tr>
<tr>
<td>PowerAmp₁</td>
<td>1</td>
<td>5</td>
<td>0.1</td>
<td>0.5</td>
</tr>
<tr>
<td>PowerAmp₂</td>
<td>1</td>
<td>12</td>
<td>0.065</td>
<td>0.78</td>
</tr>
<tr>
<td>Low Noise Amp</td>
<td>1</td>
<td>15</td>
<td>0.15</td>
<td>2.25</td>
</tr>
<tr>
<td>Fan₁</td>
<td>1</td>
<td>24</td>
<td>0.15</td>
<td>3.6</td>
</tr>
<tr>
<td>Fan₂</td>
<td>1</td>
<td>24</td>
<td>0.15</td>
<td>3.6</td>
</tr>
</tbody>
</table>

Total: 19.725
3.2.5.2 System Enclosure

The following section shows pictures of the custom designed enclosure unit to protect the prototype radar.

Figure 3.5: The enclosure unit designed and constructed for S-band noise radar system.
3.2.5.3 External Interfaces

All the received signals for the ranging system are acquired by an 8-bit A/D Digitizer (i.e. Cobra CompuScope) supplied by the company GaGe. The high speed digitizer has adjustable sampling rates with a maximum sampling rate of 2 GS/s per channel.

On the other hand, the return signals from Doppler induced phenomena are captured on the Multifunction DAQ unit by National Instruments. These signals are then used in the human activity detection algorithm.

3.2.5.4 Programming Platforms

To achieve the signal processing and coding objectives of the project, two primary programming platforms were used: LabVIEW Instruments and MATLAB. LabVIEW was used to process real-time data acquired by the Digitizer and the DAQ
unit as well as to display target information to an interactive graphical user interface (GUI). The GUI (for ranging detection) communicated system information (e.g. \textit{input voltage range, sampling frequency, number of points to collect, etc.}), target ranging (e.g. \textit{plots of the correlation output profiles}), and target tracking (e.g. \textit{successive scene subtraction}). Another GUI (for Doppler detection) showed plots of Doppler induced signals as well as their respective frequency spectra.

Moreover, MATLAB enabled post-processing of the data collected for further analysis. It also was a great tool for modeling scenarios and system testing.
Antenna Design

Tasked with striking a balance between design constraints and performance capabilities (and, as previously mentioned), several options were considered for the choice of antennas for the S-band noise radar system. Preliminary attention focused on three different antennas: *log periodic, dual quad (rectangular) horn*, and *helical*. However, after further scrutiny, much more deference was given to the *helical* antenna (as its properties proved to be most beneficial); and thus, modifications and enhancements were made to the transmitted and received helical antennas to improve their performance.

4.1 Background on Helical Antennas

Akin to most unique and integral inventions or discoveries, the helical antenna was developed by chance in one’s humble garage. John D. Kraus is credited with the design and development of the helical antenna.\[15\] It encompasses a conducting element wound in the geometrical shape of a helix. The conductor is supported by a central buttress frame, and together they are mounted on a ground plane. A generic diagram (taken from our preliminary research survey: *theoretical study and system level analysis*) of a helical antenna is shown in Figure 4.1.
Helical antennas operate in two principal modes: normal and axial. Under the normal mode of operation, where the dimensions of the helix are small compared to the wavelength, the radiation is normal to the helix axis and has an omnidirectional pattern. When operated in the axial mode, where the dimensions are now comparable to the wavelength, the helical antenna behaves like a directional endfire antenna. Additionally, the beam at the end of the helix is circularly polarized.

### 4.1.1 Advantages of Helical Antennas

Arguably, apart from cost and ease of construction, the most critical and advantageous aspect of the helical antenna is its inherent ability to generate circularly polarized electromagnetic waves, where the plane of the electric field vector rotates through a full $2\pi$ revolution with each wavelength. Thus, the antenna radiates energy in all planes along an x-y coordinate system.

Circular polarization finds significant applicability in many communication scenarios because it can enhance the performance of a given network. The researchers in [16] have identified and enumerated several areas where circular polarization has many benefits. These include but are not limited to the following: reflectivity and absorption - electromagnetic signals are reflected or absorbed in various planes depending on material composition and orientation, thus transmitted and received signal strength is not diminished entirely if the surface of the material is polarized vertically or horizontally; multi-path and phase - unlike reflected linear electromagnetic waves that may interfere with the transmitted signal due to phase changes,
reflected circularly polarized signals return in the opposite orientation, thereby eschewing direct collision with the transmitted signal; and line-of-sight - ultimately, circular polarized waves are able to penetrate and bend around obscure barriers better than linearly polarized waves.

At last, because circular polarization contains vertical and horizontal electrical field components in equal proportions, the helical antenna can work with numerous types of linearly polarized antennas (with the caveat that there would be a 3-dB loss in effective gain).

4.2 Design of Helical Antennas

The characteristics of the helical antenna hinges on its intrinsic design. Many literary works discuss and catalog the optimal design parameters (based on historical and extensive research). Therefore, we find that the operating features of the helical antenna are a function of the coil spacing, $S$, and more importantly, the diameter of the coil, $D$. The helix circumference should be on the order of the operating wavelength (for axial mode operation). Furthermore, the optimal pitch angle for a helical antenna is between 12 degrees to 14 degrees. The polarization, and thus, the handedness of the antenna is a function of the winding direction. Finally, the ground plane should be approximately $\frac{3}{4} (\lambda)$ or greater. Other design parameters, such as thickness of the conductor (i.e. the copper helix wire), seemingly are not critical according to Kraus.

According to Baker in [15], for a peripheral feed antenna, the terminal resistive impedance is given by:

$$R = \frac{150}{\sqrt{C}}$$  \hspace{1cm} (4.1)

In order to achieve a 50-ohm match between the impedance of the antenna and the source feed, the last $\frac{1}{4}$ - turn of the helix is gradually tapered and adhered parallel to the ground plane. The height of the taper above the ground plane is given by:

$$h = \frac{w}{\left(\frac{377}{\sqrt{\epsilon_r Z_0}}\right) - 2}$$  \hspace{1cm} (4.2)

where $w$ is the width of the conductor at the termination, $\epsilon_r$ is the relative permit-
tivity of the ground plane, and $Z_o$ is the characteristic impedance of the ground plane.

### 4.2.1 Ground Plane

Customarily, a ground plane is a flat conducting surface that serves as the base of an antenna. Our initial helical antenna design followed the well accepted design parameters and constraints that are available in [15] and other pieces of literature. The pictures in Figure 4.2 (taken from our research survey: *theoretical study and system level analysis*) below show one of the original helical antennas and its respective ground plane.

![Figure 4.2](image)

(a) S-band helical antenna, and (b) Circular flat ground plane with a coaxial connector.

In a series of attempts to improve the design of the helical antenna, considerations were made to alter the ground plane. Scientists in Reference [17] endeavored to enhance the gain of the helical antenna by modifying the ground plane. They witnessed that by conforming the ground plane appropriately, while the antenna operated in its axial mode configuration, there was an increase in the gain as well as a reduction in side and back-lobes. Exploring various ground conductor shapes, the researchers’ findings on a helical antenna above a short conical-like structure purport that such a design is the best option, reaffirming previous analyses in other works. Therefore, with optimization in mind and based on their simulated and experimental work, the following dimensions were desired for the construction of the new ground plane: top radius: $(r_2 = 1.25\lambda)$; bottom radius: $(r_1 = 0.375\lambda)$; height:
(h = 0.5λ). The reported peak gain according to Citation 17 is approximately 17.3 dBi, which is several dB’s higher than that of an infinite ground plane.

To avoid the challenge of creating the new ground plane from scratch, we decided to find an existing object that roughly met the design requirements, which we could then tailor to fit our needs. Surprisingly, we found a “salad bowl” that had the following dimensions: bottom diameter: ∼3.5 inches; top diameter: ∼7.38 inches; and height: ∼2.63 inches. Figure 4.3 depicts the two distinct parts (i.e. salad bowl and circular ground plate) that were merged together to form the single conical-like unit.

![Figure 4.3: Assembly pieces for the construction of the short-conical ground plane.](image)

Though the measurements are not ideally identical to the optimal dimensions, we conceded that the provisional artifact would still suffice for the prototype. Furthermore, principally concerned with the measurement of the top diameter, there was only a 4.4% error between the measured and the ideal value for that dimension. We coated the interior as well as the rim of the bowl with copper taper. Then, we bored out the bottom of the bowl to make a relief hole (with a circular lip). See Figure 4.3. To the base of the interior of the bowl, we soldered a circular flat ground plate with an affixed coaxial cable connector (as seen in Figure 4.4).
On the backside of the bowl, we epoxied to the circular lip a round wooden stub that housed the mounting unit. Finally, as mentioned previously, we adhered the copper helix wire to the base of the ground plane, where the tip of helix wire was flattened and tapered to connect to the coaxial pin of the connector. The helix wire was wound around a polycarbonate “cross-beam” with notches so that the spacing of the turns would meet the design parameters. Figure 4.5 below shows the helix wire and the support frame next to each other.

The final assembly of the new helical antenna is depicted in the two perspective views of the end product shown in Figure 4.6.
In the following section, we explore more characteristics of the helical antenna as well as further improvements (beyond a new ground plane) made in refining the prototype.

### 4.3 Antenna Measurements and Parameters

#### 4.3.1 Polarization

The polarization of an antenna is the orientation of the electric field as viewed from an observer positioned behind the antenna; it is defined for the transmitting antenna. For linearly polarized waves, the position of the antenna feed dictates the orientation of the electric field and thus, its corresponding polarization.

In the case of circular polarization, there is a “handedness” that is associated with the propagation of the electromagnetic wave. The rotation of the electric field can be either right-handed or left-handed (and such a characteristic is established by the sense of direction in which the copper helix wire is wound). Furthermore, when there is a communication link between two circularly polarized antennas, both antennas must have the same polarization sense (i.e. both RHCP (right hand circularly polarized) or both LHCP (left hand circularly polarized)) for maximum signal reception. However, if the antennas are to be operated in a bi-static radar situation and the return from the anticipated targets (e.g. wall, person, flat plate,
triangular corner reflector, etc.) generate an odd number of reflections, then the transmit and receive antennas ought to have the opposite circular polarizations (i.e. one RHCP and the other LHCP).

4.3.2 Gain

Again, as formerly suggested, the electrical properties of the axial mode helical antenna is influenced largely by its geometry. The helix operates fairly well across a range of pitch angles, but has been found to be optimal for angles between 12 and 14 degrees. Between this range, the gain and bandwidth seemingly find an appropriate compromise. Moreover, as the electric field travels down the conductor, the current along the helix continuously changes and the radiation from opposite points on the helix are nearly in phase. Hence, the magnitude of the electric field (i.e. gain) along the axis in the far field region is reinforced.\cite{cite}

Many empirical formulas (based on thorough research) have been presented to predict certain performance parameters of the helical antenna. Two such formulae (i.e. $G_1$ and $G_2$) were considered when calculating the gain. The subsequent equation:

$$G_1 = 10.8 + 10 \log_{10}((\frac{C}{\lambda})^2 N(\frac{S}{\lambda}))$$  \hspace{1cm} (4.3)

found in Citation \cite{cite2} and is commonly thought to be slightly idealistic (by 3 to 4 dB). The other expression for estimating the gain is:

$$G_2 = 6.2(\frac{C}{\lambda})^2 N(\frac{S}{\lambda})$$  \hspace{1cm} (4.4)

According to \cite{cite3}, gain calculated with equation \cite{eq} is proportional to $f^3$ and tends to increase linearly as the number of turns are incremented; therefore, if you double $N$, the gain ought to increase by 3 dB.

4.3.3 Beamwidth

In terms of the beamwidth, we found two mathematical expressions (i.e. $HPBW_1$ and $HPBW_2$) for the obtaining the half-power beam-width in degrees:
\[
HPBW_1 \approx \frac{52\lambda \sqrt{\lambda}}{C \sqrt{NS}}. \quad (4.5)
\]

\[
HPBW_2 \approx \frac{65\lambda}{C \sqrt{\frac{NS}{\lambda}}}. \quad (4.6)
\]

Equation 4.5 is referenced in [20] and equation 4.6 is cited in [18]. These aforementioned expressions offer some indication as to what geometrical parameters influence the beamwidth and how the main beam compares to the 3 dB point. Unlike some linearly polarized waves, for helical antennas the half power beam width applies to all planes because for circular polarization the main beam is almost symmetrical.

### 4.3.4 Scattering Parameters

Scattering parameters, first largely emphasized by Kaneyuka Kurokawa in the 1960's in his paper [21], describe the electrical behavior (i.e. the scattering of traveling currents and voltages) between terminals of an electrical network where the frequency of operation is usually at radio and microwave frequencies. For instance, in a two-port network, the \( S_{21} \) parameter would represent the power received at terminal two relative to an input source at terminal one. The \( S_{11} \) parameter offers insight to the reflected power from terminal one.

In antenna engineering, the \( S_{11} \) parameter indicates how much power is reflected from (i.e. the return loss or reflection coefficient of) the antenna under test and thereby denotes the resonant frequencies (and bandwidth) of the antenna. Thus, the more return loss shown by the magnitude of the \( S_{11} \) parameter the better the radiated power is from the antenna at such frequencies.

Figure 4.7 plots the \( S_{11} \) parameters for an enclosed rectangular (quad) horn antenna, a log periodic antenna, the original helical antenna, and the modified helical antenna. These plots were obtained from measurements by a network analyzer in our off-campus radar and communication laboratory.
Figure 4.7: (a) quad horn - vertical polarization: (2-18 GHz), (b) log periodic antenna: (2-11 GHz), (c) original helical antenna: (2-4 GHz), and (d) modified helical antenna: (2-4 GHz).

Figure 4.7 shows (1) that, in general, the helical antennas are more directive (operating well over a narrow band of frequency ranges) than the quad horn antenna with vertical polarization and the log periodic antenna and (2) that the modified helical antenna has a better response than the original helical antenna.

4.3.5 Radiation Patterns

Fortunately, we were able to simulate some of the designs for the modified helical antennas using computational modeling software such as, FEKO Suite, REMCOM XFDTD, and SolidWorks. Figure 4.8 shows screen captures of the FEKO Suite modeling environment for the two major components (i.e. the short conical ground plane and the elongated helix attached to the new ground plane) of the modified helical antenna.
Figure 4.8: (a) Short conical ground plane designed in SolidWorks and imported into FEKO Suite, and (b) Model of modified helical antenna assembly.

Figure 4.9: Model of the radiation pattern for the modified helical antenna.

Figure 4.9 above shows the simulated magnitude of the electrical field strength overlaying the antenna model.

Moreover, with access to an anechoic chamber (located in the Penn State Electrical Engineering East Building) we were able to collect some rudimentary radiation patterns for various antennas, in particular, the helical antenna and the modified helical antenna. We used the quad horn antenna as a standard transmit antenna to characterize the receiving antenna under test. Figure 4.10 shows a comparison between the relative antenna patterns for the original helical antenna and the modified helical antenna.
Figure 4.10: (a) Relative antenna pattern for the original helical antenna. (b) MatLAB surface plot of the relative antenna pattern for the original helical antenna. (c) Relative antenna pattern for the modified helical antenna. (d) MatLAB surface plot of the relative antenna pattern for the modified helical antenna.

The data graphed in Figure 4.10 were acquired by the Desktop Antenna Measurement System (DAMs) software offered by the Diamond Engineering: Automated Measurement Systems company. In conjunction with a vector network analyzer in the anechoic chamber, the software collected user input such as, number of points, frequency range, and positioner and configuration settings, to enable testing of small to medium antennas.

4.3.6 Comparison between original and modified helical antennas

Ultimately, to summarize some of the significant differences between the original and modified helical antennas, Table 4.1 presents a few geometrical parameters
and their corresponding values.

**Table 4.1: Original Helical Antenna vs. Modified Helical Antenna**

<table>
<thead>
<tr>
<th>Parameter(s)</th>
<th>Original Helical Prototype</th>
<th>Modified Helical Prototype</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength ($\lambda$)</td>
<td>- [m]</td>
<td>- [m]</td>
</tr>
<tr>
<td>Circumference ($C$)</td>
<td>- [m]</td>
<td>- [m]</td>
</tr>
<tr>
<td>Diameter ($D$)</td>
<td>0.028 [m]</td>
<td>0.028 [m]</td>
</tr>
<tr>
<td>Spacing ($S$)</td>
<td>0.022 [m]</td>
<td>0.022 [m]</td>
</tr>
<tr>
<td>Pitch angle ($\alpha$)</td>
<td>14.1°</td>
<td>14.1°</td>
</tr>
<tr>
<td>Number of turns ($N$)</td>
<td>11</td>
<td>19</td>
</tr>
<tr>
<td>Axial length ($A$)</td>
<td>~ 0.205 [m] (measured)</td>
<td>~ 0.353 [m] (measured)</td>
</tr>
<tr>
<td>Gain ($G_1$)</td>
<td>15.2 [dBi] (calculated)</td>
<td>17.6 [dBi] (calculated)</td>
</tr>
<tr>
<td>Gain ($G_2$)</td>
<td>12.5 [dBi] (calculated)</td>
<td>14.8 [dBi] (calculated)</td>
</tr>
<tr>
<td>Half Power Beam-width ($HPBW_1$)</td>
<td>31.34° (calculated)</td>
<td>23.84° (calculated)</td>
</tr>
<tr>
<td>Diameter (type)</td>
<td>Circular flat plate</td>
<td>Short conical bowl</td>
</tr>
<tr>
<td>Diameter of ground plane</td>
<td>$D_1 = 0.097$ [m] (measured)</td>
<td>$D_1 = 0.0889$ [m]; $D_2 = 0.18745$ [m] (measured)</td>
</tr>
</tbody>
</table>

1 Equation 4.3 was used.
2 Equation 4.4 was used.
3 Equation 4.5 was used.
4 This particular ground plane acts as a reflector; and thus, may add to the overall effective gain of the antenna.

Though we primarily explored just two major modifications to the helical antenna (i.e. different ground planes and increasing the number of turns), there exist many more (simple and cost effective) adjustments and configurations that can alter or enhance the performance of the helical antenna, making it a formidable choice for many applications.
Identifying and classifying human activity is a critical need for many applications that require either monitoring or surveillance. In order to accomplish such a task, researchers relied on investigating and interpreting Doppler signatures. The concept was to detect Doppler shifts associated with human movement using a continuous-wave signal. Traditional analysis of such received signals hinged upon the use of the Fast Fourier transform (FFT) and Short-time Fourier transform (STFT).

However, human activities produce diverse kinds of motion. Most of these movements are non-linear and non-stationary. Furthermore, some motions are extremely slow in velocity and hence the Doppler shift is not as fast or explicit as normal moving targets. Thus, in recent years, researchers in [22, 23, 24] have spent quite some time analyzing these micro-Doppler movements. Using a radar system capable of detecting micro-Doppler signals, human activity recognition becomes feasible as certain movements will generate unique features that can then be examined with a time-frequency method (e.g. STFT) and then classified based on such features (See Doppler section in Chapter 6).

When movement is not uniform nor constant, the STFT exhibits some limitations, and thus, there is a need for an adaptive method that can scrutinize such micro-Doppler signatures. Additionally, another technique must be selected to perform the classification. Authors in [25] have proposed and researched the use
of the Hilbert-Huang Transform (HHT) in conjunction with the empirical mode decomposition (EMD) method to process the non ideal Doppler data. From this signal processing technique, new features are garnered and the method of a Support Vector Machine (SVM) has been explored for classification. The background and focus of that work is fully discussed recent literature [26].
System Analysis and Experimental Results

6.1 Wall Construction

In an effort to properly test the radar system for through wall scenarios, a decision was made to construct a “wall support frame” that would house, in a dry-stack fashion, different masonry materials. Though for initial testing, attention was given to existing walls (4 to 5 inch-thick cinder block) in and around the laboratory facility, the need to isolate the testing environment (free from unwanted clutter and obstructions) became a chief concern; and thus, the option to create the structure was explored.

6.1.1 Wall Support Frame Structure

The frame was designed to support a wall (e.g. brick or cinder block) that was 8 feet tall by 8 feet wide. In addition, the frame had an adjustable width to either 4 inches, 8 inches or 12 inches. The structure stood a foot above the ground, adding additional height to the wall, on castor wheels enabling the wall to be mobile. The following pictures depict the support frame under construction.
Figure 6.1: Base of wall support structure.
Figure 6.2: Frame of wall support structure.
6.1.2 Wall Type: Brick and Cinder Block

Figure 6.3: Partially stacked 4-inch thick brick wall in the wall support frame.
Figure 6.4: Close-up of the wall support frame with the width adjusted to fit the 4-inch brick.
6.1.3 Experimental Setups

To collect data, the antennas (in use) were mounted on a wooden stand that positioned the antennas approximately 54 inches above the ground and about 6 feet from the front of the wall (under test). To a reasonable standard, care was taken to align the antennas properly since poor alignment could negatively influence the results. Six foot coaxial cables were connected to the antennas from the radar system (allowing some separation).

Varied targets were used during the collection of data; however, more attention was given to human targets and two types of trihedral targets. Table 6.1 shows some of the dimensions and characteristics of said targets. For the purposes of this thesis, favor was given to the results obtained with the large trihedral target (since it has the largest and consistent radar cross section (RCS)) as well as human targets. The RCS, which is based on the frequency of operation, is important to acknowledge as it is an indication of the strength of the reflected signal from the target. For a human target and its respective orientation, the RCS can vary.
greatly depending on the incidence of the wave and is usually much lower than that of the trihedral target. Nevertheless, background subtraction techniques [27] can be exploited to extract information about the (human) target and increase the likelihood of detection.

Table 6.1: Target dimensions and characteristics.

<table>
<thead>
<tr>
<th>Length (of edge $a$)</th>
<th>Human</th>
<th>Small trihedral (triangular sides)</th>
<th>Large trihedral (triangular sides)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Formula (RCS)$^1$</td>
<td>average height of a person</td>
<td>0.324 [m]</td>
<td>0.457 [m]</td>
</tr>
<tr>
<td></td>
<td>measured experimentally</td>
<td>$\frac{\pi (a^3)}{8}\lambda^2$</td>
<td>$\frac{4\pi (a^3)}{3\lambda^2}$</td>
</tr>
</tbody>
</table>

$^1$ Target echo cannot be sufficiently characterized by a single value.

The trihedral targets were propped up on a foam tower (to reduce reflections) and moved to different lengths behind the wall (under test). The following figures illustrate various test scenarios and setups.

Figure 6.6: Data collection (outside) with the new helical antennas and the 4-inch thick brick wall.
Figure 6.7: Side-view of scene setup (outside) with new helical antennas and the 4-inch brick wall.

Figure 6.8: Data collection (outside) with the quad horn antennas and the 4-inch thick brick wall.
Figure 6.9: Side-view of scene setup (outside) with quad antennas and the 4-inch brick wall.

Figure 6.10: Data collection (inside) with the new helical antennas and the 8-inch thick cinder block wall.
6.2 Field Results

Finally, the crux of the whole project is presented in the subsequent results with select data and brief discussions. To understand the data (i.e. the range profiles) generated, an augmented Figure 6.11 of data collected for a scene in which a small target is placed behind a laboratory wall is provided below. The first grouping of peaks indicate the antenna coupling of the system, while the second main peak is the reflection from the wall response. Beyond the second peak are either targets of interest, unwanted clutter or ghost targets that arise from the scene/experimental setup. Also, the range profiles plot relative correlation values versus lag values that have been transformed to a unit of distance.

Important to note is that in all the data shown in this document, the internal system and cable delay have not been calibrated out. In addition, to account for the test fixture (by itself) that houses the various walls further testing is required.

Figure 6.11: Target detection. A target was placed behind a laboratory wall at approximately 5 feet.
6.2.1 Ranging Detection

Figure 6.12: Target detection with new helical antennas. A small trihedral target was placed behind a 4-inch thick brick wall.

Figure 6.12 depicts the range profile after correlating the transmit signal with the received signal. The figure above shows two scenes in which there is no target present and when there is target. Moreover, in the “no target” case, we observe the manifestation of what appears to be the existence of unwanted clutter (and/or an imaginary target). Additionally, we remark these range profiles are correlation images that have been averaged for a given number of samples \( N \). From a statistical perspective, obtaining the numerical mean of the correlated noise signals reduces the unwanted noisy fluctuations and improves the signal-to-noise
ratio (SNR) by a factor of $\sqrt{N}$.

As suggested earlier, Figure 6.13 below illustrates one of the signal processing techniques that any through-wall radar system could employ, namely background subtraction. Here, a scene of the background (with no target present) is recorded along with a scene including the target. When the background is subtracted from the target scene, target information is emphasized. This is particularly useful when considering human targets as their correlation peaks can be masked by the "noise floor" (or the spreading) of the wall’s peak and/or other spurious peaks. Moreover, the system is capable of tracking moving targets not only by detecting Doppler shifts, however, it is able to track non-stationary targets by additional signal processing.

Figure 6.13: Target detection continued. After background subtraction between the two scenes in Figure 6.12, the target is “highlighted”.
Figure 6.14: Comparison of different antennas and certain antenna configurations. A small trihedral target was placed about 4 feet behind the 4-inch thick brick wall.

Noting the differences between antenna types and polarization orientation (as briefly discussed in Chapter 4), Figure 6.14 displays a particular scenario in which a target scene was measured with the quad horn antennas in both polarization senses and with the new helical antennas in a poor and good alignment configuration. Evidently, one witnesses that the vertical polarization for the quad horn antennas produce better results than the horizontal orientation.
Figure 6.15: Comparison of range (i.e. effective gain) between the quad horn antennas and the new helical antennas. Both antennas were positioned to aim in an open field with a building approximately 250 feet away. The new helical antennas were able to pick up a return echo.
Figure 6.16: Data collection (outside) with the original helical antennas and the 5-inch thick concrete makeshift wall. (a) scene with no target, (b) scene with a small trihedral target placed about 5 feet behind wall.

Prior to the construction of the wall and in the beginning stages of the radar development, we collected initial data from various places around our off-campus laboratory facility. Figures 6.16 and 6.17 show scenes in which background (or no target) and target were captured. Analysis of these range profiles indicate a peak behind the barrier’s peak where the target was located.

Figure 6.17: Data collection (inside) with the old helical antennas placed about 5 feet in front of a laboratory wall (of storage room). (a) scene of storage room with no target, (b) scene of storage room with a small trihedral target placed about 5 feet behind wall.
Ultimately, once construction of the wall support frame was completed, data were collected almost exclusively with these walls. Bricks and concrete masonry units (i.e. cinder blocks) were purchased by the pallet in order to build a wall that was 8 feet by 8 feet by some specified thickness.

As the radar system entered the final stages of development, testing continued using the wall support frame. The first type of wall explored was 4-inch thick brick and then we moved on to the most challenging structure, 8-inch cinder block.

Figure 6.18 highlights a particular setup in which the wall under test was 4-inch brick and the target (in this case a large trihedral) was placed approximately 4 feet behind that wall. For these subsequent plots, the no target scenes were plotted in dark blue and green, while the target scenes were plotted in light blue and red.

Figure 6.18: Data collection (outside) with the quad horn antennas (vertical polarization) placed about 6 feet from 4-inch thick brick wall and a large trihedral target about 4 feet behind the wall (shows overlay of scenes with no target and target).

As Chapter 4 discusses, a new design for the helical antennas was scrutinized and hence the opportunity to compare the old (original) with the new was seized. Figure 6.19 and 6.20 shows that comparison where scenes of no target and target
were plotted together for both types of antennas. The large trihedral was placed at 4 feet and 6 feet.

Figure 6.19: Data collection (outside) with the old helical and new helical antennas placed about 6 feet from 4-inch thick brick wall and a large trihedral target placed about 4 feet behind wall. (a) old helical (scene of no target and target), (b) new helical (scene of no target and target).

Finally, Figures 6.21 and 6.22 present data collected for the 8-inch thick cinder block wall using the quad horn antennas and the new helical antennas. During this testing phase, signal strength was a concern, and thus, modifications were made to the radar system to boost up the noise power. And though the target was usually
placed at the same distance behind the wall as in the case of the other setups, we noticed a slight shift in the target’s position behind the wall. Furthermore, given the increase in power, we observed more “clutter” peaks and in order to distinguish the target we needed to zoom in on the range profile. For these subsequent plots, the no target scenes were plotted in dark blue, while the target scenes were plotted in green.

Figure 6.21: Data collection (inside) with the quad horn antennas placed about 6 feet from 8-inch thick cinder block wall and a large trihedral target placed about 4 feet behind the wall. (a) quad horn with vertical polarization (scene of no target and target), (b) zoomed in - quad horn with vertical polarization (scene of no target and target).

Figure 6.22: Data collection (inside) with the new helical antennas placed about 6 feet from 8-inch thick cinder block wall and a large trihedral target placed about 4 feet behind the wall. (a) new helical (scene of no target and target), (b) zoomed in - new helical (scene of no target and target).
The subsequent plots present data collected on human targets for the two wall configurations. Again, test subjects were placed at 4 feet and 6 feet, respectively, behind the wall. For these results, unlike with the trihedral targets, the system processed the raw cross correlation data rather than averaged data. This methodology for acquisition proved to be more useful in capturing human data. Additionally, to illuminate human targets a real-time, successive scene difference scheme was implemented into the algorithm. This allowed for the tracking of human or non-stationary targets. To accomplish this, the $N$ previous correlation scenes which were aggregated for averaging were also, consequently, used to perform frame by frame subtraction.

Figure 6.23 shows the typical output for the human detection. One plot contains the background (no target), the scene with the target and a simple background subtraction while the other plot depicts the previous correlation (range) profiles and the outcome of successive scene subtraction (indicating the presence of the target during the tracking mode). In this particular case, the antenna choice was the modified helical, the wall type was 4-inch brick, and the human target was placed approximately 4 feet behind the wall.
Figure 6.23: Data collection (inside) with the new helical antennas placed about 6 feet from 4-inch thick brick wall and a human target placed about 4 feet behind the wall. (a) (1) background scene; (2) target scene; (3) background subtraction, (b) (1) $N$ previous range profiles; (2) tracking mode showing target at 4 feet.
Figure 6.24: Data collection (inside) with the quad horn antennas placed about 6 feet from 4-inch thick brick wall and a human target placed about 4 feet behind the wall. (a) (1) background scene; (2) target scene; (3) background subtraction, (b) (1) $N$ previous range profiles; (2) tracking mode showing target at 4 feet.

Figure 6.24 above illustrates the output for the human detection and tracking using the quad horn antennas. The ensuing figures continue the plots for the quad horn antennas in various scenarios.
Figure 6.25: Data collection (inside) with the quad horn antennas placed about 6 feet from 4-inch thick brick wall and a human target placed about 6 feet behind the wall.  

(a) (1) background scene; (2) target scene; (3) background subtraction,  

(b) (1) $N$ previous range profiles; (2) tracking mode showing target at 6 feet.
Figure 6.26: Data collection (inside) with the quad horn antennas placed about 6 feet from 8-inch thick cinder block wall and a human target placed about 4 feet behind the wall. (a) (1) background scene; (2) target scene; (3) background subtraction, (b) (1) \( N \) previous range profiles; (2) tracking mode showing target at 4 feet.
Figure 6.27: Data collection (inside) with the quad horn antennas placed about 6 feet from 8-inch thick cinder block wall and a human target placed about 6 feet behind the wall. (a) (1) background scene; (2) target scene; (3) background subtraction, (b) (1) \( N \) previous range profiles; (2) tracking mode showing target at 6 feet.

Again, as was seen in the case of the large trihedral target, though the 8 inch cinder block attenuated the signal greatly, the radar could still detect targets.
6.2.2 Doppler Detection

Again, apart from the ranging of targets, the S-band noise radar is capable of human activity characterization as elaborated in Chapter 5. To highlight this ability, several human movements were investigated. The following data acquired were for a human target standing a few feet behind one of the walls in the laboratory with the radar system positioned approximately 5 to 6 feet away from the other side of the wall. The person was instructed to perform the following motions: (1) swing arms; (2) pick up an object; and lastly, stand from a crouching position. As is the case with through-wall scenarios, signal degradation is a chief concern and needs to be scrutinized. Though there has been much literature investigating the propagation impairment of many a building material, the loss through the laboratory wall was analyzed with the log periodic antennas and a vector network analyzer. From this data, the two-way propagation loss was estimated to be 24 dB. Thus, the continuous tone signal would certainly be influenced by the lossy media and tend to be noisy upon its return to the radar. Also, given the frequency of operation, Doppler induced signals are no more than a 100 Hz or so.

Figure 6.28 below shows the real-time Doppler signal as well its corresponding Short-time Fourier transform (STFT) for the case where no human target was present and information about the background was captured. This information (i.e. just background noise) serves as a reference point for other data to be compared against.

![Figure 6.28: Data collection (inside) with original helical antennas and laboratory wall. (a) Doppler signal of background (empty room), and (b) STFT of the respective Doppler signal.](image)
When the human target swings their arms, this motion is periodic and can be seen in both the time domain signal as well as the frequency domain (see Figure 6.29). The periodicity in the waveform shows repeating features and characteristics. Such features are truly distinct when analyzed with other types of movements (or even the background).

Figure 6.29: Data collection (inside) with original helical antennas and laboratory wall. (a) Doppler signal of a person swinging arms behind laboratory wall (standing about 4 feet behind wall), and (a) STFT of the respective Doppler signal.

Figure 6.30: Data collection (inside) with original helical antennas and laboratory wall. (a) Doppler signal of a person picking up an object behind laboratory wall (standing about 4 feet behind wall), and (a) STFT of the respective Doppler signal.

Figure 6.30 above illustrates the motion of picking up an object. The real-time Doppler signal shows two “blips” that correspond to the human target bending
down and up (with a slight pause between the full range of motion). Not surprising, the STFT also indicates two pulses for the movement. As the target executes picking up an object, different portions of the body (e.g. head, arms, torso, etc) will experience a different aspect of the incident wave at different speeds and hence produce varied frequency responses (allowing for discrimination of body parts).

Finally, Figure 6.31 below depicts the last motion of the human target standing from a crouching position. This motion is similar to picking up an object, however, it generates just one “blip” rather than two (since the movement occurs in one cycle).

Figure 6.31: Data collection (inside) with original helical antennas and laboratory wall. (a) Doppler signal of a person standing from a crouching position behind laboratory wall (standing about 4 feet behind wall), and (b) STFT of the respective Doppler signal.

At last, these preliminary field results show the promise of the S-band noise radar system to detect targets behind obscurations. And though not the focus of this thesis, the radar system is also able to perform human activity classification via analyzing the features produced by the micro-Doppler signals from human movement.
Conclusion and Future Work

7.1 Conclusion

An S-band through-wall noise radar system was designed and developed at the Pennsylvania State University by our Radar and Communications lab. Its architecture combines a noise signal and a continuous wave tone to enable target ranging and detection. Target ranging and tracking were accomplished via a cross correlation technique while human activity (for possible human classification) was detected from Doppler induced signals.

Moreover, two types of helical antennas were fabricated with the assistance of the ARL group at Penn State. These antennas were a great antenna engineering achievement and proved to be very valuable to the successful operation of the noise radar. Finally, for an adequate testing environment, a mobile wall support structure was built to house various building materials. This frame unit allowed the radar to field test different walls in an open setting.

7.2 Future Work

The system was demonstrated as a proof of concept. Continued data collection would benefit any improvements to the design. Moreover, to get the noise radar to an operational readiness level would require further investment in the miniaturizing and integration of the architecture. Nevertheless, the research experience garnered during this project has opened new avenues of study.
7.2.1 Impulse Response via Cross-correlation

The effects of dispersive media on the propagation of electromagnetic waves are of great importance and concern for studies of through-wall radar applications. Based on statistical and mathematical notions developed and described by Yuk Wing Lee [28] and explored by [29], we know that it is feasible to obtain the impulse response of a linear system with input and output signals that are white noise or noise-like by cross correlating the two waveforms. Similarly, authors in [30] investigated the unique property of cross correlation between two random processes that suggests one random process is related to the second distorted random process via a proportionality constant between the two cross correlation functions (for the random processes) before and after the adulteration. On these premises, we envisioned and began the preliminary analysis of using the S-band noise radar to characterize the propagation and scattering environment in through-wall scenarios.

7.2.2 Medical Radar

Ultimately, another goal and potential research area is to bring the concept of noise radars to the medical field. Expanding on our impulse response work and through-wall technology, we wish to image and characterize different organs of the body with a low-power, non-invasive radar. The hope is to distinguish between a healthy or unhealthy organ or even detect hidden explosives in the human body.
Appendix A

Appendix

LABVIEW CODE

Contents

• LabVIEW Graphical User Interface segments

• Ranging Algorithm
Figure A.1: Front panel to the LabVIEW GUI.
Figure A.2: Front panel to the LabVIEW GUI continued.
Figure A.3: Front panel to the LabVIEW GUI continued.
Figure A.4: A portion of the back panel to the LabVIEW code which performs the cross correlation of the two input signals.
Bibliography


