Illumination Strategies to Reduce Target Orientation Requirements and Speckle in
Millimeter Wave Imaging

DISSERTATION

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Abstract

Millimeter wave imagers provide a unique way to see through obscurations with enough angular resolution to identify hidden objects. However, current millimeter wave imaging applications require a cooperative subject at close proximity to provide accurate target identification. In this dissertation, I develop a multi-angle illumination method that overcomes these limitations and demonstrate its target identification accuracy at a range of 50 meters.

Specular, or mirror-like, surfaces that are not in optimal alignment reflect power away from the receiver. Optimal alignment of specular targets becomes more difficult as the distance from the receiver increases. Consequently, direct illumination millimeter wave imaging applications that rely on optimal alignment of specular targets become increasingly less accurate with distance.

For randomly rough surfaces, coherent illumination causes speckle. Speckle is a granularity in an image that is caused by coherent interference from scattering elements within a pixel. The speckle granularity severely decreases target recognition of randomly rough objects.

To address these limitations, I develop a method that illuminates the target from many modes using an indirect illumination technique that increases target detection probability regardless of orientation. Additionally, illumination of the target from many
angles results in many independent speckle patterns. Averaging the independent speckle patterns decreases speckle effects and results in a significant increase in accurate target detection.

This research shows that indirect illumination techniques, combined with range resolved radar cross section (RCS) techniques, produce millimeter wave images with range information that significantly reduces speckle. The elimination of the requirement for special target orientation and the ability to produce an image with depth information at long range with minimized speckle represents a significant advance in the field of millimeter wave imaging.
Dedication

To my family
Acknowledgments

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Chapter 1: Introduction

The millimeter wave region lies between the microwave and the infrared spectral regions. In an imaging context, the millimeter wave region represents a useful compromise between the two bordering regions. It combines the higher resolution of the infrared region and the ability to penetrate dust, fog, and common packing materials of the microwave region [1]. For example, airports use millimeter wave imagers on travelers because millimeter waves penetrate all common clothing materials [2]. Additionally, many military helicopter crashes occur in dust storm conditions where visibility is nearly zero. Dust storms occur in desert climates and dust clouds can be created during the landing process [3]. Seeing through dust clouds with a millimeter wave imager can compensate for lost visibility and help prevent fatalities.

Many current applications, typically at close ranges, take advantage of the penetration capabilities of millimeter wave radiation. For example, millimeter wave imaging can detect bugs hidden inside of nut shells before processing [4]. It can be used in process control to check plastic welds for imperfections [5] or materials for correct thickness [6]. It can measure hydration levels in objects ranging from plant leaves [7] to paper products [8]. It can measure in vivo hydration return to a burn site to determine the
severity of the injury [9], [10]. Each application listed above uses direct illumination at close range and relies on a cooperative subject.

The lack of available high power sources in the millimeter wave region restricts current applications to close ranges. A direct illumination method returns the maximum possible signal to the receiver. However, direct illumination has two disadvantages. First, if a specular, or mirror-like, target is not optimally aligned with the imaging system then no power is returned to the receiver. Illumination of a specular target from many angles would increase the probability of detection. Second, illumination of diffuse targets with a coherent source causes speckle. Speckle is interference from scattering elements within a pixel that degrades image quality and impairs target recognition. Illumination of a diffuse target from many independent angles reduces speckle only if the illumination paths are incoherent.

New, high power millimeter wave sources are now available. In this thesis, I present research that extend the range of imaging applications, reduce the orientation requirements of specular targets, and reduce speckle effects through use of new illumination strategies. Multi-angle illumination reduces orientation requirements of specular targets. I analyze direct, multi-angle illumination for speckle reduction. I also investigate indirect, multi-angle illumination in two configurations, light bulb and grassy field configurations. I provide results from my investigation of two methods, beam steering and frequency modulation that make the illumination paths independent.

In the light bulb configuration, the transmit beam is aimed at the enclosing walls of a room. The reflections off of the wall illuminate the target. Illumination of the target
from many angles increases the detection probability of a specular target. Speckle would not be reduced for a diffuse target because these illumination paths are driven by the same coherent source. A rotating mirror, called a mode mixer, steers the transmit beam around the walls of the enclosure to modulate the power in each illumination angle. The power modulation of each illumination angle modulates the received speckle pattern. Averaging the modulated speckle pattern reduces the speckle contrast. I document reductions in the speckle contrast by a factor of 6.5 to 12.5 over a purely diffuse surface.

The grassy field illumination method is an indirect, multi-angle illumination method in which the transmit beam is aimed at a diffuse surface nearby the target. This illumination method can be used where the light bulb illumination method is unavailable, such as in an outdoor environment. Common outdoor surfaces, such as gravel, soil, and sand have significant diffuse reflections [11]. The transmit beam is steered over the diffuse surface to illuminate the target indirectly. The beam steering modulates the received speckle pattern. Averaging the modulated speckle pattern reduces the speckle contrast. The target is illuminated from a smaller angular extent than the light bulb illumination method. The detection probability of specular targets for the grassy field method is higher than direct illumination but lower than the light bulb illumination method. I show that the speckle contrast of a diffuse target can be reduced by at least a factor of 4.1 using a small area on the nearby surface.

Frequency modulation can be added to any illumination strategy to record the power return as a function of range. Higher range resolution requires larger transmitter bandwidths. A direct illumination method with frequency modulation can be used to
measure the intensity probability distribution of the reflection from the target. A range filter excludes any signal that is not from the target. Relative surface roughness information can be extracted from the intensity probability distributions measured with direct illumination.

To reduce speckle contrast, the range resolution must be finer than the path length difference. With direct illumination, the path length difference is on the scale of the target surface roughness. The range resolution needed for speckle contrast reduction with direct illumination often requires a fractional bandwidth over 100%. With indirect illumination, the path length difference is on the scale of the enclosure. I show that a fractional bandwidth, as small at 1%, reduces the speckle contrast by a factor of 8 in a simple case. High power sources with fractional bandwidths of 7% are in development [12].

The reduction of coherent effects, the elimination of the need for a compliant subject, and the extension to longer ranges represent significant advancements in the field of millimeter wave imaging.
Chapter 2: Millimeter Wave Imaging Background

The choice of imaging frequency affects the properties of the image and is tailored to the desired application. Image resolution, atmospheric effects, material penetration, and available source power depend on the imaging frequency.

Angular Resolution and Obscurant Penetration

The resolution of an image is determined by the radiation wavelength, \( \lambda \), and the size of the imaging optics. The diffraction angle, \( \theta_D \), for an imaging optic with a diameter of \( D_o \) is

\[
\theta_D \approx \frac{\lambda}{D_o}
\]  

(1)

The area of the diffraction limited spot size is

\[
A_{ss} = \frac{\pi}{4} \left( \frac{\lambda}{D_o r_{to}} \right)^2
\]  

(2)

where \( r_{to} \) is the distance from the target to the receiver optics. As the imaging wavelength decreases, smaller imaging optics result in the same resolution. Typical passive infrared imaging systems use imaging wavelengths between 8 \( \mu \)m and 12 \( \mu \)m [13]. Infrared imaging systems have higher resolutions and more compact imaging optics because of the 100 times smaller wavelength than the millimeter wave region. Figure 1
shows an example of an infrared passive image taken with a 324 pixel by 240 pixel room temperature microbolometer array. The image illustrates the resolution of commercially available infrared imaging technology.

Figure 1: A passive infrared image taken with a room temperature microbolometer array.

The desire to penetrate through certain packing materials to non-invasively discover potentially hazardous materials drives interest in millimeter wave imaging [14], [15]. Longer wavelengths have lower resolutions but have higher penetration capabilities. Hartwick discusses using millimeter wave imaging to see through materials such as wool, cardboard, and leather [16]. Penetration through materials is a strong function of frequency and changes drastically between the microwave and the infrared regions.

Figure 2 shows a downrange versus cross range image of a person standing behind a cinderblock wall made with a 2 to 4 GHz stepped frequency radar imaging
system from MIT Lincoln Labs [17]. The stepped frequency from 2 to 4 GHz gives the range information. The long, bright horizontal line is the cinderblock wall. The circular red region above the wall is a person standing behind the wall. Low resolution directly prevents the differentiation between a person and similarly sized objects. However, relative motion of objects can help differentiate people from stationary objects. This image demonstrates the ability of the microwave region to penetrate heavy building materials. The millimeter wave region is a useful compromise between the penetration capabilities of the microwave region and the resolution of the infrared region. The millimeter wave region is the ideal region for security screening applications.

Figure 2: A down range versus cross range image of a human standing behind a wall [17].
Penetration of certain materials is a strong function of frequency. Figure 3 shows the one way transmittance, on a linear scale, through various clothing materials as a function of frequency [18]. Alexander et al. report a more extensive list of materials [19]. Transmission through clothing materials varies up to 25% over the observed range. Transmission through building materials varies rapidly with frequency. Figure 4 shows the one way path loss, on a logarithmic scale, through common building materials that are roughly 0.5 inches thick [20]. Each material has at least 30 dB of one way attenuation at 326 GHz except drywall. At 1 THz, the signal passing through each material was below the noise floor of the measurement system. The lower penetration ability of the millimeter wave region disallows detection of objects behind all common building materials but allows detection of objects behind all common clothing materials.

![Clothing transmittance](image)

Figure 3: Clothing transmittance, on a linear scale, as a function of frequency [18].
Atmospheric Attenuation

An imaging frequency that minimized path loss from atmospheric attenuation is important for long range imaging. Figure 5 shows the atmospheric attenuation as a function of frequency from 10 GHz to 1 THz. There are frequency bands, referred to as atmospheric windows, where the attenuation is a local minimum. The atmospheric windows are the frequency regions between absorption lines of atmospheric molecules such as O₂ and H₂O. Differing rain, fog, and humidity levels affect the atmospheric attenuation levels [21].
Passive Imaging

There are two types of imaging, passive and active. In passive imaging, the thermal radiation from all of the objects in the scene provides the signal. In active imaging, a transmitter provides the signal. Figure 6 shows a passive image taken with a 300 mK $^3$He cooled bolometer with a center frequency around 650 GHz at a distance of 2 m [22]. The image looks like an infrared passive image. The face is brightest area of the body and areas covered by cloth are the least bright areas of the body. The resolution of the face is lower than an infrared image due to the longer imaging wavelength.
Objects emit thermal radiation in all directions. The total radiated power is proportional to the emissivity of the object. There are no special observing angles for high emissivity objects in passive imaging. All high emissivity surfaces with a line of sight to the receiver are visible regardless of the relative angle between the two. The uniformity of curved surfaces on the image, such as the shoulders, cheeks, and forehead demonstrate this effect. Low emissivity objects emit less power and reflect more than high emissivity objects. Metallic objects have low emissivity, appear mirror-like, and have orientation requirements in passive images.

Often there are low signal margins available in passive imaging, especially with room temperature detectors. Schuetz et al. demonstrate a room temperature passive imager with a noise equivalent temperature difference (NETD) of 2 K when operating at a frame rate of 10 Hz [23]. The NETD is the change in temperature that changes the
received power by the internal noise of the receiver. NETDs as low as 125 mK have been reported for cryogenic detectors at video frame rates [24]–[26]. In indoor applications, the typical temperature ranges from 20°C, room temperature, to 35°C, body temperature. Images of scenes where the NETD is a significant fraction of the total temperature difference have low contrast. However, there is a wider range of temperatures in outdoor environments. The cold sky, as low as -230°C at zenith in W-band, provides contrast in outdoor scenes [23].

Active Imaging

Active images can have much larger signal margins than passive images. The power radiated in active imaging is converted to a blackbody mode temperature for direct comparison. The temperature, $T$, of a single mode is

$$T = \frac{P}{kb}$$

(3)

where $P$ is the transmitter power, $b$ is the bandwidth of the transmitter, and $k$ is the Boltzmann constant. If 1 mW of power is in a bandwidth of 1 MHz, the temperature of the mode is $10^{14}$ K. The temperatures of active sources are many orders of magnitude greater than passive sources. However, temperatures of active sources can vary greatly. For example, a 10 W source in 100 Hz of bandwidth has a brightness temperature of $10^{22}$ K. These large temperatures are the single mode source temperatures. The effective temperature of the received signal depends on the scene geometry.

Active imaging signal margin is often superior to passive imaging. However, active imaging has its own set of challenges to overcome. These challenges include
special orientation requirements for specular targets and speckle for diffuse targets. Reducing these effects creates an image that looks like a passive image with the high signal margins of an active image.

Special orientation requirements result from specular, or mirror like, reflections in the scene. If a specular target is optimally aligned with the transmitter and receiver then there is a large received signal. Conversely, if the specular target is misaligned with the transmitter and receiver then there is no received signal. Figure 7 demonstrates the alignment sensitivity for specular targets [27]. The skin, a specular surface at 632 GHz, appears bright when aligned with the imaging optics as seen on the center of the forehead. The skin appears dark when not aligned with the imaging optics as seen on the cheeks, sides of the forehead, and nose. Most previous demonstrations of millimeter wave imaging show specular targets that have been optimally aligned for maximum contrast. These demonstrations would not be possible without a compliant target.
Figure 7: An active image of a balding, bearded man taken at a center frequency of 632 GHz [27].

The alignment of specular targets determines the received power. For example, consider a specular reflector much larger than the receiver imaging spot size. For a $\theta$ rotation of the object there is a $2\theta$ rotation of the reflected beam. Return signal from the object is only detected when the specular reflection and the collecting optics overlap. The angular tolerance for a flat plate is

$$\theta_{sp} \sim \frac{D_o}{2r}$$

(4)
where $\theta_{sp}$ is the specular reflection angular tolerance, $D_o$ is the collecting optic diameter, and $r$ is the distance to the target. The number of different possible alignments for specular reflection, $N_{sp}$ is

$$N_{sp} = \frac{2\pi}{\theta_{sp}^2} = 8\pi \left( \frac{r}{D_o} \right)^2$$

(5)

where the receiver is fixed at a constant distance from the target. There are 2500 different specular alignments for a 1 m collecting dish at a range of 10 m. If the target is moved to 100 m then there are 250,000 different specular alignments. As range increases, optimal alignment becomes more difficult with a direct illumination method. Indirect illumination methods can illuminate the target from many angles to increase the chance of detection, especially at long ranges.

Figure 7 also demonstrates speckle effects that degrade image quality. The image shows that beard hair is a diffuse reflector at 632 GHz. Reflections from the rough surface features create an interference pattern that makes a coherently illuminated image look speckled. Speckle degrades image quality and impairs target recognition. The hair in the passive image, shown in Figure 6, does not have any speckle because it was not illuminated with coherent light. It takes both a diffuse reflector and coherent illumination to produce a speckle pattern.

There are two methods of active imaging. The first method uses principles from the Terahertz Time Domain Spectroscopy (THz-TDS) field where femtosecond laser pulses create wideband millimeter wave and terahertz signals. The second method uses solid state sources to generate narrowband millimeter wave or terahertz signals [28].
THz-TDS Active Imaging

A THz-TDS imaging system is nearly identical to a THz-TDS system aside from additional focusing optics. Initially, a laser creates a femtosecond pulse, split by a beam splitter, and interacts with a photoconductive antenna to create a wideband THz pulse [29]. Focusing optics make a focal plane at the target in either a transmission or reflection configuration. An identical set of focusing optics focuses the beam onto the photoconductive receiver. Meanwhile, the other laser beam path interacts with the same photoconductive antenna. The received power is the terahertz power at the receiver when the laser pulse arrives. Measurement of the received power as a function of time requires variation of the delay stage on the transmit laser beam path. The Fourier transform of the received signal gives the frequency response of the target. A raster scan of the target on a mechanical stage, placed in the THz focal plane, allows measurement as a function of position. The result is a 2-D image of the reflection or transmission coefficient as a function of frequency. Additionally, the difference in the first arrival time of the THz pulse with and without the target in the transmission setup and the material index of refraction result in depth information. Depth information is useful for determining the target thickness and finding intermediate interfaces [5]. Figure 8 shows a block diagram of the experimental setup for THz-TDS imaging [30].
Figure 8: Example block diagram of a THz-TDS system. The red beam is the femtosecond laser beam and the green beam is the THz beam. The sample is placed on a 2-D movement stage at the focus in the THz beam path [30].

Figure 9 shows a wideband and a narrowband image taken with a THz-TDS imager of various objects hidden under a layer of clothing [31]. The large bandwidth of the source is useful for averaging effects of speckle. However, there are a few drawbacks to the THz-TDS approach. First, using a femtosecond laser increases the complexity and the cost of this system [28]. Second, mechanically scanning the delay stage for each pixel increases the time needed to construct an image. Third, THz-TDS must be done at close range or under a nitrogen atmosphere because the wideband source has significant power outside atmospheric windows. Finally, wideband, pulsed sources have much lower total power than solid state sources.
Continuous Wave Active Imaging

A typical continuous wave imaging system that maximizes signal to noise will use a co-propagating transmitter and receiver pair aimed at a large focusing optic. However, the transmitter and receiver are independent and can be configured differently. Motors raster scan the large focusing optic over the scene to form the image. Either the mixing product from two lasers or a solid state multiplier source produces the transmit signal. The two laser mixing source produces less power than a typical solid state multiplier source [32].

A single frequency continuous wave system measures intensity data as a function of position. Phase information and a stepped frequency transmitter gives range information. Range filters can remove signal from obscurants that differ in range from the target. Figure 10 shows an example of a fake PVC bomb under a shirt with the initial surface reflection of the shirt removed [33]. The covered object becomes easily visible.
The characteristics of the solid state, continuous wave approach are ideal for investigating illumination strategies. First, the transmitter and receiver are spatially independent. Illumination strategies may require the transmitter and receiver to be placed in different physical locations in order to optimize signal or speckle reduction. Second, solid state sources have the highest available source powers. Third, the narrow banded source can completely reside within an atmospheric window. Lower atmospheric loss allows imaging at longer ranges. Finally, this imaging configuration has a path forward.
to video rate imaging. Replacing the single pixel receiver with an array of receivers eliminates the need to raster scan the imaging optic and reduces collecting time by the number of elements in the array.

The Terahertz Gap

Historically, sources in the submillimeter wave region had low power outputs. The submillimeter wave region is also known as the terahertz gap because only small amounts of power are available [34]. Figure 11 shows a plot of solid state source power as a function of frequency for many sources between 10 GHz and 100 THz [35]. Typical sources at 220 GHz have 10 to 30 mW of output power and typical sources at 640 GHz have 1 mW of output power.
Figure 11: Power generated as a function of frequency for solid state sources between 10 GHz and 100 THz [35]. The squares are quantum cascade lasers, the circles are frequency multipliers, and the dashes are other electronic devices. Room temperature devices have solid symbols and devices that require cryogenics have hollow symbols.

New vacuum electronic amplifiers provide much greater power in this gap region. The final amplifier used in this work is an Extended Interaction Klystron (EIK) with an output power of 5 W, nearly 200 times more power than the typical 30 mW available from solid state sources near 220 GHz [36]. It has an available bandwidth of 500 MHz. Current projects are developing a 50 W wideband serpentine waveguide (SWG) amplifier with 15 GHz of bandwidth [37].
Conclusions

Previously, low power in the terahertz gap region restricted imaging applications to direct illumination at a range of a few meters [38], [39]. Demonstrations at longer range have been restricted to small imaging areas. For example, Cooper demonstrates a 1 ft² area imaged at a range of 25 m [33]. The increase in transmitter power allows investigation of current applications at longer ranges. Additionally, more power allows illumination strategies that are less power efficient but more efficient for speckle reduction to be investigated.
Chapter 3: Speckle

The discovery of speckle followed shortly after the invention the laser. Images of the laser interacting with any surface that did not have a mirror finish looked ‘speckled’ [40], [41]. An interference pattern formed by the reflection from the non-uniform features within a pixel causes the image to look speckled. Without coherent illumination, these interference patterns time-average, and consequently no speckle pattern is produced. Coherent illumination produces speckle that causes images to appear grainy and thus destroys target recognition.

Speckle creates problems in many applications because coherent illumination and a rough scattering surface are the only two requirements. Laser projection devices use many speckle reduction techniques to increase image clarity [42]. Speckle is the main obscurant of image clarity in ultrasound images, even though ultrasound uses coherent sound waves instead of coherent light [43]. Figure 12 shows an image of a laser reflecting off of a wall [44] and an ultrasound image of a kidney [45]. Both images are rich with speckle. Speckle effects can also be seen in fiber optic transmission [46] and synthetic aperture radar (SAR) [47].
The speckle pattern in the image is not random, it is deterministic. The incident wave, the orientation of the object, and surface profile of the object determine the speckle pattern. Two images with the same imaging parameters are identical except for system noise. However, statistically analyzing speckle patterns gives insight into the scattering object and the effectiveness of speckle reduction techniques. In this chapter, I analyze three techniques that can significantly reduce speckle, thus laying the groundwork for an approach that can increase object identification and image clarity at longer distances.

Speckle Intensity Probability Distributions

Different physical effects cause different types of speckle distributions. A speckle pattern from a purely diffuse surface follows a negative exponential intensity distribution. Averaging independent speckle patterns from a purely diffuse surface follows a modified
Gamma distribution. A speckle pattern from a partially diffuse and partially specular surface follows a Rician distribution.

The field amplitude sum of the scattering from each element of the randomly, rough surface is equivalent to a random walk [44]. Following the central limit theorem, a large number of steps, or scattering elements, results in a Gaussian probability distribution of the field amplitude. The distribution, as a function of intensity, is a negative exponential distribution [44], [48]. The intensity probability distribution, \( p(I) \), is

\[
p(I) = \left( \frac{1}{<I>} \right) \exp \left( -\frac{I}{<I>} \right)
\]

where \( I \) is the intensity and \( <I> \) is the average intensity.

Speckle contrast is defined as

\[
C = \frac{\sigma_I}{<I>}
\]

where \( \sigma_I \) is the standard deviation of intensity. Speckle contrast is the inverse of the signal to speckle noise ratio for the image. Speckle contrast is defined between 0 and 1 inclusive. The probability distribution for a contrast of 0 is a delta function at non-zero intensity. The probability distribution for a contrast of 1 is a negative exponential distribution.

Averaging independent speckle patterns together reduces the speckle contrast. The probability distribution of the averaged result is the convolution of the probability distributions from each independent speckle pattern. For computation simplicity, the convolution is performed in the Fourier domain. The characteristic function of the negative exponential distribution, \( M(\omega) \), is
\[ M(\omega) = \frac{1}{1 - i\omega <I>} \]  

where \( \omega \) is the Fourier domain variable [49]. The inverse Fourier Transform of the characteristic function product gives the probability distribution for the average of the individual speckle patterns.

If all of the independent speckle patterns have the same average intensity, the probability distribution of the averaged speckle pattern is

\[ p(I) = \frac{N^N I^{N-1}}{\Gamma(N) <I>} \exp\left(-N * \frac{I}{<I>}\right) \]

where \( N \) is the number of independent speckle patterns averaged. This distribution is the modified Gamma density function of order \( N \) [49], [50]. The speckle contrast of this intensity distribution is

\[ C = \frac{1}{\sqrt{N}} \]

Consequently, averaging a large number of independent speckle patterns leads to a large reduction in speckle.

A partially diffuse surface has a constant field from the specular part of the reflection and a random walk from the purely diffuse part of the reflection [50]. The probability distribution of the combined intensities is

\[ p(I) = \frac{1}{I_n} \exp\left(-r - \frac{I}{I_n}\right) I_0 \left(2 \frac{I}{\sqrt{I_n} r}\right) \]

where \( I_n \) is the average speckle intensity, \( I_0 \) is the modified Bessel function of order zero, and \( r \) is the ratio of the specular portion of the reflection to the average speckle intensity [49]. For this intensity distribution, the average value of intensity is
\[ < I > = (1 + r)I_n. \]  

The speckle contrast is

\[ C = \frac{\sqrt{1 + 2r}}{1 + r}. \]

As \( r \) approaches 0 the intensity distribution becomes the negative exponential distribution as expected for a purely diffuse surface. As \( r \) approaches infinity, the contrast approaches 0 as expected in a purely specular reflection.

**Speckle Reduction Methods**

There are a few different methods that create independent speckle patterns to reduce the speckle contrast. Diversity in illumination of polarizations, angles, and wavelengths can be used to create independent speckle patterns [51]. Each of these methods is independent and can be used in combination with the other methods [42].

**Polarization Diversity**

Coherent illumination of a purely diffuse surface will produce a speckle pattern in each polarization. Averaging both polarizations together decreases the speckle contrast by \( \frac{1}{\sqrt{2}} \) [42], [49]. Two independent sources with independent polarizations illuminating the purely diffuse surface reduces the speckle contrast by an additional \( \frac{1}{\sqrt{2}} \). A combined speckle reduction of \( \frac{1}{2} \) is possible using two independent illuminators with independent polarizations and two receivers with different polarizations [42]. Although polarization
diversity was not the focus of this investigation, an additional speckle reduction by a factor of 2 can be gained by using it in conjunction with the other methods.

Angular Diversity

Speckle reduction using angular diversity is limited by the number of independent angles available. Consider a flat, diffuse object that is aligned perpendicularly to a collecting optic of size $D$ illuminated with a plane wave. An object rotation creating a $2\pi$ phase difference across the surface produces an independent angle. Figure 13 shows the minimum rotation of the object that produces an independent angle. Equivalently, if the object is stationary, then the imaging optics must move the same angle to produce an independent speckle pattern. This angle corresponds to a shift of the collecting optic by its diameter at constant range.

![Diagram](image.png)

Figure 13: Geometry of the object rotation creating a $\lambda$ path length difference across the diffraction limited spot size, $ss$. Moving the collecting optic by $D$ corresponds to the minimum rotation to create an independent angle [52].
In direct, multi-angle illumination the transmitter illuminates the target directly with a variable angle of incidence. The transmitter and the receiver are assumed to be at the same distance from the target, $r$. The independent angle must introduce a $2\pi$ phase variation across the resolution element. Thus, the resolution element size determines the angle to produce an independent speckle pattern. This angle occurs when the either the transmitter or receiver is moved by the width of the larger focusing optic. Thus, the independent angle requirement is

$$\theta_{\text{ind}} = \frac{\text{Max}(D_{\text{Tx}}, D_{\text{Rx}})}{r}$$

where $D_{\text{Tx}}$ is the size of the transmitter focusing optic and $D_{\text{Rx}}$ is the size of the receiver focusing optic.

In the indirect, multi-angle case, the transmitter aims at a diffuse surface nearby the target. Figure 14 shows an example diagram of the transmit beam reflecting off of the floor nearby the target. The floor and the target are assumed to have a diffuse, hemisphere shaped reflections. However, only the beam path from reflection off of the floor and then the target that intercepts the collecting optic is shown. The reflection off of the nearby surface produces a speckle pattern. Moving the transmitter beam by one beamwidth on the nearby surface causes an independent speckle pattern to be radiated.
Figure 14: Example geometry of the transmit beam reflecting off of the floor nearby a target. Only power that intercepts the collecting optic after reflecting off of the floor and then the target is shown.

If the grain size of the radiated speckle is much larger than the receiver resolution element, then the entire target, consisting of many resolution elements, is illuminated by one speckle grain. If the transmitter moves causing an independent speckle pattern from the nearby surface, the received signal from the entire target is modified by an amplitude and phase factor. The new received speckle pattern is not statistically independent from the original speckle pattern. As in the direct illumination scheme, an independent speckle pattern occurs when there is a $2\pi$ phase variation across the surface of the target. This variation corresponds to the illuminated spot on the nearby surface moving by the size of the receiver collecting optic. In the limit, where the speckle grain size is larger than the receiver resolution element, the independent angle requirement is

$$\theta_{\text{in.d}} = \frac{D_{\text{RX}}}{r_{\text{TX}}}$$  \hspace{1cm} (15)
where $r_{Tx}$ is the distance from the target to the nearby surface.

If the transmitted speckle grain is smaller than the receiver resolution element, then an independent angle can be produced by one of two methods. If the transmitter spot on the nearby wall moves by one transmitter spot size, a new speckle pattern will be projected on the target. If there are many speckles within the receiver resolution element, the transmitted speckle pattern causes the target to produce an independent speckle pattern. Additionally, moving the transmitter beam on the nearby surface by the size of the receiver collecting optic creates an independent speckle pattern. The requirement for an independent angle is

$$\theta_{\text{ind}} = \frac{\text{Min}(D_{Tx}, D_{Rx})}{r_{Tx}} \quad (16)$$

when the speckle grain size is smaller than the receiver resolution element.

In an indirect multi-angle illumination scheme where the transmitter spot size on the nearby surface is much larger than the receiver resolution element, the number of independent angles, $N$, available is:

$$N = \frac{2\pi r^2}{D_{Rx}^2} \quad (17)$$

for a collecting object with an area, $D_{Rx}^2$, at a distance, $r$, from the target. The number of independent angles increases with range. Large speckle reduction is available at longer ranges. At a range of 100 m with a 1 m$^2$ collecting optic, the number of independent angles is over 60,000 leading to a speckle contrast reduction by a factor of 250.

A single source that illuminates all the independent angles at the same time produces no speckle reduction. The independent paths are coherent because they are
driven by a single source. Figure 15 shows two independent illumination angles from a single source. Each illumination path requires an independent source or the power in each illumination path must be modulated. Modulating the power in each path modulates the speckle pattern received. Averaging the modulated speckle pattern reduces the speckle contrast.

Figure 15: Example diagram of two independent illumination angles of a target by the same source.

*Wavelength Diversity*

Wavelength diversity requires path length differences for speckle reduction. For example, a purely diffuse surface is illuminated by two independent paths of lengths $L_1$ and $L_2$. Each path has a scattering amplitude, $A_1$ and $A_2$. The square of each amplitude is
a random variable with a negative exponential probability distribution. Each path has a
phase shift from the surface reflection, \( \phi_r,1 \) and \( \phi_r,2 \). The phase shift is a random variable
with a uniform distribution from 0 to \( 2\pi \). The total amplitude of the received signal, \( A_T \), is

\[
A_T = A_1 e^{i\left(\omega \frac{L_1}{c} + \phi_{r,1}\right)} + A_2 e^{i\left(\omega \frac{L_2}{c} + \phi_{r,2}\right)}
\]

(18)

where \( \omega \) is the transmitter angular frequency and \( c \) is the speed of light. The total
received power, \( P_T \), is

\[
P_T = |A_T|^2 = A_1^2 + A_2^2 + 2A_1A_2 \cos \left( \omega \left( \frac{\Delta L}{c} \right) + \Delta \phi_r \right)
\]

(19)

where \( \Delta L \) is the path length difference \( L_2 - L_1 \) and \( \Delta \phi_r \) is the phase difference \( \phi_{r,2} - \phi_{r,1} \).

Using frequency modulation and an appropriate integration time, the system measures the
average power over the frequency range. The average power, \( < P_T > \) is

\[
< P_T > = A_1^2 + A_2^2 + \frac{2A_1A_2}{\omega_f - \omega_i} \int_{\omega_i}^{\omega_f} \cos \left( \omega \left( \frac{\Delta L}{c} \right) + \Delta \phi_r \right) d\omega
\]

(20)

where \( \omega_i \) and \( \omega_f \) are the initial and final angular frequencies respectively. In addition, the
frequency variation is assumed to be small enough that it does not produce any speckle
reduction on either illumination path. Using this assumption, \( A_1, A_2, \phi_{r,1}, \text{and} \phi_{r,2} \) are
independent of frequency. If the integrand in Eqn. (20) is zero, the illumination paths are
independent. The integrand is

\[
\int_{\omega_i}^{\omega_f} \cos \left( \frac{\omega \Delta L}{c} \right) \cos(\Delta \phi_r) - \sin \left( \frac{\omega \Delta L}{c} \right) \sin(\Delta \phi_r) d\omega
\]

(21)

which is zero for any \( \Delta \phi_r \) when
\[
\int_{\omega_i}^{\omega_f} \cos \left( \frac{\omega \Delta L}{c} \right) d\omega = \int_{\omega_i}^{\omega_f} \sin \left( \frac{\omega \Delta L}{c} \right) d\omega = 0. \tag{22}
\]

The integral is zero when
\[
\frac{\Delta \omega \Delta L}{c} = 2\pi \tag{23}
\]
where \(\Delta \omega = \omega_f - \omega_i\). The frequency, \(\nu\), must change by
\[
\Delta \nu = \frac{c}{\Delta L} \tag{24}
\]
to make the two illumination paths independent.

For a direct illumination scheme, height difference between the peaks and the troughs of the surface roughness create the path length difference. The average change in path length is twice the standard deviation of the surface roughness due to the round trip path. A standard deviation of the surface roughness equal to a wavelength requires a fractional bandwidth of \(\frac{\Delta \nu}{\nu} = \frac{1}{2}\) to produce an independent speckle pattern.

Goodman shows the fractional bandwidth required to have a speckle contrast, \(C\), is
\[
\frac{\delta \nu}{\nu} = \frac{\lambda}{\sigma_h} \sqrt{\frac{1}{C^4} - 1} \tag{25}
\]
where \(\sigma_h\) is the surface height standard deviation [49]. For a purely diffuse surface where the surface height standard deviation is equal to a wavelength a fractional modulation of 1000\% is required to reduce the speckle contrast by a factor of 10. The speckle contrast is reduced by a factor of 1.5 for a single waveguide band, with a typical fractional bandwidth of 25\%, and a surface height standard deviation equal to a wavelength.
Frequency modulation requires a prohibitively large fractional bandwidth to achieve speckle reduction in a direct illumination scheme.

Previous experiments have demonstrated the difficulty in reducing speckle from surface reflections using a frequency modulated, direct illumination technique. A multispectral technique using five frequencies between 75 GHz and 110 improved the contrast on five metals strips with interface steps of 2.5 to 5 mm over the background by a factor of 2 [53]. Coherence effects still significantly impacted target recognition even after a moderate contrast reduction from the frequency modulation. As a result, mathematical algorithms for target recognition were proposed [53].

Indirect illumination techniques create path length differences on the scale of the imaging enclosure. For example, a 10 m path length difference requires 30 MHz of bandwidth to produce a statistically independent speckle pattern. This bandwidth does not depend on the imaging frequency. The fractional bandwidth required decreases as the imaging frequency increases. At 220 GHz, this bandwidth corresponds to a fractional bandwidth of $10^{-4}$. Thus, modest fractional bandwidths can lead to large speckle reduction in an indirect illumination scheme. Conversely, large fractional bandwidths are required for modest speckle reduction in a direct illumination scheme.

Conclusions

The total speckle reduction is the product of the speckle reduction from polarization diversity, angle diversity, and frequency diversity. I investigated the effect of angular diversity in both the light bulb and grassy field illumination configurations. I
investigated the light bulb illumination configuration in the large spot size limit on the nearby surface. I investigated the grassy field illumination configuration in the small spot size limit on the nearby surface. I used mechanical beam steering methods in both configurations to illuminate from each angle sequentially for speckle reduction. I examined the speckle reduction effects of frequency diversity using a range resolved imaging technique. While I studied angle and frequency diversity separately, they can be used simultaneously to achieve greater speckle reduction.
Chapter 4: Experimental Configuration

To evaluate the proposed alternative approaches, I use an experimental configuration that consists of five subsystems: the transmitter system, the transmitter beam steering system, the collecting optics, the receiver system, and the processing and display system.

Transmitter system

The transmitter system consists of four parts: baseband signal generation, a frequency multiplier, an EIK amplifier, and an antenna.

The baseband signal generation system generates two signals, one for the transmitter and one for the local oscillator of the heterodyne receiver. These two signals can be generated by either one or two independent signal generators. Scenarios with a large physical separation of the transmitter and receiver systems require two independent signal generators.

In the dual source configuration, an Agilent E8257D creates a 9.1 GHz signal that is amplified by a MiniCircuits ZX60-24-S+ amplifier and the output is connected to the frequency multiplier system. Figure 16 shows the dual source baseband signal generation along with the frequency multiplier systems.
In a single source configuration, an Agilent E8257D creates a 9.0 GHz signal with the output connected to a MiniCircuits ZFRSC-183-S+ splitter. One output of the splitter goes to the receiver local oscillator baseband generation. The other output is amplified by a MiniCircuits ZX60-14012C-S+ amplifier. The signal is mixed, using a MiniCircuits ZX05-153-S+ frequency mixer, with a 100 MHz signal generated by a dBm Corporation Inc. SSG synthesizer. The outputs of the frequency mixer are signals at 8.9 GHz and 9.1 GHz and a small amplitude signal at 9.0 GHz. The three signals pass through a tunable MicroLambda MLFP-1543PA YIG filter that filters out all but the 9.1 GHz signal. The 9.1 GHz signal is amplified by a MiniCircuits ZX60-24-S+ amplifier. The output of the amplifier is coupled to the frequency multiplier system. Figure 17 shows the single source baseband signal generation along with the frequency multiplier systems.
The frequency multiplier system has a total multiplication factor of 24. The 9.1 GHz signal from the baseband signal generation system is the input to a Spacek A271-3X frequency tripler. The output frequency of the Spacek tripler is 27.3 GHz. The next frequency multiplier is a Virginia Diodes Inc. VDI-FEM-S082 x8 solid state frequency multiplier chain. The VDI multiplier chain requires an input power of -5 dBm to +5 dBm. The power of the signal generator in the baseband system is adjusted until there is an input power of +0 dBm to the VDI multiplier chain. The output power of the VDI frequency multiplier chain is 30 mW at 218.4 GHz.

The output of the VDI frequency multiplier chain connects to the input of the final amplifier in the transmit system with a G-band waveguide 90° twist. The final amplifier is an EIK amplifier manufactured by the Naval Research Lab. The amplifier has a center frequency of 218.4 GHz with 500 MHz of bandwidth. The amplifier has a 5 W maximum continuous output power. The output of the EIK amplifier goes through 3
inches of G-band waveguide. The signal exits the waveguide through a Quinstar G-band horn.

Transmitter beam steering system

The waveguide and horn output of the transmit system are physically placed in the entrance port of the transmitter beam steering system shown in Figure 18. The enclosure of the beam steering system is a 24 inches wide, 18 inches deep, and 56 inches tall and made out of aluminum. The top and the top half of one side of the enclosure are made from polyethylene. The polyethylene is nearly transparent at 218.4 GHz and acts as the exit port for the millimeter wave signal.

Figure 18: A diagram of the transmit beam steering enclosure. The first aluminum directing mirror can be replaced with a mode mixer.
There are two directing mirrors in the transmitter beam steering system. The first directing mirror is a 17.5 inch by 23.5 inch aluminum mirror. The mirror is placed at a 45° angle to redirect the radiation from horizontal to the ground at the output of the transmit system to vertical to the ground. The second mirror is a rotatable 17.5 inch by 23.5 inch aluminum mirror that directs the vertically traveling radiation out of the polyethylene sections of the enclosure.

The first mirror can be replaced by a fast beam steering mechanism called the mode mixer. Figure 19 shows an image of the mode mixer. The mode mixer has a 15° cut from horizontal on each half of the mirror. The mode mixer is mounted on a motor that spins at 6500 to 8500 revolutions per minute. The mode mixer undergoes two to three full revolutions for each pixel dwell time.

Figure 19: A model of a mode mixer with two 15° surfaces, measured from horizontal.
The transmit beam steering enclosure also acts as a safety feature. According to the IEEE, the proper safety ration in the millimeter wave region is 10 mW/cm\(^2\) [54]. The initial output of the EIK amplifier is 5 W and the Quinstar horn has an area of 1 cm\(^2\). The beam spreads out to an area large enough such that the power density drops below the maximum allowed value before the beam exits the enclosure.

Collecting Optics

Figure 20 shows the collecting optic for the receiver. The collecting optic for the receiver is a 60 cm diameter spherical mirror with a 1 m focal length. Eccosorb is placed on the metal mounting surfaces of the mirror to reduce reflections. The mirror rotates in two directions. An identical set of Parker BE231FJ-NPSN motors with Dojen M02 100:1 speed reducers rotate the mirror in each direction. The computer controlled motors raster scan the mirror over the selected scene. The scan uses vertical scan lines because the moment of inertia about the horizontal axis is smallest. The smaller moment of inertia allows higher accelerations and a faster scan. The scan is not a true raster scan, the turns between vertical scan lines are rounded. The round turn lets the motor reverse directions smoothly and lessens the vibrations caused by the sharp turns in a raster scan. The rotational positions of the mirror are recorded using Renishaw RESR rotary angle encoder systems. The outputs of the encoder systems are sent to the digitizer in the receive system.
Figure 20: Photograph of the 60 cm diameter spherical collecting optic with a 1 m focal length.

Receiver System

The receive system consists of four subsystems: the local oscillator baseband generation system, the frequency multiplier system, the IF amplifier and filter system, and the digitization system.

As described in the transmitter system, transmitter and receiver baseband generation systems can operate using either dual sources or a single source. In the dual source configuration, a PhaseMatrix FSW-0200 generates a 9.0 GHz signal. In the single source configuration, an Agilent E8257D generates a 9.0 GHz signal and goes to a
MiniCircuits ZFRSC-183-S+ power splitter. The output of either of these two options passes through 6 ft of MiniCircuits CBL-6FT-SMSM+ SMA cable. The signal is amplified by a MiniCircuits ZX60-24-S+. The output of the amplifier must be between +17 dBm and +19 dBm to drive the frequency multiplier system. MiniCircuits MCL BW-SXW2+ attenuators are inserted after the final amplifier. The X in the model number of the attenuator corresponds to the attenuation in dB. Attenuation of 1-2 dB is typical to reach a final power of +18 dBm.

The frequency multiplier system is a Virginia Diodes Inc. VDI-MixAMC-S107B x24 heterodyne receiver. The local oscillator after the frequency multiplication is 216.0 GHz. The resulting intermediate frequency (IF) after mixing with the 218.4 GHz transmitted signal is 2.4 GHz.

The output of the mixer on the frequency multiplier system is immediately amplified by a MiniCircuits ZX60-33LN-S+ amplifier. Then, the signal passes through 6 feet of MiniCircuits CBL-6FT-SMSM+ SMA cable. Next, the signal is amplified by two additional MiniCircuits ZX60-33LN-S+ amplifiers and a MiniCircuits ZRL-2400LN amplifier. The signal is filtered by a MiniCircuits VBFZ-2575-S+ bandpass filter with a passband of 2.350 GHz to 2.800 GHz. Following an additional 3 feet of MiniCircuits CBL-3FT-SMSM+ SMA cable, the signal enters a Tektronix 2784 spectrum analyzer.

The spectrum analyzer is used as both a narrow banded filter and a logarithmic amplifier. The optical bandwidth and the integration bandwidth were both typically set to 30 kHz on the spectrum analyzer. An integration bandwidth larger than the pixel dwell time results in a smearing effect on the raster scan lines in the image. The output of the
spectrum analyzer is a -1 V to +1 V signal that corresponds to the input power level. The signal is amplified by a factor of 5 by a Stanford Research Systems SR560 preamplifier. The SR560 also has a lowpass filter that was set to 30 kHz to match the bandwidths of the spectrum analyzer. The power level is measured with an error of +/- 0.05 dB.

The FPGA board saves the pan and tilt of the mirror and the received intensity to a binary file on the computer. The FPGA board digitizes all three signals at a typical rate of 30 kHz. The digitization rate was selected to match the bandwidths of the spectrum analyzer and the SR560 preamplifier. Figure 21 shows the diagram of the receive chain, including the IF amplifiers and filters and the digitization system.

![Diagram of the receive chain](image)

**Figure 21:** A diagram the receive chain that includes the IF amplifiers and filters along with the digitization system.

**Processing and Display**

After the data for the entire image are saved, the binary file is loaded for processing. Intensity values of data points that have the same mirror position are averaged together. Then a 2-D array is created where the mirror positions (in counts) are the indices of the array. The array is converted to a grayscale bitmap with an intensity ranging from 0 to 255. A value of 0 corresponds to the pixel in the image with the least
power and a value of 255 corresponds to the pixel in the image with the most power. If there are any pixels in the image without data, the pixel value is interpolated between the nearest pixels on a horizontal line with data. The horizontal interpolation corresponds to interpolation between the vertical raster scan lines.

The noise in the receive chain determines the minimum detectable signal. The heterodyne receiver has a noise temperature of 775 K at this frequency. Due to the conversion loss in the mixer of the heterodyne receiver, the noise in the receive chain is dominated by noise in the first amplifier that is placed directly after the mixer. The Johnson noise in the amplifier is equivalent to a noise source of

\[ P_n = kT_n \left(\frac{bB}{2}\right)^\frac{1}{2} \]

(26)
directly preceding the amplifier [55]. For simplicity, only the noise temperature is tracked for the remaining calculation because the bandwidth values are easily changed. Noise from the first amplifier is tracked through the system and is calculated as an equivalent input noise temperature to a system with only ideal components.

The components in the receive chain have a combined gain of 63.5 dB and a combined noise figure of 4.6 dB through the receive chain before the spectrum analyzer. The equivalent noise input to the first amplifier is 865K from the 4.6 dB total noise figure. However, the mixer in the heterodyne receiver has a conversion loss of 4.1 dB. The noise temperature of the system is 2234 K. A typical number for both the optical and integration bandwidths is 30 kHz resulting in a minimum detectable signal level of \(9.25 \times 10^{-16}\) W.
Conclusions

The transmitter power and receiver sensitivity, in this experimental configuration, allow investigation of illumination strategies that are less power efficient. The size of the collecting optics provides the angular resolution required to identify targets at ranges of at least 50 meters. Using this experimental setup, I will evaluate the effectiveness of the proposed illumination strategies in increasing the accuracy of target identification at longer distances in the succeeding chapters.
Chapter 5: Direct, Multi-Angle Illumination

Direct, multi-angle imaging can increase the detection probability of specular targets that are not in optimal alignment and decrease the speckle contrast. Millimeter wave security scanners in airports use direct, multi-angle illumination by spinning a column of transmitters and receivers around a subject. Direct, multi-angle illumination requires either a rotation of the object or a rotation of the imaging system around the object.

I analyzed the results from a previous generation direct, multi-angle imaging system for speckle reduction [52]. Figure 22 shows the experimental setup of the 643 GHz imaging system [52]. The system uses a beam splitter between the transmitter and the heterodyne receiver to coaxially illuminate the target. Motors raster scan the mirror to direct the beam over the object.
Figure 22: The experimental configuration of a previous generation 643 GHz imaging system [52].

Figure 23 shows a millimeter wave image of a knife hidden under a lightweight robe taken at (a) +20° from normal incidence and (c) an average of 41 images taken at incidence angles between -20° and +20° from normal incidence. Panels (b) and (d) show the intensity as a function of pixel number for data across the blue line. In the single image, the knife is visible under the robe but there is significant speckle in the image. Averaging the image from many incidence angles greatly reduces the speckle contrast. The edges of the knife are less defined in the averaged image because the knife rotation changes the cross-sectional area of the knife.
Figure 23: (a) A millimeter-wave image of a knife under a lightweight robe with (b) power versus pixel number for data across the blue line. (c) The average of 41 images taken from angles spaced $1^\circ$ apart and (d) power versus pixel number for data across the blue line.

**Speckle Results**

In Figure 23(a) the areas on each side of the knife have signal that is returned from the diffuse surface of the light robe. Figure 24 shows the intensity probability distributions for the pixels in Figure 23(a) that are contained in the green and red boxes. These areas are ideal for speckle analysis because of their large homogeneous areas. The average intensity value in each region is normalized to 1.
Figure 24: Intensity probability distributions for pixels contained in the (a) red and (b) green boxes of Figure 23(a). The red pluses are the intensity data and the blue line is the fit to the modified Gamma distribution.

The intensity distribution fit, shown in Figure 24(a), for the pixels contained in the red box returned a value of $N = 1.32$. A value of $N = 1$ is indicative of a purely diffuse surface. The intensity distribution fit, shown in Figure 24(b), for the pixels contained in the green box returned a value of $N = 1.39$. These two sections of the image have speckle contrast values of $C = 0.87$ and $C = 0.85$ respectively.

The image of the knife covered with a light robe from Figure 23(b) is the average of 41 images of the knife with incidence angles between $-20^\circ$ and $+20^\circ$ from normal incidence in steps of $1^\circ$. Speckle contrast reduction by a factor $\sqrt{41}$ is not expected from averaging the 41 images. Each of the images was not taken from a statistically independent angle. In this imaging configuration, a $41^\circ$ angular span corresponds to 16
statistically independent angles [52]. Figure 25 shows the intensity distributions for the
pixels contained in the red and green boxes of Figure 23(c) along with the fits to the
modified Gamma distribution.

![Intensity distribution graphs](image)

Figure 25: Intensity distributions for pixels contained in the (a) red and (b) green boxes of Figure 23(c). The red pluses are the intensity data and the blue line is the fit to the modified Gamma distribution.

The intensity distribution fit, shown in Figure 25(a), for the pixels contained in
the red box returned a value of $N = 15.46$, which is close to the expected value of $N = 16$
for 16 independent, fully developed speckle patterns. The intensity distribution fit,
shown in Figure 25(b), for the pixels contained in the green box returned a value of $N =
17.38$. The speckle contrast values are $C = 0.25$ and $C = 0.24$ for the pixels contained in
the red and green boxes respectively. These contrast values closely match the predicted
value of $\frac{1}{\sqrt{16}}$. The fitting function requires the average intensity from each independent
angle to be equal. This assumption is not valid because the power levels vary modestly
with angle over the 41° span. The breakdown in this assumption explains the slight
differences between the intensity distribution and the fit.

Conclusions

The simple averaging of the same object directly illuminated from 16 independent
angles shows significant reduction in speckle. These images demonstrate the increase in
object recognition and the decrease in speckle contrast from direct, multi-angle
illumination. A rotation of the object is required in this method. To image a non-
compliant subject, the imaging system must be rotated. Rotation of the imaging system
about the subject is often impractical, especially at longer ranges. Therefore, I develop
indirect, multi-angle illumination methods to image non-compliant targets at long ranges
without the need to move the imaging system, the subject of the next chapter.
Chapter 6: Indirect, Multi-Angle Illumination

Indirect, multi-angle imaging has two advantages over direct, single-angle imaging. First, multi-angle illumination increases the detection probability of specular targets that are not in optimal alignment. Second, indirect illumination accesses many angles leading to speckle reduction from angular diversity without moving the physical location of the transmitter. However, indirect, multi-angle illumination has much lower signal margins than direct illumination. The image would look like a passive image if all of the angles available in the scene have equal power because of these two effects. I investigated these countervailing effects.

Hot Blackbody Illumination

Equal power in every available illumination angle is equivalent to creating a hot blackbody. The number of available modes in the blackbody is

\[ N = \frac{4\pi^2 l^2}{\lambda^2} \]  

(27)

where \( l \) is the length of the enclosure, \( \lambda \) is the wavelength, and \( N \) is the number of modes [56]. A source power of \( P = 10 \) W and 1 mW, a wavelength of \( \lambda = 1 \) mm, an enclosure of \( l = 100 \) m, and a source bandwidth of \( b = 1 \) MHz, a collecting mirror with area \( D_o^2 = 1 \) m\(^2\), and a 100 x 100 array, if applicable, are used for the numerical examples. In this
example, the number of modes in the enclosure is $4\pi^2 \times 10^{10}$. The 10 W and 1 mW sources have source temperatures of $7.25 \times 10^{17}$ K and $7.25 \times 10^{13}$ K.

The effective temperature of the mode determines the signal margin of the image. The power and effective temperature in each mode in the hot blackbody example are

$$P_m = PR \left( \frac{\lambda^2}{4\pi^2 l^2} \right) = kT_{eff}b$$

where $P_m$ is the power in each mode, $P$ is the total radiated power, $R$ is the reflectivity of the target, $k$ is the Boltzmann constant, $b$ is the source bandwidth, and $T_{eff}$ is the effective temperature of the mode. The effective temperature of each mode is $1.84 \times 10^5$ K and 18.4 K for the 10 W and 1 mW source respectively.

In contrast, a direct illumination method achieves the highest possible signal margin. All of the transmit power is incident on a single resolution element. The received power of the reflection from a diffuse source becomes

$$P_r = PR \left( \frac{D_o^2}{2\pi l^2} \right)$$

where $D_o^2$ is the area of the collecting mirror. The ratio of the area of the collecting mirror to the area of a hemisphere centered at the target is due to the amount of power reflected from the target that intercepts the receiver collecting optic. The received effective temperatures of this imaging setup are $1.15 \times 10^{12}$ K and $1.15 \times 10^8$ K for the example sources. These temperatures are for a single transmitter and a single receiver. If a $n \times n$ transmit and receive array were used, the total incident power from the transmitters illuminates $n^2$ resolution reducing the effective temperature by $n^2$. This
reduction results in received effective temperatures of $1.15 \times 10^8$ K and $1.15 \times 10^4$ K for the example sources. The direct illumination method results in no speckle reduction.

Nearby Surface Illumination

Indirect illumination off of a nearby wall is an intermediate case between the hot blackbody and the direct illumination methods. This intermediate case has higher speckle reduction than the direct illumination method and higher signal margins than the hot blackbody method. For a scattering surface reflectivity, $R$, a nearby wall scattering area, $D_s^2$, and a distance from the target, $r_{st}$, the effective temperature of the imaging mode is

$$T_{\text{indirect}} = \left( \frac{R \lambda^2 n^2}{2\pi D_o^2} \right) \left( \frac{l^2}{r_{st}^2} \right) * T_{\text{direct}} = \left( \frac{PR^2}{kb} \right) \left( \frac{\lambda^2}{4\pi^2 r_{st}^2} \right).$$

The reflectivity is squared in the formula due to the reflections off of two surfaces, the nearby wall and the target. The received signal is $80\pi$ lower than the direct illumination method, but $(l/r_{st})^2$, or 25, times larger than the hot blackbody method.

The illumination reflecting off of the nearby wall can come from more than 1 statistically independent angle leading to speckle reduction through angular diversity. The minimum number of independent speckle patterns is

$$N = \left( \frac{D_s}{D_o} \right)^2.$$

The number of independent speckle patterns is maximized when $D_s = r_{st}$. For the example case, there are 400 independent speckle patterns corresponding to a speckle contrast reduction by a factor of 20.
I investigated the indirect, multi-angle illumination method using two illumination methods. In the first method, the transmitter was configured to act as a millimeter wave light bulb in a large room. The light bulb method illuminates the targets from indirect bounces off of the walls of the enclosure. The light bulb method is an attempt to create a scenario close to the hot blackbody. In the second method, the transmit beam is aimed at a diffuse surface nearby the target. The diffuse reflection on the nearby surface illuminates the target. The transmitter beam on the nearby surface is steered to create independent speckle patterns for speckle contrast reduction. This illumination method is also known as the grassy field method of illumination. The grassy field illumination method can be used outdoors where there are no enclosing walls. DiGiovanni et al., for example, report significant diffuse components for many outdoor surfaces, including gravel, sand, and soil [11].

Light Bulb Illumination

The Physics Research Building atrium at The Ohio State University, shown in Figure 26, was selected for study because of its large size. The atrium has a length of 50 m, a width of 7 m on the near end and 15 m on the far end, and a height of 20 m. There are a few geometries of interest contained within the scene. These geometries include the beams going diagonally from left to right in the ceiling, the office windows on the left side, the far staircase with a glass divider on the right side, and wires that support light reflectors going from the lower left to the middle right of the image.
Figure 26: Picture of the Physics Research Building atrium at The Ohio State University.

Figure 27 shows a millimeter wave image of the Physics Research Building taken from the same place on the 3rd floor balcony as Figure 26. The receiving system was placed on the 3rd floor balcony. The transmit system was placed on the ground floor of the near side of the atrium. There was no direct line of sight between the transmitter and the receiver. The dual source baseband generation method was used. The position of the directing mirror within the transmit tower directed the transmit beam at the ceiling at the far end of the atrium. The mode mixer was stationary during the image collection. Every pixel on the image has power returned from the transmitter. No pixel in the image
contains only system noise. A few items stand out in the millimeter wave image including the windows on the left side of the image, a few of the beams in the ceiling, and the wires going from the lower left to the middle right of the image. These wires are more prominent in the millimeter wave image than the optical photograph. Figure 27 shows the effects of speckle throughout the image that interferes with object identification and detection in the image.

Figure 27: A millimeter wave image of the Physics Research Building atrium without mode mixing.

The transmitter, with the mode mixer off, illuminates the scene from many angles. There are a few bright, specular reflections in the millimeter wave image. Each ceiling
beam has at least one of these specular reflections. If the illumination occupied all angles with equal power, the beams would appear uniform. The appearance of these bright, specular reflections indicates not every illumination angle has the same power. Many objects in the scene are visible in the millimeter wave image regardless of orientation. Therefore, the objects in the image were illuminated by many, but not all possible illumination angles. The indirect, multi-angle illumination method reduces the need for optimal target orientation. However, significant speckle reduction is required for image clarity.

Large areas of nearly homogeneous objects were selected for speckle analysis. These areas are enclosed in colored boxes in Figure 27. The orange box on the left side of the image is drywall at a range of 10 m. The green box in the lower right of the image is from the top of a seminar room made of brick at a range of 30 m. The blue box in the upper right of the image is from drywall at a range of 10 m. The intensity distributions of the received signal from these areas were fit to both the modified Gamma distribution and the Rician distribution.

Figure 28 shows the intensity distributions along with fits to the modified gamma distribution function. The modified Gamma distribution fit of the intensity distribution in the regions enclosed by the orange, green, and blue boxes returned fit parameters of $N = 3.63$, $N = 4.31$, and $N = 3.84$ respectively. The average speckle contrast for these three regions is $C = 0.51$. 
The intensity distributions of the same regions were also fit to the Rician probability density function in Figure 29. The Rician fits for the intensity distributions in the regions enclosed by the orange, green, and blue boxes returned fit parameters of $r = 6.2$, $r = 7.5$, and $r = 6.6$ respectively. The average speckle contrast value for the fits in these three areas is $C = 0.49$. Overall, the Rician function visually fits these three
selected areas better than the modified Gamma distribution. A closer fit to the Rician distribution than the modified Gamma distribution suggests the surface of the object is partially diffuse rather than purely diffuse.

Figure 29: Intensity distributions from the atrium image without mode mixing, for areas enclosed by the (a) orange, (b) green, and (c) blue boxes, fit to the Rician probability distribution function.
Figure 30 shows a millimeter wave image of the atrium taken under the same conditions as Figure 27, but with the mode mixer enabled and spinning at 6500 RPM. The speckle contrast is greatly reduced while using the mode mixer. The edges between the windows and the drywall on the left side of the image have a much higher contrast as well as the bottoms and the sides of the beams in the ceiling. The bottoms of the beams are brighter than the sides of the beams because the illumination is directly under the beams. Finally, the wires, going from the lower left to the middle right of the image, stand out much more prominently in the image with mode mixing.

Figure 30: A millimeter wave image of the Physics Research Building atrium with mode mixing.
I analyzed the three regions shown in Figure 30, those enclosed by the orange, green, and blue boxes, for speckle statistics. These three regions are the same regions analyzed in Figure 27. The intensity distribution of each region in the image was fit to both the modified Gamma distribution and the Rician distribution.

Figure 31 shows the intensity distributions for the three regions enclosed in Figure 30 and each distribution is fit to the modified Gamma density function. The Gamma density function fit returned parameters $N = 49.9$ for the drywall enclosed in the orange box, $N = 158.0$ for the brick enclosed in the green box, and $N = 42.5$ for the drywall enclosed in the blue box. The speckle contrast values for the fits of these three regions is $C = 0.142$, $C = 0.0796$, and $C = 0.153$ respectively.
Figure 31: The intensity distribution for pixels enclosed by the (a) orange, (b) green, and (c) blue boxes in the mode mixed atrium image, shown in Figure 30, fit to the modified Gamma density function.

Figure 32 shows the intensity distributions for the three regions enclosed in Figure 30 fit to the Rician probability distribution function. The Rician probability distribution fit returned fit parameters $r = 98.8$, $r = 315.6$, and $r = 84.2$ for the regions enclosed by the orange, green, and blue boxes. These intensity distribution fits have speckle contrast
values $C = 0.141$, $C = 0.0794$, and $C = 0.153$ for the orange, green, and blue boxes respectively.

Figure 32: The intensity distribution for areas enclosed by the (a) orange, (b) green, and (c) blue boxes in the mode mixed atrium image, shown in Figure 30, fit to the Rician function.

Each of the fits to the intensity distributions shown in Figure 31 and Figure 32 appears similar. As the contrast approaches zero both the modified Gamma distribution
and the Rician distribution approach the Gaussian distribution. Each fitting function fits the intensity distributions from the image in Figure 30 equally well because the speckle contrast is small.

Each fit function fits the intensity distributions from Figure 27 better than the intensity distributions from Figure 30. The increase in illumination complexity directly decreases the fidelity of the fit function. The assumptions made in the derivation of the modified Gamma distribution can fail in three ways. First, each independent illumination angle may not have the same illumination power. Second, each illumination angle of the object may not be at a statistically independent angle. Finally, there are surface inhomogeneities in the objects studied for speckle reduction. For example, the seminar room consists of both brick and mortar that have different surface properties. The inhomogeneity in both the illumination and the targets is not ideal for speckle analysis. However, the speckle reduction using the mode mixer technique is sufficient to demonstrate that clear target identification at long ranges is possible.

Figure 33 shows the intensity distribution for the area enclosed by the green and red boxes in Figure 30 with the mean intensity normalized to 1. The intensity distribution from the green box was fit previously to probability distribution functions derived from speckle foundations. The area enclosed by the red box has inhomogeneous that include areas of the beams, walls, and windows. As a result, the intensity distribution from the red box has a long tail from the strong specular components. Due to the inhomogeneities, the intensity distribution cannot be fit well to any distribution derived from speckle foundations. The difference between the intensity distributions from the green and red
boxes shows that object homogeneity is important for fitting to either the modified Gamma function or the Rician function.

Figure 33: Intensity distributions for pixels enclosed by the green and red boxes in Figure 30. The red trace is the intensity distribution for the pixels enclosed by the red box and the green trace is the intensity distribution for the pixels enclosed by the green box.

The indirect, multi-angle illumination method was used in a light bulb configuration. The mode mixer steers the floodlight around the room. I showed that this indirect technique illuminated many but not all of the illumination angles in the atrium. The mode mixer successfully modulated the speckle patterns on the target by modulating the power of the illumination angles. Averaging the modulated speckle patterns lead to a significant reduction in speckle contrast. Speckle contrast was reduced by 6.5 to 12.5 over a direct illumination method of a purely diffuse surface.
Grassy Field Illumination

I investigated the grassy field indirect, multi-angle illumination strategy by using a diffuse reflection off of a nearby surface to illuminate the target. In this experiment, a carpeted floor was used as the nearby surface for indirect illumination. The target was a piece of Eccosorb. Eccosorb is a purely diffuse surface at the imaging frequency and is uniform aside from surface roughness.

Figure 34 shows a diagram of the transmitter beam steering system. The transmit horn was placed at the focus of a lens with a 4 cm focal length. Then the beam bounced off of two rotatable mirrors. The first mirror controlled the horizontal position of the beam on the floor. The second mirror controlled the distance from the imaging system that the beam intercepted the floor. Each mirror was moved in 1° increments over a span of 10°. A total of 121 images were taken. A change in the horizontal angle of the first mirror by 1° corresponds to a 4° horizontal change in the beam position. A change in the lookdown angle of the second mirror by 1° corresponds to a 2° change in the lookdown angle of the beam.
Figure 34: A diagram of the transmitter beam steering system. The optics are blue, the mounting components are green, the rotation directions are black, and the millimeter wave path is red.

Figure 35 shows an example of one of the 121 images of a piece of Eccosorb taken at a distance of 7 meters. The edges of the image were cropped to avoid including any effects of the mounting. The final images used for speckle analysis were 0.03 radians by 0.03 radians which corresponds to an image with 14 by 14 receiver resolution elements. The images were made using a 30 mW source without the EIK amplifier. The dual source baseband signal generation method was used. The optical and integration bandwidth were reduced to 300 Hz to increase the signal to noise ratio. In this experiment, the average signal to noise level was 30. The pixel dwell time was increased
to avoid smearing effects during the raster scan because of the decrease in integration bandwidth.

Figure 35: An example image of Eccosorb taken with nearby floor illumination. The intensities of the pixels along the white line are plotted in Figure 39.

The intensities of each of these images were normalized to an average intensity of 1. The intensity distribution of each image was fit to the modified Gamma density function and fit for $N$, the number of statistically independent speckle patterns. Figure 36 shows an example of a typical intensity distribution along with the fit to the modified Gamma density function. The fit from Figure 36 returned a fit parameter value of $N = 1.06$ and the average value of the fit for each image was $< N > = 1.03$. 
Figure 36: The intensity distribution of the image, shown in Figure 35, in red pluses and the fit to the modified Gamma density function, shown by the blue line.

All of the images were averaged together reduce the speckle contrast. Figure 37 shows the average of the 121 images on the same intensity scale as the image shown in Figure 35. An image with completely suppressed speckle is monochromatic. However, in the case of these average images, speckle is not completely suppressed.
Figure 37: An image of Eccosorb created by averaging 121 nearby floor illumination spots. The intensities of the pixels along the white line are plotted in Figure 39.

The intensity distribution of the averaged image was fit to the modified Gamma density function, shown in Figure 38. The fit returned a value of $N = 16.96$ for the number of independent speckle patterns averaged. If all of the images were statistically independent, then the expected result would be $N = 121$. However, I did not expect all of the images to be uncorrelated because the transmit beam was not steered far enough between each image to do so.
Figure 38: Intensity distribution of the image in Figure 37, shown by red pluses, and the fit to the modified Gamma density function, shown by the blue line.

Figure 39 shows the intensity distribution for the pixels covered by the white line in Figure 35 and Figure 37. Averaging the 121 images drastically reduces the variation of the signal level across the white line when compared with the same row of data from one individual image. The intensity as a function of pixel number across the image is constant if there are no effects of speckle.
Figure 39: Intensity as a function of pixel number for the pixels covered by the white line in Figure 35 and Figure 37.

Figure 40 shows the top down view of the transmitter beam intercepting the floor for all 11 horizontal transmitter beam positions for a constant lookdown angle. The area on the graph for each beam corresponds to the area where the power density is at least $\frac{1}{e}$ of the single beam maximum power density. The transmitter is located at length = 0.0 m and width = 0.0 m. The target is located at length = 7.0 m and width = 0.0 m.
The spot size of the transmitter beam on the floor and the distance from the floor to the target determine the average speckle grain size incident on the target. The effective diameter of the transmitter beam on the floor ranges from 350 mm to 680 mm. The range to the target from the beam center on the floor ranges from 4.1 m to 4.9 m. The closest range to the target corresponds to the largest beam size. The average diameter of the speckle grains projected onto the target ranges from 8 mm to 19 mm. The receiver resolution element on the target has a diameter of 16 mm. In this experiment, the projected speckle grain size is smaller or approximately equal to the receiver resolution element. As I discussed in a previous chapter, speckle reduction occurs when the
transmit beam moves such that an independent speckle pattern is projected onto the target.

Averaging together 121 images resulted in the speckle reduction equal to approximately 17 independent speckle patterns. Not every beam position in this experiment results in an independent speckle pattern. Adjacent beam positions have significant overlapping scattering areas on the floor. This overlap can cause the speckle pattern generated from the transmitter interacting with the floor to generate speckle patterns that are not statistically independent.

Figure 41 shows the effective number of independent speckle patterns averaged over all rows as a function of the horizontal angular beam center span for a constant lookdown angle. The best fit line has a slope of 0.187 and an intercept of $N = 1.21$. The coherence angle, or the angle between independent speckle patterns, is the inverse the linear fit slope. A change in beam center position by $5.35^\circ$ is required to produce an independent speckle pattern in this case.
I used the indirect, multi-angle illumination method in the grassy field configuration and showed that it achieves significant levels of speckle reduction. The significant speckle reduction requires only small areas on the nearby surface. In this experiment, the area used on the nearby surface was equivalent to the area of two collecting optics. This illumination method is suited for outdoor or urban canyon scenarios. Although the grassy field illumination method achieves significant speckle reduction, specular targets may not be detected because the illumination on the target has a small angular extent. In this chapter, I have shown that indirect, multi-angle illumination methods can significantly reduce speckle in both the floodlight and grassy field configurations, and can significantly increase target recognition.
Chapter 7: Direct, Single-Angle Illumination with Frequency Modulation to Measure Reflective Strength

In the field of microwave radar, the radar cross section (RCS) is a measure of the reflective strength of the target [57]. A system with range resolution can isolate the surface reflections of a target. The reflection strength is measured as a function of angle. I investigate the reflective strengths of specular, periodically rough, and randomly rough targets with a tabletop millimeter wave RCS measurement system. I study the intensity probability distributions of randomly rough targets to investigate relative surface roughness.

Pulsed systems and broadband systems are the two ways to determine the distance to the target. A pulsed system uses the pulse time of flight to determine the target range. The time between the transmitted pulses determines the maximum unambiguous range of the system. A stepped frequency measurement system records the amplitude and phase at each transmitted frequency. The phase of the return signal depends on the phase reflection of the target, the transmitted frequency, and the target range. Range can be extracted from the system of equations created from measurements at many ranges. In a swept frequency system, both the transmitter and the receiver local oscillator are swept in frequency. The frequency of the IF determines the distance to the target.
The radar range equation defines the target RCS in terms of the received power, $P_r$. One form of the radar range equation is

$$P_r = G_t \cdot P_t \cdot \left( \frac{\sigma}{4\pi r_t^2} \right) \cdot \left( \frac{A_e}{4\pi r_r^2} \right)$$

(32)

where $G_t$ is the transmitter antenna gain, $P_t$ is the transmitted power, $\sigma$ is the RCS of a target, $r_t$ is the distance from the transmitter to the target, $r_r$ is the distance from the receiver to the target, and $A_e$ is the effective area of the receive antenna. There are two area ratios in this formula. The first ratio is the fraction of the surface area of a sphere centered on the transmitter that intercepts the target. The second ratio is the fraction of the surface area of the sphere that is centered on the target that intercepts the receiver. Additional factors such as propagation loss and shadowing effects are omitted. The RCS of the target is the cross-sectional area of a sphere that has the same received power as the target.

Historically, radar systems have operated in frequencies ranging from HF band around 30 MHz or less for over the horizon radar to X-band or 8 to 12 GHz for missiles and missile defense [58], [59]. At these wavelengths, most of the targets are purely specular. Rough surfaces produce a negligible contribution to the total RCS and are accordingly ignored in long wavelength RCS scattering simulators. As radar systems use higher frequencies, surfaces that were previously smooth become partially rough or completely rough. I use a tabletop RCS measurement system to measure canonical shapes, periodic surfaces, and randomly rough surfaces.
Experimental Configuration

Figure 42 shows a functional block diagram of the tabletop RCS measurement system. The system uses an Agilent E8257D synthesizer that drives the transmitter and the local oscillator of the receiver. The synthesizer sweeps from 8.75 GHz to 10 GHz in 10 ms. After the signal exits the synthesizer, it passes through a MiniCircuits ZFRSC-183-S+ power divider. One output passes through a MiniCircuits ZX60-24S+ amplifier and drives a Virginia Diodes Inc. x24 210 – 270 GHz transmitter. A 1 dB MiniCircuits BW-S1W2+ attenuator is placed before the transmitter so that the input signal is between +17 dBm and +19 dBm over the frequency band as required by the frequency multiplier.

The other output of the power divider goes through a MiniCircuits ZX60-24S+ amplifier, a MiniCircuits BW-S1W2+ 2 dB attenuator, and drives a Virginia Diodes Inc. x24 210 – 270 GHz heterodyne receiver. Different cable lengths in each signal path increase the offset frequency of the recovered signal. Each meter of cable length difference increases the recovered signal frequency by 10 kHz.

The transmitter and receiver are placed in a quasi-monostatic arrangement. They are aligned perpendicularly to each other with a beam splitter placed at a 45° angle. The beam splitter creates two identical imaging paths. A lens focuses the imaging beam onto the target in one imaging path. The extraneous imaging path travels down a long, open area. The first reflection in the extraneous imaging path is at a longer range than the target. All extraneous reflections are eliminated with range filtering.

The received signal, containing information from both imaging paths, passes through a MiniCircuits ZBPF-75-S+ 63 kHz to 87 kHz band pass filter that acts as a
hardware range filter. The filtered signal passes through a SR560 preamplifier and then and is digitized by a Lecroy 42XS-A Wavesurfer oscilloscope.

![Functional block diagram of the table top RCS measurement system.](image)

Figure 42: A functional block diagram of the table top RCS measurement system.

**Frequency Sweep**

The transmitter and receiver are both swept in frequency at the same rate. The resulting IF has a frequency proportional to the target range. The frequency of the signal leaving the transmitter, \(f_t\), is

\[ f_t = f_0 + SR \times t_t \quad (33) \]

where \(f_0\) is the initial sweep frequency, \(SR\) is the sweep rate, and \(t_t\) is the time of the transmitted signal. Similarly, the local oscillator at the receiver has a frequency, \(f_r\), of
\[ f_r = f_0 + SR \cdot t_r \]  

where \( t_r \) is the time the signal enters the receiver. The frequency difference between the signal entering the receiver and the local oscillator of the receiver is

\[ f_r - f_t = SR(t_r - t_t) = SR \cdot \left( \frac{2r}{c} \right) \]  

where \( c \) is the speed of light and \( r \) is the range to the target. The mixing product from the heterodyne receiver has a frequency proportional to range.

The calculation of the range is invalid if there is radial motion of the target along the imaging path. A radial velocity adds a Doppler shift to the return signal. The frequency shifted signal causes the recovered frequency to depend both on range and velocity of the target. In controlled table top experiments there is no relative motion. However, in large scale open environments a stepped frequency or pulsed system must be used.

Performing a Fourier transform on the recovered signal results in the scattering amplitude as a function of frequency. The frequency axis is converted to a range axis using the sweep rate. Frequency filters are used to filter out scattering objects that are outside the target area. These frequency filters can either be in software or hardware.

Data Processing Procedures

The amplitude and phase of the only remaining reflection contains the target RCS information. The target may extend in range such that the scattering amplitude is distributed over many range bins. A method described by Liang et al. combines amplitude information across frequency bins to calculated RCS as a function of transmit
frequency [60]. First, the inverse FFT (IFFT) of the range gated frequency domain signal is performed. The envelope of this signal gives the scattering amplitude as a function of time and transmitted frequency. The square of the return signal from only the target is the relative scattering intensity. Then a Fourier transformed is performed. The high frequency components are filtered out leaving only the scattering intensity envelope information. The IFFT results in the scattering intensity as a function of transmitter frequency.

There is a non-linearity in the sweep electronics. This non-linearity adds a frequency modulation to the received signal. Consequently, the target appears to be oscillating in range.

The frequency modulation from the non-linear sweep can be removed with data processing. First, perform a FFT on the received signal to get scattering amplitude as a function of range. Then, range gate out any extraneous reflections other than the target. Next, perform the IFFT to get the received signal for only the target. After removing the envelope, only a frequency modulated sine wave remains. Figure 43 shows the period of each sine wave versus the period number for a single scan. The period of each sine wave is used as the instantaneous frequency.
To remove the frequency modulation, time bins where the frequency is higher than average are stretched and time bins where the frequency is lower than average are compressed. Then the time trace is resampled with evenly spaced time points. Figure 44 shows the comparison of amplitude versus frequency for an object before and after sweep linearity correction. After the correction, one main peak corresponding to the range of the target remains.

There are additional, smaller peaks on each side of the main peak. These peaks correspond to an amplitude modulation from a standing wave inside the VDI x24 transmitter. The frequency modulation does not affect the average RCS value unless there is overlap with another target in range. If the average RCS over the sweep bandwidth is desired then this process is not required. The average RCS finds the total power within the set range gate.
Figure 44: The scattering amplitude of a corner reflector as a function of recovered frequency before and after the sweep correction.

System Calibration

The scattering intensity discussed above is proportional to RCS. The proportionality constant depends on system and environmental parameters. The system parameters include transmitter power, transmitter antenna gain, and receiver antenna gain. The environmental parameters include range, atmospheric attenuation, and shadowing effects. All of these parameters are constant when changing between targets in this experiment. The RCS measurement system is calibrated using a substitution method. A sphere is often used as the reference object because it has a constant RCS as a function of transmit frequency, $\sigma_{\text{sphere}} = \pi r^2$ where $r$ is the sphere radius. The sphere RCS is constant provided that the transmit frequency resides in the optical limit, $\frac{2\pi r}{\lambda} > 10$ [61]. Using this calibration method, the formula for the RCS of an object is

$$\sigma_{\text{target}} = \frac{SI_{\text{target}}}{SI_{\text{sphere}}} \times \sigma_{\text{sphere}}$$ \hspace{1cm} (36)

where $SI$ is the scattering intensity. Figure 45 shows a plot of the RCS as a function of angle for a 2 inch diameter steel sphere. The data is normalized to the average RCS, $\pi r^2$. 86
The average value is shown by the blue horizontal line in the figure. The figure appears noisy but the variations are less than 0.05 dB.

![Graph showing RCS as a function of angle for a 2 inch diameter steel sphere. The blue line denotes the average value.](image)

Figure 45: RCS as a function of angle for a 2 inch diameter steel sphere. The blue line denotes the average value.

The results for the randomly rough surface measurements are also calibrated using a substitution method. The calibration object has the same geometry, a cylinder, as the randomly rough targets but is metallic and specular. The calibration formula is

\[
RSI = \frac{S_{I_{\text{target}}}}{S_{I_{\text{metallic target}}}}
\]  

(37)

where \(RSI\) is the relative scattering intensity. Equation (37) can be used to find \(\sigma_{\text{target}}\) because the RCS of the metallic target is known. Figure 46 shows the RCS of a
cylindrical piece of stainless steel shim stock cylindrically shaped with a 3 inch radius. The periodic variations in the plot, roughly 0.10 dB in amplitude, correspond to small variations in the metal that can be seen optically. These variations are due to the rolling of the metal in the manufacturing process.

Figure 46: RCS as a function of angle for a piece of stainless steel shim stock formed into a cylinder with a 3 inch radius.

Figure 47 shows the horizontal profile of the combined transmitter and receiver beam shape. The combined beam shape was measured by translating the 2 inch steel sphere at the target zone in the vertical and horizontal directions and recording the resulting scattering amplitude. The asymmetry in the curve is due to a slight offset of the individual antenna patterns of the transmitter and receiver. The full width at half max (FWHM) of the resulting combined antenna pattern is 14 mm.
Figure 47: Combined transmitter and receiver antenna pattern on a logarithmic scale with the peak gain normalized to 0 dB.

Periodic, Rough Surfaces

I measured two periodic rough surfaces, a perforated aluminum mesh and an aluminized 3-D printed cube with square facets, and compared the results with simulations. The aluminum mesh is a repeated pattern of a unit cell. The unit cell consisted of a 0.005 inch circular hole surrounded by a 4 by 4 perimeter of 0.001 inch circular holes. Figure 48 shows a CAD model of the mesh used for the simulation and a picture of the aluminum mesh that was used for the experimental measurements.
Figure 48: The CAD model (left) and a photograph (right) of the aluminum mesh.

Figure 49 shows the experimentally measured RCS of the aluminum mesh along with the results simulated with the V-Lox solver from IERUS Technologies [62]. Due to an error in the surface tilt of the aluminum mesh mounting, the maximum RCS values are normalized to be each other. The simulation used a plane wave to illuminate the mesh. However, the experiment used a Gaussian beam on a much larger target. Thus, the side lobe pattern created by edge effects in the simulated results is not in the experimentally measured results. Nonetheless, the agreement between the two methods is very good. The major side lobe pattern is accurately reproduced.
Figure 49: Comparison between the experimentally measured (red) and simulation results (blue) for the RCS of the aluminum mesh, shown in Figure 48, normalized for mesh tilt.

The aluminized 3-D printed cube has 2 inch sides and a square indent pattern of 1 mm x 1 mm x 1 mm. The cube was aluminized using electron beam deposition with a thickness of 10 skin depths. Figure 50 shows the CAD model of the cube alongside the aluminized 3-D printed cube. The 3-D printing technique did not completely reproduce the CAD model. There are grooves on the ridges between the indents. Every 8th row of indents has a smaller height than width. The bottoms of the indents are rounded. Despite the minor manufacturing defects, the features of the 3-D printed cube matched the CAD model well.
Figure 50: The CAD model (left) and a photograph (right) of a 2 inch cube with 1 mm square indents.

Figure 51 shows the simulation results, calculated using the V-Lox solver from IERUS Technologies [62], and experimental measurements. Both simulated and experimental measurements have peaks at $0^\circ$ and $90^\circ$. These peaks correspond to a specular reflection off of each face of the cube. The peaks at $20^\circ$ and $70^\circ$ are the expected result from a diffraction grating with 2 mm spacing. Both results have peaks near $45^\circ$. The experimental result has a much broader peak due at $45^\circ$ to the inhomogeneities in the manufacturing process. Similar to the result from the aluminum mesh, the sidelobes on the specular reflections in the simulation are from boundary condition effects. However, these side lobes on the specular reflections are not expected in the experimental data because the measurement system had a Gaussian beam that was smaller than the cube surface.
Random, Rough Surfaces

I investigated the reflection strengths of randomly rough surfaces and analyzed the results using speckle theory. Speckle in the optical regime and speckle in radar have evolved to have different definitions. Due to the small spot size from lasers, speckle theory in the optical regime describes surfaces that are homogeneous aside from surface roughness. Conversely, in traditional radar systems the spot size typically incorporates large, heterogeneous objects such as full trees or other foliage. The RCS probability distributions from inhomogeneous objects are fit empirically to many functions. Some of the fit functions are Gaussian functions, exponential functions, K-distributions, and Weibull distributions [63], [64]. I restrict my investigation to surfaces that are homogenous aside from surface roughness. Previous efforts have sought to classify RCS
measurements as a statistical processes even for inhomogeneous targets consisting of purely specular reflections [65].

The negative exponential distribution and the Rician distribution appear in radar in few different scenarios. A radar target made from many equally sized scattering elements results in a negative exponential RCS probability distribution. This scenario is described in Swerling cases I and II [66]. Swerling cases III and IV describe a target that has one large scattering element and many smaller scattering elements resulting in the Rician RCS probability distribution [66]. Additionally, these distributions appear in multipath environments. Urban radio environments may have many paths to the target of roughly equal strength. This multipath environment results in a negative exponential distribution of received signal and is called Rayleigh fading [67]. Similarly, an environment where there is a strong, direct path and many weaker paths has a Rician distribution of received signal and is called Rician fading [67].

Fried, in his seminal paper on laser radar speckle, described a method to extract Rician distribution fitting parameters from partially rough surfaces [68]. He concludes that the randomly rough target can be thought of as consisting of “two targets – one very rough and giving a Rayleigh distributed contribution to the far-field electromagnetic wave function, and the other a smooth, perfectly polished but reduced reflectivity target giving a nonrandom contribution to the far-field electromagnetic wave function” [68]. The reflectivity reduction of the smooth portion of the target depends on the relative roughness of the target. The specular component of a purely diffuse target has a reflectivity of 0. Fried suggest measuring the same smooth and rough versions of a
simple object to calculate the effective specular reflectivity [68]. This calculated reflectivity could then be used on an arbitrarily shaped object with the same surface roughness. The work presented here uses cylinders as the simple object.

For this simple model, the diffuse component of the reflection can be approximated by a Lambertian distribution, or a $\cos^2 \theta$ distribution [69]. However, Ulaby et al. makes the observation that the RCS has a $\sin^2 \theta$ distribution at shallow angles if the surface has many vertical protrusions in the surface height profile [70].

DiGiovanni et al. recently reported backscattering coefficients for various materials such as brushed concrete, unbrushed concrete, sand, shingles, soil, and gravel [11]. These materials were measured at 100 GHz and 240 GHz with elevation angles between 5° and 35° [11]. Figure 52 shows DiGiovanni’s experimental result for brushed concrete fitted to a cosine power law, $\cos^{1.74} \theta$, where $\theta$ is measured from normal incidence [11]. Each of the materials was fit to a cosine power law and all of the exponents are between 1.7 and 2.8. The Lambertian distribution assumption for the diffuse component of the reflection is a reasonable approximation because deviations from the Lambertian distribution are largest at shallow angles where scattering is small.
The random rough surfaces were all mounted to a cylindrically shaped sample holder shown in Figure 53. The sample holder was attached to a stepper motor for rotation in the azimuthal direction. Rotation of the cylinder shape makes the measurement geometry identical aside from the details of the surface roughness. There is no backing or support in the middle of the sample holder to eliminate reflections from the support structure. The material is pulled taught by a clamp that pushes down the material into a vertical groove on the holder. For the randomly rough surface measurements I report the average RCS over the frequency sweep.
The RCS as a function of angle for a random rough surface appears noisy and random. Figure 54 shows RCS as a function of angle for a piece of cylindrically mounted 36 grit sandpaper as a blue dashed line. A second scan of the same angular span on the same piece of sandpaper is shown on the same graph as a red solid line. The two measurements are nearly identical. The large signal variations are not due to system noise but are due to constructive and destructive interference from the random scattering elements, i.e. speckle. For a given complete surface map of the target and material properties the RCS can be accurately calculated. When the complete surface map unavailable, analyzing the RCS results by using speckle statistics can give insight into the relative surface roughness and average RCS.
Figure 54: Consecutive measurements of RCS as a function of angle for a piece of cylindrically mounted 36 grit sandpaper.

Each azimuthal scan spanned 90° in angle which results in approximately 17 statistically independent measurements. A rotation that moves the surface by half of a beamwidth results in a statistically independent measurement. Scans across the sandpaper were taken at 9 different heights with 6.35 mm spacing, approximately half of the 14 mm beam width. These measurements were repeated for a total of four samples. Combined, there were over 600 statistically independent measurements for each sandpaper roughness.

The transition region between rough and smooth was measured using various grit sizes of commercially available sandpaper. Typically, targets with surface height variations larger than $\lambda$ are considered rough and surface height smaller than $\lambda/8$ are considered smooth [71]. The Rician distribution was fit to the relative scattering
probability distribution of each surface roughness because he samples are partially diffuse and partially specular reflectors.

Figure 55 shows the relative scattering probability distribution from 36 grit sandpaper along with a fit to the Rician distribution. The 36 grit sandpaper has an average particle diameter of 530 μm. The normalized scattering intensity plotted on the x-axis is the RCS of the sandpaper normalized to the RCS of a cylindrically formed piece of stainless steel shim stock. The Rician fit parameters were \( r = 7.56 \) and \( I_n = 0.00237 \) with an averaged normalized intensity value of 0.020.

Figure 55: The scattering intensity distribution for a cylindrically formed piece of 36 grit sandpaper is shown by the red dots. The fit to the Rician distribution is shown by the blue line.

Figure 56 shows the scattering intensity distributions along with fits to the Rician distribution for 20 and 60 grits alongside the results for the 36 grit sandpaper from Figure
The resulting fit parameters are $r = 1.80$ and $I_n = 0.00163$ for the 20 grit sandpaper and $r = 20.39$ and $I_n = 0.0020$ for the 60 grit sandpaper. The average relative scattering intensities are 0.00456 and 0.0428 for the 20 and 60 grit sandpapers respectively. Figure 57 shows the scattering intensity distribution for 100 grit sandpaper with a fit to a Rician distribution. The resulting fit parameters are $r = 21.11$ and $I_n = 0.01073$ and an average relative scattering intensity value of 0.237.

Figure 56: The scattering intensity distributions and fits to the Rician distribution for cylindrically formed pieces of 20, 36, and 60 grit sandpapers.
The ratio of power in the specular reflection to power in the diffuse reflection, $r$, and the average scattering intensity increase as the surface roughness decreases. The decrease in surface roughness causes power that previously in the wide-angle, diffuse reflection to transition to the narrow-angle specular reflection. The average scattering intensity increased as the surface roughness decreased because the system only measured scattering within the narrow-angle specular reflection.

A surprising result is the decrease in surface roughness from 60 to 100 grit sandpaper comes with a great increase in averaged return power but the $r$ value remains nearly constant. The 100 grit sandpaper has a thinner sheet of backing material than all of the rougher sandpapers. When the sandpaper was stretched across the cylindrically shaped sample holder the paper formed a pattern of macroscopic flat surfaces rather than
a cylinder. These macroscopic fluctuations in the surface corresponded to fluctuations in the scattering intensity as a function of angle. Figure 58 shows these fluctuations occur on an angular scale two times larger than the variations shown in Figure 54. The larger angular width indicates that these fluctuations are not from simple speckle effects but rather a longer scale surface fluctuation.

Figure 58: Relative scattering intensity as a function of angle for one scan of cylindrically formed 100 grit sandpaper.

Conclusions

I demonstrated the use of a direct, single-angle illumination with frequency modulation to measure reflection strengths of targets. These targets included canonical objects, which are mainly used to calibrate the system, periodic rough objects, and randomly rough objects. I applied speckle theory to the RCS results from the randomly rough objects and the resulting intensity probability distributions closely matched the
Rician distribution. As the surface height fluctuations decreased, the ratio of the specular
to diffuse components, $r$, from the Rician distribution increased monotonically. I showed
that the RCS probability distributions give insight into the relative surface roughness of
randomly rough targets. The combination of downrange profile measurements and 2-D
millimeter wave imaging results in range resolved millimeter wave images, the subject of
the next chapter.
Chapter 8: Indirect, Multi-Angle Illumination with Frequency Modulation

In this section, I combine the indirect, multi-angle illumination with frequency modulation. I use the frequency modulation to measure the round trip distance of the illumination paths. The round trip range information places an upper bound on the distance to a target that is illuminated indirectly. I show that the distance to the target can be calculated using the measured round trip range information for simple indirect illumination geometries. Frequency modulation can also reduce the speckle in an image. I demonstrate significant speckle reduction using a simple model of the grassy field illumination. I also demonstrate range resolved imaging with indirect illumination on a laboratory scale and at ranges of 50 meters.

Experimental Configuration

Figure 59 shows a block diagram of the indirect, frequency modulated imaging system. A synthesizer that is common to both the transmitter and receiver LO sweeps in frequency with a bandwidth of 480 MHz. The bandwidth of the final amplifier in the system limits the sweep bandwidth. The output signal of the heterodyne receiver has a frequency of 2.4 GHz minus a range dependent frequency. The signal is down-converted again with a frequency mixer. A Phase Matrix FSW-0200 synthesizer provides the LO,
with a frequency of 2.4 GHz + 20 kHz, to the frequency mixer. The resulting signal, with a frequency of 20 kHz plus a range dependent frequency, is digitized by a LeCroy 42XS-A WaveSurfer oscilloscope. A FFT of the digitized signal results in a downrange power profile for each pixel. Motors raster scan the collecting mirror over the scene, resulting in a 2-D image with intensity information as a function of range for each pixel.

Figure 59: Block diagram of the range resolved millimeter wave imaging system.
Range Resolved Imaging Advantages

Range resolved millimeter wave imaging has three advantages over the traditional 2-D imaging: increased signal to noise ratio, target range information, and speckle reduction.

Range resolved imaging has a higher signal to noise ratio than traditional 2-D imaging by range filtering. A typical frequency sweep using this system is 480 MHz in 10 ms. Each frequency bin in the Fourier Transform corresponds to 100 Hz of bandwidth and 0.6 m of range. If a target extends in range for 6 m, or a total of 10 range bins, then only those 10 range bins have signal. Including only the range bins that contain signal increases the signal to noise of the image. This method filters out noise with no loss of signal.

Range resolved intensity information provides information about the distance to the target, even in non-direct illumination schemes. Figure 60 shows one example of the grassy field illumination method with a co-located transmitter and receiver. The height of the transmitter and receiver, $h_{\text{imager}}$, the lookdown angle of the transmitter to the ground, $\theta_t$, and the look angle of the receiving dish, $\theta_r$, are known. The range resolved intensity information measures the round trip path length of the signal, $r = L_1 + L_2 + L_3$. 
Figure 60: An example of the grassy field illumination strategy. The transmitter and receiver are co-located on the left side of the diagram.

The expressions for each path length are

$$L_1 = \frac{h_{imager}}{\sin(\theta_t)}, \quad (38)$$

$$L_3 = \frac{d}{\cos(\theta_r)} \quad (39)$$

and

$$L_2 = \frac{L_1^2 + L_3^2 - 2L_1L_3 \cos(\theta_t + \theta_r)}{2L_1L_3 \sin(\theta_t) \sin(\theta_r)} \quad (40)$$

The horizontal distance to the target, $d$, is

$$d = \frac{r \cos(\theta_r) (r - 2L_1)}{2[r - L_1 - L_1 \cos(\theta_t + \theta_r)]} \quad (41)$$
There is an analytical expression for the distance to the target in this simple geometry. In a more complicate geometry, the range information gives an upper bound on the target range. For a measured round trip path length, \( r \), the target is at a maximum distance from the system of \( \frac{r}{2} \). The indirect illumination strategy has a larger target range uncertainty than the direct illumination strategy. However, the indirect illumination strategy has a higher possible speckle reduction than the direct illumination strategy.

I investigated the speckle reduction in the one-bounce illumination method using a simplified model of a large room. The model of the room has a 100 m length and a 50 m width. The imaging system has a length coordinate of 0 m, a width coordinate of 0 m (center of the left wall), and at a height of 15 m. The 15 m height is the approximate height of the imaging system when it was placed on the 3\(^{rd}\) floor balcony of the Physics Research Building atrium. The target has a length coordinate of 100 m, a width coordinate of 0 m (center of the right wall), and a height coordinate of 15 m, to simulate imaging the 3\(^{rd}\) floor balcony of the far end of the atrium. Figure 61 shows a top-down view of the simulated room. The color scale corresponds to the transmitter-floor-target-receiver round trip path length for each point on the floor.
In the simulation, the transmitter, aimed at the center of the floor, has a Gaussian beam profile with a 10° beamwidth. Figure 62 shows the power per area on the floor from the transmitted beam. The power per area decreases as the square of the distance from the transmitter. Areas nearby the transmitter have higher intensities and areas farther from the transmitter have lower intensities. The highest intensity area is not located at beam center.
Figure 62: An intensity distribution from a Gaussian beam intercepting the floor at an angle.

The transmitted beam then reflects off of the floor, which is assumed to be a purely diffuse surface. Reflections from the diffuse surface are assumed to follow a Lambertian angular distribution. The target is also assumed to be a purely diffuse surface with a Lambertian angular distribution. The collecting optic for the receiver has a diameter of 60 cm. The signal at the receiver is the combination of all possible one-bounce indirect illumination paths. Figure 63 shows the contributions to the received signal from each included indirect illumination path. The highest power contributions to the received signal are from an area close to the target wall. The target occupies a larger portion of the hemisphere centered at points on the floor nearby the wall. However, the area at the base of the target wall has nearly no contribution to the received signal because the target cross-section is nearly zero.
Figure 63: A power density map of the contributions to the signal at the receiver from the floor-target-receiver illumination path for each point on the floor.

The received power as a function of range comes from the combination of the round trip distance, shown in Figure 61, and the power contribution from each point, shown in Figure 63. Figure 64 shows the downrange profile for an imaging system with a range resolution of 1.00 m. The downrange profile for range resolutions smaller than 1 m follows the exact same trend. The entire curve shifts vertically in power by the ratio of the range bins. A smaller range resolution has less power per range bin.
The received power from Figure 64 is the average power received at each range bin for a 1.0 m range resolution. The return from the target has a negative exponential intensity distribution because the target is a purely diffuse reflector. Because they are fully resolved in range, every probability distribution is assumed to be independent. The combined intensity distribution is the convolution of the probability distributions of every individual distribution. The convolution is easily calculated in the Fourier domain as the product of the characteristic functions. The characteristic function of the combined probability distribution, $M_s(\omega)$, is

$$M_s(\omega) = \prod_{n=1}^{N} \frac{1}{1 - i\omega I_n}$$  \hspace{1cm} (42)$$

where $I_n$ is the average intensity from each range bin and $N$ is the number of range bins [49]. The Inverse Fourier Transform of $M_s(\omega)$ is the probability distributions of the total received power. Figure 65 shows example probability distributions for different range

Figure 64: An example downrange profile for the grassy field illumination method with a 1.00 m range resolution.
resolutions. A narrower the probability distribution corresponds to a lower speckle contrast.

Figure 65: Intensity probability distributions for the grassy field illumination method for five range resolutions.

The contrast values of the probability distributions, shown in Figure 65, range from $C = 0.51$ for a range resolution of 2.000 m, to $C = 0.13$ for a range resolution of 0.125 m. Figure 66 shows the contrast as a function of range resolution for this example case. For sufficiently small range bins, the contrast is proportional to the square root of the range bin size. If the downrange profile is smooth, doubling the range resolution changes one range bin into two range bins with nearly equal power. The combined probability distribution of these two range bins is a modified Gamma distribution of order $N = 2$ with $C = \frac{1}{\sqrt{2}}$ and the same average intensity as the original range bin. Combining all of these intensity distributions gives the same contrast improvement as before. However, the starting contrast is lower by the factor of $\frac{1}{\sqrt{2}}$. Therefore, the speckle
contrast is proportional to the square root of the range resolution when one range bin can be split into many equal power range bins.

![Graph showing contrast values as a function of range resolution for the grassy field illumination method.]

Figure 66: Contrast values as a function of range resolution for the grassy field illumination method.

Large values of speckle reduction can be achieved with modest fractional bandwidths. A range resolution of 0.125 m requires a source bandwidth of 2.4 GHz or a fractional bandwidth of 1% at this imaging frequency.

I demonstrated the advantages of range resolved millimeter wave imaging over traditional 2-D millimeter wave imaging. First, it has increased signal to noise levels from narrowing bandwidths to eliminate frequencies with no signal. Second, the distance to target can be calculated, even in non-direct illumination schemes. Finally, power from different illumination angles can be in different range bins allowing powers to be added instead of fields, leading to a reduction in overall speckle of the image.
Laboratory Scale Range Resolved Imaging

I investigated the range resolved imaging technique for speckle reduction on a laboratory scale. A 24 inch by 24 inch sheet of Eccosorb was placed at a range of 7 meters from the receiver. The transmitter was placed 2 m to the left of the line between the receiver and the target and 3 m from the target. The transmitter directing mirror was aimed at the ceiling. The ceiling is 5 m above the floor and lights, pipes, and support beams hang down 2 m from the ceiling. The ceiling was used as a complex scattering object to reflect power in many directions. The fast spinning motor attached to the mode mixer discussed previously is replaced by a stepper motor. The stepper motor has 1600 steps per revolution. A sweep bandwidth of 480 MHz results in a range resolution of 0.625 m. The EIK amplifier bandwidth limits the range resolution. Other amplifiers in development have higher powers and potential range resolutions of 10 mm [12]. Figure 67 shows power as a function of range for one mode mixer position. The power is on a logarithmic scale and the maximum power is normalized to 0 dB.
Figure 67: Power as a function of range from a single pixel of Eccosorb.

The downrange profile was measured for each of the possible mode mixer angular positions. Figure 68 shows the power received as a function of both range and relative angular position of the mode mixer. On the linear scale, the first visible reflection on the figure occurs at a range of 36 m. The final visible reflection occurs at a range of 60 m. The highest intensity reflections occur at a range of roughly 48 m. At a fixed range, the received power is correlated for mode mixer rotations less than 5°. However, when Figure 68 is viewed on a logarithmic scale, shown in Figure 69, reflections ranging from 26 m to 240 m are above the noise floor for some mode mixer positions.
Figure 68: Power received as both a function of range and relative mode mixer angle from a sheet of Eccosorb on a linear scale.

Figure 69: Power received as both a function of range and relative mode mixer angle from a sheet of Eccosorb on a logarithmic scale.

This experiment addresses the problem of simultaneous illumination, shown previously in Figure 15. Illumination from independent angles does not reduce speckle if the illumination of the independent paths is coherent and simultaneous. However, the
imaging paths can be separated in range and the power from each range can be averaged to reduce speckle contrast. If \( N \) range bins are independent and have equal power, the maximum possible speckle reduction using this method is \( \sqrt{N} \). The current range resolution is limited by the bandwidth of the 5 W amplifier. With enough range resolution, each independent illumination path is resolved in range.

I compare four different techniques for speckle reduction. Figure 70 shows images, on a linear scale, of a mock pipe bomb placed on top of a 24 inch by 24 inch sheet of Eccosorb at a range of 7 m. The mock pipe bomb is a 1 inch diameter steel pipe with steel pipe caps on each end. If there is a pixel with no data, a linear interpolation is used between the surrounding pixels. The pipe bomb is not visible in the image with indirect, multi-angle illumination without beam steering or frequency modulation. Pipe bomb features are visible in the image with indirect, multi-angle illumination using the mode mixer for beam steering. The image with frequency modulated, indirect, multi-angle imaging, or the range resolved method, has improved speckle contrast over the mode mixing method. The renormalized range resolved method has the best speckle contrast out of all four images as well as the clearest image of the entire pipe bomb.

In the range resolved image, a few bright illumination paths dominate the image. Other imaging paths, with much less signal, contribute minimally to the image. I used a normalizing technique to weight these illumination paths equally. An image at each range was created and the average intensity of each image was normalized to 1. All images with a signal to noise ratio above about 50 are included. The normalized images
from each range were averaged together to produce the final image. Using this method, the few, bright illumination paths no longer dominate the image.

Figure 70: Images of a mock pipe bomb placed on a sheet of Eccosorb at a range of 7 m with (upper left) no mode mixing, (upper right) mode mixing, (lower left) range resolved method, and (lower right) renormalized range resolved method.

The intensity of the Eccosorb reflection is less than the pipe bomb reflection.

Figure 71 shows the normalized range resolved method image from Figure 70 with a
rescaled color map. The average speckle intensity, rather than the lowest intensity, is mapped to the darkest color. The resulting image shows nearly no signs of speckle. With the new color map, most of the speckle intensity is displayed with the darkest few colors. Color scaling makes object detection easier.

Figure 71: Image of a mock pipe bomb placed on a sheet of Eccosorb using the normalized range resolved method and a rescaled color map.

The images of Figure 70 were retaken without the pipe bomb to investigate the speckle statistics of the Eccosorb. Figure 72 shows the intensity probability distributions for the images without mode mixing, with mode mixing, using the range resolved method, and using the normalized range resolved method. The average value of each distribution is normalized to 1. The method without mode mixing corresponds to the negative exponential distribution with a speckle contrast value of 1.0. The mode mixing
distribution has a contrast value of 0.306, the range resolved method has a contrast value of 0.207, and the normalized range resolved method has a contrast value of 0.145.

Figure 72: Intensity probability distributions for reflections from Eccosorb using 4 different illumination methods.

I investigated the same speckle reduction techniques on a toy gun. Figure 73 shows the images of the toy gun with mode mixing, with the range resolved method, and with the normalized range resolved method. In both the mode mixed image and the range resolved image only the handle of the gun is visible. The barrel of the gun is a specular target. The mode mixed method and the range resolved method miss the specular reflection. Either the gun is not illuminated from the correct angle or the specular illumination angle has much less power than the other illumination angles. The normalized range resolved method weighs each illumination path equally. In this
example, the specular reflection has low power due to multiple reflections and does not contribute significantly to the mode mixed or non-normalized range resolved images.

Figure 73: Images of a toy gun placed on a sheet of Eccosorb at a range of 7 m with (left) mode mixing, (middle) range resolved method, and (right) normalized range resolved method.

Range Resolved Imaging at Long Ranges

I investigated the range resolved imaging technique at a range of 50 meters in the Physics Research Building atrium at Ohio State University. The transmitter was placed on the near side of the ground floor in the atrium and the receiver was placed on the 3rd floor atrium balcony. The same imaging geometry was used in the images of the atrium taken with mode mixed indirect, multi-angle illumination. The range resolved images are 0.2 radians by 0.2 radians, or 80 x 80 diffraction limited spot sizes. Power return as a function of range was taken for a 160 x 160 grid within this region. Averaging ten 10 ms frequency sweeps increased the signal to noise ratio. The total data collection time for each point was 100 ms. The 10 ms sweep time is the minimum sweep time allowed by the Agilent E8275D.
The pixels between each data point were interpolated using a linear interpolation method of the grayscale color value. Figure 74 shows an image on a logarithmic scale for the intensity values at a round trip path length of 61.4 m +/- 0.3 m. The darkest color is the noise floor of the image. The brightest color is the pixel in the image with the highest power. There are two wires visible in the image, going from the lower left to the middle right of the image. Two ceiling beams on top of their respective columns, and two windows between each of the columns are visible. Additionally, there is a bright spot in the lower left of the image from the corner reflector formed where the column intersects the wall at a 90° angle. There is no speckle reduction because this image is made from one range.
Figure 74: An image of the Physics Research Building atrium with signal at a round trip distance of 61.4 m +/- 0.3 m.

Figure 75 shows the downrange power profile for the red pixel in Figure 74. There is no signal return until a large peak centered roughly at 60 m and a smaller peak centered at 100 m. Most pixels in the image have two major groups of returns. The first group of reflections consists of the initial illumination of the target including any reflections that add negligibly to the total path. These small path length reflections can occur from reflections within the transmit enclosure or reflections from a nearby wall. The second group of reflections typically consists of the initial illumination reflecting off of the far wall of the atrium and illuminating the targets from the rear. This second group of reflections typically occurs at path lengths near 100 m.
Most downrange profiles have signal returns over a wider range than the downrange profile of the red pixel. Figure 76 shows the downrange profile for the red pixel and the green pixel, both shown in Figure 74. The downrange profile for the red pixel has one high power return. The downrange profile for the green pixel has power returns distributed over a larger range span. Averaging power from illumination paths with resolved path lengths reduces speckle contrast. A distributed downrange profile, as shown in the green trace, has more resolved illumination paths and reduces speckle contrast more than a narrowly peaked downrange profile, as shown in the red trace.
Figure 76: Downrange profiles from the red and green pixels, shown in Figure 74, in the red and green traces respectively.

I analyzed reflections from 20 range bins for speckle reduction. Twenty range bins span a total of 12.6 m of path length. Figure 77 is an image created from signals with path lengths of 65.5 m +/- 6.3 m. Each beam in the ceiling is clearly visible with a dramatic reduction in speckle. Two pairs of office windows are visible with a column separating of the pairs of windows. There are four of the wires that support the lighting reflectors visible in the image. Reflections of these wires are seen in the office windows. The reflections of the wires in the windows were overpowered by brighter reflections in the windows from the far balcony in the image taken with the mode mixing method. The range resolved intensity information allows differentiation between these two reflections. A small signal from a far balcony is visible in this image but the far balcony is physically at a longer range than the other objects in the image. Saturation in the system causes additional frequency components or range components that do not correspond to physical objects.
Figure 77: Image of the Physics Research Building atrium with signal at a roundtrip path distance of 65.5 m +/- 6.3 m.

Figure 78 shows the intensity probability distribution in blue for the pixels contained in the blue box of Figure 74. The intensity probability distribution for the same pixels in Figure 77 is plotted in red on the same figure. The intensity probability distribution for the image at a single range has a contrast $C = 0.865$. The intensity probability distribution for the image over a span of twenty ranges has a contrast $C = 0.359$. Averaging twenty range bins reduced the speckle contrast by an additional factor of 2.41.
Figure 78: Intensity probability distribution for pixels contained in the blue box of Figure 74 is shown in blue. The intensity distribution for the same region in Figure 77 is shown in red.

Figure 79 shows 11 images of the Physics Research Building atrium made from averaging 20 range bins together from 40.4 m to 103.0 m in steps of 6.3 m or 10 range bins. Progressively farther parts of the atrium are visible as the range of the picture increases. The beams in the upper left of each image are sequentially illuminated. Additionally, the 5 m outcropping of the stairwell, seen on the far right side of image j, becomes visible roughly 5 m before the far balconies become visible in image k. For ranges at image k and beyond, the saturation from the bright, specular reflections from the balcony at the far end of the atrium overpower the image.
Figure 79: Images of the Physics Research Building atrium with roundtrip path lengths centered at (a) 40.4 m, (b) 46.8 m, (c) 53.0 m, (d) 59.2 m, (e) 65.5 m, (f) 71.8 m, (g) 78.0 m, (h) 84.3 m, (i) 90.5 m, (j) 96.7 m, and (k) 103.0 m each with a width of +/- 6.3 m. Image (l) is an optical image of the same structures.
Conclusions

I investigated indirect, multi-angle illumination in the floodlight configuration with frequency modulation. I used the frequency modulation to measure the downrange power profile for each pixel. I demonstrated the three benefits of range resolved imaging. First, range resolved imaging can increase the signal to noise in an image. Including only the ranges that contain signal reduces the total noise displayed in the image. Second, I demonstrated calculations for target range illumination paths that are more complex than the direct illumination path. The round trip range information places an upper bound on the distance to the target in scenarios with unknown illumination paths. Finally, I showed that averaging signal from multiple ranges reduces speckle. Illumination paths that are resolved in range produce independent speckle patterns. I showed that fractional bandwidths as small as 1% reduce speckle contrast by a factor of 8 with indirect illumination in the grassy field configuration. Currently, there are sources in development that have a 7% fractional bandwidth at 220 GHz that could further reduce speckle by an even larger factor.
Chapter 9: Conclusions

The millimeter wave region offers a useful compromise between angular resolution of the infrared region and the ability to penetrate obscurations of the microwave region. The benefit of such advances in millimeter wave imagers are numerous as they are used, for example, to detect contraband hidden under clothes at airports and aid helicopter pilots by imaging through dust clouds.

Historically, lack of available high power sources in the millimeter wave region restricted imaging demonstrations to close ranges with direct illumination. Direct illumination of the target recovers maximum signal. However, direct illumination has two disadvantages, alignment of specular targets and speckle. Specular targets that are not in optimal alignment return no power to the imaging system. Optimal alignment of specular targets is more difficult at long range.

Images of diffuse targets are rich with speckle that degrades image quality and impairs target recognition. Diversity in illumination of polarization, incidence angle, and frequency all reduce speckle contrast. Angular diversity with direct illumination requires a rotation of either the target or the imaging system around the target. Without a compliant subject, angular diversity in a direct illumination scheme is difficult, especially at long range.
Frequency diversity reduces speckle of reflections with different path lengths. The path length difference is the characteristic surface roughness of the target for direct illumination. Speckle reduction from frequency diversity with direct illumination requires prohibitively large fractional bandwidths, often over 100%.

The development of new, high power sources in the millimeter wave region allow investigation of illumination strategies that are less power efficient but improve detection of specular targets that are not optimally aligned and reduce speckle. Illumination of a specular target from all possible angles guarantees the detection of a specular target.

I investigated a light bulb style, indirect, multi-angle illumination method. In the light bulb illumination method, the transmitter was placed in the center of a room and illuminates the walls. Reflections off of the walls illuminate the target. However, this multi-angle illumination does not reduce speckle because each illumination path is coherent. Reflecting the transmit beam off of a spinning mode mixer made the illumination paths incoherent. The mirror rotation caused the illumination paths to occur sequentially producing independent speckle patterns for each illumination path. I demonstrated speckle contrast values that are 6.5 to 12.5 times lower than a purely diffuse surface.

I investigated a grassy field style, indirect, multi-angle illumination method. In the grassy field illumination method, the transmit beam is aimed at a diffuse surface nearby the target. Steering the transmit beam on the nearby diffuse surface illuminates the target from multiple angles. The multi-angle illumination increases the chance of specular target detection. However, the angular extent of the illumination is limited by
the size of the nearby wall and is smaller than the light bulb illumination method. I showed that the speckle contrast of a diffuse target can be reduced by at least a factor of 4.1 using a small area on a nearby diffuse surface.

I investigated frequency diversity of illumination using the light bulb indirect, multi-angle illumination method. Speckle reduction using frequency diversity depends on the illumination path length differences. The illumination path length differences with indirect illumination are on the length scale of the imaging enclosure. Illumination path length differences with direct illumination are on the length scale of the surface roughness. Modest fractional bandwidths lead to speckle reduction using indirect illumination. I show that a fractional bandwidth of 1% reduces speckle contrast by a factor of 8 in a model of indirect illumination.

Frequency modulated illumination can also be used to obtain range information. The downrange profile places an upper bound on the distance to the target in a scenario with an unknown illumination path. I demonstrate an image normalization technique that decreases the speckle contrast in an image. The technique normalizes the power from each range equally. Specular reflections with a high return power do not overpower the image and specular reflections with a low return power are enhanced after normalization.

I demonstrated frequency modulated illumination in a direct illumination configuration to measure relative surface roughness information. Range information, acquired from the frequency modulation, allowed filtering of all extraneous reflections. I measured the intensity probability distributions for targets ranging from purely diffuse to
purely specular. I also showed that the speckle contrast of the distributions decreased as
the surface roughness decreased.

The work presented here provides an approach to target identification at greater
distances than previously demonstrated. The approach I investigated the challenges
created by specular targets and target identification degradation caused by speckle. The
work also points to avenues of further research that might lead to even more accurate
target at greater distances.

Future Research

Higher power sources allow imaging applications to extend to longer ranges.
Sources with larger fractional bandwidths increase the range resolution and can lead to
more speckle reduction using indirect, multi-angle illumination with frequency
modulation. A 220 GHz source with 50 W of output power and 15 GHz of bandwidth is
under development [12].

The imaging system presented in this work used a single pixel receiver. Future
research could include a receiver array with $n$ elements that decreases the image
acquisition time by a factor of $n$. The acquisition time per pixel ranged from 5 ms to 100
ms. If a receiver array has one element per pixel in the image, video frame rates are
possible. A transmitter array can steer the transmitter beam without mechanical rotation.
The fast beam steering of the transmitter array can be used for sequential activation of all
illumination angles in either the light bulb or grassy field illumination methods.
References


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