ANALYSIS OF POLARIMETRIC TERAHERTZ IMAGING FOR
NON-DESTRUCTIVE DETECTION OF SUBSURFACE DEFECTS IN
WIND TURBINE BLADES

BY

ROBERT WARREN MARTIN
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Adjunct Professor, Department of Physics and Applied Physics
ABSTRACT

During the manufacture of wind turbine blades, internal defects can form which negatively affect their structural integrity and can lead to premature failure. These defects are often not detected before the final installation of the blades onto wind turbines in the field. The purpose of this research was to investigate the advantages of using fully-polarimetric inverse synthetic aperture radar (ISAR) terahertz imaging techniques for scanning the interior structure of the wind turbine blades in order to detect and identify any defects in the blade’s internal structure before the blade leaves the manufacturer. Additionally, the research has investigated the use of the Euler parameter polarimetric transformation in improving defect detection, and increasing understanding of the scattering properties of such defects. Use of an image compositing algorithm and of the Euler parameters was found to enhance defect detection.
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I. INTRODUCTION

1.1 Background

During the manufacture of wind turbine blades, defects often appear in the structure of the blade. On occasion, these defects appear in the interior structure of the blade and cannot be detected by visual inspection. Such defects can lead to increased localized stress on the blades, which can lead to premature failure after the blades have been installed in the field [1].

A significant portion of the wind turbine blade structure is made up of various layers of fiberglass sheet laminates. During the manufacturing process, defects in these fiber materials can form, such as in-plane and out-of-plane material wave defects, and resin-starved regions. Fig. 1 depicts an example of an out-of-plane material wave defect [1].

FIG. 1. Cross-section view of a wave defect.
The effects of these internal defects in the structure of the wind turbine blades have been studied by the Center for Wind Energy at the University of Massachusetts Lowell. Their studies verify that wave defects cause increased stress in the turbine blades and that this leads to premature failure of the blades [1].

1.2. Prior work

There has been a great deal of research on the development of non-destructive investigation (NDI) techniques for the purpose of detecting defects in wind turbine blades. These include techniques based on digital image correlation, shearography, ultrasonic devices, and infrared thermography techniques [2-3]. Each approach has its own limitations.

Previous investigations have indicated that terahertz radiation is effective for scanning objects made of fiberglass composite materials [4-8]. Terahertz time-domain spectroscopy (TDS) and frequency modulated continuous-wave (FMCW) systems have been tested on various glass fiber composite materials similar to materials used in wind turbine blades. Tests on composite samples have indicated that terahertz NDI techniques can identify delaminations, debonds, foreign material inserts, and voids in fiberglass composites [4-8]. Terahertz NDI techniques have also been shown to be able to detect wrinkles in the fiber weaves [9].

However, these previous investigations have not yet tested terahertz methods on all components of a wind turbine blade. Deeper subsurfaces of the blades as well as the load bearing spar caps have not yet been thoroughly examined using terahertz imaging. Furthermore these investigations have not exploited the complete, polarimetric scattering
information necessary to establish a comprehensive understanding of fiberglass defect scattering phenomenology.

1.3 Current work

This thesis will report the results of an investigation into the use of fully-polarimetric inverse synthetic aperture radar (ISAR) operating at terahertz frequencies as a fiberglass NDI technique. Additionally, the Euler parameter polarimetric transformation is reported in this thesis. The Euler parameters are investigated for improvements in defect detection and for increasing the understanding of the scattering properties of fiberglass defects. Finally, an ISAR image compositing algorithm is employed to improve the contrast between regions with and without defects.
II. METHODOLOGY

2.1 Theory

2.1.1 Radar cross section

Electromagnetic radiation can be scattered by objects. The scattering is not generally uniform in all directions and the concept of a differential scattering cross section is commonly used to quantify the scattering phenomenon. It is defined as the ratio of scattered power density to incident power intensity in a given direction. The scattering cross section is typically defined as [10]:

\[
\sigma = \lim_{R \to \infty} 4\pi R^2 \frac{|E^{\text{scat}}|^2}{|E^{\text{inc}}|^2}
\]  

(1)

where \(E^{\text{scat}}\) represents the scattered electric field, \(E^{\text{inc}}\) represents the incident electric field, and \(R\) is the distance between the receiver and the scattering object. Although the \(R^2\) factor would appear to cause the limit to go to infinity, this is prevented by an implicit \(R^2\) factor contained within the \(|E^{\text{scat}}|^2\) term. In practice, the \(R\) dependence is removed through proper calibration of the system. In the field of radar scattering, this quantity \(\sigma\) is traditionally referred to as the radar cross section (RCS). The RCS can also be defined to include polarization dependence. This will be discussed in the next section.

The RCS is related to the radiation scattered in a specific direction and depends heavily on the angle between the source and receiver. A monostatic measurement is a measurement where there is no angular separation between the source and receiver, i.e.,
they are the same device. A bistatic measurement is a measurement where the source and receiver are separated by some bistatic angle. Most commonly in radar, the primary interest is in the radiation that has been scattered back towards its source. This means that monostatic configurations are ideal, and configurations with small bistatic angles relative to the wavelength are desired when the former option is not possible.

**2.1.2 Sinclair matrix**

RCS is a measure of the intensity of the scattered radiation, and therefore does not contain any information about the phase of the radiation. An alternative method of describing the scattering properties of an object that preserves the phase information is through the use of the Sinclair matrix. Using the Sinclair matrix, the relationship between incident and scattered electric field vectors is given by [10]:

\[
\begin{bmatrix}
E_{\text{H}}^{\text{scat}} \\
E_{\text{V}}^{\text{scat}}
\end{bmatrix} = \frac{e^{-ikR}}{2\sqrt{\pi R}} \begin{bmatrix}
S_{\text{HH}} & S_{\text{HV}} \\
S_{\text{VH}} & S_{\text{VV}}
\end{bmatrix}
\begin{bmatrix}
E_{\text{H}}^{\text{inc}} \\
E_{\text{V}}^{\text{inc}}
\end{bmatrix}
\]

Here the elements of \( S \) are the complex-valued polarization-dependent elements of the Sinclair matrix, and \( k \) is the wavenumber. The H and V subscripts stand for horizontal and vertical linear polarizations, which constitute a commonly-used polarization basis for radar operations. The phase of the scattered radiation contains a great deal of information and is necessary in order to perform any coherent data processing techniques such as synthetic aperture radar (SAR). Despite their usefulness, the complex-valued Sinclair matrix elements are often converted to RCS after the coherent data processing is complete. The polarization-dependent RCS can be obtained from the elements of the Sinclair matrix by taking the square magnitude.
Through Eq. (2), the complex-valued elements of the Sinclair matrix contain all of the scattering information of an object. Although the complex-valued information is necessary to properly process the ISAR data, the phase information is traditionally discarded after images are formed and only the square magnitudes of the Sinclair matrix elements (the RCS) are used in the resulting images [11-12].

2.1.3 Euler parameters

The Sinclair matrix can be transformed into a set of parameters that preserve the phase information and present the results in a more phenomenological manner. This transform is known as the Euler transform, which turns the four complex-valued Sinclair matrix elements into five real parameters called Euler parameters.

An optimized Euler transform was developed by Baird [11]. The transform is derived by diagonalizing the Sinclair matrix through a conjugate similarity unitary transform and extracting meaningful parameters. The conjugate-similarity transformation is of the form

$$S_D = U^TSU$$

(4)

where $S_D$ is the diagonalized scattering matrix and $U$ is the unitary matrix that diagonalizes $S$. The matrices $U$ and $S_D$ can be written in the forms

$$U = \begin{bmatrix} \cos(\psi) \cos(\tau) - i\sin(\psi) \sin(\tau) & -\sin(\psi) \cos(\tau) + i\cos(\psi) \sin(\tau) \\ \sin(\psi) \cos(\tau) + i\cos(\psi) \sin(\tau) & \cos(\psi) \cos(\tau) + i\sin(\psi) \sin(\tau) \end{bmatrix}$$

(5)

$$S_D = \begin{bmatrix} me^{i2\nu} & 0 \\ 0 & m \tan^2(\gamma)e^{-i2\nu} \end{bmatrix}$$

(6)
where $m$, $\psi$, $\tau$, $\nu$, and $\gamma$ are the five Euler parameters. The $m$ parameter is a magnitude parameter and the other four parameters are angle parameters. Although Eqs. (5) and (6) properly define the Euler parameters, these equations cannot be used to solve for the five parameters. Actually solving for the Euler parameters requires a step-by-step diagonalization of the associated Kennaugh Matrix [11].

One immediate benefit of the Euler parameters is that they each have a meaningful physical interpretation that relates to the properties of the scatterer rather than to the polarization state of the radiation. This is unlike an object’s RCS in the traditional polarization basis, which by itself only represents a scattering magnitude for certain transceiver polarization states. The information in Eq. (2) represents the measured electric field. The information in Eqs. (5) and (6) represent the physical properties of what caused the measured electric field.

The $m$ parameter corresponds to the maximum reflectivity that would be obtained using the optimum transceiver polarization state.

The $\psi$ parameter is the orientation angle of the scattering object for the maximum reflectivity. It can range between -90° to 90° and represents horizontal object orientation at 0° and vertical object orientation at ± 90°.

The $\tau$ parameter is the object symmetry angle. It can range from -45° to 45° and represents a scatterer that is symmetric about its axis at 0° and nonsymmetric about its axis at ± 45°.
The $\theta$ parameter is the bounce angle of the object and indicates whether the radiation bounces an even or odd number of times before reaching the detector. It ranges from $-45^\circ$ to $45^\circ$ and represents an odd bounce at $0^\circ$ and an even bounce at $\pm 45^\circ$.

The $\gamma$ parameter is the polarizability angle. It can range from $0^\circ$ to $45^\circ$ and indicates a strongly polarizing object at $0^\circ$ and a nonpolarizing object at $45^\circ$.

These Euler parameters could aid in the characterization of the scattering properties of objects. Work by Baird describes these parameters in detail and removes certain ambiguities that arise for certain special cases [11]. Fig. 2 is a figure from Baird’s Ph.D. dissertation which contains sample scattering objects which display the various Euler parameter values.
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<td>$\gamma$</td>
<td>Polarizing</td>
<td><img src="image1" alt="Polarizing" /></td>
</tr>
<tr>
<td>$\gamma$</td>
<td>45° Nonpolarizing</td>
<td><img src="image2" alt="45° Nonpolarizing" /></td>
</tr>
<tr>
<td>$\psi$</td>
<td>Horizontal</td>
<td><img src="image3" alt="Horizontal" /></td>
</tr>
<tr>
<td>$\psi$</td>
<td>±90° Vertical</td>
<td><img src="image4" alt="±90° Vertical" /></td>
</tr>
<tr>
<td>$\tau$</td>
<td>Symmetric</td>
<td><img src="image5" alt="Symmetric" /></td>
</tr>
<tr>
<td>$\tau$</td>
<td>±45° Nonsymmetric</td>
<td><img src="image6" alt="±45° Nonsymmetric" /></td>
</tr>
<tr>
<td>$\nu$</td>
<td>0° Odd Bounce</td>
<td><img src="image7" alt="0° Odd Bounce" /></td>
</tr>
<tr>
<td>$\nu$</td>
<td>±45° Even Bounce</td>
<td><img src="image8" alt="±45° Even Bounce" /></td>
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</table>

FIG. 2. Sample scattering objects that display various Euler parameter values. Used with permission from Baird [11].
Fig. 3 contains laboratory-measured Euler ISAR images of the commonly-used test object known as Slicy. Slicy contains several simple geometric objects including a trihedron, a hollow cylinder, and a solid cylinder.

FIG. 3. The test object Slicy and its associated Euler ISAR images at 0° azimuth and 5° elevation. Used with permission from Baird [11].
2.1.4 Data processing (standard ISAR)

Coherent radar systems that are capable of Doppler discrimination can take advantage of relative motion between the transceiver and the sample to obtain additional information about the scattering object. Synthetic aperture radar (SAR) takes advantage of the relative motion between the radar system and the scattering object to acquire cross range information about the sample [10].

A single detector can collect more information if the aperture is larger. SAR techniques allow for a single smaller detector to simulate a larger detector by taking advantage of Doppler effects caused by relative motion. The detector collects coherent data at several positions along a path. This path can either be a straight path or along a circular arc around the sample [10,13].

FIG. 4. A real aperture consisting of multiple detectors (left) and a single detector creating a synthetic aperture via movement (right).

Inverse synthetic aperture radar (ISAR) involves keeping the source/receiver stationary, and instead rotating the sample. This is physically equivalent to moving the
source/receiver along a circular arc path around the sample, but is often preferred in a controlled setting [13]. Fig. 5 is a visualization of a stationary system imaging a rotating sample.

\[ \Delta R_{\text{crossrange}} = \frac{c}{2f \sin(\Delta \theta)} \]  

where \( c \) is the speed of light, \( f \) is the center frequency of the radiation, and \( \Delta \theta \) is the total angle through which the sample was rotated for the specific synthetic aperture [13].

Scattering information as a function of range can also be acquired by using either a pulsed system or a frequency modulated continuous wave (FMCW) system. A pulsed system...
system acquires range data through time gating. In a FMCW system, coherent scattering
data is collected as a function of frequency and can be converted to range information
through the use of a Fourier transform. The limit of the range resolution of a system is
given by

\[ \Delta R_{\text{range}} = \frac{c}{2B} \]

Here \( B \) is the bandwidth of the system. Note that the range resolution is not directly a
function of frequency, although bandwidth is ultimately limited by frequency [13].

Performing a two dimensional Fourier transform over scattering data that is a
function of both frequency and azimuth angle produces data that is a function of both
range and crossrange. This grid of data constitutes what is called an ISAR image. It can
be thought of as a top-down image. Fig. 6 is a diagram that displays the range/crossrange
coordinate system of the resulting image.
FIG. 6. The definition of range and crossrange in an ISAR image. The grid represents the pixels of the image.

Additionally, before each Fourier transform is applied, the data are put through a Hanning window function. After the Fourier transforms have been applied, the complex-valued data are traditionally converted to RCS on a dBsm scale.

\[ \sigma_{\text{dBsm}} = 10 \times \log_{10}(\sigma_{\text{linear}}) \]  

(9)

This process is repeated for each of the four polarization orientations (HH, HV, VH, and VV). The data are also transformed into the Euler parameters.

Typically, scattering data are collected for a full range of angles in azimuth. This allows for ISAR images to be created for any azimuth angle. In addition to these individual ISAR images produced at each angle in azimuth, composite ISAR images were created to help enhance the contrast of defects and features. These composite
images were produced by back rotating multiple ISAR images and performing pixel-by-
pixel averaging.

2.1.5 Back rotation algorithms

The single-azimuth ISAR images must be back-rotated before the pixels can be averaged. The first two images in Fig. 7 are VV polarization ISAR images of a sample at 0° and 57° azimuth. The third image is the 57° azimuth image back rotated by 57° so that its pixels line up with the 0° image for compositing.

FIG. 7. VV polarization ISAR image of a sample at 0° azimuth (left), at 57° azimuth (middle), and at 57° azimuth and back-rotated by 57° (right).

Two different algorithms were developed to back-rotate the images. The first method is a simple coordinate rotation of the pixels of the ISAR images by an angle θ,

\[
x - x_0 = (x' - x_0)\cos(\theta) + (y' - y_0)\sin(\theta)
\]

\[
y - y_0 = -(x' - x_0)\sin(\theta) + (y' - y_0)\cos(\theta)
\]

where the primed coordinates are the new coordinates, and the naught coordinates are the coordinates of the center of rotation of the sample in the image. The rotation algorithm creates a new image one pixel at a time. Eqs. (10) and (11) are used to determine the
value of a pixel located at \((x', y')\) with respect to the original coordinates \((x, y)\) and the azimuth angle \(\theta\).

This algorithm has two downsides. One is that the trigonometric functions will inevitably produce non-integer values. There cannot be non-integer pixel coordinates, so there will always be some rounding error in this algorithm. The other downside is the dependence on the center of rotation of the sample within the image. While a few algorithms have been implemented to try to automatically find the center of rotation, they are imperfect and ultimately require manual adjustments by the user.

The second back-rotation algorithm was developed to eliminate the rounding issues faced by the first algorithm. This method performs the coordinate transformation during the Fourier transform of the data, rather than after.

The standard two-dimensional discrete Fourier transform has the following form

\[
F_{x,y} = \frac{1}{N_nN_m} \sum_{n=0}^{N_n-1} \sum_{m=0}^{N_m-1} f_{n,m} e^{-\frac{i2\pi nx}{N_n}} e^{-\frac{i2\pi my}{N_m}}
\]  

(12)

where \(f_{m,n}\) is the complex-valued Sinclair matrix element obtained for the \(m\)th frequency and \(n\)th azimuth, and \(F_{x,y}\) is the resulting complex-valued Sinclair matrix element for the pixel at the spatial location \((x, y)\). The image rotation is combined with the Fourier transform by applying Eqs. (10) and (11) to Eq. (12).

\[
F_{x',y'} = \frac{1}{N_nN_m} \sum_{n=0}^{N_n-1} \sum_{m=0}^{N_m-1} f_{n,m} e^{-\frac{i2\pi((x'-x_0)\cos(\theta)+(y'-y_0)\sin(\theta)+x_0)n}{N_n}}
\]

\[
\times e^{-\frac{i2\pi((x'-x_0)\sin(\theta)+(y'-y_0)\cos(\theta)+y_0)m}{N_m}}
\]  

(13)
While this second algorithm does not require any to-nearest-pixel rounding, it still requires the center of rotation of the image to be known in advance and requires manual adjustments. This algorithm is also very slow. This is due to existing fast Fourier transform algorithms being incompatible with the coordinate transformation.

After the ISAR images have been properly back-rotated, all of the pixels in the images that represent the same range/crossrange cell are averaged together. This produces a single composite ISAR image where each pixel is an average value of multiple pixels.

Several different compositing methods were considered and tested in order to optimize the algorithm. The primary compositing method used in this study was the mean of all of the pixels in a given range/crossrange cell with some basic thresholding applied. For the magnitude parameters, the thresholding involved excluding from the averaging any pixels with values of less than -80 dBsm. For the angular Euler parameters, only pixels whose $m$ parameter value were above -80 dBsm were included in the averaging.

Other compositing methods involved additional thresholding, such as including only a top percentage of the brightest pixels in each range/crossrange cell or excluding a top percentage of the brightest pixels in each range/crossrange cell. Taking the median value for each range/crossrange cell was also considered.

These composite images offer several benefits that aid defect detection. Noise caused by diffuse scattering, which may make defect detection in a single-azimuth ISAR image very difficult, is averaged away in the composite image. Defects that stand out against this diffuse scattering, even for a small sub-range of angles in azimuth, stand out against this diffuse scattering in the final composite ISAR images. Additionally, artifacts
of the imaging, such as the DC bias line, are averaged out. Fig. 8 contains a single-azimuth ISAR image and two composite ISAR images of a fiberglass sample. The two composite images were created using 8 and 360 single-azimuth ISAR images. The images used to form each composite image were uniformly distributed in the full range of azimuth angles, i.e. $0^\circ$ to $360^\circ$.

![Composite ISAR Images](image)

**FIG. 8.** Single ISAR image of a sample (left), composite ISAR images of a sample created by compositing 8 images (middle) and 360 images (right).

### 2.1.6 Quantitative evaluation

While the composite ISAR images show a qualitative contrast between regions with and without defects, there is a need for a way to evaluate quantitatively the effectiveness of the compositing algorithm, the polarization channels, and of the terahertz NDI technique in general.

Software has been developed which allows a user to draw a box on the composite image specifying the known location of a material defect. The user can also set the dimensions of a larger box drawn around the smaller box. The software then compares the pixels inside the smaller box to the pixels that are exclusive to the larger box. Fig. 9
contains a composite ISAR image of the sample where the inner and outer scoring boxes have been drawn.

![Composite ISAR image of a sample with no scoring box (left), the inner scoring box drawn in white (middle), and the inner and outer scoring boxes drawn (right).](image)

The purpose of this calculation is to establish a numerical score for how well a material defect shows up for a specific imaging approach. If the defect shows up well in the image where we know a defect to be, then the pixels in the inner box will produce a different value than the pixels in just the outer box (i.e., there will be high contrast between defect pixels and surrounding background pixels).

Image histograms play a major role in many aspects of image processing including image enhancement [14]. The method used to evaluate the composite ISAR images involves plotting two histograms of the values of the pixels in the two regions. A cubic spline function is applied to the two histograms, and the area under each spline curve is calculated using the Bode rule (also known as Boole’s rule) [15] and is normalized to one. The area of overlap of the two histograms is then determined and used as a measure of the contrast, called a defect imaging score. A defect imaging score of one...
indicates that the two histograms lie completely on top of each other and there is no contrast between the two pixel regions. A defect imaging score of zero indicates that the two histograms have no overlap and there is significant contrast between the two pixel regions. This scoring method has the advantage that it produces a defect imaging score that is unitless, independent of the size and magnitude of the defect, and always between zero and one.

To test the histogram scoring method, test images were created by directly assigning pixel values to an inner and outer region of a small image. The pixel values were determined by assigning to each region a base pixel value and then applying Gaussian noise to each region. Fig. 10 contains an example image where the inner region of pixels is clearly more intense than the outer region. Fig. 10 also shows the histogram cubic spline fits for the inner and outer regions used to determine the score. Similarly, Fig. 11 contains the same information for an image where there is little difference between the pixels in the inner and outer regions.
FIG. 10. An image of the example pixels on the left and their normalized histogram curves on the right. The histograms have an overlapping area of 18.4%, therefore this image has a defect imaging score of 0.184.

Several parameters of this scoring method had to be determined in order for the algorithm to be successful. The balance parameters of the cubic spline function could be adjusted and could lead to erroneous results if not chosen properly. Similarly, the relative size of the large and small boxes was an important factor that had to be carefully considered. The proper settings of these algorithm parameters were determined by applying the scoring algorithm to known situations (e.g. a bright box on a dark background with a known controlled amount of noise added).

The bins of the histogram plots were kept constant throughout the investigation. The magnitude parameters (HH, HV, VH, VV, and m) were all investigated using a histogram with 500 evenly spaced bins spanning a range from -80 to 20 dBsm. The bins
for the angle Euler parameter histograms were all 0.25° in width and spanned the full range of each Euler parameter.

2.2 Experiment

2.2.1 The fiberglass samples

Six fiberglass samples were included in this study. These fiberglass samples each contained several defects that are representative of defects that would be found in wind turbine blades. The fiberglass samples are described in detail.

Sample number 1 was provided by Sandia National Labs and contains multiple resin dry patches and out-of-plane material wave defects of various sizes and located at various depths. Fig. 12 contains a photograph and schematic of sample 1.

Sample number 2 was also provided by Sandia National Labs and contains a number of material insert defects such as grease and mold inserts. The sample also has two wooden 2 by 4’s attached to the underside of the sample via an adhesive bond line.
There are several material insert and micro balloon defects embedded in the adhesive material. Fig. 13 contains a photograph and a defect schematic of sample 2.

![Figure 13](image)

**FIG. 13.** Photograph and schematic for sample 2. Photograph is of the underside of the sample.

Sample number 3 was provided by TPI Composites Inc. and contains multiple out-of-plane material wave defects. Some of these wave defects have fibers bending out of the body of the sample, and these are designated "convex" material wave defects. Other material wave defects have fibers bending into the body of the sample and these are designated "concave" wave defects. There is also a discontinuity in sample thickness between the defect region and a thin region in sample 3. This thickness discontinuity should show up clearly in the images. Fig. 14 contains a photograph and a defect schematic of sample 3.
Sample 4 was also provided by TPI Composites and contains three out-of-plane wave defects. These three defects are smaller than those in sample 3 and are each convex material wave defects. Fig. 15 contains a photograph and a schematic of sample 4.
Sample 5 is the last sample that was provided by TPI Composites Inc. It consists of a defect-free layer of fiberglass with an adhesive bond layer on the underside. This bond layer is not of uniform thickness, and has six small material inserts embedded in the bond layer. The material inserts are tissue paper wrapped in Kapton tape. Fig. 16 contains a photograph and a schematic of sample 5.

![Sample 5 Image](image)

**FIG. 16.** Photograph of underside of sample 5 (top). Schematic of sample (bottom).

The sixth sample was provided by Sandia National Labs. It contains four out-of-plane wave defects and six resin-dry regions of various sizes. It is a sibling of sample 1, as both samples 2 and 6 were created using the same schematic. Despite sharing the same
original schematic, the two samples still differ physically. Of particular note is a large surface defect on sample 6. Fig. 17 contains a photograph and a schematic of sample 6.

![Photograph and schematic of sample 6.]

**FIG. 17.** Photograph and schematic of sample 6.

### 2.2.2 Data collection

The data in this report was collected in compact frequency modulated continuous wave radar ranges. One of these ranges operates at a center frequency of 100 GHz with a bandwidth of 16 GHz, while the other range operates at 160 GHz with a bandwidth greater than 10 GHz. Fig. 18 is a top-down diagram representative of each of these ranges [16].
FIG. 18. A diagram of the 100 GHz compact radar range used to collect scattering measurements [16].

The transmitter and receiver in these ranges are separated by a 0.3 degree bistatic angle. The receiver collects fully-polarimetric complex-valued scattering data across the full range of angles in azimuth and for a band of frequencies. These measurements were repeated for several elevation angles.
III. RESULTS AND DISCUSSIONS

3.1 Single and composite ISAR images

Samples 1 and 2 were tested in a 160 GHz radar range described in the previous section. The samples were imaged at a variety of elevation angles. Figs. 19 and 20 contain HH ISAR images of samples 1 and 2 respectively at 25° elevation and 0° azimuth. Alongside these images are the defect schematics of the samples (see section 2.2.1). These single-azimuth images are representative of the many ISAR images that were created using the collected data. The surfaces of the samples appear to be characterized by uniform diffuse scattering and the images fail to display the defects. Individual ISAR images created at different elevation angles, and for different polarizations and Euler parameters all fail to display the presence of defects. The dashed brown box indicates the location of the fiberglass sample. The rest of the image is the sample mounting apparatus.
FIG. 19. HH Polarization single-azimuth ISAR image of sample 1 at 0° azimuth and 25° elevation. A dashed brown box indicates the location of the sample in the image.

FIG. 20. HH Polarization single-azimuth ISAR image of sample 2 at 0° azimuth and 25° elevation. A dashed brown box indicates the location of the sample in the image.
Generally, the single-azimuth ISAR images do not reveal any defects by themselves. Multiple single-azimuth ISAR images can be combined into a single composite ISAR image. These composite ISAR images are more effective at producing contrast between defect and defect-free regions and therefore the rest of this report will focus on them.

Fig. 21 contains a composite ISAR image for HH polarization and at 25° elevation for sample 1 alongside its defect schematic. These images are representative of the composite images created using 160 GHz.

![Sample 1 composite ISAR image for HH polarization at 25° elevation with a dashed brown box indicating the location of the sample (left); schematic of defects with green boxes indicating resin-dry patches and grey boxes indicating out-of-plane wave defects (right).](image)

In Fig. 21 there is a noticeable region of brighter pixels near one of the wave defects. This defect is one of the larger wave defects in this sample. This defect is also the defect closest to the inspection surface. This suggests that the 160 GHz radiation is
not achieving deep penetration through the fiberglass material, and is only reaching surface defects.

Sample 2 was also imaged in the 160 GHz range. Fig. 22 contains a composite azimuth ISAR image for HH polarization at 25° elevation. Again, the sample in this image is characterized by uniform diffuse scattering. The absence of defects in the image again suggests that the 160 GHz frequency radiation has a small penetration depth into the fiberglass.

![Sample 2 composite ISAR image for HH polarization at 25° elevation with a dashed brown box indicating the location of the sample (left); schematic of defects (right).](image)

Samples 3-6 were each tested in the 100 GHz radar range. Each sample was imaged at elevation angles of 30°, 45°, and 60°. Data was collected for a full range of azimuths and across a 16 GHz bandwidth centered on 100 GHz, and used to generate ISAR images.
Several of the wave defects in sample 3 are visible in the composite HH polarization ISAR image, as shown in Fig. 23. All composite images in this section were created using 360 single-azimuth ISAR images. The concave wave defects in particular are quite visible in this image.

Composite ISAR images were also created using the Euler parameters. Figs. 24 and 25 contain a composite image for Sample 3 at 100 GHz for each of the five Euler parameters. Fig. 24 contains the $m$ parameter ISAR image and Fig. 25 contains the angular Euler parameter ISAR images. In general, the composite ISAR images for the angular Euler parameters are not as revealing as the traditional polarimetric ISAR images, while the $m$ parameter is typically better at producing contrast between defect and defect-free regions than the traditional polarization images.
FIG. 24. Composite $m$ parameter ISAR image of sample 3 at 30° elevation created by compositing 360 images with a dashed brown box indicating the location of the sample (left), and a defect schematic (right).
Composite ISAR images were also generated at 45° and 60° elevation. Fig. 26 contains $m$ parameter ISAR images for sample 3 at 45° and 60° elevation.
FIG. 26. Composite $m$ parameter ISAR images of sample 3 at 45° elevation (left) and 60° elevation (right). Dashed brown boxes indicate the location of sample 3 in each of these images.

All of the images above were generated using the simpler back rotation algorithm, given by Eqs. (10) and (11). Fig. 27 (left) is a composite $m$ parameter ISAR image of sample 3 at 30° elevation created using the Fourier-space back rotation algorithm described by Eq. (13). Fig. 27 also contains a composite $m$ parameter ISAR image created using the basic image back rotation algorithm. While the Fourier-space rotated image has extra bright pixels near the edges of the image, the sample itself appears effectively identical in each of the two images. Since the two techniques produced similar images and since the Fourier method took significantly longer to run, only the simpler technique was used in this study.
FIG. 27. Fourier space back rotation (left) and simple pixel back rotation (right) composite $m$
parameter ISAR images of sample 3 at 30° elevation. Dashed brown boxes indicate the location of sample
3 in each of these images.

As shown on the previous pages, many types of images were created for sample 3.
Samples 4 through 6 received the same treatment, with multiple types of images being
created. The $m$ parameter composite ISAR image consistently produced the best
defect/defect-free region contrast for all samples. Figs. 28-30 contain $m$ parameter
composite ISAR images for samples 4 through 6 at 30° elevation.
FIG. 28. Composite $m$ parameter ISAR image of sample 4 at 30° elevation created by compositing 360 images with a dashed brown box indicating the location of the sample (left), and a defect schematic (right).

FIG. 29. Composite $m$ parameter ISAR image of sample 5 at 30° elevation created by compositing 360 images with a dashed brown box indicating the location of the sample (left), and a defect schematic (right).
FIG. 30. Composite $m$ parameter ISAR image of sample 6 at 30° elevation created by compositing 360 images with a dashed brown box indicating the location of the sample (left), and a defect schematic (right).

The three wave defects in sample 4 are not easily visible in Fig. 28. There is a diagonal region of contrast in the approximate area of a wave defect in the schematic, but there is not very strong contrast by eye.

None of the defects in sample 5 are visible in Fig. 29. This is likely due to the radiation being unable to penetrate the 1 inch thick layer of defect-free fiberglass.

Several of sample 6's defects are visible in Fig. 30. The large vertical line of bright pixels is not a subsurface defect, but is an unintended surface defect. To the left of that line is a region of bright pixels that correspond to the same wave defect that was visible in Fig. 21 on sample 1. There is also a region of brighter pixels corresponding to the second resin defect from the right. The two rightmost resin defects in the schematic diagram are the thickest resin defects in the sample, and therefore the closest resin defects
to the surface. This suggests that the 100 GHz radiation penetrates the fiberglass better than the 160 GHz radiation, but is still not reaching the deeper defects.

3.2 Quantitative evaluation and parameterization of the algorithm

While these images appear to be able to qualitatively indicate defects, there is a need to quantitatively evaluate the contrast in these images between defect-free and defect-positive regions. Using the histogram scoring algorithm described in section 2.1.6, the contrast can be quantified. Fig. 31 is a composite ISAR image for sample 3 created using 360 ISAR images. The image contains a white box indicating the boundaries of the inner region used to score the defect imaging algorithm, with the outer box (not shown) extending an extra two pixels in each direction. Table 1 contains the results of the score for this particular image and box boundaries. A lower defect imaging score indicates better contrast.

<table>
<thead>
<tr>
<th>ISAR image type</th>
<th>defect imaging score</th>
</tr>
</thead>
<tbody>
<tr>
<td>HH polarization RCS</td>
<td>0.715</td>
</tr>
<tr>
<td>HV polarization RCS</td>
<td>0.619</td>
</tr>
<tr>
<td>VH polarization RCS</td>
<td>0.640</td>
</tr>
<tr>
<td>VV polarization RCS</td>
<td>0.635</td>
</tr>
<tr>
<td>$m$ Euler parameter</td>
<td>0.532</td>
</tr>
<tr>
<td>$\gamma$ Euler parameter</td>
<td>0.864</td>
</tr>
<tr>
<td>$\tau$ Euler parameter</td>
<td>0.910</td>
</tr>
<tr>
<td>$\psi$ Euler parameter</td>
<td>0.828</td>
</tr>
<tr>
<td>$\nu$ Euler parameter</td>
<td>0.636</td>
</tr>
</tbody>
</table>

TABLE 1. Defect imaging scores for a defect in sample 3 using the composite ISAR image created by compositing 360 images. A lower defect imaging score indicates better contrast.
Table 1 indicates that of the 9 different types of ISAR images created, the $m$ parameter image produces the best contrast (lowest score value) between defect pixels and defect-free pixels.

To optimize the imaging algorithm, the parameters of the image compositing algorithm were respectively swept through their full range of values and the defect imaging scores were used to determine the optimum parameters. The first of these parameters was the number of images used to create the composite image. Fig. 32 is a plot of the defect-imaging-score vs number-of-images data, for the defect box shown in Fig. 31. The four traditional polarizations and the 5 Euler parameters are included in this plot.
While the scores are very inconsistent for a lower number of images, they level out after about 120 images or so. The plot indicates that the $m$ parameter scores the best contrast of the 9 ISAR image types, and offers significant improvement in contrast over the traditional polarizations.

Next, defect-imaging-score vs number-of-images data were generated for multiple defects within sample 3, and for select defects in samples 4 and 6. Each of the defect-imaging-score vs number-of-images plots looked very similar to Fig. 32. The defect imaging score is very inconsistent for a low number of images, but the scores stabilize after including 120 images or so. The $m$ parameter proved to produce the best contrast in the ISAR images for all of sample 3's wave defects. Fig. 33 shows the inner scoring boxes of all of the visible defects included in the defect-imaging-score vs number-of-images plots. Only the defects that produced noticeable contrast are included in Fig. 33.
The included defects consist of 7 out of the 11 wave defects in sample 3, 1 out of the 3 wave defects in Sample 4, 1 out of the 4 wave defects in sample 6, and 1 out of the 6 resin-dry regions in sample 6.

To study the overall performance of the technique and the scoring algorithm, the results for each of these defect boxes were averaged together. This is possible because the score for each defect is unitless, independent of the absolute values of the pixels, and only depends on the relationship between the pixels in the inner and outer regions. The normalization of the histogram curves to 1 also makes the scores independent of the sizes of the scoring boxes. For these reasons, the scores can be averaged together within the 9 separate types of ISAR images. Fig. 34 is the resulting defect-imaging-score vs number-of-images plot for the averages of all the scores of the defects shown in Fig. 33, and Table 2 shows the numerical scores for 360 images composited together.
TABLE 2. Defect imaging score for the average of all defects shown in Fig. 33 using composite ISAR images created by compositing 360 images. A lower defect imaging score indicates better contrast.

<table>
<thead>
<tr>
<th>ISAR image type</th>
<th>defect imaging score</th>
</tr>
</thead>
<tbody>
<tr>
<td>HH polarization RCS</td>
<td>0.706</td>
</tr>
<tr>
<td>HV polarization RCS</td>
<td>0.679</td>
</tr>
<tr>
<td>VH polarization RCS</td>
<td>0.683</td>
</tr>
<tr>
<td>VV polarization RCS</td>
<td>0.595</td>
</tr>
<tr>
<td>$m$ Euler parameter</td>
<td>0.562</td>
</tr>
<tr>
<td>$y$ Euler parameter</td>
<td>0.850</td>
</tr>
<tr>
<td>$\tau$ Euler parameter</td>
<td>0.804</td>
</tr>
<tr>
<td>$\psi$ Euler parameter</td>
<td>0.748</td>
</tr>
<tr>
<td>$\nu$ Euler parameter</td>
<td>0.722</td>
</tr>
</tbody>
</table>

FIG. 34. Defect imaging score, averaged over all defects shown in Fig. 33 vs the number of images composited for each of the 9 types of ISAR images. A lower defect imaging score indicates better contrast.

These results add quantitative evidence to the observation that the $m$ parameter composite ISAR images consistently produce the best contrast, and therefore the best
imaging of defects. Interestingly, the VV polarization composite ISAR images score better than the other 3 traditional polarizations. Fig. 34 also demonstrates quantitatively that the compositing algorithm significantly improves defect detection.

As part of the histogram scoring algorithm, a cubic spline fit is applied to each histogram plot. One of the parameters of this fitting routine is called the balance parameter. The balance parameter ranges from 0 to 1. At the value of 0, the cubic spline is just a linear fit to the data. At the value of 1, the cubic spline interpolates linearly between every individual data point. Fig. 35 contains a sweep of the possible values of this balance parameter. Fig. 35 also shows the defect used for the fitting. The balance parameter was swept from 0 to 1 in steps of 0.05.

![Fig. 35](image-url)

**FIG. 35.** Defect-imaging-score vs balance-parameter plot (left) for the defect shown in the ISAR image (right). A lower defect imaging score indicates better contrast.

For comparison, this sweep was also performed in a region where the score is expected to be worse since there is no physical defect present. The result is shown in Fig.
36. As expected, the areas of overlap are much higher in this region than the region in Fig. 35, indicating worse contrast.

![Graph showing defect-imaging-score vs balance parameter plot](image)

**FIG. 36.** Defect-imaging-score vs balance parameter plot (left) for the region shown in the ISAR image where there is no physical defect (right). A lower defect imaging score indicates better contrast.

Fig. 37 is a plot of the difference of the scores shown in Figs. 35 and 36. This plot assisted in determining which value of the balance parameter to use for scoring the defects. The difference in scores tends to peak near a balance parameter value of 1.0 for most ISAR image types, before plummeting to a difference of 0.0 at a balance parameter value of exactly 1.0. To clearly avoid this drop in defect imaging performance while maintaining a reasonable difference between scores in defect/defect-free regions, a balance parameter of 0.85 was used when determining defect imaging scores throughout the study.
Different compositing and thresholding techniques for compositing images together were also considered. The standard compositing method included all pixels above a certain threshold for each range/crossrange cell. Other compositing methods applied additional thresholding or calculated the median value of the pixels instead of the mean. Table 3 contains the average score for each of these techniques across all defects included in Fig. 33, and Table 4 contains the description of each of these compositing techniques.
TABLE 3. Average defect imaging scores across all defects included in Fig. 33 for several image compositing techniques. The composite images used to obtain these scores were created by compositing 360 images.

<table>
<thead>
<tr>
<th>compositing method</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
<th>H</th>
</tr>
</thead>
<tbody>
<tr>
<td>HH polarization RCS</td>
<td>0.706</td>
<td>0.648</td>
<td>0.689</td>
<td>0.737</td>
<td>0.729</td>
<td>0.649</td>
<td>0.642</td>
<td>0.647</td>
</tr>
<tr>
<td>HV polarization RCS</td>
<td>0.679</td>
<td>0.631</td>
<td>0.631</td>
<td>0.665</td>
<td>0.686</td>
<td>0.617</td>
<td>0.619</td>
<td>0.608</td>
</tr>
<tr>
<td>VH polarization RCS</td>
<td>0.683</td>
<td>0.643</td>
<td>0.637</td>
<td>0.663</td>
<td>0.681</td>
<td>0.632</td>
<td>0.635</td>
<td>0.619</td>
</tr>
<tr>
<td>VV polarization RCS</td>
<td>0.595</td>
<td>0.604</td>
<td>0.586</td>
<td>0.632</td>
<td>0.675</td>
<td>0.598</td>
<td>0.605</td>
<td>0.591</td>
</tr>
<tr>
<td>$m$ Euler parameter</td>
<td>0.562</td>
<td>0.527</td>
<td>0.580</td>
<td>0.632</td>
<td>0.684</td>
<td>0.529</td>
<td>0.530</td>
<td>0.526</td>
</tr>
<tr>
<td>$\gamma$ Euler parameter</td>
<td>0.850</td>
<td>0.882</td>
<td>0.842</td>
<td>0.809</td>
<td>0.798</td>
<td>0.857</td>
<td>0.856</td>
<td>0.874</td>
</tr>
<tr>
<td>$\tau$ Euler parameter</td>
<td>0.804</td>
<td>0.748</td>
<td>0.788</td>
<td>0.785</td>
<td>0.804</td>
<td>0.797</td>
<td>0.790</td>
<td>0.808</td>
</tr>
<tr>
<td>$\psi$ Euler parameter</td>
<td>0.748</td>
<td>0.704</td>
<td>0.690</td>
<td>0.673</td>
<td>0.605</td>
<td>0.780</td>
<td>0.740</td>
<td>0.742</td>
</tr>
<tr>
<td>$\nu$ Euler parameter</td>
<td>0.722</td>
<td>0.687</td>
<td>0.724</td>
<td>0.739</td>
<td>0.721</td>
<td>0.702</td>
<td>0.696</td>
<td>0.697</td>
</tr>
</tbody>
</table>

TABLE 4. Description of compositing methods included in Table 3. The $m$ parameter was used to determine the "brightest" pixels for the angular Euler parameters.

<table>
<thead>
<tr>
<th>method</th>
<th>description</th>
</tr>
</thead>
<tbody>
<tr>
<td>method A</td>
<td>mean of all pixels above the threshold for each range/crossrange cell</td>
</tr>
<tr>
<td>method B</td>
<td>median of all pixels above the threshold for each range/crossrange cell</td>
</tr>
<tr>
<td>method C</td>
<td>include brightest 50% of pixels above the threshold for each range/crossrange cell</td>
</tr>
<tr>
<td>method D</td>
<td>include brightest 25% of pixels above the threshold for each range/crossrange cell</td>
</tr>
<tr>
<td>method E</td>
<td>include brightest 10% of pixels above the threshold for each range/crossrange cell</td>
</tr>
<tr>
<td>method F</td>
<td>exclude brightest 10% of pixels above the threshold for each range/crossrange cell</td>
</tr>
<tr>
<td>method G</td>
<td>exclude brightest 20% of pixels above the threshold for each range/crossrange cell</td>
</tr>
<tr>
<td>method H</td>
<td>exclude brightest and dimmest 10% of pixels above the threshold for each range/crossrange cell</td>
</tr>
</tbody>
</table>

HH appears to produce the poorest defect imaging score among the traditional polarizations, although the median technique and techniques which exclude the brightest pixels offer improvements to HH's score. HV and VH perform better than HH but not as well as VV, which produces the best contrast between defect pixels and non-defect pixels among the traditional polarizations.
The \( m \) Euler parameter consistently produces the best defect imaging score of the 9 ISAR image types, while the angular Euler parameters tend to perform worse than the traditional polarizations and the \( m \) Euler parameter. The only exception is for the compositing technique E, where only the brightest 10\% of the pixels were included. In this case, \( \psi \) reports the best defect imaging score. The differences in the \( m \) parameter defect imaging score for different compositing techniques are small. The compositing method H (excluding the brightest and dimmest 10\% of the pixel values in each range/crossrange cell) and method B (median of all pixels) applied to the \( m \) parameter ISAR images produce the best defect imaging score in the table.

Finally, Fig. 38 is a composite ISAR image of sample 3 created using the best image processing parameters determined in this study. The composite ISAR image in Fig. 38 was created by compositing 360 \( m \) parameter ISAR images using method B in Table 4 (median of all pixels).
FIG. 38. Composite $m$ parameter ISAR image of sample 3 at 30° elevation created by compositing 360 images using the median method with a dashed brown box indicating the location of the sample (left), and a defect schematic (right).
IV. RECOMMENDATIONS

There is a great deal of future work to be done in this area. From a fiberglass and wind turbine NDI standpoint, many different types of defects and different regions of wind turbine blades have yet to be imaged by terahertz radiation. A truly beneficial NDI technique will excel at detecting a wide array of defect types in many regions of a turbine blade or other fiberglass structure.

There also remains work to be done on the terahertz imaging technique itself. There remain optimizations in the data collection techniques itself and in the compositing algorithm. Other ISAR based data collection and data processing techniques such as azimuth/elevation scans, interferometric ISAR (IFISAR), and full 3D ISAR scans are techniques whose benefits to NDI have yet to be fully explored. The image compositing algorithm in its current state sweeps across the full range of azimuths. For materials such as fiberglass that are not necessarily isotropic, some azimuthal angles might offer better terahertz depth penetration than others. Identifying these optimum angles and incorporating this concept into the compositing algorithm could offer improvements in defect detection.

Finally, the $m$ Euler parameter has been shown to offer significant improvement over the traditional polarizations. There are other polarimetry transformations that can be investigated for improvements in defect detection.
V. CONCLUSIONS

Terahertz radiation has been proven capable of detecting several subsurface defects in fiberglass materials. The 100 GHz frequency system appeared to be more successful at indicating subsurface defects than the 160 GHz frequency system. Although unable to detect every defect in every sample, out-of-plane fiber wave defects and resin dry regions have been shown to be detectable via terahertz ISAR data collection.

Most importantly, traditional ISAR data processing alone was not sufficient to produce ISAR images with enough contrast for defect detection. The single-azimuth ISAR images rarely produce any images where defect contrast is present, and even then the contrast is minimal. The image compositing algorithm developed in this study offers significant improvements in defect detection over traditional single-azimuth ISAR images. This claim is supported qualitatively from the images themselves, and quantitatively from the defect imaging score data.

Additionally, the Euler $m$ parameter has been shown to produce the best contrast between defect and defect-free regions in the images generated in this study. The $m$ parameter consistently outperformed the traditional polarizations used in the radar field, as well as the other four Euler parameters. This significant improvement over any of the traditional polarizations reveals the benefit of not only utilizing a fully polarimetric system for nondestructive evaluation, but also using the optimized Euler transform on the polarimetric scattering data.
VI. LITERATURE CITED


BIOGRAPHICAL SKETCH OF AUTHOR

In 2009, Robert W. Martin received his high school diploma from Quabbin Regional High School located in the town of Barre MA. He immediately entered the University of Massachusetts Lowell to study physics. He received his B.S. in physics in 2013 and remained at the University of Massachusetts Lowell to pursue a Ph.D. in physics.