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THESIS

THZ IMAGING FOR NONDESTRUCTIVE EVALUATION OF COATED METALLIC SURFACES OF NAVAL SYSTEMS

by

Keith L. Gibson

June 2022

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13. ABSTRACT (maximum 200 words)

Structural deficiencies and subsequent repairs significantly contribute to the late completion of submarines and ship availabilities, resulting in a reduced deployment capability. Using terahertz real-time imaging to nondestructively identify structural defects could significantly reduce maintenance down time. This research investigates the possibility of using terahertz to perform nondestructive evaluation on coated surfaces of naval vessels and other systems. The Navy's THz studies, including current capabilities, are surveyed and analyzed. Theoretical aspects of THz properties of materials are studied on the framework of nondestructive evaluation. Leveraging real time, high resolution imaging to identify small surface defects, a Microxcam-384i camera in combination with a THz illumination source emitting at 0.5 THz was used to perform several tests. The ability to detect abnormalities on the coated metal surfaces such as air and water pockets, corrosion, cracks, and wrinkle without removing the coating was accessed. This study shows that many coatings used in naval systems are suitable for real-time imaging nondestructive evaluation, and defects such as cracks, corrosion, wrinkle, and water pockets can be detected without the removal of the coating. Preliminary results indicate that there are many opportunities for improvement and identification of specific characteristics of imaging systems required for different coatings.

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THZ IMAGING FOR NONDESTRUCTIVE EVALUATION OF COATED METALLIC SURFACES OF NAVAL SYSTEMS

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LIST OF ACRONYMS AND ABBREVIATIONS

CCD	charged coupled device
CW	continuous wave
ENBW	equivalent noise bandwidth
ET	eddy current inspection
FDS	frequency domain spectroscopy
FFT	Fast Fourier Transform
FPS	frames per second
GHz	gigahertz
HCN	Hydrogen Cyanide
HPUT	high power ultrasonic test
IR	Infrared
MRC	maintenance requirement card
MT	magnetic particle test
NASA	National Aeronautics and Space Administration
NDE	non-destructive evaluation
NDT	non-destructive testing
NEP	noise equivalent power
POC	Physical Optics Corporation
PT	liquid penetrant test
RT	radiographic test
SHT	special hull coating
SNR	signal-to-noise ratio
SUBMEPP	Submarine Maintenance Engineering, Planning and Procurement
TDS	time domain spectroscopy
THz	terahertz
UT	ultrasonic test
VT	visual inspection

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I. INTRODUCTION

A. BACKGROUND

Since the formation of the Congressional Navy in 1775, the United States of America placed an emphasis on building ships for the country's defense. Naval shipyards provide the Navy the ability to build, repair, and modernize the ships that our Sailors serve on today. As the Navy continues to build and implement new technologies on ships, the amount of work needed for completion exceeds the shipyards capacity to perform that work in 25 out of the next 30 years. The primary cause for shipyard delays comes from the increase in the total amount of work needed for new construction ships, all the maintenance needed for each project, and not enough personnel to perform the workload. The 30-year shipbuilding plan that the Department of Defense submitted would put the total number of warships over 400 by 2051. Currently, the Navy's four options for reducing delays are: improve the accuracy of maintenance projections to better reflect the operation schedule, increase the workforce, shift maintenance to private shipyards, or reduce the size of the nuclear fleet [1].

A different way to approach these problems involves developing new technologies and improving existing ones to decrease the amount of man-hours required for each job. Shipyards perform many types of testing including non-destructive testing (NDT), which consists of magnetic particle testing, penetrant testing, eddy-current testing, radiography, and ultrasonic testing [2]. NDT determines the integrity of a material, component, or structure without causing damage to the component itself. One method becoming more prevalent is terahertz (THz) Imaging.

THz imaging using electromagnetic waves in the far infrared (IR) ranges from approximately 100 GHz to 10 THz. It is biologically safe [3] and capable of seeing through materials such as paint, rubber, ceramic, and other non-metallic surfaces [4]. THz can be used to detect flaws in materials such as corrosion/pitting, debonds, voids, and water intrusion [5], making it ideal for use of naval platforms.

B. CURRENT NDT TECHNIQUES

The Navy's shipyards focus on the following methods of NDT: liquid penetrant test (PT), magnetic particle test (MT), radiographic test (RT), ultrasonic test (UT), eddy current inspection (ET), and visual inspection (VT) [6]. These tests used to locate structural defects in many components such as pipes and welds, are usually performed after maintenance or routine inspection. Each has distinct advantages and disadvantages. On the latter, THz imaging has a great potential to improve upon [2].

PT uses a liquid that is poured on material with defects where it enters the flawed area. From there, the surface is cleaned and developed so the surface defect can be seen. Although PT is convenient, cheap, and works well for crack detection, the flaw must not be covered or interfered with by any other material. The surface must be cleaned and easily accessible. On the other hand, THz imaging could reveal the similar flaws, while being able to work with materials that are coated and in harder to reach areas [2].

MT applies iron particles to the tested area that is magnetized. The particles move to the flawed area where a visual analysis is performed. For this process, the material must be ferromagnetic and an electrical power source is required, but the method is inexpensive and flaws can be detected below the surface. THz imaging could help detecting similar surface defects, while not requiring a ferromagnetic material [2].

RT uses a gamma or x-rays source to image a component made of any material to determine its structural integrity. RT provides high quality images compared to all other types of NDT for any type of material. Despite this, the downside of RT is that it is expensive from needing to replace the source often due to radioactive decay when gamma rays are used. RT also damages biological tissue making it a safety hazard that is regulated by the government. When using RT to inspect welding, all other work in that area stops resulting in many man-hours lost [2].

UT transmits high frequency sound waves into a component to detect flaws below the surface. Sounds reflects back to the transmitter where the signal is analyzed. UT penetrates deep into a material and can detect small defects, but requires a large scan area with a smooth surface for best accuracy. By having deep penetrating detection capabilities, UT has advantages over THz, but studies show integrating UT and THz has potential to further improve the abilities to detect defects [2].

ET relies on inducing a magnetic field where defects are seen when the induced current is altered. It is sensitive to small defects and gives fast results, but requires a skilled worker to operate and only works on conductive materials. THz images could provide similar results working on coated materials [2].

VT is straight forward and is effective at detecting surface defects on easily seen uncoated materials. It is inexpensive, but does require some inspection tool to maximize its effectiveness [2].

C. CURRENT PROBLEMS WITH THZ IMAGING

While different imaging techniques can lead to useful results, the difficulty of getting useable data quickly and easily is difficult. There is a balance between speed, resolution, and portability. Imaging surfaces at high speed leads to a low signal-to-noise (SNR) ratio that lowers the image resolution and results in a missed flaw if the image is degraded. Improving the image quality takes time. Scanning an area of 50ft by 50ft takes an entire day to get a large enough SNR ratio [7].

Portability maximizes the utility of THz imaging. The ability to apply a THz imager to active maintenance to see surface defects in real time is the motivation of this research. In order to detect flaws through coated materials, an illumination source is required in coordination with an imager. The THz source provides the THz radiation that either penetrates or reflects off the material where it can be captured by the imager. Achieving a high resolution with a portable camera is difficult and also depends on the THz source strength [8].

D. STATUS OF RESEARCH

Applications of THz imaging are not limited to NDT in a shipyard environment, but includes the fields of medical [9], security [10], and space [11] to name a few. This is a rapidly growing field of untapped potential. Nevertheless, in an attempt to solve the Navy problems associated with non-destructive testing, the NAVSEA Warfare Centers have worked on THz Imaging since 2010. They work on various projects including inspections on the hull, sensors, pipe lagging, heatblock spray foam insulation, torpedo nose array, radome, cabling, and passive countermeasures system. The results from these projects succeeded in completing the requirements for Unrestricted Operation Maintenance Requirement Card URO MRC 003 [7]. Some of this work is described in Section II.

Intending to continue the investigation on THz technology for NDE, leveraging high speed and high resolution imaging, this thesis work was conducted to help answering the following questions: What surfaces could be inspected nondestructively using terahertz technology? What coatings permit NDE using fast and high resolution THz imaging? How abnormalities such as cracks, corrosion, and wrinkle can be identified using THz imaging? How could THz technology be refined to enable effective and efficient nondestructive inspections of Naval and Marine system surfaces?

E. THESIS ORGANIZATION

Our research focuses on identifying potential targets for THz imaging technology based on characteristics of different coated materials used by the Navy. Chapter II provides an in depth literature review that summaries the work done in the field of THz imaging and shows many techniques that we intend to use as well as improve upon. Chapter III describes the basic theoretical principles that support THz imaging and a survey of THz absorptivity of several materials. Chapter IV describes the THz imaging system and the techniques used in measurements. In Chapter V, the experimental results are shown and discussed on the premise of what defects we can detect as well as improvements we need to make to our system to refine our results. Chapter VI brings the concluding remarks and highlights advantages and limitations of the used system in addition to planned future work.

F. BENEFITS OF THIS STUDY

Structural deficiencies and subsequent repairs significantly contribute to the late completion of submarines and ship availabilities resulting in reduced deployment capability and diminish the national defense capability [1]. Using THz imaging to non-invasively identify substrate structural defects prior to a vessel's arrival within a shipyard is paramount to enable the shipyard to program required resources, materials, and repair duration within the availability.

THz imaging identifies defects in coated materials such as piping, tanks, or the hull creating immense resource capacity within the maintenance environment as well as the ability for personnel to be cognizant of internal component and structural defects to exercise risk assessments for decision making not previously available. Maximizing development of this technology for waterborne applications will provide the greatest ability to exploit predictive planning, supporting on time delivery of ships and submarines, and reduce the amount of man-hours needed for NDT.

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II. CURRENT RESEARCH IN THZ IMAGING

This chapter outlines the research ongoing in the THz Imaging field and how it developed into what it is today. The THz range is defined as 100 GHz to 10 THz. The first images generated using THz radiation occurred in the 1960s [12] where the biggest challenged involved finding usable sources of THz, sensitive detectors, and ways to analyze the images taken. The invention of the hydrogen cyanide (HCN) laser allowed for a source at 1.12 THz, along with advancements in spectrometer and fast digital methods of computing Fourier transforms [8], THz imaging became an area worth investing time and money in for further enhancing its potential.

In February of 2003, the Columbia space shuttle's external tank lost portions of its foam which impacted its wing during launch. This ultimately led to the loss of the shuttle and everyone on board sixteen days later [13]. This event could have been avoided with proper inspection techniques that we are using and developing today. After the incident, the National Aeronautics and Space Administration (NASA) began to look at NDE techniques to prevent these events from happening. They looked at five NDE techniques and found that Pulsed THz Imaging at 150 GHz and Backscatter radiography had the most potential. Their testing criteria detected defects of one inch diameter cylinders down to half inch diameters and a height of no less than half an inch. They found that THz detected the voids more reliably than the backscatter radiography method [14].

In 2006, The Naval Air Warfare Center conducted work to use THz imaging for automatic NDE and detection of foreign objects in composite components [15]. They constructed a prototype THz imaging device and identified NDE techniques to be used to help identify debris in composite materials such as plain weave carbon, carbon fiber tape, and Kevlar. To establish there THz-TDS they test three different ultrafast lasers, a Kapteyn-Murnane Labs kit laser, an IMRA Femtolite F-100, and a Femtolasers Integral 50. There data showed that beam diameter and focus distance play an important role in how well the beam can focus on the target. Smaller beam diameters do not allow the laser to focus as tightly, but allow the laser to be more easily aligned. When the diameter of the laser is increased, spherical aberrations limit the beams usefulness [15].

Over time, the Navy also became more interested in THz imaging as a form of NDT and expanded on their research efforts. In 2012, PNTS Incorporated began work for Naval Sea Systems Command on how to demonstrate a THz imaging system suitable for defect detections and NDE for corrosion, hull coating delamination, and hull surface gouges. Their work merges continuous wave (CW) THz and time domain spectroscopy (TDS) THz. THz-CW accounts for changes the amplitude of a specified frequency, while THz-TDS looks at the time-domain signal, spectral amplitude, or the time-delay of the pulse. Using this method, their team wanted to increase the scanning speed to meet specific SNR targets. Their team coated the hull with an elastomeric coating and used 0.1 THz to analyze the sample. By using THz-CW, a wide area of the sample was covered to determine if there were any defected areas. The same sample was then analyzed with THz-TDS for a more detailed image once the defects were found. Even with little image processing, the results showed many of the defects [7].

In 2018, Naval Undersea Warfare Center performed research to combine THz image scanning of coated surfaces with high power ultrasound (HPUT) [5]. Their goal was to perform an inspection of special hull treatment (SHT). SHT covers the hull in order to minimize the sound profile of the submarine and needs to be taken off in order and put back on to inspect the metal underneath. Using THz imaging to perform the same inspection without removing the SHT would greatly reduce the time and cost needed for maintenance. A flaw size of 0.125 inches was analyzed, and by combining a 40 kHz HPUT source with THz imaging, the metal crack resonates into the coating material. The coating experiences density fluctuations that alter the refractive index near the crack. By changing the refractive index, the THz beam redirects in that region and is then able to be seen when analyzed. After scanning the material, the results showed that under the given conditions, the crack was not able to be detected. It was determined that excitation energy was not high enough to reach the crack and increasing the source caused the coupled material used to break down due to heat. In further research, it could still be possible for this method to be successful with strong material able to withstand a higher HPUT source [5].

The Navy expanded their use of THz research to include NDE of missile radomes. In January of 2013, the company Wavetech, sponsored by Naval Sea Systems Command, performed NDE and characterization of missile radomes [16]. By using THz-TDS, Wavetech wanted to reduce the cost of validating radomes prior to service. The Navy employs many systems that have radomes where any small surface defect can attenuate the radar's signal. They saw that using THz-TDS in the bandwidth of 0.2-3.5 THz resulted in satisfying spectroscopic analysis with low loss and dispersion. Their methods showed that defects down to the size of 0.5 mm to possible, but not for every material and the defects could not be identified in situ, which poses a significant limitation. Developing a library of data over time of to identify common defects would be useful. Another reoccurring problem seen is the speed at which the THz analysis can be done. If the speed of the THz characterization of materials is increased, the signal-to-noise ratio lowers resulting in poor imaging resolution. Overall, they concluded that more research and funding is needed to make there method of THz-TDS practical [16].

The usefulness of THz imaging is not limited to the Navy. In 2010, Physical Optics Corporation (POC) developed a lightweight, low-cost, and high resolution portable THz imaging device for the U.S. Army [17]. Their product is sensitive to THz radiation from 0.5 to 3.4 THz with a peak at 6 mW/cm^2 and response time under 90 milliseconds. The THz source emits radiation through their optical system to the intended target. The radiation that returns to the receiver is sent to a CCD camera and modulated, where an image forms. In order for the image to form, POC developed an imaging system that uses a silicon and glass substrate, where the THz beam passes through the silicon, but the glass substrate blocks the THz beam. These substrates are coated with polyimide and aligns a liquid crystal material when rubbed. The THz detector material consists of doped carriers that generate a charge that responds to the incident THz field that form charge transfer complexes, changing the birefringence of the liquid crystal. A probe reads the THz field variation and then converts to an intensity variation on the 2D receiver. The videos recorded by the camera have a frame rate of 30 fps with 33 milliseconds between frames. By using software programs like LabVIEW, the images are enhanced, so the level of detail seen increases, but still cannot be done in real-time with their current equipment [17].

The Airforce is also interested in THz technology. In 2008, Christopher Stoik et al. researched at the Air Force Institute of Technology on NDE of Aircraft Composites using

THz time domain spectroscopy. He sought to use THz imaging to evaluate different composite materials used by the Airforce to overcome some of the shortcomings of other established NDE techniques. Using two different scan methods, a transmission configuration that collected data of the optical and electrical parameters and then a reflection configuration that measured for flaws at different depths in the same materials [18]-[19].

In addition to NDE, THz imaging is also used in the medical field. In 2016, Pallavi Doradla et al. [9]. researched how THz imaging could detect colorectal cancer. Using THz-TDS and sources between 0.2-1 THz, they were able to design an endoscopic imaging tool and see the change in the absorption between healthy tissue [9]. This shows that there was a significant difference in the absorption of the materials analyzed, but not in their refractive index.

In 2005, Federici et al. conducted research to analyze how THz could be used for different security applications. This is particularly useful to identify explosives and drug since many of them including C-4, HMX, RDX, TNT, and Methamphetamine, can be distinguished from other materials in the THz spectrum. Currently, millimeter wave technology is used, but THz gives better resolution and allows easier identification of the material. They found that using a transmission setup allowed for smaller objects to be seen well. As the object size increased, THz does not penetrate as well and the object becomes opaque. At this point reflection mode worked well. Having multiple sensors to see the image also improved the image quantity [10].

Using the knowledge from this research, we performed experiments using a THz camera to develop a classification method to quickly identify defects in materials used by the Navy. By cataloging the spectral characteristic of different material, we hope to make THz imaging a fast and reliable tool used to decrease the time needed and increase the success rate for NDT of naval assets.

III. THEORETICAL ASPECTS AND SURVEY OF MATERIAL PROPERTIES

In this Chapter, techniques and technology related to THz detection are discussed. Methods used in our research, as well as other techniques used in the THz imaging field are surveyed. These methods include spectral analysis of THz frequencies, understanding absorption and reflection criteria for different materials, and properties of materials we use for THz imaging.

A. TECHNOLOGIES FOR BROADBAND DIELECTRIC MEASUREMENTS

Optical properties of dielectric materials can be obtained through spectroscopy. The systems used are either open-loop or closed-loop. Both systems contain an emitter that is the source of the THz radiation, a detector to receive the THz and image of the object being measured, and an optical set up to focus the image into the detector. In closed-loop systems, the emitter and detector are connected to a common source, whereas in an open-loop system, they act separate. Time-domain spectroscopy (TDS) and frequency-domain spectroscopy (FDS), are examples of a closed-loop system that use single THz pulse or continuous wave lasers with offset wavelengths, respectfully [20]. In our research, we use an open-loop system described in Chapter IV of this paper.

1. Time Domain Spectroscopy

The majority of the research covered in Chapter II uses TDS because it provides a large bandwidth that is convenient to configure, as well as frequency resolution up to 10 GHz. TDS used a pulsed signal from its laser on the order of femtoseconds. The interval between pulses can be adjusted to meet specific requirements. Figures 1 and 2 provide an example of TDS from National Physical Laboratory showing time domain data and how it is transformed in the frequency domain [20].

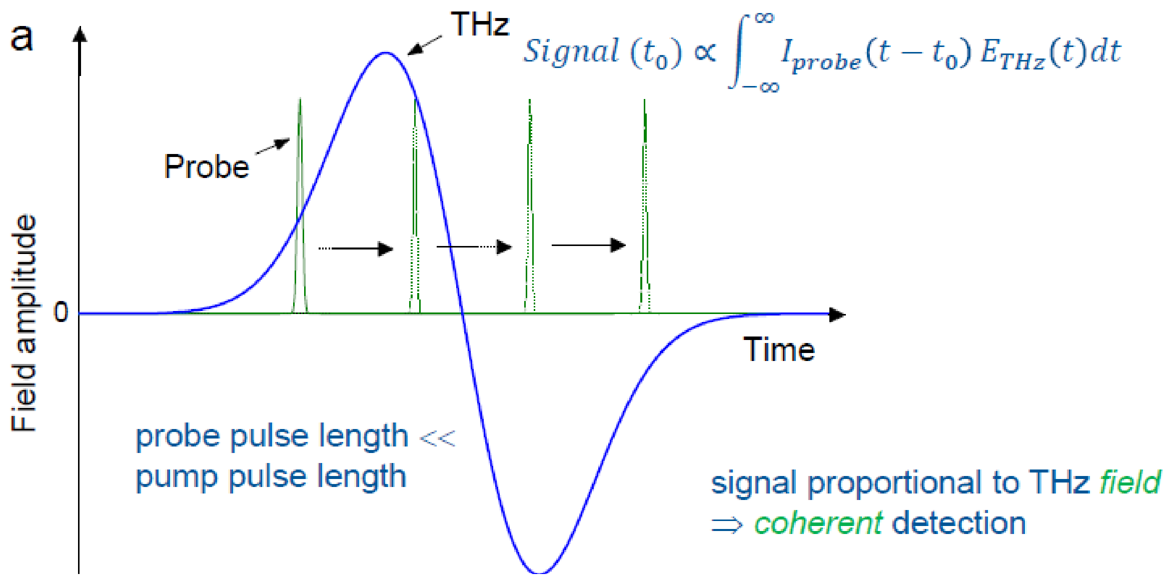


Figure 1. Plot of time vs. amplitude for a THz pulse. Source: [20].

Figure 1 shows the laser pulse from the probe, as well as, the THz signal. The probe outputs a pulse at discrete intervals on the femtosecond scale. By taking the time different between pulses and multiplying by the amplitude of the THz pulse, integration across all time allows to find out how much of the signal contributes to coherent detection. Information obtained in the time domain can then be transformed to the frequency domain using a Fast Fourier Transform (FFT) to obtain phase data. With all this information, it is possible to extract the refractive index and absorption coefficient from the TDS data. The refractive index is given by:

$$n(\omega) = 1 + \frac{(\phi_{ref} - \phi_{sample})c}{2\pi fd}$$

where ϕ represents phase for the reference and sample, c represents the speed of light, f represents frequency, and d represents the sample thickness [20]. The refractive index indicates how much a material reflects or transmits THz radiation. Materials with high refractive indexes tend to reflect THz and would not be transparent for THz imaging [21]. The absorption coefficient can be found using

$$\alpha(\omega) = -\frac{2}{d}\ln(T\frac{E_{sample}}{E_{ref}})$$

where E represents the amplitude of either the sample or reference [20]. The absorption coefficient provides a meaningful way to describe how well a material will absorb THz radiation. For our research, the coatings we examine should have low absorption coefficients in order to see the underlying surface for NDE.

2. Frequency Domain Spectroscopy

Similar to TDS, FDS uses a THz source and detector with optics in between to direct the THz beam, but instead of a single THz pulse, continuous wave lasers generate a frequency difference using two lasers with offset wavelengths [20]. With the CW lasers, sinusoidal waves that are slightly out of phase are analyzed to where a specific transmission frequency can be obtained. This gives a much narrower bandwidth compared to TDS, but provides a higher resolution.

B. ABSORPTION IN MATERIALS AT THZ FREQUENCIES

Understanding absorption to determine how a material behaves under THz radiation is important in determining if a material can be analyzed during NDE. The absorption coefficient, refractive index, frequency, conductivity, and polarity play an important role in understanding absorption. One way to measure the conductivity is using the Drude model [20]

$$\sigma(\omega) = \frac{\sigma_0}{1 - i\omega\tau_c} + i\frac{\sigma_0\omega\tau_c}{1+\omega^2\tau^2}$$

where σ represents the conductivity and τ represents the free charge carrier relaxation time. The Drude model describes how free charge carriers and carrier relaxation time effect conductivity. Figure 2 shows a plot of absorption over a frequency range and how it is affected by conductivity.

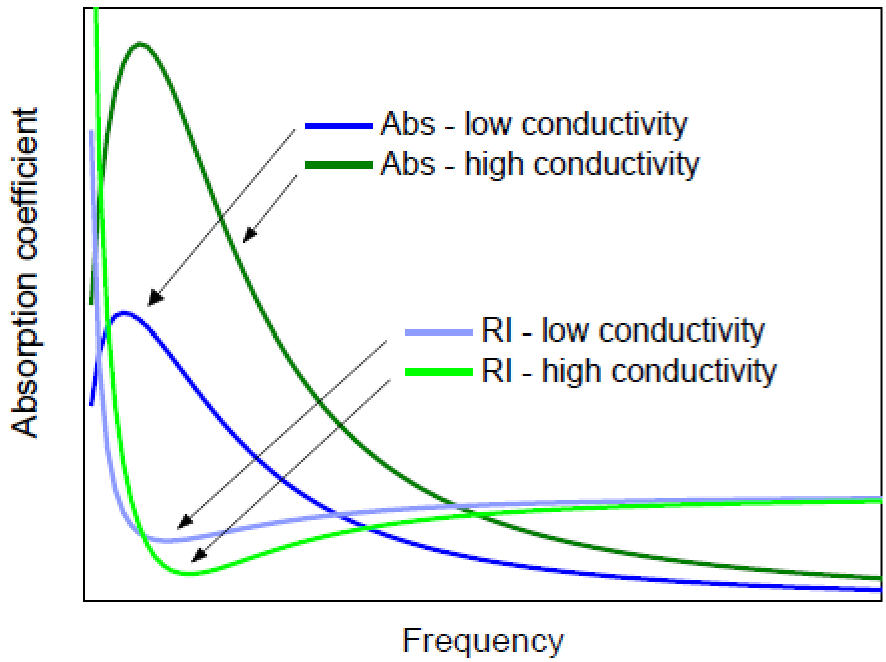


Figure 2. Absorption coefficient for different conductivities obtained using the Drude Model. Source: [20].

From the graph, we can see that absorption, abbreviated Abs on Figure 2, decreases as frequency increases, but when comparing the conductivity between two different materials, the absorption increases as conductivity increases. This means that for a specific frequency, a materials conductivity determines how suitable a specific coating is for NDE. Materials with low conductivity will be more transparent and better suited for NDE.

In order to be transparent, a material must also be non-polar. When a polar-molecule interacts with an electromagnetic field, dipoles form that oscillate at the same rate of the electromagnetic field. As frequency increases, the dipoles oscillate rapidly resulting in absorption. This effect is modelled by the Debye model [20]

$$\varepsilon = (\varepsilon_\infty + \frac{\varepsilon_0 - \varepsilon_\infty}{1+\omega^2\tau_d^2}) + i(\frac{(\varepsilon_0 - \varepsilon_\infty)\omega\tau_d}{1+\omega^2\tau_d^2})$$

where ε_0 represents the dielectric constant and ε_∞ represents the dielectric constant at high frequencies (i.e., $\omega\tau_d >> 1$). The response time of the dipoles is τ_d. Non-polar materials have low values of the difference in the dielectric constant and high frequency dielectric constant. As frequency increases the dipoles have more resistance from the material, which causes absorption. Figure 3 uses this model from National Physical Laboratory to plot an example to show how the absorption coefficient and refractive index changes with frequency for water.

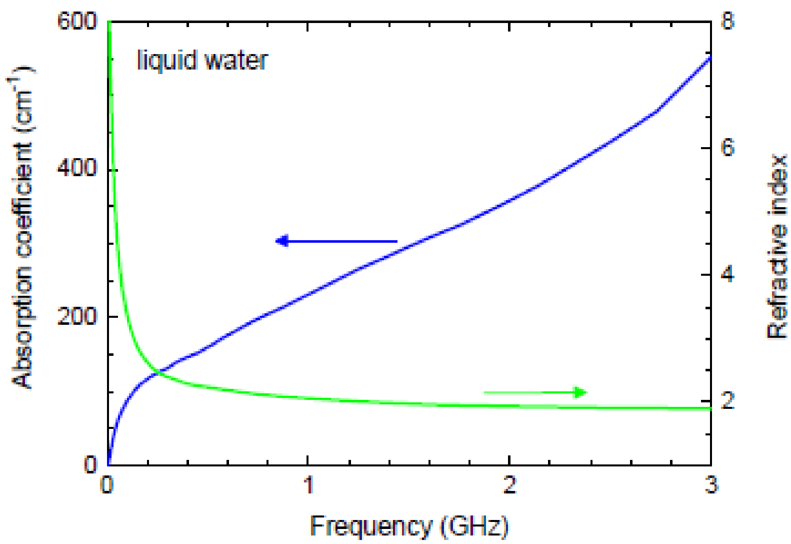


Figure 3. Frequency and absorption coefficient change for water using the Debye model. Source: [20].

Figure 3 shows the absorption coefficient in blue and the refractive index in green of water. As frequency increases the refractive index decreases rapidly at first, but quickly becomes constant. The absorption coefficient increases with an increase in frequency [20]. For our research, the THz source is at 500 GHz resulting in a large absorption coefficient. This allows us to easily detect the presence of water using the THz camera. Water causes corrosion when in contact with metal piping and can result in component failure over time. Water that has been absorbed in pipe lagging or insulation can easily be detected. This will be shown in Chapter V of this thesis.

Table 1 lists the absorption coefficient and refractive index for various representative materials, found in the open literature.

Table 1. List of Absorption Coefficients and Refractive Indices for various materials. Sources: [22]–[26].

Material	Absorption Coefficient (1/cm)	Refractive Index
HDPE	0 (0.5 THz)	1.532 (0.5 THz)
PP	0 (0.5 THz)	1.495 (0.5 THz)
Polyurethane	0.3 (1 THz)	1.34 (1 THz)
ABS	5 (0.5 THz)	1.57 (0.5 THz)
PLA	11 (0.5 THz)	1.89 (0.5 THz)
Nylon	9 (0.5 THz)	1.72 (0.5 THz)
Bendlay	1.8 (0.5 THz)	1.532 (0.5THz)
Polystyrene	0.5 (0.5 THz)	1.561 (0.5 THz)
Pyrex	0.954 (0.5 THz)	2.105 (0.5 THz)
Topas	0.20 (Avg 0.5-5 THz)	1.531 (Avg 0.5-5 THz)
Zeonex	0.184 (Avg 0.5-5 THz)	1.529 (Avg 0.5-5 THz)
Teflon	0.26 (Avg 0.5-5 THz)	1.466 (Avg 0.5-5 THz)
Silica	0.47 (0.5 THz)	1.962 (0.5 THz)
TNT	13.5 (1.62 THz)	
DNT	9.5 (0.45 THz)	
NT	99.8 (1.21 THz)	
DNB	47.5 (0.94 THz)	
Tetryl	8.8 (1.17 THz)	
RDX	108.7 (0.82 THz)	
HMX	61.3 (1.78 THz)	
PETN	131.8 (2.00 THz)	
NG	71.5 (1.43 THz)	
DMNB	148.6 (1.15 THz)	
KClO4	305.5 (2.00 THz)	
Black Powder	95.6 (1.81 THz)	

IV. EQUIPMENT DESCRIPTION

A. INTRODUCTION

In order to detect flaws through coated surfaces of materials, we use a THz camera in conjunction with a THz illumination source. Many materials such as paint, plastics, and dry, non-polar, low-conductivity materials do not absorb THz and exhibit good transparency in this band, whereas metals are good reflectors. Polar liquids such as water are good THz absorbers [20]. Detection of water damage or water content in areas it is undesirable is useful to the Navy. Water damage, as well as surface defects, can be detected with using a portable, lightweight, real-time imaging THz imaging system that could be used before, during, and after performing maintenance for non-destructive evaluation.

In this thesis work, a Microxcam-384i-THz Camera is used in combination with a 0.5 THz illumination source from the Canadian company INO. The camera outputs real-time video at 50 frames per second (fps), as well as still images. The camera's sensor is an uncooled microbolometer focal plane array (FPA) with 384 x 288 pixels. A Silicon lens optimized for THz wavelengths between 198 GHz and 4.5 THz [27] is used for focusing the image on the FPA. INO has made significant progress in reducing the noise-equivalent power (NEP) to 32 pW/Hz$^{1/2}$, resulting in an optical minimum detectable power of 35 pW on the entire electronic bandwidth [27]. Figure 4 shows an image of the Microxcam-384i that we employed for our research.

Figure 4. Image of the Microxcam-384i on a tripod stand.

The illumination source used for our research also comes from INO. The frequency of the source is 515 GHz (or 0.515 THz) with an average power of 1.25 mW at the output window. The source produces a THz beam of 160 mm by 120 mm [27]. The polyethylene optics is specifically designed to provide a flat wavefront, uniformly distributing the output power over the entire area of the output window. As the frequency increases, the image resolution improves, but at the cost of penetration depth. Decreasing penetration depth limits the amount of defects able to be seen. The balance between these two characteristics has to follow the application demands. In future work, it is the intention to use multiple THz sources of varying output power. Figure 3 shows a picture of the THz illumination source. The imaging system can be configured in either transmission or reflection mode.

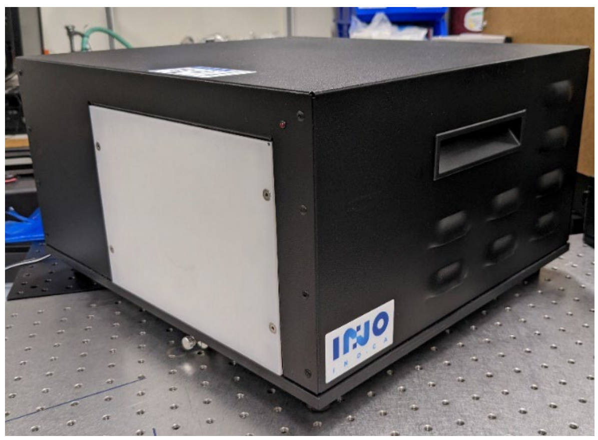


Figure 5. THz Illumination Source.

B. REFLECTION AND TRANSMISSION MODES

Figure 6 shows our setup for imaging in transmission mode. The camera is placed at approximately 40 cm away from the source.

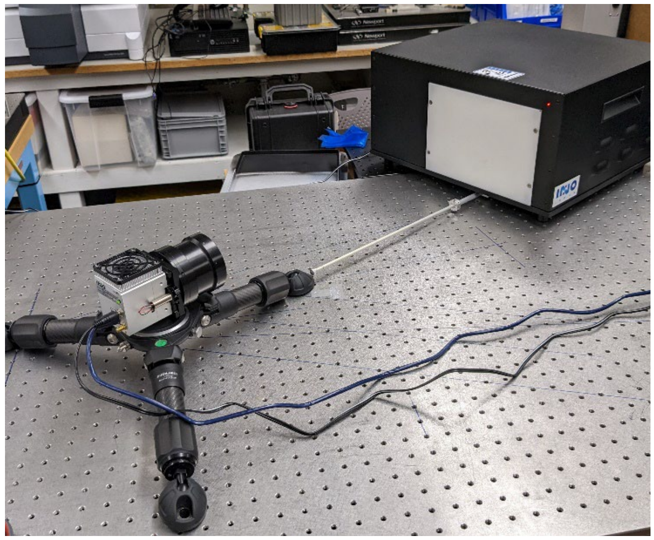


Figure 6. Camera and Source in Transmission Mode.

The image quality depends on the THz transmissivity of the object at the THz band of the source. Transparent objects allow for the camera to image the THz beam coming from the source (bright). Totally opaque objects will completely block the beam and just the silhouette can be seen by the camera (dark). In between, there will be a combination of gray tones proportional to the amount of THz absorbed by the object. Transmission mode is convenient to characterize THz transparency of coatings when applied to transparent substrates. This mode works well with thinner samples or when convenient to put the object between the source and camera, but this is not always practical. In addition, it cannot be used to detect the surface defects on metals, since metals reflect THz radiation [20].

A reflection mode setup (Figure 7) allows for detection of defects in coated metallic surfaces. By removing the focusing lens from the source, one object is placed at an angle directly in front of the THz source. Figure 4 shows the camera and source arrangement for imaging in reflection mode.

Figure 7. Camera and Source in Reflection Mode.

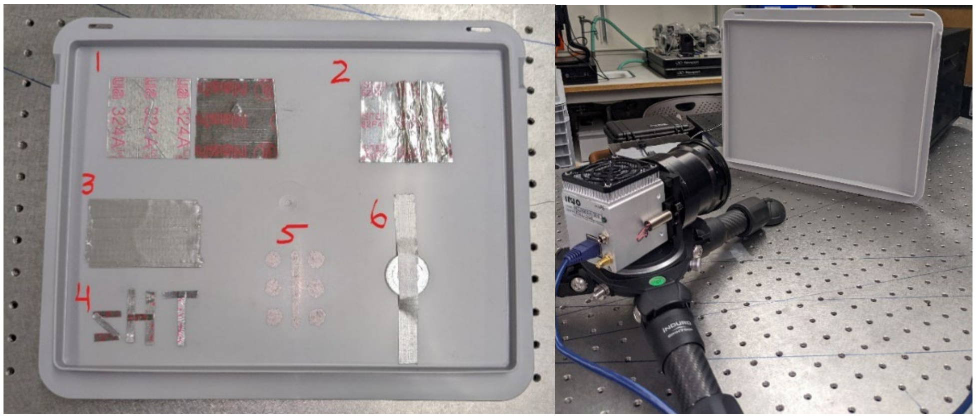
The THz beams reflected off of the object are focused by the polyethylene lens into the camera. Figure 7 shows a square steel plate coated with black paint. Flaws underneath the paint could be seen without removing the painted coating. This process can be done with any coatings that do not strongly absorb THz radiation [20]. For the experiments using reflection mode, we look at surface defects on metal objects coated with different types of coatings. We also look at how water damage affects insulation and foam. Water absorbs THz radiation making it appear black and easy to detect.

V. EXPERIMENTAL RESULTS

This chapter describes experiments in both transmission and reflection mode to characterize the imaging results in order to determine if detection of surface defects in coated metal surfaces is possible. We begin by viewing objects in transmission mode, looking about what materials are best suited for transmission mode inspection. Continuing, we use reflection mode to inspect the surface of coated metal plates to see how different coatings absorb THz radiation and how that affects the surface underneath. It is important to mention that all THz images shown in this chapter are raw still pictures extracted from the Microxcam-384i camera. Absolutely no image processing, such as edge enhancing, contrast and brightness compensation, etc., was used.

A. PLASTIC

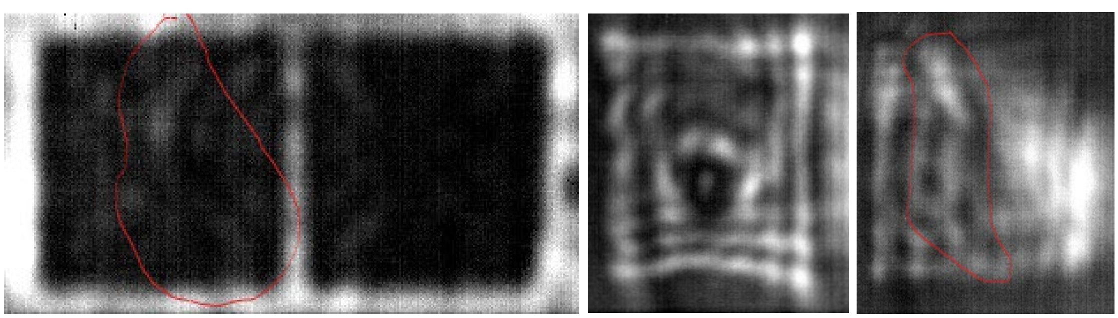
First, we tested the camera's performance for detecting several different metallic configurations through plastic. Navy NDT is used to detect the presence of flaws such as cracks, corrosion, wrinkle, leak detection, and structural characterization [6]. We set up several trials to determine if THz can detect similar characteristics. Figure 8 shows a test plastic made of 2 mm thick Polypropylene used with labelling 1 through 6. The first consists of two pieces of metallic tape, the left with a 2 mm crack down the center and the right with a 7 mm wide raised defect. Number 2 is a metallic tape used to simulate wrinkle in metal, number 3 is layered duct tape, number 4 is the letters "THz," number 5 is metallic paint, and number 6 is a metal washer with duct tape on top.



(a) (b)

Figure 8. (a) Test to detect crack, wrinkle, and visual characterization. (b) Front side presented to camera.

The upper left corner of Figure 8 (a), labeled 1, shows two pieces of metallic tape. The left square has a 2 mm wide tear down the middle representing a crack. The right square has a 7 mm wide raised defect. Figure 8 (b) shows the Polypropylene lid where none of the defects can be seen through the material. Figure 9 shows the metallic squares in transmission and reflection mode.



(a) (b) (c)

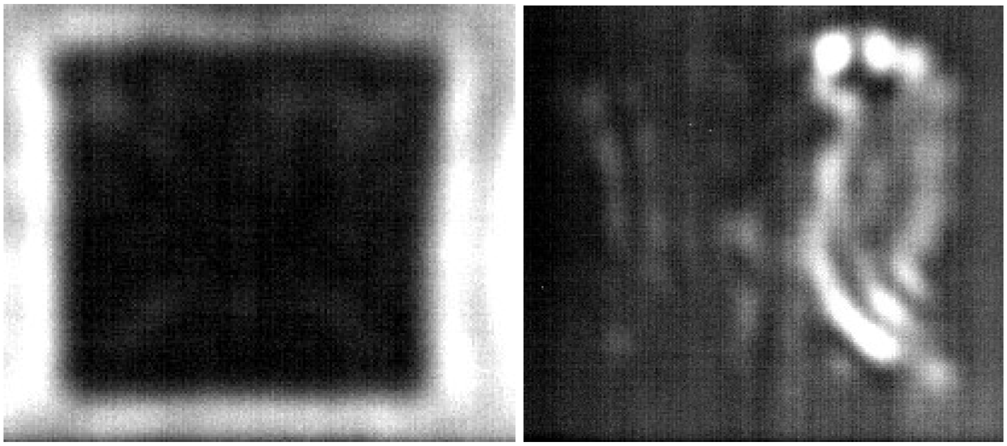
Figure 9. (a) Metallic tape with crack and raised defect in transmission mode, (b) Raised defect in reflection mode, (c) Crack in reflection mode.

In Figure 9 (a), the crack can be observed in the left most square (TM). The curved lines of the crack pattern stick out against the rest of the square, and compared to the right square, the defect is difficult to detect in a still image, but more easily detected when viewing in real time. The gap provides a difference in the areas where THz is reflected. In the right square, the raised defect is not detected. The THz penetrates through the plastic and it is reflected back to the source. Since THz does not pass through the metallic layer, the raised defect cannot be identified.

In the middle of Figure 9 (b), the raised defect is shown in reflection mode. The THz radiation is scattered by the uneven edges of the defect allowing the peaks of the defect to appear dark compared to the uniform areas. In Figure 9 (c), the crack in the metallic tape is shown in reflection mode. The crack is harder to detect in reflection mode than transmission mode.

From these examples, we conclude that cracks can be detected in both transmission and reflection mode, but are more easily seen in transmission mode due to the gap transmitting the THz and the metal reflecting it. Raised defects should be viewed in reflection mode in order to be detected. Further studies need to be conducted to determine the minimum detectable resolution of this system.

The upper right corner of Figure 8, labeled 2, shows a piece of metallic tape where a portion of it is flat and the other simulates an exaggerated case of the surface defect wrinkle. Figure 10 shows the wrinkle in transmission and reflection mode.



(a) (b)

Figure 10. (a) Metallic tape used to simulate the surface defect of wrinkle in Reflection Mode, (b) Transmission Mode.

The image on the left shows the wrinkle in transmission mode. THz radiation does not penetrate the metal resulting in a uniform black image. Taking the same material in reflection mode, the wrinkles become more apparent due to scattering.

From Figure 8, the material label 4, we determine how clearly we can resolve the lettering “THz” through the plastic. At the thinnest part, the lettering is 5 mm wide. Figure 11 shows the metallic letters in transmission mode. At 5 mm, the lettering is clearly resolved.

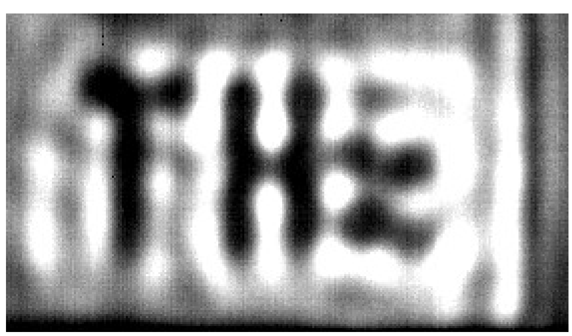


Figure 11. Metallic Lettering “THz” shown in Transmission Mode.

In the center of Figure 8, labelled 5, we draw a pattern with metallic paint to determine a minimum thickness that the camera can resolve. Figure 12 shows the metallic paint in transmission mode.

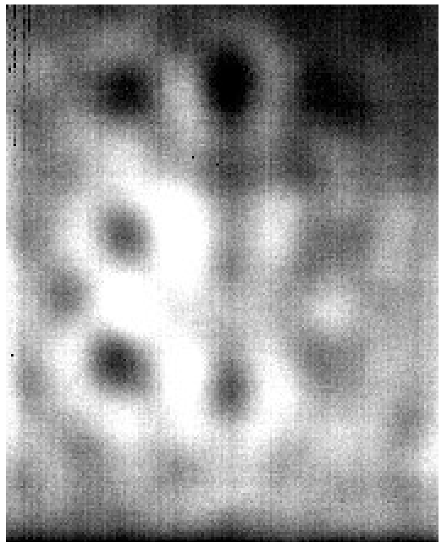


Figure 12. Metallic paint shown in Transmission Mode.

The metallic paint is the thinnest possible thickness applied to the surface. Despite the minimum thickness the paint absorbs the THz radiation and camera resolves the image.

To continue our studies of plastics, we determine the effect of adding a coating of paint to the plastic lid and add metallic tape to act as the object of interest. The paint used is a black enamel aerosol from Krylon with an estimated thickness of 50–60 microns per layer [28]. The paint consists mainly of Acetone, Propane, n-Butyl Acetate, and Butane with a relative density of 0.77 [29]. Figure 13 shows the coated plastic used. Figure 14 shows the plastic in transmission mode with no coat, one layer of paint with the metal object, and the plastic with 3 layers of paint and metal object.

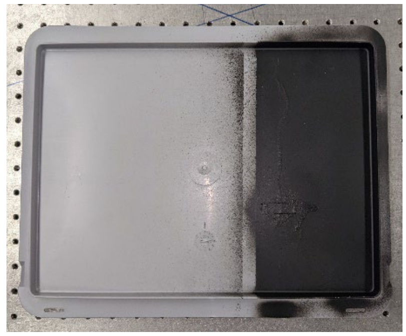
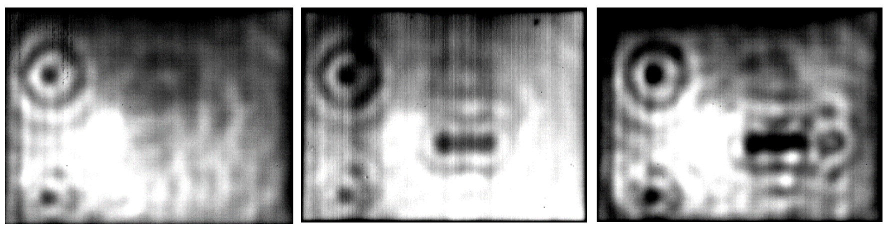


Figure 13. Plastic lid with paint coating.



(a) (b) (c)

Figure 14. (a) Plastic Lid in transmission mode with no coating, (b) 1 layer of paint coating and metal object, (c) 3 layers of paint coating and metal object.

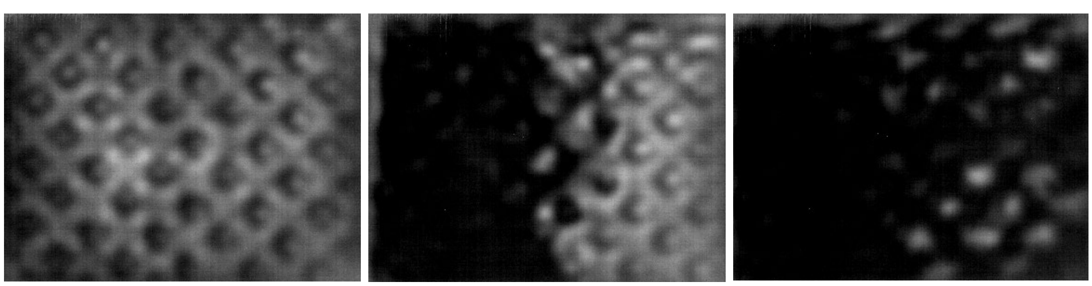
Figure 14 (a) shows that the plastic is transparent with minor surface defects that are natural to the plastic. The circles on the left side of the image are seen visibly in Figure 13, but show up clearly through the plastic in transmission mode due to their defined ridged features. A piece of metal tape is added to the plastic and a coat of paint is applied over it. The applied coating is completely transparent to THz radiation. The line of paint from top to bottom, seen in Figure 13, cannot be resolved when viewed in transmission mode. Because of this, the metal tape shows up plainly through the coating and plastic. In Figure 14 (c), three layers of paint cover the metal tape. The tape can still clearly be seen, but deformations in the paint begin to form. The paint bulges around the area around the metal tape and the different layers are seen due to the non-uniform application of the paint. By adding multiple layers, the difference in thicknesses between different layers becomes apparent. From this, we can conclude that using THz to resolve delamination in materials is possible.

B. FOAM

After performing our analysis on plastics, we examined foam to see how water intrusion and structural defects appear with THz radiation. The Navy uses foam or different types of insulating material throughout different vessels, such as to insulate piping or fill in voids between structures. Corrosion of pipes and other metal materials on ships due to water is of great concern on Navy vessels. Water soaks into the foam or lagging around a pipe from a leaking source and can cause damage that is not visible and remains undetected until a structural failure occurs.

For this experiment we determine how water absorption in foam is resolved in transmission mode. Figure 15 shows a half inch piece of convoluted foam made of polyurethane used for this experiment. Figure 16 shows the same foam in transmission mode and the effects of water absorption as it progresses through the foam.

Figure 15. Foam insulation

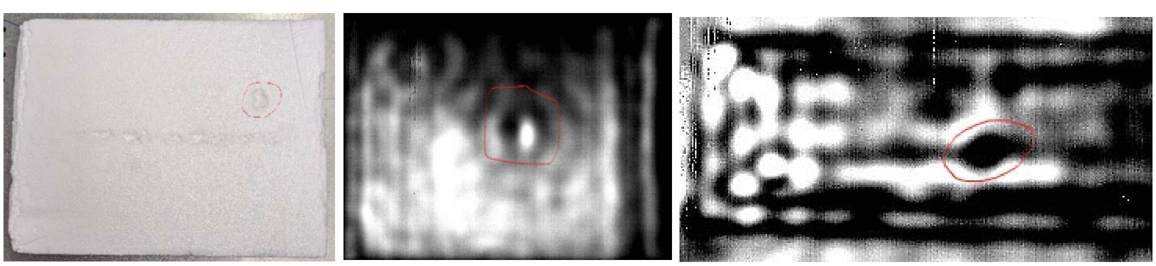


(a) (b) (c)

Figure 16. (a) Foam insulation in transmission mode, (b) partial water intrusion, (c) severe water intrusion.

The foam is non-polar with a density of 0.03 grams per cubic centimeter and transparent to THz [30], while the divited pattern can still be seen due to its thicker defined ridges that absorb slightly more THz. We then slowing soak the foam in water. Water absorbs into the foam at a rapid rate and clearly shows under THz radiation. The water absorbs THz and appears black compared to the rest of the foam, shown in Figure 16 (b). As more water absorbs into the foam, the image becomes entirely black and unrecognizable. Shown in Figure 16 (c), the foam is completely filled with water. Onboard ships and submarines, this process occurs slowly over time, but the damage would still occur if left unperturbed. Using a THz camera to inspect area likely to see water damage or that would be problematic if water damage did occur, would stop the corrosion before the pipe failed and allow the replacement of the foam or lagging.

Another defect that we examine in foam is general damage that could be holes or missing sections of the foam due to repeated impacts or damage over time. These effects lessen the protection that the foam provides resulting in potential damage to the underlying component. For this, we look at styrofoam to see the damage effects. Figure 17 shows an image of stryrofoam on the left, the stryrofoam in transmission mode in the center, and a side view of the defect on the right.



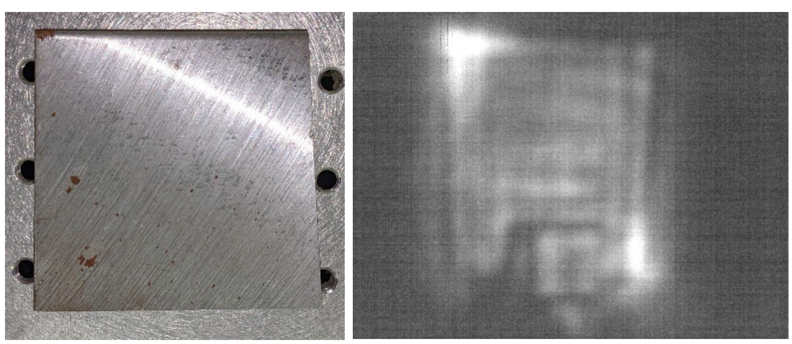
(a) (b) (c)

Figure 17. (a) Image of Styrofoam, (b) Styrofoam in transmission mode, (c) side view of Styrofoam in transmission mode.

The styrofoam block we use has a small hole in the upper right section 1.5 cm wide. The image in transmission mode captures the hole and the surrounding areas to where the viewer clearly sees the defected area. In this case, we also want to know how deep the flaw extends into the foam, but a perpendicular image does not display the penetration. We see inside the block by turning it on its side. Since the styrofoam is transparent, we see the bottom of the hole where the foam's thickness is greater from being crushed down. The defect shows up clearly in real-time, but the still photo still shows the black spot circled in red.

C. METAL PLATE

After operating the camera in mostly transmission mode, we switch to imaging metal plates in reflection mode. The majority of THz imaging's use will come from reflection mode when determining damage under coatings. Since metal does not transmit THz (due to reflection and absorption), the source and camera must be on the same side of the material being imaged and separated by an angle of less than 90 degrees similar to that shown in Figure 7. To start work on the metal plate, we establish a base line of what we should expect when viewing damage and undamaged plates. Looking at four different iron plates, we see how they differ in reflection mode. Figure 18 shows an image of a metal plate with minimal damage and no coating in reflection mode.

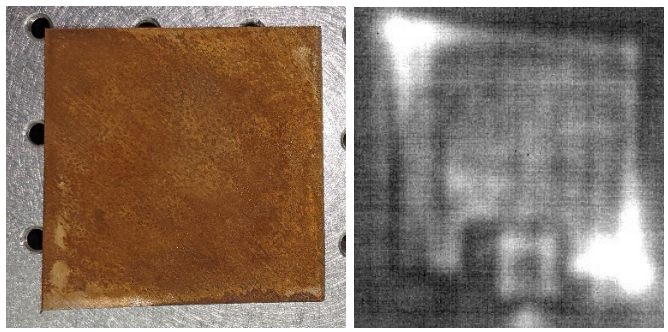


(a) (b)

Figure 18. (a) Picture of metal plate with no damage and no coating, (b) THz image in reflection mode.

The rust on the plate is no more than 1 mm at the largest spot and does not create a large enough divot in the metal to be noticed on the camera. The small amount of rust on the plate cannot be resolved in reflection mode. The image in Figure 18 (b) shows a clean plate with a square shaped fastener on the bottom that fixes the plate in place for the picture. We compare this image to the other three plate to determine any noticeable difference.

The next plate we look at in Figure 19 contains a significant amount of rust.

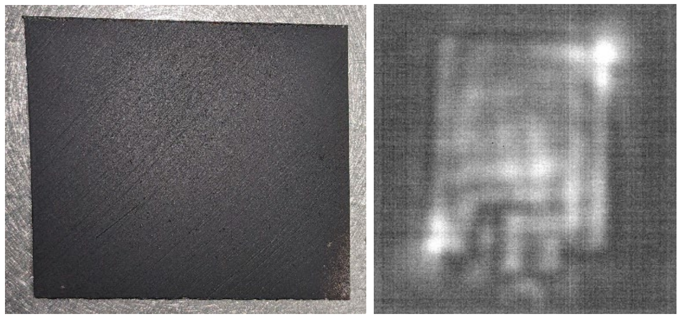


(a) (b)

Figure 19. (a) Metal plate with rust and no coating, (b) Reflection mode image.

The rust in reflection mode image appears slightly darker in general, requiring a baseline with clean metal (Figure 18) for comparison. Darkening on the entire image might indicate uniform corrosion.

Now that we observed rusted and non-rusted plates, we look at how a coating affects the image. Figure 20 shows a metal plate with coating, but no damage. The plate is coated with one layer of the same paint used on the plastic substrate (Section V-A).



(a) (b)

Figure 20. (a) Metal plate with coating and no damage, (b) Reflection mode image.

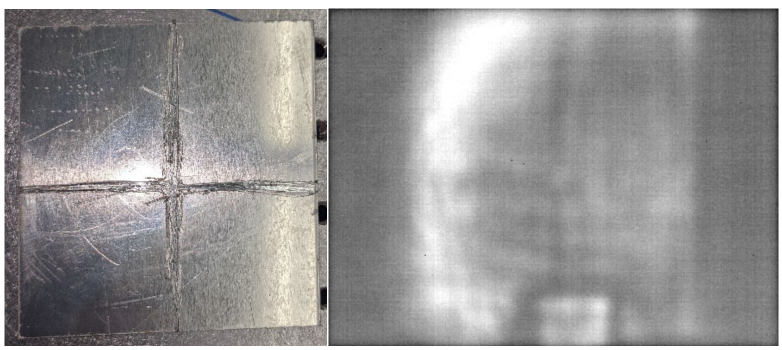
Since there is no damage underneath the coating the reflection mode image looks similar to that in Figure 18. The coating does not absorb an appreciable amount of THz radiation that is noticeable. Figure 21 shows another metal plate with rust before and after a coating of black paint was applied, as well as, a reflection mode image.

(a) (b) (c)

Figure 21. (a) Metal plate prior to coating and rust, (b) Plate with coating, (c) Reflection mode image.

Before applying the coating, the rust does not completely cover the plate, but created larger defects compared to the rust from Figure 19. The raised or lowered portions of the rust make it easier to resolve the rust in reflection mode. After applying the coating and viewing in reflection mode, the rust appears dark, but not all of the rust gets captured in the image. The large rusted areas stick out, but smaller less significant areas of rust cannot be easily resolved. Looking in the upper left corner of the THz image (Figure 21c), the paint layering significantly distorts. The rusted surface causes a non-uniform area for the applied paint where the imperfections in the paint layer are noticed. We look into this effect more when we examine how multiple layers affect the image.

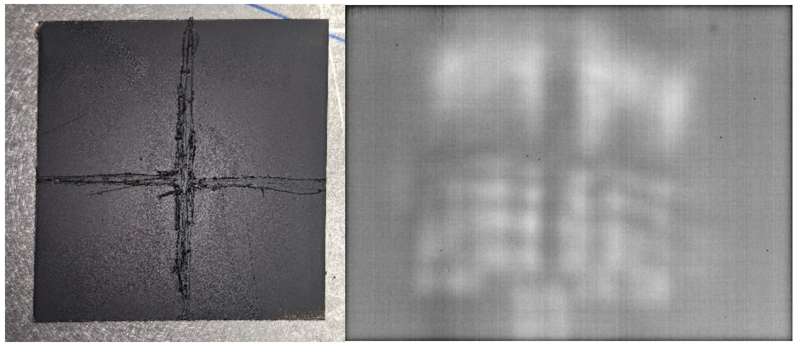
For the next series of plates, we examine an aluminum square that we gouge deep scratches into the surface. We want to further explore the effects of layered coating and their interaction with the THz radiation. The same black paint as the previous example is applied six times to simulate how a component with multiple layers of coating would appear. Figure 22 shows an aluminum plate with deep scratches to the surface in the shape of a cross on the left and the reflection mode image on the right.



(a) (b)

Figure 22. (a) Metal plate with surface damage, (b) Reflection mode image.

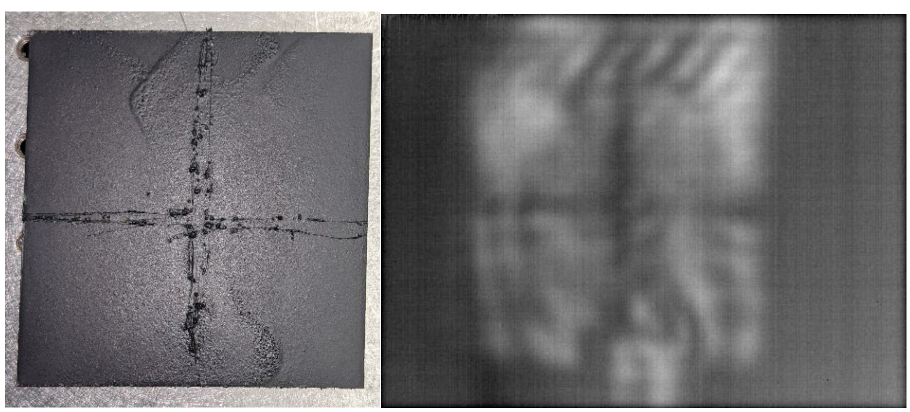
By putting scratches into the surface of the plate, we can see how that defect looks in reflection mode. The plate does not have any coating, so the THz image looks bright, but the scratches are still visible in order to compare them to the coating once applied. Figure 23 shows the same plate with one layer of paint applied to the surface.



(a) (b)

Figure 23. (a) Metal plate with surface damage and one layer of paint, (b) Reflection mode image.

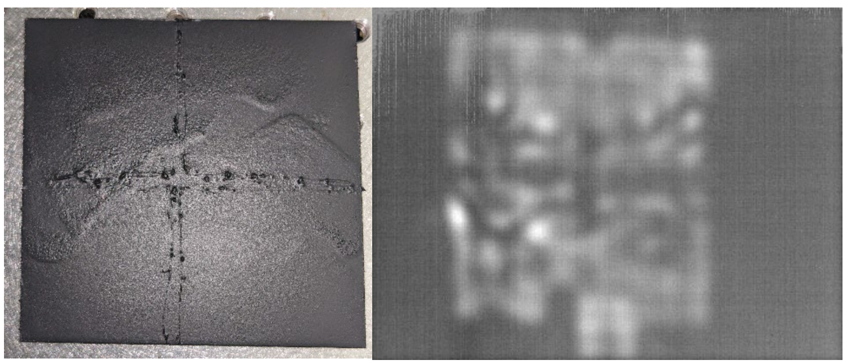
After applying the first coating, the scratches are still visible. The plate’s coating is smooth everywhere to paint touches except at the scratches. The scratches in the reflection mode image blend together due to their close proximity to one other, but an observer could still determine some kind of damage to the materials surface by this image. With only one layer, the paint does not appear in the THz image. As we add more layers, we see that this does not hold true. In Figure 24, we add two more layers of paint and view the surface effects visually and in reflection mode.



(a) (b)

Figure 24. (a) Metal plate with surface damage and three layers of paint, (b) Reflection mode image.

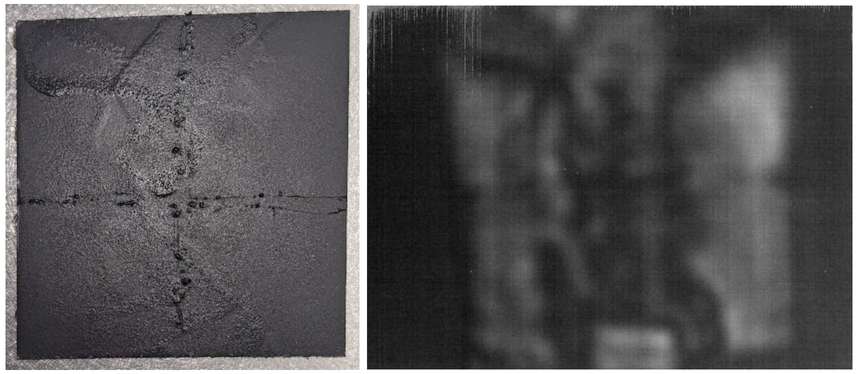
After applying the third coat of paint, we see that the original scratches start to get partially covered by the paint. The top surface is no longer smooth where the application of the paint left layered streaks, some more pronounced than others. For paint, this is normal, but for a specialized coating such as the acoustic coating used by submarines, this non-uniform layering could result in decreased performance or longevity. Looking at the THz image, we start to notice the effects of the added non-uniform layers. Darker lines show where the raised portions of the paint where applied. This effect increases as the thickness increases when additional layers are applied. Figure 25 shows five layers of paints and the reflection mode image.



(a) (b)

Figure 25. (a) Metal plate with surface damage and five layers of paint, (b) Reflection mode image

With 5 layers, the original scratches are even less noticeable compared to that in Figure 23. The compounding effects from the non-uniform layers increase as shown by the increase in the raised paint in the center portion of the plate. Now, the THz image clearly shows a distortion in the layers that matches the raised portions of the paint. Figure 26 shows the metal plate with six layers of paint with the reflection mode image.

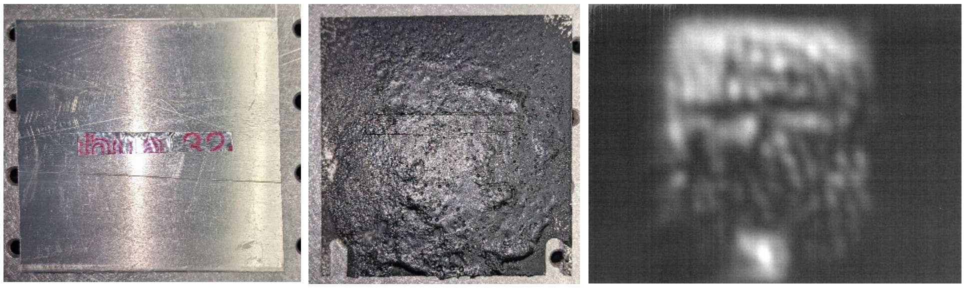


(a) (b)

Figure 26. (a) Metal plate with surface damage and six layers of paint, (b) Reflection mode image

After applying six layers of paint, the original damage is mostly hidden with paint, but still appears in reflection mode. The horizontal scratch in the center of the plate resolves, but the vertical scratch does not clearly appear due to being covered up by the increased non-uniform layering effects. By compounding these layering effects, the chances of delamination increase as impurities are added with each layer. Delamination occurs when the bonds between layers do not form correctly due to an unclean surface, uneven layering heights, or differences in temperature [31]. When delamination of paint occurs on naval ships, the underlying material is at risk for rust and other damage potentially leading to material failure or at minimum a reduction in the intended purpose.

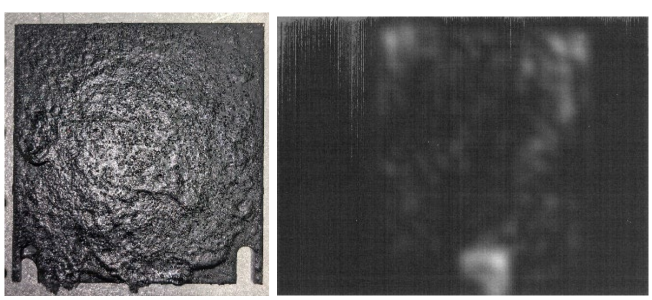
The next series of metal plates are coated with Flex Seal. The coating consists of liquid rubber that is normally used to repair leaks in many different materials. Flex Seal is a liquid rubber that when applied via the aerosol can, adhere to the metal non-uniformly resulting in a unique THz image. It is composed mostly of the chemicals Nepheline Syenite, Titanium dioxide, Butanone, Silica, and proprietary polymer, while adhering to most materials including steel, glass, aluminum, concrete, and wood [32]. For thin coatings of 0.25 mm, Flex Seal is transparent to THz. Figure 27 shows the initial plate prior to adding any coatings, the plate with one layer of Flex Seal, and the THz image in reflection mode.



(a) (b) (c)

Figure 27. (a) Metal Plate with metallic tape, (b) One layer of Flex Seal, (c) Reflection mode image.

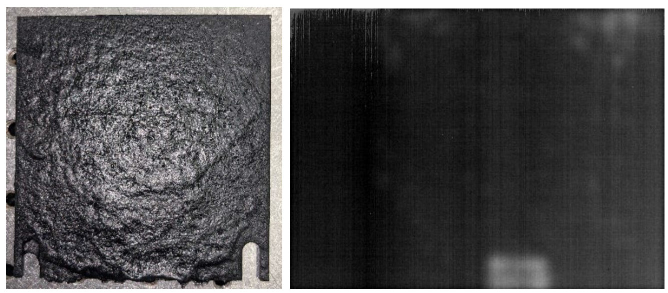
We use the same type of metal plate as the previous example, but instead of scratching the surface, we add a strip of metallic tape to use as a visual reference. In Figure 27 (b), we spray on one coating of Flex Seal to the plate. The underlying tape is still visible underneath and there are many non-uniform ridges formed on the surface from the rubber. The THz image (Figure 27c) shows the tape underneath the rubber along with the pattern left by the Flex Seal. Visually, we can tell that some areas of the plate are darker than others, meaning that the thicker dark regions absorb more THz compared to the lighter areas. By adding additional layers, we see this effect increase. Figure 28 shows the same metal plate with two layers of Flex Seal and the reflection mode image.



(a) (b)

Figure 28. (a) Metal plate with two layers of Flex Seal, (b) Reflection mode image.

As expected, with two layers of Flex Seal, the thickness of the surface increase much more than if paint was applied due to the added thickness of the rubber. In the THz image (Figure 28b), the metallic tape is barely visible and the transparency of the coating reduced significantly. The rubber absorbs much of the THz as the thickness increases making it hard to see the surface of the metal at this frequency. In Figure 29, we add a third layer of Flex Seal and view the plate visually and in reflection mode.

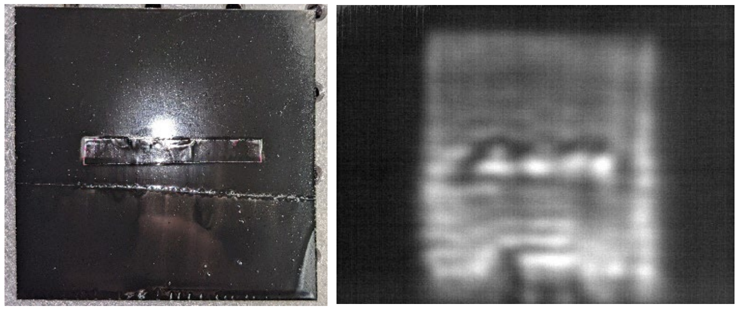


(a) (b)

Figure 29. (a) Metal plate with three layers of Flex Seal, (b) Reflection mode image.

After adding a third layer of Flex Seal, the thickness of the coating is approximately 1 mm. Flex Seal completely covers the metallic tape from view and the THz image (Figure 29 b) appears black due to the THz absorption of the rubber. At 0.5 THz, rubber absorbs too much THz radiation and prevents any meaningful examination of the surface.

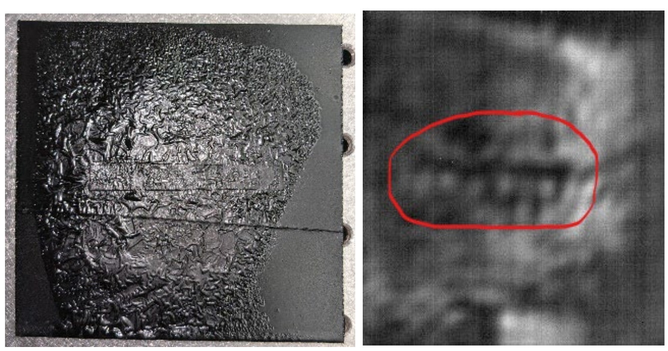
For the next coating, we look at Rust-oleum, a black paint enamel sprayed onto surfaces to stop the spread of rust. Rust-oleum consists of Acetone, Liquefied Petroleum Gas, Xylene, n-Butyl Acetate, and Ethylbenzene making it have similar properties to Krylon paint used on the plastic previously [33]. A similar metal square with a metallic piece of tape used as a visual reference is used as a base surface for the Rust-oleum. Figure 30 shows a metal plate with one layer of Rust-oleum and the THz image in reflection mode.



(a) (b)

Figure 30. (a) Metal plate with one layer of Rust-oleum, (b) Reflection mode image.

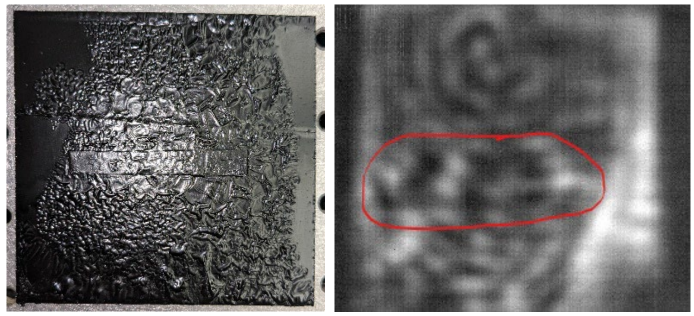
Once the applied coating dries, the surface appears glossy and smooth with one raised line of paint running left to right from the way the paint dried. The coating absorbs little of the THz radiation resulting in a clear image with the tape easily seen with no other major defects. As we add layers, we see that this is no longer the case. Figure 31 shows the metal plate with two layers of Rust-oleum and the THz image in reflection mode.



(a) (b)

Figure 31. (a) Metal plate with two layers of Rust-oleum, (b) Reflection mode image.

After adding the second coat, the metallic tape is still visible, but the surface appears wrinkled. This occurs when the top layer of the coating does not adhere properly to the bottom coating. The presence of the tape is still detectable in the THz image. In Figure 32, we add a third layer of Rust-oleum and view in reflection mode.



(a) (b)

Figure 32. (a) Metal plate with three layers of Rust-oleum, (b) Reflection mode image.

Once the third coat is added, the metallic tape is heavily covered in coating, but remains visible visually and in reflection mode. We see that the wrinkled area covers most of the plate's surface due to the same layering effect as with two layers, but is easier to see due to more dark areas on the image. This happens because the wrinkles are larger and more defined than with just two layers. A pattern identifier could probably identify the straight line due to the tape, which differs from the pattern. The measurements show that THz imaging could be used for imaging underneath of coatings and the image quality strongly dependent on the THz absorption characteristics of the coating as well as its thickness. Further enhancement of images could be done using image processing techniques that were not employed in this work.

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VI. CONCLUSION

A. SUMMARY

A Microxcam-384i THz Camera in combination with a 0.5 THz illumination source was used to study coated materials for the NDE at 50 FPS in transmission and reflection mode. Previous studies use TDS and FDS to determine the THz characteristic of different materials, but lack the portability and speed of a real-time imaging system. Portable devices are available for NDE, but have long scan times and cannot be used in real-time making them ineffective for a maintenance environment. By using a real-time imaging system, we demonstrated how coated materials could be examined for NDE. Our results support the answers for the three research questions asked previously:

What surfaces could be inspected nondestructively using terahertz technology?

Our imaging system looked at plastics, foams, and metal surfaces for NDE. Plastics and foams made of Polyethylene, Polypropylene, and Polyurethane are best suited for evaluation using transmission mode. These materials are transparent and their surface and internal defects were observed as long as they were not obstructed with THz absorbing materials. In this thesis, we looked at steel and aluminum surfaces using reflection mode. In reflection mode, as long as the coating covering the surface of the metal is transparent to THz, the underlying metal can be viewed. The surfaces studied are similar to materials used by the Navy and show promising results that need further investigation.

What coatings permit NDE using THz imaging?

We looked different paints including two enamel-based paints from Krylon, Rust-oleum and a rubber based coating from Flex-Seal. The factors that allow for NDE through the coating are polarity, conductivity, absorption coefficient, refractive index, and frequency. A thorough spectroscopic analysis was beyond the scope of this thesis, however the imaging study show that the coats studied, similar the ones used by the Navy, are suitable for NDE using THz imaging. The coatings shown in this thesis allow for the observer to determine defects at the surface layer of the substrate.

Can we identify abnormalities such as cracks, corrosion, and wrinkle using THz imaging?

Cracks, corrosion, and wrinkle are identified underneath transparent coatings using our THz imaging system. We resolved cracked of at least 1 mm, but addition metal samples are required to get an accurate measurement of resolution limitations. Advanced cases of corrosion where the surface starts to wear away are detected, but minor rust damage is difficult to detect with a 0.5 THz illumination source. Further testing using multiple different source spectral characteristics and output power is required. Wrinkle detection is likely for most conditions due to the THz illumination source reflecting off the unique pattern due to scattering.

Considering that all experimental work was solely based on raw images and did not include any type of image enhancement, pattern identification or any other kind of image processing, it is expected that the results obtained here can be significantly improved.

B. RECOMMENDATIONS FOR FUTURE WORK

Follow-on work must be done to improving the THz imaging system used in this thesis work. An important task would be to thoroughly study the THz properties of coatings used by the Navy in order to optimize the Illumination source for specific groups of coatings. A catalog containing coatings properties and required sources spectral and power characteristics could be created to provide a baseline of what Navy materials can be looked at for NDE.

The optics can be further improved to compensate on curved or inclined surfaces, better focalization across the image area and portability of the system. To be used aboard naval vessels, a coaxial illumination system could be developed making possible a handheld like equipment where the illumination source and camera are collocated.

Finally, image processing and pattern recognition algorithms could be included in the camera firmware in order to improve the image and aid the user on the identification of the potential defects.

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