

Terahertz Inspection as a Unique Enabler for Characterizing Sustainably Derived Composites

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ABSTRACT

The Sustainable Manufacturing of AirCraft (SUMAC) project at NASA is developing composites from naturally derived fibers and resins for aerospace applications, with a specific focus on advanced air mobility (AAM). Naturally derived composite materials have the potential to reduce carbon emissions in aviation manufacturing and create new markets. Naturally derived composites for AAM use can be made economically viable by using structural health monitoring (SHM) to reduce knockdown factors, to provide data for condition-based maintenance, and to increase the range and payload capacity for the AAM vehicles. Composites made from naturally derived fibers such as hemp and flax could also provide strong vibrational damping in vehicles and aircraft compared to carbon-based composites. However, the same vibrational damping also makes naturally derived composites difficult to inspect with ultrasonic testing (UT).

Terahertz (THz) radiation sits between microwave and infrared frequencies in the electromagnetic spectrum, and it has been used to characterize and inspect lossy dielectrics like thermal foams and biological materials such as plants. Unlike traditional composites, naturally derived composites are non-conductive and are thus penetrable by THz radiation. THz inspection is not used as widely as more “traditional” inspection techniques like UT and X-ray computed tomography because of its relatively new availability on the market. However, it offers sub-millimeter resolution imaging and unique spectral information while being non-ionizing and low power emission. THz can give specific information about the chemical makeup of naturally derived composites while also measuring density and thickness. THz time-domain spectroscopy (THz-TDS) can be used to interrogate different layers of a material by analyzing the THz reflections arriving at different times. THz is highly attenuated by water and responds spectrally differently to liquid and vapor water. This sensitivity to water can enable THz-TDS inspection to be used as ground truth or a calibration point for SHM sensors for detecting moisture uptake in structures. Our study examining the response of natural composites to THz radiation could enable future integration of THz sensors into vehicles for SHM. The unique capabilities of THz for inspecting and characterizing novel naturally derived composites at NASA will be presented. THz inspections were explored on a variety of flax-reinforced thermoplastic composite samples and individual constituents. This work investigates the alignment between composite layers, moisture sensitivity and moisture uptake mechanisms in the composites, and mapping of the ratios of fibers and resins in the composites as a first step toward applying THz for periodic monitoring of natural composite structures in AAM vehicles.

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INTRODUCTION

The SUsustainable Manufacturing of AirCraft (SUMAC) project at NASA is developing composites from naturally derived fibers and resins for aerospace applications [1], with a specific focus on advanced air mobility (AAM). SUMAC's primary goal is to reduce carbon emissions in the manufacturing of aircraft. SUMAC will investigate the impact of naturally derived composites (NDCs) from a lifecycle perspective of manufacturing and quantify the performance of the composites based on inspection and testing. To date, SUMAC has manufactured and inspected composite samples made from flax and various naturally derived resins [2]. NASA's AAM concept of a fleet of electrified air taxis and drones comprise the "air transportation system of the future [which] will include low-altitude passenger transport, cargo delivery, and public service capabilities [3]." AAM aims to increase the overall mobility and transportation opportunities to Americans sustainably. AAM is a nascent market in which regulations are still being established, and the small AAM vehicles will operate at low altitude for short durations. Because of these reasons, SUMAC has targeted AAM as a particularly synergistic application for the use of NDCs. NDCs are not competitive with traditional carbon-based composites on strength alone, but their vibrational damping features are potentially advantageous for passenger comfort and impact damage resilience. NDCs for AAM use can be made economically viable by using structural health monitoring (SHM) to reduce knockdown factors, to provide data for condition-based maintenance, and to increase the range and payload capacity for the AAM vehicles. The architecture of AAM includes a series of landing places with various levels of instrumentation and repair capabilities, termed "vertiports", "vertiplaces", and "vertiplaxes" [4, 5]. Sensors can be integrated into AAM vehicles for SHM and materials state awareness, and other sensors can be integrated into the AAM landing pads to collect ground truth SHM calibration data. The focus of this work is to develop inspection techniques that can supplement and calibrate SHM data.

The vibrational damping that makes naturally derived composites uniquely desirable as a material also makes naturally derived composites difficult to inspect with ultrasonic testing (UT). Terahertz (THz) radiation sits between microwave and infrared frequencies in the electromagnetic spectrum, and it has been used to characterize and inspect lossy dielectrics like thermal foams and biological materials such as plants [citations]. THz inspection has been used at NASA to inspect thermal protection system foams and adhesive loss in a prototype of the Orion Heatshield [6]. Unlike traditional composites, naturally derived composites are non-conductive and accordingly can be interrogated by THz radiation. THz inspection is not used as widely as more "traditional" inspection techniques like UT and X-ray computed tomography because of its relatively new market availability. However, it offers sub-millimeter resolution imaging and unique spectral information while being non-ionizing and low power emission. THz radiation will not interfere with radio and microwave frequencies that are essential to the safe movement and landing of AAM vehicles in congested airspace.

THz can give specific information about the chemical makeup of the composites and measure density and thickness. THz detectors have been used to probe astrochemical data, and THz radiation has been used in various biophysics research efforts [7, 8]. THz is highly attenuated by water and responds spectrally differently to liquid and vapor water. Vapor water produces specific absorption lines in THz spectra due to the rotational transitions of gaseous water [9]. Liquid water will absorb THz

broadly across the spectrum resulting in an attenuated signal through a sample for most frequencies in the THz range. The natural fibers in naturally derived composites are prone to moisture absorption. The effects of the water intake on the performance of the composites needs to be monitored to ensure the airworthiness of any vehicles that use these composites. The mechanisms by which naturally derived composites take on moisture also need to be understood, so THz's ability to differentiate between liquid and vapor forms of water is especially advantageous as a sensing modality.

THz imaging provides higher resolution imaging than microwave imaging and is nonionizing compared to X-ray imaging. Instrumentation which can produce consistent pulses of THz radiation now exists. THz time-domain spectroscopy (THz-TDS) uses a series of THz radiation pulses to interrogate a sample, and the reflected THz radiation is acquired with picosecond or better time resolution. THz-TDS can be used to interrogate different layers of a material by analyzing the THz reflections arriving at different times. While the imaging is not fully volumetric, it does reveal information about changes in materials and material states through the depth of the sample.

The unique imaging and spectral capabilities of THz-TDS inspection make it uniquely capable of providing ground truth or calibration data for SHM sensors on AAM vehicles manufactured with sustainably derived composites, especially for moisture uptake. Our study examining the response of natural composites to THz radiation could enable future use of THz sensor integration into AAM vehicles or AAM vertiplanes for SHM. Our study of THz-TDS interactions with moist and dry naturally derived composites aims to close gaps in THz-TDS moisture sensitivity in naturally derived composites and show how THz-TDS can image features and potential flaws embedded in naturally derived composites.

MATERIALS AND EQUIPMENT

The composites that are inspected in this work were manufactured at NASA Glenn Research Center (GRC) by heated pressing of interwoven layers of braided flax fiber and PLA resin thin films. The samples inspected were not manufactured using uniform parameters, and the THz inspection was used to help understand the quality of the manufactured samples to optimize their creation.

A Picometrix¹ T-ray 5000 THz-TDS system was used to collect THz-TDS data. The T-ray 5000 consists of a colinear THz emitter and receiver which are time gated to discriminate between their signals. The time gate for each sample is 320 picoseconds. All THz measurements were taken with samples placed on top of a copper plate reflector. The system collects waveform data, which can be extracted as either waveforms or spectra that have been transformed from the waveforms. The THz-TDS receiver can be considered a singular pixel, and the system is rastered across the sample to collect data at different points. Two composite panels of different surface areas but similar thickness of 3-4 mm were scanned at 0.5 mm spatial resolution in the plane of the sample. Each raster point was sampled 100 times. The intensities of the waveforms within a specific time gate across the sampled composite yield an image. Waveforms were also transformed from the time domain into the frequency domain to reveal spectral information at each point and at different reflections within the sample.

A PLA-Flax composite manufactured on October 22, 2024 (Composite B) was selected for spectral analysis as a first step towards mapping constituent components

Specific vendor and manufacturer names are explicitly mentioned only to accurately describe the test hardware. The use of vendor and manufacturer names does not imply an endorsement by the U.S. Government nor does it imply that the specified equipment is the best available.

and moisture in naturally derived composites. Composite sample B laminate was laid up with 1:1 mass ratio, six layers of A&P braided flax and pressed sheets of Pond Cycle IMF 101 HT PLA. The laminate was preheated without pressure for 15 minutes at 182 C, then pressed at 333psi at 182C for 20 minutes followed by slow cool to room temp.

A piece of Composite B was removed for separate moisture sensitivity tests. The comparison of mass change due to moisture absorption and the THz response was measured periodically while the composite was exposed to controlled temperature and humidity over time. Moisture experiments were conducted by exposing a piece of composite to 95% RH humidity at 25 C temperature over the course of a week in a Thermotron environmental chamber. Mass and THz measurements were taken daily.

RESULTS

Manufacturing Quality

Figure 1 shows a photo of a sample manufactured from braided flax and PLA on 9/19/2024 (Composite A, left) and a photo of another sample made from braided flax and PLA resin made on 10/22/2024 (Composite B, right). Figure 2 shows Composites A and B (left and right respectively) imaged with THz-TDS.



Figure 1. Photos of flax/PLA composites manufactured 9/19/2024 (left) and 10/22/2024 (right) using different manufacturing parameters. Composite A (left) is 15.24 cm x 15.24 cm and composite B (right) is 12.70 cm x 15.24 cm. Both samples are ~3-4 mm thick.

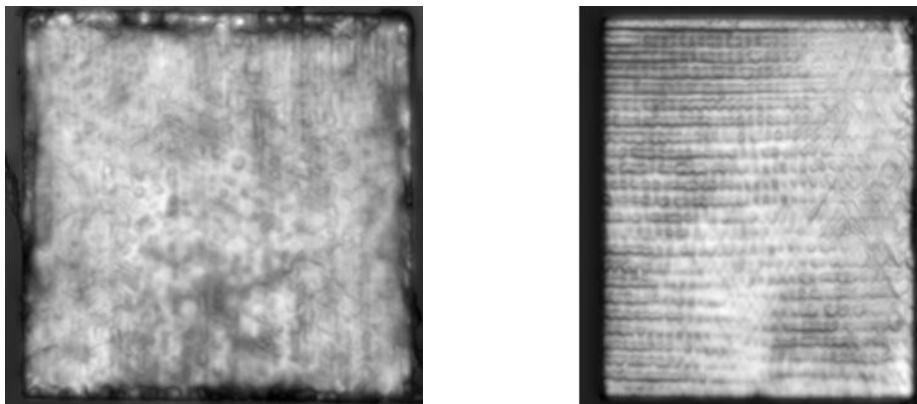


Figure 2. THz-TDS imaging through two braided flax and PLA composites made (left) on 9/19/2024 and (right) 10/22/2024. The braid pattern can be more clearly distinguished in the newer sample.

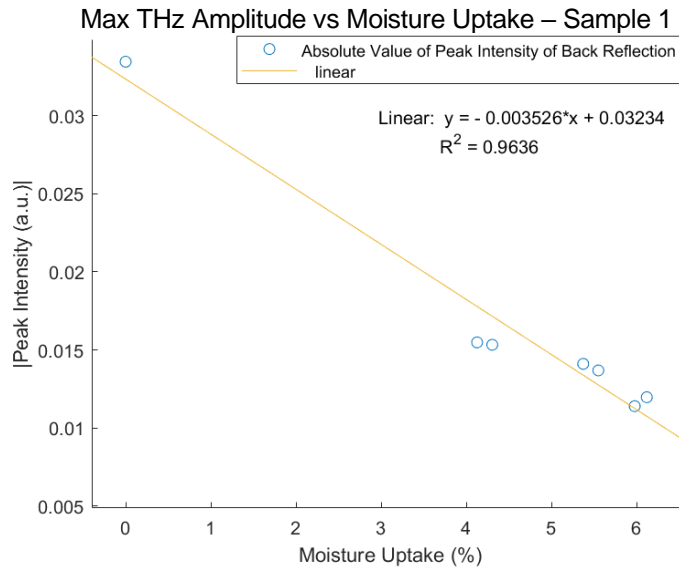


Figure 3. Moisture uptake was measured based on the increase in mass after the sample was exposed to a controlled moisture environment. THz-TDS attenuation was measured through the thickness of the sample (“back reflection”) at a point on the sample.

The sample manufactured first shows very poor alignment between layers of the flax braids, whereas the sample manufactured later shows strong alignment of the braids across different layers. While this set of images was taken to check a manufacturing process, this same sort of imaging can be used to check for suspected but nonvisible damage at a vertiport.

Moisture Sensitivity

Results in Figure 3 show increased overall THz attenuation through the sample for increased moisture absorption, which is consistent with theory and gives a start point for understanding how much moisture uptake can be measured with THz for SHM applications.

Spectral Properties of Composites and Constituents

Spectral analysis was conducted for dry composites that had not been through moisture experiments or humidity cycling. Spectra for PLA and braided flax constituent materials were taken directly from the Picometrix’s data acquisition software and are shown in Figure 4. PLA that had been processed through compressed heating was measured; processed PLA has a more crystalline structure and is more representative of the PLA in the manufactured composite samples than the thin film PLA. A sample of braided flax was folded over itself to provide a thicker radiation interaction zone. Spectra for different points on the PLA flax composite were transformed from waveform data as shown in Figure 5. Points are given in [X Y] coordinates as measured in mm from a corner of the sample and comprise both edges and internal sections of the sample. The power spectral density (PSD) is consistent between different points on the sample.

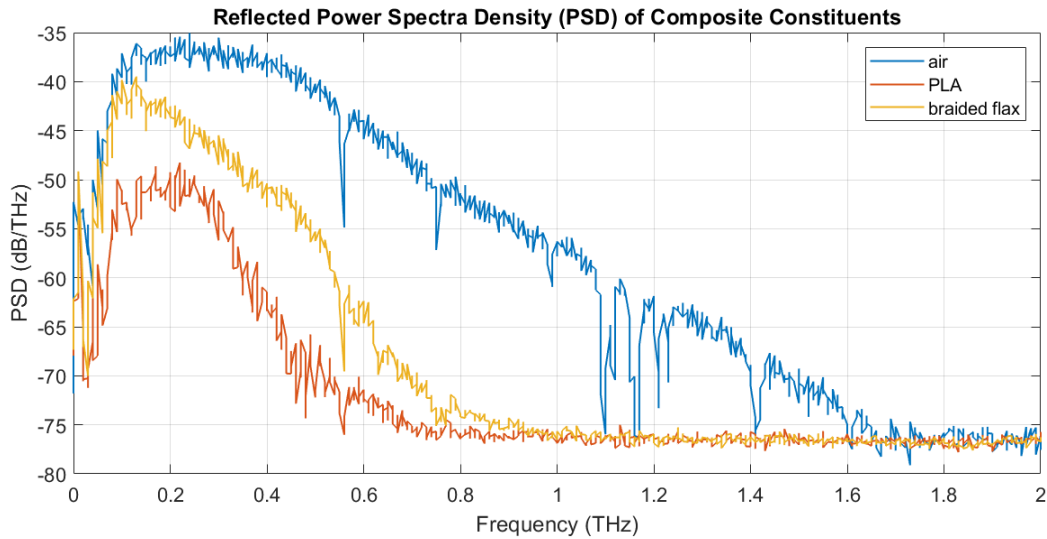


Figure 4. The air spectrum is a measurement taken with the THz being reflected from a copper plate and then back to the THz receiver. Since all measurements are taken in a laboratory (non-vacuum) environment, the air measurement is a measure of the background spectrum.

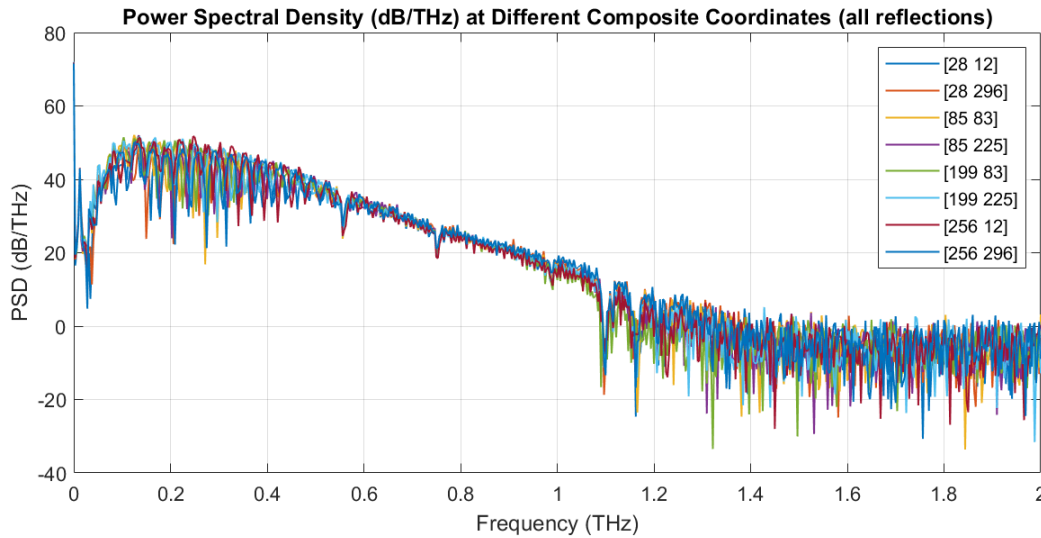


Figure 5. Absorption spectra taken at various single points on the Flax/PLA composite are shown.

The background spectrum of air shows strong water vapor absorption lines for 0.557, 0.753, 0.989, 1.164, 1.2264, and 1.4116 THz frequencies. The 0.557 THz line is present in the PLA and braided flax spectra, most likely due to the presence of air in the measurement, since the spectral results are transformed from the entire integrated THz waveform taken at a single point.

The time domain waveforms for various [X Y] coordinates on the sample are presented in Figure 6 within the 320 picosecond time gate. The first pulse is essentially the reflection resulting from the change in permittivity between air and the surface of the composite sample. The second large pulse is due to a reflection from the copper backplate through the sample. Therefore, the second large pulse can be understood to yield information through the thickness of the sample at that [X Y] coordinate point. Additional smaller reflections later in the time gate result from scattering in the sample that arrives back at the THz receiver later in time.

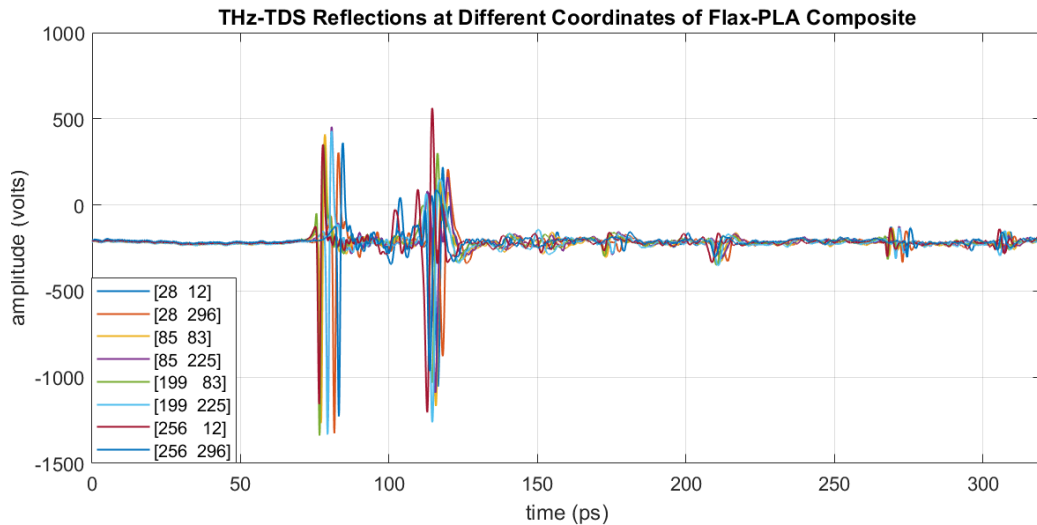


Figure 6. Waveform response of THz interrogation at different coordinates on Flax-PLA composite within the 320 picosecond time gate. The first reflection is approximately the surface of the composite sample. The second reflection arises from a reflection from the copper plate beneath the sample, and thus gives information through the depth of the sample at the specified coordinate.

The spectra for different points on the sample for only the second reflection are shown in Figure 7. Only one water vapor absorption line is present at 1.671 THz for point [256 12]. Absorption lines at 0.877 and 0.959 THz are seen at multiple points on the composite and are additional peaks of interest but have not yet been identified.

Potential lines of interest from the constituent PLA and braided flax materials include 0.12 THz in the PLA spectrum and 0.63 THz in the flax spectrum. These lines are not seen in the air spectrum. Unfortunately, these specific lines are not immediately visible in the composite spectra, and additional work is needed to characterize the constituent spectral properties in comparison to the naturally derived composite properties.

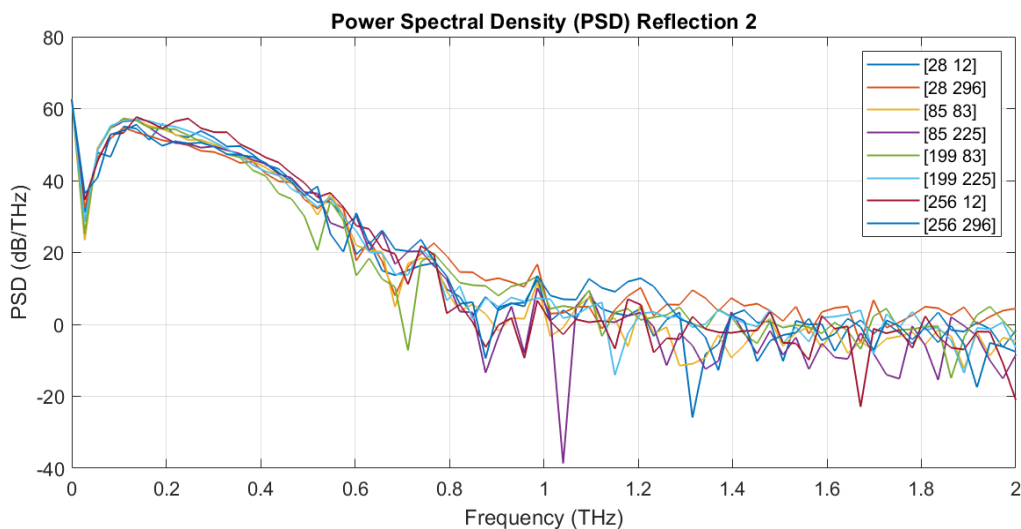


Figure 7. Spectral response for the second waveform reflection yields information about the composition through the composite sample. The THz spectra for various points on the PLA-Flax composite sample are shown.

CONCLUSIONS AND ONGOING WORK

THz inspection was executed for two separate PLA-Flax composite samples and their constituent materials in this work as a step towards using THz for SHM applications. One PLA-Flax composite was examined in terms of spectral content and moisture uptake using THz-TDS. This work shows the THz inspection capability for imaging NDCs, determining moisture sensitivity in the composites, and identifying spectral components in the composites as a first step toward applying THz for periodic monitoring of NDC structures in AAM vehicles. THz is a sensitive probe for moisture characterization and identification for NDCs, and it images submillimeter features of naturally derived materials well, but additional work is needed to map the moisture and ratios of fibers and resins within the composites.

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