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DEVELOPMENT OF A FOURIER TRANSFORM FAR INFRARED (FTFIR) SPECTROMETER TO CHARACTERIZE BROADBAND TRANSMISSION PROPERTIES OF COMMON MATERIALS IN THE TERAHertz REGION.

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science

By

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ABSTRACT


With sub-millimeter wave or terahertz devices becoming more readily available, there is interest in developing sensors in this region of the spectra. To support this interest, we have developed a Fourier Transform Far InfraRed (FTFIR) spectrometer to characterize broadband transmission and reflectance coefficients of materials. The spectrometer utilizes a broadband blackbody source, a Michelson interferometer, and silicon bolometer. The path difference in the Michelson is obtained using a linear stage and data acquisition and stage control were both implemented in a Labview programming environment. The details of the experimental setup and experimental results are presented in this thesis. The instrument demonstrated capability to measure the broadband transmission spectra of cloth and cardboard samples and we found that these spectra, which showed transmission < ~0.5 THz and increased in attenuation at higher frequencies, agreed with accepted general trends.
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1.1 Motivation

Terahertz (THz) radiation and its applications are receiving an increasing amount of interest as it is still an underdeveloped region of the spectrum and advancements have been made in source and detector development. This interest is further stimulated by the fact that many materials that are opaque in optical frequencies are transparent in the THz range. This makes THz radiation an excellent candidate for many security applications. Locally there is interest in sensor design utilizing THz technology, and for this purpose transmission and reflection measurements of samples are desirable. Specific applications include non destructive evaluation (NDE) of thermal barrier coatings, more commonly known as space shuttle tile, as well as other aircraft coatings, such as paint. Also of interest, as mentioned previously, is the use of THz for security applications, such as weapon detection through clothing or packing material. For sensor development in this area it is necessary to measure transmission and scattering through clothing and packing material. Furthermore a THz spectrometer can be used to characterize sources, specifically there is a quantum cascade laser being locally developed for which characterization is important.

Our research focused on adding to work being done on transmission measurements for the use of developing sensors for security applications and non-destructive evaluation. Measurements were made on cardboard and clothing material are in agreement with previously published work\textsuperscript{1,2,3,4}.
The two most common types of spectrometry which can record such broad spectra are Terahertz Time Domain Spectroscopy (THz-TDS), and Fourier Transform Far InfraRed (FTFIR) Spectroscopy. Both methods have their pros and cons; however the two primary reasons of why we chose the FTFIR method are as follows. First is expense with a typical TDS system typically an order of magnitude more expensive. Second is simplicity. The TDS systems are a veritable tour de force of lasers and optics in contrast to our simple FTFIR system in which a simple Michelson Interferometer is the primary optical instrument.
1.2 Background

The method of Fourier Transform Far InfraRed (FTFIR) Spectroscopy is based on the method of sending a broadband source through an interferometer which, with a controlled changing path difference, creates an interferogram (intensity vs. path difference). Once an interferogram is obtained, one performs a Fourier Transform (FT) from the path difference space to wavenumber space resulting in the spectrogram for the material. The simplest example to consider is to send a monochromatic source through the interferometer. When the path difference is changed, the intensity then varies sinusoidally due to the constructive or destructive interference of the beam upon recombination. This results in an interferogram which is a sine wave. One then performs the FT and the spectrum is a “delta function” at the monochromatic frequency. This idea can then be generalized to a broadband source by thinking of it as the superposition of many sine waves.

The following discussion was adapted from Gruner\textsuperscript{5}. The general block diagram of a two beam interferometer is shown in Figure 1.1.
Figure 1.1 Block Diagram of Two Beam Interferometer BS is the Beam Splitter, and the arm with Changing Path Difference Denoted by Variable $x$.

The spectral intensity at the detector can then be written as

$$p(\nu) = \int_{-\infty}^{\infty} I(x) \cos(2\pi \nu x) dx = 2 \int_{0}^{\infty} I(x) \cos(2\pi \nu x) dx$$  \hspace{1cm} (1)

Where $x$ is the distance in cm along the arm that moves, or the path length, and $\nu$ is the spatial frequency wavenumber ($\text{cm}^{-1}$). By writing the integral from zero to infinity it allows us to measure the one-sided interferogram instead of the symmetric interferogram.

If we look at the inverse transform and set $x$ to zero we see that we get the white light condition given by

$$I(0) = 2 \int_{0}^{\infty} p(\nu) d\nu .$$  \hspace{1cm} (2)
In other words at zero path difference (both arms at exactly the same distance), the intensity is maximized. This alerts us to look for what is called a “centerburst” in the interferogram, which is a critical system test, and necessary to know as it is the zero reference point when performing the FT.

Based on the theory above the method for obtaining the continuous spectrum is to measure the one-sided interferogram for all $x$ from zero to infinity and take its FT. Realistically of course we can only measure from zero to some $x_{\text{max}}$. This condition is what sets the ultimate limit on the resolution of the spectra. This resolution is given as

$$\Delta \nu \approx \frac{1}{2x_{\text{max}}}.$$  \hspace{1cm} (3)

Applying this to the above discussion of the interferogram of the monochromatic source, the “delta function” now has width of $\Delta \nu$.

Since we are interested in broad transmission characteristics that are greater than our instrumental resolution, we did not model the instrumental line shape. Also, since we are digitally sampling, our $x$ values are not continuous which results in a maximum frequency obtainable

$$\nu_{\text{max}} = \frac{1}{2\Delta x},$$ \hspace{1cm} (4)

where $\Delta x$ is the spatial sampling frequency.

While discussing sampling rates and/or step sizes in $x$, it should be mentioned that the most serious error that can result is not sampling the centerburst exactly. If this occurs it
creates a phase shift in the spectra. Therefore care should be taken to ensure that the zero path difference is as close to a data point as possible.
System Performance Model

2.1 Water Absorption Spectra

For calibration purposes a theoretical model was employed to take into account the blackbody source, Mylar efficiency function, the high cut-on filter, and the water absorption spectra since this experiment will be done in open air and attenuation will occur at water absorption frequencies based on the humidity level in the air.

The water lines were obtained from a computer program called “The am Atmospheric Model”. The program is designed to produce model atmospheric emission, absorption, and excess delay spectra, at frequencies from a few GHz up to several THz. This software is available from the Smithsonian Astrophysical Observatory (SAO) and can be downloaded online. Figure 2.1 shows the transmittance from 0-7.5THz over a path length of 1 meter and 50% relative humidity at 20°C.

![Figure 2.1 Water Lines from 0 - 250 cm⁻¹ at 50% relative humidity. Intensity in this figure is also the transmittance.](image)

Figure 2.1 Water Lines from 0 - 250 cm⁻¹ at 50% relative humidity. Intensity in this figure is also the transmittance.
2.2 Low Pass Optical Filter

For the filter a simple analytical function was used with a fitting parameter A and cutoff frequency $\nu_0$.

$$\frac{1}{1 + A\left(\frac{\nu}{\nu_0}\right)^2}$$  \hspace{1cm} (5)

Figure 2.2 Low Pass Optical Filter Function $A=1$, cutoff at 35 cm$^{-1}$.
2.3 Terahertz Source

The source used is a blackbody source from Barnes Engineering. The temperature can be adjusted from ~ 473K to 1273K. For our experiment maximum power is desired so the temperature is always set to its maximum amount. The spectral power for a blackbody source in our frequency range can be described by the Rayleigh-Jeans approximation (RJ). Defining $c$ as the speed of light, $k_B$ as the Boltzmann constant, $T$ as the absolute temperature of the blackbody, and $\nu$ as the frequency in wavenumbers, the expression is given by\(^7\)

$$F_{RJ} = 2\pi c \nu^2 k_B T d\nu$$

(6)

Notice that for this model the power is a relative power distribution, merely to give the frequency dependence shape of the instrument efficiency. The model implements an intensity coefficient in order to compare with actual data. Therefore for this section the scaling of the y-axis is irrelevant and it is the shape of curve which is of primary interest. A plot of both the RJ approximation and the standard Plank blackbody curve shows the validity of this approximation for our region of interest in the spectrum.
Figure 2.3 Comparison of the Rayleigh Jeans approximation (solid line) and the Plank curve (dashed line). This shows a variation of less than 8% for \( \nu < 100\text{cm}^{-1} \).
2.4 Mylar Beam Splitter

The Mylar beam splitter is our first choice as it is readily available, efficient in the FIR region, and is well modeled theoretically. It should be noted, however, that there are a few drawbacks in the use of the Mylar beam splitter. The primary downside of the Mylar is that it is in effect a thin film and has etalon characteristics. This creates a frequency dependent transmission efficiency structure which will modify obtained spectra.

The average efficiency of the Mylar for a polarized incident beam is given as

\[ \eta(v) := \frac{1}{2} \left( \eta_s(v) + \eta_p(v) \right) \]

(7)

Figure 2.4 Thin Film Effect of the Mylar Beamsplitter.

In the above expression the subscripts denote the polarization of the wave as defined in Figure 2.4. These are given by
\[ \eta_s(v) := \frac{2R_s T_s^2 \Gamma(v)}{(T_s^2 + R_s \Gamma(v))^2} \]

\[ \eta_p(v) := \frac{2R_p T_p^2 \Gamma(v)}{(T_p^2 + R_p \Gamma(v))^2} \]

(8)

Where \( R \) and \( T \) are the reflection and transmission coefficients once again denoted by subscripts based on polarization. The dependent variable \( v \) is in wavenumbers. These and the parameter \( \Gamma \) are given as

\[ \Gamma(v) := 4 \left( \sin(2\pi n v t \cos(\phi)) \right)^2 \]

(9)

\[ R_s := \frac{\sin(\theta - \phi)^2}{\sin(\theta + \phi)^2} \]

\[ R_p := \frac{\tan(\theta - \phi)^2}{\tan(\theta + \phi)^2} \]

(10)

\[ T_s := 1 - R_s \quad \quad \quad T_p := 1 - R_p \]

(11)

For our experiment \( \theta = 45^\circ \), and \( t = 1 \) mil. The average index of refraction for 50 cm\(^{-1}\) is \( n=1.73 \). This is shown in Figure 2.5. Some other examples of different thickness and incident angle are also shown for comparison in Figure 2.6.

Figure 2.5 Mylar Beam Splitter Efficiency: \( \theta = 45^\circ \) and thickness = 1 mil.
Figure 2.6 Mylar Beam Splitter Efficiency: a) $\theta = 45^\circ$ thickness = 5 mil,  b) $\theta = 30^\circ$ thickness = 1 mil,  c) $\theta = 60^\circ$ (Brewster’s angle) thickness = 1 mil.
The beamsplitter was analyzed in order to better help theoretically model the spectra. Our region of interest and what we expect to see based on the optical filter from the detector is plotted in Figure 2.7. Notice that for less than 35 cm$^{-1}$, which is the filter used to obtain all our results, the average efficiency is less than 30%. This decrease effectively adds noise since the modulation depth is also decreased. By modulation depth here we are referring to the power in the interferometer arm with the variable path length, which ideally should be exactly 50%.

Figure 2.7 Mylar Beam Splitter Efficiency for 0-100 cm$^{-1}$. 

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2.5 Overall Performance

The expected efficiency is then the product of the water absorption spectra, the filter function, the blackbody spectrum, and the Mylar function. Each of these effects are shown in Figure 2.8 in successive graphs.

Figure 2.8. The Overall System Efficiency Showing Each of the Primary Effects in Each Successive Graph.
For our region of interest, less than 100 cm\(^{-1}\), we will be looking through a much smaller spectral window. Figure 2.3 shows the model from 0-100 cm\(^{-1}\).

![Graph showing intensity vs. 1/cm from 0 to 100 cm\(^{-1}\).](image)

Figure 2.9 The Overall System Efficiency from 0-100 cm\(^{-1}\).

The theoretical model described above was implemented in Wave Metrics Igor Pro\textsuperscript{©}. Fitting parameters are modified using graph controls, which are a feature that Igor has for changing defined values quickly, for the Mylar thickness, angle of Mylar (BS), blackbody temperature, an overall intensity coefficient, A (the filter parameter), and the cutoff frequency.

To validate the model data was obtained from The Ohio State University, taken with a similar setup, and is shown in Figure 2.10.
Figure 2.10 Top: OSU Data for Model Validation. Bottom: Zoomed In.

Note from the figures that two strong low frequency water lines (~18.6 cm$^{-1}$ and 25 cm$^{-1}$) match up, as well as some of the other structure. Also note that the filter function works less than desirable and is not sufficient to accurately describe the actual roll-off. The filter did not roll off fast enough to sufficiently attenuate the $\nu^2$ dependence of the blackbody. For validation purposes however, which is what the model is intended for, we can verify that that the water lines are measured at the correct frequency. Therefore the primary goal of the model is achieved. In future models, an empirically determined filter function is recommended.
EXPERIMENTAL SETUP

3.1 Overview

Based on the basic theory of FTFIR Spectroscopy the core system must include a broad banded terahertz source, terahertz detector, interferometer, and computational data processing. Further include: a good vacuum system for the detector, a stepper motor for the interferometer, and data acquisition hardware for the computer. The basic setup is shown in the block diagram of Figure 3.1.

Figure 3.1 Block Diagram of Experimental Setup.

The blackbody source and the Mylar beam splitter (interferometer) have been discussed in Chapter 2 of this thesis and will not be further discussed here. The rest of the experiment is as follows.
3.2 Detector

The detector is a silicon composite bolometer from Infrared Laboratories\textsuperscript{10}. The bolometer in effect is a thermal detector. It has a Winston Cone\textsuperscript{11} collector, basically a thermal trap, which has an entrance aperture of 12.7 mm at a focal ratio of 1.2, and an exit aperture of 5mm. The input also has a selectable FIR low pass optical filter at either 100 cm\textsuperscript{-1} or 35 cm\textsuperscript{-1}. The bolometer has a Noise Equivalent Power (NEP) of 3.17×10\textsuperscript{-14} W/Hz\textsuperscript{1/2}. The bolometer’s electronic frequency response begins to roll-off significantly starting near 300 Hz.

For the bolometer to function correctly it must be cooled down using liquid helium which is at a temperature of \(~4.2\) K. By pumping on the helium bath, temperatures as low as \(~1.2\) K can be obtained. This increases the sensitivity of the detector dramatically. The transfer procedure and the pumpdown procedure are given in the owner’s manual\textsuperscript{10}.
3.3 Vacuum system

The vacuum system consists of a Duo Seal 1402 mechanical pump which is connected to an air-cooled two-inch diffusion pump (brand and other specs unknown). Two MKS® capacitance manometers are used to monitor the vacuum; one ranging from 0 to 1000 Torr to monitor during the helium bath pump down, and the other ranging from 0-2 Torr to monitor the vacuum guard pump down. During the helium pump down only the mechanical pump is used.
3.4 Interferometer

The interferometer built is based on the Michelson Interferometer (MI) made famous from the Michelson/Morley experiment. The MI has been utilized for many and various applications, such as a high frequency autodyne receiver, index of refraction measurements, wavelength measurements, used determine surface roughness, and of course, spectroscopy. It is a powerful optical tool, and is the backbone of our experiment. The basic geometry of the MI used for this instrumental setup is shown in Figure 3.3

![Michelson Interferometer Diagram](image)
The input and output to the MI that was built uses two four inch diameter, 90° off-axis parabolic mirrors (PM) with 15 cm effective focal lengths from Janos technology. One is used as the collection optic in order to collimate the beam; and the other, to collect the transferred radiation and focus it onto the detector. The four inch mirrors were chosen so that we could collect as much power as possible since in the sub-millimeter region we are always fighting S/N. The focal ratio of the PM is ~1.5 and was chosen as low as possible in order to maximize coupling to detector which as mentioned has a focal ratio of 1.2. M1 and M2 are standard 5” by 7” flat mirrors except for the fact that the silver coating is on the outside of the glass. The flat mirrors are from Edmund Optics. M1 is mounted on a Zaber linear stage which is computer controlled to change path difference. The beam-splitter (BS) used is a Mylar film of thickness 1 mil mounted at a 45° angle. It should be noted that after the initial split the reflections from M1 and M2 are split again and so the total throughput, assuming no other losses and a 50% beam splitter efficiency, is limited to 1/2 the incident power.

The alignment of the MI was done optically. To collimate the blackbody source using the PM, a pinhole source was placed ~2m away to approximate plane waves arriving at the PM, which then focuses the incoming radiation down to the focal point. The aperture of the blackbody was then positioned at the focal point. The rest of the system can be aligned using the collimated beam from the blackbody source.
3.5 Linear Stage

In order to control the path difference in the arms of the MI, one of the flat mirrors is mounted onto a Zaber Linear Stage (LS). The LS is driven using a leadscrew connected to a stepping motor. The drive system is incremental in nature, and the control system consists of modified National Instruments Labview® Virtual Instruments (VI) that was provided from Zaber. The control for the stepper will be further discussed in Chapter 4.

The lowest increment is 1 μstep which is equal to 0.09921875 μm. Based on the step size resolution, the LS theoretically is capable of obtaining spectra with significantly lower resolution than what is required for our experiment.

\[ \nu_{\text{max}} = \frac{1}{2\Delta x} = 50000cm^{-1} \Rightarrow \lambda = 200nm \]  

(12)

For our interests \( \nu_{\text{max}} = 100cm^{-1} \), this dictates a step size of at least 50 μm. The other necessary consideration for step size is whether or not the centerburst is being sampled. Since the experiment is set up to take an intensity measurement at every step it is critical that the centerburst is stepped through as close as possible to the exact zero path difference. We found based on trial and error that a step size of 10 μm is adequate for this purpose. Therefore, the step resolution available is two orders of magnitude greater than what is required.

According to the technical data the LS can move a total distance of 2.8 cm. This gives a total optical path difference of 5.6 cm, theoretically then the maximum spectral resolution possible for our system is
\[ \Delta v \approx \frac{1}{2x_{\text{max}}} \approx 0.1\text{cm}^{-1} \Rightarrow \Delta f \approx 3\text{GHz} \]  

(13)

In realistic scans of course one must scan through the centerburst which means that some of the path length will be lost and this maximum resolution will never be attained. In our scans \( x_{\text{max}} \approx 1.25 \text{ cm} \) which gives a resolution of

\[ \Delta v \approx \frac{1}{2x_{\text{max}}} \approx 0.4\text{cm}^{-1} \Rightarrow \Delta f \approx 12\text{GHz} \]  

(14)

Once again however the experiment is meant only to look at broadband characteristics of the spectra, and this resolution meets those needs.

Besides the step scan mode, where commands are sent to increment the position of the LS, the experiment has also been set up to take rapid constant velocity scans. The LS has a constant velocity mode which is utilized for this purpose. In the initial design it was assumed that the constant velocity would be used to quickly get a look at the interferogram and then a slower step scan, utilizing a beam chopper and lock-in amplifier would be used to increase S/N. We were surprised to see however that the “quick-scan” mode produced better results than the slow stepping method. This is due to the fact that the most convenient chopping position, and the only place dimensionally our optics allow (a three inch collimated beam takes a bigger chopper than the one we have), is right at the source or right at the detector where the beam comes back to a point. The chopper was placed at the source; however for the MI this is equivalent to chopping the background radiation. What one really wants is to modulate only the interferogram. To do this correctly one should modulate or dither one of the flat mirrors. Since equipment was not readily available, and the “quick-scans” produce such good data in little time, it was decided to use the constant velocity mode to obtain the interferogram. Unfortunately
there is difficulty in knowing the exact velocity of the LS, which made correlating position to sampled data difficult. The LS does however have a setting which returns its position at regular intervals allowing us to analyze the interferograms obtained. The utilization of this is discussed further in the software portion of this thesis Section 4.4.
DATA ACQUISITION AND CONTROL

4.1 Control and Data Acquisition

The control system for the linear stage and data acquisition was implemented in Labview. Three methods of scanning were implemented. The first is a standard step scan, which takes a step and then reads a data point and is intended to be used with a lock-in amplifier. The second is a constant velocity scan which sets the linear stage in motion at constant velocity and samples at a set sampling rate. The third was designed to take advantage of good S/N found in preliminary data using the constant velocity mode and watching for sudden fluctuations in the intensity. The problem however is that the LS is somewhat unreliable in the velocity it reports: It moves at some constant velocity but it is unknown exactly what that velocity is. Therefore a fast step scan mode was designed where after the LS is set in motion it returns its position periodically and we collect a data point at each position. Conversely one could do the traditional constant velocity scan and use the position vs. time data to calculate the velocity thereby correlating data points with position.

The data acquisition used is a National Instruments BNC 2110®. To utilize the DAQ, Labview Virtual Instrument’s (VI’s) from National Instruments were incorporated into the larger control program as sub-units. This experiment is in no way taxing of the DAQ’s capability as we are usually sampling at relatively low frequencies. For the LS control three sub -VI’s from Zaber were used to control and communicate with the linear stage. Zaber Read, Write, and Data to Bits, were implemented for this purpose. Also the scanning modes were designed around Zaber’s testpanel VI which allows the user to send
any of the various commands to the LS. The overall flowchart is shown in Figure 4.1. Each scanning mode flowchart will be shown and discussed separately.

![Flowchart](image)

Figure 4.1 Overall Flowchart of Experiment Operation.

The program begins and the user is given the option of sending a command via the testpanel, or of executing one of the scanning modes. Once a scan is executed the program waits for its next command or until the user selects quit.

The software was originally designed for the user to choose either μm or μsteps. If the user chooses μm the necessary conversions are applied, however, it should be noted that numerous errors have occurred in Labview due to rounding errors. It is recommended then to work solely in μsteps which are the “natural” units of the stepper.
4.2 Step Scan

The step scan reads its position from the feedback from the LS then takes a single data point for intensity then steps the distance defined by the step size. This process is iterated utilizing a “for loop”. The intensity vs. position array is built in this way. At the end of the scan the LS is sent back to its “home” position to await the next scan.
To step the stage, command 21, and data = step size, is written using the subvi ZaberWrite. To read the position the subvi “ZaberRead.vi” is called, when called immediately after the step command is written ZaberRead returns the absolute position. Note once again that step sizes no larger than 10 μm should be used to ensure that the centerburst is scanned through. The step scan is intended to be used with an optical chopper and lock-in amplifier to maximize signal to noise. Figure 4.3 shows an interferogram taken with the step scan.

![Step Scan Interferogram](image_url)

Figure 4.3 Step Scan Interferogram. Top: full range of stepper. Bottom: Zoomed in.
4.3 Constant Velocity Scan

The constant velocity scan is very straightforward. The user specifies a scanning time based on # of samples and a sampling frequency. The program waits a set time frame to ensure that data collection has started and then the stage is set in motion at some constant velocity. To set the stage to a constant velocity the subvi, ZaberWrite.vi is used sending
command 22, and the speed is input to data. At the end of this process one has intensity vs. time data. Figure 4.5 shows an interferogram taken in the constant velocity mode.

If the velocity of the stage were known it could be used to correlate to position and obtain the interferogram. As mentioned previously, however, the actual velocity is unknown. To rectify this problem the fast step scan was designed.
4.4 Fast Step Scan

Figure 4.4 Fast Step Scan Flowchart
The fast step scan was implemented to attempt to utilize the benefit from the step scan of always having a data point at a well known position, as well as to incorporate the improved S/N that was obtained from scanning fast and looking for rapid fluctuations.

The user inputs speed, max range, and a wait time between samples. Conversely, the wait time can be thought of as the inverse of the sampling frequency. The program resets the linear stage, sends it to the home position, and then waits 3 seconds. This wait time is to allow the stage to make it all the way home before starting the scan. The stage is then set in motion at a constant velocity. At this point in order for the stage to return its position the “mode” must be set. The mode can be set using ZaberWrite setting data to 16 and command to 40. The stage is now moving and the program reads position and intensity spaced out by the time difference specified in the input. This iterates in a while loop until max range is less than the position read. Time is also kept track of in this scan by multiplying the loop iteration by the time difference, although given the nature of Labview this time is extremely unreliable and should only be used as a rough approximation at best.

The fast step scan is ideal in the sense that it executes rapidly (scans can be taken in less than ten seconds), while still keeping track of its position at every data point. The downside is that the time difference listed above cannot be less than 1 millisecond, or a sampling frequency of 1000Hz. Also when choosing time differences of less than ~30ms the stage does not return its position for all points. This is not a huge issue however as the intermediate position points can easily be interpolated between known points. Difficulties have been discovered due to this 1000 Hz limitation. In order to get the improved S/N the
stage must be moved as rapidly as possible. This in turn demands a faster sampling rate and the design does not allow for this. I conclude that the Zaber linear stage works best as a stepping motor and is not ideal for constant velocity type scans. The design should be improved to sample the position and intensity independently, in order to utilize a constant velocity scan mode.

Figure 4.5 shows an interferogram obtained with the fast step scan (dotted line), and an interferogram obtained using the step scan (solid line). Notice the sampling error in the centerburst. This error was extremely reproducible and appeared in all of the fast scans and a suitable solution was not found to rectify the problem.

Figure 4.5 Interferogram of fast step scan (dotted line) plotted with an interferogram of a step scan (solid line).
4.5 Data Processing

The data was processed in Igor Pro using a written procedure entitled FTFIR Processing.

Figure 4.6 FTFIR Processing Flowchart.

The best data obtained was with the step scan. The interferograms exhibited good S/N and since the step scan takes a data point at a regular known interval the data is easiest to
process using the FTIR processing code. A sample interferogram pre-processed is shown in Figure 4.7. Note the symmetry about the centerburst.

Figure 4.7 Double Sided Interferogram
EXPERIMENTAL RESULTS

5.1 Verification

The next several figures show water spectra for various hardware and data acquisition configurations. These were used to verify that the spectrometer is calibrated by fitting the obtained spectra to the system model that was developed. The water lines match up very well, and even some of the weaker features are apparent in our spectra. Note however that after the $\sim 35\text{cm}^{-1}$ the optical filter kicks in and the system model is not in agreement with the experimental curve.

Also of interest is the attenuation between $\sim 25\text{cm}^{-1}$-35cm$^{-1}$. This is unexplained but is believed to be part of the instrument efficiency structure, possibly due to multiple reflections somewhere in the instrument. It is extremely repeatable, as it has shown up in all the spectra taken.

For the validation scans with the lower chopping frequency of 200 Hz, the lock-in amplifier has a sync filter, whereas with the higher chopping frequencies a pre-amp with a bandpass filter was used. The conclusion was that the lower chopping frequency with the sync filter worked well and was adequate for our needs. Figure 5.1 shows two of the validation scans at the lower 200 Hz chopping frequency with the sync filter on. Figure 5.2 shows two scans taken with a 313 Hz chopping frequency and a bandpass filter in place. Various other instrumental settings are listed as well.
Figure 5.1 Top: 200 Hz Chopping frequency, No Band Pass, $\tau = 300$ms, Bolometer Gain of 1000 Bottom: separate scan with same settings.
Figure 5.2 Top: 313Hz Chopping frequency, Band Pass Gain of 2, Bolometer Gain of 1000, sensitivity 500mV, $\tau=300$ms. Bottom: 313Hz Chopping frequency, Band Pass Gain of 2, Bolometer Gain of 1000, sensitivity 1V, $\tau=1$s.
Figure 5.3 shows a comparison of spectra taken by increasing the time constant of the lock-in amplifier from 300ms to 1s, in order to improve the signal to noise. Note the increased depth between the intensity and the water absorption lines.

Figure 5.3 Comparison of spectra taken with 300ms and 1s Time Constant
5.2 Spectra of Samples

For imaging and other applications spectra were taken of cloth samples, cardboard, and shuttle tile and are presented in this section. Reference scans were taken before each sampled scan in order to get the transmittance. The transmittance is the sample spectra divided by the reference spectra. Note that this causes the transmittance to blow up at the water lines, although at these points we know that there is little signal due to water absorption. Effectively then the water lines create “noise” or high transmission artifacts in the transmittance spectra due to dividing by a very small number. Also the dashed lines in the transmittance show the plot with heavy smoothing that was done on the data to reduce noise and bring out the general trend.

The interferometer data obtained had a large DC offset which was due to optical chopping of the source and the lock-in detection technique as opposed to a signal from the interferometer. This offset was corrected by setting the average to zero. An additional offset can be observed in the intensity in each of the graphs in section 5.1. Since the intensity at large wavenumbers (200-250 cm\(^{-1}\)) in the spectrum should be zero, the offset was subtracted out in each of the spectra taken with samples. Furthermore, reference scans were made with no sample in place in order to calculate transmission graphs, which are the sample spectra divided by the reference spectra, and an offset was subtracted from these as well. Finally, some of the transmission plots themselves showed a level and unexpected offset (≤0.1) in the in the 200-250 cm\(^{-1}\) range; therefore this was also subtracted out based on the fact that the optical filter in the detector goes to zero near 35 cm\(^{-1}\). The transmission is only plotted for \(\nu > 10\text{cm}^{-1}\) since below this the system
efficiency is low (low blackbody power and beam splitter efficiency) and the system is not sufficiently sensitive to produce reliable data.

Figure 5.4 shows the spectra with reference and transmittance through a thick cotton cloth rag. The cloth rag was simply draped in front of the detector in order to simulate typical imaging applications, such as weapon detection through clothing etc… This spectra was obtained using a 1s time constant, bolometer gain of 1000, no pre-amp, a chopping frequency of 197 and sensitivity of 1 Volt on the SRS Lock-in amplifier. The peak in the intensity of the blackbody after transmission through the cloth rag is clearly shifted to lower wavenumbers, indicating a “roll-off” in the transmission before 20 cm$^{-1}$. 
Figure 5.4 Spectra and Transmittance through cloth. The solid line in the spectra is from the reference scan and the dashed line is the scan with the sample in place. In the transmittance spectra the dashed line is after a heavy smoothing filter was performed.
Figure 5.5 shows the transmittance through a poly-cotton glove (yellow work glove). This was actually through two layers of the glove, which is realistic for any active imaging system. The time constant was 300ms, bolometer gain of 1000, chopping frequency of 197 Hz and sensitivity of 200mV.

![Figure 5.5 Transmission Spectra of Glove. The dashed line is obtained after a heavy smoothing filter was applied.](image)

The transmission of the glove is very low (~1%) above 20 cm\(^{-1}\). It is difficult to accurately determine the transmission due to the low signal to noise.
Figure 5.6 is the transmittance spectra for a single layer of cardboard. It was taken with a 300ms time constant, bolometer gain of 1000, chopping frequency of 197Hz, and lock-in sensitivity of 200mV.

Transmission for the cardboard is similar to the cotton rag and shows a steady decline in transmission from 10 cm$^{-1}$, with significant absorption greater than 20 cm$^{-1}$.

Scans were made for a two-inch piece of shuttle tile although the scans of the tile show almost no signal whatsoever. It was concluded that transmittance for this piece of the tile is zero at least for the power levels that our experiment is capable of. Figure 5.7 shows the interferograms from these scans.
Figure 5.7 Two separate scans of the 2 inch thick shuttle tile.

The first scan is only plotted from 0.5cm-2.8cm since we were making instrumental adjustments during the beginning of this scan. Note that in the first graph it appears that there could be a centerburst indicating some transmission. Further scans would be desirable after increasing the sensitivity of the system, primarily changing the beam splitter to a more efficient polarizing splitter thereby increasing the modulation depth. These scans generally agree with other measurements that were performed locally at the University of Dayton on a 1-inch sample showing transmission at lower frequencies and then falling off to zero at ~0.5THz, which is where we start having power due to the
blackbody source. We also verified on a separate system transmission up to 0.12 THz, which is the upper limit of that source. More quantitative measurements will be made on the thermal tile using that system.
5.3 Conclusions

In conclusion the FTFIR spectrometer has been shown to verify theoretical and system expectations by observation of the water absorption spectra. It has also been demonstrated that the experiment can be used to obtain broadband spectra of samples.

Figure 5.10 shows the transmittance of all three samples plotted on the same graph. Also in order to compare with other literature it has been plotted against the linear frequency as opposed to wavenumbers. From other sources\textsuperscript{1,4} we predict that at low frequencies (≤ 100 GHz) the transmittance should be significantly larger (0.5-0.9), however, in our system the blackbody source has no power output at these frequencies therefore we cannot measure this.

![Figure 5.8 Smoothed transmittance spectra of all three samples.](image)

The graph shows the transmittance spectra for different samples, with the frequency plotted on the x-axis and the transmittance on the y-axis. The samples are indicated by different line styles: cardboard (dashed blue), cloth (solid red), and glove (dotted green).
In the analysis of the cloth, cardboard, and glove it can be seen that the transmittance begins to “roll-off” before ~0.4 THz for the cardboard, cloth, and glove and there is significant attenuation above 0.8 THz. The glove shows the most attenuation. This could be due to the material but more likely the increased attenuation is the result of passing through multiple layers of a thicker material as opposed to the single layer of the cloth and cardboard. It is important to note that in all the reference scans the intensity peaks at ~30-35 cm\(^{-1}\) which shows that all the samples are less transmissive at higher frequencies. These two conclusions support the conclusions determined by Petkie et al.\(^4\), that attenuation increases with increasing thickness and with increasing frequency. This is also expected from the Beer-Lambert law, which states that the transmission will depend exponentially on thickness\(^4\).

The 2-inch shuttle tile sample showed no transmission above the noise threshold of the system. No spectra could be obtained due to the low sensitivity of the interferogram below 300 GHz. However, transmission of frequencies lower than 0.12 THz was verified.
5.4 Future Work

Transmission measurements on damp clothing are of interest. This would enable developers of security imaging to know system response if attempting to image through sweaty clothing. The setup could also be easily modified to perform reflectance measurements on materials. Specifically paint coatings on metal could be analyzed which would aid in NDE sensor development. Also reflectance measurements on shuttle tile are desired for sensors that could search for deformities.

To utilize a fast constant velocity (CV) scan the software should be rewritten in order correlate time of the CV scan to position. A couple of methods to do this have been suggested. The first is to set up a “monochromatic” source such as a Helium Neon (HeNe) laser and correlate the interferogram from the HeNe to the actual interferogram. The peak-to-peak difference in the HeNe interferogram would correspond to a distance that the mirror went 633nm. Of course the system alignment would have to be improved in order to detect the interference fringes in optical frequencies. The second approach would be to sample the output of the LS directly instead of relying on the communication of the serial port, and Zaber’s sub-VI’s. We are skeptical of this approach and conclude that the Zaber LS is primarily designed as a stepper and perhaps a different LS with access to the optical encoder is more ideal.

For the step scans it was discussed that chopping or modulating should be in one of the arms of the interferometer as opposed to at the source. To accomplish this it was
suggested to mount a small piezo-electric disk behind the mirror and locking in to this frequency. For either method improved S/N is predicted.

In order to overcome the Mylar drawbacks it was planned to modify the MI to a Martin-Puplett Interferometer\(^\text{14}\). The design is similar except that a wire grid polarizer is used instead of the Mylar beam splitter, and rooftop mirrors are in place of the flat mirrors. The rooftop mirrors are essentially two mirrors at right angle such that upon reflection it will polarize the wave 180° out of phase to allow either transmission or reflection upon returning to the beam splitter. This allows 50% power throughput once the input signal is polarized and, neglecting other losses, does not introduce any additional frequency dependent efficiencies to the spectra. Overall the wire-grid polarizer is a much more efficient beam splitter in dividing the radiation between the arms of the interferometer. The downside is that the orthogonal polarizations of the output signal must be measured separately. This can be done with two detectors or with a rotating output polarizer, which requires some additional signal processing. Unfortunately, due to time constraints this design was never implemented.
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