High Frequency Moisture Detection for Pulp and Paper Applications

A **Major Qualifying Project Report**
Submitted to the faculty of **Worcester Polytechnic Institute**

in partial fulfilment of the requirements for the Degree of Bachelor of Science

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Abstract

This project studies the development of a high frequency moisture detection sensor for pulp and paper applications. A Millimeter-wave/THz sensor is developed in this project due to its high accuracy in detecting moisture content of wet paper samples. From background research, the theoretical relationship between Power, absorption coefficient, and DBMC were understood. The software and hardware of a sensor were jointly developed to run lab experimental trials to confirm these theoretical relationships and present experimental results of Power vs Range plots as a function of DBMC.

Acknowledgements

I would like to acknowledge the following people for their contributions to this project:

- WPI Physics Department's Laboratory for Education and Application Prototypes (LEAP) facility for supplying the equipment for this MQP
- Professor Petkie for the introduction to this research endeavor at WPI and for all the guidance and feedback on my MQP, especially the report and the SOP
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1. Introduction

The industrial sector of the United States is known to account for the largest share of energy consumption in the nation. Energy efficiency improvements in this sector can significantly reduce the nation's demand for energy. National energy supply demand is often measured in quads. 1 Quadrillion British Thermal Unit (BTU) or quad is equivalent to about 1.055×10^{18} Joules. In 2012, the industrial sector consumed 30.6 quads of energy while the total energy consumption for the United States was 95 quads. Manufacturers accounted for about 74% of the industrial sector's energy consumption [1].

The Energy Information Administration (EIA) forecasts that the total energy consumption by the United States will grow to about 102 quads in 2025 with nearly all the growth coming from the industrial sector. It is forecasted that the industrial sector alone will increase its energy consumption to about 37.4 quads, a 22% increase, by 2025 [1].

Devoted to research in drying moist, porous materials such as food and agricultural products, forestry products, chemicals, textiles, and biopharmaceuticals, the Center for Advanced Research in Drying (CARD) was jointly established by WPI and the University of Illinois at Urbana Champaign (UIUC) in 2016 [4]. CARD is a National Science Foundation Industry University Cooperative Research Center (IUCRC) [3]. Being the first center in the United States devoted to such research, CARD is looking to assist US manufacturing industries in becoming more environmentally sustainable and to improve the quality of their products by using advanced and novel technologies in heat/mass transfer processes such as drying, heating, cooling, freezing, dewatering, and baking [3].

1.1 Project Goals

This Major Qualifying Project (MQP) is interdisciplinary with a professional writing component focused on the implementation of Standard Operating Procedures (SOPs) in physics. Within that MQP, an SOP was created for the sensor lab outlined in this report.

The goal of the physics component of the MQP was to develop a high frequency moisture detection sensor for pulp and paper applications to help measure the moisture content of wet paper samples at the inlet of an industrial smart dryer. The following research objectives were set to achieve this goal:

1. Understand and contribute to the development of the sensor hardware configurations
2. Understand and contribute to the development of the sensor software
3. Run lab tests and smart dryer tests with the developed sensor

This report consists of four major sections which are outlined below.

- Background: The background chapter provides important information about the history, physics, and research surrounding millimeter/THz waves, the effective medium theory, the Beer-Lambert Law, Dry Basis Moisture Content, and FMCW radar technology
- Methodology: The methodology chapter outlines the main methods used to carry out the previously set research objectives
- Results and Discussion: The results and discussion chapter provides the experimental results and analysis of their relevance to expected theoretical results

- Conclusion and Future Work: The conclusions and future work chapter provides a reflection on the overall results of the project and future work that can be implemented

2. Background

2.1 Electromagnetic Spectrum

Electromagnetic energy travels in waves and spans a broad spectrum from longer radio waves to shorter gamma waves [8]. The millimeter-wave (mm-wave) region of the electromagnetic spectrum corresponds to frequencies from 30 GHz to 300 GHz. The high frequency of mm-waves and their propagation characteristics makes them useful for a variety of applications like transmitting large amounts of computer data, cellular communications, and radar [5].

Within the electromagnetic spectrum, there is also a region known as the Terahertz (THz) gap that lies between electronic waves, like microwaves, and photonics waves like ultraviolet waves as seen in Figure 1. The THz-wave region is said to between the frequencies of 100 GHz to 30 THz. Terahertz waves are highly valued for their unique properties like their ability to penetrate materials like paper, clothing, and wood [18]. The THz region of the electromagnetic spectrum is the most elusive region and there is no standardized definition for the frequency band [17]. In some research, there is even an overlap in frequencies between mm-waves and THz waves like seen in Figure 2.

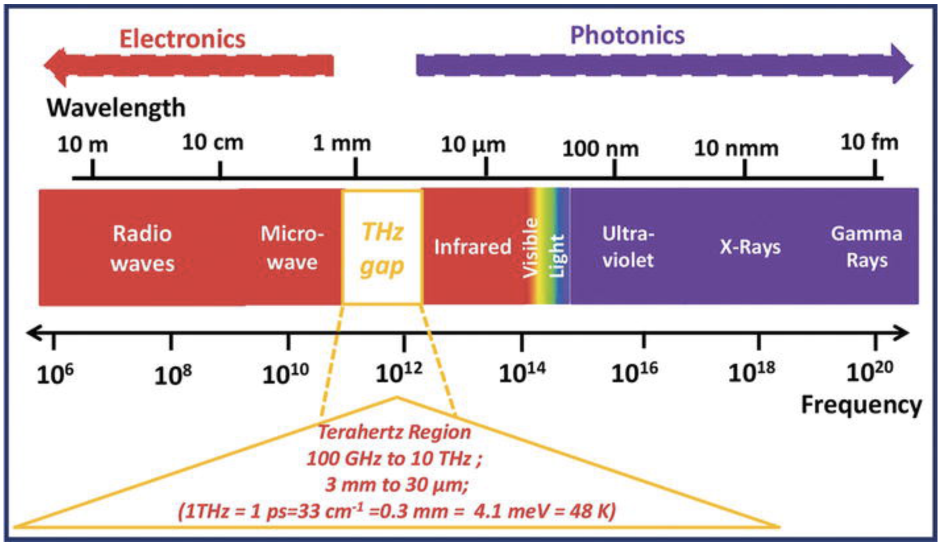

Figure 1. The Electromagnetic Spectrum Showing the THz Gap

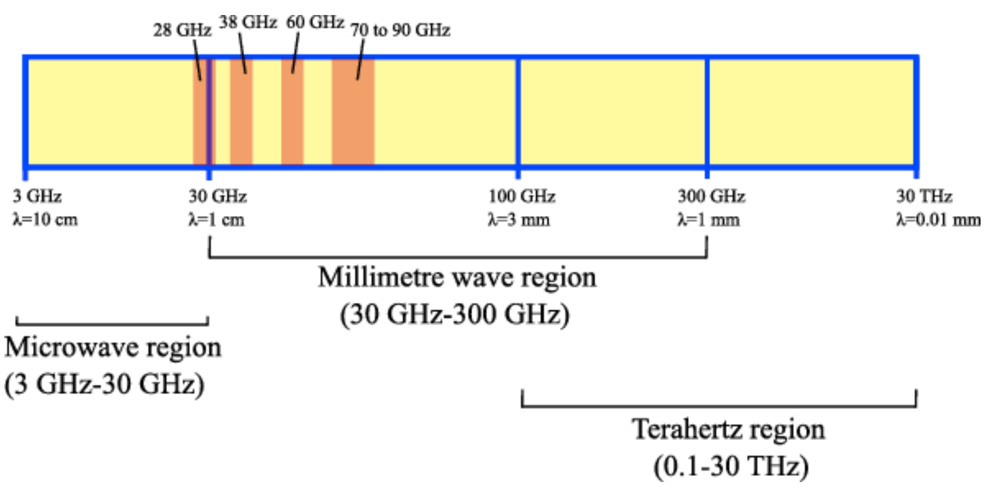

Figure 2. The Overlap in Frequencies Between the Mm-wave and THz-wave Regions

2.2 History of Millimeter and Terahertz Waves

In 1895, Jagadish Chandra Bose first demonstrated the transmission and reception of electromagnetic waves at 60 GHz over a 23-meter distance [6]. Jagadish Chandra Bose was a Bengali scientist and the first person in the world to demonstrate wireless transmission of electromagnetic waves [7]. Bose pioneered the development of mm-wave components such as a spark-gap generator, coherer detector, and other antennae subsystems [12]. Following Bose's research, the development of Millimeter Wave Integrated Circuits (MMIC) created opportunities for mass manufacturing of mm-wave products for commercial applications. In the 1990s, the beginning of automotive collision-avoidance radars at 77 GHz marked the first consumer-oriented use of mm-wave frequencies above 40 GHz [12].

The history of THz technologies is expressed differently in several papers and books. It is said that in 1897, H.Rubens, a German physicist, and E.F. Nichols, a Physics professor, explicitly noted the existence of a gap in the electromagnetic spectrum between the optical and electronic sources of radiation [16]. In the past, a lot of work has been done in the THz spectral range under the terms of far infrared and sub-mm-waves. Now, the term THz stands for a novel technique offering many applications to industry, medicine, detection of drugs and explosives, and telecommunications [16]. In addition, THz technologies are important for imaging and spectroscopy because clothing, plastic packaging equipment and microcircuit bodies are transparent in the THz spectral range [16].

2.3 Terahertz Radiation and Time-Domain Spectroscopy

THz and mm-waves are also efficient at detecting the presence of water and valuable in moisture detection related research [19]. Historically, the major use of THz spectroscopy has been by chemists and astronomers in the spectral characterization of rotational and vibrational resonances and thermal-emission lines of simple molecules. In the past twenty years, milestone achievements like the development of THz time-domain spectroscopy (TDS), THz imaging, and high-power THz generation have been researched [19]. Discovered in the 1990's, TDS makes use of ultrashort laser pulses that are converted in an emitter into picosecond broadband pulses of

THz radiation. Time-domain TDS spectroscopy can measure complex dielectric and conductivity spectra of various kinds of samples in a THz spectral range. Its frequency spectrum can be calculated as its Fourier transformation or Fast Fourier Transform (FFT) [20].

THz radiation can penetrate deeply into nonpolar and non-metallic materials such as paper, plastic, clothes, wood, and ceramics. These materials are typically opaque to optical wavelengths. As these materials are often used in packaging, THz imaging can be a useful tool for non-destructive testing and hidden object detection as they are unharmful unlike X-rays [18].

2.4 Effective Medium Theory

By recording the waveform of THz radiation through methods like THz TDS, dielectric properties of a sample like the relative complex permittivity can be measured [24]. The dielectric properties of a sample may vary along with changes of sample compositions and structures. To understand the relation between composition and dielectric properties, the effective dielectric properties of the sample can be macroscopically investigated by the Effective Medium Theory (EMT) [24].

2.5 Beer-Lambert Law

To understand the relationship between the absorption coefficient and intensity, the Beer-Lambert law is studied. The Beer-Lambert law states that:

$$I = I_0 e^{-\alpha(x)} \tag{1}$$

where I is the intensity, I_0 is the initial intensity, α is the absorption coefficient, and x is the thickness of the sample [11]. From the above equation, it can be understood that the intensity is indirectly proportional to the absorption coefficient. As the absorption coefficient decreases, the power would increase and vice versa.

2.6 Dry Basis Moisture Content

Dry basis moisture content is a mass percentage of water and important in most drying-related calculations. It is described by the percentage equivalent to the ratio of the weight of water to the weight of dry matter [9]. To measure the dry basis moisture content, the weight of water present in a sample is divided by the weight of dry material in the sample [10]:

$$Dry\ Basis\ Moisture\ Content = \left(\frac{Weight\ of\ Water\ in\ Sample}{Weight\ of\ Dry\ Material\ in\ Sample}\right) * 100 \quad (2)$$

Dry basis moisture is mostly used for describing moisture changes during drying processes. When a sample loses or gains moisture, the change in the dry basis moisture content is linearly related to the weight loss or gain [9].

2.7 Mm/THz Wave Sensors and FMCW Radar Technology

Mm-wave/THz wave sensors are a special class of radar technology that uses short-wavelength electromagnetic waves. Radar systems transmit electromagnetic wave signals which objects in their path then reflect. By capturing this reflected signal, a radar system can help to determine the range, velocity, and angle of objects in its path. Due to the short wavelengths of mm-waves, systems that operate between 76-81 GHz will have the ability to detect movements that are as small as a fraction of a millimeter amounting to high accuracy [21].

A complete mm-wave radar system includes components that transmit (TX) and receive (RX) audio frequency (RF) components and various analog and digital components like clocking, analog-to-digital converters (ADCs), microcontrollers (MCUs), and digital signal processors (DSPs) [21]. Texas Instruments (TI) has designed complementary metal-oxide semiconductor (CMOS)-based mm-wave radar devices that integrate these analog and digital components. In addition, TI devices implement a special class of mm-wave technology called frequency-modulated continuous wave (FMCW). FMCW radars transmit a frequency-modulated signal continuously to measure range. This differs from traditional pulsed-radar systems where short pulses are periodically transmitted [21].

The signals used in FMCW radars are known as chirps. In chirps, the frequency increases linearly with time. Figure 3 shows a representation of a chirp with amplitude as a function of time. Figure 4 represents this same signal with frequency as a function of time. In this example, the start frequency of the chirp is $f_c = 77\ GHz$, the Bandwidth of the is $B = 4\ GHz$, the duration is $T_c = 40\ \mu s$, and the slope of the chirp or the rate of change of frequency is $S = 100\ MHz/\mu s$ [21]. This plot is known as a frequency vs time plot or 'f-t plot' [21]. At this point, FFT is completed and the initial function of time is transformed into a function of frequency [23]. FFT is very useful for analysis of time-dependent phenomena. The peaks that are analyzed after the FFT relates to the value intensity. From Beer's Law, it is known that intensity is indirectly proportional to the absorption coefficient which is directly proportional to the DBMC of water as deemed by the effective medium theory.

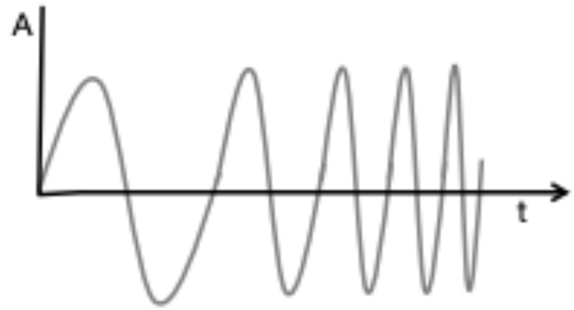

Figure 3. Chirp with Amplitude as a Function of Time

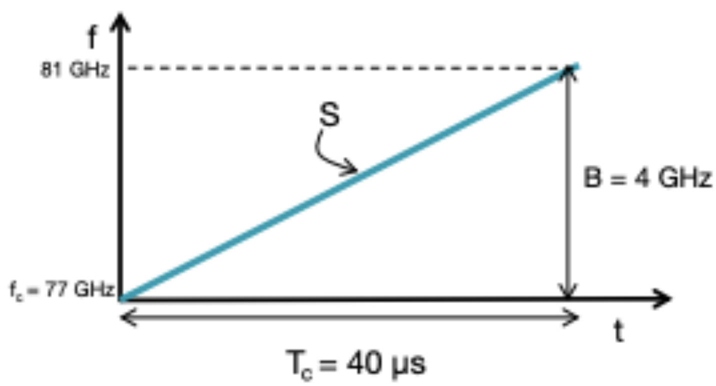

Figure 4. Chirp representation with Frequency as a Function of Time

3. Methodology

To achieve the goal of this project and develop an efficient sensor, I contributed to the development of the sensor software, hardware, and ran lab tests using the completed sensor to help prove the theoretical effective medium theory.

3.1 Sensor Setup and Hardware

3.1.1 Information about the Sensor

The selected sensor for this project was the TI IWR1642 device which is an industrial mm-wave radar sensor. As shown in Figure 5, the IWR1642/IWR1642BOOST device is an integrated single-chip mm-wave sensor board based on FMCW radar technology [13] This sensor is capable of operation in the 76 to 81 GHz band. The IWR1642 device is ideal for low-power, self-monitored, and ultra-accurate radar systems in industrial applications like building automation, factory automation, and material handling [13].

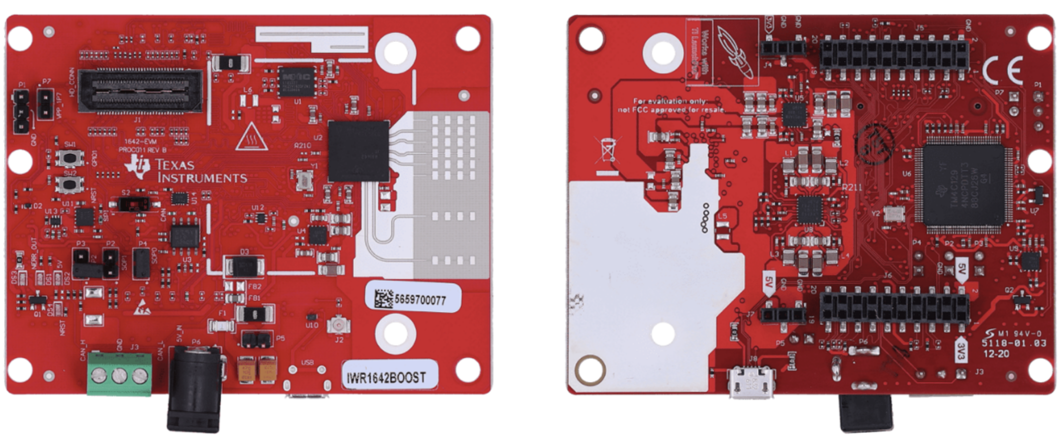

Figure 5. Top and Bottom View of the TI IWR1642 Radar Sensor Board

This sensor was used in conjunction with the DCA1000 evaluation module (DCA1000EVM) which can be seen in Figure 6. The DCA1000EVM is a real-time data capture adapter for a radar sensing evaluation module like IWR1642 [14]. The DCA1000EVM is about 90 mm x 102 mm x 1.6 mm [23]. This evaluation module provides streaming for two and four lane low-voltage differential signaling traffic from IWR radar sensor EVMs. The data can then be streamed out via 1-Gigabits per second (Gbps) Ethernet in real time to a PC running the MMWAVE-Studio tool for data capture and visualization. In addition, this data can be passed to an application of choice for data processing and further algorithm development [15].

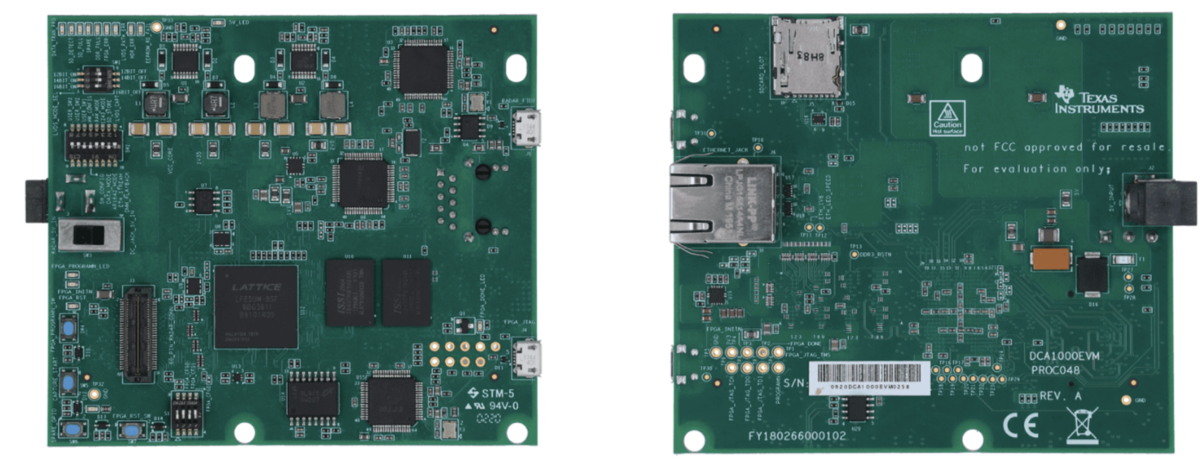

Figure 6. TI DCA1000EVM Real-Time Data Capture Adapter

3.1.2 Board and Hardware Setup

We first aligned the DCAEVM1000 and IWR1642 boards and connected them with screws, spacers, and stands. We also connected the 60-pin Samtec ribbon cable between the two boards [23]. We connected a power cable to the DC jack of the DCA1000EVM board providing it 5 Volts of power. The J1 – Radar FTDI USB connector was then connected to allow access to the IWR1642 EVM. Additionally, the DCA1000EVM supports a Gigabit Ethernet port to provide network connection which we connected to lab laptop. Following these hardware configurations, the FPGA programming was configured through the Lattice Diamond Programmer standalone tool on the laptop PC to allow for further configurations using the MMWAVE-Studio PC application was used to further configure the radar device [24].

3.2 Sensor Software Setup

MMWAVE-STUDIO is a stand-alone Windows Graphical User Interface (GUI) that provides the ability to configure and control mm-wave sensor modules. It also allows for the collection of analog-to-digital (ADC) data for offline analysis. ADC data capture is intended to enable evaluation and characterization of radio-frequency (RF) performance and PC development of signal-processing algorithms. MMWAVE-STUDIO additionally provides basic post-processing and visualization of ADC data based on MATLAB [15].

For this project, we primarily installed MMWAVE-Studio version 02_01_01_00 to the lab laptop. After running into numerous technical difficulties, we resorted to an older version, version 02_00_00_02, of MMWAVE-Studio.

The accessibility of the MMWAVE-Studio GUI is quite difficult for those who are new to using such software. With one of the output goals of this sensor to be the availability for industry partners, we developed MATLAB scripts that would help to automate many of the initial configurations within the MMWAVE-Studio interface.

Upon first opening, MMWAVE-Studio opens a main window with an output tab where the outputs of the various LUA commands, on which the software runs, are displayed. Prior to creating an automated environment, we manually had to connect the board to the software and set up various static configurations, data configurations, and test source configurations. This was a tedious process and unreasonable to go through with every data collection trial. Hence, we used a LUA demo script, that was provided during the MMWAVE-Studio download, and automated all the configuration setups past the first two setups on the landing connection page. Figure 7 shows the outputs that are shown in the MMWAVE-Studio output window after running the LUA demo script.

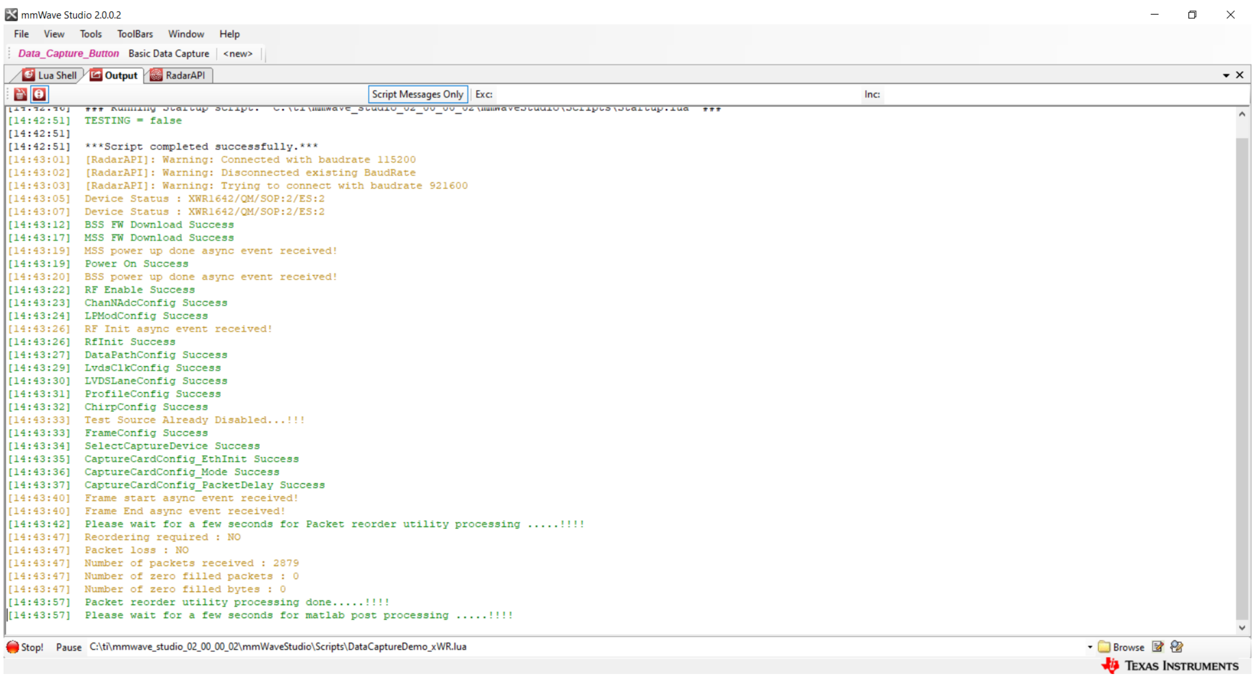

Figure 7. The MMWAVE-Studio Outputs After Running the LUA Demo Script

After running the LUA demo script, MMWAVE-Studio provided preliminary plots from the ADC raw data capture. These plots were not available to export for further analysis. Hence, we created a MATLAB script that initialized, connected, and sent a test message to the RSTD client of the sensor after the ADC raw data capture occurred. These initializations are necessary to establish connect with the MMWAVE-Studio LUA Shell from the MATLAB script.

The MATLAB script then utilized aspects of the given raw data reader script to accept the BIN file that was produced by MMWAVE-Studio and extract the values of Power and Range as CSV files. The raw data reader script is a script provided in the MMWAVE-Studio download package which reads in the BIN files created by MMWAVE-Studio and constructs raw data in frames, chirps, and channels. In addition, this script performs FFT to generate a radar cube which provided us with Range- FFT versus Range plots which we then were able to load into IGOR Pro for further analysis to understand the relationship between Power vs Range as a function of DBMC.

3.3 Lab Test Trials

Once the MATLAB script was able to connect to the sensor board and provide unique Power and Range variables for each trial, we were able to run lab-based trials to ensure the relationship between Power and Range as a function of DBMC. To perform these trials, we obtained a measurement sample from printer paper. The sample was circular in shape with a diameter of four inches which was in relation to the diameter of the weighing pan on the lab's digital measuring scale. Prior to saturating the sample in water, a dry sample mass measurement and a reference mass measurement (a measurement with only the curl-stopping ring on the weighing pan of the scale) was obtained.

This sample was then saturated in water for one and a half minutes and brought to the weighing pan of the digital scale. Over a one-hour measurement period, the MATLAB script was run every five minutes to capture the values of the Power and Range variables as the sample dried. In other words, the Power was being measured as the DBMC of the wet sample decreased. The values of Power and Range obtained from these trials were then plotted in IGOR PRO as a function of DBMC. Figure 8 displays the lab experimental setup with the sensor at a height of 0.5 m from the sample. Table 1 and 2 show the mass measurement values for two lab test trials, where the sensor was at 0.30 m and 0.53 m above the sample respectively. The DBMC was calculated by subtracting the weight of dry sample from the weight of the specific wet trial sample. This quantity was then divided by the weight of the dry sample and multiplied by 100 to create a DBMC percentage value.

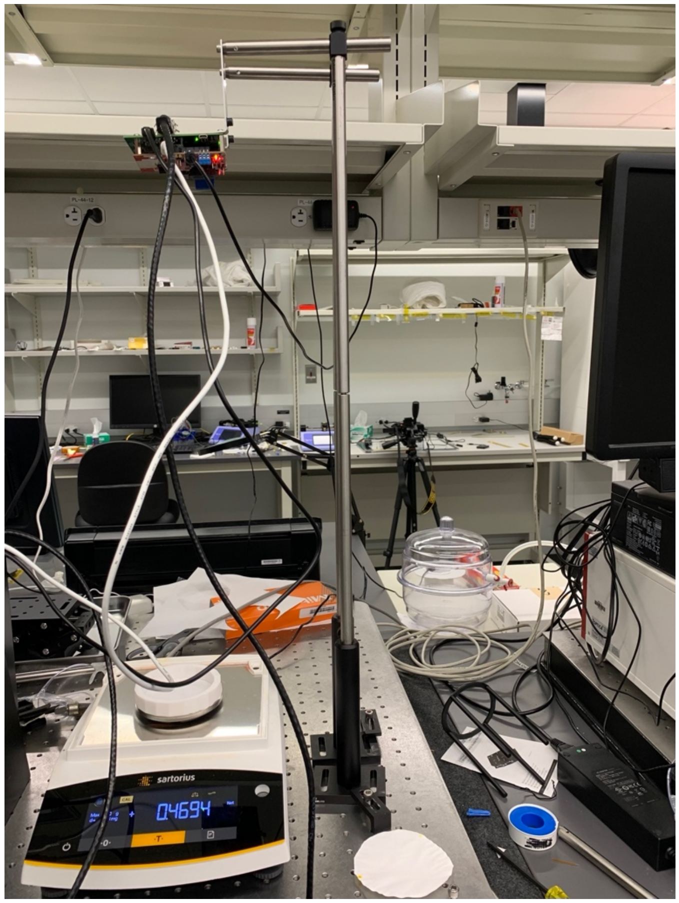

Figure 8. Laboratory Experimental Setup

Sample	Time	Mass (g)	DBMC Calculation (%)
Reference (No Sample)	-	0 g	-
Dry	-	0.468 g	0%
Wet – Trial 1	11:04 AM	0.992 g	111.97%
Wet – Trial 2	11:09 AM	0.944 g	101.71%

Wet – Trial 3	11:14 AM	0.894 g	91.03%
Wet – Trial 4	11:19 AM	0.847 g	80.98%
Wet – Trial 5	11:24 AM	0.801 g	71.15%
Wet – Trial 6	11:29 AM	0.758 g	61.97%
Wet – Trial 7	11:34 AM	0.722 g	54.27%
Wet – Trial 8	11:39 AM	0.687 g	46.79%
Wet – Trial 9	11:44 AM	0.653 g	39.53%
Wet – Trial 10	11:49 AM	0.622 g	32.91%
Wet – Trial 11	11:54 AM	0.592 g	26.50%
Wet – Trial 12	11:59 AM	0.568 g	21.37%
Wet – Trial 13	12:04 PM	0.547 g	16.89%

Table 1. Mass Measurements of Lab Test Trial 1 (Sensor Height of 0.30 m)

Sample	Time	Mass (g)	DBMC Calculation (%)
Reference (No Sample)	-	0 g	-
Dry	-	0.478 g	0%
Wet – Trial 1	12:28 PM	0.977 g	104.39%
Wet – Trial 2	12:33 PM	0.953 g	99.37%
Wet – Trial 3	12:38 PM	0.912 g	90.79%
Wet – Trial 4	12:43 PM	0.875 g	83.05%
Wet – Trial 5	12:48 PM	0.836 g	74.90%
Wet – Trial 6	12:53 PM	0.800 g	67.36%

Wet – Trial 7	12:58 PM	0.766 g	60.25%
Wet – Trial 8	1:03 PM	0.734 g	53.56%
Wet – Trial 9	1:08 PM	0.704 g	47.28%
Wet – Trial 10	1:13 PM	0.675 g	41.21%
Wet – Trial 11	1:18 PM	0.647 g	35.36%
Wet – Trial 12	1:23 PM	0.620 g	29.71%
Wet – Trial 13	1:28 PM	0.596 g	24.69%

Table 2. Mass Measurements of Lab Test Trial 2 (Sensor Height of 0.53 m)

4. Results and Discussion

This section contains and analyze the results from the methods completed to develop this moisture detection sensor.

4.1 Preliminary MMWAVE-Studio Results

After first connecting the sensor to the lab laptop and successfully running MMWAVE-Studio, we were provided with initial measurement plots from the program. These plots help to assess the competence of MMWAVE-Studio's post-processing and the functionality of our sensor to laptop connection. Figure 9 shows these four preliminary plots that result from this MATLAB post-processing after initializing the sensor configurations and running the LUA demo script. The upper right plot labeled Detection & Angle estimation Results shows that the sensor successfully can detect a point or the paper sample that we have placed on the weighing pan of the scale about 0.3 m from the sensor.

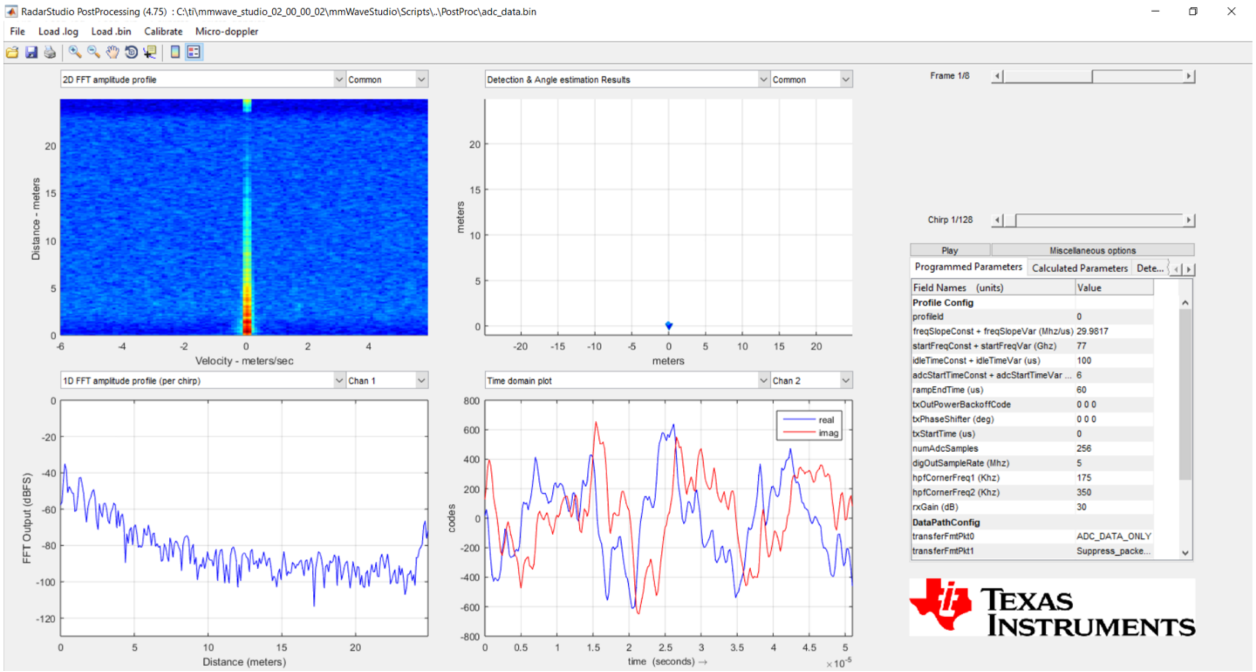

Figure 9. Preliminary Plots Obtained from MMWAVE-Studio

From these preliminary plots, the plot that we were interested in further analyzing was the bottom left plot labeled 1D FFT amplitude profile (per chirp) or the FFT output (dBFS) vs Distance (meters) plot. We wanted to further extract this plot to load the Power and Range variables into IGOR Pro but were unable to do so. Hence, we then created a MATLAB script that would allow this extraction.

4.2 MATLAB Automated Script

After running the script that we wrote on MATLAB to help automate some of the configurations on MMWAVE-Studio and to help enable further analysis of the data capture variables, we were provided the plots that are shown in Figure 10.

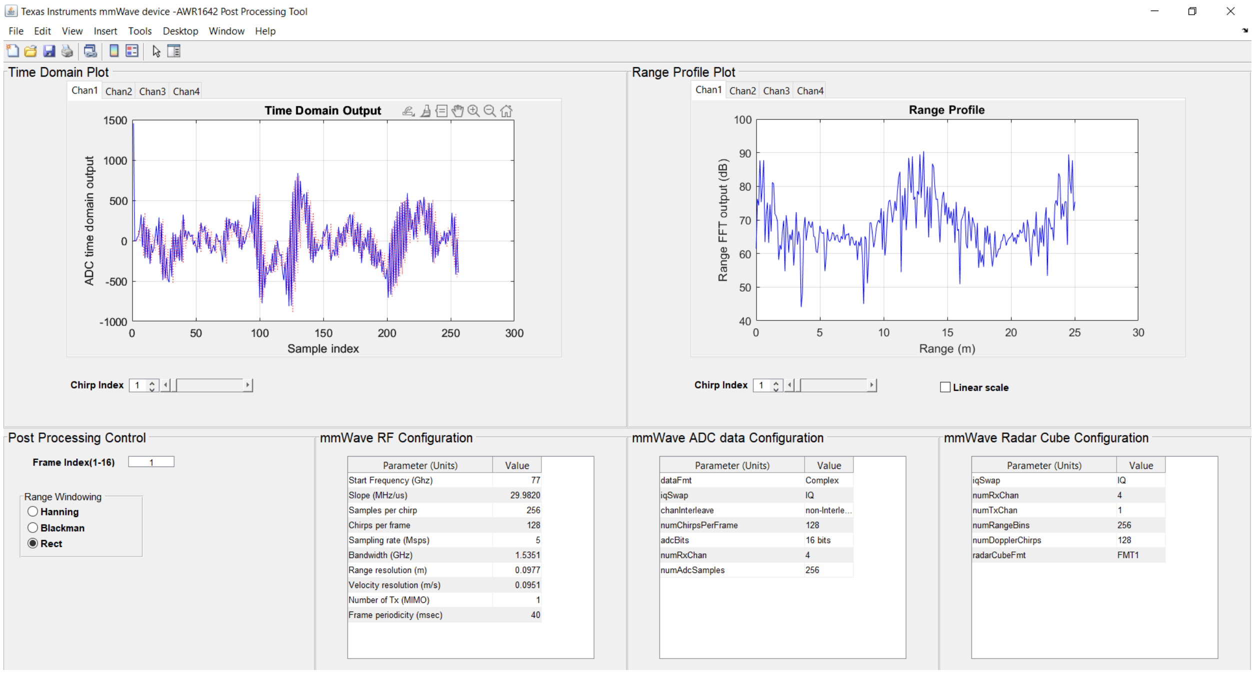

Figure 10. Plots from the MATLAB Script Used for Further Analysis

From the displayed plots, the plot that we wanted to further analyze in IGOR Pro was the top right Range Profile plot. Unlike in MMWAVE-Studio's post processed plot, here we were able to export the Power and Range variables as individual CSV files which we then can further analyze and plot in IGOR Pro.

4.3 Lab Test Trials

Once we confirmed the functionality of the MMWAVE-Studio ADC raw data capture and preliminary post processing and the MATLAB raw data reader and post processing script, we were able to confirm the relationship between our experimental results of Power and DBMC with the theoretical results from Beer's Law. Power is indirectly related to the DMBC of the paper sample. As the DBMC of the sample decreases, the absorption coefficient of water also decreases. From the definition of Beer's Law, we know then that Intensity, which is Power in our research, will increase. We should then expect higher values of power at lower values of DBMCs which is seen in Figure 11. When the paper is completely dry, there is 0% DBMC in the sample and this is shown by the trace of Power having the highest peak at that value. On the contrary, when the mass measurement of the paper sample is taken right after saturation, there is approximately 100% DBMC in the sample and this is shown by the trace Power having the lowest value. At saturation, it is important to note that the value DBMC can be greater than 100% with a higher ratio of water than paper. As seen in Tables 1 and 2, the initial DBMC values are 111.97% and 10.439% respectively. This specific plot is from a lab trial where the sensor was positioned at a fixed range, vertical height, of 0.5 m from the sensor to better analyze the differences in power.

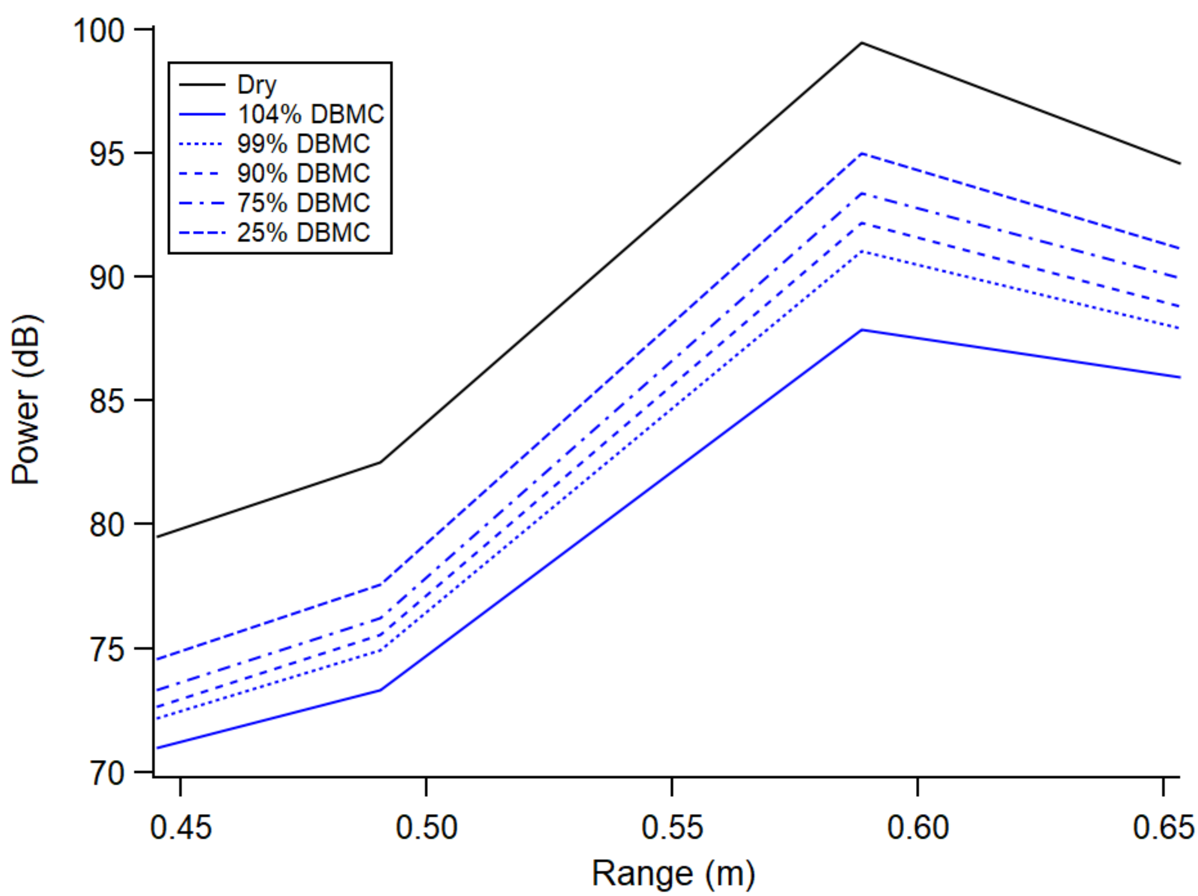

Figure 11. Power vs Range as a Function of DBMC

5. Conclusion and Future Work

This section discusses the conclusions I drew from the results of this MQP. The goal of this MQP was to develop a high frequency moisture detection sensor to be used in an industrial smart dryer for pulp and paper applications. Due to the nature of the chosen sensor being a tech demo, there were a handful of technical difficulties that were faced in the development of the sensor's software. By the end of the MQP, we were successful in creating a sensor that was successful in detecting the variability of Power, over a fixed Range, needed to detect moisture content in a sample ranging from full saturation to no saturation or 0% DBMC. We were also successful in utilizing these variables to develop Power vs Range plots as a function of DBMC to ensure the theoretical results from Beer's Law.

In the future, it would be beneficial to develop Power vs Range plots as a function of DBMC for every mass measurement calculated in the trials. This would allow further analysis of the relationship between Power and DBMC and subsequently, absorption coefficient. Since we only were able to extract results from two ranges, it would be interesting to note the changes in this relationship as the range increases since the range between the sensor mount on the dryer and the paper sample will be greater than the range we are able to measure in the lab.

In addition, this sensor can be mounted onto the inlet of the smart industrial dryer at WPI where similar moisture detection tests can be run for a variety of paper types using a physics-based artificial intelligence (AI) model. In addition, this sensor can be further developed to ease the accessibility for industry partners who may be interested in utilizing the detection capabilities of this sensor.

6. References

[1] “Barriers to industrial energy efficiency.” [Online]. Available: https://www.energy.gov/eere/amo/articles/barriers-industrial-energy-efficiency-report-congress-june-2015. [Accessed: 27-Apr-2023].

[2] “About the center,” *Center for Advanced Research in Drying " About the Center*. [Online]. Available: https://www.dryingresearch.org/about-the-center/. [Accessed: 27-Apr-2023].

[3] “Center for Advanced Research in drying (CARD),” *IUCRC*. [Online]. Available: https://iucrc.nsf.gov/centers/center-for-advanced-research-in-drying/. [Accessed: 27-Apr-2023].

[4] “Improving drying methods in manufacturing,” *ASME*. [Online]. Available: https://www.asme.org/topics-resources/content/improving-drying-methods-in-manufacturing. [Accessed: 27-Apr-2023].

[5] Ethw, “Millimeter waves,” *ETHW*, 12-Apr-2017. [Online]. Available: https://ethw.org/Millimeter_Waves. [Accessed: 27-Apr-2023].

[6] Ethw, “Milestones:first millimeter-wave communication experiments by J.C. Bose, 1894-96,” *ETHW*, 14-Jun-2022. [Online]. Available: https://ethw.org/Milestones:First_Millimeter-wave_Communication_Experiments_by_J.C._Bose,_1894-96#:~:text=For%20his%20communication%20system%2C%20Bose%20pioneered%20in%20development%20of%20entire,more%20than%20100%20years%20ago. [Accessed: 27-Apr-2023].

[7] https://www.open.ac.uk/researchprojects/makingbritain/content/jagadish-chandra-bose

[8] “Introduction to the electromagnetic spectrum,” *NASA*. [Online]. Available: https://science.nasa.gov/ems/01_intro#:~:text=Electromagnetic%20energy%20travels%20in%20waves,machine%20uses%20yet%20another%20portion. [Accessed: 27-Apr-2023].

[9] *Dry basis*. [Online]. Available: https://engineering.purdue.edu/~abe305/moisture/html/page9.htm#:~:text=Dry%20basis%20moisture%20content%20(designated,0%20to%20very%20large%20percentages. [Accessed: 27-Apr-2023].

[10] “The Global Scientific Organization and voice for Food Science and Technology,” *IUFoST*. [Online]. Available: https://iufost.org/. [Accessed: 27-Apr-2023].

[11] Admin, "Beer-Lambert law: Statement, derivation, formula, limitations, faqs," *BYJUS*, 17-Mar-2023. [Online]. Available: https://byjus.com/physics/derivation-of-beer-lambert-law/. [Accessed: 27-Apr-2023].

[12] "Advances in millimeter - DRDO." [Online]. Available: https://www.drdo.gov.in/sites/default/files/monographs-documents/40-mmwave.pdf. [Accessed: 27-Apr-2023].

[13] "IWR1642," *IWR1642 data sheet, product information and support | TI.com*. [Online]. Available: https://www.ti.com/product/IWR1642#description. [Accessed: 27-Apr-2023].

[14] "DCA1000EVM," *DCA1000EVM Evaluation board | TI.com*. [Online]. Available: https://www.ti.com/tool/DCA1000EVM. [Accessed: 27-Apr-2023].

[15] "MMWAVE-Studio," *MMWAVE-STUDIO IDE, configuration, compiler or debugger | TI.com*. [Online]. Available: https://www.ti.com/tool/MMWAVE-STUDIO#overview. [Accessed: 27-Apr-2023].

[16] "(PDF) brief history of thz and IR Technologies - Researchgate." [Online]. Available: https://www.researchgate.net/publication/332613193_Brief_history_of_THz_and_IR_technologies. [Accessed: 27-Apr-2023].

[17] "5G terrestrial networks: Mobility and coverage—solution in three ..." [Online]. Available: https://ieeexplore.ieee.org/document/7902205/. [Accessed: 27-Apr-2023].

[18] "Terahertz Technologies explained," *Nanotechnology*, 07-Feb-2023. [Online]. Available: https://www.nanowerk.com/terahertz-technologies-explained.php. [Accessed: 27-Apr-2023].

[19] A. Rogalski and F. Sizov, "Terahertz detectors and focal plane arrays - opto-electronics review," *SpringerLink*, 07-Mar-2011. [Online]. Available: https://link.springer.com/article/10.2478/s11772-011-0033-3. [Accessed: 27-Apr-2023].

[20] P. Ondrejkovic, "Introduction," *THz science and technology*. [Online]. Available: http://palata.fzu.cz/diel/thz.php. [Accessed: 27-Apr-2023].

[21] "The Fundamentals of Millimeter Wave Radar Sensors (rev. A)." [Online]. Available: https://www.ti.com/lit/wp/spyy005a/spyy005a.pdf. [Accessed: 27-Apr-2023].

[22] "Analog | Embedded Processing | Semiconductor Company | ti.com." [Online]. Available: https://www.ti.com/lit/ug/spruij4a/spruij4a.pdf. [Accessed: 27-Apr-2023].

[23] *Fast fourier transforms*. [Online]. Available: http://hyperphysics.phy-astr.gsu.edu/hbase/Math/fft.html. [Accessed: 27-Apr-2023].

[24] "Effective medium theory for multi-component materials based on ..." [Online]. Available: https://www.researchgate.net/publication/347072231_Effective_Medium_Theory_for_Multi-Component_Materials_Based_on_Iterative_Method. [Accessed: 27-Apr-2023].

Exploring Standardization:
The Implementation of SOPs in Physics

A **Major Qualifying Project Report**

Submitted to the faculty of **Worcester Polytechnic Institute**

in partial fulfilment of the requirements for the Degree of Bachelor of Science

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Abstract

This project studies the implementation of Standard Operating Procedures (SOPs) in Physics. SOPs are written documents used to maintain consistency and quality of an organization. From background research, it was understood that SOPs are widely available in lab-based sciences like chemistry and biology but lack in implementation in Physics. Interviews were conducted to further understand this problem statement and analyze the implementation of SOPs within the WPI Physics department. Another deliverable for this project was an SOP created for a physics sensor lab. To accomplish this, a literature review and task analyses were completed to understand the formatting, language, and subject content of a lab-based SOP.

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Introduction

Standard Operating Procedures (SOPs) are essentially “how to” documents that detail the activities needed to complete certain tasks. The policies, procedures, and standards laid out in an SOP are for the success of a business and subsequently help with creating efficiencies, fewer workplace errors, consistency, reliability, and protection of employers in potential liabilities and personnel matters (Brampton, n.d). The development of SOPs is an integral part of a successful quality system as SOPs provide individuals with information to perform a job properly and facilitate quality and integrity of a product or end-result. Hence, SOPs need to be written correctly, need to be re-enforced and reviewed by management, and need to be readily accessible for reference to be an asset to an organization (United States EPA, 2007).

While SOPs are common in industries like manufacturing and food services and scientific disciplines like chemistry where the use of hazardous chemicals is common, there is very little research on their existence and implementation in physics. This Major Qualifying Project (MQP) focuses on the lack in SOP implementation in Physics. This MQP is interdisciplinary with a physics component focused on the development of a high frequency moisture detection sensor for pulp and paper applications. The goal of the professional writing component of this MQP was to understand the implementation of SOPs in Physics and specifically, the WPI Physics department. In addition, the development of an SOP in terms of formatting, language, and content were also researched. As a supplemental deliverable, an SOP was created for the sensor lab outlined in the physics component of this MQP.

This report consists of five major sections which are outlined below:

- Background: This chapter provides general information on SOPs, their importance and implementation in lab-based sciences, and their lack of implementation in physics.
- Methodology: This chapter outlines the main methods used to carry out the goals of the professional writing component of the MQP.
- Results: This chapter allows for analysis of the outcomes of the chosen methods.
- Conclusions: This chapter provides a reflection on the overall results of this project.
- Recommendations: This chapter provides a set of best practices that were developed from the results and conclusions of this project.
- Appendices: The appendices include the literature review, interview questions, and task analysis protocol that were used to obtain the results of this project.

Background

SOPs are the first line of defense in any inspection, whether it be a potential partner, a client, or a firm conducting due diligence (Gough, et al., 2009). They are intended to be specific to the organization or facility whose activities are described and aim to assist that very organization or facility maintain their quality control and assurance processes (United States EPA, 2007). The effort needed behind putting an SOP in place and adhering to it can be a tempting inducement to limit SOPs to the bare minimum. However, it is imperative to implement formal documents like SOPs as they ensure that processes and activities occur as they should and yield the same results every time (Gough, et al., 2009). A valid SOP can benefit reduced work efforts, improved comparability, credibility, and if applicable, legal defensibility (United States EPA, 2007).

This background chapter further analyzes the importance of SOPs and consists of sub-sections namely:

- The Importance of SOPs in Laboratories
- The Implementation of SOPs in Lab-Based Sciences
- The Lack of SOP Implementation in Physics

The Importance of SOPs in Laboratories

In a laboratory setting, SOPS can be seen as “a document which describes the regularly recurring operations relevant to the quality of the investigation” (FAO, n.d). SOPs are written instructions that detail the steps that must be performed during a given experimental procedure (Rutgers University, 2022). Especially when laboratory work involves the use of hazardous chemicals, SOPs incorporating both safety and health considerations must be developed and followed. This SOPs must be readily available and all the researchers involved must be trained on the material within the SOP (Rutgers University, 2022).

In some laboratories, there may even be two levels of SOPs namely the moderate risk SOP and the high-risk SOP (Committee on Chemical Management, 2016). When institutional laboratory standards are not sufficient to lessen health and safety risks, laboratory personnel may use either of these SOPs depending on the situation. Moderate risk SOPs are suggested for processes and experiments that pose moderate risks and call for protective steps that go beyond the ones in accepted laboratory standards. High risk SOPs are used when chemicals and experimental conditions pose high hazard risks for both experienced and inexperienced lab workers (Committee on Chemical Management, 2016).

SOPs are the main building blocks of defining and ruling the quality organization and management of a laboratory (Barbe, et al., 2016). Good laboratory practices (GLPs) are the standards by which laboratory studies are designed, implemented, and reported to assure the public about result accuracy and experiment reproducibility (Robinson, 2003). They are developed with guidelines set forth by the Food and Drug Administration (FDA) in the Code of Federal Regulations (Bornstein-Forst, n.d). GLPs can and should be applied to all industries where laboratory work is performed including, but not limited to, drug manufacturing, food and drink production, engineering, research establishments, and universities (Robinson, 2003). For nonclinical laboratories that produce or test foods, cosmetics, and drugs, the components of GLPs must focus on quality assurance (QA) and quality control (QC) as well as the safety of the products. In more academic settings, the focus is shifted to be more about the education, training, and career preparation of the students (Bornstein-Forst, n.d).

SOPs play an important role in describing how to perform various routine operations in a GLP-based research facility. They provide a general framework enabling the efficient implementation and performance of all research work and contain step-by-step instructions that technicians, lab personnel, employees, and students, can consult daily to complete tasks reliably and consistently (Robinson, 2003). Standardizing lab procedures is of utmost significance as it establishes a systematic way of doing work and ensures that this work is done consistently by all people involved with the task at hand (Manghani, 2011). Adoption of SOPs by all department members is important as it affirms no doubt regarding the "who, what, when, how, and where" of a procedure or task (Bornstein-Forst, n.d). The development and use of SOPs are integral parts of maintaining a successful and safe laboratory environment and all laboratory personnel, students, and employees are responsible for learning and familiarizing themselves with all relevant SOPs (Committee on Chemical Management, 2016).

The Implementation of SOPs in Lab-Based Sciences

SOPs are prominent in many different lab-based sciences like chemistry, biology, and even medical laboratory science. With the presence of hazardous chemicals, intricate procedures, and even lives at risk, the absence of proper training and oversight can lead to extreme and threatening results (Bornstein-Forst, n.d).

In nuclear medicine, SOPs play an important role as being a set of detailed instructions that define and standardize procedures in clinical trials (Sajdak, 2013). SOPs even act as an effective catalyst to obtain usable results for the sponsor. The results from sponsors have large-scale effects because they ensure reproducibility and consistency from site to site which, in turn, helps to confirm the reliability of all the data (Sajdak, 2013). In addition, the key purpose of clinical research SOPs is to help a research department stay in compliance with good clinical practices or GCPs. GCPs are international ethical and scientific quality standards for designing, conducting, recording, and reporting trials that involve the participation of human subjects. SOPs support this type of strong clinical research environment and provide the best way to help a site stay in compliance with the GCPs (Sajdak, 2013).

In chemistry, SOPs are used to explain how to utilize and manage hazardous chemicals, processes, and procedures to prevent or minimize health and safety concerns (n.a, n.d). Often, a risk assessment flowchart is used to determine whether an SOP is required for the proposed work and if so, what type of SOP to develop. If the chemical is used in a specific process that involves some level of risk, a chemical of concern, a dual-use chemical, or a newly synthesized compound whose properties may not be fully known, then laboratory personnel should develop an SOP (Committee on Chemical Management, 2016).

The Lack of SOP Implementation in Physics

Although SOPs are widely published and available in many other lab-based sciences, the availability of SOPs and the literature surrounding them in physics is sparse. Scientific progress requires the ability of scientists to build on the results produced by those who precede them (Plant and Hanisch, 2020). There is a general concern by some researchers that irreproducible scientific results are being reported within the physics discipline although there is a strong theoretical footing associated with the nature of physics research (Plant and Hanisch, 2020). This can be traced back to the lack of implementation and the lack of literature around standardizing documents like SOPs.

A report from a NSF-sponsored workshop concluded that within the Mathematical and Physical Sciences (MPS), the science process simply works and there is no ongoing crisis of robustness, reliability, and reproducibility (Plant and Hanisch, 2018). However, even large-scale high-energy physics experiments, where extreme care has been taken in acquiring, calibrating, and analyzing data can produce erroneous results (Plant and Hanisch, 2020). This shows that it is equally likely for small physics laboratories to have similar problems since instrumental metadata and procedural steps are often stored in formats, containing hidden variables, that are not easily interpreted.

Due to the lack of available scholarly literature around SOPs, one of the main methods of this project will be to conduct interviews with graduate students within the WPI Physics department. This will allow to further analyze the implementation of SOPs in physics and specifically the WPI Physics department.

Methodology

To achieve the goal of this project and understand the implementation of SOPs in Physics and develop an SOP for the corresponding physics sensor lab, I completed a literature review, a set of interviews, and a task analysis.

The goal of this report was to understand the lack of implementation of SOPs in physics and recommend best practices of writing and implementing an SOP. Thus, I researched these best practices of writing and implementing SOPs by completing a literature review, conducting interviews, and conducting task analyses.

Literature Review

I sought information about developing an SOP and the contents within a lab-based SOP by completing a literature review. I analyzed sources from scholarly journals and articles to understand the general writing and formatting of an SOP. In addition, I analyzed published SOPs for both lab and non-lab procedures to understand any nuances in the content of an SOP that is specific for a lab-based science. The entire list of sources used for my literature review can be found in Appendix A.

Interviews

I conducted interviews to understand the standardization processes and the implementation of SOPs within the WPI Physics department. Interviews are an important mode of communication when gathering information that is anecdotal, personal, and often not found in published literary works. To understand the standardization behind physics lab courses and student/faculty led labs at WPI, I decided to conduct interviews with graduate students currently studying in the Physics department. These students have direct interaction with standardized documents of a lab by either being lab advisors or advising specific projects based in a lab.

I asked questions that would provide valuables answers to the following concepts:

- Standardization within labs
- The use of standardized documents within labs
- The graduate student's knowledge about an SOP
- The implementation of SOPs in the WPI Physics department

Appendix B contains the entire list of interview questions.

Task Analysis

I completed task analyses to understand the nuances of the procedures within the sensor lab of my physics MQP. Task analyses are often completed by technical writers to systematically study how users complete tasks to achieve goals. This specific task analysis allowed me to directly interact and observe the graduate student who is knowledgeable enough about the lab procedures to provide valuable information that I then implemented into my SOP. I created a task analysis protocol which was a set of questions that enabled me to gather all the information I needed to create my SOP. This protocol can be found in Appendix C.

Results

This chapter discusses the findings from the methodology of this project namely the literature review, the interviews, and the task analysis. The literature review is divided into two main sections namely formatting and language of an SOP and content of SOPs for lab and non-lab procedures. The interviews are similarly divided into two main sections namely SOP familiarity and implementation in the WPI Physics department and lab safety documentation.

Literature Review

I used a literature review to delve deeper into the development of an SOP and the contents within an SOP for lab-based procedures. Within this literature review, I focused heavily on the formatting and language of an SOP and the understanding the differences in content between SOPs for lab and non-lab procedures.

Formatting and Language of an SOP

The main goal of an SOP is to create a document that is easy for the user to understand and helpful for the work at hand. All necessary details should be included but at the same time, SOPs should serve as a basis for introductory training and be organized to ensure ease and efficiency in use. The Laboratory Quality Management System Handbook by the World Health Organization (WHO) states that SOPs need to ensure the following: consistency, accuracy, and quality. Consistency helps to make sure that all the users perform the procedures the same way so that the same result can always be expected. Accuracy helps users produce more accurate results rather than simply relying on memory and the mere steps within the SOP. Quality helps to ensure that consistent, reliable, and accurate results are the primary goals of the laboratory and hence its SOP (WHO, 2010).

The International Journal of Drug Regulatory Affairs states that every SOP should, at the least, contain the basic components namely. This journal provided general definitions for each component which I used to advise my own SOP (Beyen K et al., n.d.):

- Header
- Purpose
- Scope
- Background
- Responsibility
- Definitions
- Materials and Equipment
- Procedure
- Document Distribution
- Document History
- Reference
- Attachments

A review article from the World Journal of Pharmaceutical Research claims that technical SOPs will consist of five main elements namely:

- Title Page
- Table of Contents
- Procedures

- Quality Assurance/Quality Control
- References

In addition, the article provides a list of topics that may be appropriate for inclusion in technical SOPs but not applicable for every procedure being detailed (World Journal, 2020). These are namely:

- Scope and Applicability
- Summary of the Methods/Procedures
- Definitions
- Health and Safety Warnings
- Cautions
- Interferences
- Personnel Qualifications/Responsibilities
- Equipment and Supplies
- Procedure
- Data and Records Management

In their editorial article “Ten simple rules on how to write a standard operating procedure,” the authors claim that every SOP should consist of three main sections, not limited to, the cover page, the sequence of steps or tasks for the given procedure, and a list of references and definitions (Ait Ouares et al., 2020). The WHO handbook similarly lists the same sections namely title and purpose with the inclusion of instructions, those behind the preparation of the SOP, and official signatures and approval dates (WHO, 2010).

Language of an SOP is critical to its usability and efficiency. The International Journal of Drug Regulatory Affairs emphasizes that an SOP must be written in a language that is clear and understood and if applicable, the native language of the users (Beyen K et al., n.d.). SOPs should be written in a clear, concise, specific, step-by-step, and easy-to-read format with active voice and present tense used throughout the document (Beyen K et al., n.d). In addition, the review article states that SOPs should be written from a practical perspective concerning those who will use it (Beyen K et al., n.d). The WHO's Lab Quality Management handbook also states that SOPs should be detailed, clear, and concise. SOPs should also be easily understood by any new personnel or students in training (WHO, 2010). An article from the Penn State Extension makes similar arguments claiming that the goal of the SOP is to serve as a document that is easy for the reader to understand and helpful for the work at hand (Penn State, n.d.). This article emphasizes that the SOP should communicate well in as few words as possible and refrain from being so overly detailed that it answers all possible questions a user might have (Penn State, n.d.). However, it also mentions that the SOP should contain the right amount of detail to eliminate significant variation amongst users (Penn State, n.d).

When completing this literature review, many of the sources also provided crucial information about the procedure sections of the SOP. The Penn State Extension claimed that steps within the procedure sections should be written as short sentences and these sentences should be framed as imperative sentences in the form of a command beginning with an action verb (Penn State, n.d). If procedures are longer in nature, and specifically more than 10 steps, they should be broken up into hierarchical sub-sections or formatted graphically (Penn State, n.d). An article from Cornell University seconds this notion and states that typical users can't remember more than 10 or 12 steps and thus, longer procedures must be broken up into logical sub-tasks (Source 4). The editorial article “Ten simple rules on how to write a standard operating procedure” also emphasizes avoiding long preambles, complex words and/or sentences, jargon, and acronyms. In addition, they state that the overall process should be broken into sections, which should be broken into specific number or bulleted steps for clarity (Ouares, 2020).

Content of SOPs for Lab and Non-Lab Procedures

For the second part of my literature review, I compared the content between published SOPs that were written for lab and non-lab purposes. For the non-lab SOPs, I looked at SOPs written for hose hydrostatic testing for the Brewer’s Association Hub, airport specialist procedures for reviewing and accepting Exhibit ‘A’ airport property inventory maps, and triaging sick patients with suspected or confirmed COVID-19 at healthcare facilities. For the lab SOPs, I looked at SOPs written for safety protocols in the Don Bosco College physics lab, a laser lab SOP written by the University of Texas at Austin, and a laser use SOP template by the California State University.

SOPs for Non-Lab Procedures

The first SOP I analyzed was written about hose hydrostatic testing for the Brewer’s Association Hub (Brewers Association, 2020). Although this SOP was for a specific procedure and short in length, the basic components of an SOP that I learned from the first part of my literature review were still applicable. This SOP included components like:

- Name of author
- Date written
- Date revised
- Purpose & scope

- Environmental health and safety
- Equipment and materials
- Procedure

Here, the purpose and scope were written as a combined paragraph rather than two separate sections. In addition, the procedure was 12 steps long rather than the recommended 6-10 steps seen in my other sources from the first half of this literature review.

The second SOP I analyzed was establishing uniform airports specialist procedures for reviewing and accepting Exhibit ‘A’ airport property inventory maps (Federal Aviation, n.d.). This SOP included a three-page prologue with basic components like:

- Purpose
- Scope
- Cancellation
- Applicable regulations, policy, and guidance
- Exhibit ‘A’ requirements and objectives
- Distribution
- Revision table
- Official signatures

Following this prologue, the SOP included a few more notable components like:

- Table of contents
- Roles and responsibilities
- Process and procedures
- Appendices (Review process chart and review process checklist)

Notable in this SOP was the distinction between material that set up the background of the SOP and then the procedures of the SOP itself. This SOP also contained more niche components like requirements for the specific property inventory map and roles and responsibilities for various airport team officials. In addition, the appendices consisted of figures and charts that were unique to the process of this SOP.

The final SOP I analyzed for non-lab procedures was written for healthcare facilities triaging patients who have suspected or confirmed cases of COVID-19 (CDC, 2021). This SOP was the only website-based SOP I analyzed, and its layout still included components that were seen in the other SOPs. These components were namely:

- Summary of recent changes
- Key points
- Background/purpose
- Notes for healthcare facilities to help minimize risk of infection
- Notes for healthcare workers to protect themselves and their patients during triage
- Additional considerations for triage during community transmission
- References

This SOP was uniquely formatted from the other SOPs that I had analyzed in this literature review. Due to its browser-based format, this SOP was able to utilize hyperlinks throughout its consideration and references sections. In addition, procedures were 10 steps or shorter with hyperlinks referring users to additional information on websites or PDFs.

SOPs for Lab Procedures

The first SOP I analyzed was written about general physics laboratory safety practices at the Don Bosco College (Don Bosco, n.d.). I analyzed this specific SOP to understand the documentation of lab safety in SOPs. This SOP included components like:

- General lab safety
- Safety when handling experiments on heat
- Safety when doing electricity experiments
- Safety when doing optical experiments
- Additional guidelines regarding COVID-19

Although this SOP focused only on one aspect of a lab, the procedure sections were still logically organized and kept between five-eight steps.

The second SOP I analyzed was a laser lab SOP written by the University of Texas at Austin (Stanford, 2017). This SOP was around 29 pages long and the lengthiest SOP I analyzed. This SOP included components like:

- Title Page with signature table
- Revision history
- Table of contents
- Introduction
- Visitors and qualified personnel
- Safety protocol
- Lab maintenance operations
- Laser alignment

- Humidity monitoring and control
- Troubleshooting

Within this SOP, I was able to notice many of the basic components I learned about in the first part of my literature review. In addition to these components, the safety protocol section included various figures and tables that helped to supplement the written aspects of the protocol. In addition, one of the lab safety protocol pages included a warning that stood out in the SOP using bolded, red-colored lettering with a thick border surrounding it. This SOP did have multiple sub-sections within each of the higher-level chapters listed above but there was still a logical organization to the entire document.

The final SOP I analyzed for lab procedures was a similar laser use SOP written by the California State University (California State, 2019). The components within this SOP were namely:

- Introduction
- Instructions
- Laser registrant
- Laser system information
- Laser preparation
- Laser system procedures
- Laser system beam alignment procedures
- Laser protective eyewear
- Diagram of laser or laser system setup
- Beam hazards

- Non-beam hazards
- Laser system control measures
- Laser system maintenance
- Emergency information
- Laser use acknowledgement
- Approval signatures

This SOP included many specific sections to the laser lab at hand but also included basic components that have been seen in all the previous SOPs. Prior to the main body of the SOP, there was an instructions section that outlined the use and distribution of the SOP. In addition, this SOP was entirely written in a tabular format that were optimized for PDF usage. At the end of the SOP, there was also a print feature allowing to additionally act as a printed document.

Interviews

I completed interviews to understand the implementation of SOPs in the WPI Physics department. Within these interviews, I mainly focused on current standardization procedures in the department and current usages, if any, of SOPs. I interviewed four graduate PhD students who advised lab courses and projects and worked in labs themselves. I also interviewed the lab manager of the WPI Physics department, who not only manages all the undergraduate physics labs, but also designs the experiments and writes and edits any procedural documents. The next few sections focus on different observations from my interviews namely SOP familiarity and implementation in the department and lab safety documentation.

SOP Familiarity and Implementation in the Department

All but one graduate student were familiar with the term of SOP and had been exposed to them in some way or another. Although this may be true, there was a consensus that SOPs were not implemented in the Physics department at WPI. All the graduate students had encountered SOPs in their previous institutions or workplaces and only one graduate student had mentioned the presence of an SOP at WPI where their current research professor was actively working to write a proper SOP for their research lab.

Throughout all the interviews, there a concept that was emphasized upon was the oral tradition of learning. As one of the graduate students mentioned, there have been previous MQP students who have documented step-by-step instructions on how to run their specific experiment, but those kinds of documents have been, in a way, traded off for oral tradition. In this interviewee's opinion, they even tended to believe that students preferred oral communication and handholding in comparison to being given standardized documents that they had to sit with and digest it over a period.

Another graduate student mirrored these sentiments as they mentioned that SOPs may exist in the WPI Physics department, but they are not formally written down. They further mentioned that there exists a sort of oral tradition amongst other graduate students through which they pass information down to the undergraduate students they advise. In addition, this interviewee mentioned that if these notes were potentially written down formally, they could develop into an SOP. Similarly, another graduate student mentioned that in their personal research, they do indeed take notes, but these are more often treated as internal documents and could be potentially reproduced into a lab report by another student with significant experience about the lab at hand. They also mentioned the topic of oral tradition where a lot their research meetings with other graduate students or undergraduate students are discussion based with some informal meeting minutes.

The fourth graduate student I interviewed had previous experience working at a nuclear reactor and working closely with many aspects of standardizing processes. Thus, I was able to get valuable information about standardization and the implementation of SOPs. The two main concepts that this student believed when it came to the implementation of SOPs was the comprehensibility of the document and the clarity of the document's language. They mentioned that when writing an SOP, the language must be clear and concise, but also include enough details so that a user can use it to reproduce an experiment. In addition, many updates that are made to SOPs are usually on topics that are generally verbally trained. Format wise, they mentioned that SOPs should follow an identifiable format but also be uniquely structured for the procedure at hand. For a lab-based SOP, particularly, the specificity and usage of various procedures must be clear but at the same time, there should be some freedom within the document to allow minor alterations to occur in future repetitions of the same procedure. This goes hand in hand with their point that by nature, new and upcoming research cannot always be standardized and there needs to be room left for spontaneous changes.

The lab manager of the Physics department had direct knowledge about the introductory physics lab courses at WPI and the standardization that happens within them. The most common way that these labs are standardized is through the Canvas infrastructure and material inherited from previous lab staff. In the Physics department, there are four main introductory lab courses namely:

- PH 1110/1111: General Physics – Mechanics
- PH 1120/1121: General Physics – Electricity and Magnetism

- PH 1130: Modern Physics
- PH 1140: Oscillations and Waves

The way these labs are standardized often depends on the expertise level of the students. PH 1110/1111 students tend to get very step-by-step instructions while PH 1140 students are taught to write their own lab guides. As the lab manager mentioned, 80% of the updates to these procedural documents are completed as the labs are being run and in PH 1130 and PH 1140, students are allowed to give input.

The lab manager believed that standardization is very important when it comes to teaching and guiding students as the students' abilities to read lab guides and be at ease with them is itself a valuable skill. However, they also did mention that standardization in the department is a lot of work that needs to be undertaken but, in the end, could be beneficial. The graduate students interviewees similarly mirrored this view where standardized documents like SOPs would be beneficial in the long run but take quite a lot of time and effort by an individual or an appointed team.

Lab Safety Documentation

Throughout the interviews, lab safety was also deemed as an important, but under documented, topic when compared to other lab-based sciences like chemistry. When asked the question "Do you believe that lab processes in physics should be standardized?", all the graduate students brought up how if anything, lab safety should be standardized and well documented. As one of the students mentioned, lab safety currently also relies on oral traditions of various dos and don'ts. They believe that lab safety should not be orally taught but rather rely on standardized documents with written rules.

Task Analysis

I mainly used the task analysis to understand the steps that happened within the overarching procedures of the sensor lab in the physics component of this MQP. Within the task analysis, three main chapters were developed along with an overview chapter providing a roadmap of the task analysis. The task analysis was used to write the SOP that can be found at the end of this document.

Using the knowledge I also gained from the literature review and the interviews, I combined the results of all the three methods to develop an SOP that can be implemented as a current first draft for the sensor lab. As with any SOP, regular updates and changes need to be made but for the time being, the task analysis allowed me to develop a procedural document that can advise users, like potential industry partners, on how to operate the moisture detection sensor and receive accurate results.

Conclusions

This section discusses the conclusions I drew from the results of this MQP. These conclusions are divided into four main sections namely:

- SOP implementation in WPI's Physics department
- Lab safety
- Formatting and language content within a lab-based SOP
- Challenges throughout this MQP

Implementation of SOPs in WPI's Physics Department

Understanding the implementation of SOPs in the WPI Physics department was essential to this interdisciplinary MQP. From the results of my interview, I understood that SOPs are not implemented properly throughout the department. Although all the graduate students I interviewed had previously used SOPs in other institutions and/or industry positions, physics labs at WPI focused more on oral communication, individual guidance and sometimes, internal notes that were shared amongst graduate students and undergraduate students working together in a lab.

Throughout the interviews, none of the interviewees immediately vouched for the deliberate implementation of SOPs in the WPI Physics department. This was mainly due to the time and effort needed to implement and regularly revise such standardization. However, all of them did understand the importance in trying to implement SOPs in at least some settings where standardization would be beneficial like lab safety and high-risk labs involving equipment like lasers.

Lab Safety

Lab safety deemed to be one of the most under documented concepts from the results of my interviews. All the interviewees believed that if anything in Physics labs should be standardized and properly documented, it should be lab safety protocols. As also seen from my literature review, lab safety is a key component in the content of an SOP and must be prominently documented in the SOP to catch the attention of the user. This could be either by bolding the safety warning text or placing it prior to the main body of the SOP, which are the procedural pages, so that users will not miss it.

Formatting and Language of an SOP

Formatting and the language content of an SOP is important in its usability. From my literature review, it is evident to see that all SOPs followed a general format that was accessible and applicable to all users. Between non-lab based and lab-based SOPs, the main differences seemed to surface in the content rather than in the formatting. As three of my sources similarly noted, SOPs tend to contain basic components like a title page, a purpose, health and safety warnings, procedures, and references amongst other sections that are more niche to the task at hand. This was the case for SOPS written for both lab and non-lab procedures. From my interviews, a key component of an SOP that was mentioned by a graduate student who had extensively worked with SOPs prior to WPI, was the inclusion of a table of contents to help with ease and efficiency when understanding the layout of an SOP.

In addition, half of the sources that focused on the formatting of an SOP, claimed that procedure sections should be concisely written with only 6-10 steps per procedure. If procedures are longer in nature, they should be logically broken up into shorter sub-tasks or graphical representations. This ensures that users thoroughly understand the procedures within the document and that there is clarity throughout the logistics of the document. This was also clear from my task analysis where I learned the nuances of several procedures, which were lengthy in their original form, and further separated them into multiple sub-tasks where each sub-task had between 6-10 steps.

Challenges

A key challenge that I learned from my interviews was that although standardization and such documents like SOPs are desirable to students and faculty in the WPI Physics department, there is no appointed team to help with facilitating this implementation. Two of my graduate students who had used SOPs in prior situations emphasized that implementing SOPs and keeping them revised regularly is a lot of time and effort but would be very helpful. Currently, there is a certain push from a handful of graduate students within the department for more regular updates on introductory lab documents and the need for lab safety documentation.

In addition, another key challenge I learned from both my interviews and my task analysis was the process of standardizing new research. From my task analysis, this was seen in the instances where procedures we had created initially, took an entirely new shape a few weeks later either due to more clarity of the research material, technical difficulties that needed new solutions, or even inaccurate experimental results. Further in my interviews, a common theme from some of the graduate students was the fact that all research and all labs cannot be standardized. From my interviews, the reasons for this came from the facts that all students don't benefit from an extremely structured environment and that some processes in physics cannot be simply standardized as they require a level of creativity, openness, and variability that standardizing would restrict. In addition, as one of my graduate student interviewees mentioned, science is about finding the best ways to reach the same result and this may come from changing the smallest aspect of a procedure which would require consistent updating to an SOP. However, a nod towards standardization was consistently seen as a component to maintaining the workflow of a lab environment and ensuring there was a backbone to more consistent labs where the results are rooted in many years of theory and practice.

Recommendations

I arranged the conclusions of this report into a set of best practices for writing an SOP for a lab-based science like Physics:

- Lab safety should be prominently documented
- SOP should be logically organized with any necessary figures, sub-tasks, and charts
- Procedural steps should be between 6-10 steps long to reduce ambiguity
- SOPs should be detailed, clear, and concise
- SOPs should include basic components like a title page, purpose, table of contents, and procedures
- SOPs are revised regularly to keep the document up to date

The following sections offers examples of how I implemented these best practices into a supplementary SOP I created for my physics MQP.

Documenting Lab Safety

Lab safety is a crucial aspect of standardizing lab practices. Within an SOP, lab safety should be written in a way that catches the user's attention and enforces them to read any important protocols before continuing with the rest of the document. As seen in Figure 1, I implemented a Lab Safety page prior to the procedural pages of the SOP. Hence, this Lab Safety page acts as a prologue following the Table of Contents. Within this page, I included a warning symbol, bolded lettering, and colored borders to ensure that this page stands out from the other pages of the SOP.

Lab Safety Guidelines

LAB SAFETY IS OF UTMOST IMPORTANCE WHEN DEALING WITH IMPORTANT AND EXPENSIVE LAB EQUIPMENT.

GENERAL LAB SAFETY

- Closed-toe shoes must always be worn.
- No food and drink are allowed inside the lab.
- Long pants must be always worn.
- Hair must be tied back.
- Eye protection must be worn within the lab when dealing with dangerous chemicals and/or instruments.

Figure 1. Snippet of the lab safety guidelines page from my SOP

Logically Organizing the SOP

The organization of an SOP is important to its usability and efficiency. With a poorly organized SOP, users may not be willing to use the document as a standard practice in their labs. Logical organization can come from the inclusion of figures, charts, and/or tables when necessary. Figure 2 shows an image I included in my SOP to help users understand which scale to use when measuring the sample mass in the lab.

Figure 2. The Sartorius measuring scale in the lab

Figure 2. An image depicting a lab equipment in my SOP

Writing Procedural Steps in an SOP

The main body of an SOP is the procedures and their relevant steps. A procedure of an SOP must be between 6-10 steps to reduce ambiguity and to ensure that the users remember all parts of the procedure. Within my SOP, I created a roadmap at the beginning of a new chapter, which are high-level procedures, to help users understand the forthcoming tasks. For each task, I then created an introduction explaining the need for the task and steps that helped the users perform the task. Figure 3 shows a snippet of this initial roadmap and first task of a lengthier procedure called Parameter Extraction.

3.0: Parameter Extraction

Parameter extraction refers to finding suitable values for the parameters of the initial mass measurement model such that the measurement results and experimental results will be close in value. To perform this parameter extraction:

1. Record Initial Conditions
2. Saturate the Chosen Sample in Water
3. Record the Initial Saturation Mass of the Sample
4. Complete Data Analysis of the Initial Saturation Mass Measurement
5. Build the Initial Mass Measurement Model

3.1 Recording Initial Conditions

Initial conditions are recorded to ensure the lab is kept at an optimal temperature and humidity level. To record initial conditions:

1. Enter the lab and record the external temperature and the internal lab temperature from the wall thermostat (Figure 1).
2. Record the humidity of the room from the thermostat.
3. Write these measurements in a designated lab notebook. If multiple measurements were taken in one day, write down the date and time of each measurement as they can vary on an hourly basis.

Figure 3. A snippet from a procedural page of my SOP

Ensuring Clarity within an SOP

The level of detail within an SOP is significant to the flow and clarity of the document. An SOP must be detailed but written in a clear and concise manner. An SOP lacking detail will not be utilized as it will not help to forward the standards that exist within a lab procedure. An SOP that is overly detailed will be too jarring of a document and will replace any important training and experiences that must occur in a lab in a more interactive and fluid way. Since the scope of an SOP is for all users of a lab, which is not limited to lab personnel, students, employees, and even faculty, the language within an SOP must be accessible and any foreign terms must be clearly defined and documented.

Formatting an SOP

The formatting of an SOP is a universal component that can be seen throughout SOPs created for both lab and non-lab processes. There are key components that each SOP must include to ensure its usability. Technical SOPs, which are more often used in a lab setting, sometimes contain more material such as lists of equipment and certain equipment protocols. Figure 4 shows the Table of Contents from the supplemental SOP I created, helping to display the general formatting and components I included in the SOP.

Table of Contents

Figure 4. The table of contents within my SOP

Revising an SOP

Revising an SOP is important in keeping the document up to date and usable for a long period of time. As changes are made to a procedure, these changes must be noted down and regularly updated within the SOP. These revisions must be approved by an overseeing official.

The SOP I created is a first of its kind for this specific lab procedure and should be updated as the research within the lab develops over time.

References

Biopharm International. (2016, July 01). GLPs and the Importance of Standard Operating Procedures. BioPharm International. https://www.biopharminternational.com/view/glps-and-importance-standard-operating-procedures

City of Brampton. (n.d.). What is a Standard Operating Procedure (SOP)? Brampton Entrepreneur Centre. Retrieved from https://www.brampton.ca/EN/Business/BEC/resources/Documents/What%20is%20a%20Standard%20Operating%20Procedure(SOP).pdf

Food and Agriculture Organization of the United Nations. (n.d.). Chapter 4: Standard Operating Procedures (SOPs). FAO Corporate Document Repository. Retrieved from https://www.fao.org/3/w7295e/w7295e04.htm

Gross, J. J., & John, O. P. (2005). Facets of emotional expressivity: Three self-report factors and their correlates. Personality and Social Psychology Bulletin, 31(4), 542-553. https://doi.org/10.1177/0146167204271558

Gürbüz, E., Keskin, R., & Koç, M. (2021). A convolutional neural network-based approach for detection and classification of emotions using physiological signals. Journal of Ambient Intelligence and Humanized Computing, 12(10), 10705-10718. https://doi.org/10.1007/s12652-021-03477-8

Gurtler, V., & Mayall, B. C. (2010). Standard operating procedures (SOPs) in microbiology laboratories: Their importance and how to write them. Journal of microbiological methods, 82(3), 205-212. https://doi.org/10.1016/j.mimet.2010.06.009

Hanna, R., Rohm, A., & Crittenden, V. L. (2009). We’re all connected: The power of the social media ecosystem. Business Horizons, 52(3), 265-273. https://doi.org/10.1016/j.bushor.2009.01.003

Kased, N., Li, J., Waller, A., & Zhang, J. (2014). Standard Operating Procedures for PET/CT: A Review. Journal of Nuclear Medicine Technology, 42(3), 157-164. https://doi.org/10.2967/jnmt.113.121467

Marí Saéz, A., Weiss, S., Nowak, K., Lapeyre, V., Zimmermann, F., Düx, A., ... & Kühl, H. S. (2017). Investigating the zoonotic origin of the West African Ebola epidemic. PLoS Neglected Tropical Diseases, 11(4), e0005053. https://doi.org/10.1371/journal.pntd.0005053

National Academies of Sciences, Engineering, and Medicine. (2016). The Integration of the Humanities and Arts with Sciences, Engineering, and Medicine in Higher Education:

National Center for Biotechnology Information (US). (2016). Chapter 11: Standard Operating Procedures. In A Practical Guide to Assay Development and High-Throughput Screening in Drug Discovery (J. P. Weller & M. S. Bountra, Eds.). CRC Press/Taylor & Francis. https://www.ncbi.nlm.nih.gov/books/NBK379132/

National Institute of Standards and Technology. (2016). Metrology Perspective on Reproducibility in Science. In National Academies of Sciences, Engineering, and Medicine, Fostering Integrity in Research (pp. 67-80). The National Academies Press. https://doi.org/10.17226/21896

Plant, A., & Hanisch, R. (2020). Reproducibility in Science: A Metrology Perspective. Harvard Data Science Review, 2(4). https://doi.org/10.1162/99608f92.eb6ddee4

Reynolds, T. (2019). Standard Operating Procedures for All Dentists: A Comprehensive Text for Dental Students and Practitioners. Springer. Retrieved from https://books.google.com/books?hl=en&lr=&id=hRKaDwAAQBAJ&oi=fnd&pg=PA367&dq=types+of+standard+operating+procedure&ots=4y_ld9nJ5_&sig=FrgcTXx3JhdaETM38KmOIaES6VQ#v=onepage&q&f=false

Rutgers University Environmental Health and Safety. (n.d.). Standard Operating Procedures (SOP).

https://ipo.rutgers.edu/rehs/sop#:~:text=SOPs%20are%20written%20instructions%20that,%20involved%20with%20the%20experimental%20process

United States Environmental Protection Agency. (2015). Greenhouse Gas Reporting Program: General Stationary Fuel Combustion Sources (Subpart G), 40 CFR Part 98, Subpart G (§§98.30-98.39). Retrieved from https://www.epa.gov/sites/default/files/2015-06/documents/g6-final.pdf

Appendix A: Literature Review

To understand more about developing an SOP and the best practices of writing an SOP for lab-based procedures, I carried out a literature review where I initially researched the general format and language within an SOP and secondly researched the differences and similarities in content and formatting of lab and non-lab SOPs. My sources for this literature review were grouped into two main topics namely:

- Formatting and language of an SOP
- Contents of SOPs for lab and non-lab procedures

Formatting and Language of an SOP

To further understand how to develop an SOP for the sensor lab being developed in my physics MQP, I looked towards scholarly articles and journals that highlighted aspects of the general formatting components of an SOP and the language within an SOP

I referenced the following texts:

- Beyene, K. G. M., Nadew, S., Ali, W. G., Gebrehiwot, A. G., & Atsibeha, S. G. (n.d.). How to write standard operating procedures: Values and a practical guide. International Journal of Drug Regulatory Affairs. Retrieved April 27, 2023, from https://doi.org/10.22270/ijdra.v10i4.557

- World Journal of Pharmaceutical Research. (2020). Effects of Curcumin on Alzheimer's Disease: A Systematic Review. Retrieved from https://wjpr.s3.ap-south-1.amazonaws.com/article_issue/1588153678.pdf

- Ait Ouares, K., et al. (2020). When Chance Helps to Beat the Odds: Evolution of Symbiotic Life in Random Environments. PLoS Computational Biology, 16(10),

e1008095. Retrieved from https://journals.plos.org/ploscompbiol/article/file?id=10.1371/journal.pcbi.1008095&type=printable

- Cornell University. (2014). Standard Operating Procedures for Digital Imaging and Metadata. eCommons@Cornell. Retrieved from https://ecommons.cornell.edu/bitstream/handle/1813/36910/sopsdir.pdf?sequence

- World Health Organization. (2010). Guidelines for the treatment of malaria. World Health Organization. Retrieved from https://www.who.int/publications/i/item/9789241548274

- Pennsylvania State University Extension. (n.d.). Standard Operating Procedures: A Writing Guide. Penn State Extension. Retrieved from https://extension.psu.edu/standard-operating-procedures-a-writing-guide

- U.S. Environmental Protection Agency. (2015). Greenhouse Gas Reporting Program: General Stationary Fuel Combustion Sources. U.S. Environmental Protection Agency. Retrieved from https://www.epa.gov/sites/default/files/2015-06/documents/g6-final.pdf

Contents of SOPs for Lab and Non-Lab Procedures

SOPs can be written for a variety of purposes and organizations. To understand the differences in content between SOPs written for lab and non-lab procedures, I analyzed published SOPs that were written for both scientific labs and general businesses. I further examined the content within the SOP and the formatting components, that I had researched in the first part of this literature review, of both SOP types.

I referenced the following texts:

- Don Bosco College. (n.d.). Standard Operating Procedures for Science Laboratories. Don Bosco College. Retrieved from https://donboscocollege.ac.in/public/frontend/pdf/SOPs%20Science%20Laboratories.pdf

- Stanford University Environmental Health & Safety. (2017). Standard Operating Procedure for ThorLabs LS312-USB Laser Power and Energy Meter. Stanford University Environmental Health & Safety. Retrieved from https://ehs.stanford.edu/wp-content/uploads/SOP-ThorLaser-large.pdf

- California State University, Fullerton. (2019). Standard Operating Procedure for Class 3B and 4 Laser Use. California State University, Fullerton Environmental Health & Safety. Retrieved from https://ehs.fullerton.edu/documents/forms/Laser%20Standard%20Operating%20Procedure_V4.0_12-2-2019_LL-Abby.pdf

- Brewers Association. (2020). Standard Operating Procedures Guidance for Brewers. Brewers Association. Retrieved from https://cdn.brewersassociation.org/wp-content/uploads/2020/05/Standard-Operating-Procedures-Guidance-for-Brewers.pdf

- Federal Aviation Administration. (n.d.). ARP SOP 300: Exhibit A - Review. Federal Aviation Administration. Retrieved from https://www.faa.gov/sites/faa.gov/files/airports/resources/sops/arp-SOP-300-Exhibit-A-Review.pdf

- Centers for Disease Control and Prevention. (2021). Standard Operating Procedure (SOP) for Triage of Suspected COVID-19 Patients in Non-US Healthcare Settings: Early Identification and Prevention of Transmission during Triage. Centers for Disease Control and Prevention. Retrieved from https://www.cdc.gov/coronavirus/2019-ncov/hcp/non-us-settings/sop-triage-prevent-transmission.html

Appendix B: Interview Questions

Name:

Faculty or Graduate Student:

Position in the Physics Department:

Do you manage a lab(s)?

What is the main research conducted in your lab and any notable experiments?

How do you standardize the processes within your lab?

What kind of procedural documents, instructions, etc, if any, do you provide to your students?

How do you keep these documents relevant? Do you update them every term, every year, never?

What is your interaction and relevance to these documents? Did you write them? Find them online? Were they passed on to you from other faculty members?

What is the importance of standardization to you?

Do you believe that lab processes in physics should be standardized?

Have you ever used an SOP before? Do you believe that SOPs are implemented in the WPI Physics department?

Do you see a lack in implementation?

If yes, how do you think we could better implement SOPs?

Appendix C: Task Analysis Protocol

These were not questions asked to the subject expert, but rather questions that drove the goal of the task analyses.

What is the procedure?

What is the goal of this procedure?

What tasks are being completed by the user to accomplish this goal?

What are the physical steps taken to accomplish this goal?

Is there any prior knowledge and/or nonphysical steps needed to accomplish this goal?

Who performs these tasks?

What are potential obstacles while performing these tasks?

What do other inexperienced users need to know before performing these tasks?

Is there a sequence to these tasks?

What is the expected result?

How can the procedure be improved upon in the future?

Can this procedure by reproduced if given proper instructions?

What are details, other than instructions to the tasks, that need to be provided to be able to reproduce this procedure?

Standard Operating Procedure (SOP) for Building a High-Efficiency Moisture Detection Sensor

5G / 6G / mm Wave Lab (LEAP)
Worcester Polytechnic Institute
Physics Department

Author: Sahana Venkatesh

Date Written: April 27, 2023

WPI

UNIVERSITY OF ILLINOIS URBANA-CHAMPAIGN

CARD
CENTER FOR ADVANCED RESEARCH IN DRYING

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Lab Safety Guidelines

LAB SAFETY IS OF UTMOST IMPORTANCE WHEN DEALING WITH IMPORTANT AND EXPENSIVE LAB EQUIPMENT.

GENERAL LAB SAFETY

- Closed-toe shoes must always be worn.
- No food and drink are allowed inside the lab.
- Long pants must be always worn.
- Hair must be tied back.
- Eye protection must be worn within the lab when dealing with dangerous chemicals and/or instruments.

LAB SAFETY – SENSOR LAB

- ESD bands must be worn when working with sensor components.
- Room humidity must be always monitored (Humidity under 20% is dangerous!).
- Oven mitts must be worn when taking samples out of the oven.
- Gloves must be worn when working with optics.

LAB SAFETY – SMART DRYER LAB

- Ear and eye protection must be worn when the dryer is running.
- Keep clear of the exterior of the dryer (It will be hot!).

1.0 Document Overview

1.1 Purpose

The purpose of this SOP is to provide a standardized approach to the development of a high-frequency moisture detection sensor used for identifying the moisture content on paper samples regarding the pulp and paper industry. This SOP will be used by lab personnel, students, and faculty working on this Center for Advanced Research in Drying (CARD) research project at WPI.

1.2 Scope

This SOP is limited to those working on this moisture detection sensor for CARD. This SOP is only applicable to the building of this specific sensor.

1.3 Contact Information

LEAP Lab at WPI:
Professor Douglas Petkie, dtpetkie@wpi.edu

Center for Advanced Research in Drying:
cardinfo@dryingresearch.org

2.0: Identification of Sample for Measurement

Identification of sample for measurement refers to identifying the paper sample we want to use for the sensor lab. This sample must be consistently used throughout the lab. To perform this identification, users should create an experiment plan.

2.1 Creating an Experiment Plan

An experiment plan is created to ensure consistency throughout the lab. To create an experiment plan:

1. Set up a meeting with the Drying Technologies group.
2. Create an experiment plan for identifying a measurement sample.

   Note: Important points to consider include the following:

   i. Paper: Pulp Type
      - Type of wood (hard or soft)
      - Level of refinement
      - Bleached or not bleached

   ii. Measurement Initial Conditions
      - Pressed vs not pressed paper
      - Saturation levels
      - Thickness of sample

3. Coordinate with the Drying Technologies group to obtain a few samples.

3.0: Parameter Extraction

Parameter extraction refers to finding suitable values for the parameters of the initial mass measurement model such that the measurement results and experimental results will be close in value. To perform this parameter extraction:

1. Record Initial Conditions
2. Saturate the Chosen Sample in Water
3. Record the Initial Saturation Mass of the Sample
4. Complete Data Analysis of the Initial Saturation Mass Measurement
5. Build the Initial Mass Measurement Model

3.1 Recording Initial Conditions

Initial conditions are recorded to ensure the lab is kept at an optimal temperature and humidity level. To record initial conditions:

1. Enter the lab and record the external temperature and the internal lab temperature from the wall thermostat (Figure 1).
2. Record the humidity of the room from the thermostat.
3. Write these measurements in a designated lab notebook. If multiple measurements were taken in one day, write down the date and time of each measurement as they can vary on an hourly basis.

Note: Make sure to mark the date these measurements were taken because measurement values can vary daily.

4. Write down description of the chosen sample in the lab notebook.

Figure 1. Thermostat located inside the lab

3.2 Saturating the Sample in Water

The sample is saturated in water to add moisture content so that we can increase the dry basis moisture content for lab measurements. To saturate the sample in water:

1. Fill a plastic bucket with water from the lab room sink
2. Collect the sample we chose with the Drying Technologies group in the previous chapter
3. Cut a 4 inch diameter from that paper using regular scissors

Note: This is our sample. We chose this diameter as it is the same as the weighing pan on the scale.

4. Place this sample in the plastic bucket filled with water and press down to fully submerge.
5. Set a timer for 1.5 minutes to allow sample to submerge in the water.
6. In preparation for drying, take 2-3 paper towels and lay it on the counter next to the sink.

3.3 Recording the Initial Saturation Mass of the Sample

The initial saturation mass of the sample is recorded so that in data analysis, various traces can be created as the saturation mass of the sample decreases to being closer to the dry mass of the sample. To record the initial saturation mass:

1. Once the timer for 1.5 minutes is done, take the sample out of the bucket and pat it dry on the paper towels.

Note: Make sure not to the squeeze the surface of the sample, simply tap lightly to get the excess water off.

2. Turn on the digital measuring Sartorius scale in the lab (Figure 2).

Note: Since this is a digital scale, this will take some time. Tare the scale to account for the mass of the sample holder.

3. Place the damp sample on the sample holder on the scale.
4. Place curl-stopping ring on top of sample.
5. Record the mass of the sample.

Note: Since this is a digital scale, this will be done automatically by the scale.

6. Write down these initial saturation mass measurements in the designated lab notebook.
7. Set time parameters and run automated Python and LabVIEW data collection program on lab laptop.

Note: The Python script will ask for the length of data collection and the number of samples to be collected. The LabVIEW data program will collect the live mass of the sample determined by the parameters of the Python script. These are needed to build and verify an effective medium model.

Figure 2. The Sartorius measuring scale in the lab

3.4 Analyzing Data

Data Analysis is performed to create plots of the absorption coefficient and index of refraction in relation to the Dry Basis Moisture Content (DBMC) of the wet sample while left to dry. To perform data analysis:

1. Once data is collected, run automated MATLAB script for nelly parameter extraction code to obtain the index of refraction and absorption coefficients.
2. Import data from Nelly analysis program into IGOR Pro to plot absorption coefficient and index of refraction vs DBMC.

3.4 Building Model

Building a model allows us to verify our experimental results with the theoretical results of the effective medium theory and the Beer-Lambert's Law.

1. Log into lab computer connected to time domain spectroscopy system.

2. Power on spectroscopy system and wait for steady green light and start the Topaz control program.
3. Put on gloves before handling the same wet sample to ensure no extra oils are added.
4. Take sample and place it in the blue vacuum oven in the lab.
5. Set timer for an hour and a half.
6. Once timer is done, remove sample from oven and measure the mass measurement using the measurement scale from the previous task.
7. Run IGOR Pro model building script with permittivity data from above task and export the generated model.

4.0: Smart Dryer Tests

Smart Dryer tests refers to mounting our lab tested sensor application to the industrial smart dryer at WPI. This is important because this sensor application is being developed for potential future use by industry partners of CARD. To perform smart dryer tests:

1. Connect the Sensor to the Smart Dryer
2. Run Smart Dryer Tests
3. Complete Data Analysis

4.1 Connecting Sensor to Smart Dryer

Connecting the sensor to the smart dryer is a crucial step as the sensor must be mounted at a fixed range at the inlet of the smart dryer. To connect the sensor to the smart dryer:

1. Mount the sensor to the cage on the smart dryer.

Note: This may already be done from previous experiments, see Figure 3 below for current attachment.

2. Start MMWAVE Studio on the lab laptop.
3. Power on the radar unit.
4. Connect the radar unit to the laptop.
5. Initialize the radar in MMWAVE Studio.

Figure 3. The current mount setup for the sensor on the smart dryer

4.2 Running Smart Dryer Tests

Running smart dryer tests allows us to see the compatibility of our sensor application with industrial drying applications. To run smart dryer tests:

1. Place calibration plate on the dryer belt.
2. Place sample on the dryer belt.
3. Take radar frames, using the Data Capture Demo LUA script, on MMWAVE Studio when the plate is directly below the sensor.
4. Run automated data capture script on MATLAB to create Power and Range variables and Power vs Range plots.
5. Repeat for subsequent samples.

4.2 Analyzing Captured Data

Data Analysis will allow us to check the efficiency and accuracy of our high frequency moisture detection sensor. To perform data analysis:

1. On Power vs Range plot, compare the intensities at the specified range the paper sample is at.
2. Refer to model generated in the previous chapter to determine volumetric moisture content measurements.