Use of a Pulsed Terahertz Sensor for Coat Weight, Non-contact Caliper Thickness and Moisture Measurement

Abstract

A pilot coater trial was performed to demonstrate the ability of Time-Domain Terahertz (TD-THz or THz) reflection sensors to measure the following paper parameters: stock and final coated product basis weight, coat weight, non-contact caliper thickness and sample moisture. A major motivation for the testing is to determine if THz systems can potentially replace radioactive / ionizing sources (e.g., nucleonic beta sensors or x-ray) basis weight measurement devices. Collateral THz measurement capabilities include non-contact caliper thickness and percent moisture all using a single sensor.

Measurements of coatings over a wide range of stock materials, coat weights and coating types were tested. The coat weights used were a narrow range on the low end of coat weights typically run in the industry. During the trial, THz sensors were installed in two inspection locations in the coating process; at base stock unwind and at final cured product. All testing was for a single transverse point near the edge of the web. Cross web scanning has been previously demonstrated on similar materials.

All trial THz measurement results were compared to off-line laboratory measurements. Excellent on-process measurement correlation to basis weight, coat weight, caliper thickness, and sample moisture was established. These findings demonstrate the ability of THz to make multiple process measurements using a single-sided sensor, thus reducing the overall number of sensors. High measurement precision and fast measurement rates offer an economic advantage due to enhanced speed and precision of MD/CD feedback and startup control capability.

Introduction

Radioactive materials are used widely for process control instrumentation in the paper industry. Specifically, "beta-gauges" are used to provide measurement and feedback control of basis weight and coat weight while additional sensors are required to measure web properties such as caliper and moisture. The advantages of beta-gauges are many, including robustness to hazards in the industrial manufacturing environment, accuracy and precision of a level that provides good process control. For high flux sources, fast response times that facilitate scanned, full width measurements at typical paper machine line speeds are routine.

There are increasing concerns with beta-gauges from an environmental standpoint. The sources for beta-gauges, typically krypton 85, strontium 90, or cesium 137, pose particular concerns with regard to proper handling, safety, storage, and disposal of obsolete equipment. Proper accounting of the radioactive materials "from cradle-to-grave" imposes an administrative burden and lifecycle cost. For these reasons, alternatives to radioactive material based measurements are an active area of research.

Time domain terahertz (TD-THz) technology is a promising alternative to nuclear and ionizing sources for on-machine process control. TD-THz systems use terahertz frequency pulses (wavelengths between microwave and infrared) to simultaneously measure basis weight, caliper, and moisture in a sample. The THz system is solid state and therefore able to withstand production environments. TD-THz measurements are non-contact and advanced systems utilize sensors that have a small form factor and long length umbilical cabling amenable to scanning full web widths. The high repetition rate of the measurement (up to 1000 Hz) provides fast response times crucial to in-line measurements and process control on a paper machine at typical production speeds of ~5000fpm. Most importantly though, TD-THz does not use regulated (nuclear) materials, requires no shielding or handling precautions, and poses no special exposure, environmental or permitting concerns.

This paper details a demonstration of TD-THz technology as a replacement for on-line beta-gauges in coated paper manufacturing. The data presented show that a single sensor system can accurately measure sheet basis weight, caliper and percent moisture at the line speed of 1000fpm used for the trial (this speed was just the rate of the trial, not the limit of the sensor). The data also show that a two-sensor system can determine the applied coat weight on a range of basis weight substrates with very good correlation to laboratory measurements.

A detailed explanation of the TD-THz technology used to make the measurements is presented. The experimental section describes the basics of the coater design and materials used in testing. The results section provides data from paper coating runs that show good correlation between measured THz parameters and sheet caliper, overall basis weight, weight of coat, and percent moisture. The discussion section provides perspectives into the applicability of TD-THz technology as a replacement for beta-gauges and steps for further development of the system.

Time-Domain Terahertz Measurements

Time-Domain Terahertz systems have undergone significant development over the last ten years [i,ii,iii]. Terahertz generally refers to a section of the electromagnetic (EM) spectrum lying between the Far-IR and microwaves. A very useful aspect of THz wavelengths is that nearly all dielectric materials are transparent and thus most materials can be inspected. This section of the spectrum was difficult to use until the development of Time-Domain THz systems. With terahertz measurement systems more readily available, diverse applications such as product defect detection [iv,v], security applications [vi], art conservation imaging applications [vii], pharmaceutical product manufacture [viii, ix] and coating measurements [x] have been investigated. There have even been previous reports of the use of Time-Domain Terahertz for the thickness [xi] and moisture [xii] of paper products in the laboratory.

For TD-THz, optical and electronic subsystems are combined in sensors to generate and detect very narrow (< 1 ps) EM pulses. The EM pulse can be focused, reflected and treated in the same manner as any pulsed light source. The timing and amplitude of the output pulse, and any other pulses (e.g., from reflections), are recorded as a function of time by a receiver. The delay between the emitted pulse and the gate of the receiver is scanned over a time window. The resulting time scan data is referred to as a time-domain waveform (Figure 1), and is functionally the same as a sampling oscilloscope trace. The TD-THz technique allows extremely precise determination of a pulse's arrival time at the receiver, which can be used to measure multiple sample physical and chemical properties.
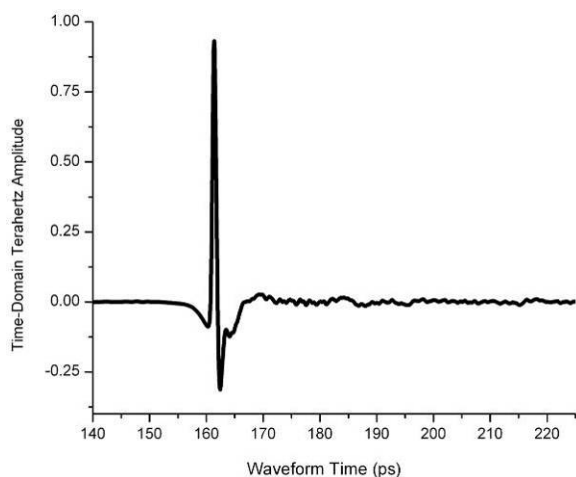

Figure 1 - Time-domain terahertz waveform data example

When a THz pulse interacts with matter, the following changes in the pulse occur (Figure 2);
   a) some of the pulse's energy will be reflected,
   b) some of the pulse's energy may be absorbed or scattered,
   c) some of the pulse's energy may be transmitted directly through the sample, and
   d) while transmitting through the sample, the velocity of the EM pulse will be slowed, from the speed of light, by a factor equal to the refractive index value. The lower velocity will result in a measureable increase in the Time-of-Flight (ToF) of the pulse.

a) Reflection

b) Absorption / Scatter

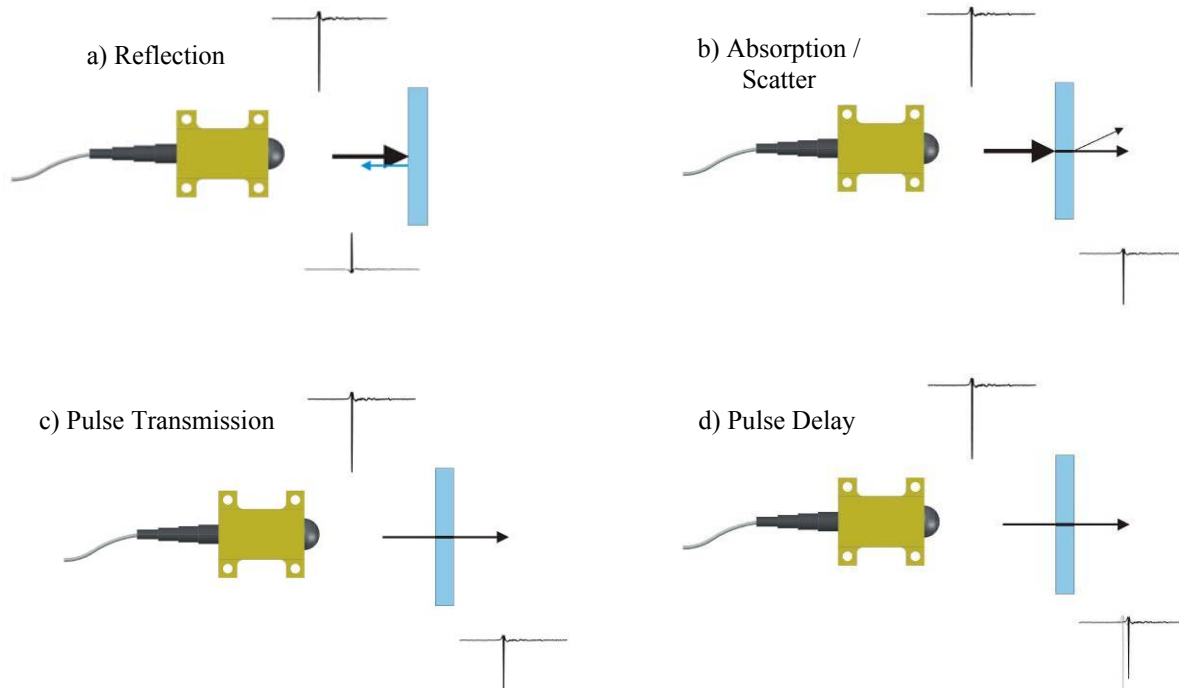c) Pulse Transmission

d) Pulse Delay

Figure 2 - Interactions of THz EM pulse with a sample

When a pulse passes through a sample, the transmitted pulse will be delayed, compared to a pulse that traveled only through air. This increase in the Time-of-Flight (ToF) delay can be precisely measured and this value used to calculate a sample's basis weight. A set of example measurements, using plastic shims, is presented in Figure 3.
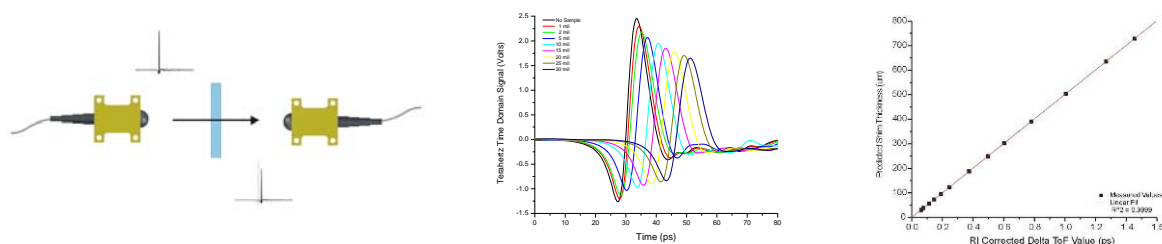

Figure 3 - THz pulse transmission pulse Time-of-Flight delay

However a reflection geometry sensor is easier to use and an improved type of measurement can be made in reflection. Reflections will occur at the front and rear surfaces of a single layer sample. In this manner, TD-THz measurements can be thought of as a non-contact electromagnetic analog to ultrasound methods. For reflection THz, the time between these sample pulses is determined by the thickness of the sample and the amount of mass in the THz beam. The method of measuring the time of reflections from the sample surfaces is very useful as the measurements are "self-referencing"; that is, the reflection off the sample's first surface always sets the zero time point. It is only the delta time between the surfaces that is used in measurements. Thus, a reflection measurement is insensitive to the position of the sample (i.e., not affected by web flutter). Also very important, this measurement method is quite insensitive to variations in the strength of the reflection pulses. If the sensor becomes dirty, decays

in output strength, becomes slightly misaligned or any other amplitude changes occur, these conditions will not affect the precise delta timing of the pulses.

In practice, the use of a beam splitter in the sensor allows the transmitted and received THz pulses to remain collinear (Figure 4a). Thus, the sensor operates best when aligned normal to the inspection surface. However, for illustration purposes, an angle is often shown between the transmitter and receiver (Figure 4b). This display method helps to clearly separate the incoming and reflecting THz pulses and thus identify the origin and timing of the reflection pulses.

(a)   (b)
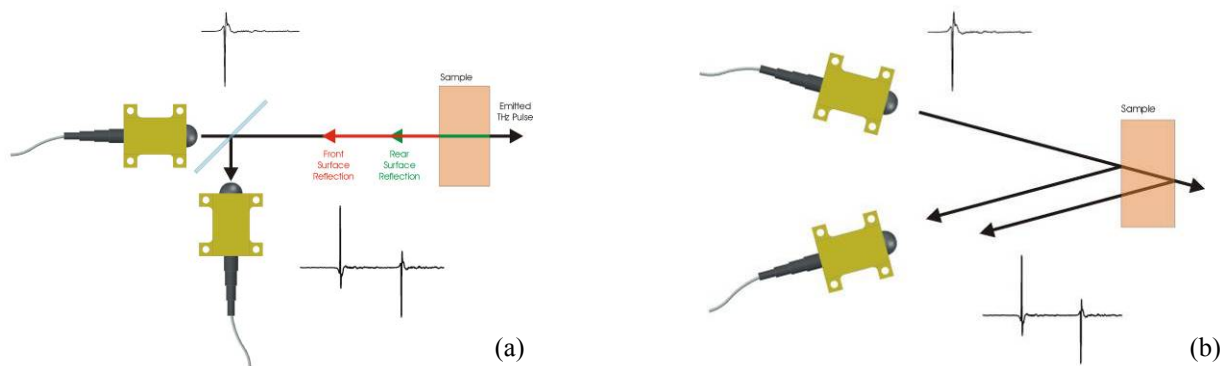
Figure 4 – (a) Collinear reflection geometry THz sensor   (b) Offset reflection sensor illustration

The very precise time measurements with reflection TD-THz systems are demonstrated in Figure 5. A histogram of a nearly 400,000 measurements (4.5 days worth of measurements) collected in 34 separate sets over a 10 day period is presented. Every single measurement fell within a 0.12% range. The ± 2σ results are < 0.03%. This measurement precision exceeds that for beta gauges and directly leads to high precision in the calculations of the properties of interest (basis weight, coat weight and caliper). The combination of high measurement precision and the insensitivity to most environmental conditions makes the method very robust.
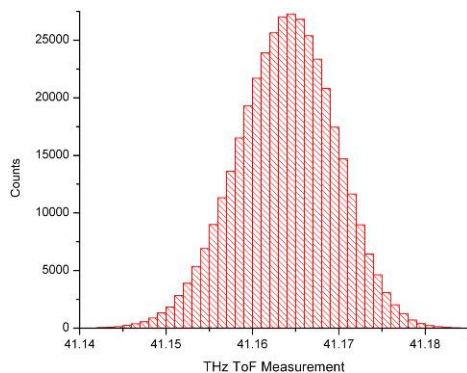

Figure 5 - Repeated measurements illustrating reflection THz delta time precision

The reflection pulse's amplitude does provide complementary simultaneous information however. The time-domain waveform can be Fourier transformed to provide full spectroscopic information. A common example of THz spectroscopy is for the detection of differing polymorph crystal structures in pharmaceutical products [ix].

For paper / coating, and many other applications, the transmitted pulse's amplitude can be used to measure the moisture in the sample. Liquid water is a wide-band, strong absorber of THz energy. The absorption is so strong that the standard absorbance method of measuring a very narrow region in the frequency domain is not necessary. Instead the amplitude or integrated area (i.e., time-domain data) of the pulse that transmits through the

sample can be directly used to determine sample percent moisture. An improvement is to ratio the sample's transmission pulse amplitude to a fixed material's reflection (e.g., sensor window) to remove any systematic amplitude variations that do occur.

Another interest in the paper / coating industry is the non-contact measurement of caliper thickness. As mentioned for reflection measurements, the pulse's transmission time between the sample's front and rear surfaces is determined by the sample's thickness and mass. In order to separate these two parameters, an External Reference Structure (ERS) is used. An ERS is a fixed structure with a transparent window (e.g., plastic, fused silica) and a reflective rear surface (metal). The reflection off the back surface of the window and rear metal reflector must always be within the waveform's time scan window. With the use of an ERS, the caliper thickness of any sample can be found in the following manner:

1) Measure the ERS empty. That is, measure the time between reflections off the rear surface of the front window and metal surface behind the web. Record this value. As the speed of light is well known, the time for the THz pulse to pass through the chamber will determine the chamber's dimensions.

2) With a single layer sample in the chamber, there will be four reflection peaks found; the window rear surface, the sample's front surface, the sample's rear surface and the rear metal surface. Determine the time of all four reflections.

3) The delta Time-of-Flight (ToF) between the window rear surface and the sample's front surface represents the transit time of the air above the sample. Similarly, the ToF between the sample's rear surface and the structure's rear metal surface represents the amount of transit time of the air below the sample.

4) The total air transit time (known from Step 1) minus the top and bottom air transit times will be the transit time from the front and rear surfaces of the sample. This time represents the transit time in air, and thus the speed of light in air can be used to calculate a caliper thickness.
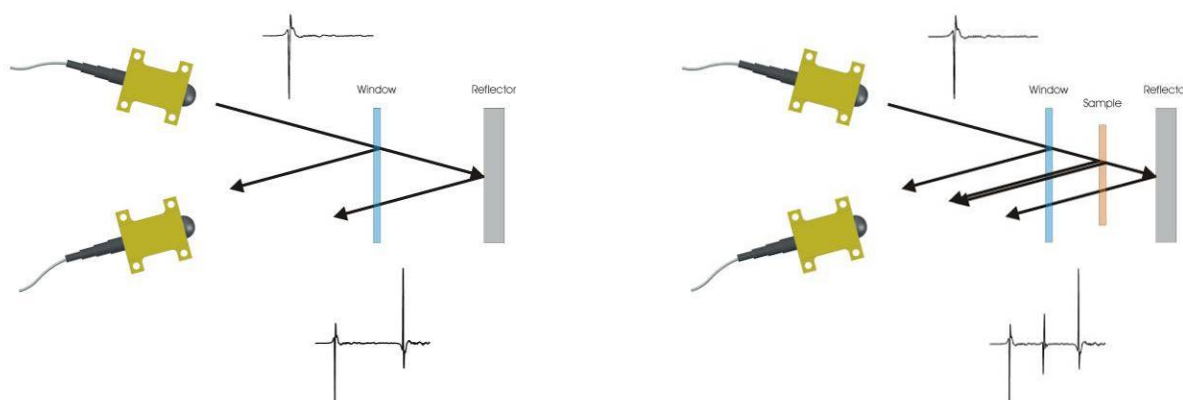

Figure 6 - External Reference Structure (ERS), with and without sample, for measurement of caliper thickness

This measurement method is very useful because the calculation of caliper thickness does not depend on any knowledge of the sample's physical properties (e.g., refractive index). Once the sample's thickness is known, then the additional delay due to the sample's mass can be computed from the original reflection measurement. This ToF delay is calibrated to basis weight. This configuration has been used to simultaneously determine caliper thickness and basis weight for a wide range of materials (e.g., plastics, rubbers, textiles, papers, foams, wood products, board stock) [xiii]. Note that the simultaneous measurement of thickness and weight provides a spot measurement of sample density. The THz pulse can be focused to a small enough spot that high quality formation images can be collected.

As caliper thickness and basis weight were measurements of interest for this trial, an ERS reflection configuration was used. The amplitude of the transmitted pulse (e.g., reflection off rear metal surface) was used to determine sample percent moisture. The ERS configuration allows the reflection off the structure window to be used to ratio the transmitted peak's amplitude thus eliminating any possible systematic amplitude variations.

For all data collected in this trial, the sensors were configured to operate in collinear reflection geometry (Figure 4a). The focal length of the optical system was three-inches. Each sensor was connected to the main THz control unit with a pair of 30 m umbilical cables.

Each reflection sensor was attached to an External Reference Structure (ERS) unit (Figure 7). Again, an ERS unit consists of an integrated window / sample area / rear reflector. One side of the ERS is open to allow the sample to be inserted. The sample area space was 1.5 inches.
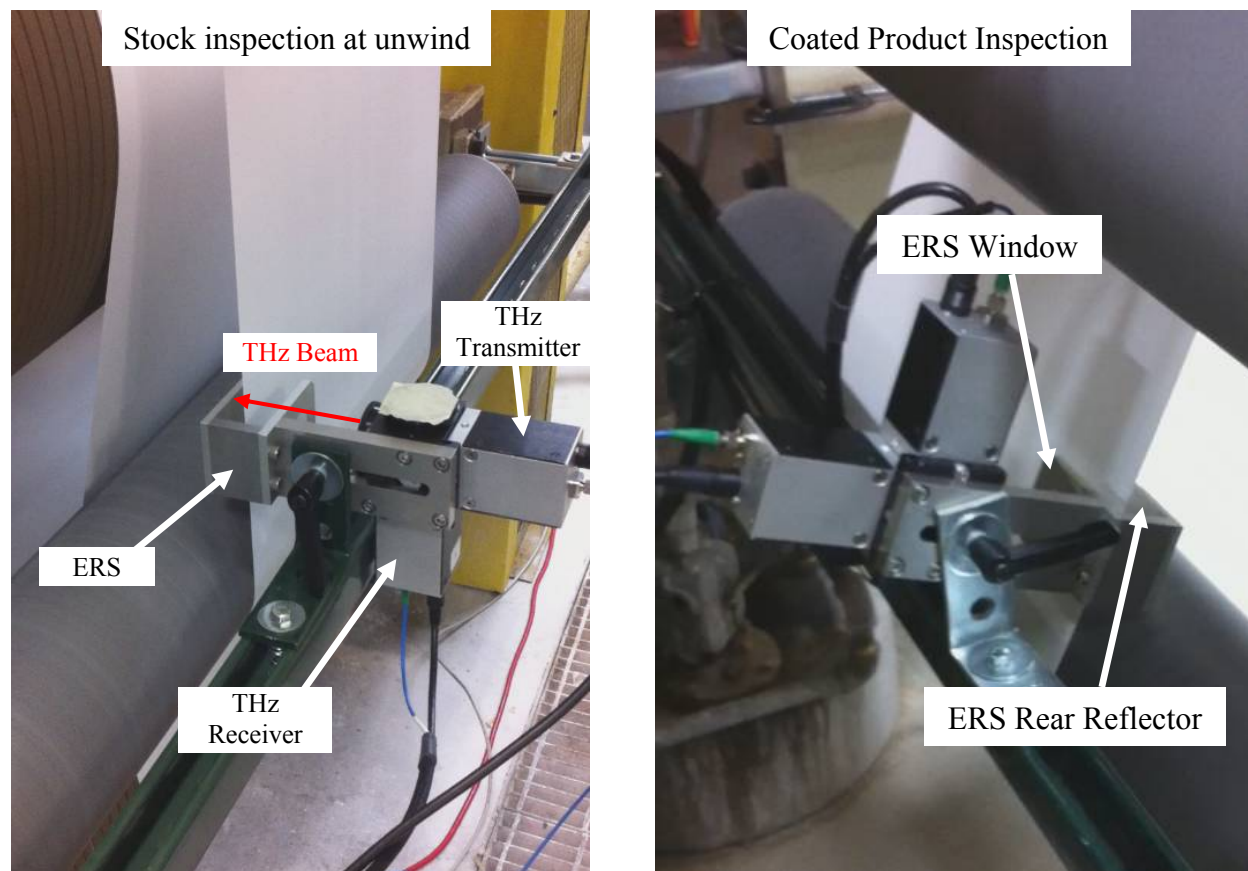
Figure 7 - Photographs of THz Sensor in ERS Configuration at Unwind and Final Product Inspection Locations

Experimental

In order to survey a range of paper calipers and weights, three base papers were used for the coating experiments. Light weight stock consisted of a 28 #/ream sheet, medium weight stock consisted of a 43#/ream sheet and heavy weight stock consisted of a 100#/ream sheet. All basis weights are listed as pounds in a 3300 ft^2 ream. The base papers had no prior coating.

Two types of coatings, with high and low pigment levels, were used in the study. The proprietary coatings consisted of pigments, polymer binders, active ingredients, and processing aids (dispersants, defoamers, etc). The coatings were formulated with proper viscosity and solids to run well on the blade/rod coating station.

Coating experiments were performed on a pilot coating line comprising a Jagenberg blade/rod coating head, forced air non-contact flotation ovens, and tension controlled unwind and reel sections. The amount of coating applied to the base paper was adjusted by altering the blade/rod pressure with increasing pressure resulting in lower amounts of coating. High pigment coatings were applied to each of the three base papers over a range of typical, to slightly less than typical, coating weights for common applications. Studying the low end of coat weights

is a good way to evaluate the capability of the system. Additional work would be needed to test the accuracy and precision over the fullest range of all variables. After the first coating pass, the medium weight base was coated on a second pass with a low pigment coating. All coatings were applied across the full 24" width of the paper web. The coated paper was dried (on each pass) to a fixed final moisture using the flotation ovens. Changes to the final moisture level were made by varying the temperature and air flow in the ovens and not by changing the line speed. Final moistures in the range of 3%-8% were obtained using this method. Coating line speed was maintained at 1000 fpm for all of the coating runs.

TD-THz measurements were obtained by mounting two sensors at separate points on the coating line. Sensors were mounted at the unwind section to measure the stock material before coating application and approximately 20 ft past the exit of the flotation driers to measure the coated material at the final moisture. At each inspection point, the sensor was able to measure product basis weight, caliper and moisture. Signals from the two sensors were used to compute the weight of applied coating using a differential method. For convenience during this trial, the sensors were held fixed positions approximately 3" from the edge of the sheet. The full width coating application of the blade/rod coater resulted in good measurement of coating in the measurement zone; however any variation across the web width would not be monitored due to the fixed mounting of the sensors. THz sensors have been successfully used in multiple previous laboratory, field and factory scanning operations.

The terahertz system used for this trial was an Advanced Photonix / Picometrix T-Ray® 4000, model TCU 4000. This system acquires measurements at a 100 Hz rate. Data collection rates of 1000 Hz are available. The data from a TD-THz system is a time-domain waveform. The desired analysis results from this time record is the precise time(s) and amplitude(s) for any transmission or reflection THz pulses recorded in the waveform. To obtain this time and amplitude data, all waveform data is filtered with a combination of standard bandwidth filtering and Weiner / Deconvolution filters [xiv]. This modified time-domain data is processed with a custom algorithm to calculate peak times and amplitude. This time / amplitude data is used to calculate the desired measurement results (e.g., basis weight, caliper thickness). For the results presented here, the measurement data was averaged into 1 second increments. Any measurement stream results were typically smoothed with a ±15 point Savitzky-Golay filter [xv].

Measurements made by the TD-THz system were compared to physical and chemical measurements of the coated sheets. Caliper was measured using a standard caliper gauge and the TAPPI standard method [T 4111]. Sheet moisture was measured by first sampling the material directly from the roll at the time of coating and sealing the material in plastic bags. These samples were then oven dried and the weight lost was used to calculate the final moisture using a TAPPI standard procedure [T 412]. The weight of coating applied to the sheets was measured by chemically analyzing certain components in each of the coatings. Analyzing separate components in each of the coatings allowed coating weights to be determined even when multiple coatings were present on the sheet.

Results and Discussion

Basis Weight

A consistent need for many industries is the measurement of basis weight. In TD-THz, basis weight values are determined from the measured time delay through the sample.
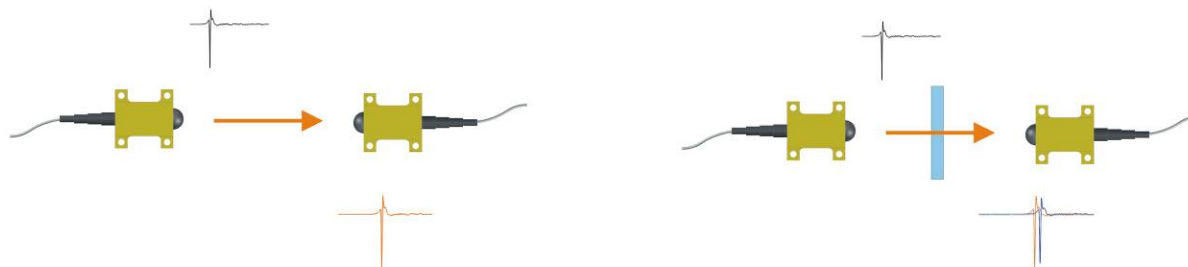

Figure 8 - Delay in THz pulse transmission

The measured time delay is calibrated against standard method determined values of basis weight. This method has been demonstrated to be effective for a wide variety of materials (e.g., paper, textiles, rubbers, foams) [xiii]. If a reflection sensor with a reflector behind the sample configuration is used, the THz beam will pass through the sample twice, thus doubling the measured delay.

Data was collected for the base stock material immediately after the unwind station. This data is used to measure the basis weight of the stock material. For this trial, laboratory measurements of the stock's basis weight were not obtained. Thus, the nominal (i.e., approximate) value for the material basis weight was used. Very good agreement with the nominal listed material basis weight was confirmed (Figure 9). The full range relative variation in uncoated stock basis weight was 2.8%, 3.5% and 1.25% for the 28#, 43# and 100# stocks respectively.
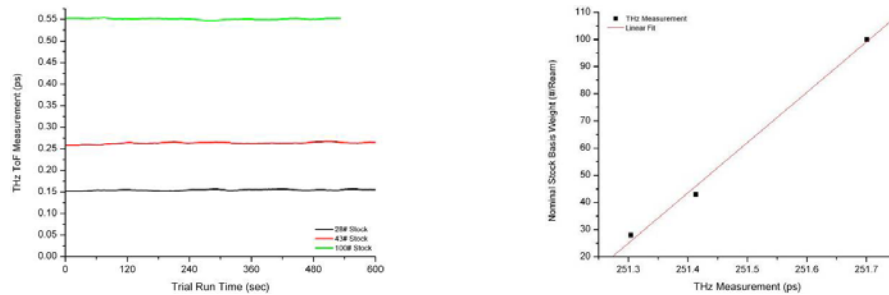
Figure 9 - Plot of stock material basis weight and linear fit of nominal basis weight to THz measurements

Coat Weight

The coat weights are obtained with a two sensor differential measurement of the material before and after coating. The coat weight values were calculated from the difference between the measured ToF delay of the coated and uncoated materials. The Machine Direction (MD) encoder signal was recorded with the THz measurement. The use of the encoder values allowed the differential measurements to be well synchronized. However, it was often found that a single basis weight value of the uncoated material could be used with essentially no discernable changes in the results.

The coat weights were typically applied in three graduated steps, starting with the heaviest coating weight then stepping to a medium and lowest weight. Each coating application run lasted approximately three minutes. THz measurements were collected at 100 Hz and averaged to provide readings every second. The measurement stream results were smoothed with a ±5 point Savitzky-Golay filter. The results for an application of a high pigment coating to a 28# stock material are shown in Figure 10. The three differing coat weight runs are highlighted in the results.
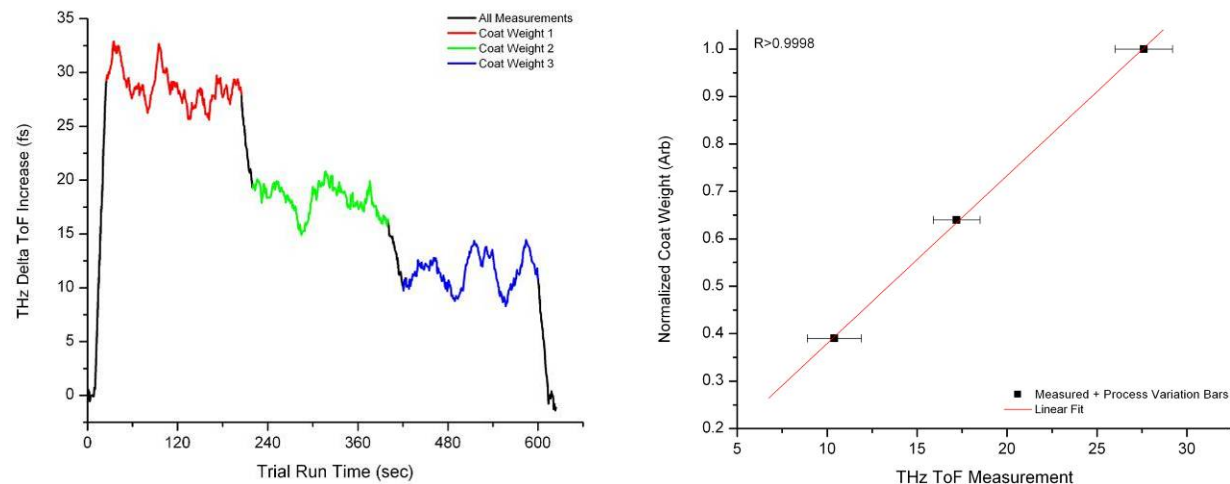
Figure 10 - Coat weight measurements for 28# stock material

The three steps in coat weight are easily visible. Note, in order to protect proprietary coating information, the three coat weights are presented as normalized measurements. That is, the heaviest coat weight is always set = 1 and all lower coat weights are ratioed by the same value. Again, these results were obtained from subtracting the two measured ToF values for the coated and uncoated measurements after using the machine direction (MD) encoder to shift and align the two sets of data. The MD encoder data was fed in the terahertz control unit on a standard input for the unit. The MD data was then recorded directly with the terahertz. Recording these two sets of data in the same file allowed for very convenient offset alignment.

A laboratory coat weight measurement was made from samples collected at the end of each run. The THz measured values were averaged over the 3 minute data collection run and the average value used to generate a calibration factor for THz ToF value to coat weight. The laboratory and THz calculated coat weight fit results are also seen in Figure 10. The agreement of three values is essentially perfectly linear (R>0.9998). Note the "errors bars" at each THz measurement are not used in the typical manner. These bars do not indicate the confidence in the THz measurement, rather are a measure of the variability ($\pm$ 1σ) in the THz measured coat weight over the 3 minute run. Thus, these ranges give an estimate of the process variability. The three calculated standard deviation values were quite consistent. Observation of the agreement between laboratory and THz measurements indicate that the measurement precision is well within the standard process variability.

Another set of coat weight measurement runs were made to determine the weight of the low pigment coating applied to a 43# paper previously coated with a high pigment coating. These results are seen in Figure 11. Again, the three distinct steps in decreasing coat weight can be observed. The fit to laboratory determined coat weight values was also excellent (R > 0.999).
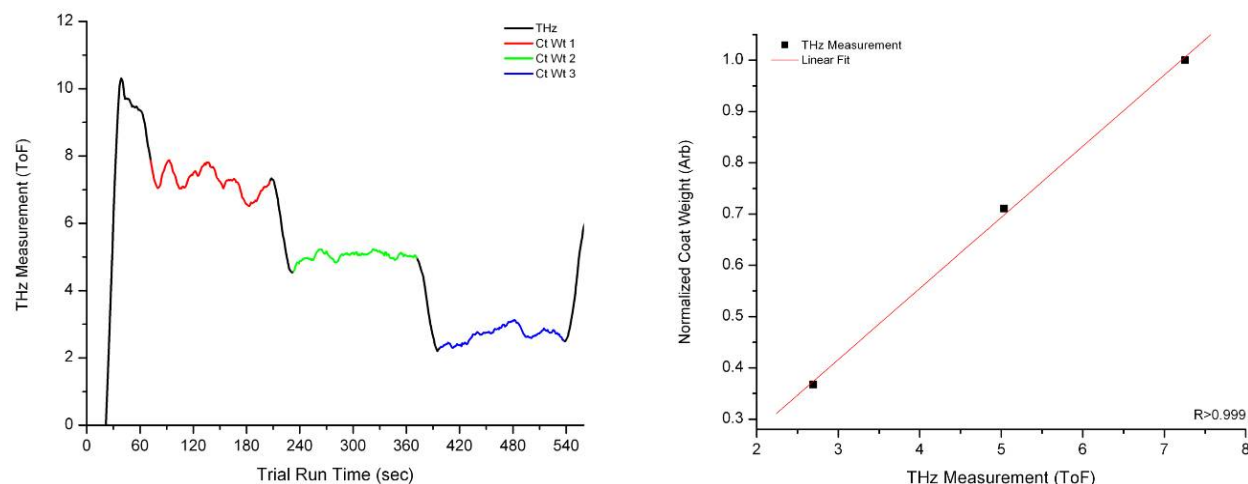

Figure 11 - Coat weight measurement of "active" coat on previously "base" coated stock

A third coat weight measurement run compared coatings applied with differing application equipment. For this trial, a rod applicator was used; all previous materials were applied with a blade applicator. Like the run above, a low pigment coating is being added to a 43# stock previously coated with a high pigment coating; however only two differing coat weight steps were used in this test. The results are shown in Figure 12.
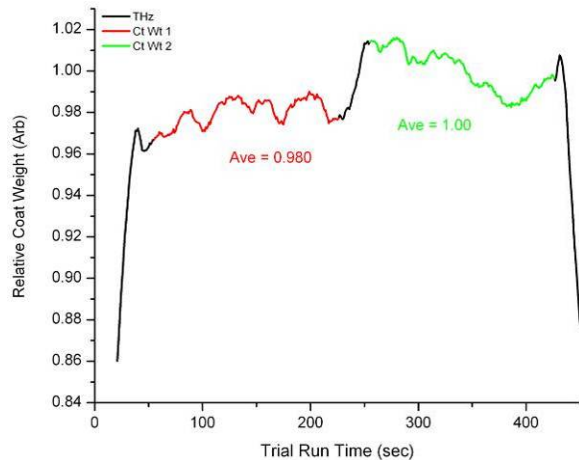
Figure 12 - Coat weight measurements, coating applied with a rod applicator

Counter intuitively, the coat weight increased with increasing rod pressure. This result was confirmed with laboratory measurements. The ratio of the two laboratory measurements was 0.980. The THz measurements were calibrated to match this result.

Caliper Measurements

A caliper measurement requires the use of an External Reference Structure (ERS). The time delta between reflections from the rear surface of a front window and the surface of a reflector behind the sample of the empty ERS need to be measured and stored. Then, when a sample is in the ERS, the combination of all four reflection pulses are used to calculate caliper values. In general, the thickness of the sample can be calculated regardless of the sample material and without any knowledge of the sample's physical properties.
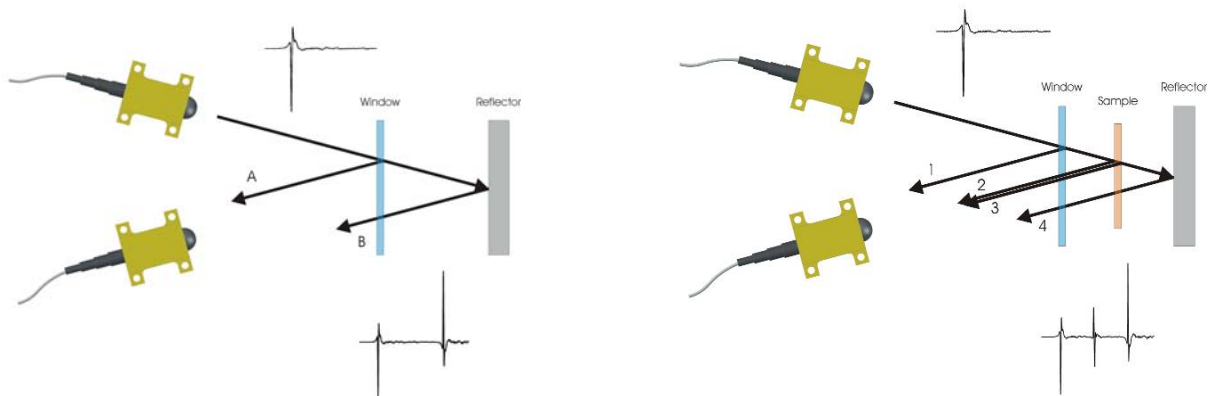

Figure 13 - ERS empty reference   ERS with sample

From the above Figures, the calculation of caliper thickness (in mm) is:

((Peak B Time – Peak A Time) – (Peak 2 Time – Peak 1 Time) – (Peak 4 Time – Peak 3 Time)) / 2 × c

    Empty ERS Transit Time   Top Air Transit Time   Bottom Air Transit Time

$$c = 0.29979 \text{ mm/ps}$$

To convert mm to mils: mm thickness / 25.4 × 1000

High resolution caliper thickness measurement results for the three differing base stock materials are presented in Figure 14 below. Each set of results are scaled separately highlighting small changes in the measured values and to illustrate the measurement precision. The large dip in caliper for the 100# stock is unexplained. A single plot, with all three sets of results is presented in Figure 15.
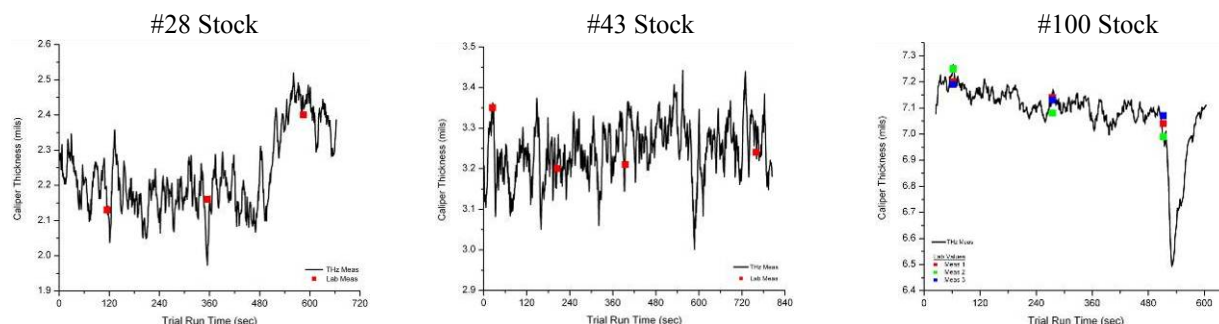

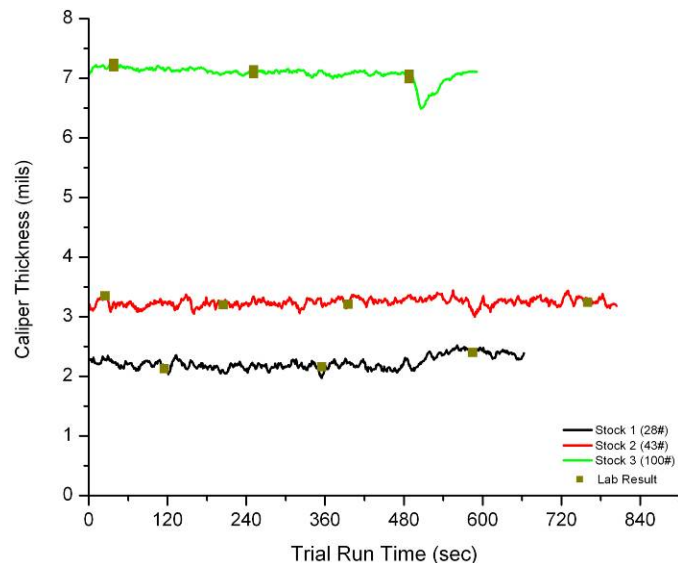Figure 14 - Caliper thickness measurement results for three coated base stock materials

Figure 15 - Caliper thickness measurement results for three differing coated stock materials

Repeated static sample single point measurements were not taken; thus only an estimate of the measurement precision can be made. From the above results, the ± 1σ standard deviation values for the three sets of data are all < ± 0.05 mils when determined form a stable 1 minute region of each set of data. The actual measurement precision is likely less than this value.

Moisture Measurement

The basis weight and caliper thickness measurements were calculated from the measured times of the reflected THz peaks. The measurement of percent moisture is determined from the amplitude of the transmission peak. In general, Beers Law measurements are made from absorbance values found over a very narrow region in the frequency domain. This method is certainly possible with TD-THz, the time domain data can be transformed to frequency data. The main reason for working in the frequency domain is so a narrow band with high absorptivity can be selected. A narrow band is chosen to keep the absorptivity of a material as constant as possible over the

bandwidth. Including absorbance measurements from varying absorptivity values usually leads to deviations in the expected linear response of concentration versus absorbance.

However, for liquid water over the THz bandwidth used (0.05 – 2 THz), the absorptivity is very strong and quite featureless (a slight ramp up at higher frequencies end). The strong relatively constant absorptivity value implies the entire integrated frequency range can be used without introducing any significant deviations. This further means the amplitude of the time domain transmission pulse contains the same percent moisture information as a frequency band absorbance measurement. The amplitude result is calculated with the peak time result and thus no additional processing is required.

In an ERS configuration (Figure 16), reflection Peak 4 transmits through the sample twice and is the best choice for this amplitude based percent moisture measurement. Peak 3, off the rear surface of the sample, also transmits through the sample twice. However, the amplitude of this peak may be sensitive to properties not of interest (e.g., sample tilt, surface roughness). The ideal measurement method is to ratio the amplitude of Peak 4 to that of Peak 1. Peak 1 amplitude, off the window rear surface, will exhibit any systematic changes in the emitted pulse's amplitude. By taking the ratio of these two peak amplitudes, these systematic variations will be removed from the measurement signal. This ratio value is then calibrated to standard percent moisture measurements.
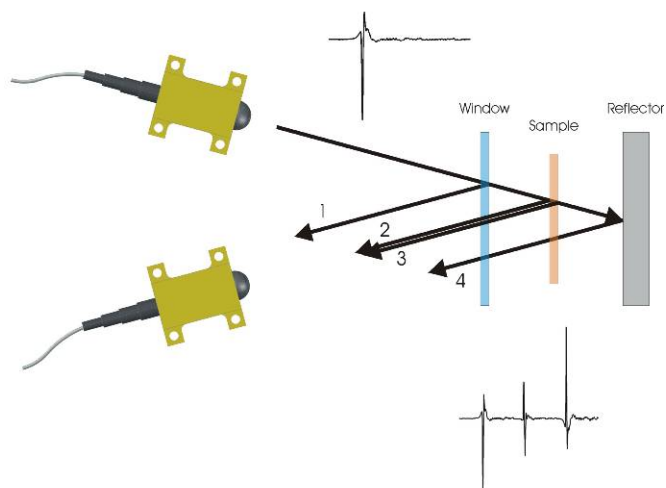

Figure 16 - ERS configuration showing four reflection peaks

Changes to the final moisture level of the sheet were made by varying the temperature and air flow in the ovens and not by changing the line speed. Final moistures in the range of 3%-8% were obtained using this method. THz measurements were collected continuously during this process.

Again, liquid water is a strong absorber. Thus, the amplitude of the transmitted Peak 4 will decrease with higher percent moisture. The trial was run with four different moisture settings, each with a 3 minute run time. The moisture was set high and slowly reduced with each setting. The resulting THz response is seen in Figure 17.
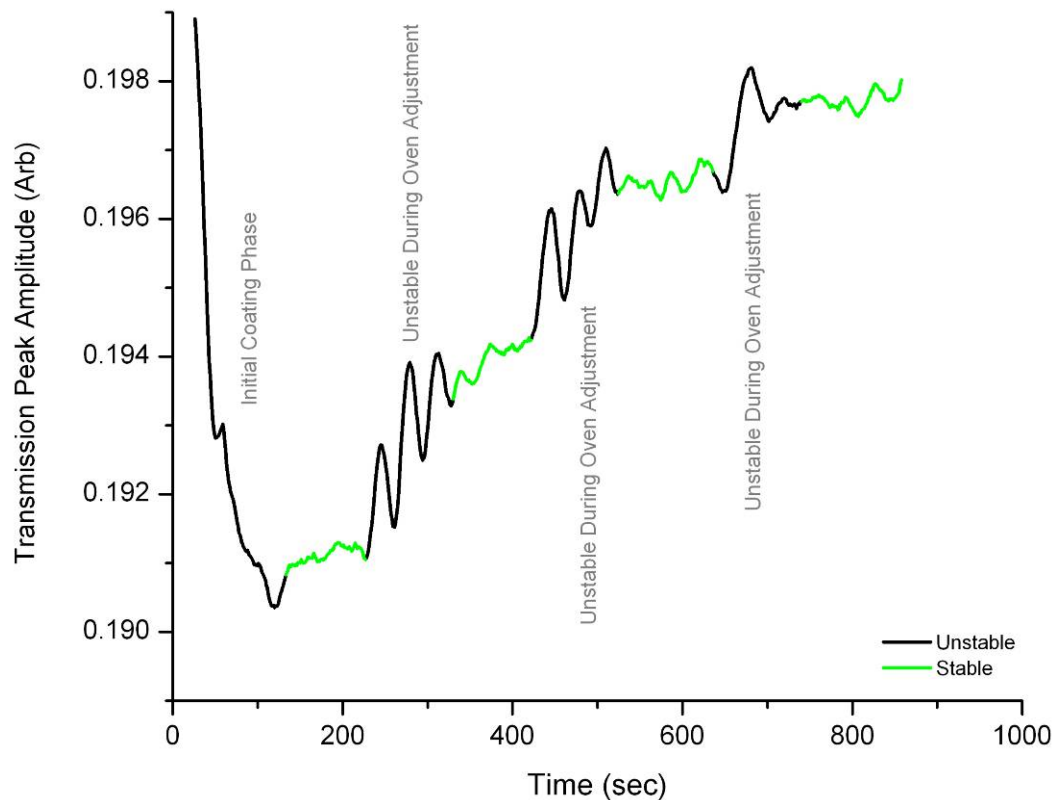
Figure 17 - THz Transmission Peak Amplitude for Final Coated Samples with Varying Moisture

Note that there are sections in Figure 17 with unstable readings immediately after the oven's settings were changed and the paper adjusted to new percent moisture levels. The unstable periods all lasted approximately two minutes. Three minutes of data was collected at each of four differing percent moisture levels. Thus, one minute of measurements at each stable level were available for analysis. These measurements were averaged and compared to laboratory balance measurements for percent moisture.
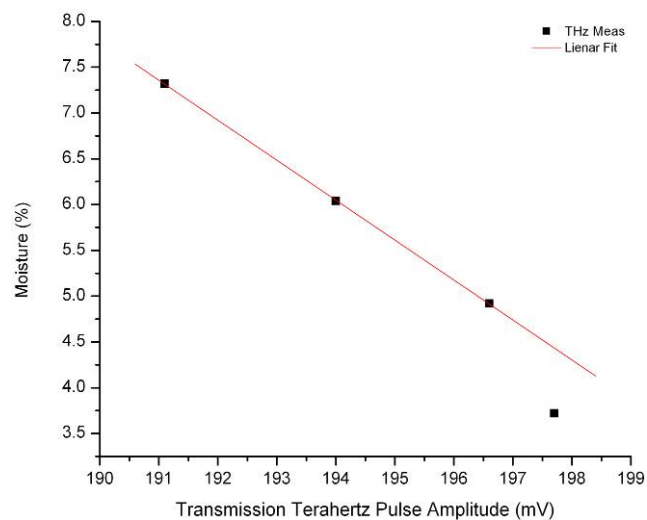

Figure 18 - Calibration of THz Transmission Peak Amplitude to percent Moisture

A linear response is found at the moisture levels >4% and a non-linear deviation observed at lower moisture levels. A deviation at the low moisture levels is not unexpected. The amplitude of the transmission peak will asymptotically approach the 0% moisture peak amplitude and a non-linear response appears to occur. A non-linear fit to this section of the response curve will address this finding. A measurement of a bone-dry sample (i.e., 0%) was not taken during this trial. The lack of inclusions of this 0% moisture measurement will also often lead to a deviation.

Repeated measurements for a fixed percent moisture sample were not taken during this trial. However, the response of the highest percent moisture reading appears fairly stable. The ± 1σ standard deviation for this section of readings was ± 0.095 mV. The slope of the linear fit section equals -0.43. Combining the standard deviation estimate and slope calculates a precision of the percent moisture of < 0.05% for this sample.

Discussion

The ability of a THz sensor to simultaneously measure stock basis weight, coated product basis weight, coat weight, non-contact caliper thickness and percent moisture has been demonstrated. As only on-line measurements were taken, absolute precision values cannot be determined, however values can be inferred from the stability of the measurement results. The excellent agreement between the laboratory and averaged THz coat weight measurements suggests the precision of the measurement is significantly less than typical process variation. Calculated from stable portions of the on-line data, the non-contact caliper thickness precision is less than ±0.05 mils and the percent moisture precision is less than ±0.05%.

THz sensors are completely safe and do not carry any regulatory burden. These advanced THz sensors have a small form factor that fits the high speed cross-web scanning needs of the paper industry. The measurement methods are very insensitive the web position, pass-line instability and nearly all environmental factors (e.g., vibration, dirt on sensor). The inherent same-spot measurement physics offered by THz ensures the measured variables are always within the same measurement position. The high precision time domain measurements will improve sample property measurement precision, reduce validation errors and improve reliability and sustainability. The ultra-fast measurement response will improve MD/CD control capability and cross-web profile visualization at start-up reducing grade change cost.

These test results indicate that Terahertz technology promises to be a replacement for nucleonic beta sensors with the added economic advantage of replacing caliper gauges with a non-contact sensor and replacing moisture sensors with a same-spot measurement.

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