

Surface and Subsurface Fiber-Orientation-Angle Measurements in Three Office Papers

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ABSTRACT

A modified fiber-orientation tester uses polarization processing of reflected light from paper to provide both surface and subsurface fiber-orientation angles. This makes possible both thickness-direction and cross-machine-direction profiling. Results obtained from two Fourdrinier machines show that subsurface angles are not well represented by a trended average of felt and wire surface angles. In fact, they can lie outside the range of surface angles and change sign unexpectedly. Sign changes suggest that the cross flows on the wire responsible for fiber misalignment may have strong shearing components that could be important to formation and hard-to-handle dimensional stability issues such as cockle. Results from office papers made on two Fourdrinier machines show significant difference in subsurface fiber-orientation-angle behavior. These include results from two papers from the same machine differing in grammage by only 10 g/m² (gsm).

INTRODUCTION

Since the pioneering work of Baum, Habeger, and others in the 1980s [1-4], measuring mechanical properties of paper using ultrasound has become standard in quality control laboratories of mills around the world [5]. Implementing the technology on-line is a continuing effort owing to the difficulty inherent in coupling ultrasound energy to and from the sheet without contacting it [6]. For on-line measurement of sheet structural properties, which can be a guide to sheet mechanical properties, a non-contacting optical reflection measurement is preferred [7].

The ultrasonic test is sensitive to fiber-to-fiber bonding and internal drying stresses in the sheet, whereas the optical test is sensitive to the distribution and physical layout of fibers, without regard to bonding or internal stress. Sheets with the same fiber distribution but different mechanical properties will measure the same optically but not ultrasonically [8]. Nevertheless, orientation of in-plane fiber and stiffness distributions by the two methods will frequently correlate. As a result, both methods have been proven useful in troubleshooting twist warp, diagonal curl, and other effects of in-plane fiber or stiffness misalignment.

Where the tests part company is in their relative ability to deal with more subtle papermaking issues, such as those related to drying (e.g., baggy edges) or sheet two-sidedness (e.g., copier curl). The ultrasonic test has the advantage of detecting stiffness variations associated with non-uniform drying, whether from variable wet-straining in the draws or variable drying restraints near the edges. However, the wavelength of ultrasound used in in-plane testing, typically 3-6 cm, is many times greater than the thickness of the sheet. This prevents the ultrasound signal from detecting information about variation of properties in the thickness direction. Optical testing relies on the use of light having a wavelength many times smaller than the thickness of the sheet. Although light cannot detect subtle structural changes associated with the drying process or bonding, except on a fiber scale, it can detect gross structural changes that are a common source of sheet two-sidedness.

The goal of the present research is to expand the role and capabilities of optical-based fiber-orientation measurement. The first step in this direction is to demonstrate the ability of the measurement to detect fiber misalignment variations within the sheet, as well as at the two surfaces. We have found examples where internal fiber-alignment angles are not accurately expressed as a trended average of the surface angles. This leads to speculation that the cross flows on the wire leading to fiber misalignment have a complicated z-direction profile that could be reflected in paper performance issues, such as those involving formation and dimensional stability.

METHODOLOGY

Known optical-based measurements of surface fiber orientation use a well-collimated and polarized light beam incident on a sheet at an oblique angle and several light detectors strategically positioned in the half-space above the sheet to collect reflected light [7,9]. The distribution of reflected light among the various detectors is indicative of

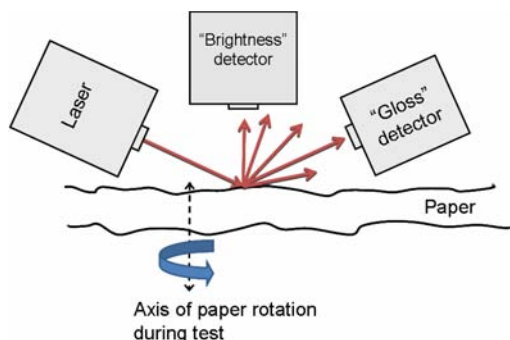


Figure 1. Schematic diagram of the surface fiber-orientation tester (S-FOT).

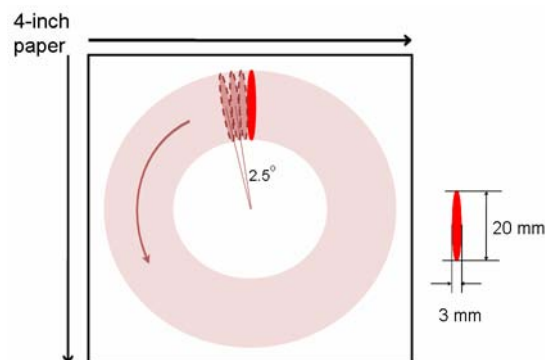


Figure 2. Locus of points measured by the S-FOT during a surface scan. Inset shows shape of projected laser beam.

the fiber orientation at the location probed by the incident beam. The measurement is restricted to the surface or near-surface of the sheet by processing the polarization and intensity of the reflected light at each detector. Light reflected from the surface of paper tends to retain its polarization, while light that enters the paper and ultimately reflects back into the measurement half-space tends to be unpolarized. By discriminating against volume scattered light, the detected signal is localized at or near the surface.

Figure 1 is a schematic of the surface fiber-orientation tester (S-FOT) [9]. A 5-mW laser operating at 670-nm wavelength illuminates the sheet at 75° from the vertical, the same angle of incidence associated with TAPPI gloss measurement [10]. Light reflected at the specular angle is detected photometrically, by what we will call the "gloss" detector. A second, identical detector looks directly down on the sheet, at 0° . If the laser were incident at 45° rather than 75° , the configuration would be similar to TAPPI directional brightness measurement [11]. The "gloss" detector is primarily sensitive to light reflected from fibers parallel to the projection of the laser beam on the sheet. The "brightness" detector is primarily sensitive to light reflected from fibers perpendicular to the projection of the laser beam. The sheet rotates beneath the laser beam in 2.5° increments. Reflection data are gathered after each step. After 360° of rotation (144 steps), the fiber-orientation angle and anisotropy of the specimen most consistent with the data are determined. Figure 2 shows the pattern of the scanned laser beam relative to the 101.6-mm (4-in.) width of the square sample.

Depending on how the polarization of reflected light is handled by the S-FOT, "surface" fiber orientation can refer to the first material encountered by the laser beam (mode 1); the first material plus a small contribution from subsurface material (mode 2); or subsurface material with a small contribution from the first material (mode 3). The light detectors of the S-FOT contain 1-cm-diameter silicon photodiodes, divided into four 90° quadrants. Each quadrant is capable of acting as an independent detector, but in this application diagonally opposed quadrants are coupled to act as a single detector. Polarizers having orthogonal axes are placed over each quadrant pair, so that separate measurements are made of the two polarizations contained in the detected light. The normal mode of operation of the S-FOT takes the difference of the signals from the two quadrant pairs to generate a combination signal indicative of the first material encountered by the laser (mode 1) [12]. The other modes of operation use one or the other of the two polarizations. Polarization parallel to that of the laser beam gives mode 2, mostly first surface reflection [7]. Polarization perpendicular to that gives mode 3, mostly subsurface reflection. The choice of modes is software-selectable in the S-FOT. We report on the use of the S-FOT in modes 1 and 3 to provide coarse z-direction profiling of fiber-orientation angles in office papers from two different Fourdrinier papermachines.

EXPERIMENTAL

Samples

Samples for in-plane fiber-orientation testing with the S-FOT were obtained from two different mills. One mill sent cross-machine strips from a single run of blue copy paper spanning more than 12 h of production. Ultrasound-based tensile stiffness orientation (TSO) data for each sheet were also provided, along with curl data representative of the reels from which the strips were taken. We selected five strips for testing. The strips were chosen to cover the range

of curl performance observed. The TSO profiles for the five strips were similar, suggesting that machine changes during the run were either minimal or had minimal effect on fiber and stiffness distribution.

Another mill sent six cross-machine strips, three of 89- and three of 79-g/m² (gsm) grammage, covering a broader span of production time. Not all sheets from a given grammage appeared the same; for example, one of the three sheets from each basis weight showed an obvious brightness increase. In-plane, ultrasonic-based TSO data [5] were provided for each sheet. Despite the grammage and brightness variations, the TSO profiles were similar. No curl or other information about the sheets or the process was provided. The papers appeared to be white office papers having good visual uniformity. Both mills' specific interest in S-FOT testing was to see the comparison between optical-based fiber orientation and ultrasonic-based tensile stiffness orientation. This comparison is addressed in a separate publication [13]. TSO testing is an incidental part of the present report.

Testing and Data Analysis

Blue copy papers. Because the TSO profiles for the five selected reels were similar, we averaged the corresponding S-FOT data for the sheets to filter noise and produce the most representative state of the fiber-orientation distribution over the course of the run. Eight cross-machine positions were selected for measurement. Two specimens each were taken from the front (F1, F2), front-middle (FM1, FM2), back-middle (BM1, BM2), and back (B1, B2). The sheets were spaced to produce a roughly uniform distribution of eight cross-machine positions across the web, excluding the extreme front and back of the machine. There were slight reel-to-reel variations in the positions of the eight specimens relative to the edge of sheet, but this was not taken into account in the averaging of results.

The S-FOT was used to make measurements on all 40 specimens with a certain polarization setting, either to measure first-surface fiber orientation or subsurface fiber orientation. Then the 40 specimens were measured with the opposite polarization sensitivity. A deficiency of the measurement at present is that we do not know exactly how far beneath the surface the subsurface measurements actually extend. A range of depths is represented by the subsurface light that finds its way to a detector. This range can be explored experimentally, as by splitting sheets to bring various "subsurface" depths to the surface [14]. Modeling the depth using modern software tools [15] is another option with greater generality to diverse papers and different experimental configurations. This work is important but beyond the scope of the present paper.

We believe that the subsurface measurement is neither noise nor a duplication of the surface measurement because (1) the subsurface fiber-orientation angles can differ substantially from the surface angles and (2) five surface and adjacent subsurface values from each cross-machine position plotted without averaging show a good linear correlation, especially if one allows the elimination of an occasional outlier. These claims are supported by the data in Tables 1 and 2.

Table 1 shows results of the testing and averaging over the five reel strips. The four rows of z-direction information and the eight columns of cross-machine (CD) information constitute a complete, if low resolution, map of the interior of the average sheet. The S-FOT average angle through the thickness and the corresponding TSO values are shown for comparison in the last two rows.

Table 1. S-FOT and TSO angles for blue copy paper

z-layer	Fiber orientation angle (deg) at eight cross-machine positions ^a							
	F1	F2	FM1	FM2	BM1	BM2	B1	B2
Felt	-2.4	-4.1	-7.0	-1.7	-5.4	-2.1	-0.2	4.7
Subfelt	-6.5	-3.7	-9.8	-2.9	-13.4	-5.4	-1.8	1.2
Subwire	-4.4	-2.2	-8.6	0.5	-7.9	-2.8	-0.4	7.3
Wire	-7.4	-5.8	-10.1	-3.6	-9.2	-4.1	-1.5	3.1
S-FOT average	-5.2	-4.0	-8.9	-1.9	-9.0	-3.6	-1.0	4.1
TSO	-2.7	-3.9	-4.5	-4.7	-2.8	-1.3	-0.7	1.0

^a F, front; FM, front-middle; BM, back-middle; B, back.

Table 2. Correlations between layers for blue copy paper

Adjacent z-layers	R^2 values for correlation between layers at eight cross-machine locations ^a							
	F1	F2	FM1	FM2	BM1	BM2	B1	B2
Felt/subfelt	0.76	0.69	0.57	0.97	<u>0.97</u>	0.72	0.99	0.96
Subfelt/subwire	0.72	<u>0.89</u>	0.86	<u>0.88</u>	0.98	0.99	0.46	0.88
Subwire/wire	1.00	0.73	0.98	0.65	0.96	0.87	0.98	0.87
Average	0.83	0.77	0.80	0.83	0.97	0.86	0.81	0.90
Felt/wire	<u>1.00</u>	0.91	<u>0.49</u>	<u>0.44</u>	<u>0.91</u>	0.75	<u>0.98</u>	0.67

^a Underscore indicates one outlier was eliminated from the correlation. F, front; FM, front-middle; BM, back-middle; B, back.

Table 2 shows the R^2 values when five angle measurements from one cross-machine position and one layer are correlated with five measurements from an adjacent layer at the same cross-machine position. The five angle measurements come from each of the five reels tested. High R^2 values imply that when the angles in adjacent layers change, as they might from process drifts over time, they tend to change in tandem. The correlations between adjacent layers in the z-direction are on average stronger than the correlations between the felt and wire surfaces. This suggests that greater distance between layers increases noise, as expected. It is interesting that the correlation between subfelt and subwire layers is intermediate between the other two adjacent layers, on average, and stronger than the felt-versus-wire correlation. This suggests that the adjacent layers may be close to equidistant

In five reel samples made over a 12-h period, it is reasonable that one sample may be an outlier to a trend exhibited by the other four. This could result in a low correlation coefficient that obscures an underlying relationship. In Table 2, when the five-point correlation coefficient drops below 0.6, one of the outlying points is eliminated, and the resulting four-point correlation coefficient is used in its place with an underscore. The outlier suggests that exceptions must be made to the general statement that the layers move in tandem in response to process drifts. The cross-machine position and depth at which outliers are found, as indicated by the positions of the underscored values in the table, suggest where there may be process instabilities from time to time. Our samples were made hours apart. Therefore these results reflect process changes or drifts rather than short-term instabilities. It would be interesting to study cross-machine strips taken as multiple plies from the same reel, or taken as adjacent samples from a narrow machine-direction paper roll.

Figure 3 shows cross-machine profiles of the felt and wire S-FOT angles versus the corresponding TSO angle. These are taken from data rows 1, 4, and 6 in Table 1. This is the normal profile presentation for the S-FOT. Note two features for later discussion: (1) the zigzag character of the S-FOT profiles compared with the TSO profile and (2) the untypical result at position FM2, where the S-FOT angles are smaller than the corresponding TSO angles and generally out of character with the rest of the profile.

White office papers. White office papers from a second mill were tested in the same way, though samples were collected differently. Two specimens each were cut from five cross-machine positions, F (front), FM (front-middle), M (middle), BM (back-middle), and B (back). The specimens from each position were cut adjacent to each other, so that they shared a common machine-direction edge. The results from adjacent specimens were averaged to produce a more representative value for the five cross-machine positions.

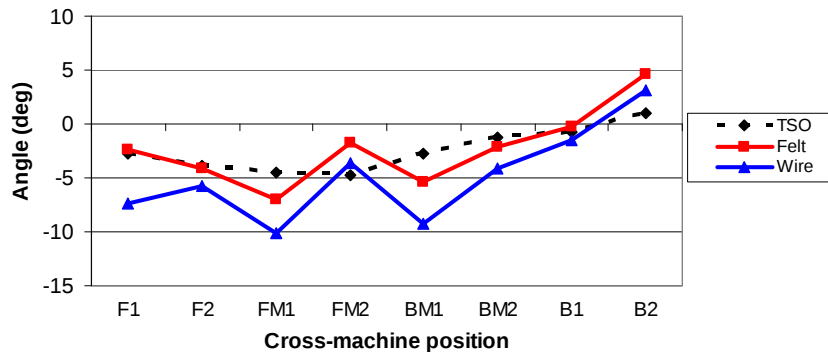


Figure 3. S-FOT felt and wire surface profiles versus the TSO profile for blue copy paper.

Table 3. S-FOT and TSO angles for white office papers

	Fiber orientation angle (deg)				
	F	FM	M	BM	B
79 gsm					
Felt	6.0	10.7	6.2	3.4	6.7
Subfelt	0.1	1.5	-6.1	-5.0	4.5
Subwire	8.3	12.7	-3.3	-7.0	-4.9
Wire	0.6	1.7	-4.8	-8.9	-6.5
S-FOT avg.	3.7	6.6	-2.0	-4.4	-0.1
TSO	-2.4	5.3	3.3	0.8	6.5
89 gsm					
Felt	3.0	12.5	7.9	4.7	7.9
Subfelt	-13.3	-0.9	9.0	-3.6	-1.0
Subwire	-1.5	4.2	7.5	6.6	10.8
Wire	-2.0	-0.6	-2.0	-5.8	-5.8
S-FOT avg.	-3.5	3.8	5.6	0.5	3.0
TSO	-3.4	2.4	1.4	-0.7	5.4

As with samples from the first mill, TSO testing of the cross-machine strips showed little variation among the reels provided. Results from all six reels were averaged until it was realized that the 89-gsm samples had very different subsurface fiber-orientation profiles than the 79-gsm samples. From that point, averaging was done separately on the three reels from each basis weight. Table 3 shows the results, along with TSO angles for comparison. Table 4 shows the R^2 values when the six un-averaged angles from one layer are correlated with the six un-averaged angles from an adjacent layer.

Underscores in Table 4 indicate when one of the angles is removed from the regression analysis as an outlier. The logic for this was discussed in connection with Table 2, for blue copy paper. In contrast with Table 2, outliers are evident at more positions, and small R^2 values frequently remain even after one outlier is removed. This shows that adjacent angles do not readily change in tandem with each other as process conditions change. This suggests more randomness on the wire, in comparison with the machine making blue copy paper. This may be associated with the visual impression that sheet formation is much better in the white papers than the blue.

Table 4. R^2 values for correlations between layers for white office paper

	R^2 values for correlation between layers ^a				
	F	FM	M	BM	B
79 gsm					
Felt/subfelt	<u>0.99</u>	0.81	<u>0.82</u>	0.88	0.50
Subfelt/subwire	<u>0.58</u>	<u>0.21</u>	0.76	<u>0.61</u>	<u>0.24</u>
Subwire/wire	<u>0.82</u>	<u>0.38</u>	0.83	<u>0.86</u>	<u>0.32</u>
Average	0.79	0.47	0.81	0.79	0.36
Felt/wire	<u>0.64</u>	<u>0.53</u>	0.54	<u>0.64</u>	<u>0.79</u>
89 gsm					
Felt/subfelt	<u>0.76</u>	<u>0.35</u>	<u>0.86</u>	<u>0.99</u>	<u>0.53</u>
Subfelt/subwire	0.83	<u>0.39</u>	<u>0.26</u>	<u>0.98</u>	<u>0.15</u>
Subwire/wire	<u>0.96</u>	<u>0.72</u>	0.73	<u>0.92</u>	<u>0.25</u>
Average	0.85	0.49	0.62	0.96	0.31
Felt/wire	0.88	<u>0.42</u>	0.67	<u>0.90</u>	<u>0.51</u>

^a Underscore indicates one outlier was eliminated from the correlation.

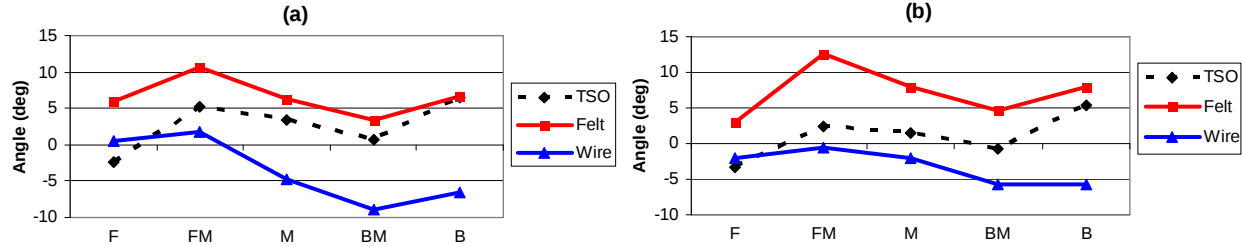


Figure 4. S-FOT averaged felt and wire profiles versus TSO profiles for white office papers of two different basis weights: (a) 79 gsm, (b) 89 gsm.

Figure 4 shows the profile presentation of the S-FOT felt and wire surface angles and the TSO angle, obtained from data in Table 3. Although the averaged felt and wire angles move in tandem, Table 4 shows that there were outliers in all but the middle position. In other words, profiles for individual reels can differ significantly from the average profile shown.

Analysis: Inferred cross-machine flows. Tables 1 and 3 represent two-dimensional maps of fiber misalignments within the volume of a sheet of paper. An often-expressed idea is that fiber misalignment angles are generated by cross-flows on the wire during forming [4,8]. Extending this idea to three dimensions, the variations observed in misalignment angles with depth suggest that the cross-flows are changing with depth as well. In further interpreting the data of Tables 1 and 3, it may be instructive to think in terms of cross flows rather than angles. Assume that positive angles represent front-to-back cross flows proportional to the magnitude of the measured angle. Assume that negative angles represent back-to-front cross flows sized according to angle magnitude.

RESULTS AND DISCUSSION

Potential for Density Two-Sidedness

Cubic-spline interpolation of the angle matrices in Tables 1 and 3 is used to produce contour plots showing the locations of constant angle or, in the above model, constant cross flows within the paper volume. Figure 5 shows the results for blue copy paper. Adjacent contours are separated by 2° steps, ranging from -12° near the felt-side subsurface at position BM1 to $+6^\circ$ near the wire-side subsurface at the back of the papermachine, B2. Areas where the contours are widely separated, as at the front side (F1) and back/back middle (BM2/B1), suggest areas of relative calm and stability. Although cross flows exist, they change slowly both in cross-machine and in z-direction. In other areas (FM1 and BM2, for example), contour lines tend to be vertical but closely spaced. This indicates a stable situation in the z-direction but not in the cross-machine direction. If cross-flows were truly one dimensional (as the designation implies), conservation of mass requires that areas of high flow move material into adjacent areas of low flow. As a result, high-flow areas lose mass, while low-flow areas gain mass. Although it is speculative to replace fiber-orientation angles by proportional cross flows, and to apply one-dimensional flow conservation to three-dimensional flow on the Fourdrinier wire, these choices provide a simple, possibly useful basis for discussing the data and their impact.

Areas of Figure 5 are identified as being high (HI) or low (LO) in mass in accord with the model. The oscillation between HI and LO in the cross-machine direction of Figure 5 parallels the zigzag pattern of S-FOT data in the front of the profile in Figure 3. However, the zigzag pattern does not indicate that the HI and LO areas tend to lie on opposite sides of the sheet. These areas, if they exist, could translate into two-sided density variations in the sheet that could be associated with curl.

Sheets with profiles similar to that in Figure 5 are unbalanced and asymmetric with respect to the z-direction. Such asymmetry causes dimensional instability, including curl, and reduced strength and stiffness. A simple tensile test will have significant shear stress and a misalignment of the principal stresses relative to direction of applied load. Internal shear stresses caused by fiber-orientation gradients will contribute to a complex stress state and less-than-optimum use of fiber based on strength-per-weight ratio.

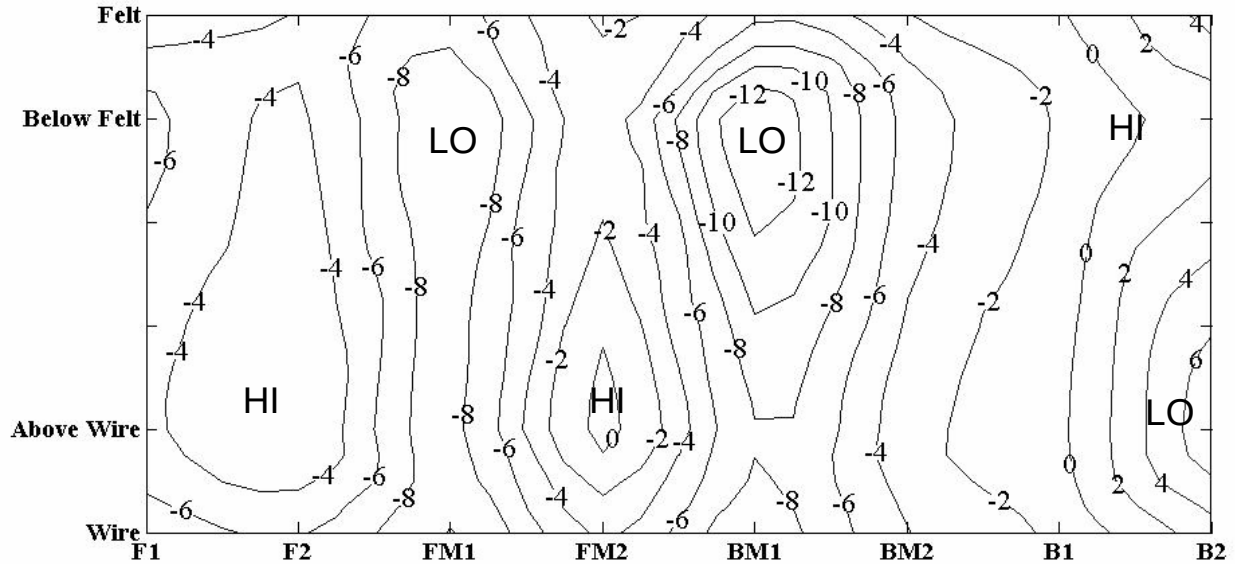


Figure 5. Contour plot of cross-machine flows inferred from surface and subsurface fiber-orientation angles of blue copy paper.

Sensitivity to Basis Weight

Figure 6 shows the comparable contour plots for 79- and 89-gsm office papers. The main contrast with Figure 5 is that the areas of high gradient tend to have horizontal rather than vertical contour lines. Horizontal contours are associated with shear flows layered in the z-direction. They may be a source of the good visual formation appearance in these sheets. The 79-gsm sheets have high shear extending from the front to the back-middle of the sheet along the felt side, and from the front to the middle of the sheet along the wire side. The back of the sheet has a lower density of horizontal contours, especially on the wire side. However, no obvious deterioration in formation is observed in connection with this. The 89-gsm sheets have high shear on the felt side in the front of the machine and on the wire side in the back of the machine. The middle of the machine is less well represented by shearing flows. Again, no discernable deterioration in formation is connected with this.

Other features are shared in common by 79-gsm and 89-gsm papers. A main central lobe in each profile suggests an area of flow stability. The angle associated with this lobe is -6° in the 79-gsm sheets and $+8^\circ$ in the 89-gsm sheets; in other words, nearly equal and opposite. The lobes are to some extent upside down with respect to each other, as well. There are horizontal contours (shearing flows) on the felt-side of the lobe in the case of 79-gsm papers, and on the wire side of the lobe in the case of 89-gsm papers.

Both basis weights have other high-magnitude-angle areas that change sign and shift in moving from one basis weight to the other. The 79-gsm papers have a closed contour at $+12^\circ$ in the subwire/front-middle part of the profile. This island appears to move upward and to the left to the subfelt/front part of the 89-gsm profile, and to change sign from $+12^\circ$ to -12° . Meanwhile, vertical contours near the middle of the 79-gsm profile are pulled lower and to the left, while also changing sign. At the same time, the -8° contour at the wire/back-middle position moves upward to the right and becomes a $+8^\circ$ contour at the subwire/back position.

The many changes from adding 10 gsm incline one to speculate that major process moves are involved. For example, moving from a rush to a drag condition would tend to be associated with changes in the sign of the angles and a redistribution of contours. However, the felt and wire surface angles shown in Figure 4 do not change much at all in going from one basis weight to the other. Linear regression between the average angles measured for 79 and 89 gsm (Table 3) shows a high correlation coefficient of 0.88 when only the surface angles are considered. In the case of subsurface angles, the correlation coefficient is only 0.09; that is, there is virtually no correlation at all between the two basis weights when comparing angles within the subsurface.

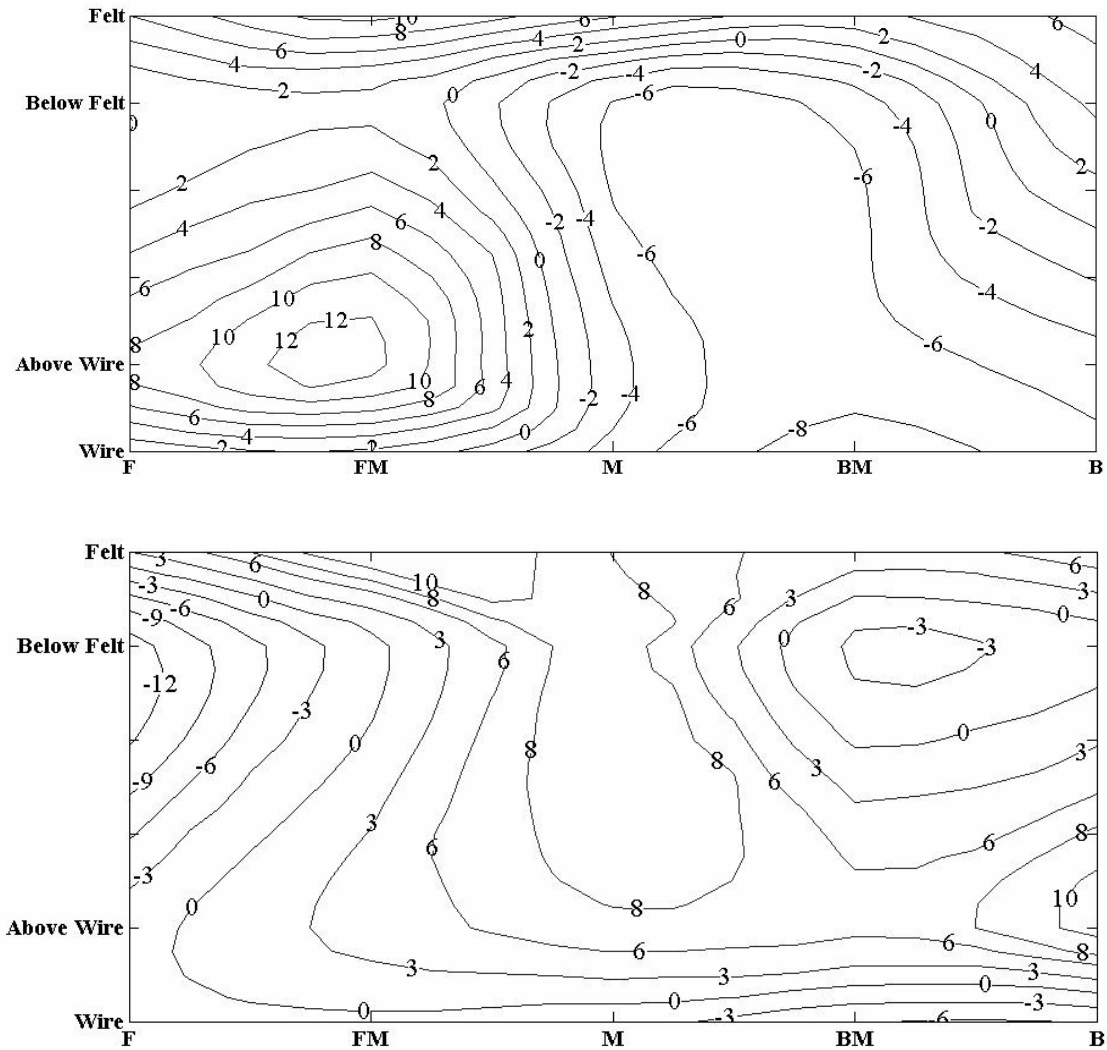


Figure 6. Contour plot of cross-machine flows inferred from surface and subsurface fiber-orientation angles of white office paper: (top) 79 gsm, (bottom) 89 gsm.

CONCLUSIONS

The hardware of the S-FOT is configured so that a software adjustment allows the instrument to measure fiber-orientation angles either at or beneath the paper surface. A comparison between surface and subsurface measurements in three samples from two different Fourdrinier machines indicates that the measurements are meaningful. However, their relation to paper performance can only be speculated at the present time.

In blue copy paper from one machine, the surface and subsurface angles tend to change in predictable ways relative to each other as the process drifts and changes over 12 h of production (Table 2). In white office papers from a different machine, made over a longer course of time, there is an association between surface and subsurface angles at some cross-machine positions but not at others (Table 4). The positions and the degree of association change significantly when the basis weight changes from 79 to 89 gsm. The 79-gsm sheet shows more stability over time than the heavier sheet. Both white sheets appear well formed in comparison to the blue copy paper, suggesting the possibility that higher subsurface variation can be a source for improved formation. In particular, the angle contours for the white office papers suggest the presence of shearing flows (Figure 6) that are not duplicated by the blue copy paper (Figure 5).

In all samples tested, the standard measurements of S-FOT angle and the TSO angle do not give much indication of observed complexity in the sheet interior. In particular, the two different weights of white office papers have very similar S-FOT and TSO profiles despite the interior differences. In the case of blue copy paper, the S-FOT and TSO profiles track each other fairly well except in the front-middle of the machine. Subsurface measurements of the optical angles show high cross-machine gradients in that location. Although these could be a factor in the observation, drying issues could be influencing the TSO value, as well.

Plausible arguments suggest how angle gradients can result from the same flow phenomena leading to mass gradients. These arguments, applied to the data for blue copy paper, predict alternating high and low density centers in the z-direction (Figure 5). These could be a source of two-sidedness leading to curl and low sheet stiffness for the amount of fiber used.

Finally, work is needed to show the relevance of subsurface angle measurements to paper performance issues. Anecdotally, there are many cases of paper performance in the areas of strength, stiffness, and dimensional stability that are not understood using conventional fiber and stiffness orientation measurements. These become candidates for evaluation using subsurface fiber-orientation measurements.

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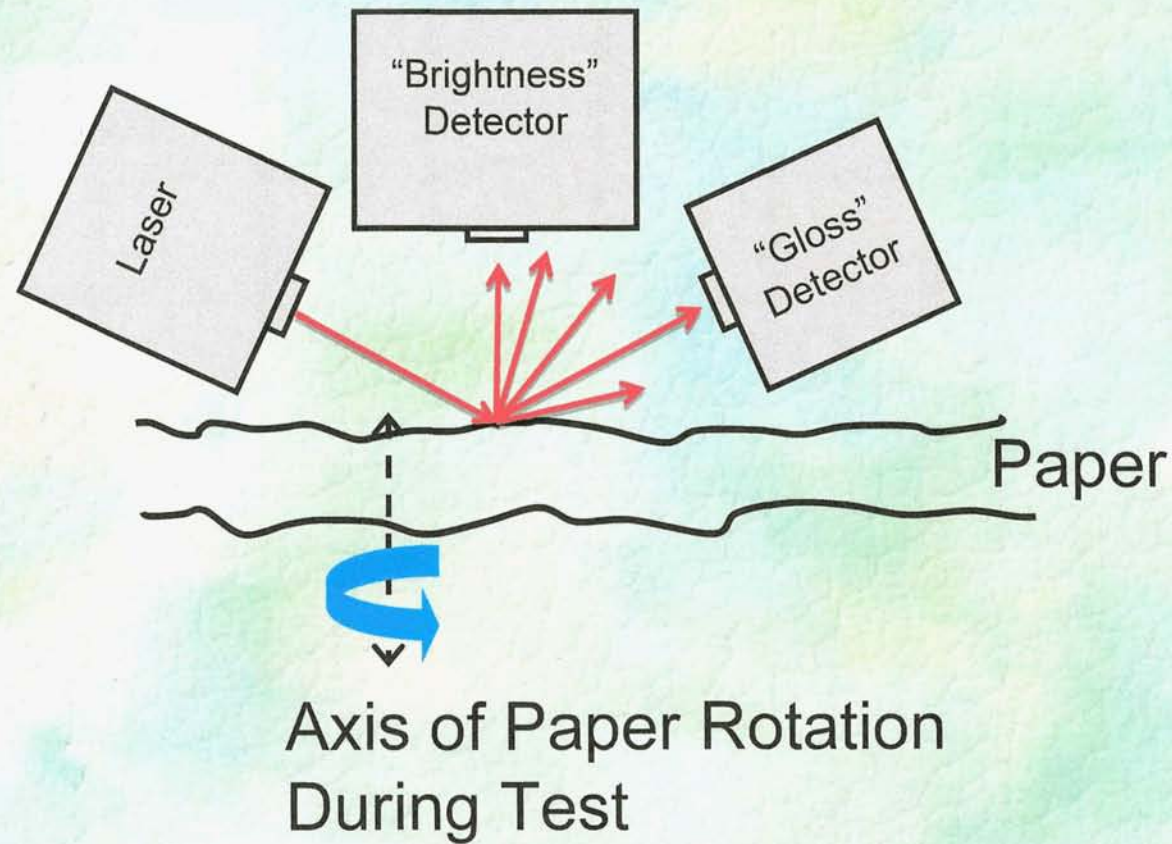
Surface and Subsurface Fiber Orientation-Angle Measurements

David Vahey and John Considine
US Forest Service
Forest Products Laboratory
Madison, WI 53726

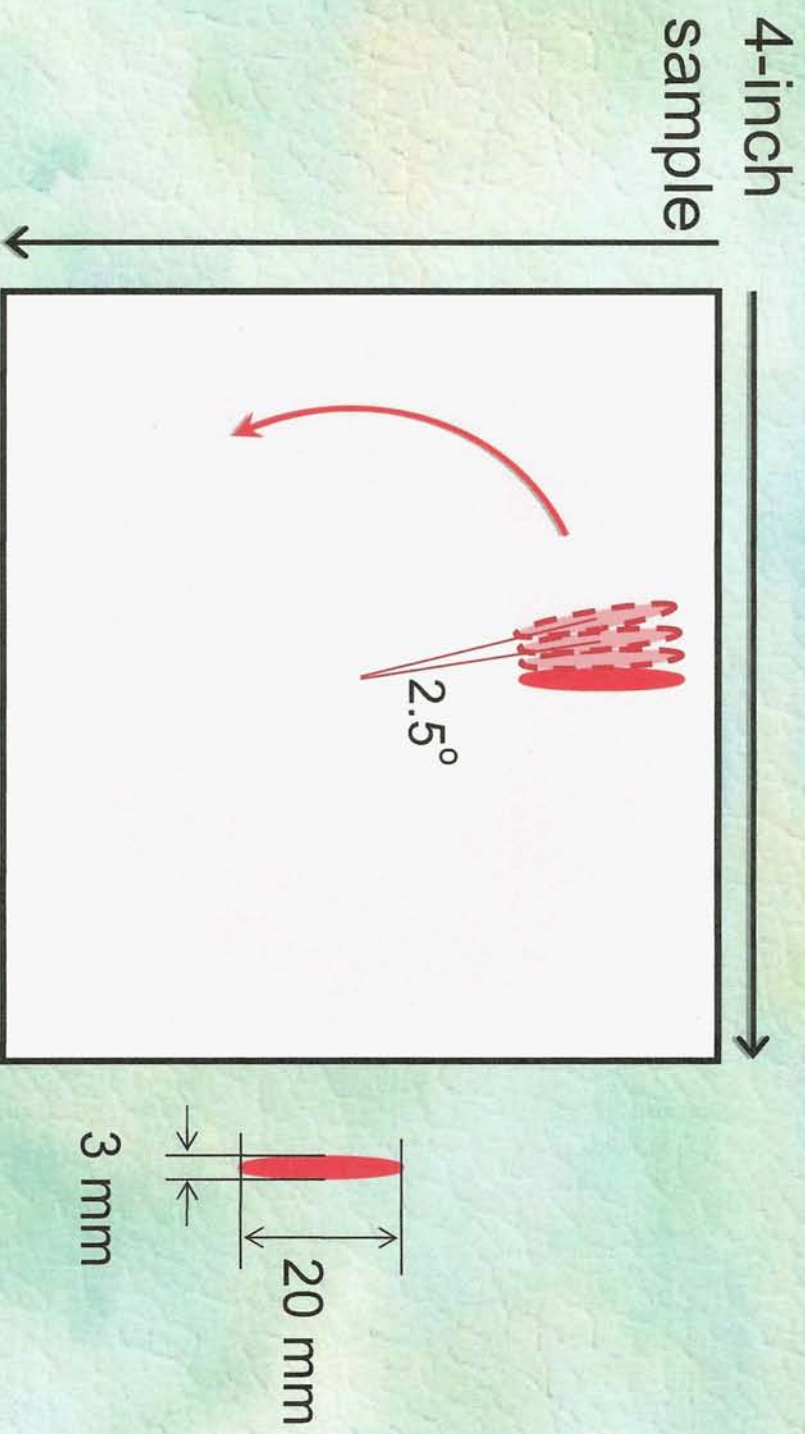
Outline

- Surface and Subsurface Fiber Orientation Measurements
- Samples and Testing
- Results
 - Surface and Subsurface Profiles
 - Nature of z-Direction Variation
 - Contour Plots of Paper CD-ZD Cross-sections
- Conclusions/Next Steps/Acknowledgements

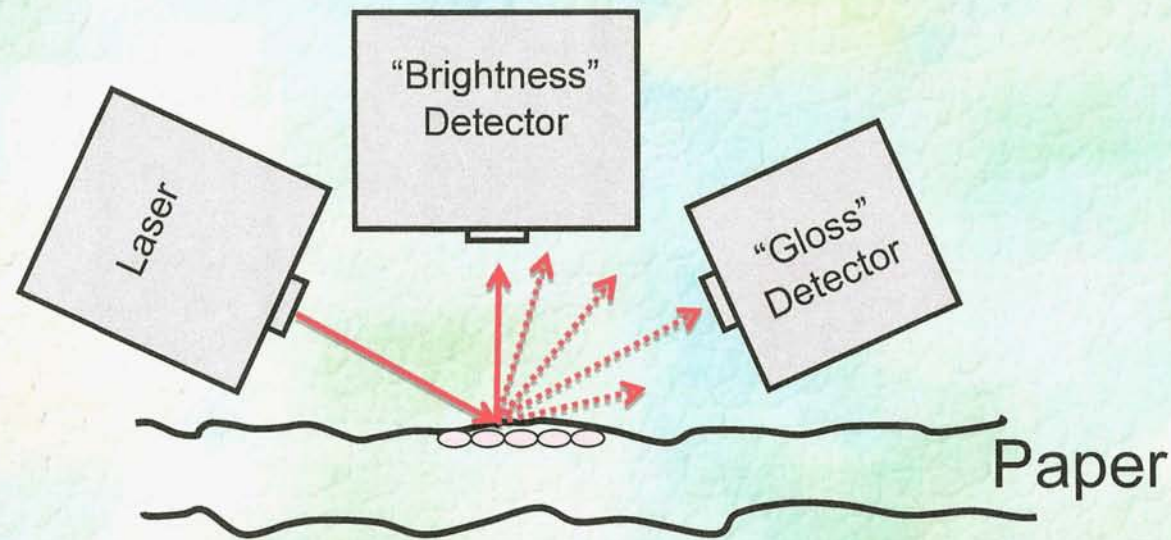
Surface Fiber Orientation Measurement



Measurement Footprint

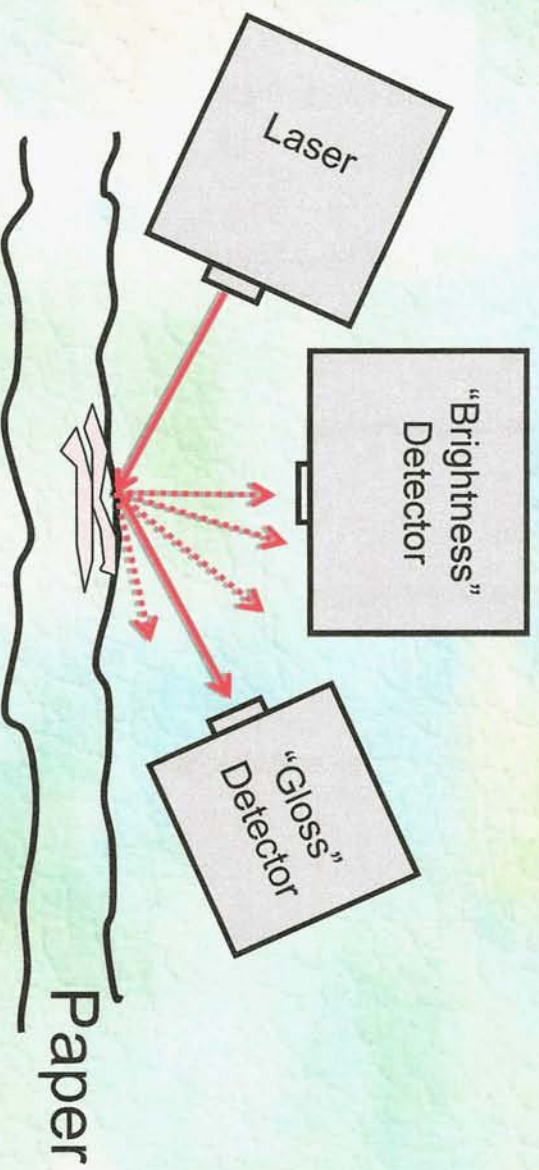


“Brightness” Detector Responds More to Cross-Direction Fibers



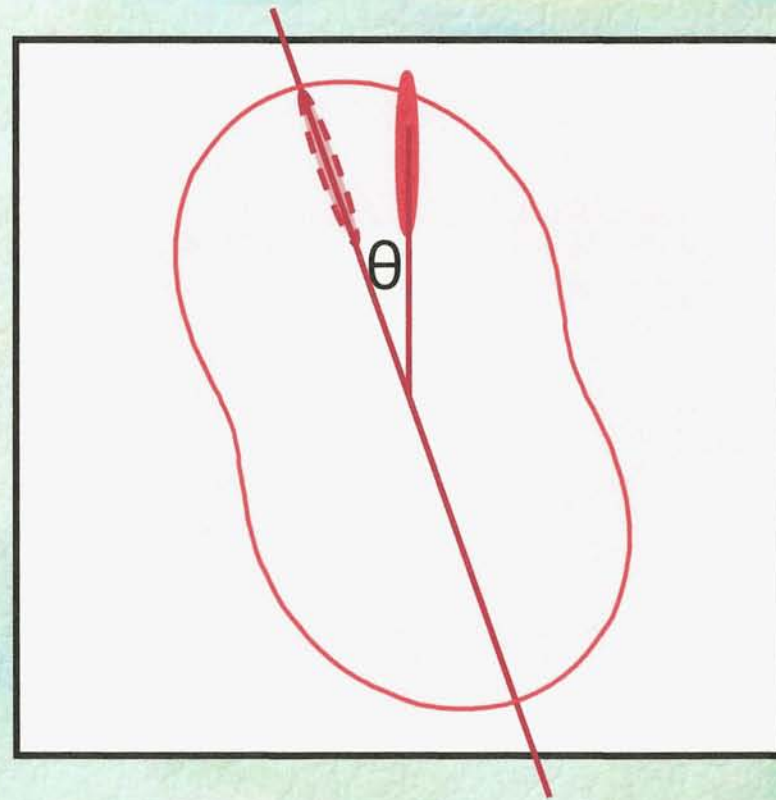
$$V_{\text{Brightness}} \sim \# \text{ CD fibers}$$

“Gloss” Detector Responds More to Machine-Direction Fibers



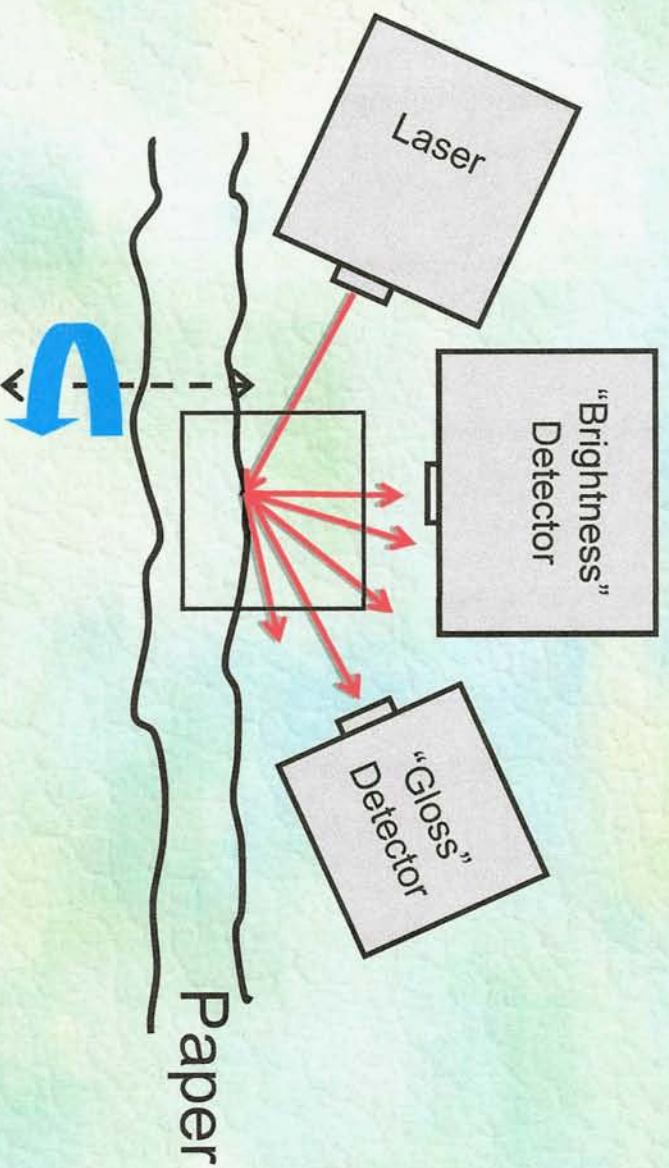
$$V_{\text{Gloss}} \sim \# \text{ MD fibers}$$

Measurement Output



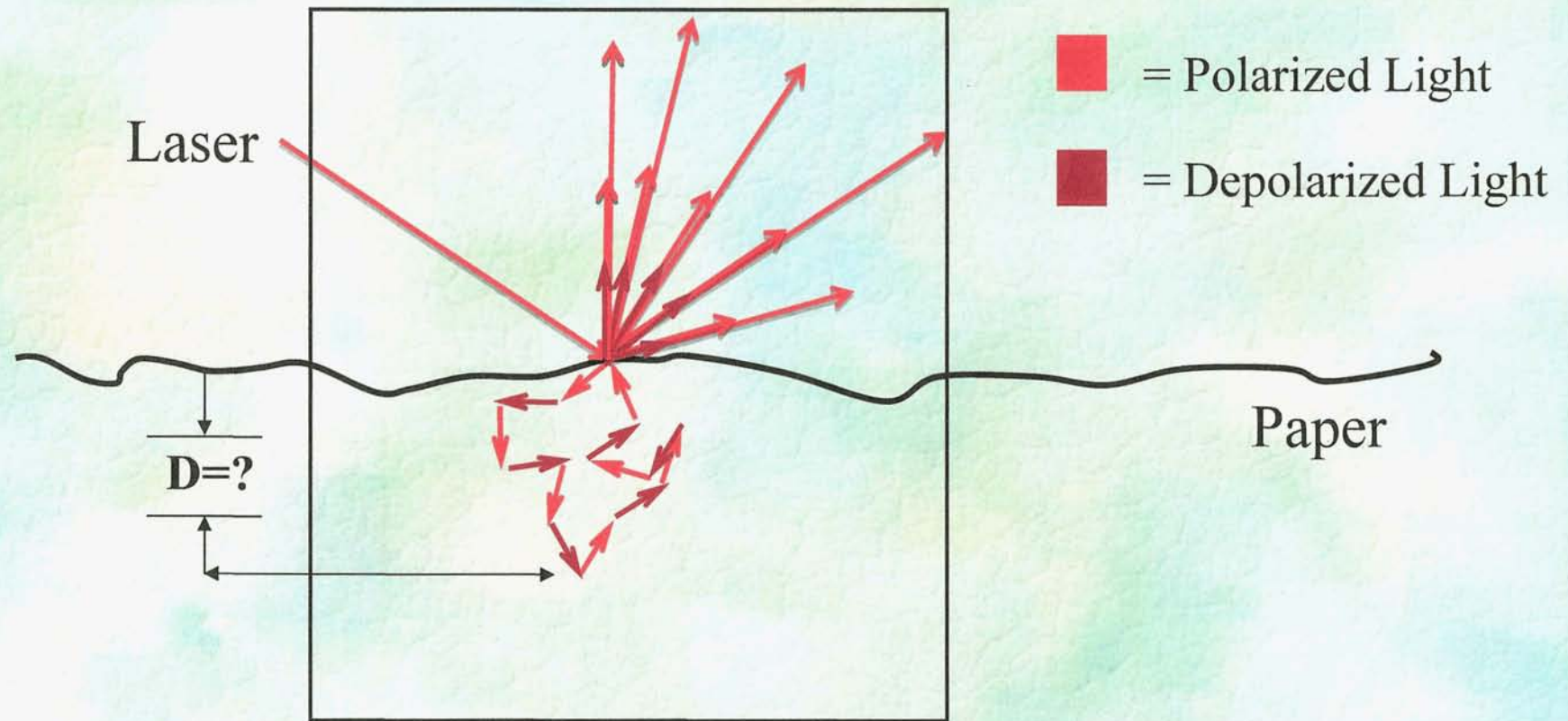
Major Axis indicates MD/CD Fiber Orientation Ratio and Fiber Orientation Angle

Surface Fiber Orientation Measurement in Detail

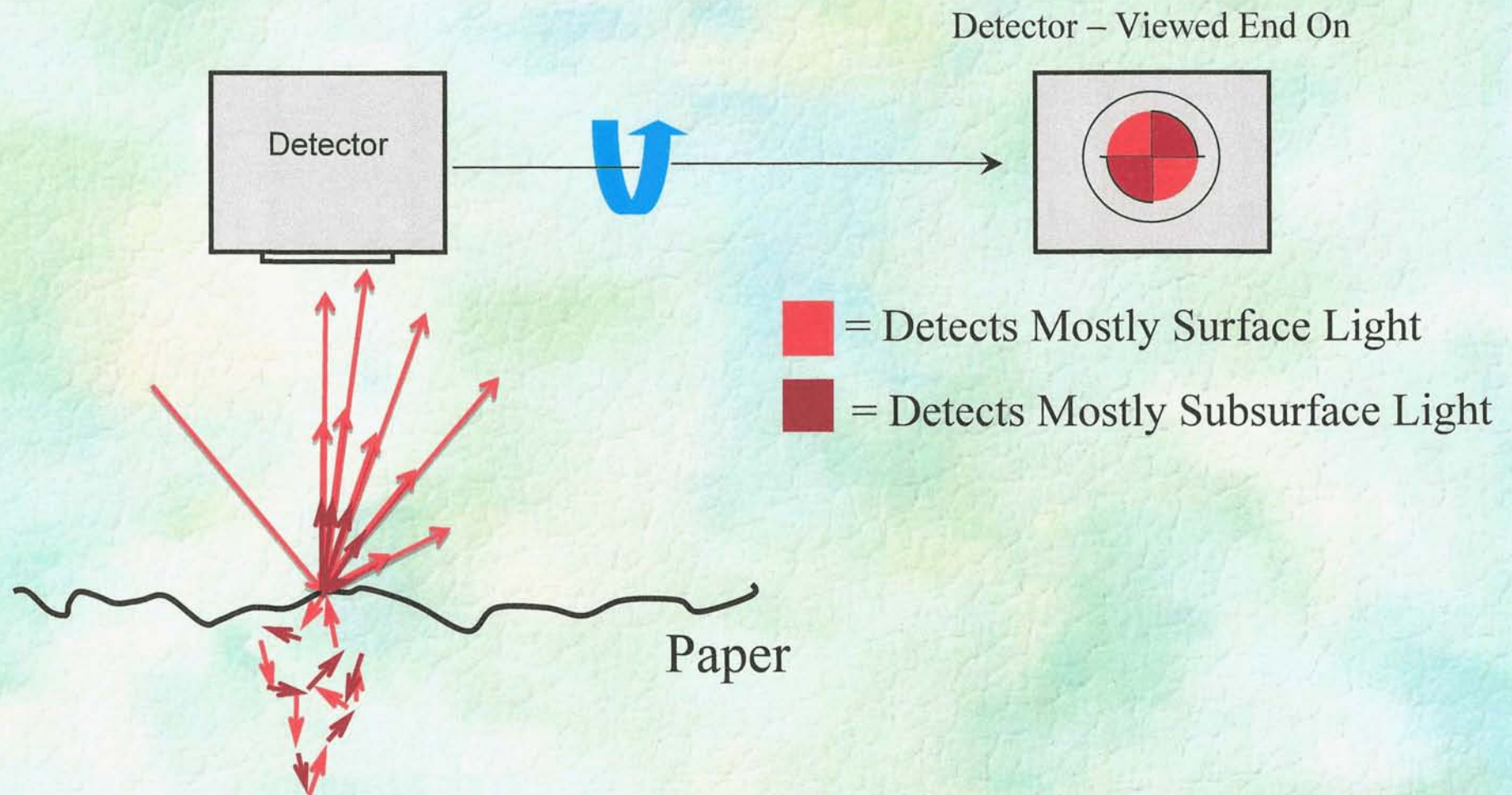


What goes on inside the box?

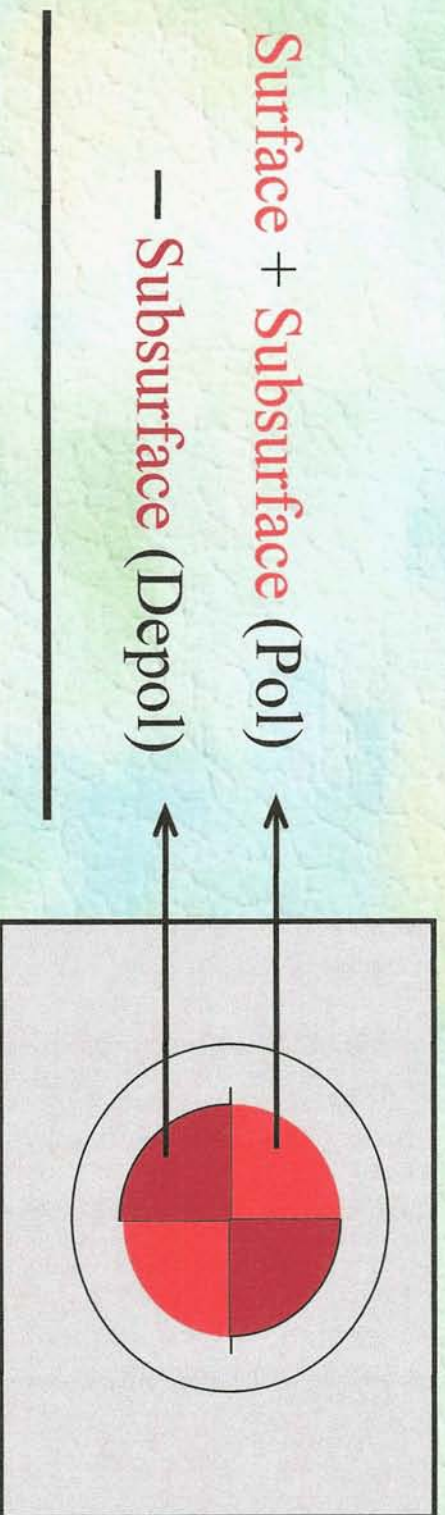
Subsurface Light Scattering



Quadrant Light Detectors with Polarizers



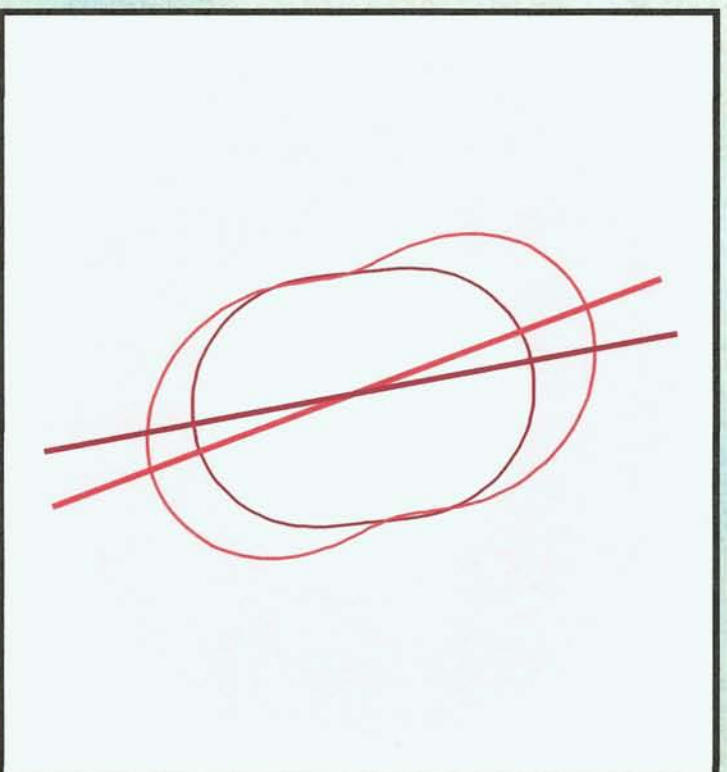
Processing Detector Voltages



$$\begin{aligned} &= \text{Surface} + \cancel{\text{Subsurface (Pol)}} - \cancel{\text{Subsurface (Depol)}} \\ &= \text{Surface Signal Only!} \end{aligned}$$

Or Process Subsurface Signal Only!

Surface and Subsurface Fiber Orientation Measurements



= Surface

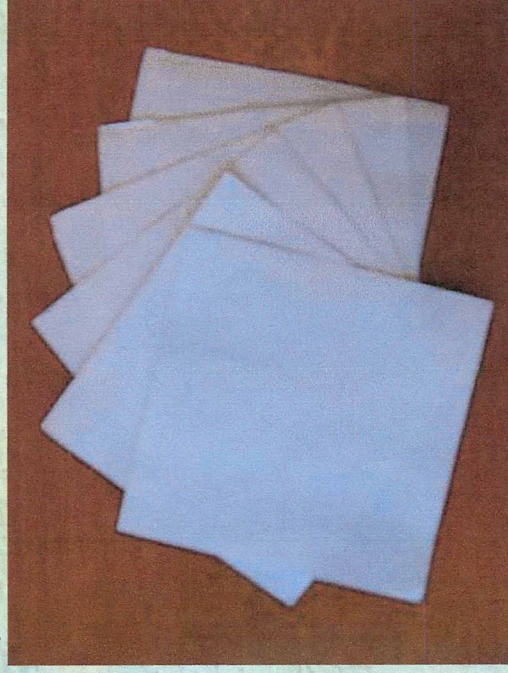
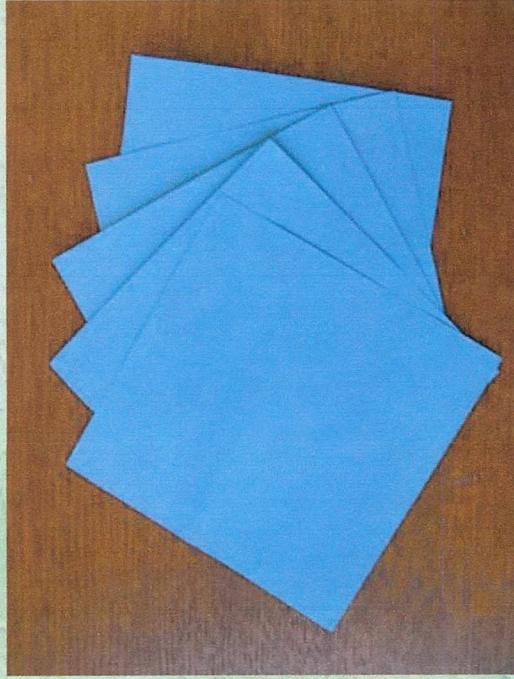


= Subsurface

Samples

- Fourdrinier Machines – Two Mills
- Blue Copy Papers
 - 5 reels from 12 hour span
 - 1 reel strip from each reel sampled at 8 cross-machine positions (40 specimens)
- White Office Papers
 - 3 reels each of 79 and 89 gsm grammage
 - 1 reel strip from each reel sampled twice at 5 cross-machine positions (60 specimens)

Samples Representative of One Cross-Machine Position

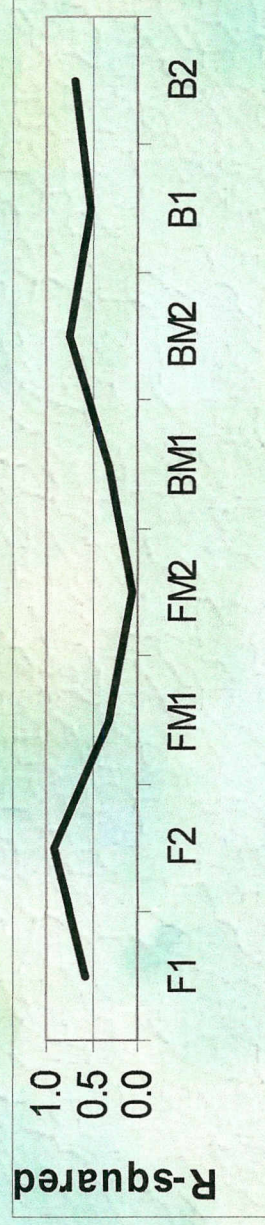
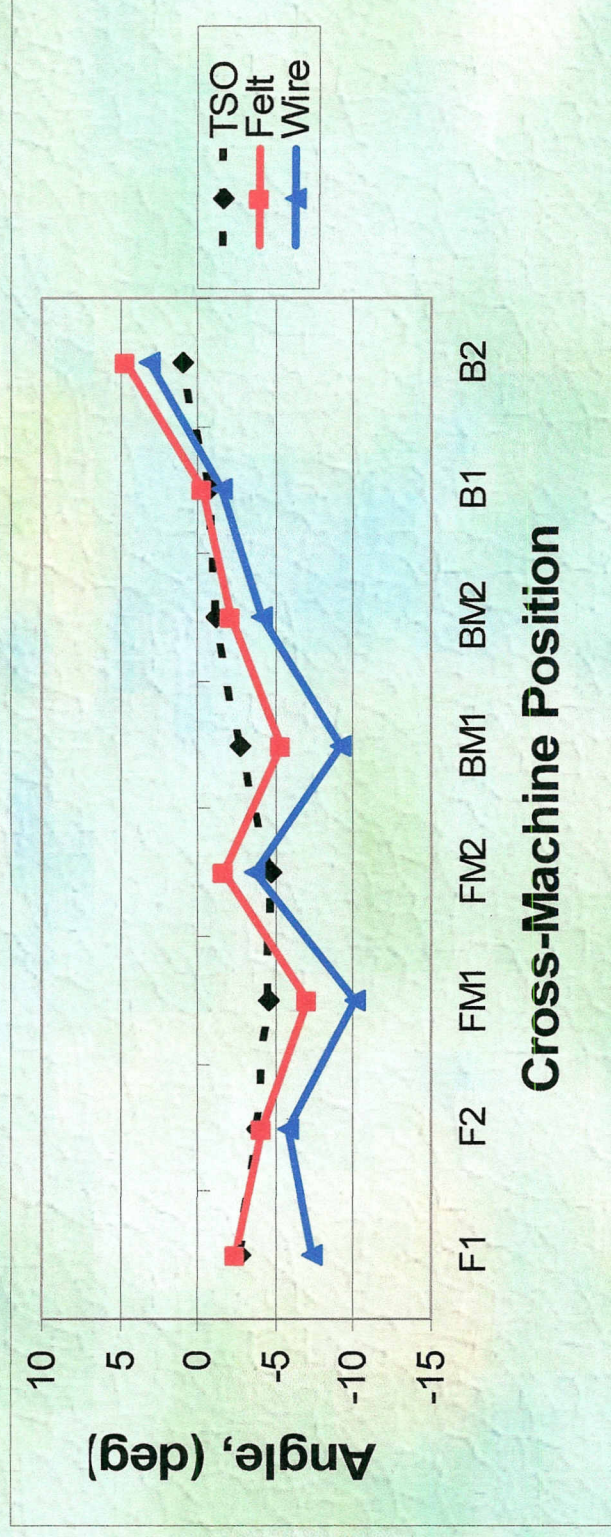


Blue Copy Papers (top left)

79 gsm Office Papers (top right)

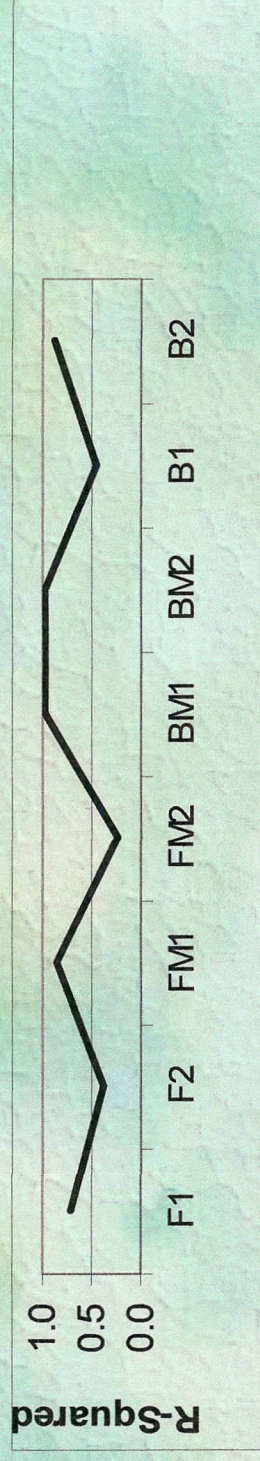
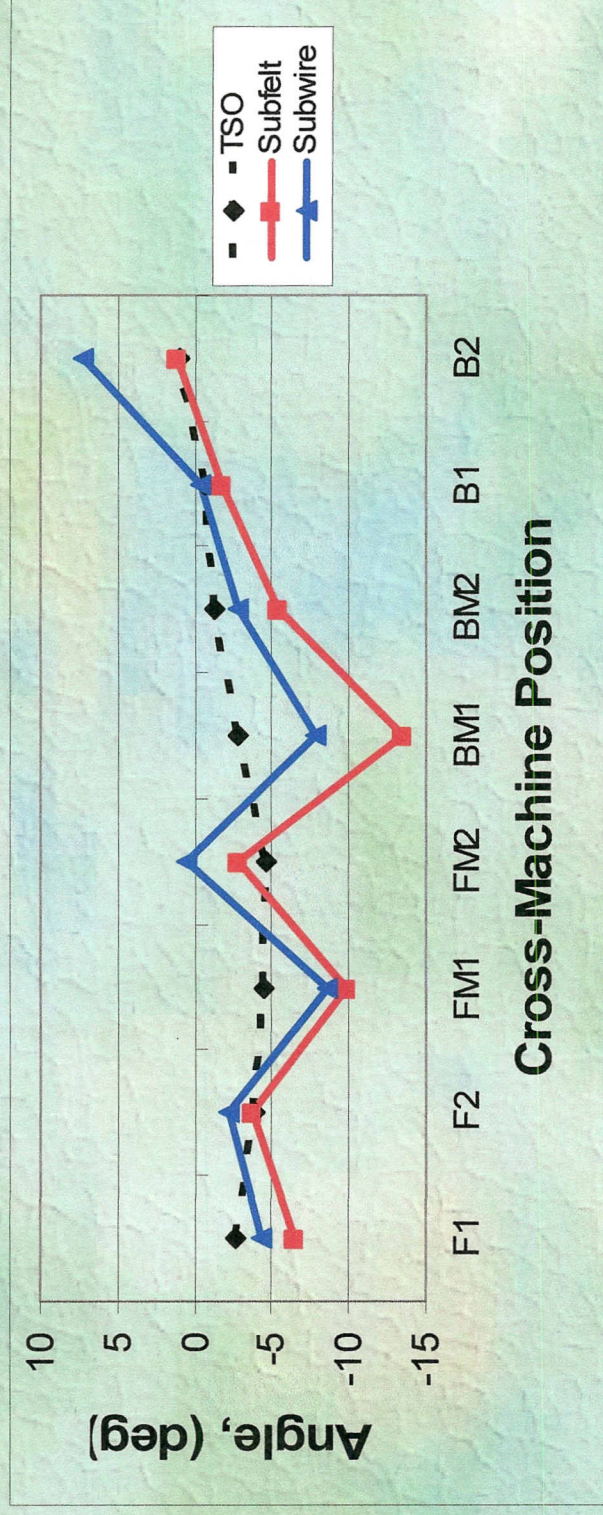
89 gsm Office Papers (lower left)

Blue Copy Paper: Surface Angles



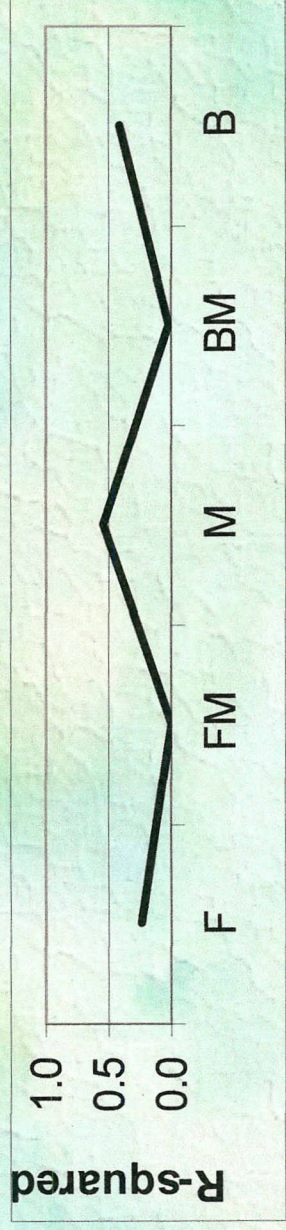
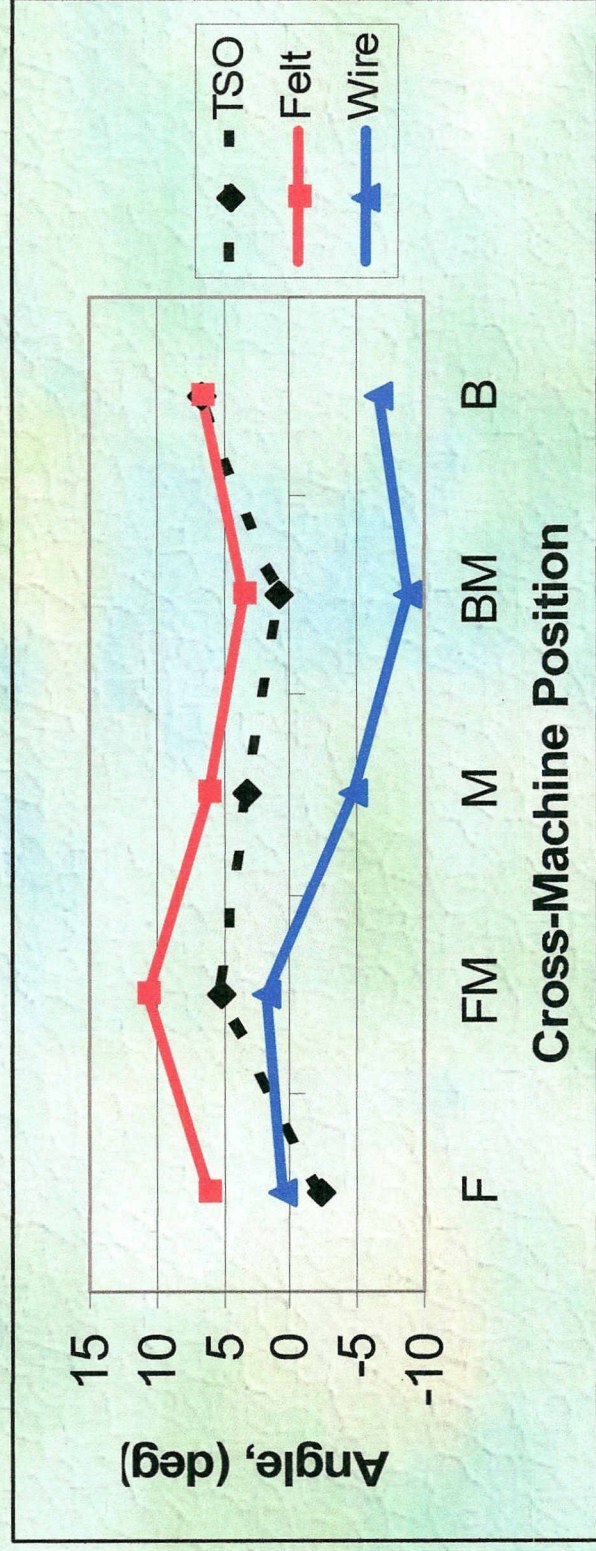
Results of Regression Analysis for 5 Felt and 5 Wire Values at Each Position

Blue Copy Paper: Subsurface Angles



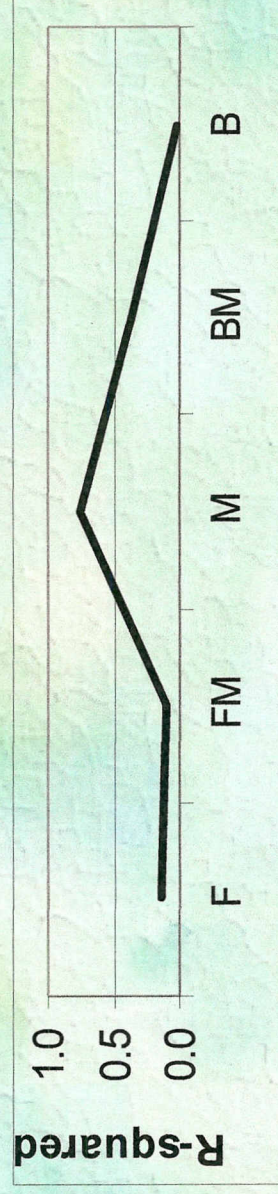
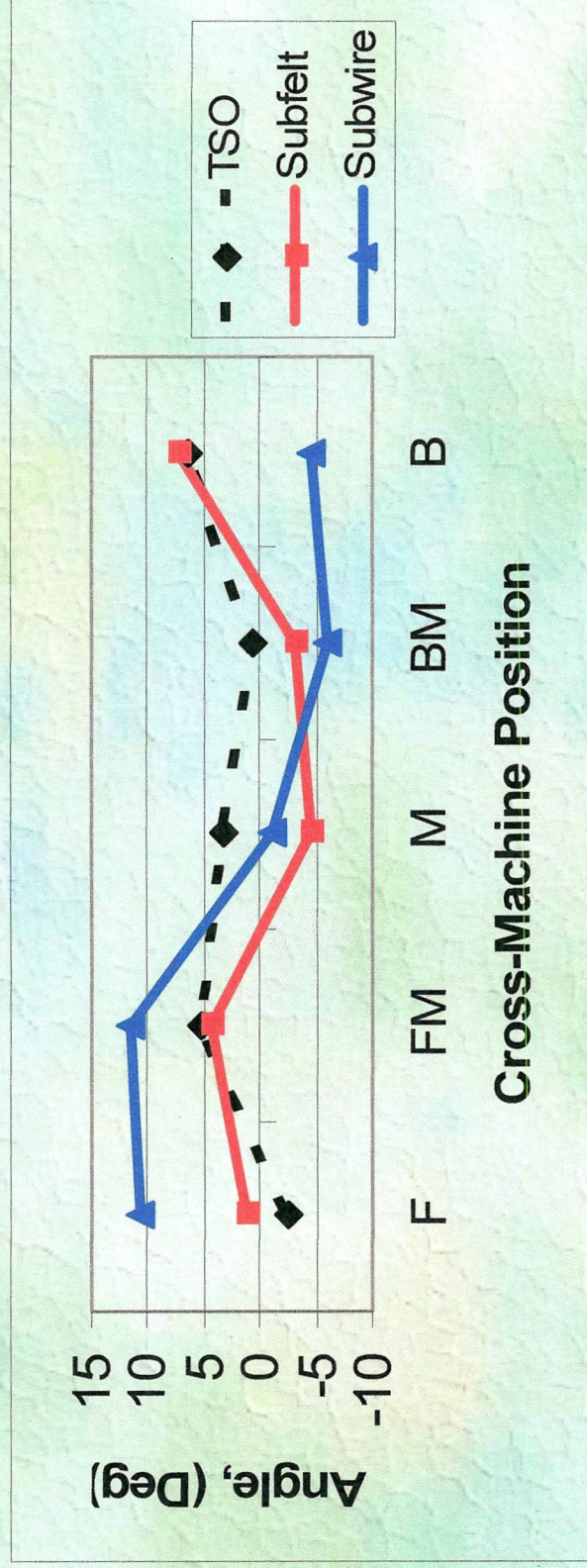
Results of Regression Analysis for 5 Subfelt and 5 Subwire Values at Each Position

79 gsm Office Paper: Surface Angles



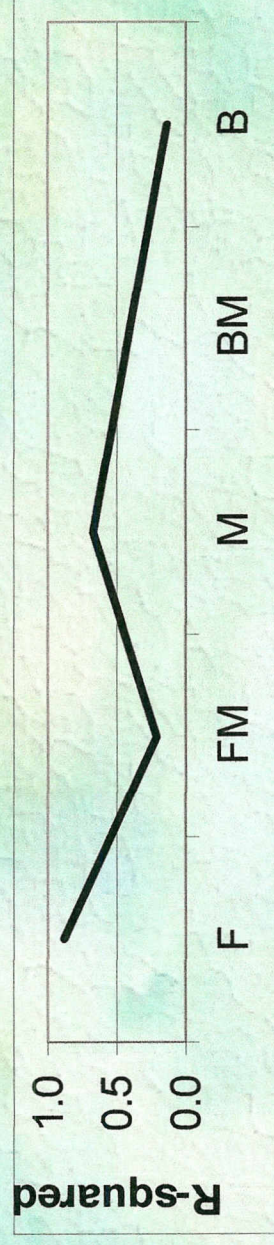
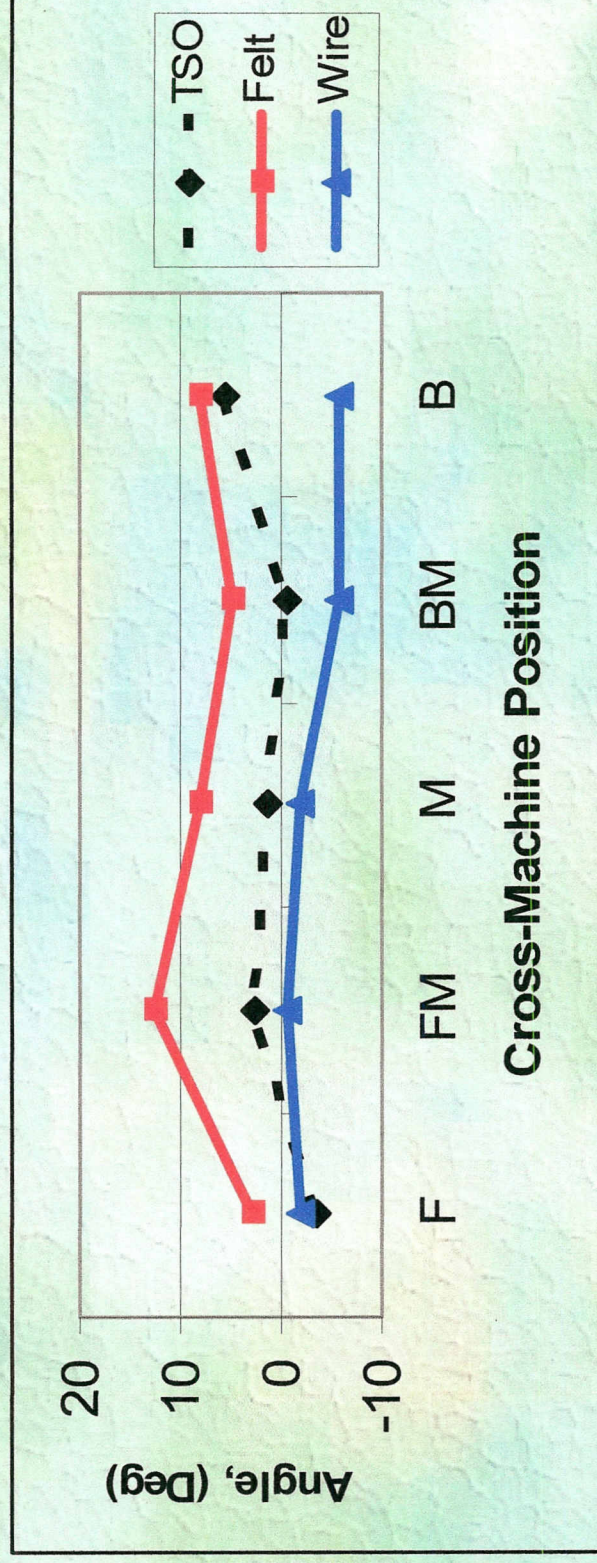
Results of Regression Analysis for 6 Felt and 6 Wire Values at Each Position

79 gsm Office Paper: Subsurface Angles



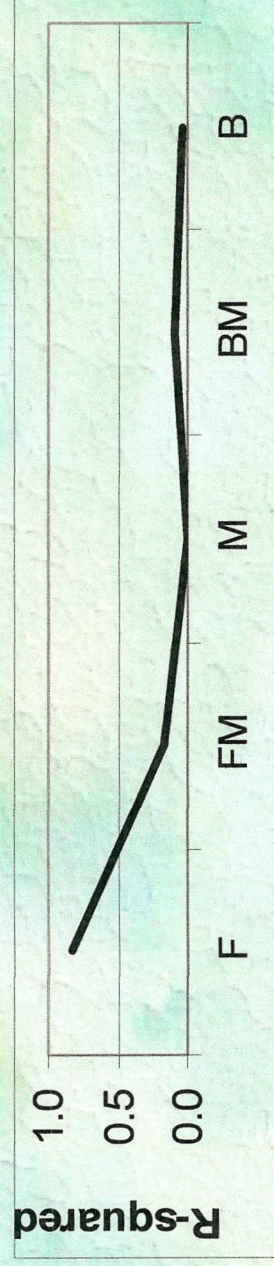
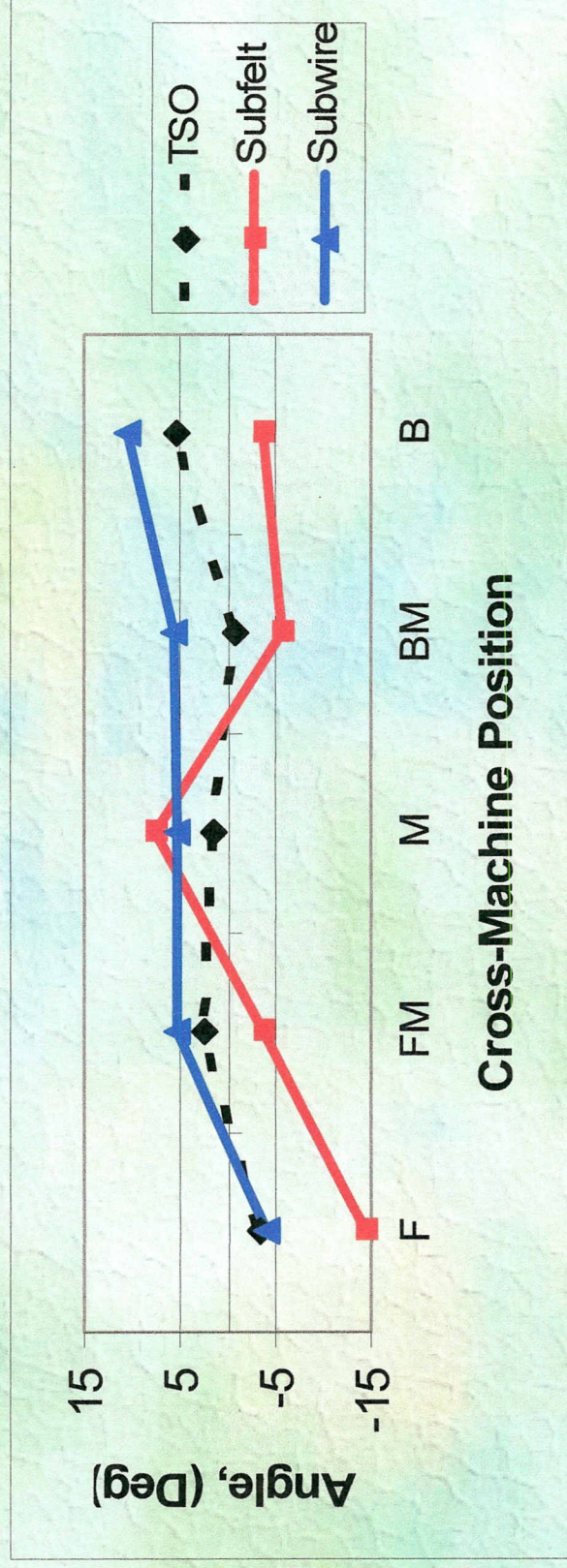
Results of Regression Analysis for 6 Subfelt and 6 Subwire Values at Each Position

89 gsm Office Paper: Surface Angles



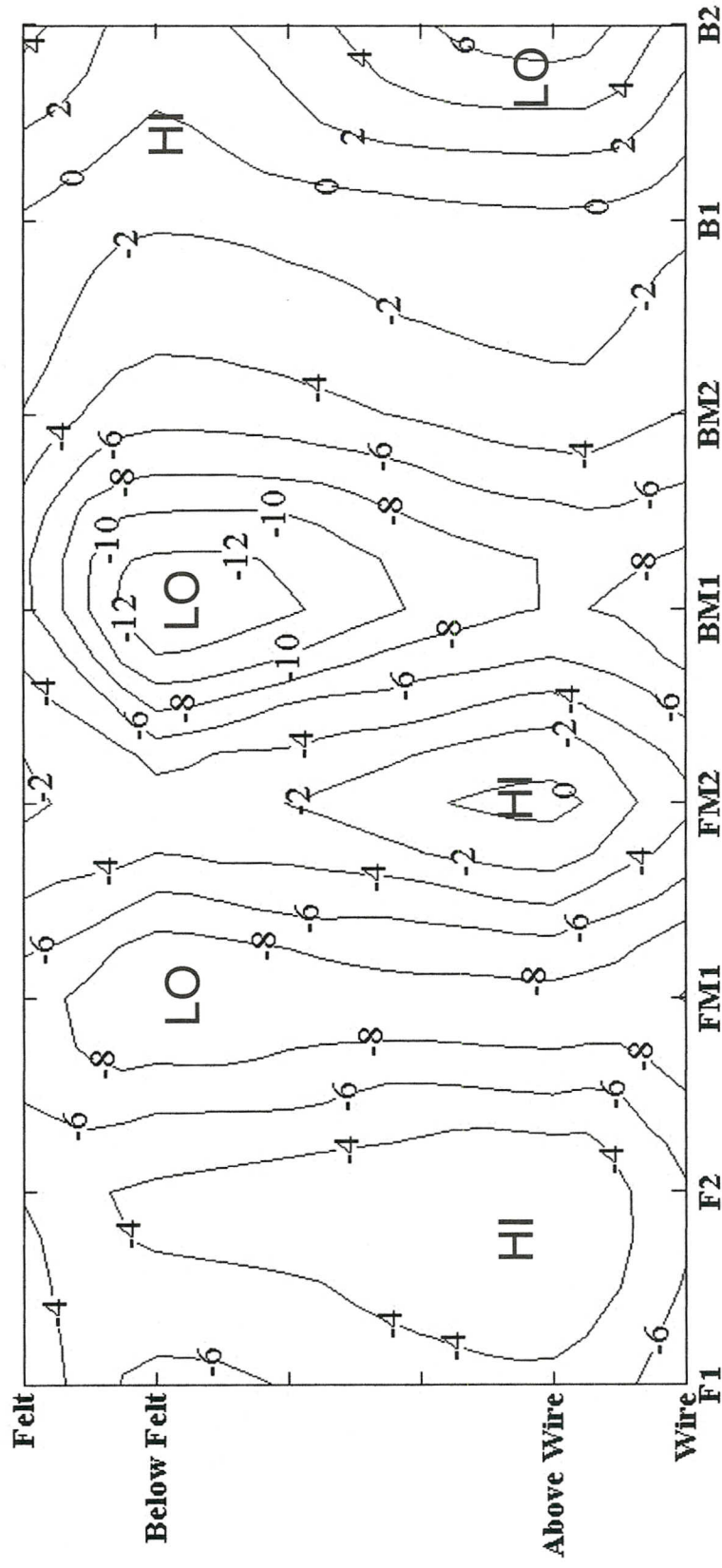
Results of Regression Analysis for 6 Felt and 6 Wire Values at Each Position

89 gsm Office Paper: Subsurface Angles



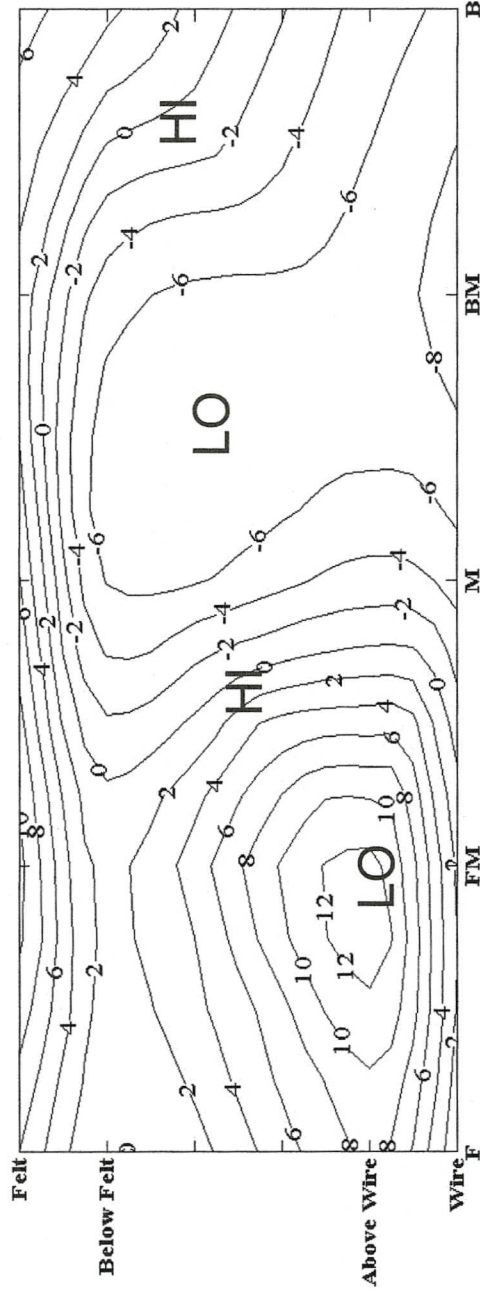
Results of Regression Analysis for 6 Subfelt and 6 Subwire Values at Each Position

Blue Copy Paper: Angle Contours

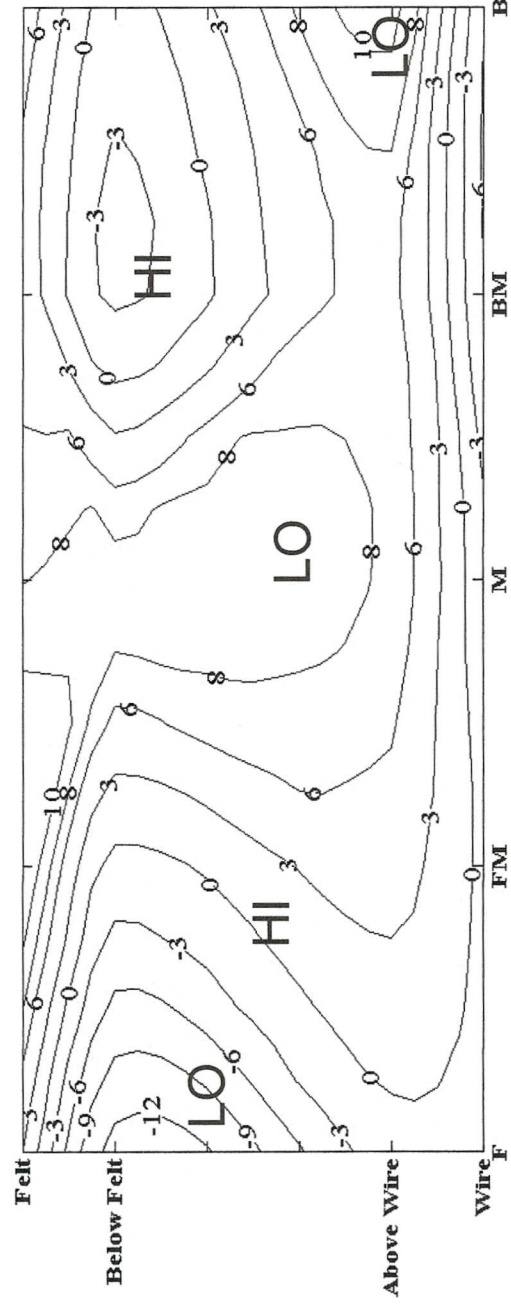


HI and LO indicate proposed regions of high and low sheet density.

Office Paper: Angle Contours



79 gsm



89 gsm

Conclusions

- Optical Measurement of Fiber Orientation is Strongly Influenced by Light Polarization
- The Hypothesis that Depolarized Light Can be Used to Measure Subsurface Fiber Orientation is Speculative
- However, Application of the Hypothesis to Commercial Papers Leads to a Broad Range of Supportive Results that Encourages Further Investigation

Next Steps

- Produce Sheets with Known Fiber Orientation Variation in the z-Direction
- Measure the Sheets Using Depolarized Light to Characterize
 - The Correlation between Measured and Actual Fiber Orientation Angle and Anisotropy Ratio
 - The Range of Depths Spanned by the Measurement
 - Factors (such as smoothness, density or color) that May Influence the Accuracy of the Measurement

Acknowledgements

- Mark Scotch and Andy Kahra of L&W for Mill Interface and Technical Support
- Un-named but Appreciated Mills for Providing Samples
- Dennis Crawshaw and Matt Bovee of International Paper for Providing the Surface Fiber Orientation Tester
- Ake Hellstrom of ABB for Thought-Provoking Discussion

Vahey DW, Considine, JM 2008. Surface and Subsurface Fiber Orientation Angle Measurements in Three Office Papers, In: Proceedings, PaperCon'08 TAPPI/Pima Conference and Trade Show, May 4-9, Dallas, Texas, Talk 32.2.