THE WAVELENGTH DEPENDENCE OF TRANSMITTED LIGHT FORMATION MEASUREMENT

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ABSTRACT

The point-to point intensity contrast produced in transmitted light by the mass distribution in paper is known to vary with the wavelength of the incident light. Perceived "look-through formation" requires matching the colour response of the formation measuring instrument to that of the eye. Since the range in the coefficient of variation of transmitted light in commercial newsprints is only a few percent, the instrumental sensitivity has to be maximized to discern changes in process variables. This can be done by using short wavelength incident light and optimizing the spatial and temporal response for on-line instruments. Examples are drawn from practical adaptations of on-line and off-line video formation measurements, comparison with radiographic results and paper machine performance.

INTRODUCTION

The measurement of product quality is central to a company that manufactures a product. The uniformity of paper, commonly referred to as the "formation" of paper is an acknowledged fundamental descriptor of the quality of a sheet since it refers to the areal mass distribution of paper and ultimately all end use properties are dependent on the degree of the variation of the mass of the sheet. For example, fracture toughness is formation dependent [1] and more well known is the dependence of print mottle on the severity of formation [2,3,4].

Traditionally, many measurements made in the pulp and paper industry are made by visual subjective means, probably out of convenience. This includes holding paper to a light source to examine the "look through". Historically, many paper machines were optimized for jet to wire speed ratios, vacuum levels, wire tensions etc., using visual subjective evaluation of the paper sheet. Small changes in formation were considered to be more readily and reliably detectable by "expert" eyes than by using formation measuring instruments. It is clearly difficult, if not impossible, to routinely optimize a papermaking process and maintain day to day quality control based on such highly variable and subjective evaluations. Competitiveness is attained only when nebulous quality parameters can be quantified in a reliable fashion. The concern of this paper is the proper measurement technique for formation with sufficient sensitivity for quality control use particularly for the current range of formation encountered in commercial printing papers.

A variety of formation testers based on visible light transmission have come and gone during the last sixty years [5,6,7]. These are based on the idea to provide a quantitative value to the non-uniformity that is perceived visually. The variations in the transmitted light provide an indirect indication of the variation of the basis weight through the well-known Lambert-Beer relation:

$$I(x,y) = I_0 \exp - (\mu_\omega * \omega_{x,y}) \qquad (1)$$

where μ_ω is an effective absorption coefficient of paper and $\omega_{x,y}$ is the local basis weight at point x,y in the plane of the sheet, I_0 is the intensity of the incident light illuminating the sheet from behind. Unfortunately, for the visible range wavelengths the Lambert-Beer law (1) is only a rough approximation since paper has varying optical properties which affect the effective absorption coefficient μ_ω significantly [8]. For example, the machine calendering of paper from a typical initial density of 0.5 g/cm^3 to a commercial density of 0.65 g/cm^3 will lower the variation in transmitted light intensity by 40%.

Other process manufacturing variables affect μ_ω as well. The amount of fines or the addition of clay or other filler material will usually serve to diffusely scatter light thus masking the mass variations of paper. The addition of dyes or brightened furnish components are also known to seriously affect the relationship between the transmittance of white light

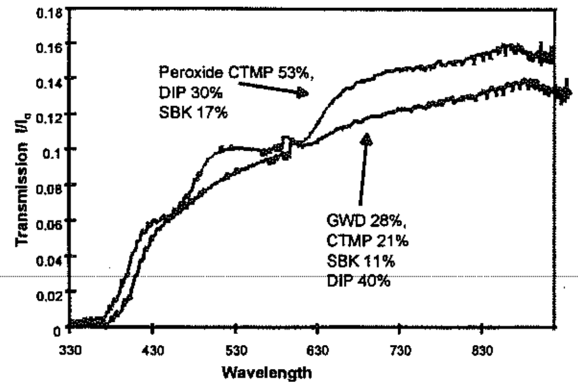

Figure 1. Transmission through 36 gsm TD sheets of different furnishes.

and basis weight. Figure 1 for example, shows the spectral transmission characteristics through 36 gsm telephone directory papers produced on the same paper machine but with different furnishes. In this case, the inclusion of peroxide brightened pulp is attributed to increase the transmission of light through the sheet.

WAVELENGTH DEPENDENCE OF THE KUBELKA-MUNK EQUATION

The interaction of visible light and paper is more rigorously and commonly described by the Kubelka-Munk equation:

$$D = \log (b/a) + aW \qquad (2)$$

where D is the optical density defined in terms of the percentage transmission T by $D = \log(1/T)$ and

$$a = (k(k+2s))^{1/2}$$

and $b = (k + s)$ where k is the absorption coefficient and s is the scattering coefficient. Therefore, if the scattering and absorption coefficients remain constant, the formation defined as the areal variation in optical transmission, is related to the mass density. As can be expected, small particulate matter such as clay fines or chalk fillers scatter more in the blue end of the spectrum. The lignin content in mechanical pulps affects the absorption coefficient k such that it is 50 times greater in blue region than in the NIR [9]. In reference 9, Figure 15 shows the absorption coefficient spectrum for newsprint and Figure 11 shows the scattering coefficient spectrum which shows a comparatively modest 20% increase from the NIR to the blue 400 nm region of the spectrum.

The wavelength dependence of the absorption coefficient is attributed to the lignin chromophores [10]. Therefore, to have the optimum sensitivity, a formation tester based on light transmission would preferably have a high blue response.

Inverting the Kubelka-Munk equation for the transmission produces the useful form:

$$T = a/b * e^{-2.303(aW)} \qquad (3)$$

which is reminiscent of the Lambert-Beer law. The following considerations are illustrative. For example, at 700 nm, deep red wavelengths, $k = 1$ m^2/kg, $s = 55$ m^2/kg and for a typical basis weight of 48.8×10^{-3} kg/m^2 the transmission is 8 %. If however, the wavelength of interest become 440 nm, one of the prominent lines of the Hg spectrum, then $k = 11$ m^2/kg and $s = 58$ m^2/kg and the transmission decreases to 0.6 % a factor of 12. Thus a mechanical pulp paper is an effective red band pass filter, hence its inherent brownish appearance often ameliorated somewhat by the addition of blue dyes.

Moreover, the wavelength sensitivity from the definition of transmission $T = I/I_o$, through differentiation of expression (3) with respect to the basis weight shows:

$$dI/dW \propto a(\lambda)I \qquad (4)$$

so that $a(\lambda)$ is 3.7 times greater at 440 nm than at 700 nm. The high sensitivity and low transmission at blue wavelengths for lignin containing papers is particularly significant for those formation testers that rely on incandescent filament light sources and Si photodetectors (photodiodes). The response of such a light source detector system may be expressed as:

$$I(\lambda) = \int_{\lambda i}^{\lambda f} I_o(\lambda,\lambda_o)R(\lambda,\lambda_o)T(\lambda)\, d\lambda$$

where the integration is over the white light spectral range of the light source emission with center wavelength λ_o, $R(\lambda,\lambda_o)$ is the wavelength response of the detector and $T(\lambda)$ is expression (3). Most common incandescent light bulbs have colour temperature of 2000 - 3000 ° K so that by the Wien displacement law, λ_o for an incandescent source may be taken to be as:

$$2.90 \times 10^{-3}\ (m)/T\ (°K) \approx 1450 - 967\ nm$$

which is the near infra-red. The response of a GaAs Si or Ge based photodiode peaks at 800 nm, 900 nm and 1050 nm respectively [11]. Photoconductive CdS or CdSe cells have responses in the visible regions but have unacceptable long time responses in tens of milliseconds and their output is also temperature sensitive. Photomultiplier tubes are a bulky and expensive alternative to photodiodes and are rarely selected as photodetector elements in analogue instruments.

EFFECT OF FINES, FILLERS, BLEACHING, YELLOWING

The wavelength effect of the presence of fillers on the formation measurement is expected to be small. Following the Lepoutre et al. [12] confirmation of the dependence found by Gate:

$$s = \alpha\lambda^{-\beta}$$

here β is a function proportional to the microvoid size and α is a constant. However, the power law is quite weak for $CaCO_3$ and clay fillers as was shown by Lepoutre for highly (26 - 30 %) filled sheets. In general, it is expected that the presence of fillers should contribute to the diffuse scattering of light thus masking the variations in transmitted light intensity. Fines are higher in both s and k, however, their distribution throughout the sheet is considered to be homogeneous [13,14] thereby causing a diffusing masking effect of the floc structure.

The differential chromatic influences are affected by the amount and degree of bleaching. In practice, the most profound effect to date has been the effect or peroxide brightening which causes an increase in the green reflectivity of the sheet and in turn, the relative green band transmittance. From the preceding discussion, the increase in blue-green wavelength transmission also results in an apparent improvement in the look-though formation. This effect has been quantified at MacMillan Bloedel Research through a systematic study of specially prepared handsheets of varying brightness produced through either dye addition or mixing bleached with unbleached pulp in various proportions. The effect can be quantified by a linear relation between the CIE L* value measured on a suitable spectrocolorimeter and the decrease in the measured look-through formation. Therefore, direct comparisons of look-through formation should only be made between papers of similar L* value. The optical effects were ascertained to be the cause of changes in look-through formation in the handsheet study by radiographic C^{14} beta transmission formation measurements of the handsheets. All dyed and peroxide brightened handsheets in this study had the identical mass variation confirmed by radiographic scanning measurements.

The effect of yellowing has been quantified in a similar fashion. Newsprint samples were exposed to varying amounts of xenon arc UV light in a fadeometer to drop the brightness. The drop in brightness measured by an Elrepho meter was found to correlate linearly with an increase in the look-through formation.

Therefore, the effect of brightness increase in to decrease the look-through formation through an increase in the blue-green transmission and has been quantified by the increase in L*. Increase in yellowing results in an increase in the look-through formation, correlated to the decrease in Elrepho measured brightness. The effects of bleaching and yellowing on light based video formation measurements are summarized in the table below.

Table 1. Yellowing and bleaching effects.

	MEASUREMENT	EFFECT	FORMATION #
Yellowing	Elrepho brightness	decreases	increases
Bleaching	L*	increases	decreases

APPLICATION : VIDEO BASED FORMATION

As mentioned previously, there have been numerous attempts at quantifying the variation of visible light transmittance through paper [5,6,7]. These have been largely single point scanners that processed the detected transmitted light intensity through signal filters to determine the frequency components of the transmitted light intensity. This remains to this day, the simplest method of measuring the formation of moving paper in production as it requires the least sophistication in technology and so is used in several commercial on-line production sensors.

For static sheet measurements in the test laboratory, it is preferable to have the scanning performed electronically rather than mechanically. A CCD video camera is ideally suited for this purpose. The advent of commercially available image analysis hardware and software in the late 1980's has made this task simpler to implement. In this arrangement, a sample is placed over a light table, the transmitted light is imaged by a CCD video camera whose output is sent to a video digitizer and the variation in the transmitted light is calculated by the microcomputer. The MacMillan Bloedel Research (MBR) embodiment of this concept has an 8.5 x 11 " area illuminated by a bank of fluorescent lamps behind a white Plexiglas screen acting as a diffuser.

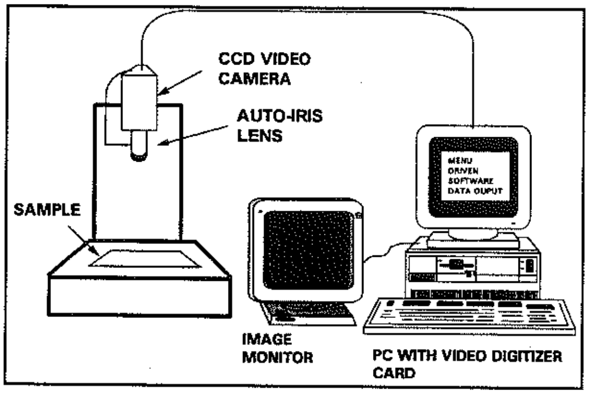

Figure 2 Schematic of the lay-out of the video formation tester.

Interestingly, it was discovered that fluorescent lamps have a significant time variable output that is influenced by vibration and temperature gradients. These variations are imperceptible to the eye but are of sufficient intensity to mask the small variation in transmitted light through a typical commercial newsprint sheet. Therefore the captured transmitted light image I(x,y) has to be processed through a digital filter to remove the low frequency variations caused by the uncontrollable variations in the fluorescent tube light output. For a 512 x 480 pixel resolution, a kernel of 30 x 30 pixels was determined to be sufficient to be used as a high pass filter to remove the time variant fluctuations of the 13 watt fluorescent tubes in the light bank. Therefore floc structures of the order of 60 pixels or 1.6 cm are smoothed from the image by necessity. The matrix kernel high pass spatial filter operation consists of comparing each pixel intensity of the original digitized image with its 899 nearest neighbours and replacing that pixel's intensity with the weighted difference in intensity normalized to the average intensity for the image, a common image analysis technique available on many commercial image analysis packages available nowadays.

A Pulnix [14] TM-C7 CCD video camera was selected which has a peaked response in the 550 nm region to match the response of the human eye.

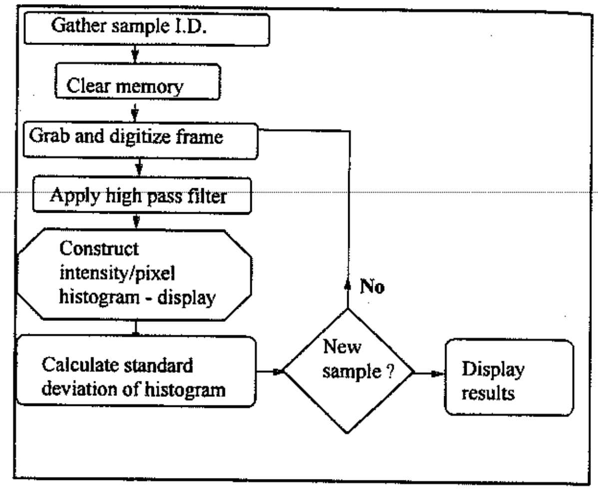

Figure 3 Algorithm for the video formation tester software.

The response of the system coupled with the spectrum of fluorescent tube bank is thereby biased to the blue green region. The electronic gain of the video frame-grabber digitizer board is set to maximum gain by software. The mean light intensity reaching the video camera is maintained to be constant at the center of the linear range of the camera by an auto-iris lens. Maintaining the intensity to be constant allows a measure of the variance of transmitted light levels irrespective of the basis weight of the sample on the light table. This is analogous to increasing the electronic gain to maintain the dc level constant which is the more common practice in single point detector instruments.

Removing the effect of the mean basis weight can also be achieved by varying the incident light intensity, varying the tranmitted light intensity reaching the detector by an auto-iris, or by varying the electronic gain of the detector to maintain a constant I at the detector. All methods were found in practice to produce an essentially equivalent mean basis weight independence of the video formation measurement. However, a potential disadvantage is suffered if a formation tester varies the incident light intensity of an incandescent lamp by voltage or current control. At lower basis weights, the incident light intensity must be lowered meaning that the colour temperature of the bulb must be reduced and hence a greater part of the lamp emission spectrum will lie in the red/infra-red region.

Verification of the operation of the video formation tester was established through correlation with the visual subjective ranking of a range of commercial newsprints ranging from those produced on fourdriniers to those produced on Vertiformer blade formers. The measurement was optimized to produce a range of a factor of two in the output corresponding to good to bad formation. Reliability of the measurement technique was further assured for newsprints by correlation with single point scanning radiographic measurements of the mass standard deviation. A scintillator-photomultiplier detector was used to accumulate point data of the beta transmission of C^{14} beta rays through the newsprint samples. Correlation of the visual method with the radiographic was about 70%.

MEASUREMENT OF WIREMARK AND TEXTURE

A variation of the video formation tester that has been provided is for the measurement of the fine scale structure that is associated with the impressions left on the surface by the drainage through the forming fabrics. Measurement of the severity of this "wiremark" have found utility in evaluating the effect of the replacement of the forming fabrics and their influence on printability. A measurement of the wiremark impression of the sheet is a measure of its two-sidedness. Experimentally, it has been found that the transmitted light formation measured on a scale greater than 1 mm is independent of which side is facing the optical detector. However, when measurements of transmitted light formation are made at a scale of one millimeter and less, the wiremark impression that is on the side facing the detector can be readily perceived and measured as the side facing the light source now acts as a light diffuser.

An established technique to measure wiremark is to employ a two dimensional Fourier analysis of the transmitted light image of paper [16]. Upon close examination of a magnified image of paper, one can see flocs of random size typically of the order of a few millimeters in diameter superimposed upon a regular mesh pattern. This periodic pattern is the "wire mark" and can be readily separated as distinct periodicities in the two dimensional Fourier transform of the transmitted light image of paper. A 2-D Fourier power transform is ordinarily too computationally intensive for a personal computer to perform on a routine measurement basis. Instead, a filtering technique using the concepts used in analogue formation testers has been adopted [5,17].

The wiremark intensity in the transmitted light image is known to be in the range of 1.5 mm to 0.2 mm. Therefore, digital filtering of various spatial size is applied to minimize all features that lie outside the wire mark size range. The 512 x 480 pixel image of a 1.9 x 1.4 cm area of paper is first "blurred" to remove all high frequency artifacts such as pinholes that are smaller in size than 0.2 mm in the image. The blurring operation replaces each pixel of the image by the average of its neighbours using a kernel operation as described previously. A high pass filter is then applied that obliterates the flocs that are larger than 1.5 mm. What remains then is an image where the mesh pattern in the sheet is enhanced. The "wire mark" value reported is the standard deviation of this processed image. The algorithm is depicted in Figure 4.

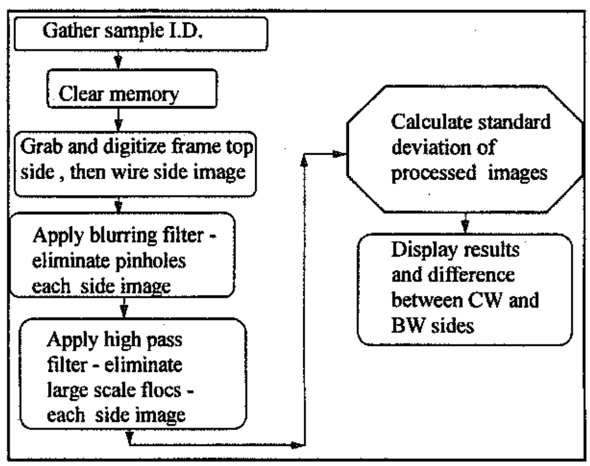

Figure 4. Algorithm for video wiremark measurement.

This feature to measure the "wire mark" has received the greatest utilization in measuring the effect of wire replacement on the paper machine. The drainage wires in the forming section are periodically replaced as a routine maintenance measure. It is the aim of fabric manufacturers to minimize the wire mark impression while optimizing the drainage rate so that this instrument provides a means of quantifying the effects of various fabrics on a paper machine.

Two samples can have the same mass distribution as measured by the variation of transmitted light but still have a different appearance due to the spatial distribution of the mass, i.e., the samples are said to have differing textures. There have been various attempts over the years to quantify variations in texture. A common method is to segment the image areas in a transmitted light image of a paper sample on the basis of their lower transmitted mean light intensity. More specifically, the threshold is set so that one half of the total number of pixels in the image exceed the threshold intensity. The texture is then the measure of the quantity referred to as the specific perimeter [18] SP defined by the relationship:

$$SP = 1/\text{Area of image} \sum^{\text{number of flocs}} \text{Perimeter}$$

were the summation is the total length of the segmented contour. A high SP indicates a fragmented "grainy" texture comprised of many small floc areas , whereas a low SP will characterize a more uniform and even texture.

The SP has been shown mathematically to be related to the mass correlation function, power spectrum and feature size statistics. Moreover, it is the product of the average feature perimeter and the number of features per unit area. Measurements of the specific perimeter of papers has been shown to correlate with increased levels of inking in GFL prints. In this case, a higher level of graininess requires a greater amount of ink to achieve the same neutral density irrespective of the smoothness of the sheet.

Directly related to the specific perimeter is the MBR method of producing a floc map image based on segmentation at an intensity one standard deviation ~~above~~ below the mean. The method is akin to the technique of describing the texture in terms of "textons" [19] where algorithms are devised to describe grey level images in terms of discrete elements. The flocs are actually psychophysical artifacts constructed in part by the Mach-band effect [20] of the retina.

Accordingly, the segmented image at one standard deviation ~~above~~ below the mean intensity has all the flocs interconnected, although the eye perceives the flocs in the grey image as disjoint. Therefore, a sequential process of three pixel erosion-dilations is performed which preserves the segmented feature convexity but separates the "islands". A sample processed binary image of a heavily flocculated fourdrinier paper is shown in Figure 5, note that the flocs are elongated in the machine direction which is from top to bottom.

The floc size distributions are typically of log-normal form, the mean floc size and its standard deviation are produced as outputs for the user. Paper specimens with smaller flocs and narrower distributions are considered to be the preferred textures for print mottle considerations.

ON-LINE FORMATION SENSORS

Laboratory test equipment is used routinely for product quality control however, it is not optimum for process optimization. This is due to the samples used in the bench tests are taken once every ninety minutes or so thus sampling perhaps only 1/60,000 or less of the paper that has been produced in the interim. Paper is produced at a rate of approximately 1000 meters per minute so that a sampling period of once every 90 minutes is hardly statistically

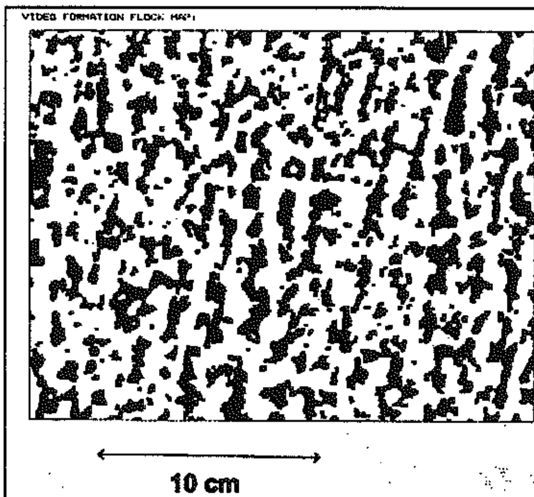

Figure 5. Binary image of segmented flocs for floc size measurement. MD↑.

significant given the variability in the nature of the raw materials that make up paper. It is also preferred to have instantaneous quality feedback during a paper machine optimization trial to avoid the convolution of other concurrent changes such as stock composition variation or changes in refining levels from affecting the results.

Therefore, the video camera technology mentioned previously has been incorporated into an on-line version of the formation tester. Sufficient millimeter scale resolution has to be achieved through stroboscopic imaging of the moving web. Although electronic shuttering of the CCD video camera is possible in principle at the cost of finding a suitably intense continuous light source, this is commonly limited to 1/10,000 of a second which translates to several millimeters in resolution and is unacceptable for sensitive formation measurement.

The CCD array in the video camera is a light intensity integrating device during the blanking period in between its read cycles at 60 Hz. Therefore, a short light pulse can be used for stroboscopic imaging when synchronized so that the flash occurs during the blanking period. In our arrangement, we have used the frame grabbing software to produce a pulse via one of the RS-232 serial port control lines to trigger a xenon-flash tube General Radio Strobolume 1540. Typically xenon flash tubes have a black body colour spectrum of some 7000 °K which is optimum to enhance the contrast of transmitted light intensities as discussed previously.

The strobe lamp is placed underneath the sheet and the video camera is overhead. Due to the dusty, warm and humid environment found at the paper machine, air cooling, air purges as well as a pneumatically controlled wiper had to be incorporated to ensure continuous operation of the sensor.

The on-line formation tester operated in much the same fashion as the off-line formation tester. An image of the moving sheet would be grabbed by the combination of synchronized strobe lamp and video camera and the digitized image processed and analyzed for the standard deviation of transmitted light intensities. The basis weight compensation was adjusted by varying the strobe light intensity through a feedback servo-control of the AC power to the strobe lamp. The main utility and advantage of the on-line formation tester is that it produces a continuous stream of data that indicates the degree of variability of the formation of paper. Correlation of the fluctuations of the formation with other process data through a statistical time series analysis allows operators the opportunity to stabilize the paper machine.

The continuous use of a strobe lamp for the on-line sensor unfortunately required a high degree of maintenance in the environment of the dry end of the paper machine. The video camera and strobe lamp required sealed moisture-proof enclosures with pneumatically actuated window wipers and continuous air cooling. The computer, power supplies, monitors were housed in an NEMA 4/12 cabinet with closed loop air conditioning.

Greater application success was had through the use of a technically simpler single point scanner modified to enhance its sensitivity. In this case, a commercial transmitted light single point formation tester was rebuilt to have a biased response in the blue end of the spectrum.

An NIR cut-off filter with 25% transmission at 650 nm was placed in front of the silicon photodiode. The reduction of the amount of light reaching the

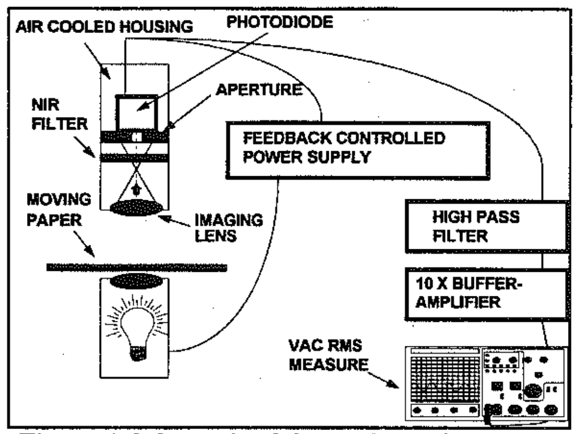

Figure 6. Schematic of the analogue formation tester.

photodetector had to be compensated by increasing the power of the lamp by a factor of five requiring the inclusion of a higher wattage power supply and attendant heat sinks into the circuitry. Spatial and temporal resolution were increased to 20 kHz by the inclusion of a sub-millimeter aperture at the focal plane of the imaging lens in front of the detector and by coupling the photodetector output to a low output impedance buffer amplifier current line driver arrangement. The effect of sheet flutter is minimized by a high pass filter in the electronics with a cut-on frequency of 300 Hz. A schematic diagram of the analogue single point formation tester is shown in the Figure 6.

An example of the application of the on-line single point scanner has been to detect the relatively small incremental changes that occur with the inclusion of various dewatering blades on a twin wire former. In Figure 7, the inclusion of new foil blades is seen to decrease the rms voltage signal by 0.1 volts which is near to the detectable difference limit by visual means.

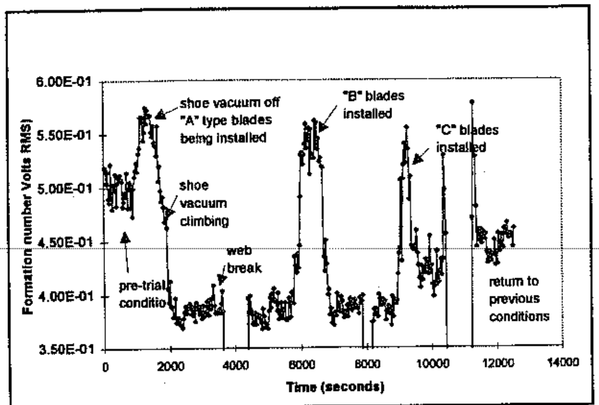

Figure 7. On-line formation trend data showing machine change effects.

The formation is first observed to rise sharply with the decrease in forming shoe vacuum which is required to enable the dewatering blades to be removed. Upon re-establishment of the shoe vacuum after installation of the blades the formation is observed to decrease to levels prior to the trial.

CONCLUSION

The blue weighted absorption of mechanical pulp containing papers must be exploited to produce a usefully sensitive transmitted light formation measurement that is applicable to current quality control and machine optimization programs. The sensitivity of transmitted light formation testers are increased five-fold or more when the detected light is restricted to the blue end of the spectrum.

Applications have been shown incorporating the blue absorption principle in video based formation testing instruments and on-line analogue formation testers.

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