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ESTIMATION OF BASIS WEIGHT OF PAPER: LIGHT TRANSMITTANCE MEASUREMENTS OVER EIGHT ORDERS OF MAGNITUDE OF SPATIAL SCALE

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Abstract – Basis weight of paper web is an important property for quality management, but rather slow and expensive to measure. It is known that light transmittance is related to basis weight and thus a potential means for estimating the basis weight of paper. The basis weight is of interest in quality management from single fibre scale (0.1 mm) to scale of paper machine control effects scale (more than 10 km). This paper studies the relationship between basis weight and light transmittance, and how the relationship changes over the eight orders of spatial scale magnitude. It was noticed that the correlation is best in fairly small scale such that the large scale variations do not change the relationship but white noise in measurement has been filtered out. In paper measurements noise reduction by filtering is powerful because the interesting information is divided over eight orders of scale magnitude. This means that high resolution results can be transformed to lower resolution measurements almost without any noise.

Keywords: measurement, estimation, basis weight, transmittance images

1. INTRODUCTION

The basis weight is the most important single quality property of paper. The interesting basis weight measurement scale in paper making process starts from a single fibre scale (0.1 mm) and ends to control effect scale (more than 10 km in the running direction of the web continuously produced). The basis weight measurement is based on transmittance of beta radiation. Radiation activity achievable and acceptable in mill environment limits the measurement of small scale variations. Therefore high resolution measurements are measured to offline arrangements only. The large scale variation in basis weight can be measured online with a scanning measurement system which traverses across the paper web being manufactured. In such scanning online method the spatial resolution is poor, and only a small portion of the web is covered. Nowadays, fault detector systems based on digital cameras and LED light panels are installed on paper machines. The cameras imaging the web obviously measure light transmittance of paper.

It is known that light transmittance of paper is related to basis weight. This means that the basis weight can be estimated indirectly in all interesting scales from 0,1 mm to 10 km by using light transmittance measurements of paper. However, the relationship between these two paper properties varies over time and products. Therefore the present scanning online basis weight measurement is also needed to update information about the relationship used in estimation.

This paper is organized as follows. In Section 2 the data used in this research is presented. Data is composed of basis weight and light transmittance measurements of paper, and must be pre-processed before the analyses. Section 3 introduces how basis weight and light transmittance are related and shortly describes why the relationship varies over time. The section also discusses how the reduction of resolution is implemented with low pass filtering. The noise reduction method in paper measurements is discussed. Sometimes it is more advantageous to measure the paper with higher resolution and low-pass filter the result to resolution relevant in the application. That way the noise in measurements can be reduced.

A Section 4 reports the results and Section 5 concludes about the usability of light transmittance based basis weight estimation in real-life applications and discusses the generalization of results.

2. THE MEASUREMENTS

The data comprises 1D and 2D basis weight measurements, and 2D light transmittance measurements.

2.1. Measurement arrangements

The 1D data was measured with Tapio paper analyser in the laboratory of Metso Paper Inc.. Paper analyser measures the typical paper properties such as basis weight, gloss, density and ash content while the paper strip moves automatically through the sensors. The speed of paper was 1 m/s in paper analyser. The light transmittance of paper was measured with the commercial fault detector camera system which comprised one VGA camera and one LED light panel. The light panel was on the opposite side of paper to the camera. The size of the LED light panel was 300 mm x

200 mm, and the size of the picture area in pixel was 640 x 224 and in millimetres 160 mm x 56 mm. The camera and light panel were attached to paper analyser and now the basis weight and light transmittance was measured together simulating the online arrangements in paper machine.

The 2D data was also measured in the laboratory of Metso Paper Inc.. The 2D light transmittance was measured with industrial optical scanner. The measurement of 2D basis weight was based on beta radiography method such as the 1D basis weight measurement. The basis weight measurement system comprises planar C^{14} beta radiation source, film for detection, and film reader. The detection film was on the opposite side of paper to the beta radiator, and the amount of beta radiation transmitted through the paper was read from the film. The film is read and digitized with storage phosphor screen (SPS) device. [6] The SPS detection is based on capability of film to transform to an excited state when charged beta particles strike it. The excited state can be released in SPS with laser light. The releasing of state produce photo stimulated luminescence and the intensity of emitted light can be detected with photomultiplier, for example. [6], [10]

2.2. 1D signal

In the first measurement a 25 cm wide (in cross direction of paper machine, CD) and 1500 m long (in machine or running direction, MD) paper strip was measured in machine direction, the values forming a 1D signal. The sample was measured simultaneously with a beta radiation basis weight measurement sensor and with light transmittance camera system.

The raw image data was composed of small VGA images which were pre-processed and connected together before the analysis. The imaging rate in measurements was 20 Hz, so the overlap between the consecutive images was 6 mm. First, the uneven illumination was corrected. The point wise mean from all small images was computed and knowing that the illumination remains during the measurements the mean image was subtracted from all small images. Next, the geometric distortions of images were eliminated. The rotation and skewnesses of camera can be removed with planar projective transform. The projective transform in 2D is determined as follows with homogenous coordinates [7]

$$\begin{bmatrix} x' \\ y' \\ 1 \end{bmatrix} = M \begin{bmatrix} x \\ y \\ 1 \end{bmatrix}, \qquad M = \begin{bmatrix} a & b & c \\ d & e & f \\ g & h & i \end{bmatrix} \tag{1}$$

where (x,y) are the points in the image, (x',y') are the points in the paper, and M is the transformation matrix. The i assumes value 1 [7]. The (1) can be solved to following form

$$\begin{cases} x' = ax + by + c - gxx' - hyx' \\ y' = dx + ey + f - gxy' - hyy' \end{cases} \tag{2}$$

Now we have eight unknowns and two equations. Thus, four corresponding points in image and paper is enough to solve the transformation matrix M. The positions of the corresponding points cannot been determined absolutely, so the coefficients of M are obtained in the least-squares sense from multiple corresponding points. The position of paper was unknown, so also the points (x',y') are unknown. However, the paper position is not required if the transformation matrix is computed based on the corresponding points from overlap area between the consecutive images. The corresponding points determine the transformation, and because the position of camera was not moved during the measurements the transformation is valid for all small images.

Finally, the overlap between the consecutive images was removed. The size of the overlap was determined based on maximizing absolute value of point-wise cross correlation. The point-wise cross correlation were computed all possible shifts between the consecutive images [8]. Now, the small images form a paper strip of size 1500 m in MD and 25 cm in CD.

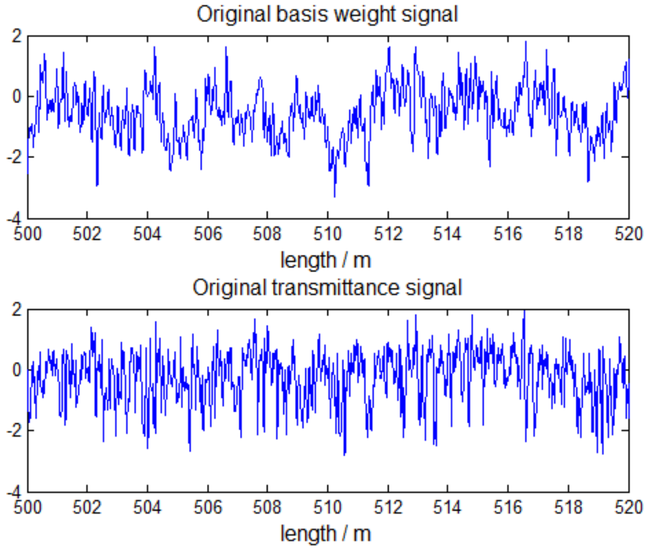

Fig. 1. Figure shows a section of the original aligned 1D signals with full resolution (25.6m m / sample), basis weight and light transmittance. The variation is high and therefore the correlation between the signals is only -0.26.

The size of beta radiation sensor was 150 mm in CD and 15 mm in MD, and the result is one single basis weight value the average of this area. The 2D light transmittance images were transformed to 1D signal by computing the mean value from the areas of 150 mm (CD) x 15 mm (MD) at the same sampling rate as in beta radiation measurement. The resolution for both signals was 25,6 mm/sample. Because the position recordings of the two measurements were separate the measurement signals were aligned before the analyses. The alignment was based on maximizing absolute value of cross correlation with respect to shifts and scales between the signals. Fig. 1 shows the common part of the 1D signals. The mean of both signals has been removed and the variances scaled to 1. The signals correlate negatively so the transmittance signal is multiplied by minus one to see the correlation visually.

2.3. 2D signal

In the second set of sample the 2D images of light transmittance of paper and the 2D basis weight map of paper were measured. The measured paper sheets were 10 cm wide in both CD and MD, and the data was composed of 14 paper sheets. The resolution in these 2D measurements was 0.1 mm/pixel in both directions. The signals were aligned at subpixel resolution before the analyses with the method presented in [4]. Fig. 2 shows 2D signals of one sample with full resolution. Again the mean of both signals was removed and the variance scaled to 1, and the transmittance signal is inverted because of the negative correlation.

The high wavelengths caused by the bending of paper and uneven illumination were filtered out from transmittance images before the analysis. The removing of high wavelengths was based on separate kernel filtering. First, the 1D analog Bessel filter was designed and the filter was conversed to discrete digital filter. In this work the wavelengths higher 20 mm were removed.

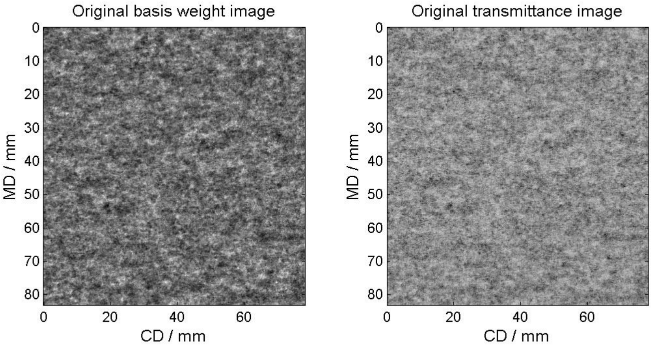

Fig. 2. The original aligned 2D signals of a sample. The resolution is 0.1 mm / pixel, and the correlation between the images is -0.74.

3. THEORETICAL BACKGROUND

This chapter introduces a model between the basis weight and the light transmittance. The phenomenon due to which the relationship changes over time is shortly described. Finally, the method of decreasing the resolution with filter implementation is shown.

3.1. Relation between the basis weight and light transmittance measurements

In this paper the light transmittance of paper is denoted as x(t) and the basis weight value is denoted as y(t). By using these notations the basis weight and light transmittance are assumed to be linearly related as follows

$$y(t) = ax(t) + b \tag{3}$$

where *a* and *b* are parameters which define the transformation from transmittance intensity to basis weight intensity [1]. However, there is always noise in measurements so the measurements of the two properties are denoted as

$$x_{meas}(t) = x(t) + n(t) \tag{4}$$

$$y_{meas}(t) = y(t) + m(t) \tag{5}$$

where *n(t)* and *m(t)* are noises specific for measurements, assumed white. Now, the (3) can be rewritten as follows

$$y_{meas}(t) = a x_{meas}(t) + b + N(t) \tag{6}$$

where *N(t)* is the sum of noises *n(t)* and *m(t)*. This is sufficient transformation function for small scales. However the relationship between the two paper properties varies slowly over time, i.e. in large scale. For example, moisture variations, filler content, color, calandering and many other factors on paper machine and in paper structure can change the relationship, but such changes are typically slow as their causes vary slowly in the production process. Therefore, the parameters *a* and *b* depend on time in manner that is stochastic. If we do not have measurements on all affecting factors the coefficients must be continuously estimated. The stochastic behaviour of parameter *a* can be described as follows

$$a(t + \Delta t) = a(t) + \xi(t) \tag{7}$$

where the $\xi(t)$, a stochastic process, describes the change of parameter *a* over time. In what follows, we assume the stochastic process to be a random walk diffusion. Random walk describes the decreasing of information. In case of normal distribution the expectation value remains the same in following time steps but the variance increases linearly as follows

$$x(t) = N\left(x_0(t), \sigma^2(t)\right) \tag{8}$$

$$x(t + \Delta t) = N\left(x_0(t), \sigma^2(t) + D\Delta t\right) \tag{9}$$

The speed of variance increasing depends on the diffusion parameter D. [9]

The change of parameter *b* can be represented similarly as that of parameter *a*. Section 4 discusses how the relationship between basis weight and light transmittance of paper changes over the eight scale orders of magnitude. Also, the effect of stochastic variation $\xi(t)$ in our test data is studied.

3.2. Reduction of resolution

In this work the 1D signal and the 2D images are low pass filtered to simulate the reduction of resolution in on-line applications that would be based on defect camera data. The 2D signals are filtered with elliptic filter, and 1D signals with a moving average filter. Choosing the elliptic filter is based on small order of the filter, adjustable ripple in pass and stop bands, and sharp edge between the pass and stop band [3]. In this work the ripple in pass band was 0.005 decibels and the minimum attenuation in stop band was 20 decibels. The order of the filter was 6. The elliptic filter is not used with 1D signal because of unwanted effects near the zero frequency. Such happens because of significant reduction of resolution with 1D signals. In moving average filter the amplitude response is not flat in stop band, but it is a simple and fast choice to simulate the reduction of resolution which in on-line applications needs to be done with such simple filters [2].

4. RESULTS

This chapter introduces how the correlation between the basis weight and light transmittance of paper changes over eight orders of scale magnitude. Also, the noise reduction method in paper measurements is discussed.

4.1. The correlation over the eight orders of spatial scale magnitude

First, the correlation between the basis weight and light transmittance in 2D images is studied. The reduction of resolution is simulated evenly from 0,1 mm/sample to 20 mm/sample and the cross correlation between the signals for all simulated resolutions is computed. The correlation curve is computed for all 14 data sheets, and by averaging of curves the generalized behaviour is found. Fig. 3 shows the averaged dependency between the correlation and resolution in 2D data.

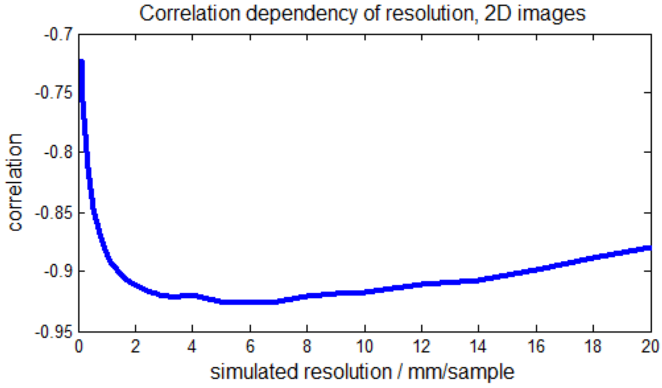

Fig. 3. Correlation between basis weight and light transmittance as a function of resolution in 2D images.

From Fig. 3 can be seen that the correlation achieve the maximum value at 6 mm/sample resolution. After that the correlation starts to decrease slightly. This suggests some paper structure variations at length scales of 10 mm and higher affecting the parameter a and b in (3).

Next, the correlation between the basis weight and light transmittance is studied from 1D signal. Fig. 4 shows the correlation between basis weight and light transmittance as a function of resolution. In 1D signal the absolute value of correlation increases continuously while the resolution is decreased.

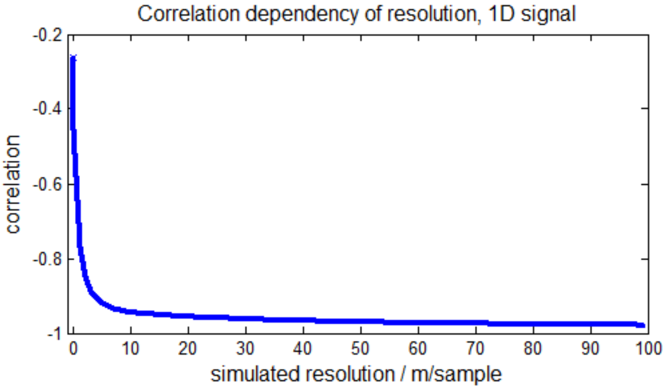

Fig. 4. Correlation between basis weight and light transmittance as a function of resolution in 1D signal.

One goal of this work was to study and find the effect of stochastic variation $\xi(t)$ in the test data. Such phenomenon can be seen in Fig. 5 which visualizes the common part of 1D signal at resolution of 10 m /sample. On the left the bias of light transmittance is higher as the bias of basis weight, but on the right the bias values are almost the same. Also, the difference of signals and difference filtered with moving average are drawn to the Fig. 5. The difference illustrates the difference of bias terms between the signals. The filtered difference illustrates the more general behaviour of the difference of bias terms.

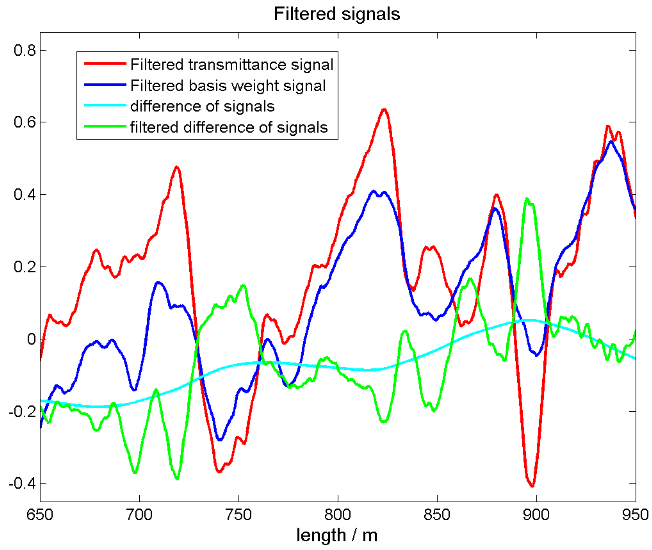

Fig. 5. Figure illustrates how the relation between the common parts of the signals changes over time.

In Fig 6 the complete signals, the difference of signals, and the filtered difference of signals are drawn. The effect of stochastic variation can be seen also in Fig. 6 but in larger scale. On contrast to Fig.5, on the right the bias of basis weight signal is higher as the bias of light transmittance, but on the left the bias of light transmittance is higher.

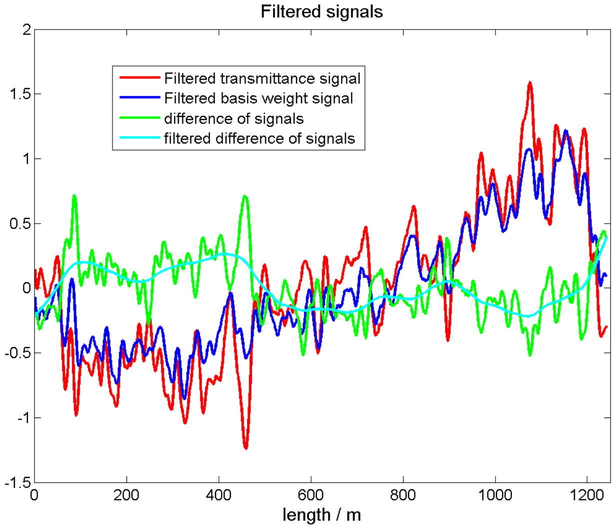

Fig. 6. Figure illustrates how the relation between the complete signals changes over time.

It can be seen from Fig.3 and Fig. 4 that the correlation over the eight orders of scale magnitude between the basis weight and light transmittance of paper is significant. This means that light transmittance can be used in an estimation of basis weight. However, as Fig. 5 and Fig. 6 illustrate, scanning online basis weight measurement is required together with light transmittance measurements to continuously estimate the linear relationship between the two paper properties and thus to reduce the effect of stochastic variation.

4.2. White noise reduction in paper measurements

The low pass filter removes the high frequencies from signal, but it also removes the white measurement noise. The rapid increase in correlation at start of the correlation curves (in Fig. 3 and in Fig. 4) reveals the noise removal phase. The slowly increasing (in 1D) or decreasing (in 2D) in correlation after the noise removal is due to normal variation of paper; the correlation between the basis weight and light transmittance is higher or lower in low frequencies.

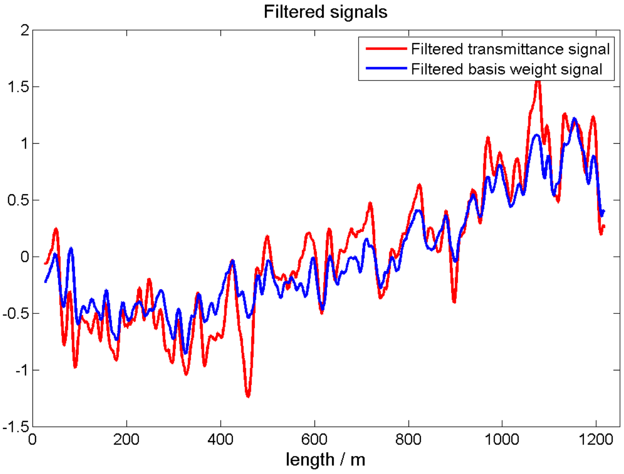

Fig. 7. The simulated resolution of 1D signal is 10 m / sample. The correlation is -0.93 at this resolution.

Removing of noise removes also small scale information from measurements. In paper measurements this is not a problem, because the basis weight is of interest over eight orders of scale magnitude: paper can be measured with higher resolution and low pass filter the result to almost any relevant resolution. Fig. 4 shows that the correlation is constant resolutions above 10 m/sample between the 1D signals. This means that in such resolution the measurement noise is filtered. Fig. 7 illustrates the 1D signals at 10m/sample resolution.

Also between the 2D signals the absolute value of correlation increases rapidly at the start of the curve (see Fig. 3) because of noise removal. The correlation curve is quite constant above the 2 mm/sample resolution, which means that the measurement noise is filtered in such resolution. Fig. 8 illustrates the 2D signals at 2mm/sample resolution.

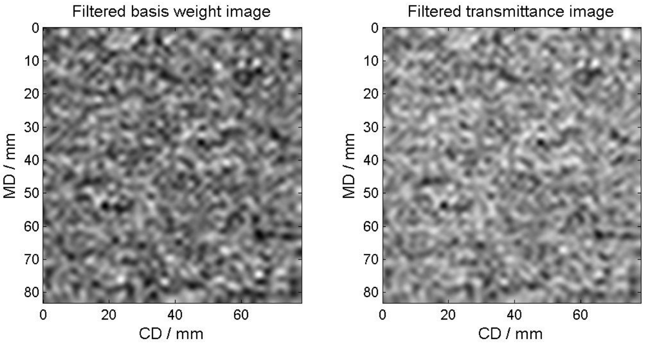

Fig. 8. The 2D images are drawn with 2 mm / sample resolution. The correlation reaches the -0.93 value on this resolution.

5. CONCLUSIONS

The correlation results indicate that the relationship between the basis weight and light transmittance of paper is significant. This means that light transmittance measurements provided by defect detections cameras together with scanning direct basis weight measurement are potential means for estimating basis weight web wide. Such approach has been suggested already a decade ago [5], but is becoming technically realizable on with the most recent camera and image processing technology. It was noticed that the correlation is the best at fairly small scales such that the large scale variations due to paper structure and processing conditions do not change the relationship but white measurement noise has been filtered out. In large scales the relationship changes over time because of stochastic variation due to control of paper machine and properties of paper. Therefore, the light transmittance measurement requires the present scanning online basis weight measurement in paper machines to update the estimation result.

The papers analysed in this work are uncoated. Coating changes the relationship between the basis weight and light transmittance substantially. In small scales the correlation of coated papers between the two paper properties is positive in contrast to uncoated papers. However, in large scales the correlation is negative similarly as that of uncoated papers. The complex relationship between the two paper properties in coated papers is a subject for future research.

In paper measurements the low pass filtering can be used efficiently in noise reduction. The information of properties of paper is divided over eight orders of scale magnitude, and the technology to measure the paper in all scale magnitudes exists. This means that paper web can be measured at a higher resolution and low pass filter the result to wanted resolution.

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