The OptiTopo Technique for Fast Assessment of Paper Topography — Limitations, Applications and Improvements

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The printability of paper is extremely dependent on the topographical properties of the substrate. Imaging instruments make it possible to obtain detailed 3D scans of paper surfaces that can be further used to calculate valuable quality predictors. A new imaging instrument, OptiTopo, based on the photometric stereo principle was developed at the Swedish Pulp and Paper Research Institute (STFI) with the advantages of an extreme acquisition speed and the possibility of simultaneously acquiring topographic and reflectance information. The topographical imaging of paper surfaces using this technique has now been investigated and improved. Eleven paper samples covering a wide range of different grades have been analyzed by OptiTopo and their scans compared to those obtained using a reference imaging technique. By applying a suitable signal treatment it is possible to improve the instrument's performance in terms of detail rendering capability. The positive results have been confirmed using visual assessment, classical statistical indicators and frequency analysis. The present limitations of the technique in relation to the physical properties of the substrate are discussed and absolute boundaries for the instrument are proposed.

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Introduction

Paper is currently by far the most widely used medium for printed images. Printing is a dynamic interaction between the physical and chemical properties of the printing forme or system, the ink and the substrate. The homogeneity of the paper surface, in both chemical and topographic terms, is a key to obtaining a superior print quality.[1,2] Paper topography has a strong and direct impact in several important quality attributes of a printed image[3-5] like gloss, contrast, colorfulness and sharpness. During image formation throughout the printing process, paper topography also plays a decisive role. Different printing technologies will induce different demands on substrate smoothness depending on its transfer principle. So called non-impact printing (NIP) methods like ink jet and electrophotography typically present low demands on smoothness since ink or toner transfer do not rely on pressured contact between print forme and substrate. In mechanical printing methods, on the other hand, the printing result is greatly dependent on a precise and controlled contact between the substract surface and the ink film,[6] thus implying higher demands on smoothness.

The constant search for smoother paper surfaces, in order to improve printability, is the driving force for the development of methods and devices capable of quantifying and classifying such paper surfaces. Surface topography is usually evaluated using a roughness, i.e., degree of unevenness or irregularity over the surface, or smoothness, i.e., degree to which a surface is free from irregularities or inequalities, index. These two concepts are complementary and express oppositely measured quantities, even though their magnitude is device dependent.

Most currently available topographic devices can be separated into two main families according to their general characteristics and the type of data obtained; viz.: air leak and imaging. The most common air leak instruments are the Parker Print Surf™ (PPS), Bendtsen, Bekk and Sheffield instruments, all of which are standard equipment within paper testing.[7–10] Their active principle is very similar: roughness is measured as a function of the amount of air leakage between a measuring head of standard design and the paper surface to be evaluated. These instruments are widely used both by industry and research due to their simplicity, speed, relatively low cost and reasonably good correlation with printability. This type of instrument provides a single value corresponding to the magnitude of the surface roughness or smoothness. Some attempts to establish a correspondence between the different indexes have been made, but there are important differences between them.[11]

Imaging, or rather 3D scanning by instruments, is employed to obtain 3D plots of paper surfaces. They have an implicit advantage over air leak devices with regard to detail rendering and spatial detection capacity. Surface images or maps can also be used to calculate numerical parameters relating to different quality attributes. Such instruments are normally extremely pre-

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cise, costly, and rather slow, attributes that are essentially dependent on the detection principle. Some examples of techniques successfully used for the topographic evaluation of paper surfaces are: mechanical contact stylus, chromatic aberration scanning, laser triangulation, autofocus, white light scanning interferometry, confocal laser microscopy, atomic force microscopy and topographic scanning electron microscopy, among others.[12] In any comparison of their applicability to paper surface inspection, criteria such as acquisition area, spatial versus vertical resolution and sensitivity are the most important, although speed and cost cannot be neglected.

In 1999, a new scanning technique based on a photometric stereo principle was introduced for paper evaluation at STFI,[13] and this later gave birth to a new imaging instrument – OptiTopo. Using standard video acquisition equipment, two images of the same region of a paper surface are acquired, illuminated by grazing light from opposite directions. Assuming a model for the light scattering properties of the paper surface and measuring the variation between the shadows and highlights produced by a fully characterized grazing light source, it is possible to compute the slopes of such a surface. In this way, a partial derivative of the surface height is obtained and later integrated to generate a topographic 3D image. The method has been partially tested for paper[14] and plastic[15] surfaces with very encouraging results. The advantages are obvious: ease of use, speed (acquisition and calculation time do not exceed 5 seconds, compared to several minutes for the most performing techniques at equivalent resolution) and a variable range of scanned area sizes (the system is based on video image acquisition so that the scanned area is dependent on the lens and focal conditions used). Another strong advantage is the possibility to acquire simultaneously a reflectance image representing ink distribution in the case of a printed sample.

Nevertheless, in its present form, the method assumes that all paper surfaces follow the same Lambertian matte light scattering model, which is known to be not completely true since many paper grades are more or less glossy. It also assumes that to a first degree approximation all samples are macro-flat. The technique still lacks a full characterization of its potential and its limitations when applied to the topographic analysis of paper surfaces. The present work attempts to answer such questions by considering OptiTopo as a measurement instrument working on an absolute scale and in this context characterizing its technical specifications. The work also intends to provide feasible and tested means of improving the OptiTopo performance.

Method and Materials

The absolute characterization of any measuring system is largely dependent on the use of high quality reference materials fully described on a standard referential scale employing defined units. However the hygroscopic nature of paper linked to its dimensional instability and, for some grades, the chemical and optical degradation occurring with time makes it almost impossible to define a time stable topography reference made of such material. A characterization based on the use of standard reference materials was therefore replaced by the use of a comparative imaging technique. In this way, any paper sample can be used to obtain temporary reference data, an approach earlier taken in other work.[16]

When choosing a reference height imaging technique, the main criteria were: vertical and lateral resolution, depth of field, lateral working range, accuracy and, on a minor level, the maximum slope angle and acquisition frequency. These properties should agree as closely as possible with those of OptiTopo, but with a higher level of accuracy and precision.

Mechanical contact stylus scanning was abandoned because of its damaging effect on paper surfaces and slow data acquisition.[17] The results of white light scanning interferometry depend on the reflective properties of the analyzed surface, and its lateral working area is small.[18] The vertical resolution of laser triangulation is too low for the technique to be used as a reference. Confocal laser microscopy presents a limited lateral working area in its present stage of development.[19] Atomic force microscopy also has too small a lateral working range. Topographic scanning electron microscopy is a non-standard and complex technique.[20] However, both autofocus laser and chromatic aberration scanning fulfill the main selection criteria with only minor risks of optical reflectance errors. The faster acquisition speed and the higher resolution of the chromatic aberration method determined the choice.

A MicroProf® instrument manufactured by FRT-Fries Research and Technology GmbH[21] based on a CHR 150 chromatic aberration sensor was used. On a chromatic aberration sensor, the sample surface is sensed using a white light chromatically split focus. A spectro-meter detects the dominant wavelength of the reflected light, which is related to the analyzed surface's height position. The instrument has the following characteristics: vertical resolution 3 nm, lateral resolution 2 μm, depth of field 300 μms, lateral working range 300 mm × 300 mm, maximal slope angle ±30° and point acquisition frequency 1000 Hz.

A selection of 10 samples covering a wide range of commercial paper grades was chosen for the comparison (see Table I). The grades included uncoated and coated papers (different coat weights), and graphic boards, altogether representing a wide range of roughness levels as well as very different optical scattering properties. A further sample was a 60 g/m^2 modified cellulose sheet made of dissolving pulp, prepared according to ISO 5269-2:1998. Such a surface, made of pure cellulose fibers, contains no pigments, additives, or optical brightening agents which may affect the optical properties, and is therefore interesting for assessing the importance of light scattering. The papers were glued onto glass plates (5 cm × 5 cm) using 3M SprayMount™. Only a very low pressure was applied, to avoid any degradation of the surface. The mounting procedure assures stable macro-flatness and minimizes topographic variations with time, and the glass edges provide a secure relative positioning referential to minimize relative rotation between instruments.

A square area of 8 mm × 8 mm, located approximately in the centre of each sample, was first scanned by OptiTopo (illumination angle 71.6°) and later using the MicroProf. A pair of 512 × 512 pixels matrixes, containing the respective topography maps in micrometers, was generated for each sample. The same resolution of 15.625 μm was used on both instruments to facilitate the matching process. The MicroProf data were first subjected to a plane subtraction and subsequently to a correction for invalid data as suggested by the instrument manufacturer. These corrections were performed separately and were intended to reproduce the functions implemented in the instrument software. The plane subtraction compensates for any possible misalignment between the scanning head and the sample placed on the holding table.

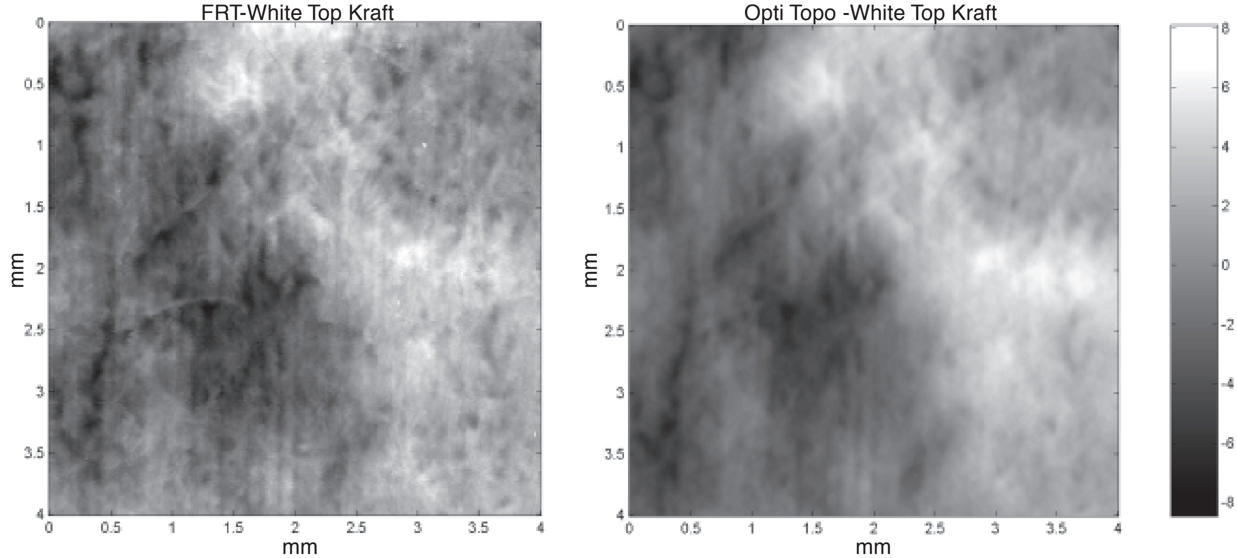

Figure 1. Topographic pictures of a white top kraft liner sample illustrating the result of the matching process (color z scale in mm).

The correction for invalid data fills in data points as the average of its valid neighbors at points where the scanning system did not record a valid signal (height values below three times the data standard deviation).

A successful area matching between two images requires a total correspondence of: scales, planar positioning and relative rotation, and assumes that all types of geometrical deformation are non-existent or corrected for. In the present study, the scale correspondence was assured by using the same resolution on both instruments and, since no major geometrical deformations were detected, no correction was applied. The relative rotation between the motives represented in both matrixes was estimated to be lower then 1°, due to the sample mounting procedure previously described. An area matching between the two matrixes was performed using a cross correlation function in order to minimize the impact of the positioning errors. A moving window of 4 mm × 4 mm (corresponding to 256 × 256 pixels) scans the MicroProf matrix and finds for each *xy* position the corresponding coordinates on the OptiTopo matrix. In this way, a correlation map was obtained per pair and the optimal matching was calculated for each of the 11 samples.

Experimental

Point-Wise Comparison

Two matrices, each containing the 3D topographic maps of exactly the same area and scanned respectively using the MicroProf and the OptiTopo instruments, were calculated for each of the paper samples. This allowed the techniques to be compared and the performance of OptiTopo to be assessed. Three main approaches were considered for estimating the magnitude of resemblance: visual assessment, statistical indicators, and frequency analysis.

The visual assessment had a merely qualitative value and was used as a confirmation of the success of the matching process, as shown in Fig. 1. Nevertheless, the dissimilarity between the general characters of the images provided visual evidence and a strong hint about the possible major differences between the two scanning techniques, essentially in resolution.

Two classical statistical indicators were chosen (see Table I): 2D correlation and the standard deviation ratio. Their statistic validity is assured by the large quantity of measuring points, a total of 65,536 per map if each pixel is considered to be a valid topographic measure. The spatial correlation quantifies the degree of success of the area matching process and the standard deviation, also referred to as *RMS* or *Rq*, provides a dispersion amplitude parameter characterizing the surface.[22] The ratio between the standard deviations of the two surface profiles therefore provides a suitable macro-indication of the instruments' output differences and of the type of deviation induced. This ratio can also be perceived as a hypothetical damping or amplification factor induced by OptiTopo.

The frequency analysis was performed to investigate the spatial limitation of the proposed amplitude parameter and to verify the frequency dependence of the previously calculated standard deviations ratio. The commonly used power spectrum representation was applied with the power here corresponding to the profile variance. The power spectrum of random white noise, i.e., equal power per frequency unit, displayed in a double logarithmic graph, has a negative slope of –2, and this makes the detection of non-random artifacts more difficult. As suggested by previous research in the field,[23] substituting the variance per frequency unit representation by a variance per logarithmic wavelength band unit (in the present case an octave) facilitates the detection. Using this form of representation, the random white noise spectrum would have a negative slope of –1, and this would make outstanding variance components in certain size classes more easily noticeable. The calculation is carried out by a straightforward application of the one-dimensional Fast Fourier Transform (FFT) algorithm where the final spectrum is the result of averaging the coefficients of the multiple one-dimensional power spectra generated. A windowing operation using a Hamming function is performed in the spatial domain to minimize the "window effect".[24,25] The signal attenuation induced by the windowing operation is compensated via a weighting factor applied in the spatial domain. The relative logarithmic bandwidth transformation previously mentioned is subsequently applied.

The comparison between the two resulting spectra corresponding respectively to the proposed and the refer-

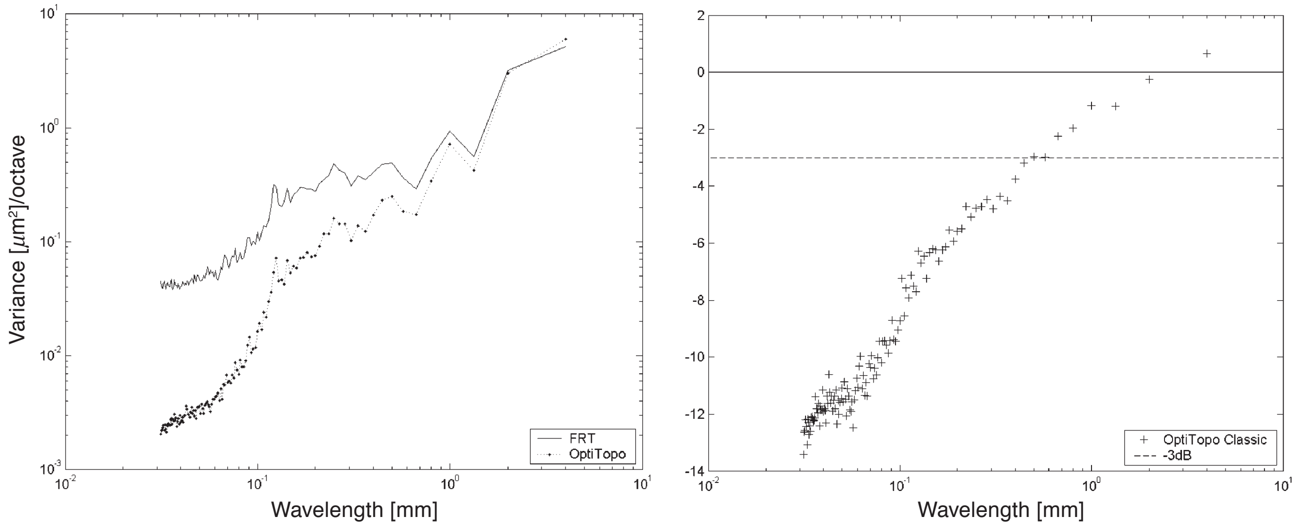

Figure 2. Variance spectra obtained using the two scanning techniques and their quotient for comparison.

ence scanning techniques, provides immediate conclusions on detail rendering and resolvability limits, as shown in Fig. 2. The calculation was extended to all samples and the ratio of the signals was converted into a standard decibel scale according to the common procedure: 10*LOG10 (Power of measure/Power of reference); with variance being analogous to power. Such a graphic representation made it possible to determine the OptiTopo cut-off wavelength for each paper grade. The cut-off frequency, or wavelength as presented here, is an intrinsic property of each measuring instrument that basically determines its working range. The definition of cut-off wavelength was inspired by the electronics of linear amplifiers, where cut-off frequency is commonly the frequency either above or below which the output of the amplifier is damped by 3 dB (half power). The complete set of the short wavelength cut-off values can be found in Table I, where it is evident that their level is far too high to permit fine detail detection.

Technique Improvement

In the halftoning process, printed images are composed of binary raster dots. The final print quality and the successful prediction of surface topography induced print faults are dependent on the accurate reproduction of these raster dots. In such circumstances it is therefore reasonable to associate the resolution and resolvability requirements of any topographic equipment to the dimensions of the raster cell. In the case of a modern high quality mechanical printing system, the limit is typically ca. 100 μm (200 dpi corresponds to a cell size of 127 μm). It is important to note that the cell size defines a critical area that will be affected differently depending on the percent coverage to be achieved. The previously determined short wavelength cut-off values are definitely out of such range. However previous experience with OptiTopo's bandpass topography profiles had made it possible to successfully detect artifacts much smaller than the determined cut-off, and this suggested that a lower cut-off value was achievable.

The core theory of OptiTopo technology is supported by generalized assumptions for an all purpose and wide range signal-to-noise ratio, compensated via a Wiener filtering stage. The origins of the noise include the image acquisition system, assumptions regarding the paper optical transfer function, and the character of the paper surface, all of them repeatedly added during the integration process.[14] A general comparison of the shape and detail of the energy spectrum curves indicates that OptiTopo has a tendency to over-damp the high frequency components while still achieving a significant acquisition. Figure 2 shows that details such as picks in the high frequency part of the variance spectrum are present in both spectra but at different magnitudes. To verify the hypothesis of over-damping and to ameliorate the detail rendering capability then becomes a highly interesting possibility.

Given the physical meaning of variance, the square root of the ratio of the variance spectra is the OptiTopo's induced amplitude damping factor. The over-damping frequency response and subsequently required compensation were determined using the variance spectra of some representative paper grades. Figure 3 shows the inverted square root of the variance spectra ratio, and this represents the minimal gain required at each frequency used as a basis for the creation of a restoring filter. Three main assumptions were followed when designing the filter. Its shape should be kept as simple as possible, basically providing the minimal required gain and avoiding any general over-compensation that would artificially increase the measured roughness of the sample. The impact on the low frequency components of the signal should be minimized in order to avoid adding macro-variations. The maximal attainable gain should be frequency limited to avoid over-amplification of high frequency noise. An excessive amplification would compromise the filter detail rendering action by drowning the signal in noise. Figure 3 also shows the proposed filter frequency response, which was implemented in the frequency domain using zero padding to minimize deterioration due to edge effects.[26] The new amplification filter was applied to the complete set of samples, and new statistical indicators, spectra and high frequency cut-off wavelengths were calculated. The general improvement is detectable by a visual comparison between Fig. 4 and Fig. 1, which respectively display the topographic profile of the same sample measured using OptiTopo, before and after the application of the new filter. The first part of Fig. 5 contains the variance spectra of all three previously stated images, and part two shows the spectra corresponding to the comparison

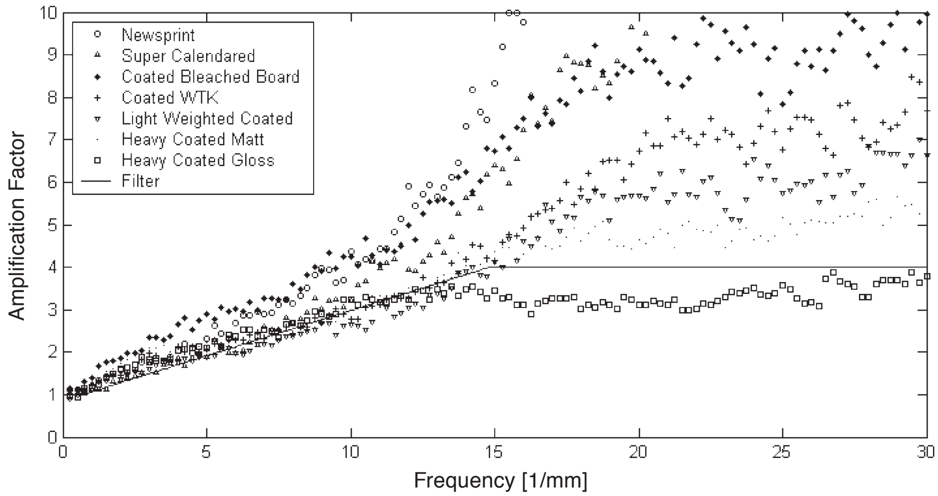

Figure 3. Required spectral amplification for the main paper grades studied and the frequency response of the proposed filter.

of both the classic and the improved versions of OptiTopo against the MicroProf reference.

Results

The variance spectra obtained from the classic and filtered versions of OptiTopo are compared with correspondent spectra from the MicroProf reference instrument. The general improvement achieved with the new filtered version of OptiTopo is indicated by the better correspondence between its spectra and those of the reference instrument. The decibel comparison clearly displays the improved detail rendering obtained by lowered cut-off wavelength limits at –3 dB.

The collected and analyzed data are summarized in Table I and in Figs. 5 to 10.

Discussion

The additional amplification stage added to OptiTopo gave a substantial improvement in the technique when applied to the majority of the different paper grades. The quality of the result is confirmed by the good spatial correlation together with the high level of correspon-

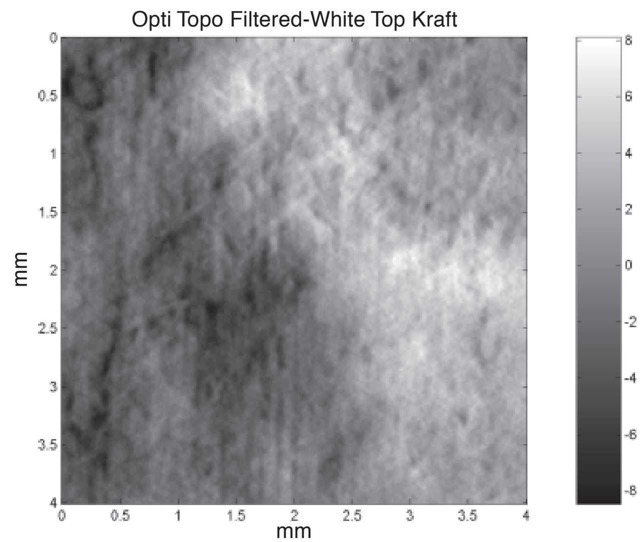

Figure 4. OptiTopo topographic picture of a white top kraft liner using the new improved version (compare to Fig. 1).

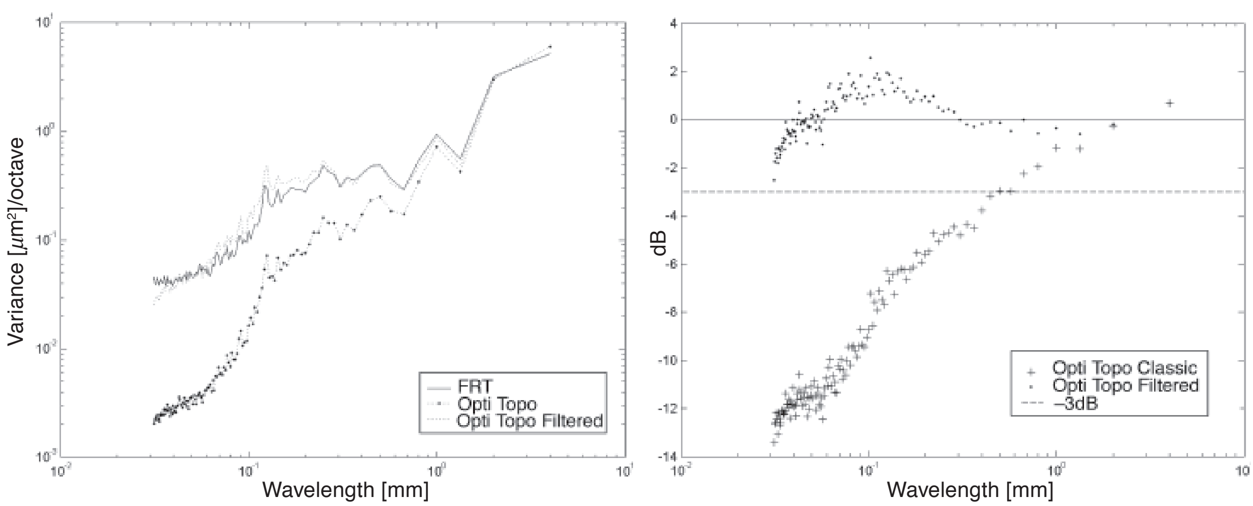

Figure 5. The general improvement generated by the new filtering stage is detectable by comparison of the different variance spectra. Example showing the same white top kraft liner sample.

TABLE I. Comparison of Roughness Indicators from FRT MicroProf and OptiTopo (Classic and New Version)

		FRT Correlation		Standard Deviation			Std. Dev. Ratio		High Freq. Cut-Off**	
Paper Sample	PPS 10*	Classic	New	FRT	Classic	New	Classic	New	Classic	New
Super Calendared	1	0.93	0.92	5.09	4.42	4.54	0.87	0.89	400	71
Light Weighted Coated	1.6	0.93	0.94	3.61	3.62	3.79	1.00	1.05	571	56
Cast Coated	<0.9	0.88	0.84	1.25	1.10	1.15	0.88	0.92	148	571
Newsprint	4.5	0.83	0.80	6.78	5.24	5.96	0.77	0.88	667	85
Multi Purpose Copy	5.3	0.82	0.83	5.97	3.96	4.48	0.66	0.75	571	200
Heavy Coated Gloss	<0.9	0.94	0.92	2.04	1.91	1.97	0.93	0.96	571	<min
Heavy Coated Matte	1.2	0.95	0.94	2.58	2.42	2.49	0.94	0.96	667	34
White Top Kraft	2.1	0.92	0.93	2.74	2.98	3.08	1.09	1.12	444	<min
Coated Bleached Board	5.0	0.93	0.93	6.55	5.33	5.49	0.81	0.84	800	90
WTK – coated 7 g/m²	2.3	0.84	0.82	2.71	2.39	2.60	0.88	0.96	667	57
Regenerated cellulose	-	0.57	0.58	8.11	4.24	4.95	0.52	0.61	800	571

* PPS 10 – Parker Print Surf roughness measured at 1 MPa (traditionally expressed as 10 Kgf)
** High Freq. Cut-Off is here given as short wavelength value [μm]

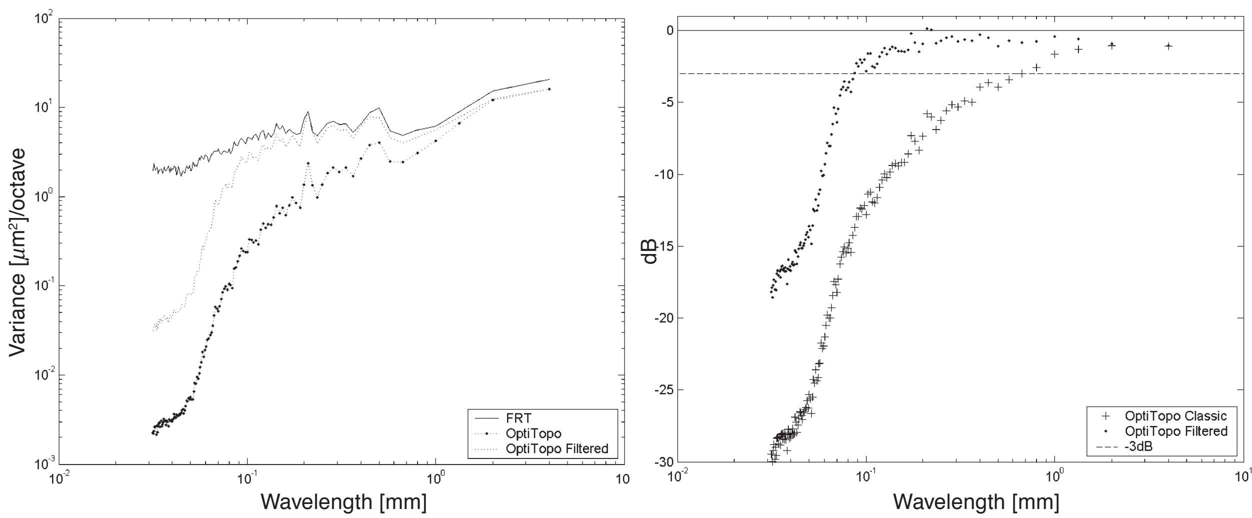

Figure 6. Variance spectra of the scans made using the classic and filtered OptiTopo together with the reference instrument on newsprint. Comparison to reference in decibel scale.

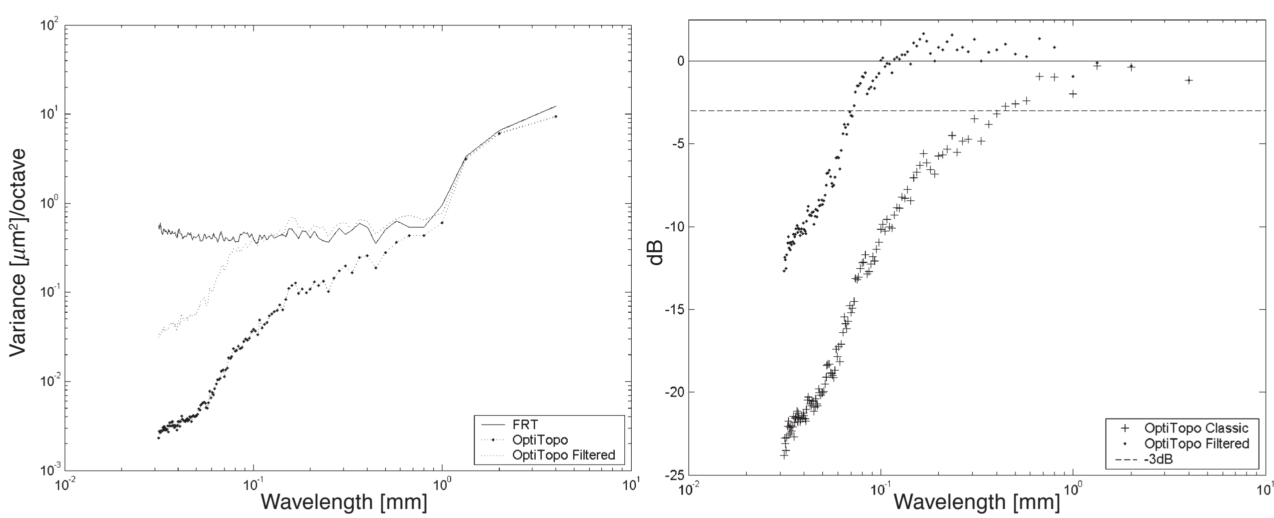

Figure 7. Variance spectra of the scans made using the classic and filtered OptiTopo together with the reference instrument on super calendared uncoated paper. Comparison to reference in decibel scale.

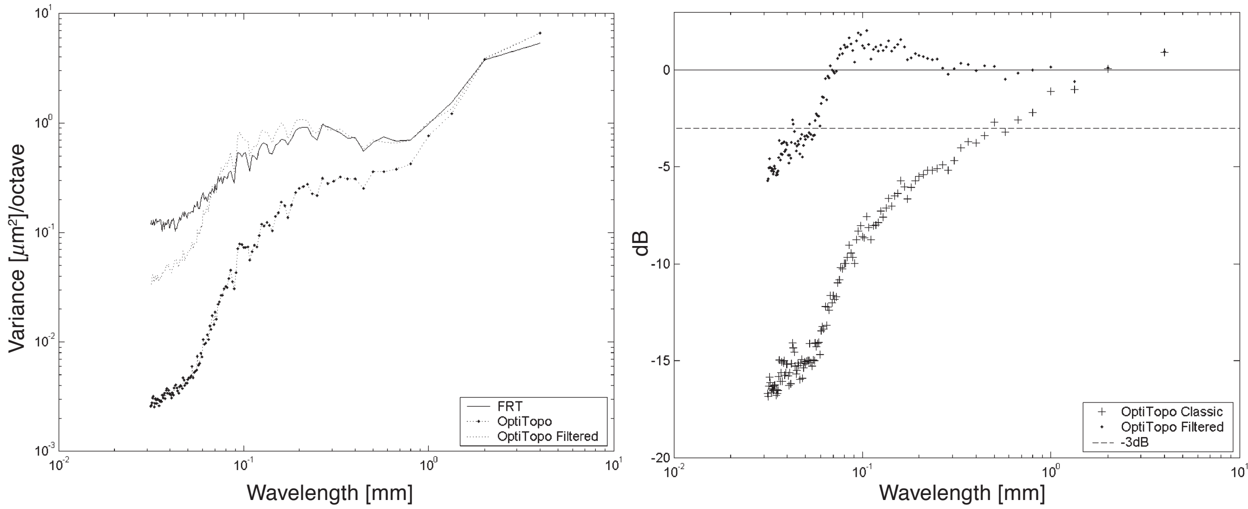

Figure 8. Variance spectra of the scans made using the classic and filtered OptiTopo together with the reference instrument on light weight coated paper. Comparison to reference in decibel scale.

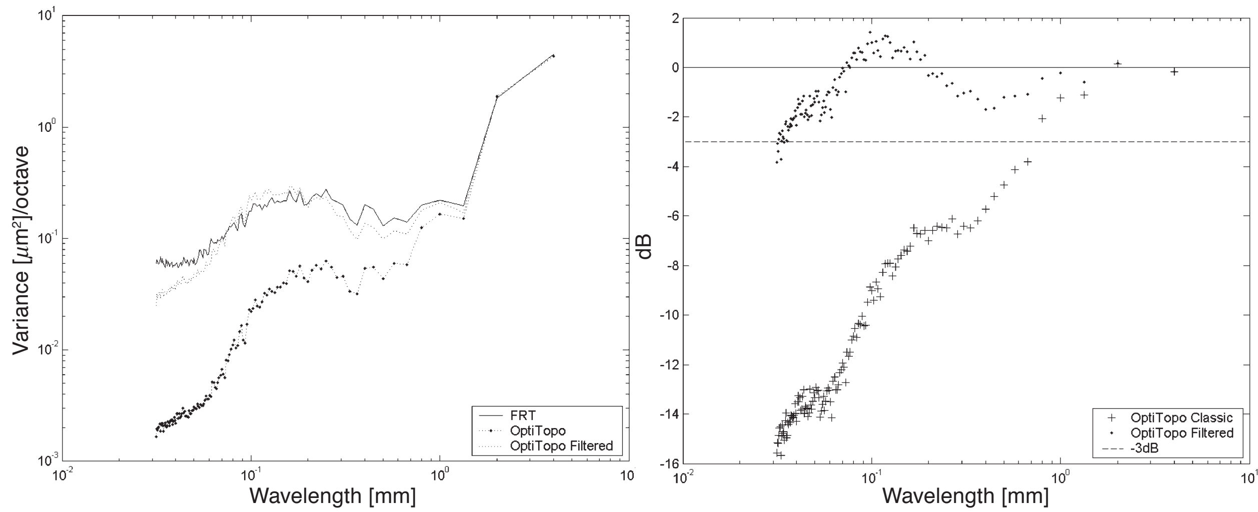

Figure 9. Variance spectra of the scans made using the classic and filtered OptiTopo together with the reference instrument on heavy coated matte paper. Comparison to reference in decibel scale.

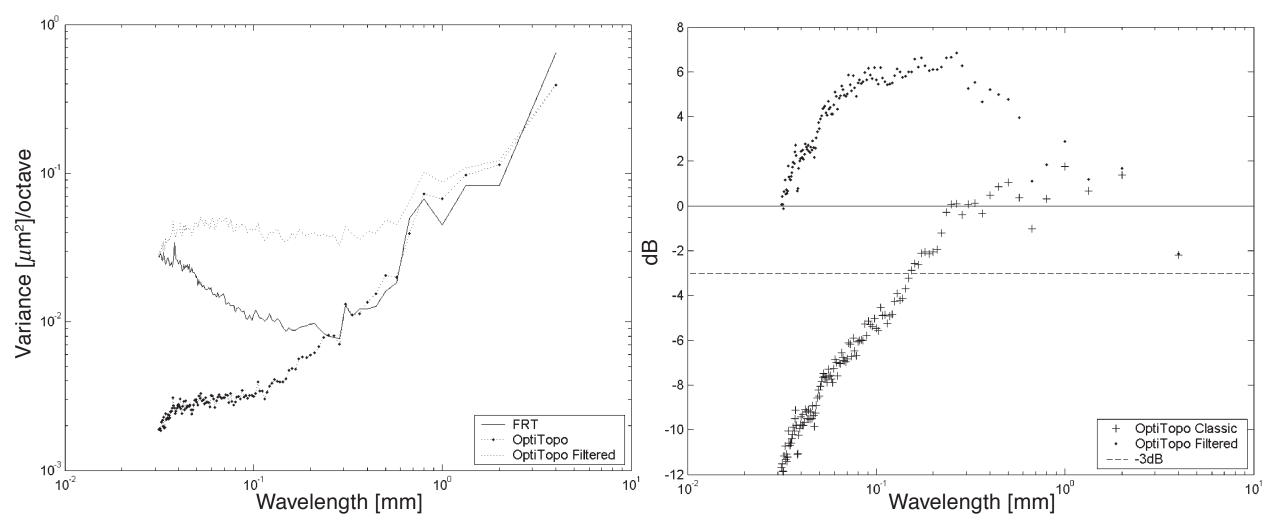

Figure 10. Variance spectra of the scans made using the classic and filtered OptiTopo together with the reference instrument on cast coated paper. Comparison to reference in decibel scale.

dence achieved between the variance spectra of the two techniques.

The generally high correlation coefficient suggests a very good correspondence between both imaging techniques, but in any further analysis of the results of this study, it is important to separate the area matching process from the instrumental comparison. The area matching is an intermediate procedure required to achieve an absolute comparison over exactly the same surface at a pixel level, in order to provide a basis for the instrumental comparison. The overall process from measurement to the area matching represents an additive sequence of possible small sources of error that may reduce the correlation strength. These are possible sources of error related directly to the samples due to their preparation, assembling, transportation and manipulation. Even if the measuring process were conducted under fully controlled conditions, it is impossible to completely eliminate the possibility of local deformation or damage to the sample surface during transport between the instruments, which would result in a local irremediable mismatch. The hygroscopic nature of paper and the natural instability of the gluing boundary layer also add to the total uncertainty. In addition, the MicroProf topographical scans used as a reference are in fact a sampled representation of reality with their own accuracy and precision defined by the physical properties of the instrument. The mathematics of the matching process may also introduce a certain degree of uncertainty. For example there is a noticeable tendency for the correlation with the reference using the new improved version of OptiTopo to be less than that with the original version. In fact, the application of the new filtration stage corresponds basically to an image sharpening and therefore an increase in energy of the high frequency components (like micro-roughness), and this makes it difficult to achieve full correspondence at the pixel level. Nevertheless, considering the complete range of possible sources of mismatching, a very acceptable and stable level of correlation was achieved. Any further differences between the topographic profiles were considered to be induced by the OptiTopo technique and were quantified during the instrumental comparison.

The standard deviation ratio is used as an amplitude parameter to characterize the tendency of the OptiTopo to amplify or damp the topographic readings of a given paper grade. The tendency for damping is by far the most common, and this suggests that there is a need for amplification. When applied with the new amplification, filtration adds energy to the topographic profile and increases the standard deviation, and this brings the OptiTopo result closer to the reference, as shown by the evolution of the ratio parameter. This parameter provides an incomplete representation of the evolution, but it still works as a good macro-indicator of the amplitude correspondence success. With regard to the standard deviation ratios of the filtered version, it is useful to establish an acceptance limit at 0.9, corresponding to samples that had their amplitude attenuated by a maximum of 10%. The outliers correspond to paper grades that are very rough and/or uncoated, two factors which independently lead to signal losses. A very rough surface introduces a limiting factor linked to the reading of extreme artifacts like deep holes that tend to be attenuated by OptiTopo. Extreme pits with very steep edges will not be completely illuminated, and this limits the maximum detectable slope angle and leads to an underestimation of depth. The present work was concentrated on improving detail rendering, and such effects were not therefore totally explored. With regard to the upper wavelength limit, the comparison of the variance spectra for the different samples verified an operational range up to a wavelength of 1 mm for the configuration studied. The fact that uncoated papers performed worse was merely a confirmation of the basic theory. The technique requires a certain minimum surface light scattering level in order to operate accurately.[15] Sufficient light scattering will occur if a critical concentration of small particles exists on the surface of the paper; in the form of mineral fillers, coating color or fines resulting from mechanical pulping. Uncoated or low charge-containing zones of a paper surface will tend to absorb light and internally redirect it to another point of the surface (if that same quantity of light is not absorbed by the bulk or even transmitted) and thus create erroneous readings. The very poor results obtained for the regenerated cellulose sample, where hardly any form of diffusant is present, confirm this.

Copy paper made of bleached chemical pulp charged with mineral pigments constitutes another illustration of the previous problem. The mineral particles are mainly distributed in the bulk of the sheet leaving surface fibers uncovered and thus giving less light scattering. This morphology in turn leads to underestimation of the roughness, which is not fully compensated for by the new filtering stage. In comparison with other paper grades, the lower standard deviation ratio, together with the higher short wavelength cut-off confirm this.

The cast-coated sample is highly coated and very smooth, constituting an extreme surface compared to that of other paper grades. When scanned using the traditional instrumentation, the wavelength variance spectrum provides a good estimation of the roughness from long wavelengths to around 150 μm, and further signal treatment is not therefore required. The sub-micron nature of the high frequency component leads to a weak signal-to-noise ratio, and this means that an amplification treatment is unsuitable. In fact, applying the same filter here as for the other paper grades results in an over-amplification in the mid-range wavelengths without producing relevant fine detail.

The calculated variance spectra displayed along a logarithmic scale of wavelength make it reasonable to introduce the notion of μm^2 per logarithmic unit, in the present case, octave wavelength bands. This choice of unit is relevant because of its direct relation to the unit of physical height. In the present study its usage was restricted to the relative comparisons between spectra that were obtained using the same algorithm, so that the unit used had no impact on the results. Nevertheless, such variance spectra are well suited for the characterization of different surfaces in terms of topography—the shape of the spectrum acting as a fingerprint of the surface.

It is clear that the general quality of the OptiTopo technique is linked to the nature of the sample, essentially to its optical response. The present work also shows that the solution of using a general approach to the compensation question is a workable compromise that provides very acceptable results for the most common commercial paper grades. If a customized amplification stage were adapted for each family of paper grades, a higher degree of detail would certainly be achieved. Another feasible idea would be to adapt the integration stage in terms of a new optical transfer function (OTF) together with a noise profile for each paper grade or family of papers. Both solutions would provide an extra high level of sensitivity to the technology with higher levels of detail rendering. In practice, the possibility is linked to the definition of an independent property whose quantification would pilot the choice of function to be applied. Nevertheless in its present form the OptiTopo technique with its extremely short acquisition and processing times can be a valuable tool for assessing paper surfaces' general quality. Its general performance and usefulness are largely dependant on the final application and the required frequency range. Uncoated grades, partially identified as problematic, represent only a fraction of the current paper market. The technique can in any case be very useful for performing relative comparisons among similar paper grades and represents a valuable production control tool for the paper industry.

Conclusions

The fast topographic imaging of paper surfaces using the OptiTopo photometric stereo principle has been investigated and improved. A number of different paper grades were studied and data from surface scans by a FRT-MicroProf color aberration instrument were used as a reference.

By suitable signal treatment, a higher level of information could be obtained in the fine detail part of the spatial spectrum than was possible with the earlier version of the OptiTopo. A high degree of correspondence was found between the two instruments both in statistical measures and in point-wise correlation, which was also visually confirmed by comparing matched topographic maps.

The principle behind the photometric stereo technique requires light to be scattered locally from the surface element whose inclination should be detected. Therefore pigmented and coated surfaces will be better characterized using this method than uncoated surfaces. The height values from uncoated wood-free paper surfaces tend to be reduced in amplitude because too much light is scattered inside the sheet, whereas newsprint works well since the fines in the mechanical pulp provide the necessary level of surface scattering.

It was established that the operational range of the technique in terms of spatial resolvability is securely defined between 0.1 mm and 1 mm for an acquisition area of 16 mm^2. The resolved wavelength range can also be increased or decreased by choice of a larger or smaller acquisition area. The final conclusion is that, when suitable light scattering is present in the paper surface to be analyzed, the OptiTopo approach gives fast and precise topographic information over a comparatively large area, valuable for the prediction of printability and for other quality evaluations.

Future Work Suggestions

In order to provide an even more accurate description of the OptiTopo limits, other configurations of the instrument should be tested further, including the use of other image acquisition areas and resolutions together with different angles of illumination, in order to take full advantage of the technique's versatility. An investigation of the possible dependence of the results on the lightness level of the paper, corresponding for example to the whiteness or even to the presence of transparent ink on the surface, would also provide a better knowledge of the technique.

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