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A DIGITAL METHOD FOR ANALYZING DROPLETS ON SENSITIVE PAPER

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A Digital Method for Analyzing Droplets on Sensitive Paper

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Abstract

Sensitive paper has long been used to detect droplet impingement in several processes, including drift measurement. Identifying, counting, and measuring the individual droplet stains has been a tedious, labor-intensive task involving microscopic examination and statistical extrapolation; because, counting all the stains has previously been impractical. Digital techniques now in common use, however can reduce this previously labor-intensive task to a rather simple one of graphical data screening. Furthermore, all the stains are counted, reducing the uncertainty of the results. The conventional (manual/optical) and digital methods are compared for actual samples as well as the effort and equipment involved.

Introduction

The sensitive paper method of measuring droplet count and size distribution was developed by J. D. Womack in the 1970s at the Environmental Systems Corporation. The sensitive paper is prepared by first soaking it in a solution of Potassium Ferricyanide [$K_3Fe(CN)_6$] and allowing it to dry. Then the paper is dusted with Ferrous Ammonium Sulfate [$Fe(NH_4)_2(SO_4)_2{\cdot}6H_2O$] powder. The resulting surface is ferric yellow in color. When any moisture, such as a droplet, comes in contact with the paper, it produces a deep ammonium blue stain. The relationship between droplet and stain size was determined by a series of experiments using precision-generated drops as described in the Appendix. Frequently, 47 mm diameter filter papers are used for convenience and consistency.

Traditionally, the stains are examined with a microscope and the size, shape, and number are used to infer the count and size distribution of the impinging droplets. As there may be hundreds, even thousands of stains on a single paper, a statistical approximation has traditionally been used rather than an exhaustive examination. In this practice, a series of precision grids are overlaid on the paper and the stains fitting within several grid cells are counted. The counting continues from cell-to-cell until some statistical measure of sample significance is met. The examination can be facilitated by using a magnifying projection device, a digitizing tablet, computer software, and an audible signal.

This process has been successfully carried-out for decades and has provided a reliable and accurate way of measuring airborne transport of droplets. Still, it is very labor-intensive. Tests often require dozens and may require hundreds of papers. Considering the limited equipment and trained technicians required for this task--not to mention the individual endurance for such tedium--it can take quite a while to complete the processing of samples from a single test.This process has been known to take weeks to complete and is done away from the site of the measurements. Returning for more data was also not considered practical. This is the motivation for developing the current digital processing.

Digital Processing of the Sensitive Papers

Precision digital color scanners are now readily available. These units are surprisingly inexpensive, quickly installed, easy to use, and come with powerful software. While their intended purpose is primarily photographic, they can be used for a variety of other tasks. One such purpose would be eliminating the microscope and projector from this sensitive paper examination. The same manual counting methodology and statistical sampling could be applied to the scanned papers. This would at least preserve them digitally from any degradation or contamination with moisture during storage while they await processing. Given the ubiquitous availability of computing power, the logical next step is digital processing.

Several scan resolutions were tested and 4800 dpi (dots per inch) was found to be adequate. At this resolution a 47 mm sensitive paper results in an 8800x8800 pixel image. With default JPEG compression each scan produces a file of approximately 4 MB in size.

In order to digitally determine the size and quantity of the droplets, it is essential to delineate what is and is not a droplet-formed stain and to distinguish one stain from another. Ultimately, the stains must be converted to individual closed polygons. A single polygon may represent more than one overlapping droplet; but this situation exists whether the processing is optical/human or digital/automated. Once the stains are reduced to polygons, a variety of statistical tests can be performed. Additionally, the papers can be examined exhaustively. Approximation by statistical sampling of part of the paper is no longer necessary.

The ammonium blue on ferric yellow of the sensitive paper technique is particularly well-suited to digital analysis, as this color combination provides excellent contrast; because ferric yellow and ammonium blue are almost color counterparts. Simple black-and-white rendering does not adequately reveal just how fortuitous this color combination is. Gray shade discrimination is inherently a mater of degrees: How light is white? How dark is black? Ferric yellow/ammonium blue discrimination is much easier.

All Color Separations are Equal

As children we were taught that ***the*** three primary colors are: red, yellow, and blue. As well-intentioned as they might have been, our teachers were misinformed. In fact, ***one*** set of primary colors is: magenta, yellow, and cyan. ***Another*** set of primary colors is: red, green, and blue. Except that, if this green is the color of grass, the corresponding red isn't the color of fire trucks and the other isn't the color of the deep blue sea. [Realization of this foundational misconception can be quite disturbing for some people!]

The fact is, that there are an infinite number of primary colors, in that all other colors can be made from an infinite number of sets of three. The only requirement is that the colors comprising a set of three (triad) bear a certain relationship to each other. All color separations are equally valid, provided they are based on a proper triad. A CMY (cyan, magenta, yellow) color separation is just as valid as an RGB (red, green, blue) separation. Some color separations are more useful than others depending on the availability of ink or the desire to assure that the grass is always green on television.

This is where the definitions of hue, saturation, and luminosity become useful. The position of a color in HSL-space is defined in spherical coordinates. Hue is what we ordinarily think of as color. The hue axis is basically that of the rainbow and varies from 0 to 360°. In spherical coordinates hue is analogous to longitude. Saturation is what we ordinarily think of as the purity of a color and varies from 0 to 100%. The saturation axis is analogous to the radius: 0% being the center and 100% being the surface. Luminosity, which is what we ordinarily think of as brilliance, varies from -180° to +180°. The luminosity axis is analogous to latitude.

The color sphere shown in Figure 1 was developed by Philipp Otto Runge (1810). Any simple, non-metallic color can be represented by its HSL coordinate triad. [Note: In computer systems it is common to use a scale of 0-255 for hue, saturation, and luminosity.] There is also an equivalent RGB coordinate triad for the same color as well as a CMY coordinate triad. Simple relationships are readily available for converting from one coordinate triad to the other. Most graphics programs provide the common color coordinate transformations internally. The formulae are available from many sources, including Wikipedia (2008).

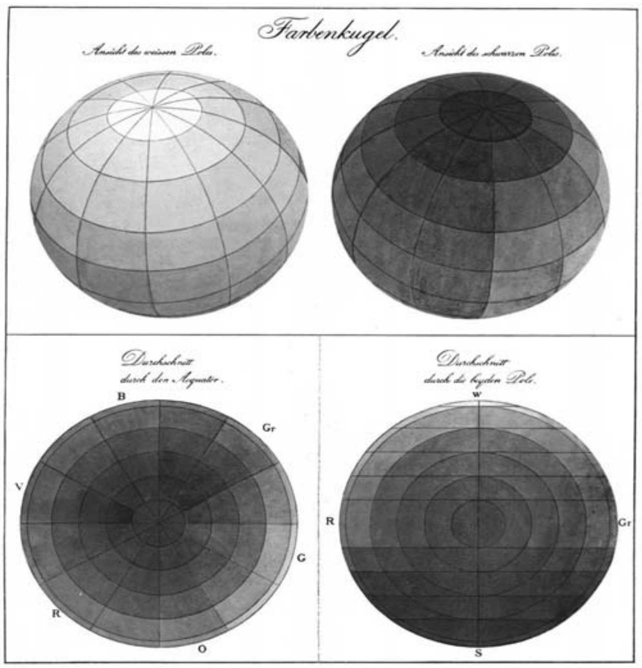

Figure 1. P. O. Runge's Color Sphere

The essential requirement for a valid color separation triad is that the three primary colors have 100% saturation, 0° luminosity, and be 120° apart in hue. If you choose one color the other two are automatically defined. Color television transmission is based on green so that the grass in a football field always looks good; because it's generated by the green color "gun," which never requires hue adjustment. Red and blue naturally follow from the selection of green. Color ink cartridges are based on CMY; because yellow is the most difficult color to produce with blended ink, although some very old or specialized printers use RGB ink. Interestingly, the yellow pigment used in ink cartridges is ferric-based, just like the sensitive papers.

By transforming the color triad from one coordinate system to another, any desired color separation can be easily achieved. This is particularly convenient for 24-bit or 3-byte color, which is the most common storage format for digitized images. If a custom color separation is performed, based on a triad, one color of which exactly matches the ferric yellow of the unstained sensitive paper, the distinction between stained and unstained areas will be maximal. The ferric yellow has a hue of 56° (RGB: 255, 240, 1). Banana yellow has a hue of 60° (RGB: 255, 255, 0). The other two colors in this sensitive paper-tailored color separation triad are turquoise at 176° (RGB: 1, 255, 240) and lavender at 296° (RGB: 240, 255, 1). Ammonium blue has a hue of 190° (RGB: 1, 210, 255); whereas cyan has a hue of 180° (RGB: 128, 255, 128). The difference in hues between ferric yellow and ammonium blue is then 134°. [Exact color counterparts are 120° apart.]

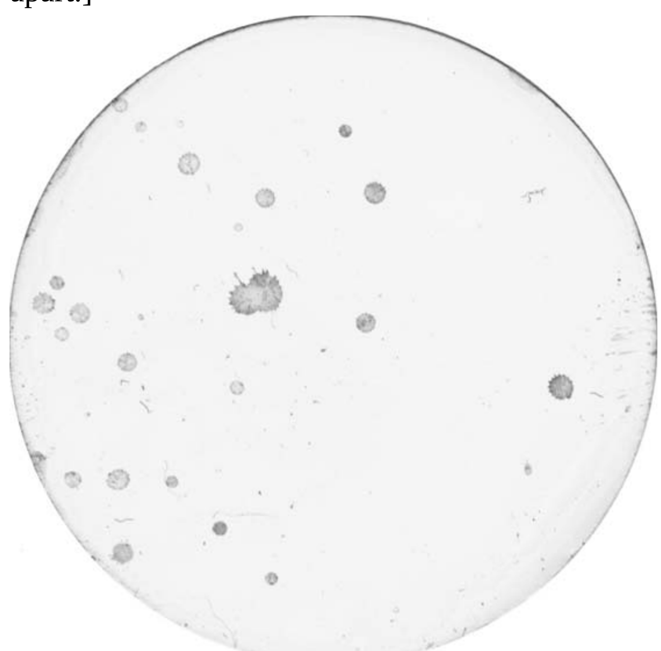

Figure 2. Gray-Scale

The effect of this custom color separation can be achieved digitally by several means. Custom software is one method and is the obvious choice considering the subsequent identification and analysis of the polygons. The same effect can be achieved using the photograph manipulation software that comes with most scanners by rotating the hue of the scanned image by +4° and performing a CMY color separation or by rotating it -56° and performing an RGB color separation. [Rotation is accomplished using the "hue adjustment" feature.] The advantage of performing this specialized color separation can be seen by comparing the relative contrast available in a gray-scale vs. the three color separations as shown in Figures 3 through 6.

Figure 3. Ferric Yellow Separation

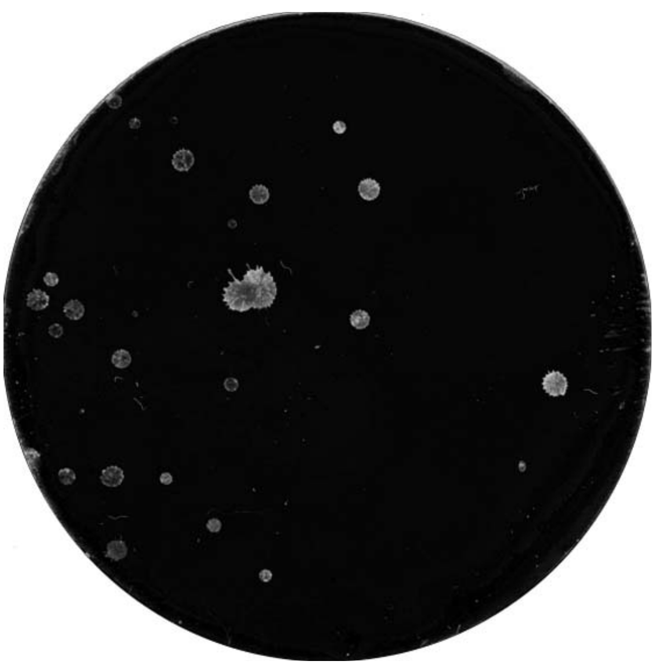

Figure 4. Turquoise Separation

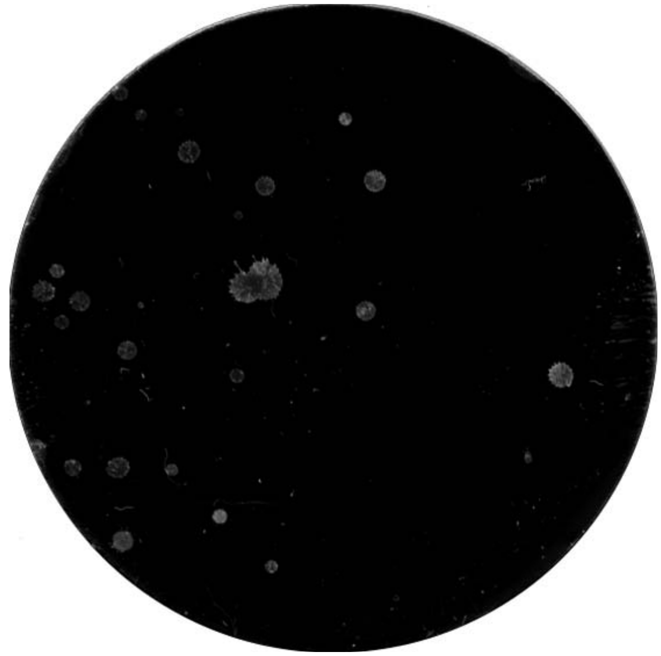

Figure 5. Lavender Separation

For this particular paper the degree of unadjusted contrast between the ferric yellow and turquoise (unstained and stained) images obtained by custom color separation is 1.8 times that of the contrast between white and black (unstained and stained) in the gray-scale image (c.f., Figures 2 and 5). For the papers analyzed this contrast enhancement varied from 1.6 to 2.3 with an average of 1.9. Recognizing and utilizing the fortuitous contrast between the ferric yellow and ammonium blue colors basically doubles the distinction between unstained and stained areas. [The degree of contrast is typically displayed on the luminance histogram and varies from 0 to 100%.]

Reduction to Polylines

The next step in the process of digital analysis is reducing the stained areas to closed, continuous polygons (polylines). This is accomplished by the color transformation known as "solarization" followed by taking the negative of solarized image and performing a logical NOT operation on the two images (solarized and non-solarized). The solarization transformation is defined by a threshold value: pixels having a luminosity above the threshold value are changed to black while those below the threshold are changed to white. Either the ferric yellow or turquoise separated images can be used. The turquoise image is preferable, as it always has less noise. Stray marks, fingerprints, and dust on the scanner are much less likely to have a predominantly ammonium blue color component than is an actual stain (c.f., Figures 3 and 5). [There is little useful information in the lavender image; so it is discarded.]

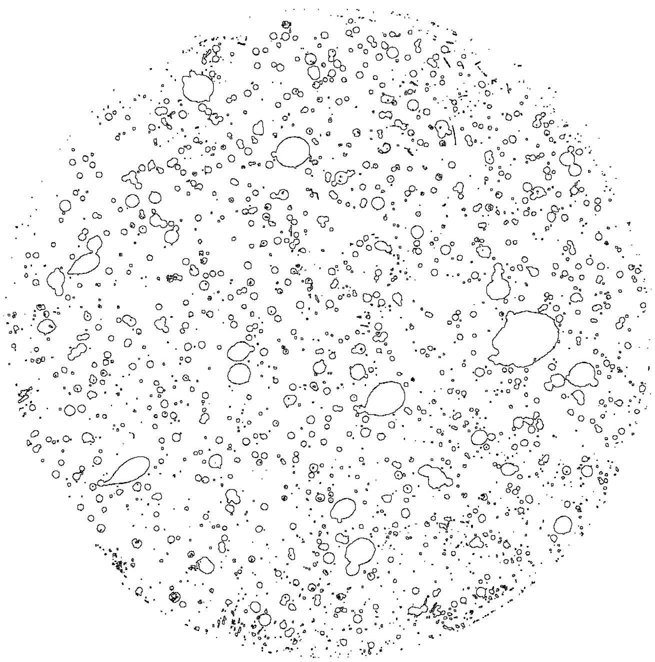

Figure 6. Typical Polylines

While this process doesn't necessarily require custom software, it can be very helpful and greatly speed the process. Selection of the threshold value is critical, as exposure varies from one scanned paper to the next. Photographic manipulation software, such as that which typically comes with the scanner, can perform these steps sequentially and the optimum threshold value can be selected by trial-and-error in a multi-step process. Custom software developed by the author allows a technician to quickly select the threshold value with a slider and see the results immediately in enhanced color rather than black-and-white. The unstained areas are displayed as pure ferric yellow (below the user-defined threshold luminosity) and the stained areas are displayed as pure ammonium blue (above the threshold) with black borders separating the two (equal to the threshold). The black borders become the polylines. A simple contour collection algorithm is then used to concatenate the contiguous black pixels into digital line segments. A typical processed image is shown in Figure 6 with a close-up in Figure 7.

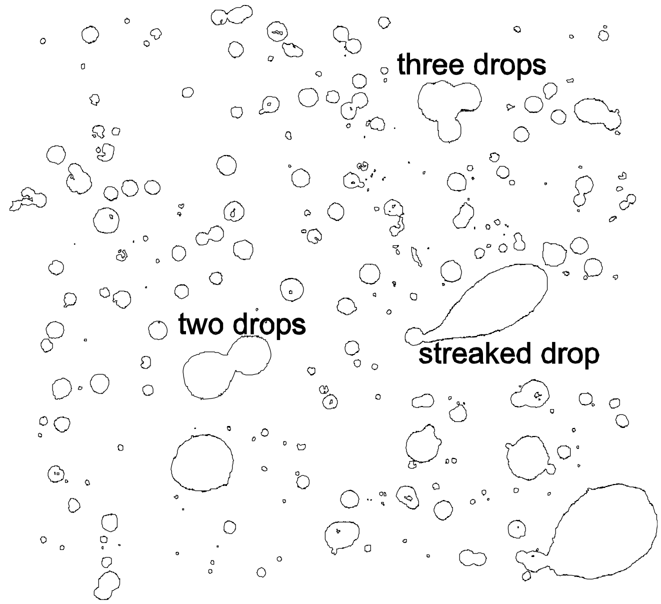

Figure 7. Common Anomalies

Dealing with Anomalies

If all of the stains were circular and non-overlapping, the rest of the process would be quite simple: compute the diameters and count the stains. There are, however, several common anomalies which must be addressed, including: irregularly-shaped stains and overlapping stains. These must be considered, regardless of the methodology, whether optical/manual or digital/automated.

Streaked or elongated stains as identified in Figure 7 were investigated experimentally by the Environmental Systems Corporation (Webb and Culver 1979). These experiments indicated that the minor diameter should be used, as the extent of elongation was indicative of impingement rather than size.

Overlapping stains are also identified in Figure 7. These can be handled numerically and can optionally be highlighted for attention by a technician. A non-overlapping, elongated stain (e.g., one shaped like a zucchini squash) will have an area closely equal to that of an ellipse: the product of the major and minor diameters times $\pi/4$; however, an overlapping stain (e.g., one shaped like a peanut or Mickey Mouse ears) will not; because the elongated stain is convex; whereas, the overlapping stain is not. The location of the stains on the paper is not of interest; therefore, the polygons can be sorted and re-displayed in order of increasing size or convexity. Two common types of anomalies are shown in Figures 8 and 9.

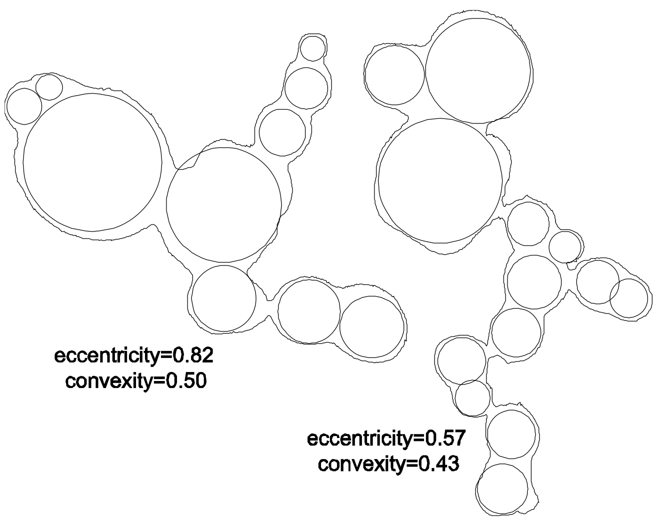

Figure 8. Overlapping Stains

Of the 2249 polyline objects shown in Figure 6, only 13 (0.6%) are degenerate. Upon examination

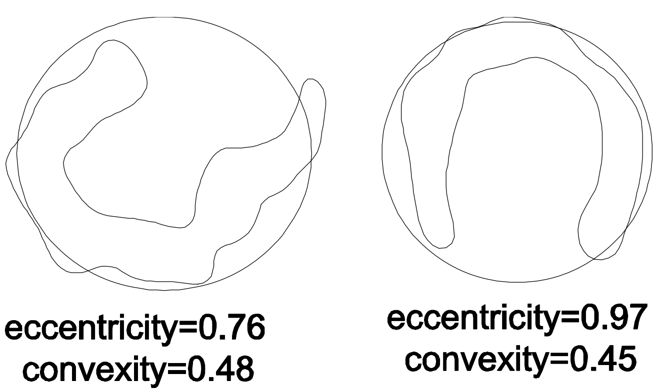

Figure 9. Other Anomalies

these appeared to be scratches, streaks, or hairlines, rather than stains formed by droplets, and were discarded as irrelevant artifacts. These degenerate objects were easily identified; because they have an eccentricity (ratio of the minor to major diameters) much less than 1. [Eccentricity ranges from 0 to 1. Almost all of the objects have an eccentricity significantly greater than 0.1.]

Convexity is the ratio of the polygonal area to the area of the inscribed circle. If the polygon were a circle, the value would be 1. If the polygon were a square, the value would be $4/\pi$. Convexity ranges from 0 to $4/\pi$. Of the 2249 polyline objects shown in Figure 6, only 28 (1.2%) exhibit the type of anomalous behavior illustrated in Figures 8 and 9. These all have a convexity less than 0.5. Almost all of the other objects have a convexity significantly greater than 0.5; so these are also easily identified computationally. If the anomalies are sufficiently few, they could simply be discarded.

There are several ways to interpret the anomalies shown in Figures 8 and 9. One possible interpretation is to speculate as to the round stains which might coalesce to form the resultant complex stain, then subdivide the polygon accordingly. This could be done manually or possibly automated, provided some sufficiently accurate algorithm could be developed. For the current analysis this was done manually using a polygon editor developed by the Author.

Size Distribution

Once the equivalent stain diameters have been determined, the size distribution is determined by first dividing the range of diameters into equal intervals (or "bins") based on the logarithm, then counting the number of stains that fall into each interval. More bins result in greater resolution along the log(diameter) axis, but less resolution along the count-per-bin axis, as the total number remains constant. The number of bins is a trade-off, especially when the total number of stains is small. The stain diameter distribution for the paper shown in Figure 6 is given in Figure 10.

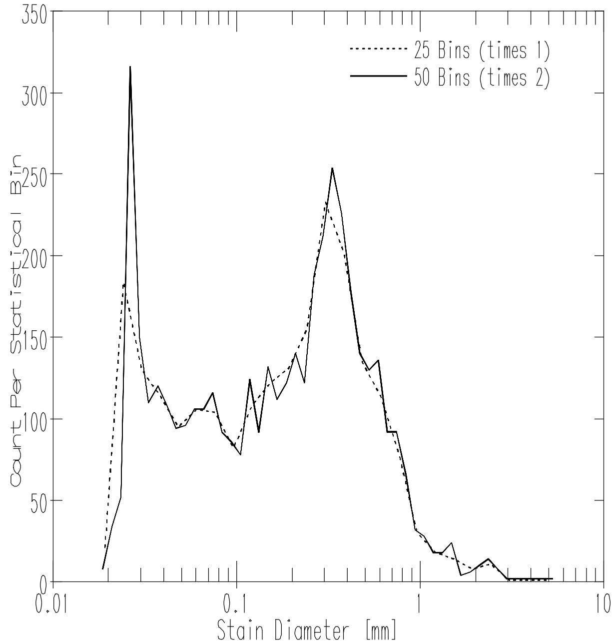

Figure 10. Stain Diameter Distribution

Two bin sizes are illustrated in Figure 10: 25 and 50. The actual (times 1) count is shown for the 25 bin curve. The count is doubled (times 2) for the 50 bin curve. The total number of stains is constant; so this makes the two lines have the same order of magnitude. This completes the digital analysis of the sensitive paper.

Summary

In summary, a digital method has been presented for analyzing water droplet stains on sensitive paper. This method begins by scanning the paper at a resolution of approximately 4800 dpi. A color separation is then performed in order to maximize the contrast between the paper and the stains. A solarization filter is applied along with a logical pixel operation which eliminates everything but the borders surrounding the stains. The borders are concatenated to form continuous, closed polygons. The eccentricity and convexity of the polygons is used to eliminate extraneous objects and identify anomalies such as incomplete and overlapping stains. The anomalous polygons are corrected or discarded. The equivalent diameters are divided into statistical bins and counted in order to determine the size distribution.

Conclusions

The digital method described herein is straight-forward and easily implemented using readily available, inexpensive equipment--at least when compared to the traditional method, which involves a microscope, projector, digitizing tablet, and much tedium. The software that comes with most scanners can be used to accomplish the graphical tasks. Customized software can streamline this process and further reduce time and effort. Anomalous stains are relatively few and must be handled regardless of the method, whether traditional or digital. Digital analysis of droplets on sensitive paper is the logical next step for this measurement technique.

Recommendations

The digital method described herein should be implemented and become the standard approach to analyzing sensitive paper data. Tests should be performed comparing this method to the traditional one. This could be accomplished as part of a future data collection effort or be based on a past effort, provided the sensitive papers (or photographs) are available and in good condition. A computational algorithm should be developed to handle the anomalous stains, possibly eliminating this manual step.

References

Runge, P. O. (1810) "Farben-Kugel oder Construction des Verhältnisses aller Mischungen der Farben zu einander, und ihrer vollständigen Affinität, mit angehängtem Versuch einer Ableitung der Harmonie in den Zusammenstellungen der Farben," Hamburg: Friedrich Perthes (as quoted in Wikipedia 2008).

Webb, R. O. and E. D. Culver (1979) "Calibration Study of Special Water Sensitive Paper Including Droplet Impaction at Oblique Angles," Environmental Systems Corporation Report for the Electric Power Research Institute, RP 1260-3, Amendment No. 1.

Wikipedia (2008) "HSL and HSV," http://en.wikipedia.org/wiki/HSL_color_space

Appendix: Drop vs. Stain Size

As mentioned previously, experiments were performed by Womack, Culver, Webb, and others in order to quantify various aspects of the droplet/sensitive paper interactions. A key relationship is that between initial droplet size and stain size. This is essential in order for the sensitive paper results to be useful. Precision droplet generators were used to create drops which were captured on sensitive papers and the stains measured. Webb and Culver (1979) provided the following figure summarizing these data.

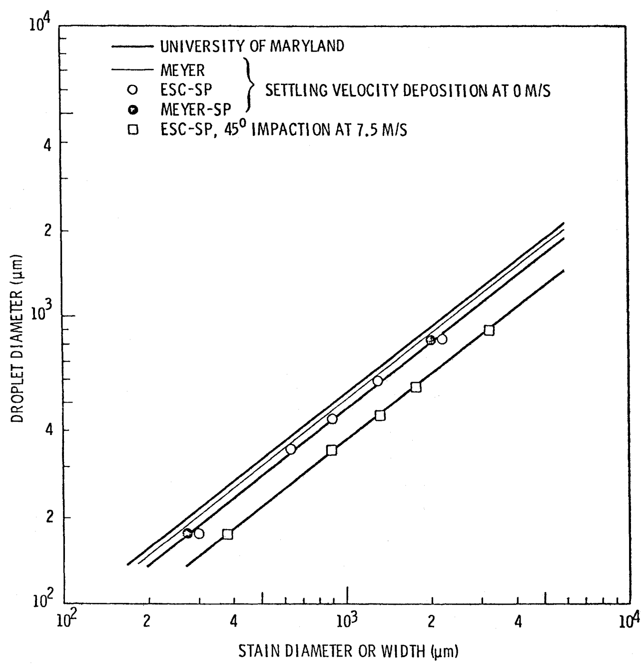

Figure 11. Droplet vs. Stain Size