ENHANCEMENT OF DIGITAL METHODS FOR DETERMINATION OF OPACITY

SI-1465

Performing Organizations

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September 21, 2007

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

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1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
16-03-2007	Final Technical Report	4/2006 - 3/2007

4. TITLE AND SUBTITLE
Enhancement of Digital Methods for Determination of Opacity

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
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5d. PROJECT NUMBER
1465

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
University of Utah
1471 Federal Way
Salt Lake City, UT 84112

8. PERFORMING ORGANIZATION REPORT NUMBER
UU1465

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Strategic Environemtnal Research and Development Program Office
901 North Stuart Street, Suite 303
Arlington, VA 22203

10. SPONSOR/MONITOR'S ACRONYM(S)
SERDP

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

Many DoD installations are subject to environmental regulations that require them to monitor opacity using EPA Reference Method 9, which relies on certified human observers. Maintaining EPA human-observer certification is expensive because each observer must attend a certification course twice annually. Furthermore, these opacity measurements are subject to potential inaccuracies and lack of reproducibility. Thus, DoD could benefit from a system that generates accurate and reproducible opacity measurements. Some methods currently exist for determining opacity digitally, and they perform well under sunny, cloudless conditions or with the use of an artificial physical background. This project developed an algorithm to determine opacity for stacks under challenging background conditions, such as trees. The algorithm is based on the principles of light attenuation and uses a stereo approach, in which a user takes two pictures: one of the plume and one of the background behind the plume. This method performed well for black plumes and for white plumes (opacity < 85%).

15. SUBJECT TERMS
opacity, air quality, digital camera

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			JoAnn S. Lighty
					19b. TELEPHONE NUMBER *(Include area code)* 801 581 5763

Reset

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

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ACRONYMS

DOCS	digital optical compliance system
DoD	Department of Defense
ETA	Eastern Technical Associates
EPA	U.S. Environmental Protection Agency
ROI	region of interest
SERDP	Strategic Environmental Research and Development Program
σ	standard deviation

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ACKNOWLEDGEMENTS

This project was supported by the Department of Defense's Strategic Environmental Research and Development Program. We wish to thank the Utah Department of Environmental Quality, Hill Air Force Base, and Eastern Technical Associates for supporting our participation in smoke school. The University of Utah and Visual Influence Inc. jointly developed and evaluated the algorithm approach presented in this report.

EXECUTIVE SUMMARY

Many Department of Defense (DoD) installations are subject to environmental regulations governing visible emissions and are required to monitor opacity using EPA Reference Method 9, which relies on certified human observers. Common sources of visible emissions include road dust, military exercises, and stacks from incinerators and boilers. Maintaining EPA human-observer certification is expensive because each observer must attend a certification course twice annually. Furthermore, human-observer opacity measurements are subject to potential inaccuracies and lack of reproducibility. Thus, DoD could benefit from a system that generates accurate and reproducible opacity measurements. In fact, some methods are currently available for determining opacity digitally, and they perform well under sunny, cloudless conditions or with the use of an artificial physical background.

The University of Utah and Visual influence team developed an approach to calculate opacity from digital images of stack emissions under challenging background conditions (e.g., trees, mountains, buildings) that employs a contrast-based method and stereo-image pairs. This new approach comprises two parts: a new computer algorithm and a new image collection method. First the user takes two pictures, one of the plume and background and one of only the background behind the plume, and the images are then registered (or aligned). The user then selects a region of interest, and opacity is calculated using the new computer algorithm, which is based on the relative contrast of the images, as defined by standard deviation.

We evaluated this approach for 342 images of black and white plumes collected during smoke school. For opacity values less than 85%, this contrast-based stereo approach agreed well with smoke-school measurements within acceptable error limits, as defined by EPA Method 9. This contrast-based stereo approach offers several advantages:

- The existing environment is the background. In other words, it does not require the introduction of a physical background behind a plume.
- It limits the need for camera calibration because it relies on the relative contrast of two identical cameras with identical camera settings.
- The raw results agree well with smoke-school measurements without the use of any correction factors.
- The approach should be applicable to most cameras.
- It is motivated by physical principles and has few free parameters.

Although the evaluation of the contrast-based stereo approach provided promising results for the evaluation of stack emissions, this approach is not applicable to blue-sky backgrounds, and it needs additional testing under various lighting and background conditions before it could be more widely accepted. We submitted a peer-reviewed publication to Environmental Science & Technology describing the results, and we are discussing the incorporation of this approach into existing software for calculating opacity.

1. OBJECTIVES

The objective of this project is to develop improved methods for determining opacity from stack emissions based on the analysis of digital images that will provide accurate and reproducible opacity measurements as well as a permanent record of the measurements. The objectives were developed in response to the SERDP (Strategic Environmental Research and Development Program) SEED statement of need (CPSEED-0601) to develop miniature sensors for monitoring air quality parameters. Our approach was evaluated using digital images collected during Eastern Technical Associates (ETA) smoke school that have corresponding transmissometer results. This approach represents an improvement over existing digital methods for estimating opacity by:

- working under a conditions under which are challenging for current digital-opacity methods;
- functioning for a wide range of commercially available digital cameras;
- being based on principles of light attenuation;
- not requiring the introduction of a physical background behind a plume; and
- being readily transferable to the next generation of digital-image-based opacity measurements.

Over the long term, the improved digital approach offers numerous advantages to the Department of Defense (DoD) including: the potential for wide use, cost savings, ease of use, small size, long lifetime, and reproducible measurements.

2. BACKGROUND

Many DoD installations are subject to environmental regulations governing visible emissions, defined in terms of opacity, through their air quality permits. Common sources of visible emissions include stacks from processes, such as incinerators and boilers, and dust from unpaved roads, military exercises, and construction activities. Remaining in compliance with environmental regulations, including opacity limits, is important to maintaining DoD operations. For example, exceeding permitted limits can result in operating restrictions and fines up to $27,500 per day per source. Additionally, many state and local regulatory agencies are beginning to require periodic, self monitoring as a condition of operating permits. In addition to regulatory requirements on visible emissions, particulate matter, the primary source of visible emissions, is a risk to human health (Dockery et al. 1993, Lighty et al. 2000, Tolbert et al. 2000).

Control and quantification of visible emissions is a challenge for DoD facilities. Some emission sources require in-stack monitors as part of a facility's permit, but, due to their installation and maintenance costs, in-stack monitors are a less common method for quantifying visible emissions than the Environmental Protection Agency (EPA) Reference Method 9, which relies on certified human observers (Federal Register 1971). The use of EPA-certified human observers for measuring opacity is also expensive because it requires each observer to attend two training courses per year, and large DoD installations can require numerous EPA-certified

observers. Beyond the costs, opacity measurements from human observers are subject to potential inaccuracies and lack of reproducibility. For example, it is not uncommon for facility personnel and regulatory agency personnel to arrive at significantly different opacity values when applying a Method 9 (i.e., human observer) approach (USEPA 1975). Furthermore, Method 9 results cannot be reanalyzed after the observations are recorded. Despite the current dependence on EPA-certified human observers in establishing compliance with regulatory opacity levels, EPA-sponsored field studies have demonstrated that human observers have difficulty in discriminating between opacity levels of 15%, 20%, and 25% (USEPA 1990). Thus, the problems associated with human-observer inaccuracy in measuring opacity as well as personnel certification costs have significant regulatory and economic implications throughout the DoD and for U.S. industry as well.

Visible emissions from individual sources are defined in terms of opacity, while visible impacts on the environment (i.e., haze) are defined in terms of visibility. Opacity is the portion of light that is attenuated (blocked) by air emissions. For example, an opacity value of 20% indicates that 20% of the incident light is blocked by air emissions while 80% is transmitted (USEPA 1975). In most cases, aerosols are responsible for light attenuation, and they block light transmission by scattering and absorbing it. Light attenuation by aerosols varies with an aerosol's composition, size, and humidity (Hinds 1999). For example, a black aerosol, such as soot, tends to absorb light, while a lighter colored aerosol, such as white smoke, tends to scatter light.

Light attenuation for a parallel beam of light is given by the Beer-Lambert law:

$$I = I_o e^{-\sigma L}$$

Where,
I = the light intensity after passing though the aerosol
I_o = initial light intensity
σ_e = extinction coefficient of the aerosol
L = distance between an object and the observer

Visibility is defined as the greatest distance at which an object of specified characteristics can be seen by the naked eye. Visibility impairment is often discussed as haze, which forms when sunlight encounters tiny particles in the air, thereby reducing the clarity and color of a visible scene, such as a landscape. Visibility is given by the following expression (AMG 1989).

$$C = C_o e^{-\sigma d}$$

Where
C_0= the inherent contrast,
C = the contrast of an object or target of observing,
σ = the extinction coefficient of the atmosphere, and
d = is the distance from observer to the object.

2.1 EPA Method 9

In many cases, the U.S. EPA and state regulatory agencies employ opacity estimates as a surrogate measure of compliance with particulate mass emission rates. Although US EPA requires many regulated sources to install continuous opacity monitors in their air emission stacks, the most common method for determining compliance with federal opacity standards is EPA Reference Method 9. Method 9 relies on trained human observers to visually estimate the opacity of a plume by taking a series of opacity measurements (USEPA 1975 and 1990; Federal Register 1971). To qualify as a Method 9–certified visual observer, an individual must successfully complete an EPA-approved Method 9 visual opacity "smoke school" once every six months. Successful completion of an EPA-approved Method 9 smoke school requires that during the opacity field test, the candidate must be able to assign an opacity reading to each of 25 white and 25 black smoke plumes with a margin of error not to exceed 7.5% on average (ETA 1990). The appearance of a plume as viewed by an observer depends upon a number of variables, including the angle of the observer with respect to the plume, the angle of the observer with respect to the sun, and the point of observation of attached and detached steam plume. EPA Method 9 includes specific guidelines for the observer with respect to these variables (USEPA 1975).

2.2 Automated methods for determining opacity

Because of the disadvantages of EPA method 9, investigators have proposed alternative methods for estimating opacity, including models based on aerosol properties (Ensor and Pilat 1971), new instrumentation (Lilienfeld et al. 1981), and techniques involving digital cameras (Malm et al. 1983, McFarland et al. 2003, Du et al. 2007). Ensor and Pilat (1971) proposed a model for estimating opacity from aerosol properties: mean particle diameter, standard deviation of the particle diameter (from the particle size distribution), aerosol density, and extinction coefficient of the aerosol. They successfully compared this model with simulated experimental data. However, collecting the detailed aerosol property information for a real-world plume is time consuming, expensive, and in some cases not practical. Lilienfeld et al. (1981) developed an instrument for remotely measuring the opacity of smoke-stack plumes, based on the attenuation of the polarized component of the Rayleigh-scattered background skylight. They used a two-color difference measurement of the polarization of the skylight through the plume is compared with a similar measurement of the unattenuated skylight adjacent to the plume.

As digital cameras became less expensive and produced higher quality images, new methods began to emerge. Although Malm et al. (1983) did not calculate opacity, they developed a method to compare air pollution effects using two digital images of the same scene and equations to describe atmospheric transmittance and path radiance for each pixel of interest. They applied this technique to images of clean-air conditions and simulated images of hazy conditions. More recently, a digital optical compliance system (DOCS) for determining the opacity of stack emissions was evaluated under a DoD Environmental Security Technology Certification Program project (McFarland et al. 2003). This digital method is based on pixel color, in particular saturation, in the plume and surrounding sky, and it performs reasonably well for black or white plumes under sunny, cloudless conditions. It does not perform as well under different conditions, such as when the plumes have significant color content (saturation) or when the plume is photographed against a cloudy sky or cluttered background.

Du et al. (2007) describe another digital method for determining opacity. They developed a two-part model based on contrast and transmission. First the camera response must be calibrated. Under clear-sky conditions, the user selects a transmission model, which calculates a relationship between the radiance in the plume and that in the background based on average pixel values to estimate opacity. They use a proportionality coefficient to tune this model for typical conditions. Under other conditions, a user must physically place a target or background behind the plume and selects a contrast model. The contrast model quantifies plume opacity from the change in contrast between two contrasting backgrounds that are located behind the plume and next to the plume (artificial target). They report that both methods perform well when tested against an EPA-certified smoke generator.

Although they did not measure opacity, it is interesting to note that Kwon (2004) used digital video images to identify visibility impairment for traffic applications. Specifically, the compared image contrast for targets located at multiple, known distances along a road during the daytime.

3. MATERIALS AND METHODS

3.1 Overview of the contrast-based stereo approach

The SERDP team selected a simple contrast-based algorithm for determining the opacity of an obscurant, such as smoke, in stereo-image pairs with sufficient background contrast. Contrast can be defined as the amount of visible detail in an image, which might come from trees, mountains or even buildings in the background. The contrast-based stereo approach includes the following steps (Figure 1):

- Image collection and registration
  - Capture stereo images
  - Register stereo images
  - Select a region of interest (ROI)
- Opacity calculation
  - Calculate aggregate standard deviation in each ROI

    σ_b = standard deviation of background colors

    σ_f = standard deviation of final colors
  - Calculate opacity:

$$\text{opacity} = \left[1 - \left(\frac{\sigma_f}{\sigma_b}\right)\right] \times 100$$

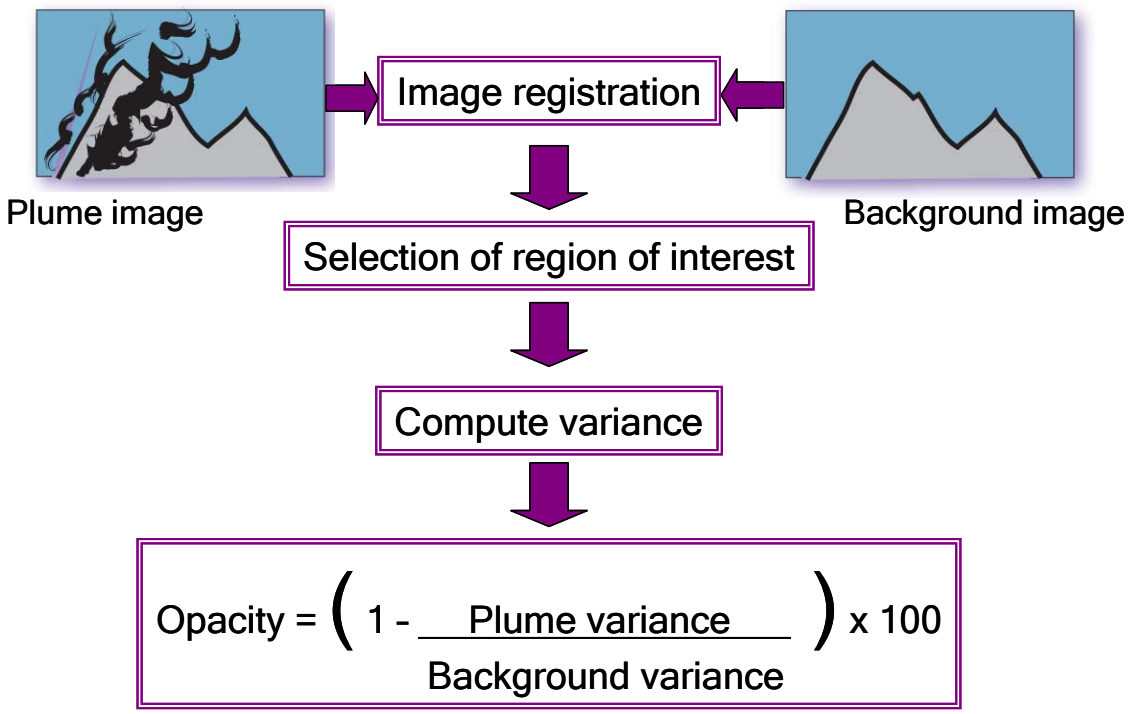

Figure 1. Opacity calculation using the relative contrast approach.

3.2 Image capture, registration, and selection of the region of interest

The first step of the relative contrast approach is to capture stereo images, one image of the plume and the other of the background behind the plume (Figure 2). Based on the registration requirement for stereo images, we developed the following rules of thumb for camera positioning and image capture:

- The observer should follow EPA Method 9 with regard to camera positioning, including distance from the stack, location of the sun, and other factors (Federal Register 1971, USEPA 1975).
- To capture a second stereo image (the background image), the second camera should be moved about 1.5 times the stack diameter in a direction that is perpendicular to the original view direction. Visually, the camera should be moved the minimum distance that exposes the complete background for the plume ROI.
- Registration of the two image pairs becomes difficult when objects in the background of one image occlude objects in the background of the second image. For example, leaves on a tree located just behind a plume in image #1 can occlude leaves and other features in image #2, because the images come from slightly different viewpoints. In general, the depth of occluding objects in the background, e.g. leaves in a tree, should be small relative to the distance between the plume and the background. Ideally, the background should be flat or planar, e.g. a distant hillside.

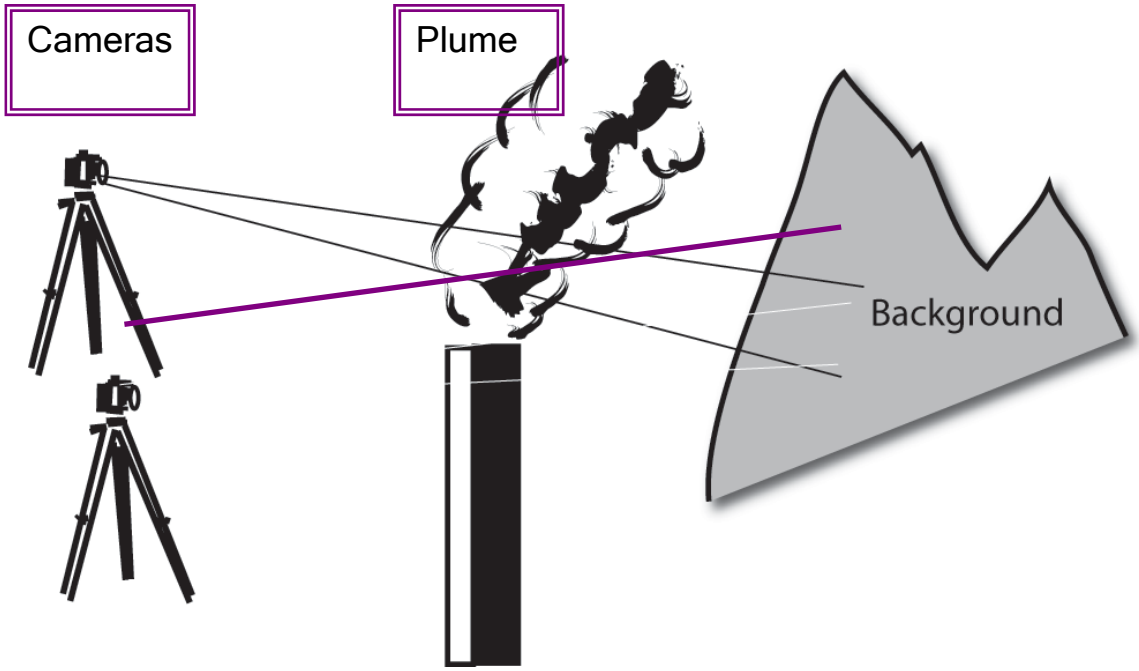

Figure 2. Stereo image collection.

Once stereo images have been captured, they need to be registered so that the portion of the plume just above the top of the smokestack is aligned with the corresponding portion of the background in the second image. Image registration is a key pre-processing step. The objective of the image registration step is to align the opacity-filled region of the image just above the stack with the same opacity-free region in the corresponding stereo image. An example of stereo image pairs is shown in Figure 3.

Figure 3. An example of stereo image pairs. Note that region of interest is discussed in the following paragraphs.

Automated registration would be prohibitively complex for stereo images containing smoke or some other obscurant. As a result, we developed an interactive manual 2D registration application called Reg2DViewer. The Reg2DViewer application allows a user to load in two images and hand align them using the mouse or the arrow keys. Several rendering modes are provided along with zooming and panning to ease the process of registration. For simplicity, we incorporated the ROI selection tool and opacity analysis into the Reg2DViewer application.

Following image registration, the user selects a ROI that includes the full width of the plume, starting just a few inches above the stack and including about 1/5 stack-width high (Figure 4).

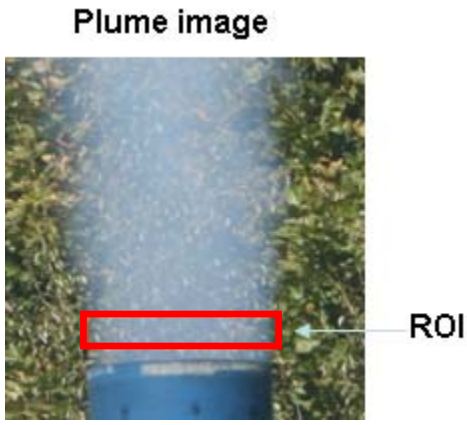

Figure 4. Selection of the region of interest.

3.3 Description of the computer algorithm

We represent contrast mathematically as standard deviation, a statistical measure, which is the square root of variance. Specifically, this algorithm uses *relative* contrast to measure opacity. In this case, relative contrast is the ratio of contrast with obscurant to contrast without the obscurant. As opacity increases, the contrast of the background (i.e. the amount of visible detail) decreases. When the opacity is 100%, no background detail is visible and therefore the contrast is 0. More formally, contrast is inversely related to opacity; as opacity increases, contrast decreases, and vice versa. This mathematical relationship between relative contrast and opacity allows us to calculate opacity for digital images. The need for comparing plume image values with corresponding background image values motivated the use of stereo-image pairs to capture both the plume and its background simultaneously. We selected aggregate standard deviation as a stable measure of contrast.

It is interesting to note that smoke school, under certain conditions, recommends an informal contrast method. That is, students are told to position themselves so that there is a background with visible detail behind a plume and to then use the decreasing visible detail as an aid in determining opacity.

For reference, the EPA Reference Method 9 definition of plume opacity is “the obscuring power of an emission expressed in percent” (USEPA 1975). Percent opacity is defined as

$$\text{Opacity} = \left[1 - \left(\frac{I}{I_0}\right)\right] \times 100$$

I_0 = incident light flux

I = light flux leaving the plume along the same light path

In order to relate digital-image pixel values with light, we use the absorption plus emission lighting model described by Max (1995). Figure 5 presents a simplified view of this lighting model. If we think of a pixel as a window and zoom in on a single pixel, some percent of what we see is obscurant (i.e., smoke) particles of some color, and the remaining percent is background color.

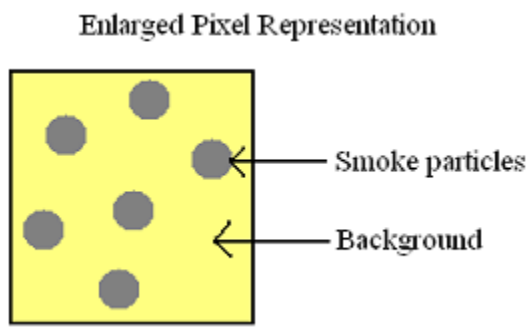

Figure 5. Simplified absorption plus emission lighting model (Max 1995).

If α (alpha) is the fraction of the pixel covered by obscurant particles, then (1 - α) is the fraction of the pixel covered by background color. The composite color of the pixel is

$$(\alpha \times \text{ obscurant color}) + [(1 - \alpha) \times \text{ background color}]$$

The generalization of this formula is called alpha blending or alpha compositing within the computer graphics domain. Alpha blending is simply a linear interpolation between two values to obtain a composite value. Max (1995) describes the derivation of the alpha compositing formula based on the absorption plus emission lighting model.

As described by Max (1995), α represents opacity. Because α is a fraction and opacity is defined by Method 9 as a percent, we let opacity = $\alpha \times 100$. In order to compute opacity we solve for α by taking advantage of the relationship between relative σ (standard deviation) and α.

$$\alpha = 1 - \left(\frac{\sigma_f}{\sigma_b}\right)$$

σ_b = standard deviation of background colors

σ_f = standard deviation of final colors

The mathematical proof of this formula is provided in Appendix A. The resulting equation for opacity is:

$$\text{opacity} = \left[1 - \left(\frac{\sigma_f}{\sigma_b}\right)\right] \times 100$$

Our relative contrast algorithm uses this formula for opacity. As an example, if opacity is 100%, there is no variance in the pixel colors (modulo the relatively minor effects of camera sensitivity, compression artifacts, etc) and therefore $\sigma_f = 0$ and $\alpha = 1$. At an opacity of 0%, $\sigma_f = \sigma_b$ and $\alpha = 0$.

The relative contrast algorithm requires two images for which contrast is calculated and compared. One image has a background with some amount of contrast, and the other image has the same background with a plume obscuring it. These images could hypothetically be two different regions from the same digital photograph, or corresponding regions from two different digital photographs of the same scene. We first evaluated the use of two regions from the same photograph, with the hypothesis being that the background behind a plume could be approximated by selecting a same-sized, statistically similar area of the image near the plume. The standard deviation for the plume region and the neighboring background region would be compared to calculate opacity.

To assess this hypothesis, we evaluated the statistical similarity of nearby image regions by calculating the relative opacity for the two regions. If the regions were statistically similar, the resulting opacity would be near zero. Any non-zero opacity would represent error that would be introduced into the opacity calculation if one region were used as a substitute for the other region. We considered less than 5% opacity to be acceptable error. The results indicated that it is actually quite difficult to reliably find nearby ROIs (regions of interest) with sufficiently similar standard deviations. We conducted a similar test with varying ROI sizes. The intuition was that as ROI size increased, feature size would decrease and the standard deviations would become more similar for neighboring ROIs. However, no region size reliably produced statistically similar standard deviation (i.e. opacity always less than 5% for neighboring regions) for all images, although larger regions tend to provide more similar statistics.

These results led us to reject the possibility of using two different regions from the same digital photograph for contrast-based opacity calculation. The next approach we evaluated was the use of stereo images. This scenario requires observers to change the camera location slightly to take images of both the plume and the background behind the plume (Figure 2). These images would be registered (aligned) prior to opacity calculation. We found that stereo images provided sufficient accuracy as long as the plume and its background region from the second image were registered to within a few pixels.

The aligned portion in both images is used as the ROI for opacity calculation. Aggregate standard deviation is then calculated for both ROIs. To calculate aggregate standard deviation for red, green, blue pixel values, the standard deviation is computed of the red channel for all the pixels, then for the green channel, then for the blue channel; and then those three values are

averaged. Finally, the ratio of standard deviation is used to calculate opacity. The resulting algorithm is simple and does not require the use of correction factors.

The opacity of the plume near the opening of the smokestack (before the smoke is dispersed much) can be modeled as an ellipse function from left to right, corresponding to the circular shape of the smokestack opening. The opacity in the center of the plume is higher than the opacity near the edges. Therefore even with a uniform background, the pixel values for a plume image have non-zero standard deviation. It may be useful to take this into account when calculating opacity based on relative aggregate standard deviation. Our algorithm contains no adjustment for the standard deviation within the smoke itself. Rather, we chose to defer this step until after we had a chance to evaluate the algorithm in its simplest form.

It should be noted that the relative contrast algorithm requires some minimal amount of contrast in the background image, otherwise relative contrast has no meaning. In other words, we cannot measure a reduction in contrast due to a plume if there was no contrast in the background initially. This is why contrast-based methods do not work in blue-sky conditions. The ratio $\left(\frac{\sigma_f}{\sigma_b}\right)$ is undefined if $\sigma_b = 0$.

3.4 Collection of images from smoke school

The SERDP team collected and analyzed three sets of stereo images from plumes. The first set of images was primarily collected to evaluate the data collection process itself including camera settings, camera location, and data organization. We experimented with automatic versus manual settings for white balance, focus, shutter speed, ISO, raw picture files, and more standard high-resolution images. Based on our analysis of the data from the first collection, we identified four key camera settings:

- The cameras should be identical having identical settings (ISO, shutter speed, zoom, focus etc.). Note, we did not evaluate the use of two different cameras.
- Selection of the correct white balance for the conditions is important.
- The plume and the background should be in as much in focus in possible.
- The images should be collected simultaneously with a remote control. Time synchronization of the stereo pairs is important, as lighting changes and background objects moving (e.g. leaves blowing) can adversely affect the ability to register images.

Using these findings, we modified our image collection procedure slightly, including the use of camera remote control, which allowed us to collect time-synchronized images. The second set of images was collected during the Utah Department of Environmental Quality smoke school. Unfortunately, blue sky was the only available background, given the sun angle and other location constraints, so the second set of images was not as useful for testing the stereo-image algorithm for more challenging background conditions.

The third set of images was collected during ETA smoke school at the Utah State Fairgrounds on September 27, 2006 between 9 am and noon, and this location offered a background of a stand of trees. The digital image collection procedures were consistent with those of EPA Method 9 (USEPA 1975). During testing, the weather conditions were sunny with light winds from the south, southeast at 0 – 6 mph, a temperature ranging from 55 – 68 °F, visibility of 10 miles, and a barometric pressure of 30.27 mmHg. The sun was oriented in the 160° sector to the back of the cameras. All images were collected with two Cannon D30 cameras with identical settings: ISO 100, aperture 13, shutter speed 100, large image size, zoom 200, focus 10, and white balance set to sun. The cameras were positioned approximately 70 feet away from the emission stack on tripods, approximately 2 feet apart, and had clear, unobstructed views of the plume and background. The stack was approximately 15-feet high, and EPA Method 9 requires that visual observations at a distance of no less than 45 feet (3 stack heights) from the stack. Each camera was labeled, and the images were stored on a 1 gigabyte memory card. Following each dataset (25 white plumes and 25 black plumes), the images were stored on a computer file, which was labeled with the camera ID, date, and time. ETA provided transmissometer readings for each of the smoke-school images. We collected a total of 152 images of black plumes and 190 images of white plumes from ETA smoke school in Utah. All opacities were randomly selected by the smoke school operator and ranged from 0 to 100%.

4. RESULTS AND ACCOMPLISHMENTS

As a first step in evaluating the algorithm, we used synthetic images in order to verify that our software correctly implemented the relative contrast algorithm, as well as to provide empirical evidence of the established mathematical relationship between alpha and standard deviation. The synthetic images were created by adding a known opacity to existing images. The alpha-blending formula was used to combine background color and opacity-added color for each pixel. The synthetic images ranged in opacity from 0% to 100% in increments of 10%. For all images the software correctly calculated the opacity of the synthetic smoke, validating the software implementation and providing some validation of the viability of the algorithm itself.

The next step was to test the algorithm with real data collected in the field, as described in Section 3.2 (Figure 4). The analysis consisted of registering stereo images, selecting a ROI, computing opacity for the ROI, and finally comparing computed opacity with actual opacity. The analysis was completed for 190 white plume images and 152 black plume images, with known transmissometer opacity values ranging from 0% to 100% in intervals of 5%. For white plumes this means that there were 95 white plume image pairs (190 actual images), each of which contributed two opacity readings for a total of 190 data points for white plumes.

Opacity was computed for the selected ROI using the relative contrast algorithm as described in Section 3.3. Figure 6 depicts the contrast algorithm steps, from image collection through opacity calculation.

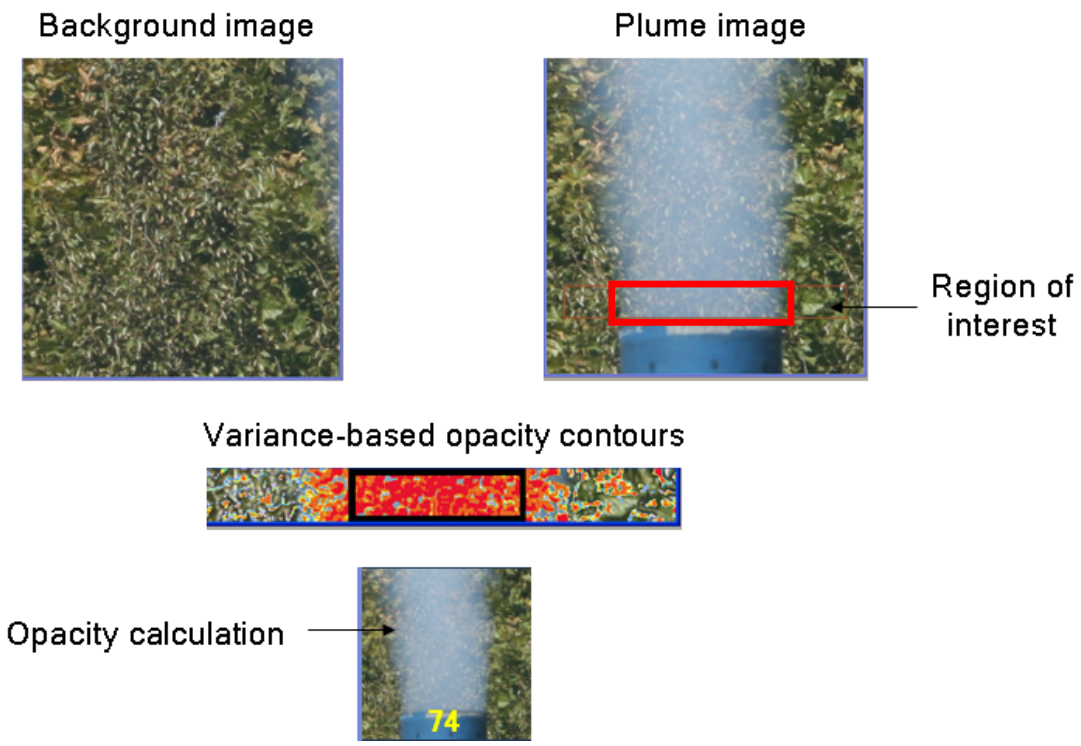

Figure 6. Calculation of opacity using smoke-school images.

Figures 8 and 9 show scatter plots of the calculated opacity values and the true transmissometer readings for white and black plumes, collected at smoke school. For the white plumes, the average error was 7.5%, the maximum allowed in smoke school, and a few of the individual regions exceeded the 15% error. For black plumes, the average error was 5.5%, within smoke school allowed error.

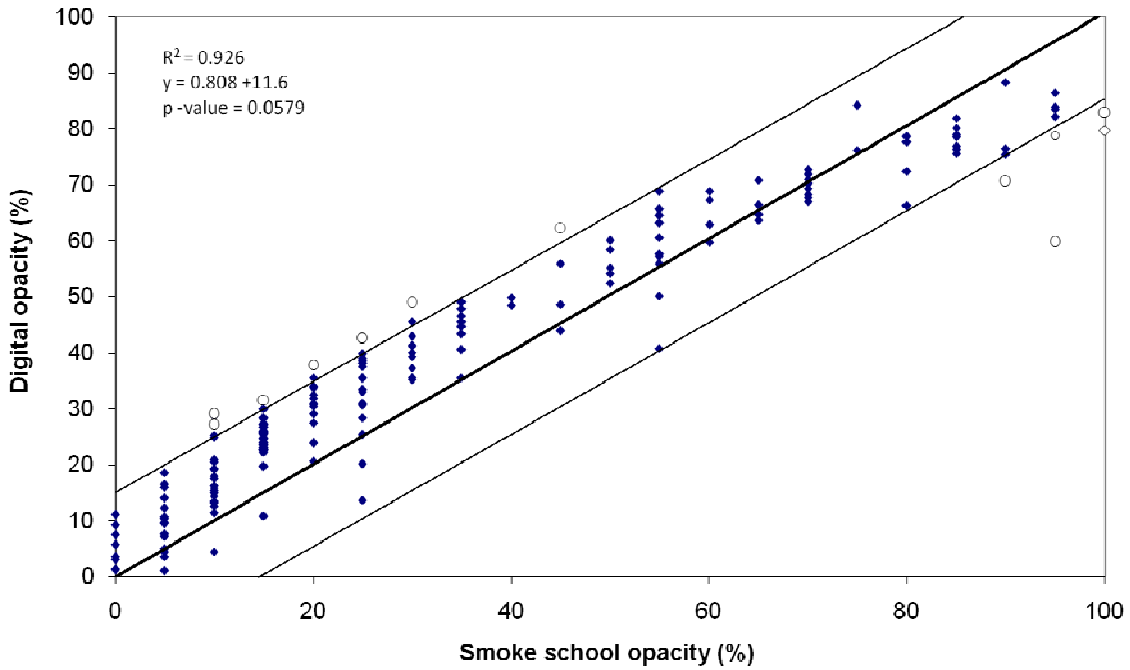

Figure 7. Scatter plot of calculated opacity from digital images and actual transmissometer opacity for white plumes. The thick black line shows the correct transmissometer opacity value; the thin black lines show the maximum 15% error allowed for any single reading (according to EPA Method 9 certification procedures). The dark diamonds show the data from the contrast-based algorithm, and hollow circles show values that exceed the maximum 15% error. The R2 value refers to the correlation between the calculated and actual opacity values. The slope and intercept are presented as if line were drawn through all the calculated opacity values. The p-value is for a calculated opacity that differs by at least 15 opacity points different from the actual opacity value.

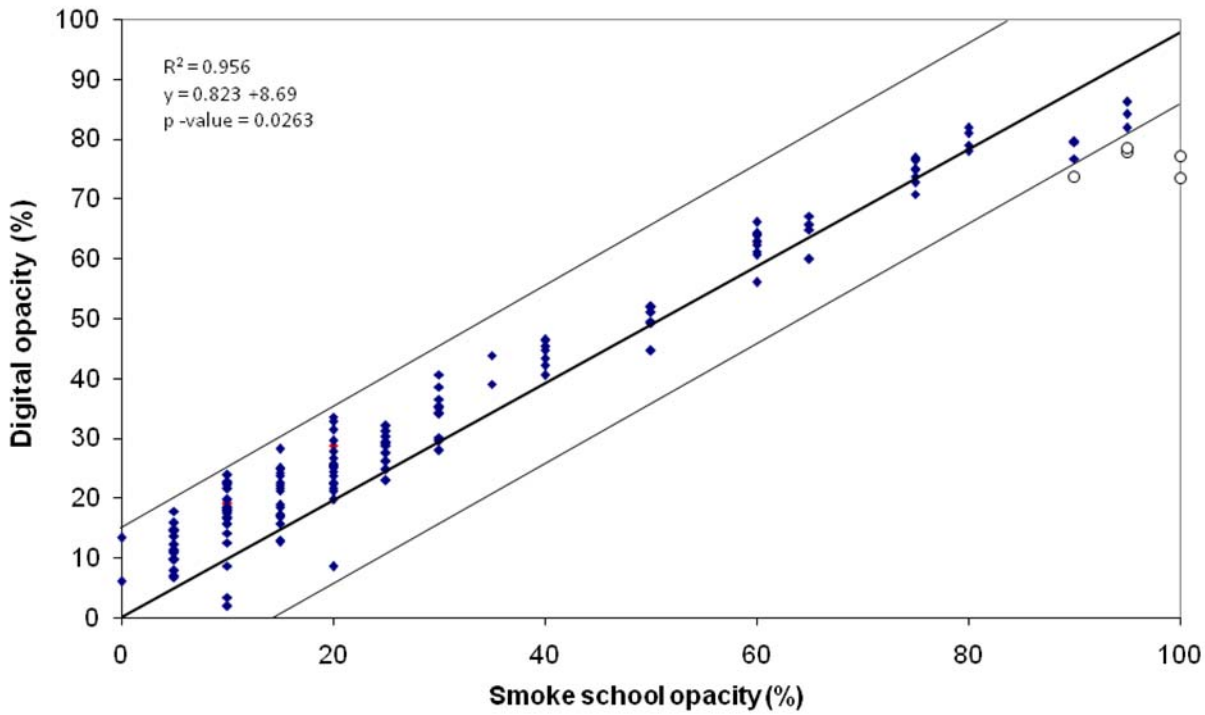

Figure 8. Scatter plot of calculated opacity from digital images and actual transmissometer opacity for black plumes. See the legend for Figure 8 for a description of the lines, symbols, and definition of the statistical measures.

For both black and white plumes, our contrast-based algorithm tends to underestimate opacity at the highest levels (above 85%). However, opacity limits above 80% are extremely rare. The algorithm also tends to over-estimate opacity for low-opacity values, although these are often within acceptable error limits, as defined by EPA Method 9. Further investigation will be necessary to determine the reasons and potential solutions for this. If these trends were reproducible under various lighting conditions, then a correction factor could be developed to tune our computed opacities.

In order to evaluate the stability of the computed values in Figures 8 and 9 to image mis-registration, we performed a sensitivity analysis. For each registered image pair (one showing the plume, and one showing the corresponding background), we computed a total of 73 opacity values. These 73 opacity values correspond to slightly mis-registered plume and background images, as well as to slight changes to the selected ROI. The 73 permutations were chosen by:

- Holding the background ROI fixed and modifying the source ROI by translating it by 3 or 6 pixels vertically and/or horizontally. Ignoring the case with no translation, this gives 24 permutations (a 5x5 grid, less the center point).
- Moving the background ROI and foreground ROI together, translating the ROIs by 3 or 6 pixels vertically and/or horizontally. This again generates a 5x5 grid and ignores the center case and also yields 24 permutations.

- Again modifying the background and foreground ROIs together, growing/ shrinking the ROI by 6 or 12 pixels vertically and/or horizontally. This adds another 24 cases.
- Evaluating the original ROI (no translation or scaling). This yields the last case.

For the 73 permutations associated with each sample (a plume image, its corresponding background image, and the ROI of the plume), we computed the following values over those 73 permutations: the average opacity, the variance of the opacities, and the maximum difference between any pair of permutations (Figures 11-13). Note that the black plumes and white plumes have been combined for these graphs.

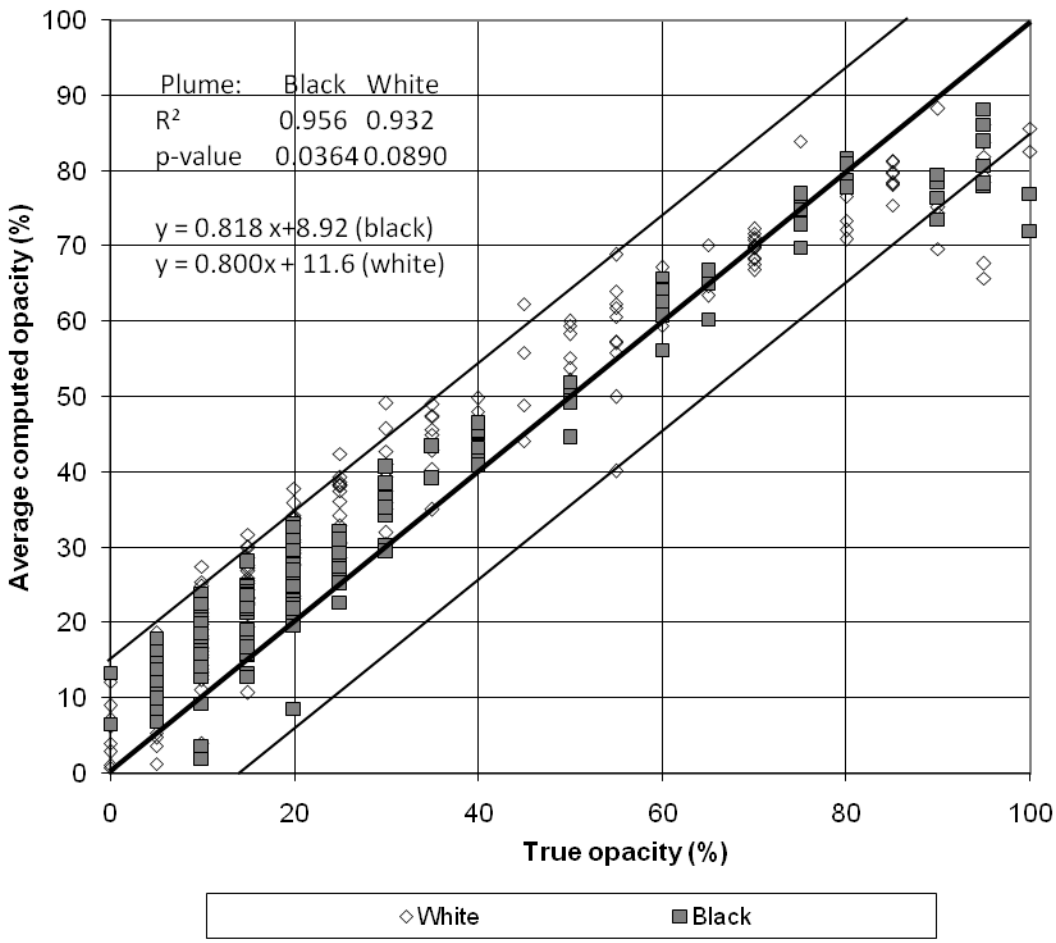

Figure 9. Average value of permutations for each sample. See the legend for Figure 8 for a description of the lines, symbols, and definition of the statistical measures.

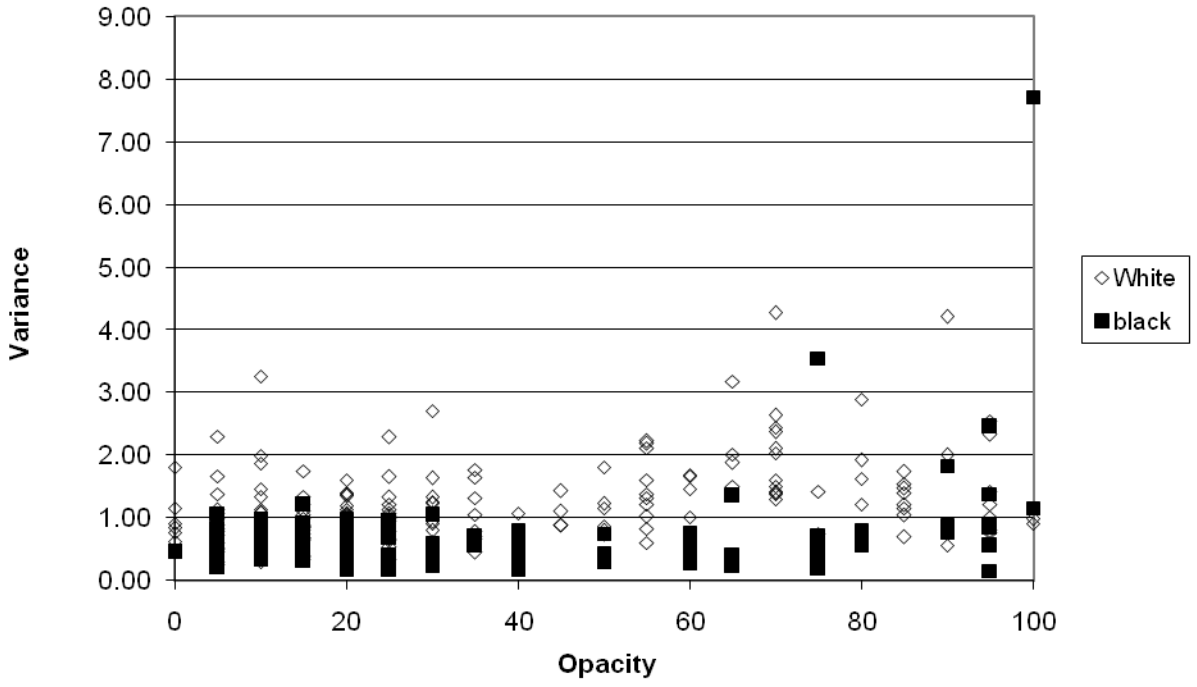

Figure 10. Variance of permutations for each sample.

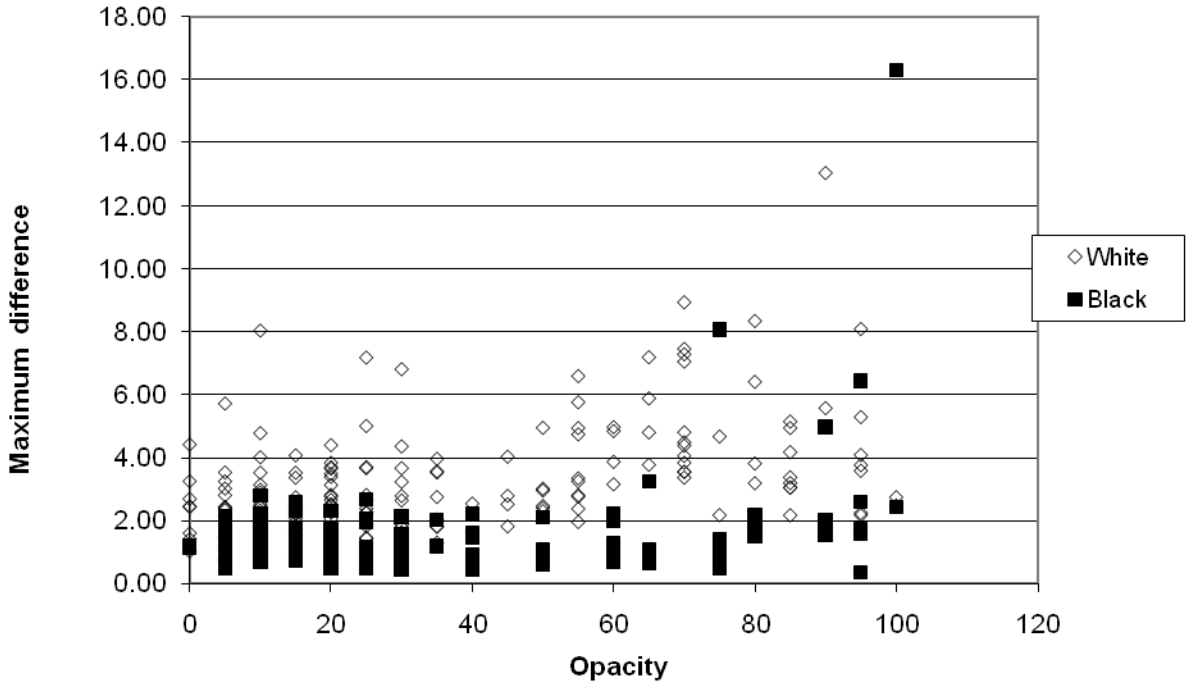

Figure 11. Maximum difference of permutations for each sample.

Figures 9 – 11 show that mis-registration can affect opacity values, although its effect is generally small, less than 5% variance. However, misregistration tends to have a larger effect at opacities of 80% or greater.

One recommended direction for future work would be to collect and analyze additional stereo-image pairs under different lighting and background conditions to assess whether the underestimation of high opacities and the slight overestimation of low opacities are consistent trends. It would also be worth analyzing whether "tuning" the model using the data we collected (by pushing it through the inverse of the trendline) would produce results within the bounds prescribed by Method 9. Furthermore, it may also be possible to identify family of trends based on a single parameter (e.g. latitude).

5. CONCLUSIONS

The University of Utah and Visual influence team developed an approach to calculate opacity from digital images from stacks under challenging background conditions that employs a contrast-based approach and stereo-image pairs. We evaluated this approach on 342 images of black and white plumes from smoke school. For opacity values less than 85%, our contrast-based stereo approach agreed well with transmissometer smoke-school measurements within acceptable error limits, as defined by EPA Method 9. In summary, the contrast-based stereo approach offers several advantages:

- The existing environment is the background. In other words, it does not require the introduction of a physical background behind a plume.It limits the need for camera calibration because it relies on the relative contrast of two identical cameras with identical camera settings.
- The raw results agree well with smoke-school measurements without the use of any correction factors.
- The approach should be applicable to most cameras, although cameras with manual settings, especially white balance, are preferred.
- It is motivated by physical principles and has few free parameters.

Although the evaluation of the contrast-based stereo approach provided promising results, it is not applicable to blue-sky backgrounds, and it needs more extensive testing under various lighting and background conditions before it could be more widely accepted. We expect that this approach will be incorporated into one of the existing digital methods for calculating opacity. Our team has begun discussions with Hill Air Force Base to incorporate our approach into the DOCS system for stacks. In addition, we submitted the results of this work to journal, Environmental Science & Technology.

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APPENDIX A: PROOF OF THE RELATIONSHIP BETWEEN α AND σ

$$\alpha = 1 - \left(\frac{\sigma_f}{\sigma_b} \right)$$

<u>Given</u>

Note: opacity = 100 * α
σ = standard deviation
c_{b_i} = background color for a single pixel (without smoke)
c_{f_i} = final color for a single pixel (with smoke)
c_s = smoke color, assumed to be constant for all pixels
σ_b = standard deviation of background colors
σ_f = standard deviation of final colors

Alpha-blending formula:

$$c_{f_i} = \alpha c_s + (1-\alpha) c_{b_i}$$

rewritten as:

$$c_{f_i} = c_{b_i} + \alpha (c_s - c_{b_i})$$

Definition of standard deviation:

$$\sigma = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (x_i - \overline{x})^2}$$

$$\sigma_b = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (c_{b_i} - \overline{c_b})^2}$$

$$\sigma_f = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (c_{f_i} - \overline{c_f})^2}$$

<u>Proof</u>

Using $c_{f_i} = c_{b_i} + \alpha (c_s - c_{b_i})$ as given,

$$\sigma_f = \sqrt{\frac{1}{N}\sum_{i=1}^{N}((c_{b_i} + \alpha(c_s - c_{b_i})) - \overline{(c_b + \alpha(c_s - c_b))})^2}$$

$$\overline{(c_b + \alpha(c_s - c_b))}$$
$$= \overline{(c_b + \alpha c_s - \alpha c_b)}$$
$$= \overline{c_b} + \alpha c_s - \overline{\alpha c_b}$$
$$= \overline{c_b} + \alpha c_s - \alpha\overline{c_b}$$
$$= \alpha c_s + (1-\alpha)\overline{c_b}$$

$$\therefore\ \sigma_f = \sqrt{\frac{1}{N}\sum_{i=1}^{N}((c_{b_i} + \alpha(c_s - c_{b_i})) - (\alpha c_s + (1-\alpha)\overline{c_b}))^2}$$

$$= \sqrt{\frac{1}{N}\sum_{i=1}^{N}(c_{b_i} + \alpha c_s - \alpha c_{b_i} - \alpha c_s - (1-\alpha)\overline{c_b})^2}$$

$$= \sqrt{\frac{1}{N}\sum_{i=1}^{N}(c_{b_i} - \alpha c_{b_i} - (1-\alpha)\overline{c_b})^2}$$

$$= \sqrt{\frac{1}{N}\sum_{i=1}^{N}((1-\alpha)c_{b_i} - (1-\alpha)\overline{c_b})^2}$$

$$= \sqrt{\frac{1}{N}\sum_{i=1}^{N}((1-\alpha)(c_{b_i} - \overline{c_b}))^2}$$

$$= (1-\alpha)\sqrt{\frac{1}{N}\sum_{i=1}^{N}(c_{b_i} - \overline{c_b})^2}$$

$$= (1-\alpha)\sigma_b$$

$$\sigma_f = (1-\alpha)\sigma_b$$

$$\sigma_f = \sigma_b - \alpha\sigma_b$$

$$\alpha\sigma_b = \sigma_b - \sigma_f$$

$$\alpha = 1 - \left(\frac{\sigma_f}{\sigma_b}\right)$$

Q.E.D.

APPENDIX B: PRESENTATIONS/PUBLICATIONS

K.E. Kelly, J.S. Lighty, R.T. Whitaker, J. Desha, D.M Weinstein (2006) Enhancement of Digital Methods for Determination of Opacity, Partners in Environmental Technology: Technical Symposium and Workshop, Washington, DC, November 28 – 30, 2006.

K.E. Kelly, J.S. Lighty, R.T. Whitaker, J. Desha, D.M Weinstein (in preparation) Enhancement of Digital Methods for Determination of Opacity.