2.3 APPLYING PHOTOGRAMMETRIC TECHNIQUES TO STUDY SMOKE PLUMES

Kerrie J. Long, Sue Ellen Haupt, Michael Hendrickson, Janice Keay
Applied Research Laboratory, The Pennsylvania State University, University Park, Pennsylvania

1. INTRODUCTION

The goal of the experimental study is to characterize the plumes from military search and rescue (SAR) marker smoke grenades. Because the SAR markers are specifically constructed to optimize visibility of their smoke plumes, we can employ readily available, highly sophisticated sensors for the visible portion of the electromagnetic spectrum; that is, we use single lens reflex (SLR) cameras and video cameras as measuring devices. Note that photogrammetric measurement can be highly sophisticated and is equivalent to the particle imaging velocity methods frequently employed for visualizing fluid flow. Thus, we have adapted photogrammetric techniques and developed new methodologies to measure the properties of the smoke plumes emitted from the SAR markers.

Note that the plan to characterize a typical smoke plume in the open atmosphere is an ill-posed problem. Due to the turbulent nature of the atmosphere, the dispersion of an airborne contaminant is sensitive to initial conditions and thus, unpredictable (Lorenz 1963). Thus, every realization of contaminant dispersion will be somewhat different (Wyngaard 2010). A typical modeling approach to dealing with this chaotic dispersion is to run an ensemble of simulations (Kalnay 2003, Hamill et al. 2000). In fact, by nature, any model of atmospheric transport and dispersion represents an ensemble average estimate (Wyngaard 2010). The ensemble approach has also been applied to experimental measurements of contaminant dispersion (Storwold 2007) and the approach taken here.

The methods that we used for measuring the plumes are described in section 2. Section 3 describes the experiment site. The experiments themselves are documented in section 4. Section 5 describes the results of data post-processing. The work is summarized and further discussed in section 6.

2. PHOTOGRAMMETRIC METHODS

The advantage of using SAR markers as the contaminant source is that they are constructed specifically to optimize their visibility properties. Thus, they are a useful source of airborne contaminant that can be measured using easily available equipment (cameras) to record their signature in the visible spectrum. The disadvantage to the SAR markers is that they are pyrotechnic; thus, an element of uncertainty is added to the emission source due to an uneven burn rate and a temperature induced buoyancy effect on the resulting plume. We deal with these issues using the same philosophy that is employed for the turbulent fluctuations – we conduct an ensemble of realizations of our experiment under similar meteorological conditions and seek to find an average condition that represents an ensemble average behavior of the plume under these conditions.

In order to fully characterize the plume, we used three cameras situated so that one SLR camera (camera 1) is perpendicular to the plume axis and views the plume in front of a specially constructed background (described in section 2.1). A second SLR camera (camera 2) is located just upwind of the SAR marker smoke release and perpendicular to the line of sight of the first camera. Camera 3 is located in the far field and situated to best record the full plume. Figure 1 depicts the experimental layout. The rationale for the camera positions is to best enable three dimensional reconstruction of the plume at any specified time using methods akin to those described by Rasmussen et al. (2003). We used surveying tools to accurately measure the relative locations of the cameras, release location, and meteorological instrumentation. Records were kept of the manual camera settings as well as for the release times and durations. Photographs of each plume were taken at 5 second interval which yielded approximately 10 photographs for each release.

For our purposes the plume must be visible from a distance and we needed to develop tests that quantified visibility. Specifically, we were interested in developing a test that was repeatable so that we could gain an understanding of the typical smoke grenade release.

**Corresponding author address:* Kerrie J. Long, Applied Research Laboratory, P.O. Box 30, The Pennsylvania State University, State College, PA, 16804-0030; e-mail: kjl203@psu.edu

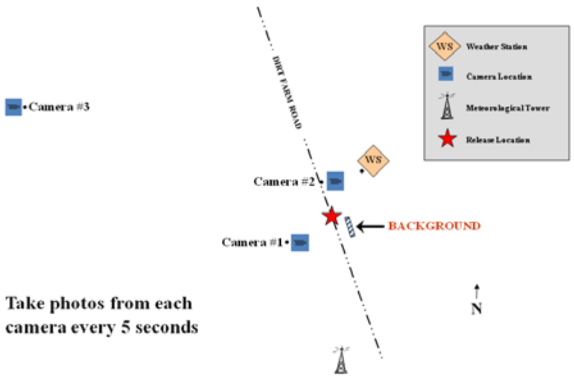

Figure 1. Experimental site layout.

2.1 *Opacity Measurement*

Opacity measurements allow us to quantify the visibility of the plume in a way that is repeatable and measurable. A method for measuring plume opacity was adapted from Du et al. (2007). We constructed a black and white checkerboard background to be mounted behind the plume and parallel to its axis. The background was constructed to be 3.05 m tall and include six alternating black or white squares (as will be visible in photographs of the plume in figures 3 through 8). The plume opacity is calculated by taking photographs with a digital SLR camera and obtaining the light intensity from the pixel values from the photographs in Photoshop. A contrast model can then be used to determine opacity based on pixel values from the plume transmittance determined through both the white and the black backgrounds. Specifically opacity can be calculated as

$$\mathbf{Opacity} = 1 - \frac{\mathbf{N_{wp}} - \mathbf{N_{bp}}}{\mathbf{N_w} - \mathbf{N_b}} \qquad (1)$$

where N_w and N_b are defined as the pixel values of the target unobstructed by the plume while N_{wp} and N_{bp} are defined as pixel values of the plume in front of the target. Figure 2 demonstrates the geometry of the variables.

Figure 2. Geometry defining the variables for computing opacity by (1).

2.2 *Optical Depth Measurement*

A related measurement of the optical depth of the plume is based on the transmittance of light through the plume. Optical depth (τ) is the amount of light removed from a beam of light (by scattering or absorption) during its path through the air to the camera. An optically thin cloud would have a value of $\tau << 1$ and an optically thick cloud would have a value of $\tau >> 1$. For this part of the experiment we used light sources affixed to the background used for the opacity measurements. These light sources are bike lights that can be set to three different intensities. Once again, Photoshop is used for post-processing to determine the relative amount of light transmitted through the plume. Specifically, we determined the intensity (quantified by the pixel value in the image) of the light source with no plume present (I_0) and that with the light passing through the plume (I_{plume}). The optical depth is then

$$\tau = -\ln\left(\frac{\mathbf{I_{plume}}}{\mathbf{I_o}}\right) . \qquad (2)$$

3. MEASUREMENT SITE

The locale selected for these experiments is the Rock Springs test site in central Pennsylvania nearby State College. The site is owned by The Pennsylvania State University and is instrumented with several meteorological towers that measure environmental fluxes in addition to wind and temperature variables at several different heights at several locations. The terrain includes parallel mountain ridges separated by valleys well known for their agricultural value. In addition, our colleagues in the Meteorology Department at Penn State produce twice daily fine-resolution runs of the Weather Research Forecast (WRF) model with nested domains that could be used in subsequent modeling studies. The topography of this Central Pennsylvania region is depicted in Figure 2. The mountain ridges are oriented Southwest to Northeast and separated by broad valleys.

The vicinity of the experimental site is richly instrumented for meteorological variables. A 10 m tower within a few meters of the release site measures three dimensional winds at 2 and 9 m and temperature at 2, 3, 5, 8, and 9 m. Within a few kilometers of the release site, there is also instrumentation to measure longwave and shortwave radiation, both incoming and outgoing.

In addition, we set up an additional AIRMAR Weather Station PB100 in the near field of the release to obtain additional wind and temperature data on the day of the experiments. The locations of the meteorological tower of the Weather Station are indicated on Figure 1.

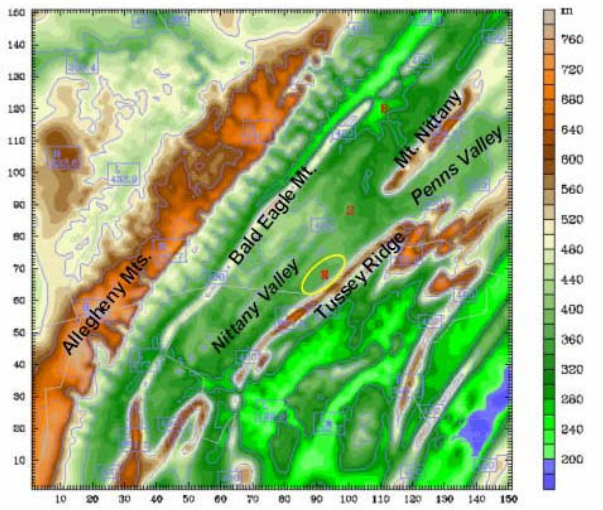

Figure 2. Topography of the region surrounding the Rock Springs site. The oval indicates the local observation network.

4. THE EXPERIMENTS

The primary experimental day was June 12, 2009, which proved to be a mild summer day with light winds and overcast skies.[1] The wind was generally out of the northwest for the entire period at an average speed of 0.8 ± 0.4 m/s (Figure 3). The average temperature was 26.5°C.

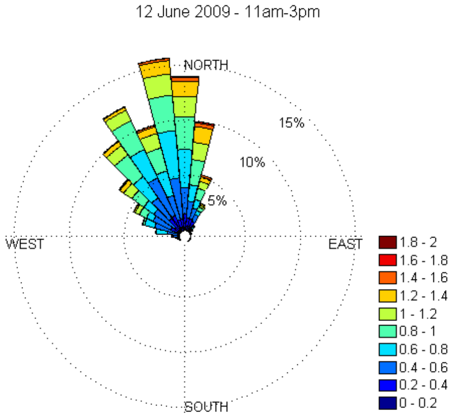

Figure 3. Wind conditions

We performed twenty five experiments from 11:30 am to 2:30 pm. Both red and violet colored SAR markers were tested. In addition, we did four releases of fire extinguishers for comparison to an inert tracer that does not involve a buoyant release (although the extinguisher valve mechanism imparts an initial velocity to the material instead). To aid in interpreting the resulting images, each camera-person kept a log of photos taken that include the manual camera settings and we added "metadata" photos at the beginning of each release to record the experiment number on each camera. Each of the cameras recorded photographs at 5 s intervals from the release of the plume. The photographs were synchronized so that data from the three different perspectives can be combined in postprocessing.

The violet smoke plume in test 9 was fairly representative of all the plumes tested on 12 June. In addition to the microscale effects, the smoke grenade pulsated and thus the plume is not uniform – see variations in the vertical in figure 4. It meandered slightly with the changing wind (figure 5) and exceeded 33 ft in the vertical (figure 6).

Figure 4. Violet smoke plume (test 9) as seen from Camera #1 - 15 s and 55 s after the release.

Figure 5. Violet smoke plume (test 9) as seen from Camera #2 - 15 s and 55 s after the release.

Figure 6. Violet smoke plume (test 9) as seen from Camera #3 - 15 s and 55 s after the release.

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[1] Additional planning experiments were accomplished several months earlier in order to test the experimental design. Those results are not reported here.

The red smoke plume in test 18 exhibited a bit more variation due to the wind. There is considerably more vertical lift immediately following the release (figure 6). There is substantial meander as depicted in figure 7. In figure 8, you can see that the plume rose considerably more than the violet plume of test 9.

Figure 6. Red smoke plume (test 18) as seen from Camera #1 - 25 s and 60 s after the release.

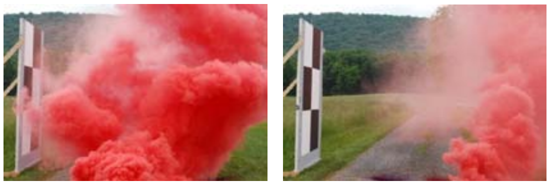

Figure 7. Red smoke plume (test 18) as seen from Camera #2 - 25 s and 60 s after the release.

Figure 8. Red smoke plume (test 18) as seen from Camera #3 - 25 s and 60 s after the release.

5. POSTPROCESSING

The first metric we calculated is the opacity of the plume. The results in Table 1 represent the average of ten images taken 5 seconds apart. In test 9, the plume generally followed the ground so the opacity is naturally higher over the bottom portion of the backdrop (Table 1). Test 18 was considerably more buoyant and as a result the plume was more opaque across the entire backdrop.

Table 1: Opacity measurements.

Opacity	Test 9 Violet	Test 18 Red
Top	8%	80%
Middle	37%	89%
Bottom	82%	75%

In addition to opacity we used lights mounted to the backdrop to calculate the optical depth of the plume. The results reported in table 2 represent the average of ten images. In general the values for each type of smoke grenade are close to 1.

Table 2: Optical depth measurements.

	Left light	Right light
Test 9	1.06	0.76
Test 18	0.61	0.90

In order to explore the inherent differences in an ensemble mean and single realization, we reconstruct the mean plume dispersion pattern. Figure 9 represents the ensemble mean of ten smoke grenade plumes 30 seconds following the release. Each photograph was superimposed at 10% transparency to reconstruct mean. All the releases occurred on the same afternoon under similar meteorological conditions. Because of the calm wind even with as few as ten members you can begin to see diffuse, broad plume shape indicative of an ensemble mean.

Figure 9. Ensemble mean of ten smoke grenade plumes at 30 seconds.

6. DISCUSSION

We were able to obtain measurements of ten realizations of SAR marker smoke plume releases on a single day under moderately convective conditions. The experiments were designed to allow post-processing in order to determine the plume opacity, optical depth, and to reconstruct three dimensional images of the plumes at specific measurement times. This design allowed us to study the differences and similarities between the plumes for these specific conditions.

We did see variation between the plume realizations, but this variation was relatively minimal because the dispersing eddies on that day were relatively small. The transporting wind did not vary greatly over the time of the experiments.

The results shown here are only valid for this particular locale under these specific conditions. To further study plume dispersion, the experiments would need to be repeated for a variety of locales under differing meteorological conditions. Note that the SAR markers used here as a contaminant source are pyrotechnic, and thus, add to the variability of the realization with the transient buoyant release characteristics.

We plan to further post process the results after additional automation, to quantify the ensemble mean plume and the variances between the realizations in an effort to compare to Taylor dispersion theory. In addition, we expect to model the ensemble average release using computational fluid dynamics to compute a site-specific wind field and Lagrangian particle methods to simulate the dispersion.

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Table 3. Basic characterization of plume height and duration.

Run #	Type	Start Time (Watch)	Grenade Duration	10 sec Plume Height[1], ft	Max Plume Height, ft	Max Plume Distance, ft	Avg Wind Speed, knots[2]	Average Wind Direction
1	red	11:37	1:06	13	>33	>150	1.79	351.2
3	red	11:48	1:11	13	>33	>150	0.66	358.7
6	red	12:10	1:02	14	>33	>150	0.92	22.6
8	red	12:20	1:01	16	>33	>150	2.04	335.2
10	red	12:27	1:07	16	>33	>150	2.23	322.9
12	red	12:33	1:01	13	>33	>150	2.27	340.7
14	red	1:14	1:02	14	>33	>150	2.50	3.4
16	red	1:20	1:07	15	>33	>150	1.78	2.2
18	red	1:43	1:05	11	>33	>150	1.61	353.2
20	red	1:53	1:02	15	>33	>150	1.64	343.1
22	red	2:01	1:04	14	>33	>150	1.24	317.3
24	red	2:07	1:08	13	>33	120	1.30	313.0
26	white FE	2:18	0:12	17	19	15	1.02	299.4
27	red FE	2:22	0:15	15	16	48	0.84	299.4
28	2 white FE	2:24	0:27	15	20	58	1.10	309.1
29	2 red FE	2:26	0:27	8	30	100	1.11	289.5

[1] 9 sec used for FE runs

[2] 1knot = 1.15 statute miles