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Daytime atmospheric plume opacity measurement using a camcorder

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HIGHLIGHTS

- Camcorder successfully demonstrates measurement of plume opacity in near real time.
- Average opacity error decreases when contrast between two backgrounds increases.
- Contrast can be changed by changing backgrounds or camera's detected wavelengths.
- Background choice is the most important factor that affects opacity uncertainty.

GRAPHICAL ABSTRACT

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ABSTRACT

Digital Optical Method (DOM) software, developed earlier to measure atmospheric plume opacity with digital still cameras, was tested with a camcorder, which captures digital images (as video frames) in visible light wavelengths at 30 Hz. The effect of contrast between two backgrounds when using DOM contrast model was demonstrated through the use of different pixel value measurement wavelengths and different background pairs. Unique contributions presented here are: (1) the camcorder is within the United States Environmental Protection Agency Method 9 individual and average opacity error limits, for black and white plumes with opacity values between 0% and 90%, while enabling real-time opacity measurements; (2) increasing contrast between two backgrounds decreases the opacity measurement error and uncertainty, with all measurements within individual and average opacity error limits for contrast parameter ≥ 0.92; and (3) background choice affects the opacity measurement uncertainty more than camcorder calibration and number of pixels sampled for tested conditions. These contributions are important because they are the first demonstration and evaluation of applying digital image analysis with camcorders to quantify atmospheric plume opacity. Moreover, the results show that obtaining higher

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contrast between two backgrounds is the most important factor for reducing error in plume opacity measurements to meet acceptable performance criteria. This knowledge increases the reliability of image analysis to provide a low-cost and real-time monitoring method for quantifying atmospheric plume opacity.

1. Introduction

Environmental sensors that are low-cost and Internet-enabled are of interest because of their portability; ability for rapid data acquisition, transmission, storage, and analysis; and potential for crowdsourcing (Snyder et al., 2013). This research examines the applicability and uncertainty of using a low-cost (US$200–1,000), widely available, and real-time (30 Hz digital image capture) sensor to monitor atmospheric plume opacity from stationary point sources. Plume opacity is defined here as the percent of visible light attenuated by an atmospheric plume. Plume opacity relates to the concentration of particulate matter (PM) and the length of the observing path through the plume, and is measured for regulatory purposes because PM is an air pollutant that has impacts on human health (Pope and Dockery, 2006), reduces visibility (Watson, 2002), and affects climate (Anenberg et al., 2012). In 1974, the United States Environmental Protection Agency (USEPA) promulgated Method 9, specifying the use and performance requirements of trained human observers to measure plume opacity (USEPA, 1993). Before Method 9, plume opacity was evaluated by humans visually comparing the plume with Ringelmann Charts, which have five levels of density inferred from a grid of black lines on a white surface, and correspond to different opacity values (USEPA, 1993). Other countries such as Canada (Environment and Climate Change Canada, 2017), Taiwan (Environmental Protection Administration Executive Yuan, 2013), and South Korea (Ministry of Government Legislation, 2011) also regulate opacity, based on Method 9 or the Ringelmann Chart methods.

Methods using images from digital still cameras (DSCs) and software were developed to quantify plume opacity by McFarland et al. (2003, 2006, 2007) and Du et al. (2007a, b, 2009). Use of DSCs and software to determine plume opacity offers improved measurement objectivity compared to human observers (Du et al., 2007a), reduced costs by US$200 million/yr compared to Method 9 (Page, 2006), the capability to separate measurement from analysis of the images to avoid potential conflicts of interest, and the capability to archive the digital images used to determine plume opacity for verification testing, reproducibility testing, and evidence for possible litigation that could occur years after the plume's opacity was measured. Use of DSCs and software to quantify atmospheric plume opacity was approved by ASTM International (ASTM Standard D7520, 2016) and by USEPA as Alternative Method ALT-082 (USEPA, 2012).

This research focuses on the Digital Optical method (DOM) that includes two models to accommodate different measurement situations: the contrast model, which applies when a plume is in front of and near two contrasting backgrounds, and the transmission model, which applies when a plume is in front of and near one background in contrast to the plume (Du, 2007). Field campaigns demonstrated that: (1) compact DSCs with DOM meet Method 9 performance requirements for measuring plume opacity values during daytime (Du et al., 2007a); (2) compact DSC positions relative to the sun and plume affect the resulting opacity values (Du et al., 2007b); (3) opacity values measured by compact DSCs have lower error than measurements from human observations (Du et al., 2007b); (4) compact DSCs can measure opacity values during nighttime over a range of more limited opacity values than required by Method 9 (Du et al., 2009); (5) compact DSCs with DOM can determine the opacity values of fugitive PM emissions (Du et al., 2013); and (6) smartphone DSCs with DOM can measure plume opacity values while meeting Method 9 error requirements, and background conditions were identified as important for determining opacity measurement errors and uncertainties (Yuen et al., 2017).

This research is motivated by the potential of commercial camcorders (i.e., video camera recorders) operating at visible light wavelengths to provide low-cost (US$200–1,000) real-time opacity measurements, since commercial camcorders are easily available to capture video frames (digital images that form a video) at high frequencies of 24, 25, or 30 Hz (Chaney, 2016). Measurements at 30 Hz, as used to complete this research will be referred to as real time in the following text. This research examines the applicability of DOM to quantify plume opacity with a digital camcorder by extracting frames from the resulting video at up to 1 Hz, and then applying DOM to each frame to determine plume opacity values. Such real-time opacity measurement has the potential to provide improved opacity measurements by averaging opacity values during multiple seconds, instead of basing opacity values on one instantaneous image obtained by a DSC, or a human observation once every 15 s (ASTM Standard D7520, 2016). Currently, ASTM Standard D7520 and ALT-082 only apply to DSCs, and no methods are proposed for camcorders in measuring/ monitoring plume opacity. This research serves as the first demonstration that camcorders can measure plume opacity with DOM. Although this research focuses on the use of a camcorder, there are advanced DSCs that offer "burst mode" which can capture digital images at 1–5 Hz and can serve a similar purpose for real-time opacity monitoring.

In the following sections, we describe the methods and results of applying DOM on camcorder frames. Unique contributions of this paper are: (1) a camcorder can accurately measure a wide range of opacity values (0%–90%) and in real-time (1 Hz) for white and black plumes during daytime; (2) opacity measurement error and uncertainty, when using the contrast model, decreases as the color contrast between two backgrounds increases; and (3) opacity measurement uncertainty due to background choice is more than due to camcorder calibration and number of sampled pixels, as long as the camcorder