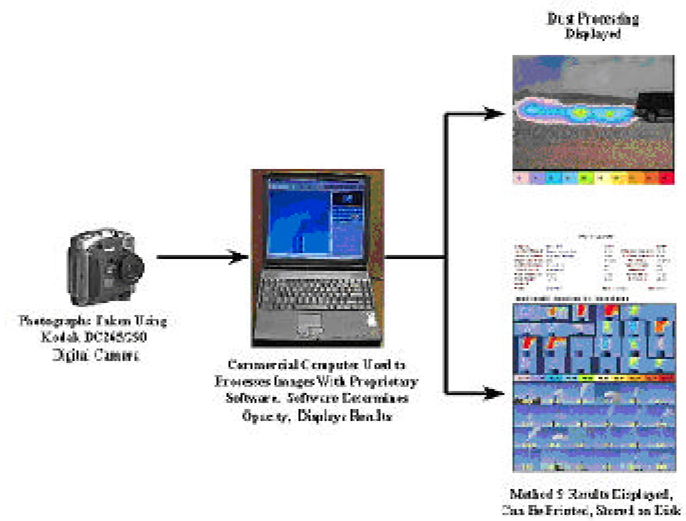
ESTCP
Cost and Performance Report

(CP-0119)



An Alternative to EPA Method 9 – Field Validation of a Digital Opacity Compliance System (DOCS)

November 2004

ENVIRONMENTAL SECURITY
TECHNOLOGY CERTIFICATION PROGRAM

U.S. Department of Defense

COST AND PERFORMANCE REPORT
ESTCP Project: CP-0119

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ACRONYMS AND ABBREVIATIONS

AFB	Air Force Base
AFRL	Air Force Research Laboratory
CEM	continuous emissions monitor
CES	Civil Engineer Squadron
CFR	Code of Federal Regulations
COTS	Commercial Off-The-Shelf
DOCS	Digital Optical Compliance System
DoD	Department of Defense
DQO	Data Quality Objective
EMC	Emissions Measurement Center
EPA	Environmental Protection Agency
ESTCP	Environmental Security Technology Certification Program
ETA	Eastern Technical Associates
Method #9	40 CFR 60, Appendix A, Method #9
MLQL	Materials Directorate, Air Expeditionary Forces Technologies Division
NASA	National Aeronautical and Space Administration
SDL	Space Dynamics Laboratory
SIP	state implementation plan
SOP	standard operating procedure
WPAFB	Wright-Patterson Air Force Base

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1.0 EXECUTIVE SUMMARY

1.1 BACKGROUND

For most Department of Defense (DoD) installations, the prime method of determining compliance with air regulations (and usually the primary backup for in-stack instruments) relies on trained observers to visually estimate the opacity of a plume every 15 seconds for a specified period, then average those estimates to determine a single reading that is compared to permitted levels. This is known as Environmental Protection Agency (EPA) reference Method #9 (40 Code of Federal Regulations [CFR] 60, Appendix A, Method #9). [11] The sampling period may be as short as 6 minutes or as long as 1 hour. To qualify as a visual observer, an individual must attend a "smoke school" every 6 months. A smoke school consists of both classroom and field training, with a series of visual observations of a calibrated smoke source, constituting the qualification examination. That examination requires that the observer estimate the opacity of 25 white and 25 black smoke plumes within ±15% accuracy for an individual observation and be within 7.5% overall. Sample opacity ranges from 0 to 100% in 5% increments.

While Method #9 has an extensive history of use, it is both subjective and expensive in terms of dedicated work force. In addition to the cost of the school (approximately $350 per student and per diem/travel as needed), the 5 days of missed work add up significantly when multiplied by the number of students — for example, 35 at Hill Air Force Base (AFB), 25 at Elmendorf AFB —and the twice-yearly training requirement.

1.2 OBJECTIVES OF THE DEMONSTRATION

The objective of the demonstration was to field a digital opacity compliance system (DOCS) to be usable as an alternative to certified EPA Method #9 observers. To accomplish this, a digital recording and analysis system for opacity compliance measurements was demonstrated and validated as an alternative to the current opacity measurement procedure (40 CFR 60, Appendix A, Method #9). The system uses a commercial-off-the-shelf (COTS) digital programmable camera to capture images of a smoke plume. These images are then downloaded to a standard personal computer where they are analyzed[1] to determine opacity. DOCS is designed to produce opacity readings, which are accurate, and *provide a permanent digital record of the image for future reference*. Preliminary testing showed the system to be highly effective in quantifying smoke plume opacity and in determining the opacity of fugitive dust. For example, DOCS had been used to take preliminary, limited measurements at a visible emission-training program; this preliminary investigation showed that DOCS easily passed the requirements of precision and accuracy as established by Method #9.

1.3 DEMONSTRATION RESULTS

Demonstrations in this effort were conducted at three commercial smoke schools—Ogden, Utah; Augusta, Georgia; and Columbus, Ohio—to demonstrate the system's ability to qualify as a smoke reader would. Also, demonstrations at commercial and government sites in Ohio and

[1] The analysis software is a proprietary product developed by Scientech, Inc. Hill AFB is presently pursuing patent rights for all of DoD.

Alaska were conducted to evaluate quantitatively how the system performs compared to Method #9 observers in the field. Site measurements were necessarily confined to the < 40% opacity that is allowed by existing permits for most measurements with some excursion measurements at start-up. It was a good test of the suitability of the technology for use in the regulatory environment that exists currently rather than a test of its ability to replicate observers' readings over the complete range of 0 to 100% opacity.

1.4 REGULATORY DRIVERS

The EPA Emission Measurement Center (EMC) in Research Triangle Park, North Carolina was a partner in this study because the ultimate goal of the effort was to receive regulatory acceptance of the newer technology as an alternative to Method #9. The data gathering and analysis was closely coordinated with the EMC to ensure data integrity and sufficiency for their purposes.

1.5 DEMONSTRATION RESULTS

The DOCS image acquisition and processing system was demonstrated in both the relatively controlled environment of a smoke school and at industrial sites. Results indicated that the digital camera system can replace certified smoke readers in instances where contrast is expected to be good, where weather is most often clear, and where expected opacities are low. When opacities are regulated at 0%, the system is very attractive because of its forensic record of the plume. Technicians at Hill AFB have been using the system since November 1999. They and State of Utah air quality regulators are pleased with the results and are committed to future use of the methodology.

DOCS is more costly to install than training Method #9 certified observers, but a comparison of the annual operating costs showed an annual saving of $8,090 using DOCS versus certified readers at a large urban facility and an annual saving of $14,890 at a remote facility. In both cases, the purchase cost of a DOCS system, which is continually trending downwards, would easily be paid back within a year.

1.6 STAKEHOLDER/END-USER ISSUES

General

The use of digital opacity measurements will assist primary end users such as Hill AFB, Utah; Wright Patterson AFB, Ohio; Fort Stewart, Georgia; and Eielson AFB, Arkansas, in demonstrating compliance with emission standards. Each base/facility will benefit to an extent, depending on the level of compliance mandated by the size and mission of the facility. Regulators' air pollution control programs will benefit because the records of visible emissions will be better documented. This technology has far-reaching potential and could be used by many agencies currently attempting to comply with opacity requirements via EPA Method #9, particularly if the permitted opacity is very low, as is most often the case.

EPA Perspective

At the request of the EPA's EMC, a meeting was held in August 2003 at Research Triangle Park to discuss the results of the Environmental Security Technology Certification Program (ESTCP) tests and their implications in the use of the DOCS as an alternative to Method #9. Present at the meeting were EPA personnel from Research Triangle Park and EPA Regions 4, 6, and 8; and representatives from U.S. Army and U. S. Air Force facilities in Florida, Kentucky, Tennessee, Texas, and Utah. The following is a summary of the meeting discussions and conclusions:

- For the present time, Method #9 must remain as the baseline against which digital imaging technologies are compared. The goal is to develop a separate reference method for digital imaging opacity measurements.
- It is important to note that the DOCS measurement capabilities are a result of field testing. This process has defined what can be done using digital imaging at the present time. Other technologies will have to meet this same level of performance.
- The performance specification developed by the group will define the operational requirements of any future digital-imaging-based opacity determination system.
- The standard will specify that comparison is between the system under consideration and a transmissometer reading (i.e., the transmissometer remains the standard against which opacity readings are made).
- Separate consideration should be given to the camera and the software used for analysis.
- A set of standard photographs would be used for the performance comparison testing.
- Method #9 will still have to be used for any enforcement actions.
- There is considerable interest in using digital imaging for the analysis of fugitive emissions. Several group efforts will be carried out to explore development options, including ESTCP or individual DoD component funding.
- Proceed with the development of tests in Utah (and perhaps Arkansas, Texas, Tennessee, and Kentucky) where the facilities' Title V permits currently include the option of utilizing the DOCS technology as a valid opacity screening tool. Ensure that definite measurement objectives are set up so tests can be objectively evaluated.
- Include a recommendation to extend the DOCS to fugitive emissions in the final ESTCP report.
- Efforts to include digital opacity measurements in State Implementation Plans must ensure that no new stringency requirements (either more or less) are imposed.
- Take measured steps with a DOCS approach, build confidence, and show consistency. This will open the door for future acceptance and use as a separate standard.

Clearly, the EPA's EMC is strongly supportive of the potential use of digital imagery as a method for quantifying visual opacity. To provide federal and state regulators with a clear understanding of the conditions under which digital imagery may be a technically superior and/or scientifically equivalent compliance methodology, EMC has endorsed the following activities:

- Proceed with a year-long regulatory pilot test of the DOCS technology in selected states—namely Arkansas, Texas, and Utah—with the full involvement of their respective EPA regional offices and state air quality compliance personnel. The purpose of these tests would be to demonstrate the use of DOCS as a screening tool for opacity measurements required under existing Title V air permits. Photographs taken would be cataloged and analyzed according to the protocols established under the ESTCP project. EMC personnel feel that positive results from such tests will help provide technical and programmatic support they need to build a case for the development of a formal alternative to Method #9. (The tests began in January 2004.)

- Use a subset of the photographs obtained under the ESTCP DOCS field tests to produce a test protocol for any digital imaging approach to opacity measurements. These photographs would be tied directly to smoke generator transmissometer opacity values and would, therefore, be an acceptable standard for validating new digital-imaging-based opacity measurement systems. EMC has continued to stress the importance of establishing an EPA-approved test protocol for verifying the performance of all future digital imagery technologies.

- There is substantial interest at EPA and within state regulatory agencies in using digital imaging technology for fugitive emissions. Since the DOCS software package consists of computer algorithms specifically designed to estimate the opacity associated with fugitive emissions, EMC has indicated its willingness to support further testing and development of this capability.

<u>Air Force Perspective</u>
There are several key points to be made:

- The field testing program, as carried out under the ESTCP project with close EPA supervision, demonstrated that the DOCS could, in fact, make accurate opacity measurements under proper conditions (i.e., clear weather with good contrast conditions and opacities <40%).

- Generally, as weather conditions grow worse (i.e., increased cloud cover, overcast skies, or stormy skies), both Method #9 certified readers and the DOCS opacity readings demonstrated decreased accuracy in measuring visual opacity.

- The ability of the DOCS to provide a permanent record of opacity for a given set of measurement conditions is a significant advantage over the subjective record of a certified human observer.

- There are valid technical reasons to expect that known software deficiencies (e.g., problems with cloudy or overcast skies, improvements in the graphical user interface, and opacity readings >60%) can be corrected or substantially improved through carefully targeted additional development.

Recommendations

- ESTCP provides additional funds for DOCS software enhancements as well as DOCS regulatory compliance verification activities. Specific issues to be addressed with supplemental funding support would include: (1) refinement of the DOCS opacity algorithms to improve their ability to quantify visible opacity under variable sky conditions, (2) support of the 1-year DOCS regulatory pilot testing activities currently being conducted at Elmendorf AFB, Arkansas; Hill AFB, Utah, and Fort Hood, Texas, as well as commercial facilities in Utah, and (3) development a technology evaluation protocol for documenting the performance of digital imagery technologies under EPA-specified test conditions. Estimated amount required is $100,000.

- The EMC should take the digital opacity test protocol developed under this project and certify DOCS—to the set of conditions under which it meets Method #9 requirements—as an alternative to Method #9. Alternatively, the test protocol could be developed into an entirely separate test method for digital-imaging-based opacity measurements. Either way, a definitive roadmap should be forthcoming for the establishment of another opacity measurement protocol.

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2.0 TECHNOLOGY DESCRIPTION

2.1 TECHNOLOGY DEVELOPMENT AND APPLICATION

The equipment tested consisted of a commercially available digital camera, specifically a Kodak 290 zoom digital camera with programmable features. The data card from the camera was analyzed using proprietary software to produce opacity readings using a Pentium II laptop or equivalent with Windows. See Figure 1.

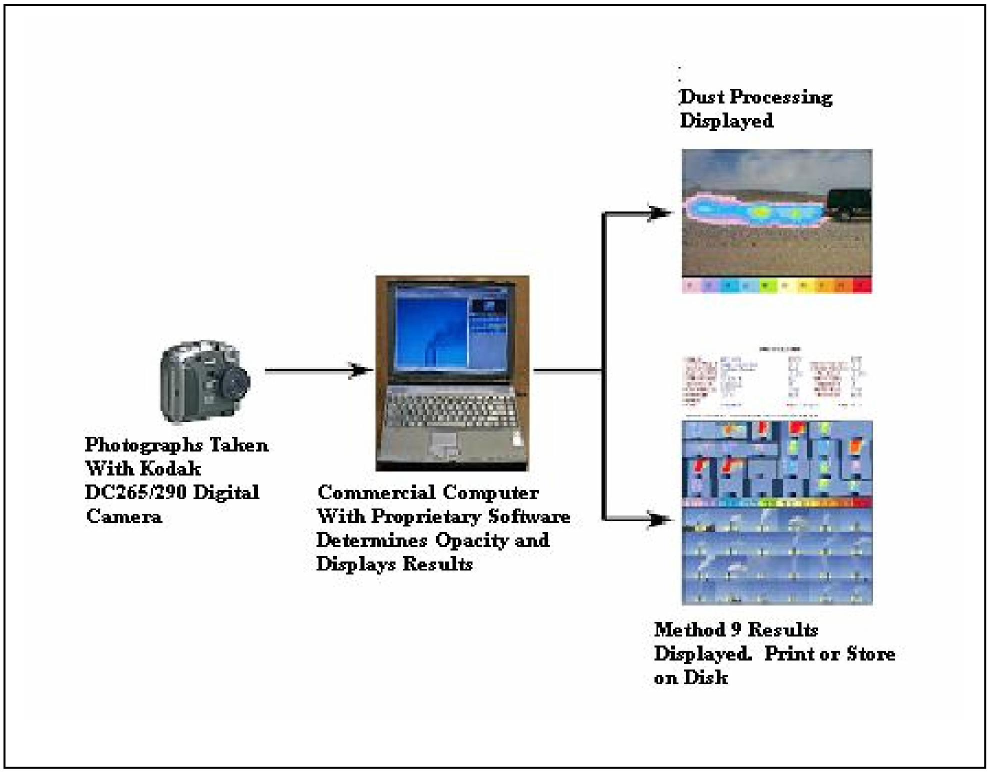

Figure 1. Schematic of DOCS.

The use of digital image processing is novel in its approach to determining opacity for regulatory compliance. It makes use of commercially developed image capture technology for sampling the data on site. Other than the human observer, the only competing technology in use today requires sampling from in-stack fixed monitors. Such systems have no portability and are costly to purchase and maintain. Digital image processing, on the other hand, is portable and the analysis can be done either on site, using a standard notebook computer, or later in the office using a common desktop system. The images/samples can be archived by storing them on computer media, and analysis can be re-accomplished at any time, an advantage obviously denied to the human observer.

2.2 PREVIOUS TESTING OF THE TECHNOLOGY

The subject digital image acquisition and processing system has been preliminarily demonstrated in the relatively controlled environment of a smoke school and at some industrial sites, both for smoke plumes and for quantifying fugitive dust. Technicians at Hill AFB have been using the system since November 1999. With the encouraging results, the state of Utah has incorporated the option of using the DOCS for quantifying visible opacity within Hill AFB's Title V permit.

The system's development and funding history prior to this field test is as follows:

- SCIENTECH Corporation sponsored a "quick look", feasibility study, providing $10,000 to the Space Dynamics Laboratory (SDL), a nonprofit research institute at Utah State University.

- Concept development and demonstration was funded through the National Aeronautical and Space Administration (NASA) Stennis Research Center's Affiliated Research Center Program. NASA funds were provided directly to the SDL to support both staff and graduate student involvement for an 8-month effort. Estimated expenditure was $80,000.

- Prototype development and demonstration of algorithms to allow for quantification of fugitive dust were sponsored by the Air Force under 3600 program funding provided by the Air Force Research Laboratory at Tyndall AFB, Florida. The value of that contract was $32,500, for which Hill AFB received one camera set and four software licenses.

- SCIENTECH Corporation has invested approximately $25,000 in completing development of the analysis algorithms and finishing the graphic user interface and report generator.

- The state of Utah's Division of Air Quality purchased one system for field examination in February 2000 at a cost of $5,000 and Hill AFB purchased four systems in addition to their original site license for $8,000. Those funds have been re-invested into further system development.

2.3 FACTORS AFFECTING COST AND PERFORMANCE

Scientific reliability and forensic reproducibility are the biggest factors affecting cost and performance. The cost of maintaining certified smoke readers as per EPA Method #9 is considerable, but variable. Semiannual training will cost approximately $350 per student for the class. The additional costs for travel, per diem, and lost productivity are widely variable. Bases with large work forces, such as U.S. Army, Navy, and Air Force maintenance depots (e.g., Hill AFB) and other industrial/rework facilities can absorb lost productivity with existing manpower and some minor inconvenience, but smaller organizations, such as in the 611th Civil Engineer Squadron (CES) with primary environmental compliance responsibilities for remote U.S. Air Force facilities throughout Alaska have limited capability to absorb such costs. In these situations, twice yearly EPA-certified, contract replacement workers need to be transported to each site at the same time as the certified readers are transported off site for recertification. Establishing a DOCS system methodology, which requires one-time training, followed by online or CD-based retraining, could save considerable financial resources and enhance mission accomplishment by reducing these semiannual work force migrations for recertification.

2.4 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

Advantages for this technology fall into two distinct categories. The first advantage is that it will save the DoD money. While the need for training is similar to smoke school training and will not be eliminated, the number of people who need to be trained will be cut nearly in half. Also, it is expected that they will need training only on familiarization with opacity measurements for one day per year instead of two or three days of smoke school training and qualification twice per year. The second advantage is in the forensic reliability and reproducibility of the measurements with the digital camera. Currently, Method #9 is a visual judgment of opacity; individuals record their observations on forms and may be asked to provide expert testimony in the future. The expert testimony then becomes merely an honest affirmation that the documented opacity is what the observer recorded on that day. The DOCS method will provide reproducible, reliable data. The digital photograph will represent an archive of the plume, as it existed at the time in question.

Limitations of this technology are similar to that of a human observer. Current regulations governing the measurement of visual opacity place constraints on the angle of the observation with respect to the sun, and other meteorological parameters. Equivalency demonstrations have constrained this testing to those same parameters. Also, certified observers find it somewhat difficult to accurately discriminate plumes from background when sky conditions are overcast or when the background of the plume is complex. This technology has similar limits and, in fact, the system cannot adapt as well as humans to less than ideal field conditions (i.e., poor weather). The technology as it exists today is best used in good weather conditions and with homogeneous to low variability sky backgrounds. Also, opacity measurements with the digital system as presently developed should be limited to less than 40% opacity. This encompasses nearly all regulated plumes at this time.

Finally, DoD facilities in Alaska, Texas, and Utah as well as EPA Regions 6 and 8 are conducting a 1-year DOCS regulatory pilot test during which both visual observations and digital photographs of emissions from regulated industrial processes are being evaluated during normal compliance inspection activities. For many of the permitted sources, a measured nonzero visible opacity constitutes a regulatory violation. The digital opacity compliance system with its forensic record is considered ideal for this purpose.

Once approved by EMC as an acceptable method for estimating visible opacity, the procedure for allowing the incorporation of digital imagery technology into air quality permits will be through the appropriate modification of existing state implementation plans (SIP). Once in the SIP, regulated facilities would have the option of requesting the use of digital imagery to demonstrate compliance with visible opacity limits.

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3.0 DEMONSTRATION DESIGN

3.1 PERFORMANCE OBJECTIVES

The objective of this technology demonstration was to determine whether the ability of the DOCS to measure opacity is equivalent to EPA Method #9. The EPA EMC was a participant in this test program which required that the digital measurement of smokes and computer computation of opacity be thoroughly explored. EMC also required that the system be able to measure opacity during smoke school with the same reliability as human observers who qualify for EPA Method #9 certification. Moreover, the EMC requires that the system successfully operate in the field at least over the range of opacities currently permitted for today's sources. If equivalency were successfully demonstrated, DOCS would be considered an acceptable alternative to EPA Method #9 for verifying visible emission compliance. Table 1 describes the performance criteria and metrics used to characterize the equivalency of DOCS to EPA Method #9.

Table 1. Performance Objectives.

Type of Performance Objective	Primary Performance Criteria	Expected Performance Metric	Actual Performance Objective Met?
Quantitative	1. Determine the statistical equivalency of the DOCS to EPA Method #9.	Demonstrate that the DOCS opacity measurements are statistically within the EPA Method #9 acceptable margin of error (i.e., ± 7.5%) at the 99% confidence level.	Partially
	2. Estimate reliability of the DOCS relative to certified human observers.	No statistical difference between the variability at 99% confidence of the mean difference in opacity readings reported by the DOCS and the variability of the mean opacity differences reported by recently certified smoke readers.	Partially
Qualitative	1. Reproducible results	Included into above	Yes
	2. Near real-time monitoring	Increased number of observations.	Yes

3.2 SELECTING TEST SITES/FACILITIES

The goal was to collect a wide range of opacity measurements representative of various types of smoke emissions. Sites were selected, with the concurrence of the EPA EMC, in different climatic regions of the United States where smoke school certification was being conducted and ultimately where regulated smoke stacks exist and there is a professed need for this technology. Locations representing the atmospheric conditions and climates of the Southeast, Midwest, and Western United States as well as Western and Central Alaska were all of concern to the EPA.

3.3 TEST SITE/FACILITY HISTORY/CHARACTERISTICS

Sites for smoke schools included Columbus, Ohio; Augusta, Georgia; and Ogden, Utah. The EMC recommended attending smoke school with the DOCS system at the locations approximating those discussed in Section 3.2, using Eastern Technical Associates (ETA) of Garner, North Carolina, as the preferred smoke school. ETA represents more than 80% of the smoke school business in the United States and there was an established, professional working relationship between ETA and EPA EMC. By using the test smoke generated by a smoke school opacity source, the DOCS was exposed to the same range of opacity challenges, and under a variety of environmental conditions as smoke school students are required to view (25 black and 25 white smokes ranging from 0 to 100% opacity). The follow-on test site demonstrations then showed the feasibility of operating the equipment at practical real-world facilities under a variety of atmospheric conditions on the range of smoke-generated opacity that is seen and regulated in the field. It was important to the project's advisory committee and to the EMC that the technology be tested under differing environmental conditions. However, the sites chosen also allowed for measurement of practical smokes from combustion of diesel fuel, natural gas, coal, miscellaneous trash, wood chips, and waste oils.

3.3.1 Eastern Technical Associates

ETA was founded in 1979 and currently is overwhelmingly the predominant U.S. provider of smoke school training in support of 40 CFR 60, Appendix A, Method #9.

To certify as a qualified observer, a person must be tested and demonstrate the ability to accurately assign opacity readings in 5% increments to 25 random black plumes and 25 random white plumes. Error cannot exceed 15% opacity on any one reading and average error cannot exceed 7.5% opacity for each smoke category. The DOCS was required to demonstrate the same proficiency.

3.3.2 Augusta, Georgia, Smoke School

Fort Stewart is the largest Army installation east of the Mississippi River and is home to the 3rd Mechanized Infantry Division. They expressed an interest in possibly using a digital system as backup of their stack monitoring system. The nearest smoke school to Fort Stewart was at Augusta, Georgia. Climatic conditions in Augusta are representative of those throughout the Southeast United States, which includes Fort Stewart and many other installations.

3.3.3 Columbus, Ohio, Smoke School and Wright Patterson AFB, Ohio

Wright-Patterson AFB (WPAFB) is the largest, most diverse and most complex base organizationally in the Air Force. The base is located near Dayton, Ohio and the nearest smoke school was in Columbus. WPAFB is home base for more than 60 units representing a host of Air Force and DoD organizations. It has a work force of approximately 24,600, with nearly 15,500 being civilians, making it the fifth largest employer in Ohio and the largest employer at a single location. The 88th Air Base Wing Environmental Management Office is responsible for the environmental programs on base, including the management of all air permits.

3.3.4 Ogden, Utah

Hill AFB, Utah located near Ogden, is home to the Ogden Air Logistics Center. The Hill AFB Environmental Management Directorate is responsible for the environmental programs at the base, manages all permits, including air permits, and sponsors a smoke school, which was held at Ogden.

3.3.5 Facilities Within Alaska

The EPA EMC indicated that several facilities in Alaska have been asking for technology to replace Method #9 and that HMH Consulting of Anchorage would be able to test the technology at various facilities within the state, including the following:

- Anchorage Water and Wastewater Utilities smoke generator and sludge incinerator at the J.M. Asplund Wastewater Treatment Facility in Anchorage;

- Golden Valley Healey Electric Association coal-fired power plant in Healy, approximately 110 miles southwest Fairbanks;

- Alyeska Pipeline Service Company trash incinerator at Pump Station #7, which is near Milepost 400 on the pipeline outside Fairbanks;

- Eielson Air Force Base coal-fired heating plant at Eielson AFB, approximately 20 miles southeast of Fairbanks; and

- Williams North Pole Refinery in North Pole, approximately 15 miles southeast of Fairbanks.

All sites were visited and the technology demonstrated during the first week of September 2002.

3.4 PRESENT OPERATIONS

Installations that generate their own steam or power or that have special purpose industrial operations, such as medical waste incinerators, hush houses, and small foundries are regulated with respect to the visible emissions from stationary smoke stacks. This regulation relies on EPA Reference Method #9, Visual Determination of the Opacity of Emissions from Stationary Sources [1, 2].

Method #9 requires trained observers to determine compliance by visually estimating the opacity of the smoke from sources. The level of regulation, i.e., the opacity allowed for the specific source, can vary usually between 0 and 40%, depending on the location of the source and the perceived impact to the environment the source represents as determined by the local, state, or federal regulators. Qualified observers are trained in accordance with EPA Reference Method #9, Section 3.

3.5 PRE-DEMONSTRATION TESTING AND ANALYSIS

The technology had undergone a number of successful preliminary field demonstrations at Hill AFB as well as at other locations in the United States. In addition, a project scientific advisory panel met frequently to review the basic approach involved in the opacity measurements to ensure that testing was fundamentally sound and based on accepted methods, which are in general use. The panel also assisted in developing protocols to ensure that equivalency with Method #9 was achieved.

3.6 TEST AND EVALUATION PLAN

3.6.1 Demonstration Setup and Start-Up

The equipment was hand carried to each smoke school location or industrial facility. Each demonstration was conducted as prescribed in EPA Method #9, Appendix C, and in standard operating procedures (SOP) (refer to Appendix E of the Final Report [3]). A certified smoke generator was operated specifically for the purposes of testing the DOCS system during Phase I smoke school demonstrations. These measurements were accomplished as part of a certified smoke school. SOPs were followed at smoke schools and in field validations and they provided for technology maintenance and for operations in the event of unforeseen problems.

3.6.2 Period of Operation

3.6.2.1 Phase I Operations

EPA-approved smoke schools lasted for a total of three days at each site. The DOCS demonstration was run continuously during the duration of the smoke school.

3.6.2.2 Phase II Operations

Phase II field demonstrations were conducted, as much as possible, to encompass a representative sample of all the different conditions experienced during a complete day's operation at each field site. Operating hours were roughly 0700–1800 hours, adjusted to ensure samples were taken during daylight hours.

The Anchorage Water and Wastewater Sludge Incinerator. At this field demonstration site, smoke readings were taken in conditions thought to be challenging to the software, i.e. reading light colored smoke against a gray background sky. However, the opacities experienced were relatively low and, therefore, would have been adequately handled by the software. The plume was generated by incineration of municipal water and wastewater treatment sludge.

The City of Anchorage Public Works Facility Smoke Generator Test Facility. This field demonstration site provided a unique opportunity for testing the DOCS system on the full range of opacities in both black and white smoke. Six smoke-school-type testing runs were monitored with four camera systems and seven certified readers reading in parallel (>1,500 data points).

The Golden Valley Electric Power Station #1. This site provided an opportunity to measure soot from coal-fired combustor systems (black smoke) against a variable background. The six runs captured there, although on the low end of opacities, provided a measure of practical use for the camera system in the field.

The Alyeska Pipeline Pump Station # 7. This trash incinerator was barely able to generate visible smoke and was unable to sustain opacity greater than 20% for more than a minute or two. However, the tests there provided the project with a broad variety of opacities from the facility testing the camera system's ability to capture quick and dramatic changes in opacity alongside smoke readers.

The Eielson Coal-Fired Boiler Plant. This was another facility that found it difficult to generate visible smoke for more than very short periods of time. The variety of opacities and variability over short periods of time were a stiff test of the digital system. Of concern here was the potential for reading smoke during winter months when smoke, steam, no sunlight, and a gray background as well as very low temperatures typically below –40°F made conventionally reading smoke difficult.

The Williams North Pole Refinery. People at this facility were very helpful to the team and provided as much variability in opacity as they were capable of producing. Although it was not possible to obtain the high opacities that were thought to be possible, the data were a good test of the system at levels of opacity that would be encountered in routine use. These winter measurements added to the overall data.

3.6.3 Experimental Design

The field demonstration program in both phases strictly followed EPA Method #9 for certified smoke readers, and the design of the DOCS demonstration was as stated in the DOCS SOPs. Phase I qualification testing was conducted in the same way as for smoke school attendees with the transmissometer results being the standard of comparison for both the students and the DOCS. The Data Quality Assessment Process is described in Appendix B of the Final Report [3]. Statistical comparisons (see Table 7 in Section 4.3.3) were made between the DOCS and students qualifying on any particular run.

The second phase of the field demonstration operated the DOCS system in a real-world environment subject to the same conditional parameters as stated in EPA Reference Method #9. Measurements were made of the six sources chosen at specific locations described in Section 3.6.2.2 per direction from the advisory committee and EPA EMC. Each field validation test site either had continuous opacity measurement devices available and certified smoke readers as a backup or used smoke readers as a primary opacity measurement method. The sites represented different sources of smoke under varied circumstances and therefore produced different types of smoke plumes. Although the DOCS SOPs and EPA Method #9 prescribe that the DOCS and certified smoke readers from the units being tested should be given an opportunity to "calibrate" against generated smoke of known opacity (contracted from a smoke school) prior to observing and determining opacity for real plumes, this was not possible in the field.

Expert Panel: An expert panel was assembled of select members from academic, EMC, EPA Regions, the U.S. Air Force, and other governmental sources who had demonstrated expertise in digital computer-based algorithm processing, measurement of opacity and smokes, visibility determination and modeling, or statistical experimental design. This panel reviewed the scientific basis of digital opacity measurements to provide EMC with the basis for recommending an alternative to Reference Method #9 in the Federal Register. The panel reviewed the data quality objectives (see Appendix B of the Final Report [3]) for both the smoke school and field test measurements and developed specifications/parameters within which the field work was conducted for EPA acceptance.

3.7 DEMONSTRATION SCHEDULE

3.7.1 Phase One

Smoke School Demonstrations: First year fieldwork during late 2001 and early 2002 involved measurements of opacity concurrent with established smoke schools in Ogden (September 2001), Augusta (December 2001), and Columbus (March 2002). These field measurements were designed to demonstrate the ability of the digital opacity system to qualify as a certified smoke reader over the complete range of test smokes, i.e. 0% to 100% opacity.

3.7.2 Phase Two

Site Demonstrations: The objective of the Phase Two measurements was to demonstrate the technology's ability to generate actual measurements in the field, i.e., over the fairly narrow range of permitted opacities under various environmental conditions. Measurements were made concurrent with trained observers having variable levels of residual calibration (since they would not be freshly trained via smoke school.) The DOCS was field-tested at each of the following sites:

- Anchorage Water and Wastewater Sludge Incinerator – September 5, 2002
- City of Anchorage Public Works Facility Smoke Generator Test Facility – September 6, 2002
- Healy Golden Valley Electric Power Station #1 – September 9, 2002
- Alyeska Pipeline Pump Station # 7 Trash Incinerator – September 10, 2002
- Eielson AFB Coal Fired Boiler Plant – September 11, 2002
- Williams North Pole Refinery – September 13, 2002

Like Phase I, four COTS digital cameras (Kodak DC290 or Kodak DC265) were used to photograph visible emissions generated during the Phase II field tests. The DOCS commercial digital imaging software was installed and tested on each of the cameras before any photographs were taken. No technical adjustments or physical modifications of the cameras were necessary to operate the DOCS camera software.

Rather than having fixed positions relative to the sun, the DOCS camera operators (four in all) were allowed to position themselves in any valid Method #9 location relative to the stack. In addition to the four DOCS camera operators, from six to eight Method #9-certified readers were available at each industrial site to estimate plume opacity. The certified readers consisted of facility personnel as well as members of the DOCS technical evaluation team.

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4.0 PERFORMANCE ASSESSMENT

Under clear weather conditions, the performance objectives were met in the 0-40% range of opacity. At higher opacities, the performance of the DOCS system was more variable. When sky was employed as background, DOCS achieved Method #9 performance criteria, was at least as accurate, and was more reliable than certified smoke readers. However, under less than optimal sky conditions, human observers, who can employ background other than sky to improve the visual contrast of the plume, performed better.

DOCS opacity measurements were reproducible and could be made in near real-time if the photographic images were downloaded to a personal computer and evaluated in the field using the proprietary software.

More observations were possible with the DOCS system compared to using certified human observers because one human observer was able to capture and evaluate several DOCS images in a given time period compared to making a single human observation of a plume in the same time period.

4.1 PERFORMANCE DATA

4.1.1 Phase I Performance Data

Approximately 6,400 opacity readings of visible emissions were taken as part of the DOCS field evaluation in Utah. Of that number, 4,741 opacity readings (2,336 black plumes and 2,405 white plumes) or nearly 75% of those computed were deemed acceptable for DOCS statistical analysis (see Table 2). The decision to exclude 2,161 opacity readings from the DOCS statistical analyses was based on technical problems that included: (1) physical obstruction of the smoke plume (e.g., trees, clouds, telephone poles, etc.), (2) folding, twisting, or other significant physical disruptions to the plume; and (3) inappropriate modification of digital image through use of the "brush" function that was available in the DOCS software package.

The weather conditions during the smoke school field tests in Augusta were characterized by scattered clouds and partly overcast skies. Not only were the weather conditions in Augusta found to be appreciably different from those encountered in Ogden, but the physical landscape of the two smoke school locations were drastically different as well. For example, while the Ogden smoke school field tests were conducted in a large open parking lot located adjacent to a university athletic stadium, the venue for the Georgia smoke school was smaller and more secluded in a parking lot surrounded by a dense pine forest. The combination of cloudy conditions and tall trees provided a more variable background against which the DOCS and certified human observers were estimating plume opacity.

Unlike the Utah smoke school field test, in the analysis of the Georgia smoke school DOCS data, the brush function was not used to analyze any of the digital photographs. Furthermore, several DOCS camera operators were certified as EPA Reference Method #9 visual observers so a larger number of EPA Reference Method #9-certified readers were available to participate in the side-by-side opacity method comparison during the first day of smoke school.

Weather conditions during the Columbus field tests were considerably different from either the Utah or Georgia smoke schools. The climate in Columbus for the field tests was characterized as near freezing temperatures, light rain mixed with snow, and thick, overcast skies.

Table 2. Statistical Data Summary of Ogden, Utah Smoke School DOCS Evaluation.

Color of Smoke—Opacity Measurement Approach	Opacity Range	Mean Deviation (%)	Number of Samples	95% CI[1] (%)	99% CI (%)
Black—DOCS	0–100%	6.4	2,336	6.1– 6.7	6.0–6.8
Black—certified observers	0–100	6.7	246	5.7–7.8	5.4–8.1
Black—DOCS	0–60%	5.6	1957	5.3–5.9	5.2–6.0
Black—certified observers	0–60%	5.4	212	5.5–6.4	4.1–6.8
Black—DOCS	0–40%	5.4	1745	5.0–5.7	4.9–5.8
Black—certified observers	0–40%	4.8	194	3.8–5.7	3.5–6.1
White—DOCS	0–100%	10.0	2405	9.5–10.5	9.4–10.6
White—certified observers	0–100	8.5	282	7.5–9.6	7.1–10.0
White—DOCS	0–60%	6.7	1897	6.3–7.0	6.2–7.2
White—certified observers	0–60%	8.2	224	7.0–9.4	6.6–9.8
White—DOCS	0–40%	5.9	1686	5.5–6.2	5.4–6.3
White—certified observers	0–40%	7.4	199	6.1–8.7	5.7–9.0

CI – confidence interval

Like the Augusta smoke school, in the analysis of the Columbus smoke school DOCS data, the brush function was not used to evaluate any of the digital photographs. Furthermore, since all the DOCS camera operators were also certified as EPA Reference Method #9 visual observers, more certified readers were available to participate in the side-by-side opacity method comparison during the first day of smoke school as compared to the Utah smoke school.

4.1.2 Phase II Performance Data

The performance confirmation method used in this study essentially consisted of statistically verifying that the mean difference between the in-line transmissometer opacity readings estimated over the full range of opacity and the opacity readings recorded by the digital opacity compliance system is within the acceptable margin of error established for EPA Method #9 certification, i.e. ± 7.5 %. To ensure that sufficient data were collected to support a final decision at the 99% confidence level, the EPA's Data Quality Objectives (DQO) process (Reference #6) was applied to estimate the minimum number of samples necessary to limit the decision errors to an acceptable rate. This is reflected in Appendix B of the Final Report [3].

Preliminary application of the DQO process in developing a DOCS technology sampling plan resulted in an experimental design that consisted of taking at least 86 opacity measurements (43 black smoke and 43 white smoke) at each location to maintain the rate of committing a decision error to no more than 1% (99% confidence level). Since each opacity EPA Method #9 certification run consists of 50 opacity measurements (i.e., 25 black smoke readings and 25 white smoke opacity readings), a minimum of at least 200 randomly generated opacity data points is collected each day (assuming two certification runs conducted in the morning and two in the afternoon) during the certification program. Collecting a much larger number of data points than that estimated by the DQO process ensured that the final decision was supported by strong statistical evidence.

A secondary objective in the technology evaluation program was to compare the reliability of DOCS to consistently and accurately measure plume opacity relative to certified EPA Method #9 smoke readers. Reliability testing provides potential users of the DOCS technology a means for predicting its performance under field conditions. Comparative reliability testing involved taking simultaneous opacity measurements by both human smoke readers and DOCS and estimating their respective statistical variability. The estimated magnitude of the statistical variability (as reflected in the breadth of the 99% confidence interval) for each measurement system (certified human observers and DOCS) is used as an indirect measurement of its reliability. For example, if the DOCS plume opacity measurements were found to exhibit a statistical variability that was significantly less than the variability estimated for certified smoke readers, the conclusion would be that DOCS is more reliable than certified smoke readers.

Except for the EPA-approved smoke generator in Anchorage and the coal-fired power plant in Healy none of the smoke stacks evaluated were equipped with opacity monitors. Without the benefit of a reliable and regulatory approved opacity monitor, questions relevant to the accuracy of the DOCS could not be addressed at these sources. However, field data from stacks not equipped with opacity sensors could be used to determine whether the DOCS and EPA Reference Method #9 would yield significantly different results when applied simultaneously to evaluate the opacity of smoke plumes. Therefore, the opacity data collected in Alaska were analyzed differently based on whether the recorded smoke plume opacity was supported by the measurements made by a continuous emission monitor (CEM).

For data collected using the EPA-approved smoke generator and at the coal-fired power plant (i.e., those industrial sites supported by a CEM), the ability of the DOCS to measure plume opacity was compared with the results obtained from EPA Method #9-certified human observers (Table 2). For data collected at the industrial sites, the mean opacity deviations together with the 95% and 99% confidence intervals were provided. The mean opacity, which was computed from the digital photographs using the DOCS, was compared to the Method #9-certified human observer's reading. Table 3 and Table 4 summarize the statistical results obtained from aggregating the results from both field tests.

Table 3. Statistical Data Summary of Alaska (CEM Data versus DOCS and Certified Observers).

Opacity Measurement Approach	Opacity Range	Mean Deviation (%)	Number of Samples	95% CI[1]	99% CI
DOCS - CEM	0–100%	14.1	215	12.2–16.0	11.6–16.6
Certified observers - CEM	0–100%	6.0	224	5.4–6.6	5.2–6.8

CI = confidence internal

Table 4. Statistical Data Summary of Alaska (DOCS versus Certified Observers).

Opacity Measurement Approach	Opacity Range	Mean Deviation (%)	Number of Sampling Means	95% CI[1]	99% CI
DOCS - Certified observers	0–100%	10.5	360	9.3–11.8	8.9–12.2
DOCS - Certified observers	0–40%	5.0	255	4.0–6.0	3.7–6.3

CI = confidence internal

During both the smoke generator and coal-fired power plant field tests, Method #9-certified readers appeared to generate opacity readings that were more consistent with the CEM opacity readings. It should be noted that there was no attempt to verify that the CEMs installed in either the smoke generator or at the coal-fired power plant were generating accurate opacity readings. In any event, the observation that certified readers were able to record opacity measurements more consistent with the CEM readings than the DOCS was surprising but not unexpected since the DOCS performance is sensitive to sky conditions. Moreover, since many of the Method #9 human observers involved in the side-by-side study were actually full-time operators at the coal-fired power plant, their extensive historical experience in estimating opacity from a particular industrial stack may have provided them with a unique advantage in reading visual opacity compared to the DOCS photograph readers who were observing the stack emissions for the first time. Despite the fact that Method #9-certified readers appeared to generate more accurate opacity measurements, the inability to visually establish the sun's position raises concerns regarding the validity of some of the field results.

4.2 PERFORMANCE CRITERIA

The goal for this field demonstration project was to demonstrate the DOCS technology in the field and determine if this technology was a scientifically defensible alternative to EPA Reference Method #9 for opacity measurements from stationary sources. ESTCP's criteria for determining the performance of the technology with respect to the reference method were generated with the help and guidance of the EPA Emissions Measurement Center and are listed in Table 5.

Table 5. ESTCP Performance Criteria.

Performance Criteria	Description	Primary or Secondary
Validate as a scientifically defensible alternative to EPA Method #9*	Ensure that the DOCS opacity measurements are statistically within the acceptable margin of error established for EPA Method #9 certification at the 99% confidence level.	Primary
Validate forensic reliability of system**	Process the DOCS and certified human observer opacity measurement data and compute the mean difference and the associated 99% confidence intervals.	Primary
Improve amount of data collected	Show the DOCS can operate continuously with no degradation to output.	Secondary
Ease of use	Show that one trained individual can observe multiple emission sources with one system.	Secondary

* This was the initial part of Phase I.

** Reliability of human smoke readers was compared to reliability of the DOCS in terms of precision and accuracy of data obtained in both phases of demonstration.

Supporting a decision on whether any proposed technology for measuring visible opacity (including DOCS) can be considered scientifically equivalent to EPA Reference Method #9 would require that the approach meet, at a minimum, the standard of accuracy established by the published method. EPA Reference Method #9 requires that individuals applying for certification as visual opacity observers be able to estimate the visible opacity of 50 variable smoke plumes with a margin of error of no greater than 7.5%. The EPA Reference Method #9 accuracy requirement provides a primary performance criterion against which the DOCS technology can be evaluated. To minimize the potential of drawing erroneous conclusions from the opacity field data, the statistical accuracy of the DOCS technology in measuring visible opacity was characterized at the 99% confidence level.

Beyond the question of whether the DOCS technology achieves the accuracy criterion specified within the EPA Reference Method #9 approach, the reliability of the DOCS relative to certified EPA Reference Method #9 human observers represents a critical usability consideration for environmental regulators, DoD compliance personnel, the private sector, and the public. To characterize the DOCS reliability relative to certified EPA Reference Method #9 human observers, the mean opacity differences between the DOCS and the EPA-approved transmissometer was compared to the mean differences estimated between the certified EPA Reference Method #9 human observers and the EPA-approved transmissometer. The variability of the mean opacity differences (as expressed by their 99% confidence intervals) was calculated using opacity field data. If the variability in the DOCS performance was found to be equal to or less than the variability characteristic of the opacity readings reported by the EPA Method #9 human observers, the conclusion drawn would be that the DOCS is as reliable as EPA Reference Method #9.

To estimate both the mean difference and its associated 99% confidence interval, a paired t-test statistical approach was employed. In this approach, for each opacity level reported by transmissometer (CEM), a corresponding DOCS and a certified EPA Method #9 visual observer measurement are used to establish the paired differences.

The 99% confidence interval that characterizes the mean differences between the CEM and DOCS opacity readings can be used to determine whether the DOCS accuracy is equivalent to EPA Reference Method #9. For example, if the range of the 99% confidence interval contained values that were above 7.5% (or below -7.5%), the conclusion drawn from the data would be that the DOCS is not as accurate as EPA Reference Method #9. On the other hand, if the range of the 99% confidence interval was 7.5% or less (or equivalently, above -7.5%), the data would support the conclusion that the DOCS was equivalent to EPA Reference Method #9 (from the standpoint of accuracy). Table 6 shows the performance metrics and methodologies for evaluating the opacity measurements.

Table 6. Expected Performance and Performance Confirmation Methods.

Performance Criteria	Expected Performance Metric (pre demo)	Performance Confirmation Methods	Actual (post demo)
PRIMARY			
Validate as scientifically defensible alternative to EPA Method #9	Ensure that the DOCS opacity measurements are statistically within the acceptable margin of error established for EPA Method #9 certification at the 99% confidence level.	Paired t-test 99% confidence Interval	11.6–16.6 DOCS to CEM 5.2–6.9 Observers to CEM
Validate forensic reliability of system	Mean difference in opacity readings between DOCS system and EPA Method #9 certified smoke readers is zero at 99% confidence.	Paired t-test 99% confidence interval	8.9–12.2 at 0–100% 3.7–6.3 at 0–40%

4.3 DATA ASSESSMENT

4.3.1 Phase I Data Assessment

Data from the Phase I field study indicated that the DOCS can accurately and reliably measure the opacity of smoke plumes when weather conditions provide optimum color contrast between plume and background. Under clear, blue-sky conditions, the DOCS was able to consistently meet the EPA Reference Method #9 performance standard and, over opacity ranges of regulatory importance (i.e., 0 to 40 % opacity), DOCS accuracy was significantly better than that achieved by Method# 9 certified human observers (shown Table 6).

As climatic conditions deteriorated, the DOCS had difficulty in accurately measuring plume opacity. Under weather conditions characterized by dark overcast skies, the DOCS consistently failed to meet the EPA Reference Method #9 performance standard. However, Method-#9-certified human readers also experienced difficulty in accurately quantifying opacity under these conditions. In situations where the emissions can be viewed against backgrounds other than sky, human observers have a clear advantage over the DOCS during overcast sky conditions. Method #9 certification smoke schools, where the smoke generators were equipped with stacks that are only 15 feet above the ground surface, provided such an environment since this relatively short stack height allowed human observers to make opacity measurements using objects other than sky (light poles, vegetation, buildings, etc.) as background.

4.3.2 Phase II Data Assessment

Several industrial sites were selected in Alaska to assess the performance of the DOCS system on real-world smoke stacks in the field. The opacity data collected in Alaska were analyzed differently depending on whether the stack was equipped with an in-stack CEM opacity sensor (Table 3) or not (Table 4). Testing on the stack fitted with a CEM (Table 3) showed that DOCS failed to perform as well as the certified observers over the 0-100% range due to poor weather conditions. However, Table 4 shows that at the lower end (0-40%) of the range, DOCS performance more closely matched that of certified observers.

During Phase II field tests, climatic conditions were consistently unfavorable for measuring plume opacity. Light rain and overcast skies characterized the Alaska field test conditions. Results generated from the Phase II statistical analysis were consistent with those obtained during Phase I, namely, when the apparent opacity decreased due to the reduced visual contrast, both Method #9-certified human observers and the DOCS were unable to consistently achieve the EPA Reference Method #9 accuracy standard. Testing on stacks without a CEM showed that the performance of DOCS of certified observers was closer at lower operatives (Table 4).

4.3.3 Hypothesis Testing

The initial documentation of method equivalency was established by computing the confidence intervals about the mean difference or deviation between the DOCS and transmissometer opacity readings. Based on a recommendation received from the EPA EMC, a more direct but comparable statistical approach for evaluating method equivalency is to determine if the DOCS field data supports the rejection of a null hypothesis (H_o). In significance testing, a null hypothesis (H_o) is developed that will be assumed to be true in the absence of strong quantitative evidence to the contrary. The null hypothesis (H_o) for the present study may be stated as follows: the true mean difference between the transmissometer and the DOCS opacity measurement methods is greater than 7.5%. This statement reflects the assumption that, in the absence of strong quantitative data to the contrary, the two opacity measurement methods are not equivalent. (The reader should note that the 7.5% mean difference is the allowable opacity deviation for human observers specified in EPA Reference Method #9.) Similarly, the alternative hypothesis (H_a) may be constructed as follows: the true mean difference between the transmissometer and the DOCS opacity measurement method is equal to or less than 7.5". The rationale for constructing the null and alternative hypothesis in this fashion is to shift the burden of proof for demonstrating EPA Method #9 equivalency to the strength of the DOCS field data. In other words, in the absence of field data that strongly supports the rejection of the null hypothesis, the conclusion drawn from the data will be that DOCS is not equivalent to EPA Reference Method #9. Alternatively, if the strength of the data is sufficient to reject the null hypothesis (acceptance of H_a), the conclusion drawn from this study will be that the DOCS is statistically equivalent to EPA Reference Method #9.

Table 7 summarizes the statistical comparison between the mean DOCS opacity measurement and the mean opacity measurement recorded by the certified human observers at facilities where there was no CEM installed. Over the full range of opacity evaluated, on average, the difference between the DOCS and certified human observers was approximately 10.5 %.

When the comparison was made using a limited opacity range of 0 to 40% (based on certified reader measurements), the mean difference between the DOCS and certified human observers decreased to 5.0%. These data indicate that the difference between the two methods of opacity determination (DOCS and EPA Reference Method #9) is significant and that, on average, the DOCS tends to read smoke plumes at higher opacity levels than certified human observers. It should be noted that the data in Table 7 only addresses the issue of whether or not the response of the DOCS is significantly different from the observations recorded by certified human observers. The data does not address the issue of measurement accuracy.

Table 7. Summary of Hypothesis Testing Performed at the 0.05 Significance Level (at Smoke School Locations).

Smoke School	Color of Smoke	Opacity Range (%)	Mean Difference (%)	Number of Samples	Significance Level (α)	Critical[1] t-value	Test Statistic	Rejection[2] of Null Hypothesis?
Utah								
	Black	0–100	6.4	2,236	0.05	1.96	-6.77	Yes
	Black	0–60	5.6	1,957	0.05	1.96	-12.08	Yes
	Black	0–40	5.4	1,745	0.05	1.96	-12.50	Yes
	White	0–00	10.0	2,405	0.05	1.96	10.39	No
	White	0–60	6.7	1,897	0.05	1.96	-4.35	Yes
	White	0–40	5.9	1,686	0.05	1.96	-8.99	Yes
Georgia								
	Black	0–100	8.6	4,949	0.05	1.96	8.06	No
	Black	0–60	8.2	3,620	0.05	1.96	4.49	No
	Black	0–40	7.9	2,896	0.05	1.96	2.22	No
	White	0–100	13.2	3,535	0.05	1.96	19.93	No
	White	0–60	8.5	2,565	0.05	1.96	4.72	No
	White	0–40	7.2	2,203	0.05	1.96	-1.47	Yes
Ohio								
	Black	0–100	10.9	3,498	0.05	1.96	16.83	No
	Black	0–60	9.4	3,066	0.05	1.96	10.24	No
	Black	0–40	8.1	2,753	0.05	1.96	3.53	No
	White	0–100	21.6	4,394	0.05	1.96	46.81	No
	White	0–60	15.0	3,758	0.05	1.96	36.32	No
	White	0–40	12.3	3,131	0.05	1.96	28.67	No

[1]From standard statistical tables, for ά = 0.05 and n> 120, t-critical is approximately 1.96.
[2]Where the null hypothesis is rejected, the data indicate that DOCS is equivalent to EPA Reference Method #9. Conversely, if the null hypothesis is not rejected, the conclusion is that DOCS is not equivalent to EPA Reference Method #9.

4.4 TECHNOLOGY ASSESSMENT

Although the DOCS is limited to the use of sky conditions to establish plume background, an added feature that was not employed in the current study was the DOCS "brush" function. The brush function essentially allows the photograph analyzer the option of selecting any segment of the digital image as background. The analyzer then "brushes" the selected background on both sides of the plume. The DOCS computer algorithm then compares the contrast between the plume and the selected background to generate an opacity reading. The opacity science advisory board determined that use of the brush function could lead to claims of bias or otherwise negatively impact the objectivity of the study. However, in a technical sense, certified readers who employ background other than sky are achieving the same goal as the brush function. In other words, human observers attempt to locate a background that provides maximum contrast with the plume in order to estimate opacity. Clearly, use of the brush function would have significantly altered the DOCS reading, but whether its use introduces significant bias and, therefore, challenges the legitimacy of the analyses has not been fully resolved by the opacity science advisory board.

A third circumstance accounts for a potential advantage to digitally measuring opacity. Many small to medium size sources such as emergency power supplies or generators are regulated at 0% opacity. It is considered plausible by many local regulators that a digital system could be used for these sources (perhaps 50% of regulated sources) under existing state implementation plans requiring that the operators not necessarily be very extensively trained if at all. The value over existing Method #9 would be in the archived digital pictures, which are a good stand-alone forensic record for demonstrating the nonexistence of visible emissions at a specific time and place. In these instances, the cost, although undeterminable at this time, would be very small compared to the EPA Method #9 approach.

Several western states including Alaska, Texas and Utah are currently applying the DOCS technology within their air emissions compliance inspection activities. Depending on the results from this activity, data collected from both DoD and commercial facilities within these states during the 1-year DOCS regulatory pilot study may be used as the technical and legal basis for EMC to press forward in formulating a new EPA-approved test method for visible opacity determination.

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5.0 COST ASSESSMENT

5.1 COST REPORTING

Existing methodology for source compliance with the EPA Reference Method #9 consists of training two individuals every 6 months. The cost of the training is $350 per class plus 40 hours of lost work (3 days of training and 2 travel days) at $15/hr and approximately $1,100 travel costs (hotel @$300, per diem @$105, $700 average airline costs) shown in Table 8 and Table 9. It is estimated that there are more than 3,400 training slots across the DoD every year. Current training and lost productivity costs are estimated at $11 million per year.

The digital technology compliance costs cited here (Table 8 and Table 9) are for an initial class similar to smoke schools costing $350 per class, but for only 32 hours of lost work (2 days of class and 2 days of travel) at the same labor and travel rates. Recurring semiannual cost for the digital refresher class would be $350 for the class but would not involve travel costs because the class would be done on computer. Lost labor time would be no more than 8 hours and may not impact productivity as workers could take the class from their work stations in most cases.

Each DOCS system costs approximately $3,000 and has a projected life span of more than three years. (Note that this cost is continually decreasing.)

Table 8. Initial Cost Elements Used in Cost Analysis

Conventional Method #9 Training		Proposed Initial Digital Computer Training	
Remote Site	**Urban Site**	**Remote Site**	**Urban Site**
$350/person training	$350/person training	$350/person training	$350/person training
Labor: $15/hr—40 hrs	Labor: $15/hr—40 hrs	Labor: $15/hr—32 hrs	Labor: $15/hr—32 hrs
2 ea readers/source	2 ea readers/source	2 ea readers/source	2 ea readers/source
$1,100 travel/student	$1,100 travel/student	$1,100 travel/student	$1,100 travel/student
$1,100 travel/replacement		$1,100 travel/replacement	
Total: $6,300/source	**Total: $4,100/source**	**Total: $6,060/source**	**Total: $3,870/source**

Table 9. Refresher Cost Elements Used in Cost Analysis

Conventional Method #9 Refresher Training		Proposed Digital Computer Refresher Training	
Remote Site	**Urban Site**	**Remote Site**	**Urban Site**
$350/person training	$350/person training	$350/person training	$350/person training
Labor: $15/hr—40 hrs	Labor: $15/hr—40hrs	Labor: $15/hr—8 hrs	Labor: $15/hr—8hrs
2 ea readers/source	2 ea readers/source	2 ea readers/source	2 ea readers/source
$1,100 travel/student	$1,100 travel/student	$0 travel/student	$0 travel/student
$1,100 travel/replacement		$0 travel/replacement	
Total: $12,600/source (Train every 6 months)	**Total: $8,200/source (Train every 6 months)**	**Total: $1,880/source (Train every 6 months)**	**Total: $1,880/source (Train every 6 months)**

Equipment purchases for use of the digital system are estimated in Table 10 and Table 11 at approximately $3,000 per source. This includes:

- Digital programmable camera system: $750
- Dedicated computer: $1,500

- Software and license: $500
- Miscellaneous support materials: $250

A digital system such as DOCS is most applicable for monitoring sources that are regulated below 40% opacity, particularly for monitoring sources regulated to produce no visible emissions. This represents more than 80% of the regulated sources currently. The methodology for training digital camera operators to monitor opacity is expected to be similar to smoke school initially since there is a need to learn about smoke emissions and the laws being applied. The field work is not expected to take as long (32 hours instead of 40 for traditional smoke school) because the individuals will not need the practical exercises associated with calibrating themselves to read smoke. All other initial costs will be similar to the traditional smoke school (Table 8). The recurring training, i.e. the semiannual refresher training will be where the cost savings are incurred as there is an expectation that this training would be provided online, if it is required at all. Tuition costs are estimated to be the same as for traditional smoke school, but savings will be incurred in that there will be no travel expenses and the labor time will be reduced considerably (Table 9).

Cost savings in using the digital method for opacity monitoring is expected to vary by the size of the facility or installation doing the monitoring. Large urban sources are impacted by the need to monitor emissions for opacity to a lesser extent than the smaller, remote sites. At large sites individuals are sent to smoke school and the lost labor is absorbed by redundancies in the relatively larger work forces than at smaller sites. Remote sites have work forces that are only one deep at each position. This requires them to import replacement labor, incurring duplicate travel costs and double labor costs. Savings realized by allowing for online refresher training are quite striking for these facilities (Table 10, Table 11, Table 12, and Table 13).

Table 10. DOCS Costs by Category for Single Source at Large Urban Source.

Direct Environmental Activity Process Cost				**Indirect Environmental Activity Costs**		**Other Costs**	
Start-Up		**O & M**					
Activity	$ K	Activity	$	Activity	$	Activity	$
Equipment purchase	3.0*	Consumables and supplies	0.075	Compliance Audits	0	Overhead associated with process	0
Equipment design	NA	Equipment maintenance	0.10	Document Maintenance	0.06	Productivity/cycle time	0.48**
Training operators	3.87	Training of operators	1.88	Environmental management plan preparation and maintenance	0.06	Worker injury claims and health costs	0
				Reporting requirements	0.12		
TOTAL	6.87		2.055		0.24		0.48

* Costs for an initial DOCS type system will be considerably less as a practical issue. Costs cited are for a dedicated computer to be purchased at $1,500. This will seldom be necessary. Rights to the software are cited at $500 per unit, but negotiation is proceeding at this time to provide the government with cost-free rights to use this technology. Current camera costs are much less than the $750 cited and are continually trending downward.

** Replacement labor as cited may not always be needed at larger facilities since there is often enough redundancy in the labor force to cover for workers who are absent for training.

Table 11. DOCS Costs by Category for Single Source at Remote Site.

Direct Environmental Activity Process Cost				Indirect Environmental Activity Costs		Other Costs	
Start-Up		O & M					
Activity	$ K	Activity	$	Activity	$	Activity	$
Equipment purchase	3.0*	Consumables and supplies	0.075	Compliance audits	0	Overhead associated with process	0
Equipment design	NA	Equipment maintenance	0.10	Document maintenance	0.06	Productivity/cycle time	0.48**
Training operators	6.06	Training of operators	1.88	Environmental management plan preparation and maintenance	0.06	Worker injury claims and health costs	0
				Reporting requirements	0.12		
TOTAL	9.06		2.055		0.24		0.48

* Costs for an initial DOCS type system will be considerably less as a practical issue. Costs cited are for a dedicated computer to be purchased at $1,500. This will seldom be necessary. Rights to the software are cited at $500 per unit, but negotiation is proceeding at this time to provide the government with cost-free rights to use this technology. Current camera costs are much less than the $750 cited and are continually trending downward.

** Replacement labor as cited is probably not needed when using the digital system since recurring training will likely consist of, at most, computer-aided "refamiliarization" training.

Table 12. EPA Method #9 Costs by Category for Single Source at Large Urban Source.

Direct Environmental Activity Process Cost				Indirect Environmental Activity Costs		Other Costs	
Start-Up		O & M					
Activity	$ K	Activity	$	Activity	$	Activity	$
Equipment purchase	0	Consumables and supplies	0.025	Compliance audits	0	Overhead associated with process	0
Equipment design	NA	Equipment maintenance	0	Document maintenance	0.06	Productivity/cycle time	2.4*
Training operators	4.1	Training of operators	8.2	Environmental management plan preparation and maintenance	0.06	Worker injury claims and health costs	0
				Reporting requirements	0.12		
TOTAL	4.1		8.225		0.24		2.4

* Replacement labor as cited is probably not needed when using the digital system since recurring training will likely consist of, at most, computer-aided "refamiliarization" training.

Table 13. EPA Method #9 Costs for Single Source at Remote Site.

Direct Environmental Activity Process Cost				Indirect Environmental Activity Costs		Other Costs	
Start-Up		O & M					
Activity	$ K	Activity	$	Activity	$	Activity	$
Equipment purchase	0	Consumables and supplies	0.025	Compliance audits	0	Overhead associated with process	0
Equipment design	NA	Equipment maintenance	0	Document maintenance	0.06	Productivity/cycle time	4.8
Training operators	6.3	Training of Operators	12.6	Environmental management plan preparation and maintenance	0.06	Worker injury claims and health costs	0
				Reporting requirements	0.12		
TOTAL	6.3		12.625		0.24		4.8

5.2 COST ANALYSIS

Smoke school costs used are actual costs for the smoke schools attended in this field work. Tuition costs are standard at $350 per class per student. Labor rates are averages for the Hill AFB work force. Travel is estimated to be the same for each worker regardless of the type training. Training time is less for digital smoke readers since they are educated in a classroom and will not be required to go through exercises designed to calibrate their impressions of plume opacity.

Cameras and software used for this test were still usable after 3 years; however, there have been quantum leaps in the advancement of this technology. Better quality equipment is now available at much lower cost and we expect this trend to continue. Software availability is an issue at the time of this report since the original vendor of the DOCS technology has quit producing, marketing, and promoting the technology. Demand is high enough that Hill AFB is pursuing purchase of the patent for the technology for the Air Force and DoD and licensing it to private industry. This will make government use even less expensive and may result in cost savings and technology advances for the market in general.

DOCS needs little or no maintenance. With proper cleaning and care the system should operate for at least 3 years, perhaps considerably longer. Cost of upgrades to hardware and software should be negligible. The system contains no inherent hazardous chemicals, and disposal of this system will require no unique disposal methodology. Our field experience indicates that occasional rechargeable batteries will need replacement as will data cards and disks, and some minor camera repair will be needed with on-hand technology. This would amount to no more than $175 per year per source.

Consumables and supplies in support of Method #9 measurements are estimated to cost $25 per year. For digital opacity measurements the consumables costs are estimated to be approximately $75 per year as batteries and memory chips for the cameras will need replacement at times.

There will be no equipment maintenance cost for Method #9 measurements and only nominal equipment maintenance costs for the digital systems, estimated at $100 per year per source.

5.3 COST COMPARISON

The potential cost benefits to employing digital opacity monitoring technology vary with the size and type of facility being regulated for stationary source opacity. On the one hand, large facilities such as Air Force logistics facilities, Navy rework facilities, and Army depots have large work forces that are flexible enough to be able to cover for workers who are absent for training. Modest per-source savings, however, add up when considering the large number of sources at such facilities. (Hill AFB has more than 1,600 emissions sources and trains more than 35 smoke readers twice each year.) At the other end of the size spectrum are remote facilities where only one or two sources are regulated, the work force is very small, and there is little organic ability to cover for workers absent for training. In such instances, i.e., remote sites in Alaska and elsewhere, replacement workers will always need to be scheduled and transported to the sites in time for the existing labor force to travel for training. This overlap in labor cost accounts for the demonstrable cost advantages to employing a digital type system (Table 11 and Table 13). It is at facilities such as these where the benefits of the digital system are greatest.

DOCS is more costly to install than training certified observers but comparison of the annual operating costs presented in Table 10 through Table 13 shows an annual saving of $8,090 using DOCS versus certified readers at a large urban facility and an annual saving of $14,890 at a remote facility. In both cases, the purchase cost of a DOCS system, which is continually trending downwards, would easily be paid back within a year.

Operator training for certified smoke readers currently would cost $4,100 for a large facility and $6,300 for remote site training. We anticipate that similar training for camera operations would cost $3,870 and $6,060, respectively, since it is anticipated that initial training will be 1 day shorter. These costs include:

- Recurring training of operators will differ considerably since certified readers will need to attend smoke school every 6 months. (Annual cost would be $12,600 for remote sources and $8,200 for larger facilities.) The method of retraining for digital operators is anticipated to be computer generated training for recurring familiarization of the camera operators. They will not need to "calibrate" their eyes as certified readers would. Costs are estimated to be $1,880 for both large and remote facilities.

- There is no expectation that there will be any difference in indirect environmental costs regardless of the method of opacity chosen.

- We anticipate no costs associated with overhead or worker injury claims, regardless of which process is employed to measure opacity. Productivity/cycle time costs will vary with the process employed, as lost productivity associated with employees absent for training needs to be accounted for. At large bases the productivity lost for recurring training of smoke readers is anticipated to be $2,400 (2 individuals, 40 hrs at $15/hr twice a year). This will be doubled for remote sites, as replacement workers will be employed. Digital productivity losses will possibly be for the 8 hrs that employees spend retraining at the computer, $480 per source.

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6.0 IMPLEMENTATION ISSUES

6.1 ENVIRONMENTAL CHECKLIST

This system falls solely under EPA Method #9. DOCS will be used only at facilities currently required to observe smoke stack opacity pursuant to this method. There will be no adverse environmental impacts associated with this technology.

6.2 OTHER REGULATORY ISSUES

EPA Reference Method #9 remains the standard reference method as per the CFR. To be considered an alternative to EPA Reference Method #9, language describing it as an alternative will need to be inserted into the CFR. The EPA EMC, which is the gatekeeper for this type of action, is currently monitoring the preliminary results from the DOCS 1-year regulatory pilot tests being conducted in Alaska, Texas, and Utah before proceeding with the development of an alternative test method. EMC agrees that the DOCS technology has utility and they are willing to monitor progress toward developing the technology further. They strongly recommend, however, that before EPA can move forward in the method approval process, the DOCS 1-year regulatory pilot study must collect a sufficient amount and type of field opacity data under a range of regulatory inspection conditions to demonstrate that the technology meets the credible evidence standard.

The Air Force Research Laboratory (AFRL) will support the conduct of the 1-year credible evidence study; however, a new lead organization such as the EPA itself will need to be the program management element for such a study. Alaska, Kentucky, Tennessee, Texas, and Utah are in general support of this credible evidence 1-year test. The long-term potential for this technology and its general use may hinge on market forces rather than EPA rulemaking; however, initial interest in the general approach is universally high. Should enough credible evidence be gathered to demonstrate utility of the technology, then the permitting process within individual states can be worked via the Title V process and—potentially, at least—digital technology could be interwoven into each SIP. Limited use then will follow and after time, as use increases, the EPA EMC would have the bottom-up support it needs to consider adopting it as an alternative method.

The AFRL has been approached to develop this technology as a means of measuring fugitive/nuisance dusts. There is some need for such technology within the Air Force, particularly on training and testing ranges, but it is felt that such a project will be better served if it were jointly led by both the U.S. Army and the U.S. Air Force, particularly since the U.S. Army has the lead between the services for range R&D. A follow-on ESTCP project proposal focused on the use of the DOCS technology for quantifying visible opacity associated with fugitive dusts was recently submitted, with the U.S. Army and U.S. Air Force listed as co-leads together with EMC, EPA Regions 6 and 8 as well as the state regulatory agencies of Alaska, California, Kentucky, Tennessee, Texas, and Utah identified as project collaborators.

6.3 END-USER ISSUES

Tech transfer should be relatively straightforward. The hardware associated with DOCS is COTS technology and easily procured. Algorithms for the software are proprietary and have been patented. Hill AFB is investigating the potential for purchasing the patent for the technology, advertising for potential clients to license the technology for commercial distribution, and providing it free for DOD use.

7.0 REFERENCES

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3. Air Force Research Laboratory, Tyndall AFB, Florida. ESTCP Final Report. An Alternative to EPA Method #9—Field Validation of a Digital Optical Compliance System (DOCS). October 2003.

4. McFarland, M.J., D.A. Stone, M.J. Calidonna, P.E. Kerch, S.L. Rasmussen. and S.H. Terry (2004). "Measuring Visual Opacity Using Digital Imaging Technology" Journal of Air and Waste Management Association, Vol. 54, pp. 296 – 306.

5. McFarland, M.J., S.H. Terry, D.A., Stone, M.J. Calidonna, and S.L. Rasmussen (2003). "Evaluation of the Digital Opacity Compliance System (DOCS) in High Mountain Desert Environments," Journal of Air and Waste Management Association vol. 53, pp. 724-730.

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APPENDIX A

POINTS OF CONTACT

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