Summary

We surveyed commercial off-the-shelf instruments that would meet the Forest Service's needs for real-time continuous smoke sampling at a reasonable cost in remote locations. Our survey originally included gravimetric and optical devices. We narrowed our evaluation to optical devices because they can provide smoke or air quality managers with continuous, real-time estimates of particle concentrations.

Optical instruments use light absorption, forward-scattering, or backscattering to infer the presence of particles. Based on the size, shape, and refractive index of the particles, a series of equations relates the amount of light scattered or absorbed to the particulate concentration. Aerosols having a consistent size and shape distribution can be estimated fairly accurately with these equations. However, smoke particles have a wide variety of sizes and shapes and their physical characteristics are dependent on the fuel characteristics and on whether the particles were formed during flaming or smoldering combustion. Once in the atmosphere, the particles continue to change with temperature, moisture content of the air, sunlight exposure, and other factors.

The greatest amount of change occurs immediately after combustion, but the process continues for days at a reduced rate. Because of this variability in the size and shape of the smoke particles, it is difficult using current optical techniques to define a highly accurate equation for determining particulate matter concentrations. Another difficulty is that aerosols have different light-scattering and absorption responses, depending on the orientation of the light receiver to the particles and to the light source. The response from a forward-scattering device may differ from that of a backscattering device. We did not evaluate whether the algorithms selected by the instrument vendors were appropriate for a particular biomass smoke event or not.

Our standard measure during most of the field tests and during the 2000 test was provided by two Federal Reference Method monitors, the Partisol Model 2000 and the BGI PQ200. The FRM monitor is gravimetric and has been selected by the U.S. Environmental Protection Agency as the approved method for measuring fine particles (2.5 µm and smaller). For the purpose of this study, the two monitors compared well against each other, showing less than 3-percent variability. A gravimetric device built and used by Forest Service research for aerial particle sampling was used as the standard for the 1998 high concentration evaluation. On average, it reported concentrations about 10 percent lower than the FRM.

The five brands of optical instruments we evaluated were similar in many ways. All of them were more or less portable for one person and rugged enough to withstand frequent relocation in the field. All but the aethalometer were battery powered. Each instrument was reasonably easy to operate and acceptably reliable. The brands for which we had two identical instruments showed good measurement consistency between instruments. In other words, there were few fundamental discriminating characteristics other than accuracy that showed one or more instruments to be clearly superior to the others. Our summary of some instrument features (table 2) and our subjective rating of characteristics other than accuracy may help users choose one instrument over another for a particular application (table 3).

Conclusions

The instruments had substantial differences in their measurement performance. Our data were collected in four distinct experiments, two in a smoke chamber, where a handful of pine needles were burned in a flaming and smoldering state, and two in ambient conditions near open forest fires. One indoor test and the two outdoor tests were conducted when the particle concentrations in the vicinity of the samplers were relatively low (less than about 150 µg/m^3). In the other indoor experiment, concentrations reached almost 500 µg/m^3. Some of the low-concentration indoor tests were conducted while the relative humidity (RH) was raised above 70 percent. The high-humidity tests were intended to evaluate two aspects of particle sampling; one was to show the relative difference in concentration using optical devices when the humidity was high and when it was low; the other was to compare the response of identical instruments when they were tested with and without a heater.

When the instruments were tested in a smoke chamber and exposed to moderately high particle concentrations (similar to those experienced by firefighters) their approximate performance was:

- MET One GT-640—Unavailable.
- MIE DataRam—Overestimated by about 93 percent.
- Radiance Research—Overestimated by about 85 percent.
- Optec NGN-3—Unavailable.
- Andersen aethalometer—Unavailable.

At lower particle concentrations (closer to the ambient air-quality standards and at levels where visibility is noticeably impaired) the instruments' approximate performance was:

- MET One GT-640—Underestimated by about 53 percent.
- MIE DataRam—Underestimated by about 25 percent.
- Radiance Research—Overestimated by about 13 percent.
- Optec NGN-3—Underestimated by 10 to 32 percent.
- Andersen aethalometer—Unavailable.

During field tests when particle concentrations were close to the ambient air-quality standards and at levels where visibility is noticeably impaired, the instruments' approximate performance was:

- MET One GT-640—Overestimated by about 10 percent, but data were scattered.
- MIE DataRam—Overestimated by about 21 percent.
- Radiance Research—Overestimated by about 42 percent, but substantial difference in the two instruments.
- Optec NGN-3—Unavailable.
- Andersen aethalometer—Insufficient data.

During laboratory tests when the concentrations ranged to 350 µg/m^3 and the humidity was above 70 percent, the approximate performance was:

- MET One GT-640
  Heater: Underestimated by 6 percent.
  No Heater: Underestimated by 15 percent with some data scatter.

- MIE DataRam
  Heater: Overestimated by 40 percent.
  No Heater: Overestimated by 30 percent.

- Radiance Research
  Heater: Overestimated by 51 percent.
  No Heater: Overestimated by 65 percent.

- Optec NGN-3
  Heater: Underestimated by 5 percent.
  No Heater: Unavailable.

- Andersen aethalometer
  Heater: Unavailable.
  No Heater: Unavailable.

These optical instruments are not suited for evaluating whether particles in the air are from biomass smoke or some other source; nor are they intended to ascertain whether ambient air-quality standards are being met. The best use for these instruments is to determine whether the local aerosol concentration is relatively high or low and whether concentrations are going up or down. For these purposes, each of the instruments has some capability.

Recommendations

Accurately estimating ambient particle concentrations from their light-scattering and absorption properties is a difficult proposition. Accu-racy could be improved by calibrating the instruments for a type of fire event and accounting for meteorological conditions and the existing levels of ambient particles. Conditions to consider include the:

- Age of the smoke.
- Type of fire, whether flaming or smoldering.
- Fuel moisture.
- Relative humidity.
- Background particle concentration without smoke from the fire.

Monitoring estimates also could be compared to the estimates from a good real-time smoke model.

Appendix—Instrument Specifications

RTAA 800 Real-Time Aethalometer	**Andersen Instruments, Inc.** 500 Technology Ct. Smyrna, GA 30082 Home Page: http://www.Andersoninstruments.com
Flow rate	2 to 6 L/min, user adjustable 0- to 10-L/min mass flow meter standard.
Analysis time base	2 s to 1 h.
Pump	Internal diaphragm pump.
Optoelectronics	Analysis at 880 nm, 22-bit A/D.
Display	Four-line LCD panel with keyboard and status indicator lamps.
Processor	Embedded 386-class computer, program and operating parameters stored in EPROM.
Size and weight	10.5 x 12.5 in (rack mount), 20 lb.
Power requirements	110 V, 69 Hz, 100 W.
Data output	3.5-in floppy disk, RS-232, analog outputs.
Filtration medium	15-m roll of quartz fiber tape.

PQ200A Air Sampler

BGI, Inc.
PQ200A Air Sampler
58 Guinan St.
Waltham, MA 02451
Home Page: http://www.bgiusa.com

Filter .... 2 μm, 47-mm Teflon.

Flow rate .... 16.7 L/min.

EPA designed-specified hardware .... EPA omnidirectional ambient particle inlet.
Inlet sample transport tube.
EPA $PM_{2.5}$ Well Impactor Ninety-Six (WINS).
47-mm filter holder assembly, 47-mm Teflon.

Size and weight
Enclosure .... 48 lb.
Without battery .... 40 lb.
Dimensions .... 16 x 19 x 18 in.
Height of inlet aboveground .... 6.57 ft.

EPA performance-specified and PQ200 featured hardware
Ambient temperature sensor range .... -30 to +50 °C ±0.16 °C.
Ambient barometric pressure sensor.
Volumetric flow control and measurement system.
Microprocessor.
RS-232 communication.

GT-640 Logger Particulate Monitor	**Met One Instruments** 1600 Washington Blvd. Grants Pass, OR 97526 Home Page: http://www.metone.com
Range	0 to 10,000 μg/m^3.
Sensitivity	1 μg.
Accuracy (1 min)	2-percent concentration 0.000 to 1.000 mg.
Accuracy (1 h)	1-percent concentration 0.000 to 1.000 mg.
Particulate data period	1-min standard (1- to 60-min option).
Logger sample	Once per second.
Logger data period	Selectable 1, 5, 15, 60 min.
Flow rate	Up to 5 L/min (depending on inlet).
Power	12 V dc, 1 A (including inlet heater) from external battery or using No. 3813 universal power supply. (No. 3813 supply accepts 90 to 264 V ac, 47- to 63-Hz power sources).
Operating temperature range	0 to 50 °C with internal heater, 0- to 100-percent relative humidity with inlet heater.
Outputs	RS-232 for modem, radio, or direct connection to PC.
Alarm channels (optional)	Two with relay contacts (normally open) (maximum power 24 V dc at 20 mA).
Analog output (optional)	0 to 1 V analog, 0 to 1 mg/m^3.
Data storage	210 days at 1-h data period.

DataRam	**MIE, Inc.** 7 Oak Park Bedford, MA 01730 Home Page: http://www.mieinc.com
Concentration measurement ranges	0.1 to 999.9 μg/m^3 (resolution: 0.1 μg/m^3). 1.0 to 39.99 mg/m^3 (resolution: 0.01 mg/m^3). 40.00 to 399.9 mg/m^3 (resolution: 0.1 mg/m^3).
Wave length	880 nm.
Scattering coefficient ranges	1.5 x 10^{-7} to 6 x 10^{-1} m^{-1}.
Concentration display averaging/updating time	1 to 10 s.
Instrument comparison/repeatability	±0.3 μg/m^3 for 10-s average, ±1.0 μg/m^3 for 1-s average.
Accuracy	±5 percent of reading ± precision.
Temperature coefficient of zero level	Less than 0.05 μg/m^3 per degree Celsius.
Particle size range of maximum response	0.1 to 10 μm.
Sampling flow rate	1.7 to 2.3 L/min.
Data logging averaging periods	1 s to 4 h.
Total Number of data points in memory	20,000 (each point: average, minimum, and maximum concentrations).
Real time and date data	Seconds, minute, hours, day of month, month and year, with leap year compensation.
Clock accuracy	±1 min/month or better.
Digital output	RS-232, 9,600 baud, 8 data bits, 1 stop bit, no parity bits.
Operating environment	0 to 40 °C (32 to 104 °F), 0 to 95 percent relative humidity.
Dimensions	134 (5.28) x 184 (7.25) x 346 (13.63) mm (in) (H x W x D).
Weight	5.3 kg (11.7 lb).

NGN-3 Open-Air Integrating Nephelometer

Optec, Inc.
Open-Air Integrating Nephelometer
199 Smith St.
Lowell, MA 49331
Home Page: http://www.optecinc.com

Extinction range	0 to 32,768 count (serial output); 0 to 10 V (analog channel 1 or 2).
Resolution	±1 count (serial output; one Rayleigh is equal to 12 counts).
	±2.44 mV (analog channel 1 or 2; one Rayleigh is equal to 12 mV).
Accuracy	±10 percent of true value for air near Rayleigh and using 2 min of integration.
Measured wavelength	550 nm center wavelength, 100-nm bandwidth (photopic response)
Output, serial	RS-232, RX, TX, GND; 8 data bits, 1 stop bit, no parity. Televideo 920 emulation, full-duplex mode 9,600-baud default, others selectable.
Output data, serial	Status, raw scattered light count, raw lamp brightness count, normalized scattered light count, integration time in minutes, temperature, date (year:month:day), time (hour:minute).
Output data, analog	Channel 1, normalized scattered light.
Output data, analog	Channel 2, status value.
Power supply	13.8 ±0.3 V dc, 4.5 A, regulator required.
Operating temperature	-20 to 45 °C.
Size	10.7 x 8.2 x 16.5 in.
Weight	27 lb.
Meteorological sensors temperature	±0.5 °C from -30 to +70 °C.
Humidity	±2 percent relative humidity from 0- to 100-percent relative humidity at 25 °C.

M903 Nephelometer (ROM version 2.37)

Radiance Research
535 NW. 163 St.
Seattle, WA 98177

Principle parameter	Light-scattering extinction coefficient, integrating nephelometer.
Range	0 to 1 km^{-1}.
Lower detection	Less than 0.001 km^{-1} at 30-s average.
Outputs	Four analog (0- to 5-V dc) and RS-232 serial, baud rate selectable, 9,600, 4,800, 2,400, 1,200.
Time constant	Adjustable: 2 to several minutes.
Electronics	Computer-based, MD68HC11 at 8 MHz operating parameters, diagnostics through serial port, three sets of default operating parameters selected with panel switches.
Optics	No lenses. Reference brightness measurement and chopper-stabilized span. Chopper rate adjustable (typically, 20-percent duty cycle).
Wavelength	530 nm.
Sample volume	0.44 m^3.
Weight	About 2.6 kg (6 lb) depending on application configuration.
Size	56 x 13 x 17 cm (L x W x D).
Operating voltage	12 V dc (0.8 or 1 A supplied).
Power usage	2.5 to 3 W (230 mA at 12 V dc) without fan at maximum flash rate; less power at lower flash rates. The supplied fan is 0.8 W.
Selected averaging periods	20 s to 1 h.
Internal data storage	Diagnostic parameters, zero and span settings and time stored in RAM.
Internal clock	Two weeks of 5-min averages can be stored.

Inhouse Filter System	**USDA FS, Rocky Mountain Research Station** Fire Chemistry Group P.O. Box 8089 Missoula, MT 59807 Phone: 406–329–4866

Flow rate .... 28 L/min.

Filter medium .... 37-mm Teflon filter.

About the Authors

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Mary Ann Davies is a Project Leader working for the Facilities, Recreation, Fire, and Watershed, Soil, and Air Programs. She received a bachelor's degree in mechanical engineering with a minor in industrial and management engineering from Montana State University in 1988. Her Forest Service career began in the Pacific Northwest Region where she worked with facilities, tramways, fire, and recreation. Mary Ann worked for the Rocky Mountain Research Station's Fire Sciences Laboratory in Missoula before coming to MTDC in 1998.

Rich Fisher has bachelor's degrees in life science (U.S. Air Force Academy) and in meteorology (North Carolina State University). He has master's degrees in earth science (Colorado State University) and in international and strategic studies (Naval War College). He is a certified consulting meteorologist and is Reserve Assistant to the Director of Weather for the Air Force in the Pentagon.

Harold Thistle received a Ph.D. in plant science specializing in forest meteorology from the University of Connecticut in 1988. He is certified by the American Meteorological Society as a Certified Consulting Meteorologist (CCM) and was a consultant in private industry before joining MTDC in 1992. He served as the Center's Program Leader for Forest Health Protection until 1998, developing modeling techniques that accurately describe transport of pesticides in the atmospheric surface layer and evaluating meteorological instrument systems for environmental monitoring. Harold now works with the Forest Health Technology Enterprise Team in Morgantown, WV.

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Library Card

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Evaluates five commercially available optical instruments to measure particulate for forest fire smoke in real time. The instruments include the Met One GT-640, MIE DataRam, Radiance Research Nephelometer Model M903, Optec NGN-3 $PM_{2.5}$ Size-Cut Nephelometer, and the Andersen RTAA 800 Aethalometer. Airborne particulates, especially those particles smaller than 2.5 μm in diameter ($PM_{2.5}$), pose potential health, visibility, safety and nuisance problems. Measuring airborne particulate concentrations is very important to land managers as the use of managed forest and rangeland burning increases. The key items of the evaluation were accuracy in measuring or estimating smoke concentrations, comparing results from identical instruments, reliability, cost, and operational characteristics such as portability, power requirements, and data collection. The data were from lab and field settings. The five brands of optical instruments had few fundamental differences. Accurately estimating ambient particle concentrations from light-scattering and absorption properties is difficult. However, optical instruments can estimate the direction of change and magnitude of the overall ambient particulate concentration, providing useful information to air-quality specialists and land managers.

Keywords: aethalometers, air quality, gravimetric samplers, nephelometers, real time, samplers, smoke management, wood smoke

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