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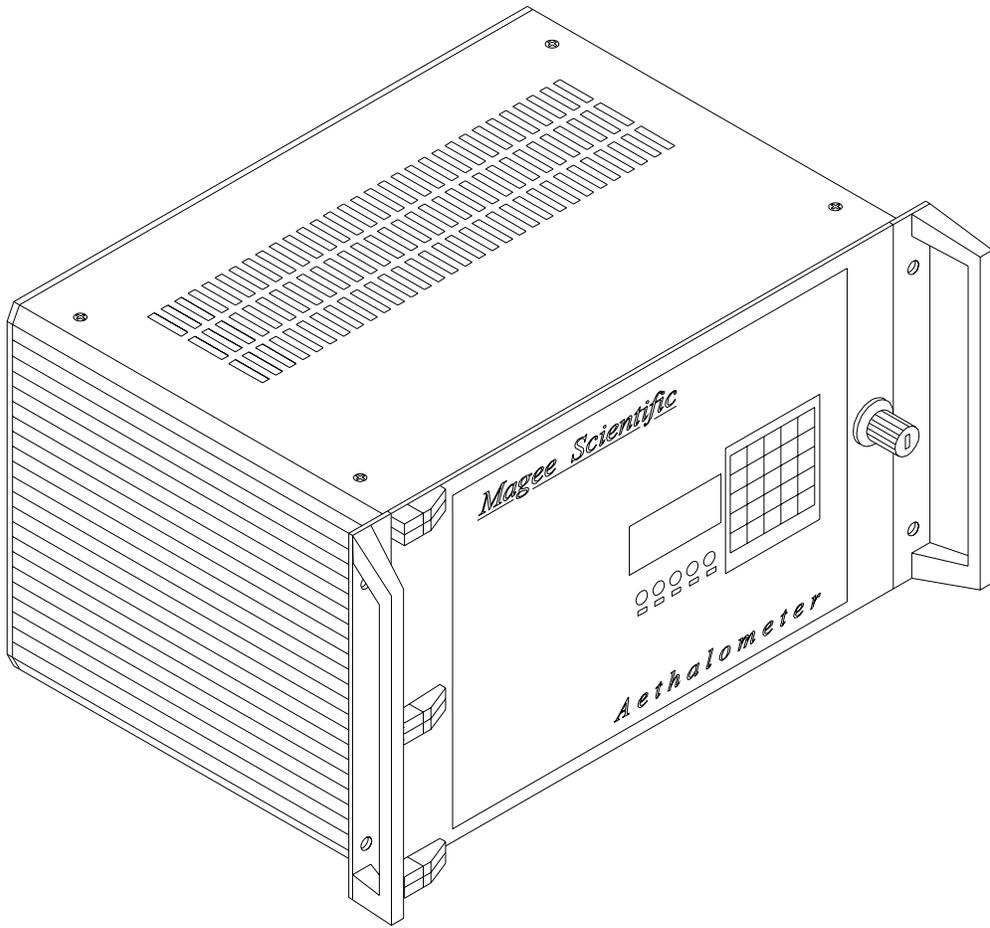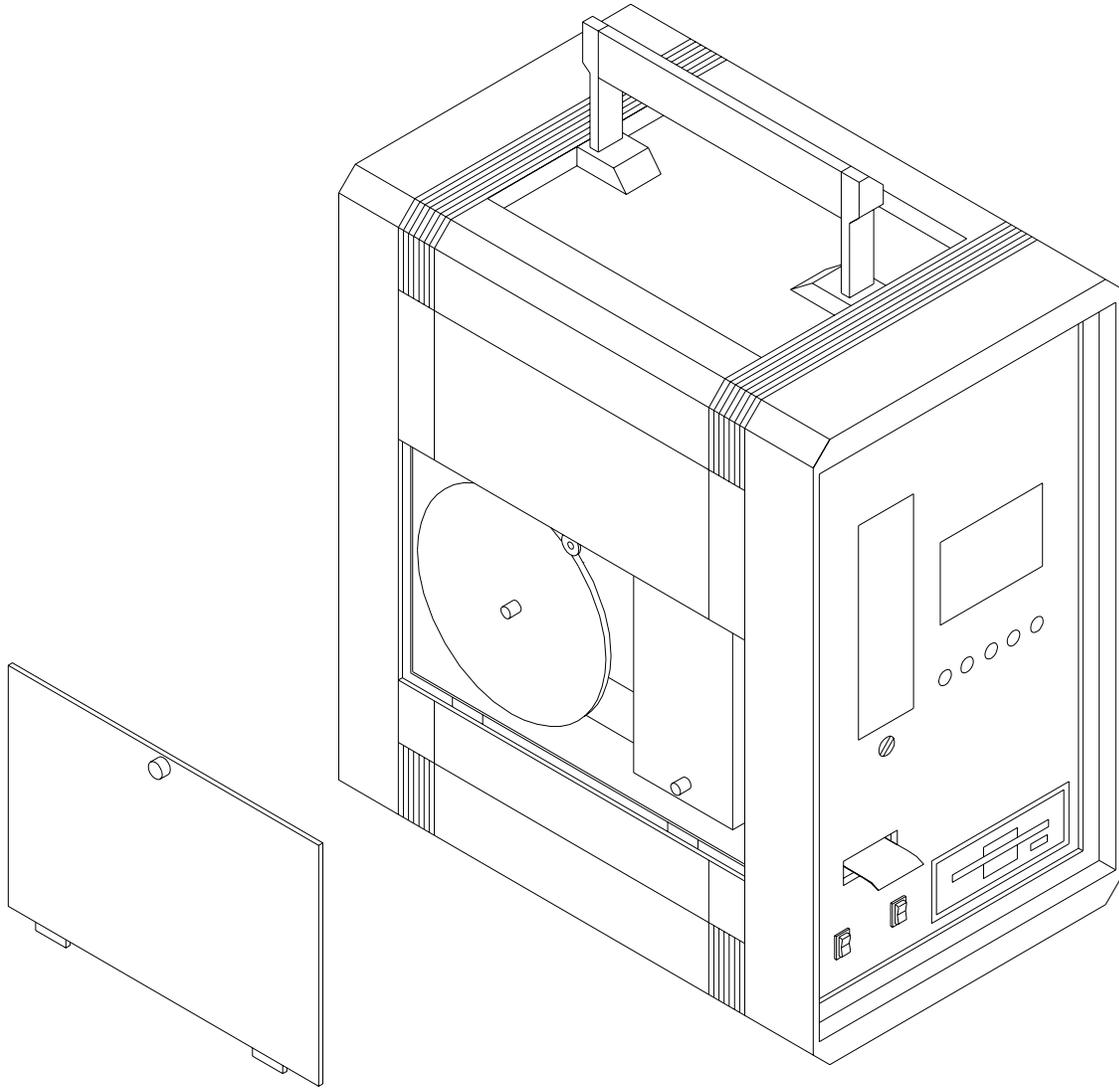

The Aethalometer ™

2005.07

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The Aethalometer ™ - 19-inch rack mount chassis version

The Aethalometer ™ - 'Portable' chassis version

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The Aethalometer ™ - 19-inch rack mount chassis version

1. INTRODUCTION

The Aethalometer™ is the foremost instrument for the real-time measurement of optically-absorbing 'Black' or 'Elemental' carbon aerosol particles. It was first conceptualized in 1979; its prototypes evolved during the 1980's on research projects at remote locations; the first commercial unit was shipped in 1986; production was transferred to Europe in 1995; and as of this date of writing (2005) there are many hundred Aethalometers in use on all continents from the Sahara Desert to the South Pole, from Brazil to Tibet, from the streets of New York City to the mountaintop of Mauna Loa, Hawaii. The development of the 'Portable' model extended its applications in the area of public health and epidemiological studies, by allowing for real-time measurements of carbon particulate concentrations on buses and trains, in living and working areas, in hospitals, airports and other public spaces.

Aethalometers provide fully automatic, unattended operation. The sample is collected as a spot on a roll of quartz fiber filter tape: depending on location, one roll of tape may last from months to years. No other consumables are required.

In 1999, the basic AE-16 Aethalometer measuring aerosol 'Black' carbon was joined by models offering optical analysis at additional wavelengths. The AE-21 series adds analysis in the near-ultraviolet at 370 nm, which is found to respond with great sensitivity to aromatic organic species such as are found in tobacco smoke, wood fire smoke, and fresh diesel exhaust. The AE-31 series performs optical analysis at seven different wavelengths from 370 nm to 950 nm, and has found widespread application in studies of atmospheric optics, radiative transfer etc.

In 2001, the 'Portable' model of Aethalometer was announced, offering the same optics, electronics, analytical performance and instrument features, but packaged in a smaller chassis with internal battery operation and connection for GPS mobile tracking.

In 2002, the 'Extended Range' inlet was offered on all models for enhanced performance in locations of high aerosol concentration, as an alternative to the 'High Sensitivity' inlet.

All Aethalometers are unconditionally supported by Magee Scientific Company. We provide warranty service as well as offering advice and assistance in selecting the correct model for the intended application, setting up the instruments, interpreting the data, and ensuring satisfactory operation. Please do not hesitate to contact us directly for any reason. For further scientific or technical information, please contact us as shown below, or refer to the web site http://www.mageesci.com . This site provides a wealth of information on Aethalometers, examples of Aethalometer applications, downloadable documentation, and other related material.

Thank you for your interest in the Aethalometer™.

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2. "QUICK-START" SUMMARY

2.1 WHAT DOES IT MEASURE?

The Aethalometer™ is an instrument that provides a real-time readout of the concentration of 'Black' or 'Elemental' carbon aerosol particles ('BC' or 'EC') in an air stream. These particles ("soot") are emitted from all types of combustion, most notably from diesel exhaust.

'BC' is defined by 'blackness', an optical measurement. The Aethalometer uses a continuous filtration and optical measurement method to give a continuous readout of real-time data. The 'EC' definition is based on a thermal-chemical measurement, an analysis of material collected on a filter sample for several hours and then heated in a gas stream. There is no accepted definition of 'elementarity'. Different thermal parameters as used by different EC analysis protocols will actually yield different EC numerical results, even on portions of the same filter samples. The optical analysis for BC is consistent and reproducible. A wide body of published research shows that the Aethalometer BC measurement is closely proportional to filter-based EC measurements.

The Aethalometer performs the optical analysis and data readout '*on the spot*'. The results are available immediately to the user, without waiting for analysis of a sample at a laboratory.

The Aethalometer is a self-contained, automatic instrument. It requires no consumable materials, no gas cylinders, no operator attention. It runs automatically: plug it in, walk away. It requires no calibration other than periodic checks of the air flow meter response.

2.2 HOW DOES IT WORK?

The Aethalometer™ draws the air sample through the inlet port, typically at a flow rate of a few liters per minute, using a small internal pump. The flow rate is monitored by an internal mass flow meter and is stabilized electronically to the setpoint value entered in software.

The Aethalometer collects the sample on a quartz fiber filter tape, and performs a <u>continuous</u> optical analysis, <u>while</u> the sample is collecting. During this process, the tape does **not** move. The tape **only** moves forward when the spot has reached a certain density. In a city, the tape may advance 3 or 4 times per day. In a rural location, each spot may last a day or longer. The roll of tape contains 1500 spots.

The analysis gives one new reading every <u>timebase</u> period. The user sets the timebase for the desired data rate, usually 1 to 5 minutes, although data to one reading per second are possible. The data is written to diskette; transmitted by the COM port; and produced as an analog voltage.

Faster timebase = more rapid response, but more instrument noise.
Slower timebase = less noise, but you 'lose' the time details.

Recommendation:

For typical urban monitoring, set timebase to 5 minutes.

To study individual events, set timebase to 1 minute.

2.3   U SEFUL U SER F EATURES

The software automatically runs the Aethalometer™ if it is simply plugged in. If the power fails, it will automatically re-start when the power resumes.

The control panel has five lights of different colors to indicate operational status:

GREEN = normal operation, gathering valid data.
FLASHING GREEN = OK, re-initialization after tape advance.
YELLOW = Needs attention, but instrument still running, data still OK.
RED = Problem, instrument stopped.

A diskette typically holds <u>months</u> of data. Diskettes can be changed without stopping the instrument.

The only attention that the instrument needs is:

<u>Once per day</u>, look at it. Green light = OK.
<u>Once per week</u>, check to see how much diskette space is left.
<u>Once per month</u>, replace the diskette, check the tape roll.

The COM port transmits a replica of the diskette data. This includes internal diagnostic signals that confirm that it's working correctly. This data can go to a datalogger.

The analog output can be programmed to be <u>either</u> a voltage representation of the data, <u>or</u> an alarm function if the concentrations exceed a certain level.

The front door can be locked, and the keypad requires a password to stop measurements or change parameters. This provides security against tampering.

The operating system software can be upgraded by inserting a diskette: as new features become available.

There is an automatic 'Optical Test Strip' procedure that provides a QC/QA assurance routine.

The measurement does <u>not</u> require an exact setting of the sample air flow rate. The Aethalometer includes a mass flow meter whose reading is passed to the computer. The data are equally valid at 2, 4 or 6 LPM.

Higher flow = smoother data, but uses more tape
Lower flow = noisier data, but uses less tape.

In most cases, the flow setting depends more on the customer's requirement for a certain inlet, standard protocol, etc. The flow rate setting does not affect the Aethalometer's operation.

In <u>extremely polluted locations</u>, use the 'Tape Saver' feature to reduce filter tape consumption.

2.4   GUIDELINES FOR SETTING UP AN AETHALOMETER

(a)   Unpack, check for any damage. Equipment should include:

- Aethalometer instrument

- Operations Manual

- Factory Certification documents; Optical Test Strip

- Power cord; inlet sample tubing and connectors; Door Lock Key.

Check inside the door, make sure the tape roll did not come loose in shipping.

(b)   Insert a diskette into the drive.

(c)   Remove the red cap plug from the Aerosol Sample Inlet socket on the rear panel, and select a threaded fitting from the bag of connectors that best suits the inlet tubing that you will use.

(d)   The main power switch is on the front panel inside the door: but there is another switch on the rear, where the power cord enters. This second switch is for security only (prevents unauthorized operation in a rack-mounted installation). Make sure the rear switch is in the 'ON' position but for normal use do not use the rear switch! Connect power cord, switch on.

(e)   Instrument will power-up, screen will light. Software takes about 30 seconds to load and run. Check that the internal pump starts running.

(f)   *If Present*: check to see if there is a 'Filter Protection Strip' of paper installed in the optical analysis head. If so, press the 'Tape Advance' switch up, while simultaneously pulling the paper strip out to the right.

(g)   Screen will countdown to automatic restart. After 30 seconds, it will beep. IGNORE THIS. After 60 seconds, automatic operation starts, green light will flash. Walk away for a while.

(h)   After about 30 minutes, the green light should be steady, and the lowest line of the screen should display a BC concentration reading representing the ambient air at your location.

(i)   Press STOP. Screen will say 'Press STOP again'. Press STOP a second time. Screen will ask for 'Security Code' i.e. password. Press 111 (factory setting) and then press ENTER.

(j)   Measurements will stop; screen will show 'Main Menu' and '*Operate*'.

(k) Press the DOWN-ARROW key to scroll through the Main Menu options. The options are:

Operate	Make measurements
Change Settings	Change operational parameters
Signals and Flow	Verify optical signals and sample flow rate
Self Test	Exercise and test hardware
Calibrate Flowmeter	Re-calibrate flowmeter response
Software Upgrade	Upload new software
Optical Test	Perform QC/QA procedure
Install New Tape	Guided instructions

(l) Go to *Change Settings* menu. Press ENTER. You now have the settings sub-menu.

(m) The first item is *Date & Time*. Press ENTER.   Use the RIGHT- and LEFT-ARROW keys to move the blinking cursor over each number. Use the UP- and DOWN-ARROW keys to change the numbers so that the date and time are correct. Press ENTER when done.

(n) The next item is *Timebase*. Press ENTER. Use the UP- and DOWN-ARROW keys to select a timebase value. We recommend 5 minutes for ambient monitoring. Press ENTER when done.

(o) The next item is *Flowrate*. Press ENTER. Use the numerical keypad to enter a suitable sample flow rate in LPM (Liters Per Minute). We recommend 2 LPM in very highly polluted locations, 4 to 5 LPM for normal ambient monitoring. Specific inlet requirements (size-selective inlets, pre-separators, or manifold flow balancing) may require specific flow rates. The Aethalometer uses the actual value of flow measured by its flowmeter, and gives valid data at any flow.

(p) The rest of the parameters are self-explanatory, and are detailed in the operations manual. For most purposes, you only need to set up the correct date, time, timebase and flow.

(q) Press ESC to escape from the *Change System Settings* menu: you will get a prompt to 'Save Settings?'. Press ENTER to confirm the Yes. You will return to the '*Operate*' main menu item. Press ENTER to re-start operation.

2.5 FIELD REFERENCE SUMMARY

This page is a convenient summary to copy for for field reference

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Aethalometer™ for measurement of Particulate Elemental Carbon

To Start: Plug in and switch on. Instrument starts automatically without any operator attention. Data collection will begin after approximately 5 minutes. *Instrument takes about 30 minutes to warm up and finally stabilize.*

To Stop Quickly: Simply switch off. Data file on disk will be current up to this time.

To Exit Cleanly with Data Summary: Press STOP key, watch screen. Press STOP key again. Enter "Security Code" of **111**. Summary file will be written to disk.

Data Diskette may be exchanged at any time with a fresh one, no need to stop.

Flow Rate is set by software and automatically stabilized. Flow may read out in 'Standard' units (sea level) or 'Volumetric' units (corrected for altitude and temperature).

To Change Settings: Switch on, get opening screen.

Press any key to get top item in Main Menu, *'Operate'.*

Press **down-arrow** to get next menu item, *'Change Sys. Settings'.* Press **Enter.**

Scroll through settings list with down-arrow. Press **Enter** to access an item.

First one is *Date & Time*.

Next one is *Timebase* : usually set to 1 - 5 minutes, depending on need.

Next is *Flowrate* : usually 2 to 5 LPM

To change an item, use arrow keys, make selection, press **Enter** to confirm, press **Esc** to escape from the systems-settings menu. Confirm change.

To Advance Tape to a Fresh Spot: Press the 'Tape Advance' switch **upwards** and hold for about **15 seconds**. The mechanism will engage and take about 1 minute to advance the tape: data will settle down after about another 1 minute.

Data Tradeoffs: lifetime of tape spot. When spot saturates, tape automatically advances, data will be interrupted

Shorter timebase = better response to rapid changes in concentration, but noisier data.

Note: data can always be smoothed afterwards to reduce noise. Suggest running at 5 minute timebase.

Higher flowrate = smoother data, but shorter lifetime of tape spot. When spot saturates, tape automatically advances, data will be interrupted for few min.

Increase flowrate to reduce noise if spot doesn't saturate too quickly.

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3.   AEROSOL BLACK CARBON

3.1   ORIGINS

Aerosol black carbon ("BC") is a particulate pollutant species emitted from the combustion of any carbonaceous fuel. Its emission factor is frequently expressed as grams of BC emitted per gram of carbon consumed in the fuel. This factor can vary to an extreme degree depending on the nature of the combustion process, from as much as 10^{-1} for the conflagration of asphalt, to less than 10^{-7} for the controlled combustion of natural gas. Thus, the emissions of BC can <u>not</u> be predicted simply from knowledge of the fuel consumption rate. Also, the emissions of BC from two very similar combustors or processes may be very different, depending on the microscopic details of the combustion process, the degree of technical maintenance of the combustors, and other factors that have relatively little influence on the primary purpose of the combustion. Two diesel trucks may consume fuel at similar rates, and yet one may emit a thousand times more BC than the other.

For this reason it is necessary to actually measure BC, both in the ambient atmosphere and in the exhaust streams from combustors. This measurement is performed by the **Aethalometer™**.

The name "Aethalometer" is derived from the classical Greek verb 'aethaloun', (αεφαλουν) meaning 'to blacken with soot'. It is this optically-absorbing material that the 'standard' Aethalometer measures. Carbonaceous particulate emissions from combustors include a wide range of other compounds, including fuel molecule fragments, pyrolysis and reduction compounds, agglomerates, compounds containing nitrogen (from the combustion air as well as from trace compounds in the fuel), compounds containing sulfur and other trace elements from the fuel, and almost every other organic species known. The fractions of this material that concern us at present are the optically-absorbing components: 'black' material, and also those compounds that absorb ultraviolet light. The 'black' material ("BC") is sometimes also termed 'elemental carbon' ("EC"). Its definition is largely based on operational and analytical considerations: it is the portion of combustion emissions that is insoluble in polar and non-polar solvents: it is stable in air or oxygen at temperatures up to approximately 350 - 400°C: it displays the Raman spectral shifts characteristic of the graphitic ring structure, but in a disordered microcrystalline form: and it is strongly optically absorbing.

The only known source of aerosol black carbon in the atmosphere is the combustion of carbonaceous fuels. There are no known significant biological, geological or meteorological sources. It is generally believed that volcanic emissions, although distinctly opaque, are primarily composed of mineral dust and contain relatively little aerosol black carbon. A certain amount of carbonaceous dust is injected into the upper atmosphere from infalling meteorites, but this is considered to be a relatively small source.

The presence of BC in a local, regional or remote air mass is a certain indicator that combustion emissions had impacted that air mass at some earlier point in time. When considered on a logarithmic scale, it is always possible to measure some concentration of BC at any point on the surface of the planet: the assessments of 'presence' and 'impact' are relative in degree.

The major sources of aerosol black carbon are:

- combustion of fuels for the generation of energy;

- biomass burning for agricultural purposes;

- naturally-occurring forest fires.

The first two of the above categories represent anthropogenic activities. On a global scale, these sources are believed to be the major input to the atmosphere. Forest fire emissions are copious and may be locally overwhelming, but it is not thought that they are a major contributor to the atmospheric burden of BC on a global, year-round basis.

Aerosol black carbon is removed from the atmosphere by wet and dry deposition. These removal rates will depend on the particle size, and its likelihood of being involved in condensation and precipitation processes. Emissions of BC particles at the combustion source may produce a wide range of particle sizes and surface physical and chemical characteristics. It is very rare to find combustion sources that produce BC particles of uniform size or nature. Thus, the removal mechanisms in the atmosphere tend to act as an 'editing' process acting on a diverse initial population: the longest-lived particles are the subset of the initial emissions that have most successfully survived or eluded the removal processes during residence and transport in the atmosphere. The BC aerosol detected at the South Pole is only a tiny fraction of emissions produced many tens of thousands of kilometers distant, able to survive the rigorous meteorological conditions during transport to that distant measurement station.

Clearly, aerosol black carbon is removed from the atmosphere. Otherwise, the atmosphere would be entirely filled with smoke from centuries of combustion. Studies of the correlation of variations in BC concentrations with meteorological trajectory analyses at remote locations allow us to study the effect of these removal processes: deposition along non-precipitating trajectories as a function of transit time from the source region, the effect of passage through precipitating systems, and so on.

Aerosol black carbon is of interest for two major reasons:

- its own direct and indirect effects, both physical, chemical, and physiological; and

- its use as a tracer to indicate the movement of meteorological air masses.

3.2 EFFECTS

The direct effects of the presence of BC in the atmosphere include the following:

(a)   Physiological Effects

Aerosol black carbon has a great porosity and the ability to adsorb other species from the vapor phase, especially organics. The BC particles are usually small enough to be readily inhaled, where they have a certain probability of depositing in the lungs or other airways. They may therefore act as vehicles for the transport and localized deposition of harmful compounds to the human pulmonary system. A wealth of epidemiological evidence supports a link between adverse health effects and the sub-2.5 micron component of ambient aerosols. Public health concerns are one of the largest motivators for the study of fine particulates, as it has been asserted that urban and regional air pollution leads to adverse health effects, both chronic and acute, in large numbers of people.

(b)   Chemical Effects

Although the graphitic form of carbon is itself relatively inert, it provides a surface that may catalytically promote certain other reactions in the atmosphere, especially in the presence of water. A slurry of carbon particles in water greatly accelerates the oxidation of SO_2 in solution. Activated carbon is used as a scrubber for ozone in consumer, scientific and industrial processes. It is believed that the presence of carbonaceous aerosols in polluted atmospheres can lead to increased production of aerosol acidity.

(c)   Physical Effects

The large optical absorption cross-section of BC leads to the extinction of radiation, both infrared and visible. In heavily polluted cities, this produces brown skies and reduced visibility. In a polluted tropospheric column over a high-albedo (e.g. snow) surface, net absorption optical depths as large as 0.05 to 0.1 may seriously perturb the solar radiation balance. In regions whose appeal derives from their supposedly pristine nature, the long-range transport of pollutant aerosols can dismay tourists attempting to see across the Grand Canyon, several hundred miles downwind of Los Angeles. The deposition of optically-absorbing material to snow and ice surfaces may reduce the surface albedo sufficiently to accelerate springtime thawing. It has been postulated that increases in the optical depth of the atmosphere may be a contributor to global warming.

(d)   Microphysical Effects

Under certain conditions, carbonaceous aerosols may act as condensation nuclei, altering the size distribution, optical properties and rainfall

potential of clouds. The ability of these particles to remain in the atmosphere for long periods of time may allow them to be transported to regions of the atmosphere that normally have extremely low concentrations of cloud condensation nuclei. Although it is not generally believed that pure BC is an efficient CCN, it is possible that its surface may be modified chemically during transit in such a manner as to reduce the supersaturation necessary for its nucleation. At that point it may then grow to a size more readily removed from the atmosphere, so its participation in cloud modification is fatal to its continued existence in the atmosphere: but the effect is achieved. The incorporation of BC into cloud droplets may substantially affect the cloud's albedo and rainfall potential. It has been asserted that smoke emissions from the Indian subcontinent have perturbed the pattern of monsoonal rains over south-east Asia.

As a tracer, the presence of aerosol black carbon in an air mass is a certain indicator that the air being sampled has been impacted by combustion emissions. This knowledge may then assist with decision-making for other sampling and analysis, for calling public health alerts, or in the interpretation of other data. The capability of the Aethalometer to perform the BC measurement in real time can provide this information on the spot to assist with the decision making or the calling of other studies that require time integration and *post-facto* lengthy laboratory analyses. As an indicator for health-effects studies, high levels of BC can be linked to other components of PM2.5 to indicate patterns of source strengths and population exposure. As an indicator of local pollution, the BC record at a study location can reveal unintended events of local contamination, such as (for example) whether a diesel truck had been unintentionally operated upwind of the sampling site. In meteorological studies, the arrival at a measuring station of an air mass containing a significant relative increase in BC may allow for the identification of that air mass as having passed over a candidate combustion source region some time earlier. The presence of BC in the air mass may discriminate between two candidate trajectories, and provide the meteorologist with additional information that can not be given by measurements of species that also have natural origins.

3.3   DEFINITIONS AND ANALYTICAL TECHNIQUES

Aerosol black carbon is defined both specifically and also operationally. Specifically, we believe that it is a form of graphitized carbon in which the immediate environment of most of the carbon atoms is the six-member ring. This provides a large number of electrons in pi bonds whose mobility allows them to absorb optical photons, i.e. be moved by incident electromagnetic fields. The limited number of available states for these electrons results in a moderately high resistance, as may be measured for bulk graphite. The result of this is that the electrons in graphite are mobile enough to respond to photons, but resisted enough so that they dissipate the incident energy and effectively absorb it. Graphitic carbon has one of the largest broad-spectrum absorption cross-sections known, approximately 10 square meters per gram in the mid-range of the visible spectrum. This absorption is proportional to the frequency of the incident electromagnetic field, and so the absorption is proportionately increased in the blue spectrum and reduced in the infrared. When irradiated at a specific frequency, the molecular structure results in a Raman shift such that a small amount of radiation may be detected in emission at frequencies reduced by an amount corresponding to the energy of generation of lattice phonons. The intensity of the Raman peak was found to be proportional to other quantitative analyses as described below. These facts may lead one to a definition of 'elemental' carbon distinct from that of diamond or completely amorphous carbon.

In the form found in combustion effluent, the carbon exhibits many of the above properties but with the addition of a microstructure. This means that while the immediate environment of a particular carbon atom may resemble that of graphite with mobile, light-absorbing electrons, the regular order may only extend for a few hundreds or thousands of atoms in any direction. Electron micrographs frequently show combustion particles as composed of aggregates of tiny spherules each with a characteristic dimension of fractions of a nanometer. These microscopic observations provide the explanation for the secondary peak in the Raman spectra of aerosol black carbon that is associated with phonon modes generated at the microcrystallite edges.

Chemically, we may formulate other definitions yet. Almost all organic and inorganic carbon compounds are soluble in some appropriate polar or non-polar solvent. Bulk graphite is not, nor is the BC component of an ambient aerosol sample. Using 'blackness' as a yet-unquantified indicator, we note that a sample of urban aerosol collected on an inert quartz fiber filter will retain its 'blackness' despite treatment with extremely powerful solvents: provided that the mechanics of the extraction process do not physically dislodge the particles from the filter (e.g. by sonication, etc.). We may recover a vast spectrum of organic compounds from the solvents, frequently amounting to more than 80 or 90 percent of the total original mass of carbon, yet the 'blackness' is unaffected.

These samples may also be investigated for their thermal stability. An aerosol sample collected on a quartz fiber filter may be gradually heated from room temperature in a controlled atmosphere. If this atmosphere contains oxygen, there will be a tendency for the various species in the sample to evaporate, decompose, or oxidize. A downstream catalyst can convert all released carbonaceous species to CO_2 for subsequent quantitation of the rate of release of carbon atoms from the sample. (Note the need for the sample to be collected on quartz fiber, a material that is stable to very high temperatures and which can be pre-fired to remove any initial carbon contamination). Again, the 'blackness' of the sample may be monitored during this process. The result is that even in an atmosphere of pure oxygen, the 'blackness' does not start to disappear until temperatures of 350 to 400°C are reached. At lower temperatures, we observe the vaporization of volatiles and the decomposition of medium-molecular-weight compounds. If the sample had been previously solvent extracted, those lower-temperature peaks in evolved carbon would be absent or greatly reduced. At the high temperatures, the rate of detection of carbon combusting from the sample is exactly mirrored by the rate of disappearance of 'blackness', and a linear proportionality is found between the optical measurement and the chemical quantitation of carbon that has survived both the solvent extraction processes and the temperature processing in pure oxygen up to about 350 °C.

Based on these observations, in the late 1970's we proposed an <u>operational definition</u> of 'aerosol black carbon':

'**Black Carbon'** is that fraction of aerosol particulate matter that is insoluble in polar and non-polar solvents; is stable in a pure oxygen atmosphere to a temperature of 350 °C; which displays the Raman spectral lines characteristic of both the graphitic structure and the features of microcrystallinity; and which is strongly optically absorbing in the visible spectrum. The actual quantitation of the material is performed by a chemical analysis of the CO_2 produced by combustion of a sample after extraction and thermal pre-treatment. This analysis yields a mass of carbon expressed in micrograms, and provides the basis for the calibration of the optical absorption measurement of sample 'blackness' in terms of a mass of 'BC'.

The 'blackness' measurement, as described in the following chapter, was found to be sensitive <u>only</u> to the amount of carbon thus defined and measured. It is <u>in</u>sensitive to any amounts of extractable organic carbon, or other aerosol species that frequently contribute substantially to the total aerosol mass, yet are not optically absorbing. The result implies that black carbon is the only aerosol species that is optically absorbing in the visible spectrum, and that a measurement of visible light absorption may be interpreted directly in terms of a mass of BC. This result is generally valid for aerosol samples taken from sources, and in urban

and many remote areas. It is <u>not</u> valid in cases where the sample contains a very large amount of mineral dust. Dust has an absorption cross-section that is smaller than that of BC by a factor of from 100 to 1000. Thus, if the amount of dust is 100 to 1000 times greater than that of BC, a comparable optical absorption may be produced. This interference can not be eliminated in the real-time measurements of the Aethalometer, though it can be determined in a *post-factum* analysis of the filter sample as will be explained.

4.   THE OPTICAL ATTENUATION METHOD

The optical method that we use is a measurement of the attenuation of a beam of light transmitted through the sample when collected on a fibrous filter. When calculated as shown, this quantity is linearly proportional to the amount of BC in the filter deposit.

Define I_0 as the intensity of light transmitted through the original filter, or through a blank portion of the filter: define I as the intensity of light transmitted through the portion of the filter on which the aerosol deposit is collected.

The 'Optical Attenuation' ATN is defined as

$$ATN = 100 * \ln (I_0 / I)$$ [1]

The factor of 100 is for numerical convenience: without this factor, the definition is simply that of transmission optical density. In these units, and with the measurement made using white light, we find that an ATN value of 1 is barely perceptible (a contrast between 'deposit' and 'blank' of only 1%), while an ATN value of 100 corresponds to an aerosol spot that is quite dark gray.

This measurement is affected by the wavelength of the light with which it is made, provided that the particle size is somewhat smaller than the wavelength. The absorption of light by a broad band absorber such as graphitic carbon is inversely proportional to the wavelength of the light used. Thus, for a given mass of black carbon [BC], the optical attenuation at a fixed wavelength λ may be written as

$$ATN(\lambda) = \sigma (1/\lambda) * [BC]$$ [2]

where [BC] is the mass of black carbon, and $\sigma (1/\lambda)$ is the optical absorption cross-section ('sigma') that is wavelength dependent, and which is referred to as the 'Specific Attenuation'.

Aethalometers operate at one or more fixed wavelengths, and so the optical intensity functions are products of terms that may or may not be wavelength-dependent. The intensity of light detected after passing through a blank (clean) portion of the filter is

$$I_0(\lambda) = IL(\lambda) * F(\lambda) * OC(\lambda) * D(\lambda)$$ [3]

where

$IL(\lambda)$ is the emission intensity of the light source,

$F(\lambda)$ is the spectral transmission function through the filter,

$OC(\lambda)$ is the spectral transmission function through all the other optical components, and

$D(\lambda)$ is the spectral response function of the detector.

If we now measure the optical transmission through an aerosol deposit on this filter, using the same light source and detector, the net intensity will be

$$I = I_0(\lambda) * \exp - \{ A(\lambda) \} \qquad [4]$$

where the absorbance is

$$A(\lambda) = k(1/\lambda) * [BC] \qquad [5]$$

and [BC] is the amount of black carbon whose optical absorption is inversely proportional to the wavelength.

The logarithmic ratio of I to I_0, giving the optical attenuation ATN, is therefore proportional to the mass of absorbing black carbon, with the wavelength dependence of optical components and detector being weighted by the $1/\lambda$ function. The coefficient of this proportionality is defined as the Specific Attenuation, usually referred to as 'sigma'.

Note that the above derivations assume that the actual optical absorption is linearly proportional to the mass of absorbing material. This assumption is valid under the following conditions that are found to apply in practice:

(a)   the particle sizes are considerably smaller than the wavelength size parameter, $2*\pi*\lambda$;

(b)   the amount of absorbing material in the sample is not so great as to lead to saturation;

(c)   the effect of the embedment of the aerosol particles in a deep matrix of optically-scattering fibers is to eliminate any reduction of the optical transmission through the filter by optical <u>scattering</u> by the particles, and to render the measurement sensitive to <u>absorption</u> only.

These conditions are met when we sample ambient aerosols on quartz fiber filters, and limit the measured optical attenuation to values of approximately 150 or less: the measured attenuation is found to be linearly proportional to the mass of 'black carbon' determined by chemical procedures as defined above. The coefficient of proportionality is the 'specific attenuation', ATN / BC. From equation [4] this is

$$\sigma(1/\lambda) = ATN/BC = 100 * k(1/\lambda) \qquad [6]$$

The Aethalometer model AE-16 uses a solid-state source operating in the near-infrared at a wavelength of 880 nm. Other models of Aethalometer include the use of other wavelengths, as will be discussed below, and the algorithm must always use the appropriate value of Specific Attenuation that is correct for the wavelength of measurement. This quantity is frequently simply referred to as 'sigma', the specific attenuation whose units are measured in square meters per gram. Note that it is essential to remember that sigma is not a 'physical constant' but is wavelength dependent, and that its value must be ultimately related to a chemical or other standard measurement.

4.1 INTERCOMPARISON OF THE METHOD WITH OTHER ANALYTICAL TECHNIQUES.

The optical transmission method as described above relies on an intrinsic physical attribute of "elemental" carbon: its optical absorption cross-section per molecular unit i.e. per unit mass. This method may be compared against other optical methods, as well as to thermal or chemical techniques that derive their analyses from other attributes of the carbonaceous aerosol material. Note, however, that **_all_** techniques for 'BC' – including that of the Aethalometer – are essentially method- and instrument-dependent. There is no way to assess the 'blackness' or 'elementarity' of a sample of aerosol particles in an absolute sense, in the manner in which one can absolutely determine its sulfur or lead content, for example.

4.1.1   Comparison with Optical Methods

The historical 'Coefficient Of Haze' tape sampler collected the aerosol on a spot for fixed time durations, and measured the reflectance of light from an incandescent bulb source. As the sample spot increased in loading, the reflectance was diminished due to the BC component. The final reading after a typical 2-hour collection period was factored by the air flow volume and reported as 'Coefficient Of Haze Units per 1000 Lineal Feet or Air'. Science and technology at that time had not progressed to the point where this reading could be interpreted as a mass of an identifiable species ('BC') per cubic meter. Nevertheless, large numbers of COH tape samplers were deployed and some still remain in service.

In one field study in a rural area (Allen et al., 1999), an Aethalometer was operated in parallel with a COH tape sampler. The intercomparison is shown in the following figure. The results were directly proportional to each other but with the important distinction that the Aethalometer reports its data as micrograms per cubic meter of a defined species.
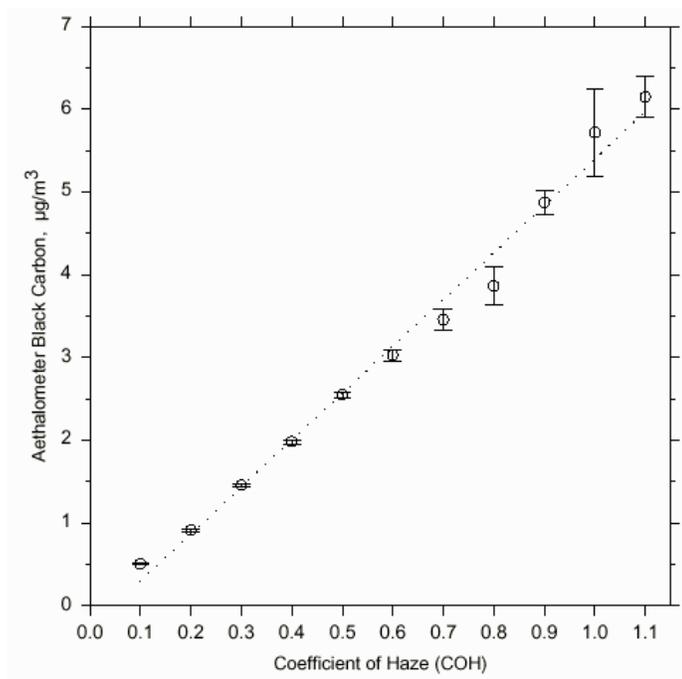
Intercomparison of Aethalometer (µg/m³) with Coefficient Of Haze tape sampler (COH): from Allen, Lawrence, and Koutrakis, "Field Validation...", *Atmos. Env.* **33**: 5 (Feb 1999).

Other optical intercomparisons have been performed. Yasa et al., (1979), reported that the attenuation of a beam of light transmitted through an aerosol sample collected on a filter showed excellent agreement (slope = 1.03, r = 0.98, n = 82 samples) with the photoacoustic signal derived from the energy absorbed by the aerosol deposit itself. This indicates that the transmission attenuation technique responds linearly to the optical absorption of the aerosol, and not to any optical scattering from the collected material. Scattering from the matrix of filter fibers eliminates the effect of scattering from the aerosol deposit itself, rendering the measurement unaffected by the scattering component of the sampled aerosol. Similar excellent agreement was reported in more recent comparisons of the Aethalometer with photoacoustic measurements by Moosmuller et al., (1998).

The 'Particle Soot Absorption Photometer' (PSAP) is an instrument that uses an optical transmission measurement to report the aerosol optical absorption coefficient, although there is debate about the ability of an on-filter measurement to represent an *in-situ* property.   At the 'Atlanta Supersite' instrumental intercomparison, 3 Aug. – 1 Sept.1999, Aethalometer and PSAP data were collected in parallel and yielded excellent agreement.

Intercomparison of EC Measurement Methods at Atlanta Supersite

PSAP Photometer

$y = 10.78x$
$R^2 = 0.97$
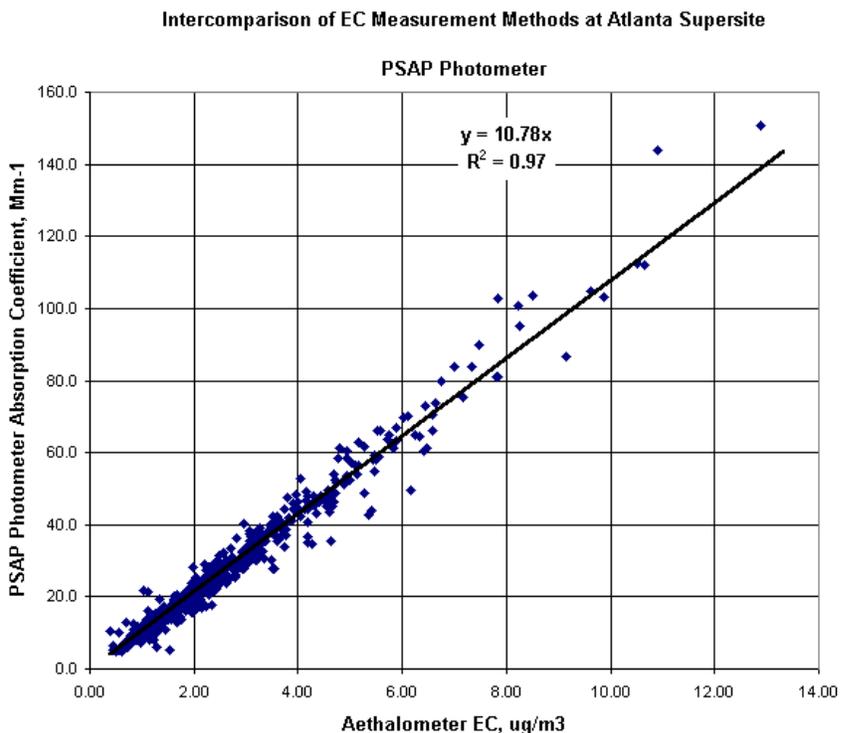
Intercomparison of Aethalometer data (μg/m³)
with 'Particle Soot Absorption Photometer' (Mm^{-1})

The PSAP reports absorption coefficient in units of inverse meters: the Aethalometer data is in units of grams per cubic meter. The slope of the data correlation is 10.8 m²/gram, which is directly in the generally-accepted range of values reported for the optical absorption cross-section for BC aerosol.

At the Egbert site in rural Canada, an Aethalometer was operated simultaneously while samples were collected concurrently for analysis by the 'Laser Integrating Plate Method'. This method is also believed to yield a result that depends only on optical absorption: the effects of scattering are eliminated by surrounding the filter-collected sample by diffusely-translucent media. Plotting the optical absorption coefficient in inverse meters versus Aethalometer data in units of grams per cubic meter of BC yields a slope of 8.5 m²/gram, which is again directly in the generally-accepted range of values reported for the optical absorption cross-section for BC aerosol.
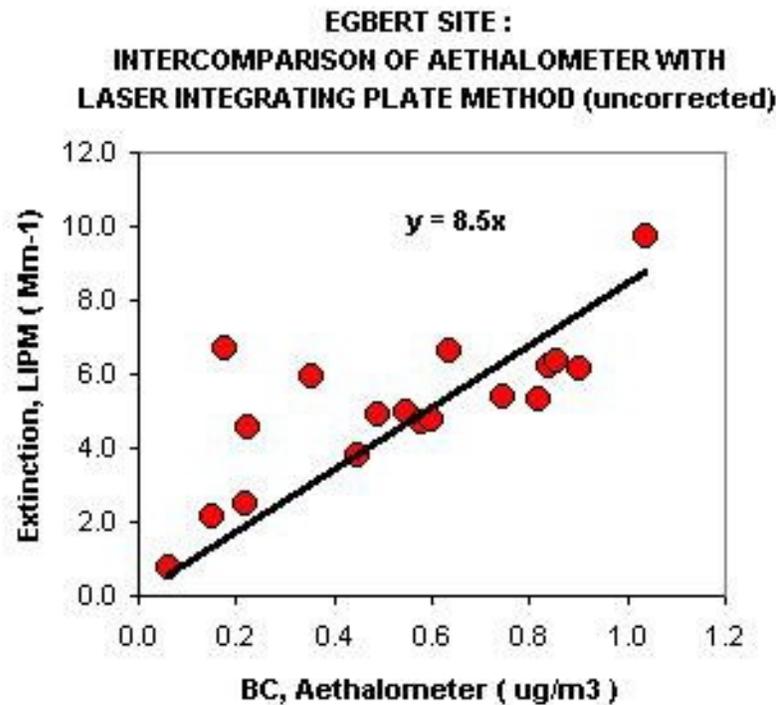
Intercomparison of Aethalometer data (μg/m³)
with 'Laser Integrating Plate' analyses (Mm⁻¹)

During a study in southern China, an Aethalometer was operated simultaneously with a Photo-Acoustic Spectrometer. This technique derives its signal from actual *in-situ* optical absorption by suspended particles. The agreement between the two techniques was very good, with a slope of 8.3 m²/gram:
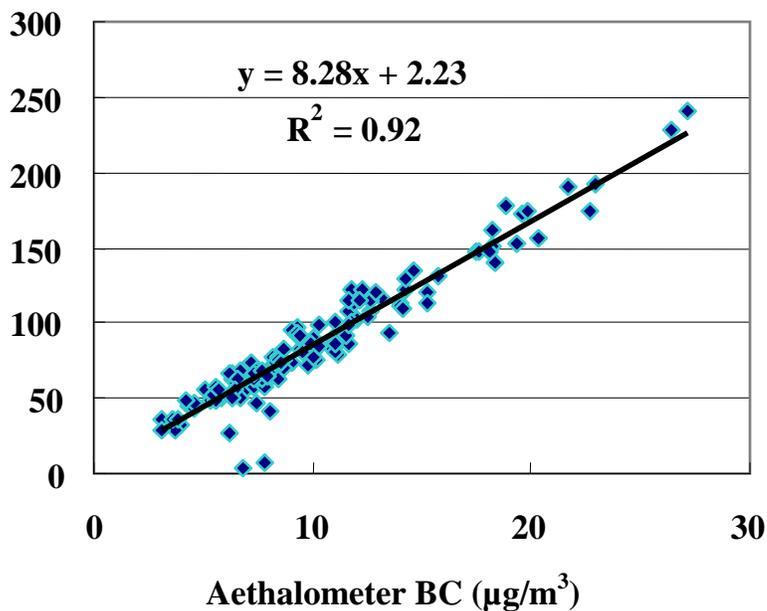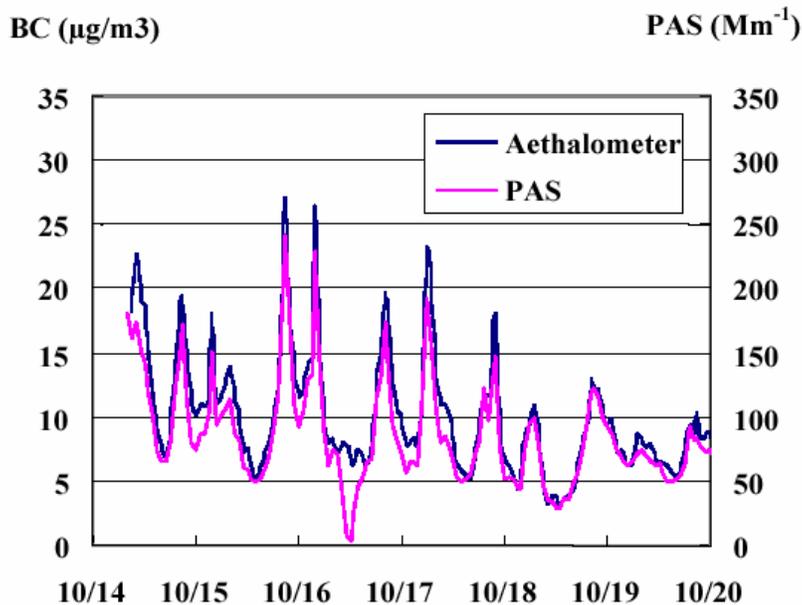
Otmar Schmid, D. Chand, and M. O. Andreae, Max Planck Institute for Chemistry; Aerosol Optical Properties in Urban Guangzhou; PRD workshop Beijing, January 13-14, 2005

4.1.2 Comparison with Thermal and Chemical Methods

Intercomparison against chemical analytical methods a was first performed for aerosol samples containing BC taken from a very wide range of situations: some collected at or near combustion sources, where the collected material is dominated by the characteristics of that source; ambient samples taken in several urban areas, with a varying mix of other pollutant species; and ambient samples collected in remote regions where the aerosol has been in transit from its sources for long periods (Gundel et al., 1984). Carbon content was measured by combustion in oxygen following rigorous chemical pre-treatment to remove organic species, yielding a result that was termed "insoluble, high-temperature-stable carbon", dubbed 'Black Carbon'. Optical attenuation was then measured at the helium-neon laser wavelength of 632 nm. The result was that the proportionality between optical attenuation and Black Carbon content was independent of the origin of the sample. This implies that the optical absorption is due to a fundamental property of the graphitic microstructure that is unaffected by larger-scale differences in particle size, morphology, or the presence or absence of other chemical species.

Hansen and McMurry (1990) reported on an intercomparison of data taken in parallel an urban area. One set of samples were collected on impactor foils and analyzed for 'elemental carbon' by programmed thermal oxidation: the other data were from transmission attenuation. For 17 data comparison points, the agreement showed a slope of 1.02 and correlation coefficient r of 0.99.

In the rural study mentioned above, Allen et al. (1999) demonstrated an excellent agreement between transmission attenuation results and the analyses of separately-collected filters for 'elemental carbon' by the "TOR" thermal oxidation / reflectance technique: for n = 62 samples, the slope was 0.95, the correlation coefficient was r = 0.97.
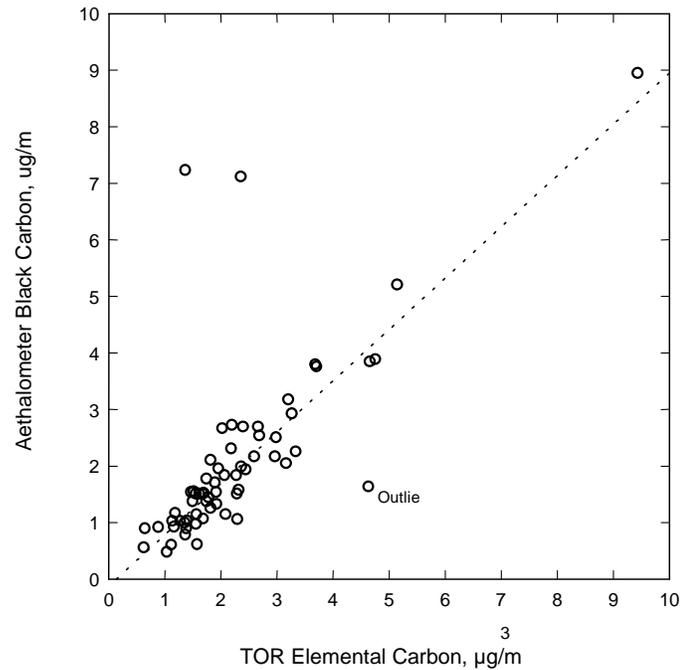
Intercomparison of Aethalometer data with 'TOR' analysis of parallel samples: from Allen, Lawrence, and Koutrakis, "Field Validation...", Atmos. Env. 33: 5 (Feb 1999)

The "Rupprecht & Patashnick Model 5400" is an instrument that collects an aerosol sample by impaction onto a refractory substrate for a fixed time period, and then performs a thermal decomposition analysis. The high-temperature carbon analysis result is reported as an 'EC' concentration. At the 'Atlanta Supersite' instrumental intercomparison, 3 Aug. – 1 Sept. 1999, Aethalometer and 'R&P 5400' data showed good agreement.

Intercomparison of EC Measurement Methods at Atlanta Supersite

R&P Model 5400 Carbon Analyzer
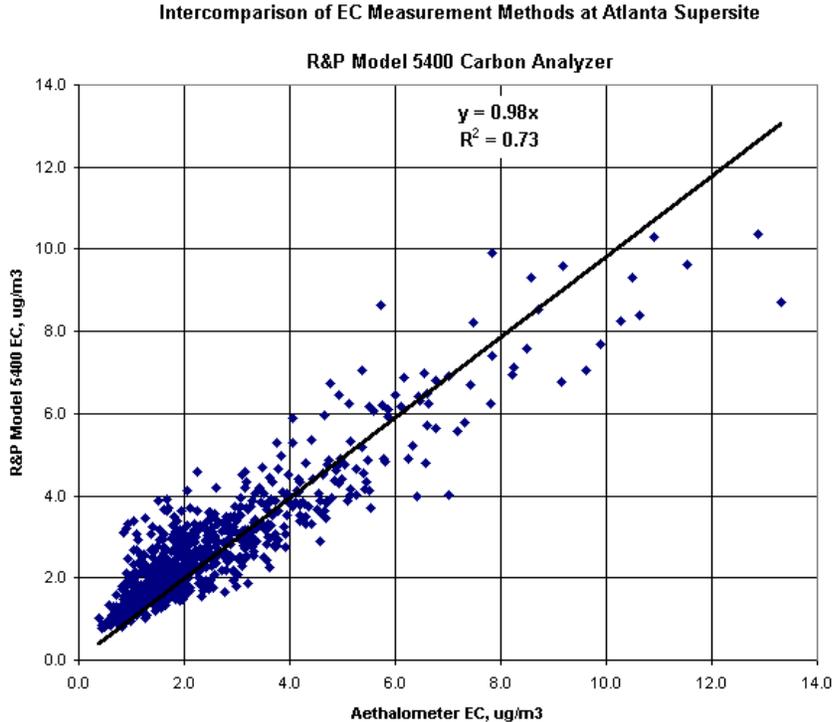
Intercomparison of Aethalometer data with 'R&P 5400' thermal EC analyzer
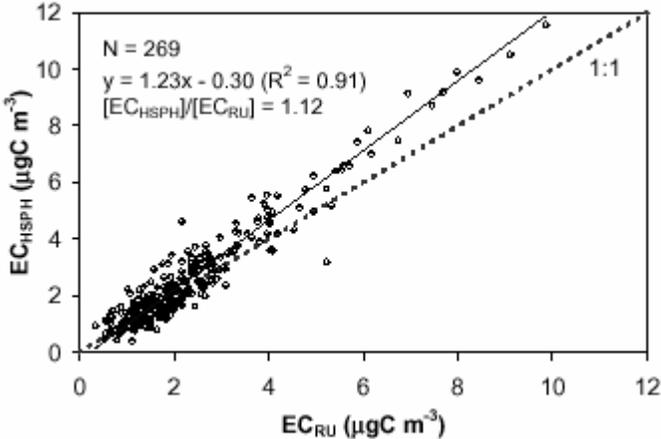
At the same 'Atlanta Supersite' intercomparison, a filtration-based thermal analyzer was operated by Rutgers University. Comparison of this data ('RU') with the Aethalometer (operated by Harvard, 'HSPH') also showed excellent agreement.

By far the most extensive intercomparison of Aethalometer data with the analysis of parallel samples was performed during the "Six Cities" study program during the period 1997-1999. Instruments were deployed in the field at six widely differing locations over all four seasons. The results showed an identical relationship for all sites and seasons, demonstrating that the optical absorption of an aerosol sample is independent of the mix of sources contributing to the aerosol, and is directly proportional to the 'Black' or 'Elemental' carbon component.

Quartz EC vs. Aethalometer using 'EC' calibration
24-hour average
Riverside, Chicago, Phoenix, Dallas, Bakersfield and Philadelphia

$R^2 = 0.94$
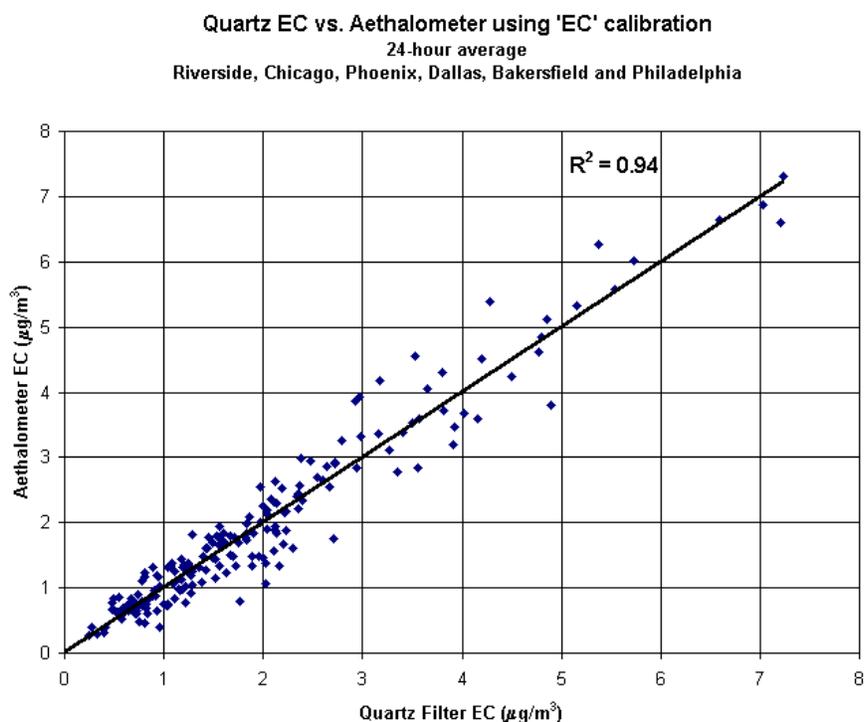
Intercomparison of Aethalometer data with 'TOR' analysis of parallel samples: from Babich et al., Harvard School of Public Health (2000)

Based on these results, we propose an **operational definition** of 'Black Carbon': it is that fraction of the carbonaceous aerosol that absorbs light over a broad region of the visible spectrum, and is measured by determining the attenuation of light transmitted through the sample when collected on a fibrous filter, and applying a calibration factor. This calibration factor is traceable to the absolute chemical determination of the mass of carbon on a sample following a prescribed pre-treatment procedure.

4.2 INTERPRETATION OF OPTICAL ATTENUATION IN THE ULTRA-VIOLET: DEFINITION OF 'UVPM'

The discussion presented above relates the mass of a defined species ("black carbon") to the optical absorbance in the visible portion of the spectrum. At these wavelengths, no other species has as strong an absorption, and the optical attenuation measurement can be reasonably interpreted in terms of a mass of this material.

As the illumination wavelength becomes shorter, the absorption cross-section of the six-member graphitic carbon rings increases as the photon frequency increases. Thus, the 'specific attenuation' at blue-violet wavelengths of 440 nm is expected to be twice that for illumination in the near-infra-red at 880 nm, as used for the standard 'BC' measurement of the Aethalometer. However, as the wavelengths become shorter, other molecular absorption processes become active. In particular, these involve spectrally-specific absorbance (i.e. absorption in lines or bands) rather than the broad-spectrum, all-photon absorption that is characteristic of 'black' carbon. (Indeed, if the absorption by elemental carbon were spectrally-specific rather than spectrally broad, it would appear 'colored' rather than 'black'.) At wavelengths shorter than about 400 nm, certain classes of organic compounds (such as polycyclic aromatic hydrocarbons, and also certain compounds present in tobacco smoke and fresh diesel exhaust) start to show strong UV absorbance. Some of these compounds are photo-ionizable, others of them exhibit fluorescence at these higher energies of photon excitation. As a descriptive (though incorrect) term, we sometimes refer to these compounds as '**blue**' carbon - suggesting the spectral specificity and also the spectral region.

It is essential to note, though, that the absorption cross-section of these compounds is **highly variable**. The absorption efficiency per molecule may vary by *orders of magnitude*. In UV spectrophotometry, the absorbance per mole must be calibrated for each species of interest. If a sample containing a mixture of these species is illuminated with UV light, the UV-specific absorption can be detected but *cannot* be quantitatively interpreted as an exact amount of a specific compound. A few picograms of one PAH species may absorb as much UV as some tens of nanograms of another PAH compound.

An aerosol sample containing 'black' carbon particles onto which organic compounds have been adsorbed will therefore provide two means of absorbing for incident UV photons. The six-member 'black' carbon rings will absorb photons with the $1/\lambda$ efficiency described above. The 'blue' (i.e. UV-absorbing) organic species will add to this absorption with their own spectrally-specific and compound-specific behavior. The overall absorption in the UV will be greater than that attributable to 'black' carbon alone, due to the addition of 'blue' carbon. This is represented by the addition of a second term to the absorbance equation [4]:

A(λ') = k(1/λ') * [BC]   +   Sum { P(λ') * C(P) }   [7]

where P(λ') is the UV absorbance (at the short wavelength λ') of the quantity C of compound P, and this UV activity must be summed over <u>all</u> participating compounds, each of which will have a different absorption efficiency P at each different wavelength λ'.

If the aerosol contains a large concentration of a particular organic compound that has a *strong* UV absorption cross-section, then the overall absorbance in the near-UV may be considerably larger than would be predicted by scaling the visible absorption by a 1/λ factor. This enhancement is due to the presence of the UV-active material, i.e. the "blue" carbon species. These species are colorless in the visible and may therefore be added or removed *without* affecting the 'black carbon' determination based on absorption in the visible or near-infrared: their effect is only seen in results measured by ultraviolet light.

The AE-2 series Aethalometers include light sources illuminating at 370 nm, in addition to the 'standard' illumination at 880 nm to detect absorption due to 'black' carbon. The 880 nm measurement yields an absorbance of

A(λ) = k(1/λ) * [BC]   [8]

while the 370 nm measurement yields an absorbance of

A(λ') = k(1/λ') * [BC]   +   Sum { P(λ') * C(P) }   [9]

which is enhanced by the UV-specific absorption of the mix of organic compounds P. In the absence of chemical speciation of the mixture P, we ***cannot*** interpret the enhancement in terms of a mass of any exactly-given compound: we *cannot* assert that the added UV absorption indicates the presence of an exact number of nanograms of PAH's, for example.

What is done in practice is to *define* an equivalent material based on the optical absorption measurement. We *define* "**UVPM**" (**UV**-absorbing **P**articulate **M**aterial) as if it were a "blue" material that absorbed UV photons with the same efficiency as Black Carbon does, at the UV wavelength in question. From equation [9], the defined 'mass' of UVPM is

[UVPM] = Sum { P(λ') * C(P) } / k(1/λ')   [10]

where   Sum{P(λ')*C(P)} is the ***actual*** UV absorption due to the mix of organic compounds, and k(1/λ') is the absorption cross-section of 'Black' carbon ***at this same wavelength*** . This fictional material 'UVPM' is expressed in units of 'BC Equivalent'.

Equations [8] and [9] can then be re-expressed as the following comparison: the 880 nm 'black carbon' measurement yields an absorbance of

$$A(\lambda) = k(1/\lambda) * [BC] \tag{11}$$

while the 370 nm 'black carbon + blue carbon' measurement yields an absorbance of

$$A(\lambda`) = k(1/\lambda`) * [BC + UVPM] \tag{12}$$

In the absence of UV-specific organic compounds, - i.e. if the sample consisted purely of 'elemental' carbon - the absorbance measurement made at 370 nm would simply be 880/370 times as large as the absorbance measurement made at 880 nm. If we used the appropriately-scaled values of 'sigma' for these two measurements, the absorbances when divided by differing efficiencies would yield *identical masses* of BC or BC-equivalent material. In this situation, 'UVPM' is zero.

However, if we now *add* UV-specific absorbing "blue" compounds to the mixture, then the UV absorption will be enhanced. The absorbance at 370 nm will be *greater* than 880/370 times the absorbance at 880 nm which was due to the 'black carbon' component. This enhancement can be displayed by the algorithm as if it were due to the presence of an equivalent material called 'UVPM', expressed in nanograms or micrograms of a substance that has the same absorption efficiency as the 'black carbon' structure. The added absorption is represented by a non-zero value of [UVPM] in equation [12].

'UVPM' is NOT a real physical or chemical material!

The above definition is for convenience ONLY. If the display of an AE-2 series instrument reports a concentration of 1.5 µg/m3 of BC and 2.0 µg/m3 in the 'BC + UVPM' data, this does ***not*** mean that there is 0.5 micrograms of ***any*** organic species present. What it means is that the UV measurement data shows an additional optical absorption that is of the same magnitude as if it were produced by the presence of 0.5 µg/m3 of black carbon. This additional absorption might ***actually*** be produced by just a few picograms of one particular strongly-absorbing compound: some PAH found in tobacco smoke, for example.

The screen display of an AE-2 series instrument shows two quantities on the lowest line: on the left-hand side, the 'BC' result from the 880 nm measurement. This result is always identical to the result from an AE-16 series instrument, since it is obtained in an identical manner using the same light source wavelength. On the right-hand side of the AE-2 display, there is a second result shown as 'UV'. This represents the ***total*** UV-data signal, i.e. the entirety [BC + UVPM] of equation 12. If sampling a 'normal' aerosol, this 'UV' result will be closely equal to the 'BC' result. If sampling an aerosol that has a strong "blue" component (e.g. fresh diesel exhaust or tobacco smoke), then this 'UV' result will be substantially larger than the 'BC' result. The UV data is increased by an amount expressed in nanograms or micrograms ***as if*** it were BC causing this additional absorbance, but with the clear understanding detailed above that this is an equivalence definition only.

4.3 **INTERPRETATION OF OPTICAL ATTENUATION 'SPECTRUM': MULTI-WAVELENGTH INSTRUMENT**

As discussed above, we expect that in the absence of specific molecular absorption processes the absorption cross-section of the six-member graphitic carbon rings will increase with increasing photon quantum energy. Thus, the attenuation due to the presence of a certain quantity of 'pure black carbon' at a blue wavelength of 450 nm should be almost twice that for illumination in the near-infra-red at 880 nm. The AE-3 series 'Spectrum' models of Aethalometer use an optical source assembly that incorporates **seven** different solid-state light sources. These sources are activated sequentially to illuminate the aerosol sample at seven discrete wavelengths each timebase cycle. In this way, we determine the optical attenuation at seven points across the spectrum from <u>ultraviolet</u> to <u>near-infra-red</u>

4.3.1 'Standard Wavelength Set' Optical Source

.Two sets of sources are available for the AE-31 'Spectrum' models of Aethalometer. The "Standard Wavelength Set" emits at the following wavelengths:

UV	370 nm
Blue	470 nm
Green	520 nm
Yellow	590 nm
Red	660 nm
IR-1	880 nm
IR-2	950 nm

The emission spectra of each of these sources has a typical half-width of 20 nm.

If the optically-absorbing material collected on the filter spot consisted only of a 'pure black' material, i.e. one whose absorption spectrum was uniform, then at any wavelength λ the measured absorbance due to this BC material would be

$$A(\lambda) = k(1/\lambda) * [BC] \qquad\qquad [13]$$

Scaling the absorbance measurement $A(\lambda)$ by a wavelength-dependent cross-section $k(1/\lambda)$ would be expected to yield a wavelength-independent calculation of [BC]. If the aerosol was of this 'pure black' composition, measurements of Optical Attenuation at the above seven wavelengths would simply be proportional to the factor $(1/\lambda)$.

However, most scientific progress is achieved by studying the *deviations* from expected rules. The conditions of spectral uniformity of absorbance are predicated on the following assumptions:

- Particle size is much smaller than any illuminating wavelength

- Absence of any 'coloration' of the material, i.e. no enhancement of absorption at specific wavelengths.

- Failure to adhere rigorously to these conditions could lead to 'coloration' of the response as shown by deviations of absorbance from the $(1/\lambda)$ proportionality - or, using the displayed result of the algorithm - differences in the calculation of [BC] at the various wavelengths. For example:

- Shorter-wavelength photons are less efficient at penetrating larger-sized particles, with the turnover point being scaled by the size parameter $2*\pi*\lambda$. If the sampled aerosol includes BC-containing particles of (say) 2-micron size, the 'apparent' BC result calculated from the optical attenuation measurement at 450 nm will be *smaller* than the BC result calculated from attenuation data taken at 950 nm. Thus, if the calculation of BC from attenuation shows a steady decline at shorter wavelengths, one contributing factor **could be** that the particle size distribution includes super-micron-sized particles which are not effectively detected in the shorter-wavelength measurements.

- Certain other aerosol components may have specific 'coloration' in certain ranges of the spectrum:

Hematite mineral dust may have a *red* coloration: the addition of this dust to the aerosol may change the response of the 660-nm data.

Certain **inorganic compounds** may show the onset of molecular absorption in the near-infra-red: their presence may *increase* the apparent result in the 880-nm and 950-nm data.

Tobacco smoke often has a yellow coloration, which may change the response of the 590-nm data.

Certain **aromatic organic compounds** exhibit the onset of strong absorption in the near-ultraviolet, as discussed above for the basis of the UV measurement in the AE-2 series Aethalometers. This absorbance will obviously be seen in the 370-nm data but may also extend to longer wavelengths and lead to an enhancement of the result in the blue 450-nm data.

The AE-3 series 'Spectrum' Aethalometers provide the instrumental hardware with which to investigate these issues. The data are calculated as an 'apparent' (or 'equivalent') BC based on the specification of 'sigma' cross-section factors for each wavelength. The starting point for investigations is to assign 'sigmas' with a $(1/\lambda)$ proportionality scaled to the standard 880-nm wavelength from which the chemical intercomparisons have been made. If the aerosol consisted only of 'pure black' material, then the values of BC calculated at each wavelength would be identical: and, indeed, this is seen when sampling moderately dilute, well-aged primary aerosols. However, in a manner analogous to the calculation of Angstrom exponent to investigate the wavelength dependence of optical scattering, it is possible to construct various ratios to investigate the deviations of aerosol optical absorption from spectral uniformity.

4.3.2 'Alternative Wavelength Set' Optical Source

For some research applications, it is desirable to make measurements of aerosol optical absorption at wavelengths that match as closely as possible to those used by specific models of multi-wavelength nephelometers for measuring aerosol optical scattering. One such set of 'scattering' wavelengths is 450, 550 and 700 nm. We offer an 'Alternative Wavelength Set' optical source assembly that may be substituted in the 'Spectrum' Aethalometer to provide measurements at:

UV	370 nm	
Blue 1	430 nm __	take average for 450 nm
Blue 2	470 nm /	
Green 1	520 nm __	take average for 550 nm
Green 2	565 nm /	
Red	700 nm	
IR-2	950 nm	

In almost all cases, the Aethalometer absorption data at the two 'Blue' wavelengths are very similar, as are the data at the two 'Green' wavelengths. These may be averaged to estimate results for 450 and 550 nm.

4.4   ABSORPTION CROSS-SECTION CALIBRATION OPTIONS

There are two calibrations for the aethalometer. The "Classic Magee BC" calibration is the factor originally derived in the early 1980's. This calibration converts optical attenuation to a mass of "Black Carbon", based on the Malissa-Novakov methods for 'BC' determination as published by Gundel, Dod et al. However, as shown in Section 3.1 above, Harvard School of Public Health operated aethalometers side-by-side with quartz-fiber filter samplers at widely different locations over several years. These filters were analyzed by the 'TOR' thermal-optical method which gives a result denoted "Elemental Carbon". The assignment of this analysis is instrumentally-dependent but is widely accepted.

The result was that the 'EC' data from the TOR thermal analyses of the filters tracked the Aethalometer data very well, but with numbers that were higher than 'BC'. One interpretation of this result is to propose that "BC" is a subset of "EC"; or, alternatively, that the TOR method has a systematic analytical attribute that causes its "EC" result to be higher. An alternative thermal analysis procedure, the 'TOT' method, gives results for the EC component of aerosol samples that often differ markedly from the TOR result on the same samples. It is therefore plausible that the thermal methods do not offer an absolute determination of Elemental Carbon content: the Aethalometer optical measurement of 'BC' can be as method-dependent as that of the thermal analyses of 'EC', provided it is consistent and reproducible.

In order to recognize this difference without necessarily resolving it, we offer two calibrations for the aethalometer in terms of the 'SIGMA' specific attenuation parameters. Mie theory for small uniform spheres predicts that to first order, 'SIGMA' is inversely proportional to the optical wavelength λ. We therefore use the following values:

For "Magee BC" calibration : $\sigma = 14625 / \lambda$
For "Harvard TOR-EC" calibration : $\sigma = 11115 / \lambda$

For the optical sources used in the Aethalometer, these values are:

Lamp	λ	Sigma(BC)	Sigma(EC)
UV	370 nm	39.5	30.0
Blue	470 nm	31.1	23.6
Green	520 nm	28.1	21.3
Yellow	590 nm	24.8	18.8
Red	660 nm	22.2	16.8
IR-1	**880 nm**	**16.6**	**12.6**
IR-2	950 nm	15.4	11.7

Note: "IR 1" (880 nm) is the standard BC ('EC') data output in 1- and 2-wavelength instruments.

4.5   EXAMPLES OF MULTIPLE WAVELENGTH AETHALOMETER DATA

The first figure shows the response of a dual-wavelength Aethalometer to the noticeable local impact of smoke from a vegetation fire. The UV data shows a clear increase, while the 'BC' data registers very little. This is interpreted as the addition of UV-absorbing aromatic organic species to the background urban aerosol.
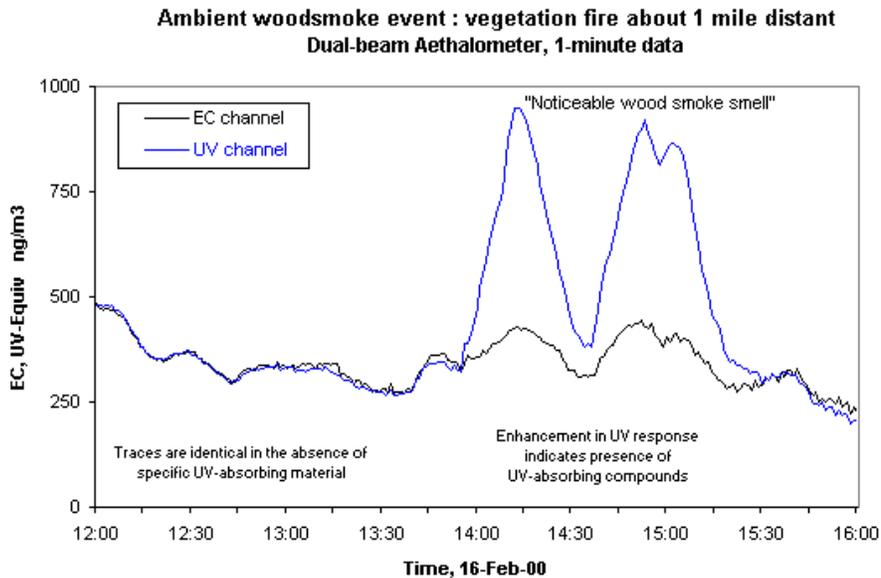
Dual-wavelength Aethalometer data during impact of smoke from burning vegetation.

The next two figures illustrate 'dual' and 'multi' -wavelength Aethalometer data, taken on different days in an urban location, but subject to *local* wood-fire smoke on both occasions. The 'urban ambient' data show the typical large variations in BC concentration that occur as a result of the interplay between source emission strength and meteorological dispersion. However, this location was also impacted by 'local' smoke from residential fireplaces burning wood. The lack of spectral differentiation during the day is clear, as is the signature of UV-absorbing organics in the evening.
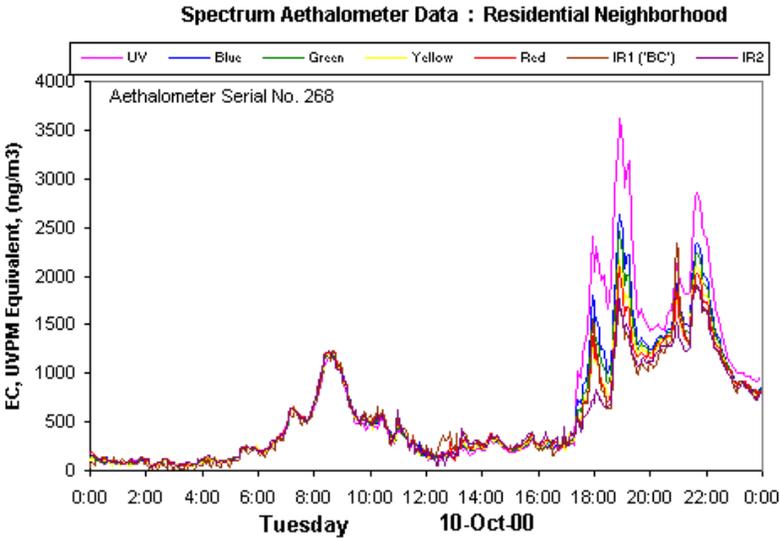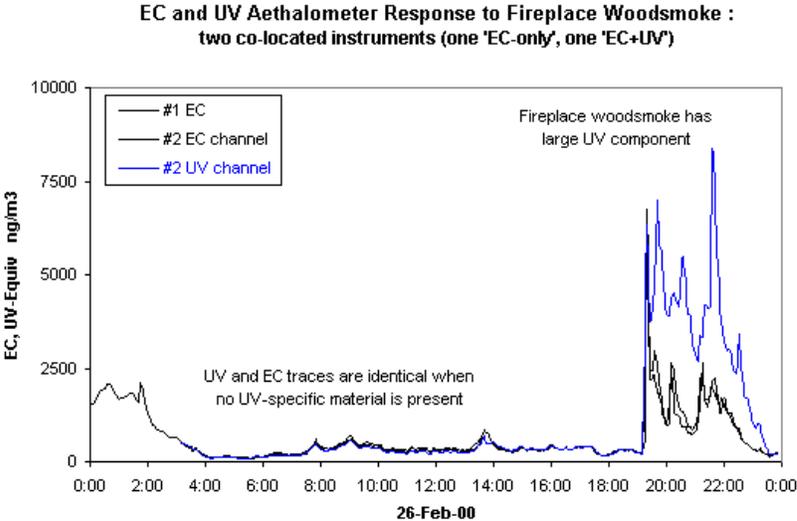
Dual- and 7-wavelength Aethalometer data during impact of fireplace smoke

The last figure shows the hourly averages of dual-wavelength Aethalometer data taken at a rural location in wintertime, when many residents were burning firewood for home heating. The UV data show sustained increases over the BC data during episodes of woodsmoke impact.

Millersville Surface Aethalometer Data - 1-hour means
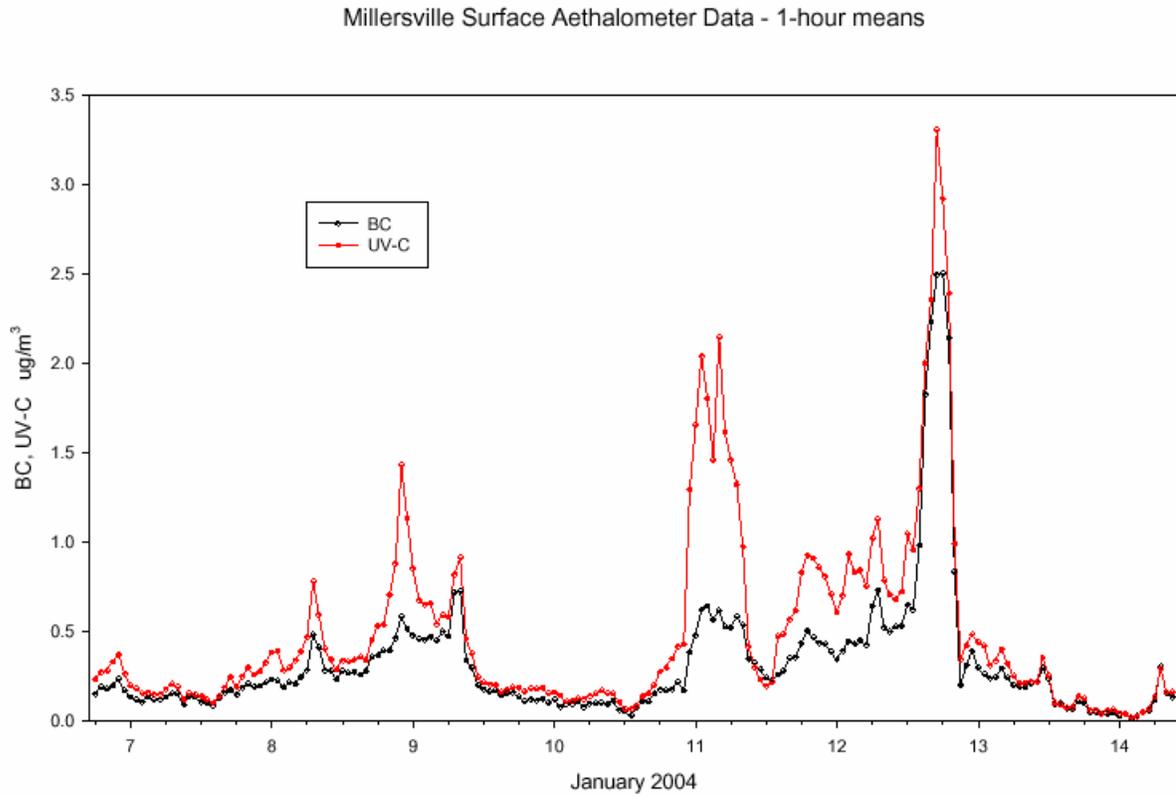
The final figure illustrates 'Spectrum' 7-wavelength Aethalometer data taken in an urban location where the aerosol is essentially uniformly absorbing across the wavelength range from 370 to 950 nm. The tracking of the data in all seven wavelengths vindicates the assumption of the 1 / λ dependence of absorption.
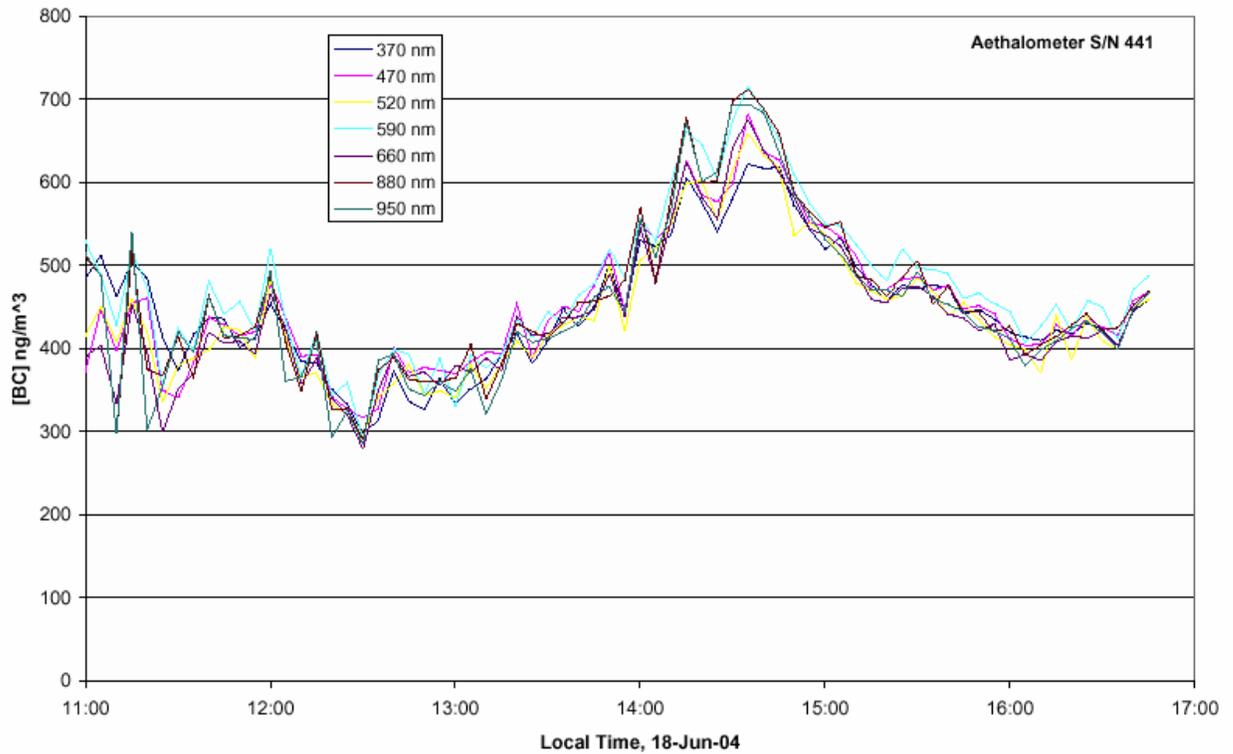
4.6   THE AETHALOMETER PRINCIPLE

The principle of the Aethalometer™ is to measure the attenuation of a beam of light transmitted through a filter, while the filter is continuously collecting an aerosol sample. This measurement is made at successive regular intervals of a timebase period. By using the appropriate value of the specific attenuation for that particular combination of filter and optical components, we can determine the black carbon content of the aerosol deposit at each measurement time. The increase in optical attenuation from one period to the next is due to the increment of aerosol black carbon collected from the air stream during the period. Dividing this increment by the volume of air sampled during that time, we calculate the mean BC concentration in the sampled air stream during the period. If the timebase is short compared to the time scale of other variations in the air mass under study, the measurements appear to be continuous. If the mean concentration does not vary greatly from one measurement period to the next, we may assert that the period average is a reasonable representation of the time behavior of the actual BC concentration during the period.

The objectives of the Aethalometer hardware and software systems are thus as follows:

(a)   to collect the aerosol sample with as few losses as possible on a suitable filter material;

(b)   to measure the optical attenuation of the collected aerosol deposit as accurately as possible;

(c)   to calculate the rate of increase of the BC component of the aerosol deposit and to interpret this as a BC concentration in the air stream;

(d)   to display and record the data, and to perform necessary instrument control and diagnostic functions.

Detailed technical descriptions of the hardware and software components are presented in following chapters. The general principles are as follows:

4.7   AEROSOL SAMPLING

The aerosol sample is collected on an area of quartz fiber filter at a moderate face velocity. The 'High Sensitivity' ('HS') sampling head provides a collecting spot area of 0.5 cm², while the 'Extended Range' ('ER') sampling head collects on a spot of 1.67 cm², i.e. 3.3 times larger. Sampling is optimal at air flow rates from 2 to 6 standard liters per minute. The rate of accumulation of BC on the spot is proportional to both the BC concentration in the air stream, and to the air flow rate. The greatest sensitivity is achieved by using the highest air flow rate through the smaller 'HS' spot: however, in areas of higher concentration, this also means that the filter will become overloaded more rapidly, leading to more frequent need for the instrument to automatically change the filter to avoid optical saturation. The time taken for these filter changes can lead to interruption of data. In urban areas, or when sampling other air streams of high BC concentration, good performance is achieved using an instrument with the 'ER' head at lower air flow rates, with the benefit of less frequent filter changes. In remote regions where BC concentrations are extremely low, use an instrument with the 'HS' head at higher flow rates for best sensitivity.

The aerosol sample is handled by plumbing of nominal 1/4" (~6 mm.) internal diameter, with the flow being expanded in the sampling head to fit the collecting spot grid. Aerosol black carbon is usually of small aerodynamic diameter, typically less than 0.2 microns, and we have found in our experience that very little BC mass is lost in the inlet plumbing.

The sample air stream is drawn through the filter by a continuously-operating pump. A mass flow meter is installed in the plumbing between the rear face of the filter and the inlet of the pump. The gauge vacuum at the pump inlet is usually no more than approximately -0.2 atmospheres at the highest flowrate, decreasing as the flow is reduced. The mass flow meter that we use is specified for accuracy at these slightly reduced absolute pressures.

4.8   MEASUREMENT OF OPTICAL ATTENUATION

The optical attenuation of the aerosol deposit on the filter is measured by detecting the intensity of light transmitted through the spot on the filter. The light source in the Aethalometer Model AE-16 is comprised of high-intensity LED lamps emitting at 880 nm: in other models, additional sources emitting at different wavelengths are also installed in the source assembly. The light shines through the transparent aerosol inlet onto the aerosol deposit spot on the filter. The filter rests on a support, through which the pumping suction is applied. Light penetrating the diffuse mat of filter fibers passes through the support grid to a photodiode placed directly underneath the filter support mesh. As the black carbon content of the aerosol spot increases, the amount of light detected by the photodiode will diminish.

For highest accuracy, we must make further measurements: the amount of light penetrating the filter is relatively small, and a correction is needed for the 'dark response signal' of the overall system. This is the electronics' output when the lamps are off: typically, it is a very small fraction of the response when the lamps are on. To eliminate the effect of the dark response, we take 'zero' readings of the system response with the lamps turned off, and subtract this 'zero' level from the response when the lamps are on.

The other measurement necessary for the highest accuracy is a 'reference beam' measurement to correct for any small changes in the light intensity output of the source. This is achieved by a second photodiode placed under a different portion of the filter that is not collecting the aerosol, on the left-hand side where the fresh tape enters. This area is illuminated by the same lamps. If the light intensity output of the lamps changes slightly, the response of this detector is used to mathematically correct the 'sensing' signal. The reference signal is also corrected for dark response 'zero' as described above.

The algorithm in the computer program (see below) can account for changes in the lamp intensity output by always using the ratio quantity [Sensing] / [Reference]. As the filter deposit accumulates black carbon, this ratio will diminish. If for some reason the lamp light output intensity was reduced by a (say) a factor of two, then although the quantities [S] and [R] would be halved, their ratio [S]/[R] should remain unchanged.

In practice, the algorithm can account for lamp intensity fluctuations to first order, but we find a residual effect when operating at the highest sensitivities. To minimize this effect and to realize the full potential of the instrument, it is desirable for the lamps' light output intensity to remain as constant as possible from one cycle to the next. The software monitors the repeatability of the reference signal, and issues a warning message if the fluctuations are considered unacceptable. When operating properly, the system can achieve a reference beam repeatability of better than 1 part in 10,000 from one cycle to the next.

The electronics circuit board converts the optical signals directly from small photocurrents into digital data, and passes it to the computer for calculation. These data and the result of the BC calculation are written to disk and displayed on the front panel of the instrument.

4.9   THE AETHALOMETER ALGORITHM

The algorithm that the Aethalometer™ system uses to calculate the aerosol black carbon content of a sampled air stream is based on the following measurements:

(a)   Measurements of the Reference and Sensing beam detector outputs with the lamps OFF, to determine their zero offsets;

(b)   Measurements of the Reference and Sensing beam detector outputs with the lamps ON, to determine the transmitted light intensities;

(c)   Measurement of the air flow through the system;

(d)   Knowledge of the active collecting area of the spot on the filter, and of the specific attenuation of the particular combination of light source, detector, optical components and the filter medium in use. (see chapter 2 above).

Note that since the algorithm uses only ratios, with the 'zero' levels subtracted, the results are not dependent on any scaling, offset or proportionality constant of the photodetectors' response: the only requirement is that the response be linear with respect to the incident light intensity. The question "what do the detector signals exactly represent?" does not need to be answered in order to calculate BC concentrations from the measurements.

We use the following notation:

SB   =   Sensing Beam detector output with lamps on.

SZ   =   Sensing Beam detector Zero offset output with lamps off.

RB   =   Reference Beam detector output with lamps on.

RZ   =   Reference beam detector Zero output with lamps off.

A   =   Aerosol collecting spot area of filter, [cm²].

F   =   Flow rate of air through filter, liters per minute.

T   =   Sampling timebase period, minutes.

ATN   =   Optical attenuation due to aerosol deposit on filter.

B   =   Surface loading of black carbon on filter, [g/cm²].

SG   =   Specific attenuation cross-section for the aerosol black carbon deposit on this filter, using the optical components of this instrument, [m²/gram].

BC   =   Concentration of black carbon in the sampled air stream, expressed in nanograms per cubic meter.

The 'true' detector responses to the light beam are (SB-SZ) and (RB-RZ). The correction to the sensing beam response for possible variations in light intensity output is performed by using the ratio (SB-SZ)/(RB-RZ). The optical attenuation is then defined as

$$ATN = -100 * \ln ((SB-SZ)/(RB-RZ)). \tag{14}$$

Note that the absolute value of this attenuation is not very important, as the determination of BC is calculated from its rate of change. The factor of 100 is introduced for numerical convenience. The increase of ATN is proportional to the increase of surface loading B of black carbon on the aerosol deposit spot, with the relation

$$d(ATN) = SG * d(B) \tag{15}$$

This increase of black carbon is the amount filtered from the air stream during the timebase interval T. If the air stream concentration is BC, the flow rate is F and the area of the filter onto which it is collected is A, then

$$d(B) = (BC * F * T) / A \tag{16}$$

The measurement sequence is thus as follows:

- Lamps are OFF. Measure SZ and RZ

- Turn lamps ON. Wait for system to stabilize.

- Measure SB and RB.

- Calculate and record the attenuation,

- ATN(0) = -100 * ln ((SB-SZ)/(RB-RZ))

- Measure the air flow rate F.

- Turn lamps OFF.

- After time interval T minutes, repeat steps (a) - (f).

- Calculate increase in surface loading of black carbon,

- d(B) = (ATN(T) - ATN (0)) / SG

- Calculate the volume of air sampled, V = F * T .

- Calculate the mean aerosol black carbon concentration during the period,

- BC = d(B) * A / V

- Use ATN(T) as the starting value ATN(0) for the next period.

5.   THE AETHALOMETER™

The Aethalometer™ is a self-contained instrument that provides a means to measure the rate of change of optical transmission through a spot on a filter on which aerosol is being continuously collected, and to convert this to a calculation of the concentration of optically-absorbing material in the sampled air stream. The instrument measures the transmitted light intensities through the 'sensing' portion of the filter, on which the aerosol spot is being collected, and a 'reference' portion of the filter, as a check on the stability of the optical source. A mass flow meter monitors the sample air flow rate. The data from these three measurements is used in the calculations described in the previous chapter to determine the mean black carbon content of the air stream. The display on the front panel shows the calculated BC concentration, and provides a keypad for interaction with the instrument's embedded computer. Connectors on the rear panel provide for power input and fuse, an analog output whose voltage may be scaled to represent the measured BC concentration, and RS-232 digital communications with an external computer. The aerosol inlet is plumbed through a connector on the rear panel: suction is provided by an internally-mounted variable-speed pump. The sampling flow rate is stabilized by software control of the pump speed, based on the mass flow meter reading. The aerosol collecting filter tape is held in a spring-loaded optical head behind the front panel. The instrument is constructed in a standard 19-inch rack mounting chassis with temperature stabilization for the electronics, or in a smaller 'Portable' chassis. An external mounting cabinet can be supplied for benchtop use.

The computer is programmed to operate automatically upon switching on, if there is no keypad interaction from the user. The pump establishes the correct air flow rate, the filter tape is advanced as necessary, and the optical measurements are converted to aerosol BC concentrations and recorded to the built-in diskette drive. No operator attention is required for fully automatic, unattended operation. The roll of filter tape will last for periods ranging from months to years, depending on location, concentration, and instrumental settings.

5.1 OPTICAL HEAD AND PHOTODETECTORS

The heart of the Aethalometer™ is the optical head. This unit holds the filter in the passing air stream, while illuminating it from above and determining the intensity of light transmitted by means of photodetectors mounted below. The upper portion of the inlet body includes a transparent window mounted in a metal reflector. The inlet provides a passage for the aerosol-containing air stream while also allowing the optical source(s) to illuminate the filter. The optical source assembly is mounted at the top of the inlet piece: the air stream enters on the rear side, and turns down to meet the horizontal filter surface. The lower part of the optical head contains the support for the filter in the center: at the left is the optical channel for the reference beam, and at the rear is the vacuum pumping connection. The active collecting spot area of the filter tape rests on a stainless-steel support. The air flow exits to the rear, while directly underneath the support is a light guide to transmit light to the sensing detector located on the underside of the lower inlet base body. Towards the left of the instrument is a second detector attached to a light guide that provides the reference beam measurement. This light guide presses up against the unexposed part of the filter tape, in an area that is fully illuminated but which does not collect the aerosol.

The two photodetectors are mounted on the main circuit board together with all electronic components for power, control and for data conversion from analog to digital signals. This board is powered by a supply that can operate from any line input voltage without switching. Although the electronics are very stable, the instrument's measurement depends on determining extremely small changes in intensity of the optical signals. As a precaution, the electronics area is thermally insulated and its temperature is actively stabilized by a thermistor-controlled circuit. This minimizes any possible effects of ambient temperature fluctuations.

5.2 SAMPLE COLLECTING SPOT: "EXTENDED RANGE" VS. "HIGH SENSITIVITY" INLETS

The optical head contains the aerosol inlet, the optical source assembly, the light guides for the photodetectors, and the filter tape support. Upper and lower apertures, between which the filter tape is clamped, define the aerosol spot collecting area. This *aerosol spot size* defines the area over which the collected sample will be dispersed. A <u>smaller</u> spot area will concentrate the sample more, while a <u>larger</u> spot area will disperse the sample. For a given sample flow rate and aerosol BC concentration, the smaller spot size will result in a more rapid rate of accumulation of optical density, while the larger spot will result in a slower accumulation of 'attenuation'. Current models of the aethalometer offer the option of two sizes of aerosol collecting spot: the **"High Sensitivity"** inlet, with a circular sample collecting spot of area 0.5 cm², and the **"Extended Range"** inlet, with a rounded-rectangular sample collecting spot of area 1.67 cm². The 'High Sensitivity' ('HS') inlet is recommended for use in locations of low areosol concentration, or where the most rapid time response is required. The 'Extended Range' ('ER') inlet is recommended for general use in urban areas or other locations of moderate to high aerosol concentration, where time resolutions of 5 minutes are acceptable. The ER inlet disperses the sample over a spot area that is 3.3 times larger than for the HS inlet: this reduces the rate at which aerosol optical density accumulates, and therefore prolongs the lifetime of each spot. In locations of high concentration, filter tape spot advances may be quite frequent when using the HS inlet. This leads not only to a greater consumption of tape but also a loss of data coverage when the instrument is inactive during tape advance and re-initialization. Use of the ER inlet, coupled with lower sample flow rates and use of the 'Tape Saver' option (see chapter 5.11 below), results in greatly reduced tape consumption and interruption of data.

Filter tape spots: "High Sensitivity" 0.5 cm² spot size.

5.3 AUTOMATIC TAPE FEEDER

The tape feeder has been specially designed to handle the quartz fiber material that is optimal for the black carbon measurement. It draws the 25-mm. wide tape from a supply spool mounted on the left side of the instrument. Each roll contains 15 meters length of tape, sufficient for approximately 1500 aerosol collection spots. The aerosol inlet upper body is clamped by a spring-loaded mechanism, and this pressure provides the seal on the tape when it is in the operating and sampling position. The spring pressure is released for tape advance by a lifting solenoid located at the top of the framework. The tape advance motor draws the tape forwards by approximately 1 cm. per revolution, pulling fresh tape from the left-hand spool. The right-hand spool collects the used tape with a tensioning motor operating together with a tension-sensing microswitch. The motors are controlled by the computer interface, and can also be activated by a switch on the front panel. The tape advance motor needs to complete one revolution to complete its cycle. This is controlled by a microswitch attached to the motor shaft. Once the motor has started for a few seconds, it will continue automatically until the full revolution has been performed.

NOTE: The tape would distort or break if the motor attempted to move it while the pump was applying suction to the filter support screen. Thus, the suction is removed automatically by a solenoid 'bypass' valve whenever the tape advance is active.

5.4 PANEL CONTROLS AND DISPLAYS

The front panel door covers the tape spools and optical head, the inner chassis panel with the data disk drive and control switches: the outer surface of the door holds the display screen and control keypad.

The sensing beam, reference beam and air flow rate signals constitute the fundamental data inputs to the algorithm. For diagnostic testing these may be displayed on the front panel display screen, but are normally not shown. The beam intensity displays are of arbitrary scaling, as the algorithm is based only upon ratios and differences. The air flow rate is shown in units of liters per minute, either at standard conditions (SLPM) or corrected for ambient temperature and pressure (volumetric units, vLPM). The computer program contains a calibration procedure for the air flow actual measurement, which sets two points on the relation between system response and actual flow. The mass flow meter is highly linear and we have found that this two-point calibration is sufficiently accurate.

The tape feeder may be activated by pressing the "Tape Advance" switch upwards. This should be held for a few seconds until the shaft-mounted switch is engaged to ensure one complete revolution. The tape take-up tensioning motor may be activated by pressing the "Tape Tension" switch downwards.

Power to the instrument is controlled by the right-most switch, which interrupts the AC line voltage input. The front panel indicator is a 12-volt LED connected to the output of the power supply, and it shows that 12-volt power is being provided to the internal circuitry. The rear panel AC power entry module also has a switch marked '0' and '1': this will also interrupt power to the instrument, but we recommend that this rear switch *not* be used in normal circumstances.

5.5 AIR MASS FLOW METER

The Aethalometer™ algorithm uses the change in optical signals to determine the mass of aerosol black carbon collected on the filter tape spot during each sampling timebase period. In order to convert this to a mass concentration, it is necessary to know the sample air flow rate through the instrument. The value of this flow rate controls the absolute scaling of the final calculation of aerosol black carbon concentration, but does not affect the relative variation from one measurement to the next, assuming that the air flow rate is constant.

It would be possible in principle to measure the flow by some external means (e.g. volumetric gas meter, rotameter, bubble meter etc.) and to then assume that the value remains constant. However, it is clearly desirable to *measure* the air flow rate during operation, and the Aethalometer includes an air mass flow meter. This sensor produces an electrical output that is linearly proportional to the air mass flow rate, independent of absolute pressure, and thus it can be installed in the flow system downstream of the sample collection and analysis head. The flowmeter output signal voltage is calibrated in terms of Standard Liters Per Minute, defined as 70°F (20ºC) temperature, and 1013 mb pressure. If desired, the computer can convert this to volumetric flow (vLPM) if the external ambient temperature and pressure are provided as inputs. The flow meter that is normally used has a range of 0-10 SLPM. The software operating system includes an internal two-point calibration procedure to allow for re-calibration of the flowmeter response during operation if required.

The Aethalometer draws its sample from the inlet port by suction provided by an internal pump (see section 8.8.1). This pump has an electronically-controlled variable-speed motor, and the air flow rate is stabilized by closed-loop control by the computer to match the desired value entered by the user on the front panel keypad. Even if the flow rate varies slightly, the Aethalometer algorithm always uses the actual value of measured flow, and the BC data output is independent of the actual flow value.

5.6   COMPUTER OPERATION

It is possible in principle to perform the calculation of aerosol black carbon concentration entirely from numbers written down from voltage measurements, using the algorithm described in Chapter 4.3 above. However, it is obvious that the repetitive nature of the measurement is ideally suited to automatic data acquisition and control. This is achieved by the system software operating together with the internal computer, interface and electronics. The photodiode signals are passed by a multiplexer switch to a 24-bit sigma-delta type analog/digital converter on the main electronics board close to the detectors. The digital data output from the converter is acquired by the embedded computer's digital interface port. Control signals from this port are used to control the light source(s), the variable-speed pump, the suction switching 'bypass' valve, the tape advancing and tensioning motors, and other instrument functions. The interface between the main electronics board and the computer is entirely digital, allowing for flexibility in selecting and upgrading the computer. Data is written to the floppy disk drive, sent to the rear-panel COM port, and also returned in digital form to the electronics board for conversion to an analog output voltage.

**5.7	POWER REQUIREMENTS**

5.7.1	A.C. Line Power Operation

All of the internal circuitry in the Aethalometer™ operates from DC voltages provided by a regulated switching power supply. This power supply accepts any input voltage in the range of 85 to 250 volts AC, at frequencies from 50 to 400 Hertz.

The power consumption of the Aethalometer is small: 10 to 20 watts for the electronics, depending on activity; approximately 15 watts for the internal pump; and up to 20 watts for the temperature stabilization to heat the lower (insulated) chassis enclosure. The typical maximum power consumption is on the order of 50 watts. The instrument is protected by a slow fuse of 2 amp rating in the power entry module on the rear panel.

5.7.2	Low-Power 12-Volt Operation

The 'Portable' models of Aethalometer (AE-4 series) operate from a 12-volt internal battery. Voltages for internal operation are provided by DC-DC converters as required. These converters are protected by two fuses in the lower electronics compartment. A rear panel connector is provided for operation from an external 12-volt source such as the AC-powered charger or an external battery. Total power consumption is approximately 30 watts. The Portable instruments include most of the components of the 'full-size' models (computer, pump, electronics, diskette drive, ..), but with the exception of the temperature stabilization heater, take-up drive for used tape, and the air flow bypass valve.

'Full-Size' rack-mount chassis Aethalometers may be specially ordered with 12-volt input power supplies and 'power saver' wiring junctions that permit the disconnection of temperature stabilizing heaters. Total power consumption can be reduced to as little as 20 watts. This permits operation of the instrument from low-power sources such as solar panels and batteries.

5.8   INSTALLATION REQUIREMENTS

The Aethalometer™ contains sensitive electronics and photodetectors, a computer and an internal pump. It generates little heat, and does not explicitly require cooling or air-conditioning. However, we recommend that the instrument should not be placed in an environment where the ambient temperature may exceed 100°F (40°C), nor where high relative humidity may lead to condensation. Although the algorithm corrects for any slight drift of the detectors, and although the electronics is in a temperature-stabilized enclosure, large or rapid changes in ambient temperature may contribute second-order errors to the calculation of aerosol black carbon concentration. Thus, we ***strongly recommend*** that the instrument ***NOT*** be placed in the direct air flow from a heater, vent or air-conditioner that may cycle on and off. This last point is particularly directed towards field installations in instrumented trailers, if the air-conditioning thermostat has substantial hysteresis and the equipment is exposed to forced air whose temperature undergoes large cycles.

The last installation concern is that of the aerosol inlet plumbing. Normally, aerosol black carbon is found in particles of small aerodynamic diameter, typically in the range of 0.03 to 0.3 microns. At the air flow rates that the Aethalometer normally uses, these particles can pass through relatively long lengths of tubing with only small losses due to either impaction or diffusion. The Aethalometer responds to the total mass of optically-absorbing material, so the loss of the smallest particles by diffusion is less important as a source of measurement error. It is our experience that inlet tubing runs of 30 feet (10 m.) of tubing of internal diameter 1/4" (6 mm.) result in losses of less than 10 percent of the mass of aerosol black carbon measured at remote marine locations. This may not be true if sampling aerodynamically-large particles very close to sources: in that case, the length of the inlet tubing should be minimized. This may also be a concern if the aerosol is highly charged, in which case explicitly-electrically-conducting tubing should be used. Aerosol losses due to electrostatic precipitation in the inlet tubing are normally very small, but we always recommend that *Teflon*® tubing should ***not*** be used for the sample inlet.

The sample inlet port on the rear panel is a standard ¼" female pipe thread socket. It accepts any fitting that the user may wish to employ for connection to the air sampling stream. A selection of fittings is provided with each Aethalometer, including a gray plastic 'instant' push-to-fit connector for the 3/8" (6 mm.) OD tubing that is supplied. If using this fitting, it is ***very important*** that the tubing must be pushed firmly all the way into the fitting, in order to make a leak-proof seal on the o-ring that is inside the connector. To *remove* the tubing from the connector, *press firmly* on the release collar ring closest to the tubing, while simultaneously *pulling* the tubing out of the fitting.

5.9 FILTER TAPE

The Aethalometer™ is normally operated with web-reinforced quartz fiber filter tape. This material has two essential attributes. First, it has a deep mat of optically-scattering fibers within which the aerosol particles are collected. As discussed in chapter 2, this has the result of nullifying any effect on optical transmission by light scattering from the collected particles. The measurement is therefore sensitive only to incremental light absorption. This vital point is only true if the aerosol is collected on such a filter. Collecting media such as surface-interception polycarbonate membranes (e.g. 'Nuclepore') have a completely different optical response to the accumulation of an aerosol deposit that may be both scattering as well as absorbing. For correct operation, it is *essential* that the Aethalometer use a deep fibrous type of filter. Differing filters may have differing spectral responses, leading to different values of the attenuation per unit mass, as discussed in chapter 3. If other filters are used for particular reasons, it is necessary to calibrate their response against parallel measurements on quartz fiber filters, in order to determine the specific attenuation factor. ***Do not use*** a different type of filter tape without first consulting Magee Scientific.

The other valuable attribute of the quartz fiber material is that it is thermally stable to high temperatures. This means that it may be heat treated by firing to 600°C to remove all combustible carbonaceous compounds from the filter prior to use. In manufacture, the quartz fiber material is laid down upon a reinforcing web of cellulosic material. This provides mechanical strength: the pure quartz material itself is extremely brittle and friable. After sample collection, it is possible to carefully peel up the quartz layer containing the aerosol sample spot from the underlying reinforcement web. The aerosol deposit that is collected may then be analyzed by solvent extraction, temperature-programmed desorption/evolved gas analysis, etc., without problems due to the carbonaceous content of the filter material itself. Obviously this criterion can not be met by cellulose-fiber filters: less obvious is the fact that normal *glass-fiber* filters can not withstand the high temperatures needed to burn off all carbon species prior to filter use. Thus, if it is desired to perform quantitative chemical analysis for carbonaceous species on the collected aerosol deposit, the quartz fiber filter is required.

The drawback of quartz fiber is that it is brittle and friable: it has little mechanical strength. It must be handled with some care, and it poses special requirements for automatic tape handling. For this reason, the web underlayment was developed.

5.10   FILTER SPOT ADVANCING

The Aethalometer™ filter must be changed periodically to avoid overloading and saturation of the optical absorption. As the aerosol deposit accumulates, the optical transmission through the filter spot diminishes. However, the digitization resolution of the measuring electronics and the amplitude of electronic noise remain constant. Thus, the relative importance of noise and measurement error increase, as the aerosol deposit loading increases. There is also the effect of light bypass, in which some of the intensity of light incident on the filter is actually conducted through the filter fibers in a manner analogous to explicit propagation through fabricated macroscopic optical fibers. This 'bypass' light is unaffected by the accumulation of aerosol black carbon on the filter: although it only accounts for an extremely small fraction of the total transmitted light under normal conditions, it becomes an important effect if the filter loading becomes very large, and acts to reduce the sensitivity and linearity of the measurement at the highest loadings.

5.10.1 'Maximum Attenuation Value'

The Aethalometer automatically advances the tape to provide a fresh filtration spot before the aerosol black carbon loading becomes too large. From experience, a suitable advisory limit is at an optical attenuation value in the range of 75 to 125, i.e. an optical absorption depth of 0.75 to 1.25. At 880 nm, these values correspond to a surface loading of aerosol black carbon of approximately 4 to 6 μg/cm² on the collected spot. When the maximum attenuation value is reached, the program halts temporarily to advance the filter tape, and re-initializes automatically when the fresh spot is in place before resuming measurements. The value of this 'Maximum Attenuation' parameter may be changed by the user if desired, up to a highest value of 150 units.

In the case of multi-wavelength instruments, the algorithm bases its decision to advance the tape on the highest value of attenuation at any wavelength. The optical attenuation of an aerosol deposit is usually inversely proportional to the wavelength of light (see sections 3.2 and 3.3), and is therefore usually highest at the 370-nm UV wavelength of 2- and 7-wave instruments. An attenuation value of 75 units at 370 nm corresponds to an attenuation of only 31.5 in the 'BC' wavelength of 880 nm: i.e. a very lightly-loaded deposit. Advancing the filter tape at this value could lead to frequent interruptions in the data in urban areas. Many users of multi-wavelength instruments choose to set the 'Maximum Attenuation' value to 125: an attenuation of 125 units at 370 nm corresponds to an attenuation of 52.5 at 880 nm. This results in less frequent tape advances and fewer interruptions of the data.

5.10.2 Data Loss during Tape Advance

This re-initialization process takes a certain amount of time: time during which the output of valid data is suspended. The tape advance itself may be set in software to '**1**' or '**2**' spots, depending on user preference for spot spacing. This has no effect on analytical performance, but some users prefer the spots to be clearly separated. Each spot advance requires one minute: the tape drive motors move extremely slowly in order to not tear or stretch the tape. In addition to this, the algorithm allows for a period of stabilization before valid data are reported for analyses on the fresh spot. Thus, realistically, if the timebase is set to 5 minutes, a tape advance will result in the loss of up to 15 minutes of data. This is based on the fact that the fresh filter tape surface requires time for equilibration with the ambient composition and humidity of the sampled air stream as distinct from the storage environment inside the chassis.

For this reason, we recommend that timebases be set to *no longer than 5 minutes* in urban locations, where tape advances may be more frequent, in order to not lose any more data than necessary.

5.11 "TAPE SAVER": FLOW BYPASSING

This feature controls a flow bypass valve that can divert the flow of particle-laden sample air away from the filter spot for a controllable fraction of each timebase period. The application of this feature is to reduce the amount of sample accumulation in situations of high aerosol concentration, by a known fraction that may be accounted for in the BC calculation algorithm. This prolongs the lifetime of each filter tape spot, reducing the consumption of tape and the interruptions due to tape advance and instrument re-initialization. This feature is available for timebase settings of *5 minutes* or greater, and is *not* available on the 'Portable' Aethalometer models. The selections available in the software parameter setup are: 'OFF', 'X3', and 'X10'. Flow bypassing is disabled if this parameter is set to 'OFF': the full sample flow passes through the filter spot for the entire duration of each timebase period. If 'Tape Saver' is set to X3 or X10, the instrument periodically switches the valve to divert the air flow to bypass the filter tape spot for a certain fraction of the time, although still passing through the flow meter. The fraction of active-collection time is automatically scaled by the program according to the BC concentration. The X3 setting varies the aerosol collection time from 50% at low BC concentrations (tape saving factor of 2) to 30% at high BC concentrations (tape saving factor of 3). The X10 setting varies the aerosol collection time from 50% at low BC concentrations (tape saving factor of 2) to 10% at high BC concentrations (tape saving factor of 10). All other functions of the instrument are identical, and the operation of this feature is not perceived by the user. When 'Tape Saver' is used, the time-proportioning of the sample collection will lead to the fact that the data reflects the average of a series of 'snapshots' of the true aerosol concentration, rather than a continuous average. However, if the BC concentration is high (greater than 10 µg/m3), the reduction in the rate of accumulation of BC on the spot will not only result in a significant reduction in the amount of tape used, but also fewer interruptions in the data due to the time taken by the tape advance process.

Note ! – the 'Tape Saver' feature is *not* available on the AE-4 series 'Portable' aethalometer: its hardware does not include the solenoid valve.

The figures on the following page show data from two co-located Aethalometers operated for two successive periods of several days each. The first figure displays results when both instruments were operating identically at "Full Flow" (i.e. Tape Saver OFF): the second figure shows the result when *one* instrument was operated with maximum flow bypassing, i.e. Tape Saver X10. The data inter-correlation is essentially identical. The fact that the regression slope is 0.93 (rather than 1.00) may be attributed to a slight calibration inaccuracy in of one of the flowmeters.

**Co-Located Aethalometers – 30 minute data averages
Instruments operating identically**

$y = 0.92x + 80$

$R^2 = 0.98$
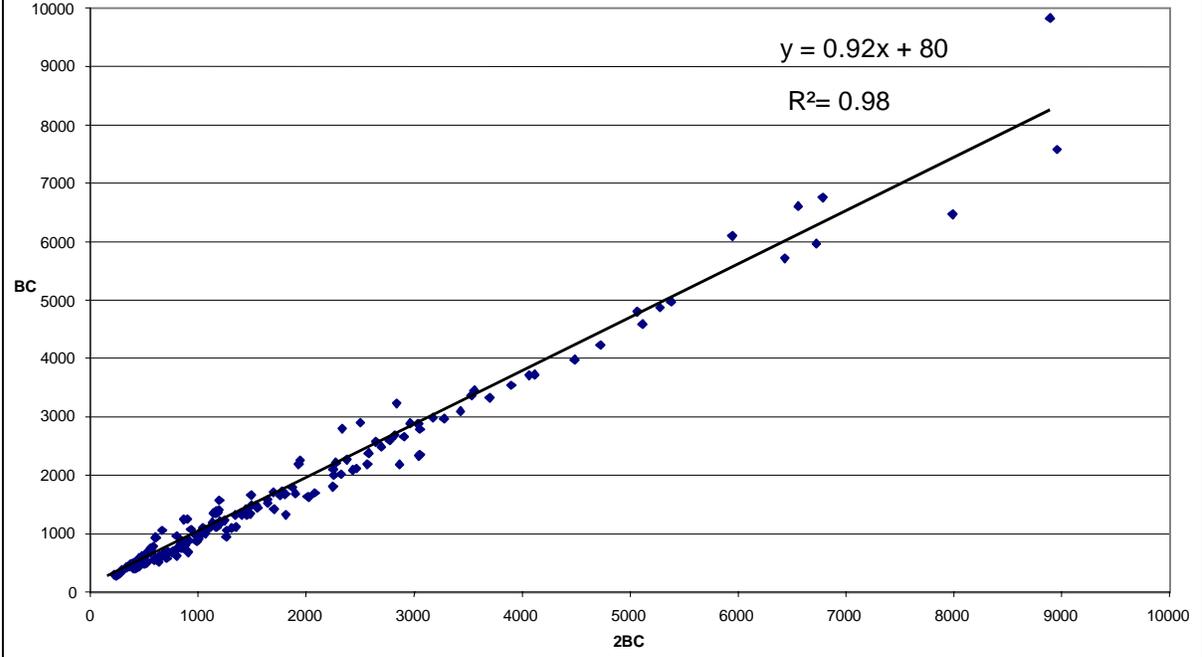
**Co-Located Aethalometers – 30 minute data averages
Instrument #1 using 'Tape Saver X10'**

$y = 0.93x + 105$

$R^2 = 0.92$
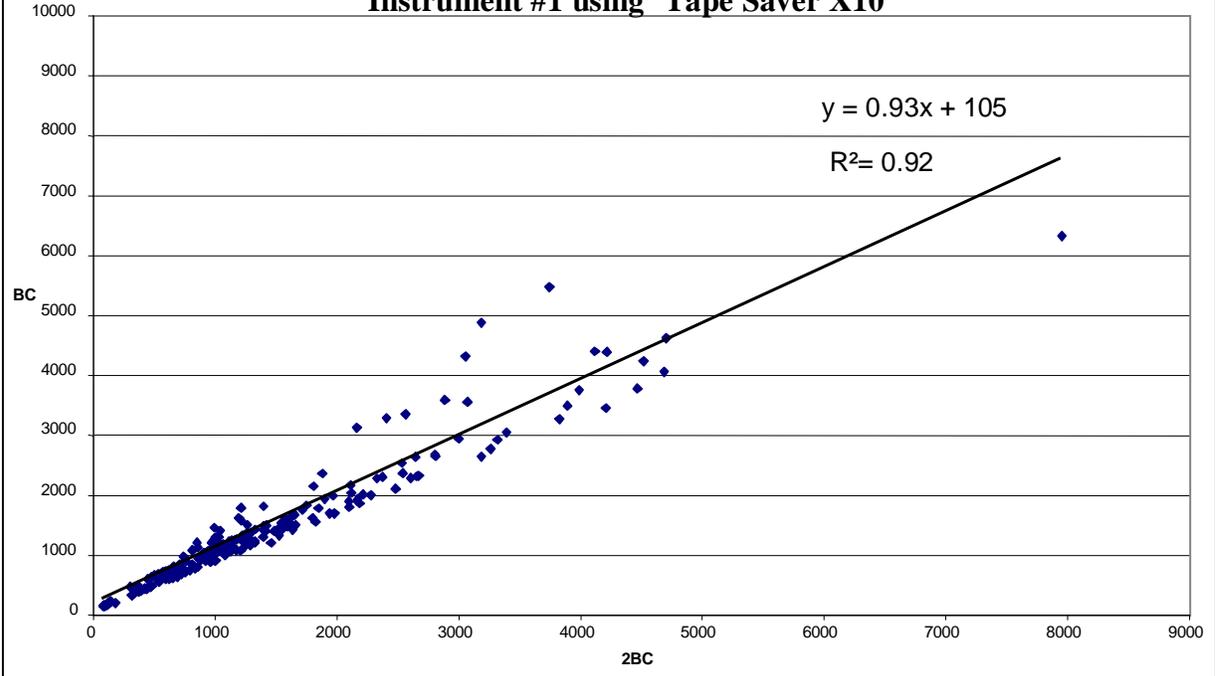
5.12 PRECISION AND REPRODUCIBILITY

The Aethalometer™ was independently tested by the 'Environmental Technology Verification' program of the US EPA in 2000-2001. This program tested instruments under real-world conditions to study accuracy, precision, reliability and ease of use, and comparison with other methods. Copies of the 'ETV Joint Verification Statement' and the 'ETV Report' are included in the appendix.

Comparison of Two Co-Located Aethalometers:
5-minute Smoothed Data - 880 nm 'EC' channel

$$y = 0.98x$$
$$R^2 = 0.95$$
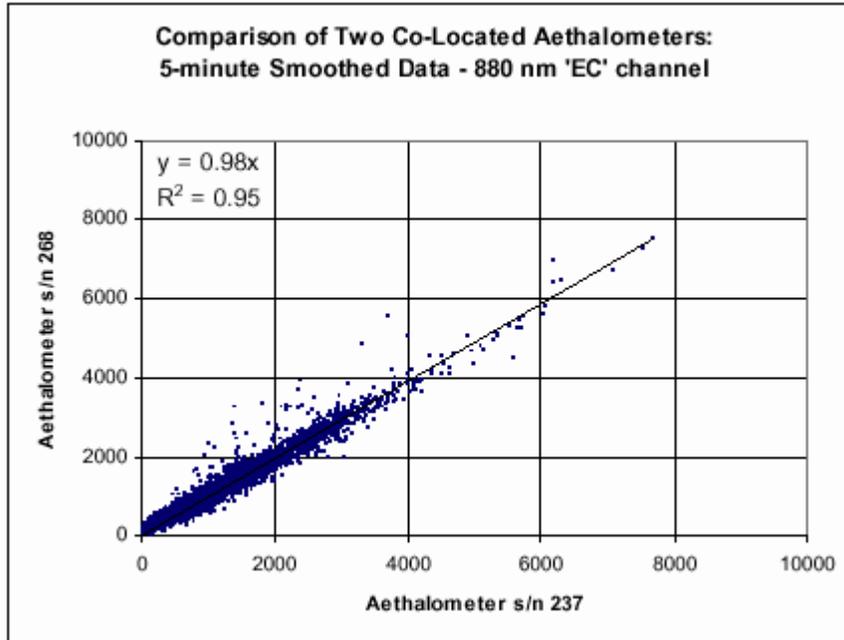
Comparison of data from two co-located Aethalometers under test at the ETV Pittsburgh site.

6. THE "PORTABLE" MODEL AE-42 AETHALOMETER

The 'Portable' Model AE-42 Series Aethalometers™ use the same aerosol collection, analysis and data systems as the 'full-size' 19-inch rack chassis models, but are constructed in a smaller chassis and equipped with an internal battery. The AE-42 series may be equipped with 1-, 2- or 7-wavelength optics, designated as models AE-42-1, AE-42-2 and AE-42-7: however, the single and dual-wavelength models find the most widespread applications for portable or mobile measurements of exhaust emissions impacts. The features of the AE-42 series include:

- 12-volt operation

- Variable-speed BLDC pump to aspirate the sample; electronic flow stabilization

- Sample collection on filter tape roll

- Optical analysis at 880 nm, 370 nm, and other wavelengths

- Electronics and computer system to perform the measurement and calculation

- Floppy disk drive for data recording (optional flash memory card)

- Analog voltage output for external display or datalogging

- COM port for external data connection

- Option for GPS Receiver to be connected to COM port to provide geographic position input during mobile operation (see below)

- Front panel display with detachable Keypad Terminal for parameter setup

- Sample air flow visual indicator (rotameter)

- Operation from external power supply, 12-volt connection from external battery, or internal battery operation (approx. 3 ~ 4 hour battery life)

Operation of AE-42 series 'Portable' instruments is essentially identical to that of the 'full-size' rackmount models: identical parameter setups, data recording format, etc. However, the following special notes must be observed:

- Always leave the instrument connected to its AC charger when not in use. If the internal battery is completely discharged, it may take 8 hours to recharge. The internal battery *will* recharge from the AC

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charger, although more slowly, if the instrument is also being operated. If the internal battery is *completely* discharged, the instrument must be connected to the AC charger for at least 30 minutes before switching on.

- The instrument includes an air flowrate sensor and electronic stabilization of the pump: the panel-mounted rotameter is for quick visual reference only.

- The air flow sensor in the 'Portable' series instruments is *not* a pressure-corrected *mass* flow sensor: it is an inertial 'velocity' type sensor. As such, its calibration is only correct at sea level. At substantially higher altitudes, e.g. over 1 km (3000 ft.), we recommend that the flowmeter response be re-calibrated as described in this manual. This re-calibration may be expressed in terms of 'Standard' or 'Volumetric' units, depending on the readout of the external device used for the recalibration.

- The variable-speed pump motor is stabilized by an internal electronic circuit that derives feedback from the air flow sensor, compared to a setpoint entered into the computer program. This acts to maintain a constant flow rate even if the battery voltage changes. The stabilization time constant is long, and the pump will start very slowly when the instrument is first switched on.

- The used filter tape is not collected on a spool, but is ejected through a slot in the front panel. If not required for subsequent analysis, the used tape should be cut off with scissors and discarded.

- The 'Portable' chassis does *not* include the flow-diverting 'Bypass Valve'. Consequently, the 'Tape Saver' function is not available in the parameter setup menu.

Examples of data obtained with 'Portable' Aethalometer (courtesy of G. A. Allen, Harvard and NESCAUM):
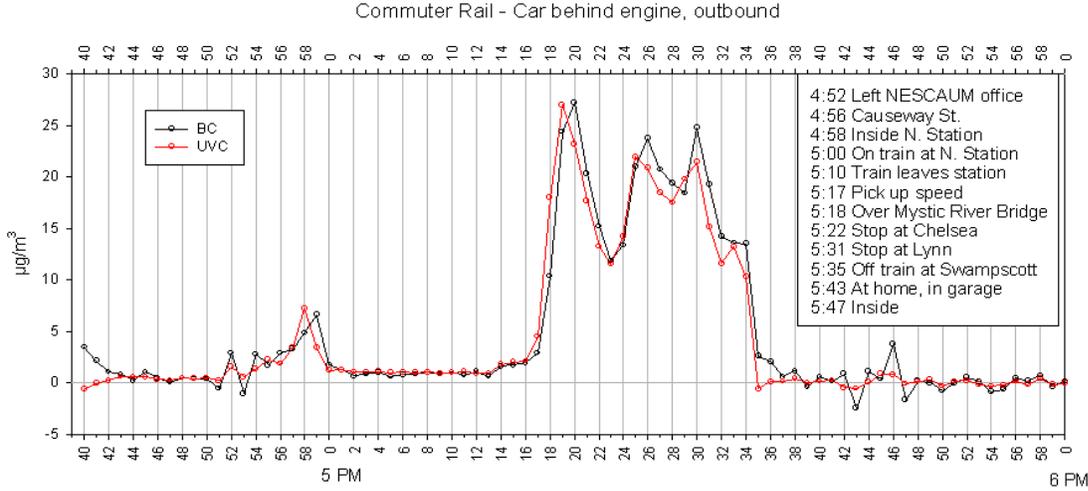
Measurements on board commuter train, Boston, MA, area
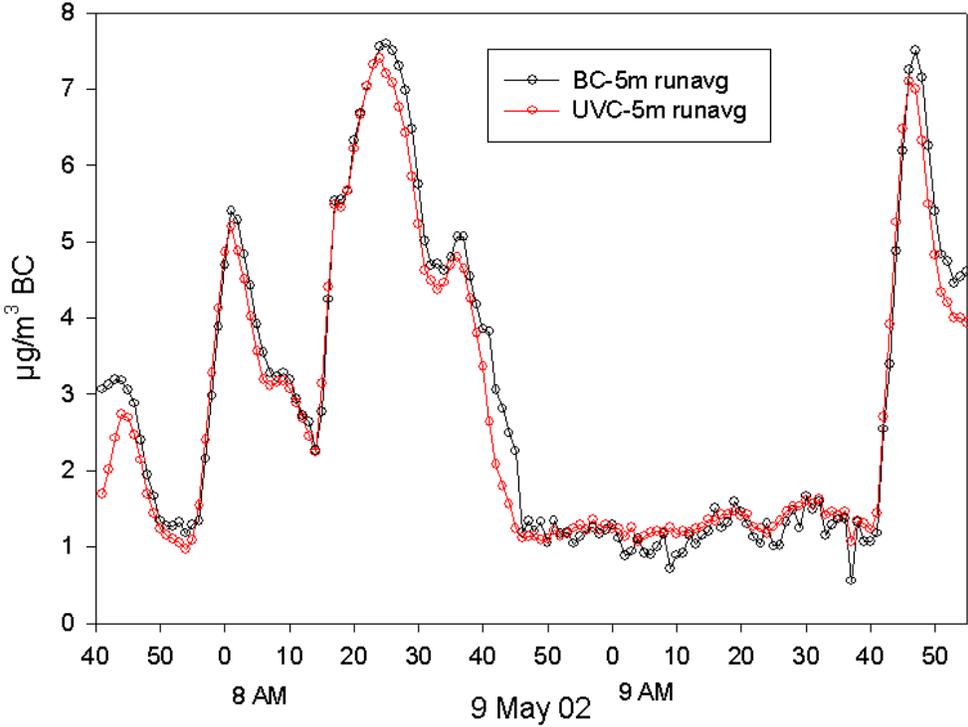
Measurements in car on highway during morning commute, Boston, MA, area.
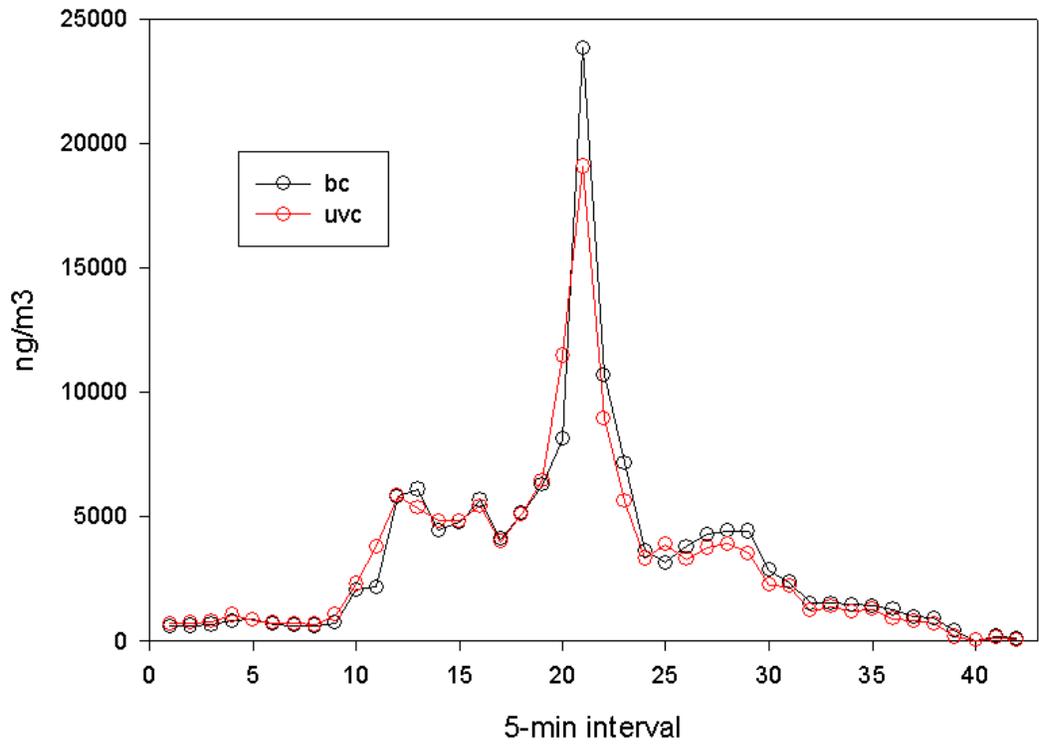
Measurements in schhol bus yard, Boston, MA, area.

7. AEROSOL INLET REQUIREMENTS

As discussed in the previous section, the aerosol inlet plumbing requirements are not very stringent and may be easily achieved in almost all installations. The aerodynamic size of the usual ambient BC particles is small, normally less than 0.3 μm diameter. These particles are small enough that their losses in transit due to impaction are not severe, and large enough that losses due to diffusion to the tubing walls are also not serious. We have achieved satisfactory results with estimated BC mass losses of less than 10 percent using tubing of 1/4" (6 mm.) internal diameter and inlet tubing lengths of up to 30 feet (10 m).

If the installation allows, it is obviously desirable to construct an aerosol inlet system that minimizes all losses. Such a system typically consists of a large-diameter vertical inlet stack through which ambient air is aspirated. Smaller lines take fractions of this air stream to different instruments, through isokinetic probes inserted into the stack. It has been our experience that these precautions do not produce a substantial improvement in the recovery of ambient BC aerosols, relative to a moderate (e.g. 2 meter) length of the 'normal' 6-mm. ID inlet tubing.

7.1   INSECTS AND RAIN

It is important, however, to protect the BC aerosol inlet stream from two 'macroscopic contaminants': *rain* and *insects*. The quartz fiber filter will clog and will radically change its optical property if it becomes wet: it is very important that rain, spray or other water be excluded. In some installations on board ships, we have inserted a 1-liter bottle upstream of the Aethalometer to trap any water droplets that may have entered the inlet line. Our experience was that this trap bottle did not materially affect the BC measurement. We strongly recommend using a trap if there is **any** possibility of rain or other water entry.   It is also necessary to exclude *insects* from the inlet. A small mosquito sucked onto the filter can cause a gigantic change in optical transmission, and will certainly ruin the data from that period.
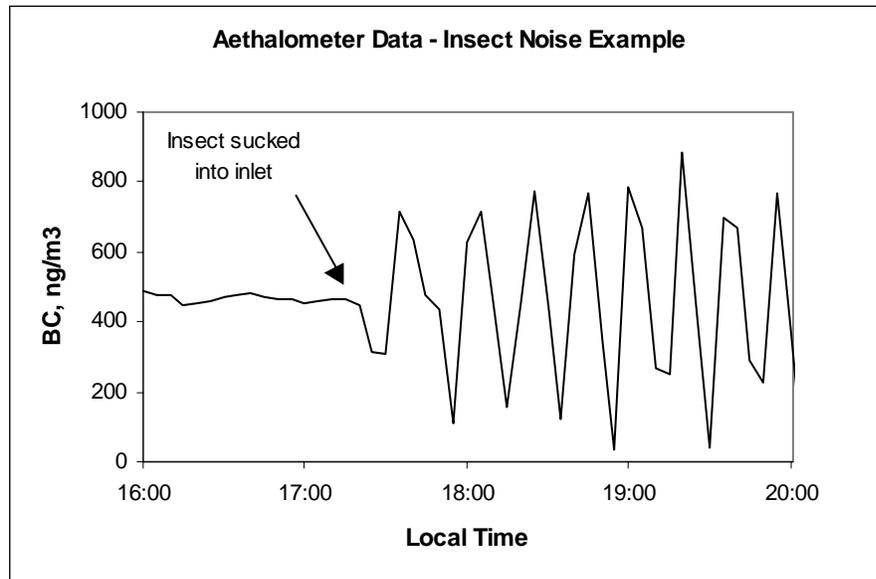
7.1.1 Recommended Inlet Construction

For the above reasons, we recommend that the aerosol inlet be constructed as follows:

(a)   a run of 1/4" ID black tubing of moderate length from the instrument to the inlet stack;

(b)   a run of vertical tubing to a height sufficient to avoid any local ground-level sources;

(c)   a 180-degree turn over, of radius at least 10 cm.;

(d)   a cover to protect the actual inlet tube from rain or spray;

(e)   an enclosing bag of mesh screen with a weave close enough to exclude insects.

In practical terms, the requirements of the final point of inlet are easily met by attaching an inverted funnel to the downward-facing turned end of the stack tube, and then stretching some screen mesh across the funnel face.

7.2   SAMPLE INLET TUBING CONNECTORS

The sample inlet port on the rear panel is a standard ¼" female pipe thread socket. It accepts any fitting that the user may wish to employ for connection to the air sampling stream. A selection of fittings is provided with each Aethalometer, including a gray plastic 'instant' push-to-fit connector for the 3/8" (6 mm.) OD tubing that is supplied. If using this fitting, it is ***very important*** that the tubing must be pushed firmly all the way into the fitting, in order to make a leak-proof seal on the o-ring that is inside the connector. To *remove* the tubing from the connector, *press firmly* on the release collar ring closest to the tubing, while simultaneously *pulling* the tubing out of the fitting.

8.   PUMPING

8.1   GENERAL PRINCIPLES OF SAMPLE COLLECTION

The Aethalometer operates by accumulating a deposit of particles filtered from the air stream by a fibrous medium. The greater the airflow rate, the more rapid the rate of accumulation and the more sensitive the measurement. However, this also results in a more rapid rate of saturation of the deposit on the filter, and a shorter time before a filter tape spot advance is required.

In locations of *high aerosol concentration*, such as urban areas, the Aethalometer sensitivity is actually far greater than is required to obtain good data; rapid filter spot saturation leads to frequent tape advances with loss of data continuity during re-initialization. In these cases, it is desirable to reduce the sample flow rate per unit area of the filter material. This is achieved by operating at lower flow rates (e.g. 2 LPM); by using the 'Tape Saver' option; and by specifying the Aethalometer with the larger "Extended Range" inlet that provides a sample collection spot area of 1.67 cm².

In areas of *low aerosol concentration*, or whenever the highest sensitivity is required, best performance is achieved by using an Aethalometer at higher flow rates (e.g. up to 6 LPM); by making sure that the 'Tape Saver' option is switched OFF; and by specifying the instrument with the "High Sensitivity" inlet that concentrates the aerosol onto a spot area of only 0.5 cm².

8.2   PUMP OPTIONS

Air flow through the Aethalometer is produced either by an internally-mounted pump, or by an external pump of the user's selection. The flow rate is controlled either by electronic motor speed control (internal pump option), or by valve connected to the pump (external pump option). Since the mass flow meter monitors the actual sample flow, and passes this value to the algorithm, the BC analysis result is independent of the flow rate actually used. The user may set the flow to a higher or lower value according to preference or the nature of the location – polluted or relatively clean. In most urban and regional locations, the instrument has more than enough sensitivity and will give excellent performance at flow rates of 2 to 4 SLPM. Some users precede the Aethalometer with an impactor or cyclone in order to positively exclude particles of large aerodynamic diameter: one design provides a 50% cutpoint of 2.5 µm at a flow rate of 5 LPM, another provides a cut of 1 µm at a flow rate of 2 LPM. In these cases, the Aethalometer flow rate must be set to whatever value is called for by the controlling external circumstance. The various pumping options and features are as follows:

8.2.1   Internal diaphragm pump – Variable-Speed DC Motor

The Aethalometer is most commonly supplied with a dual-diaphragm pump operated by a variable-speed brushless DC motor. The motor speed (and hence the flow rate) is controlled automatically by the computer and electronics to achieve a flow rate as defined by the software parameter setup, based upon feedback from the mass flow meter. At sea level, this pump can produce a maximum sample flow of approximately 6 SLPM. This is adequate for most sampling situations. At lower flow rates (2 to 3 LPM), this pump is very quiet. This pump is always installed on the 'Portable' Aethalometer models.

8.2.2   External Pump

Use of an *external pump* to provide airflow through the Aethalometer may be chosen as an option to meet certain requirements or preferences.

At high altitudes, the maximum flow rate of the internal pump decreases. It is completely satisfactory for urban measurements, but higher flow rates may be required to achieve the highest performance at background sites or other situations requiring accurate measurements of low concentrations. For these cases, the Aethalometer may be shipped with a quick-disconnect suction fitting on the rear panel, and a valve provided to attach to the pump to adjust the flow. There is no specific requirement on the type or model of pump, other than that it can provide the necessary flow at a gauge vacuum of up to –0.5 atmosphere. Typical pumps that may be used include diaphragm and vane-type pumps.

9. SENSITIVITY AND NOISE

9.1 GENERAL PRINCIPLES

The Aethalometer™ operates by detecting a very small <u>increment</u> of optical attenuation on the filter. This incremental absorption is due to the accumulation of aerosol black carbon removed from the volume of air filtered during the timebase period. The ultimate sensitivity of the instrument depends on two factors:

(a)   the rate of collection of aerosol on the filter.

        This is linearly proportional to the airflow rate through the instrument. The sensitivity and performance scale directly with this flow rate. In our experience, there are no undesirable *scientific* consequences of using higher flow rates: however, the tape spot will reach saturation more quickly, leading to an increased consumption of tape and more-frequent interruptions of data due to tape advances. Most urban and regional locations have BC concentrations that are high enough to allow use of low to intermediate flow rates (i.e. 2 to 3 LPM) and still provide good signal-to-noise ratio on the data. "High" flow rates are only really necessary in 'remote' or 'clean' locations.

(b)   the minimum detectable increment of BC on the spot. This is determined by a number of factors, most of them electronic in nature:

        Firstly, consider the stability of the signals from the photo-detectors. The photodiodes are connected via an electronic multiplexer switch directly to a 'sigma-delta' type digitizer. There is inevitably a small 'dark response' signal that appears even when the lamps are off. This is partly produced by thermal excitation of electrons and holes in the detector, and thus the signal levels are very slightly temperature sensitive. Provided that these changes are SLOW in comparison with the signal acquisition cycle of the instrument, the algorithm subtracts out the slow drifts to first order. If the changes are rapid, there may be second-order effects that may be important at the highest sensitivity as required for measurements at remote locations. Thus, the avoidance of rapidly-changing temperatures is definitely necessary to achieve optimum sensitivity of the instrument. For this reason, the electronics enclosed in an insulated area whose temperature is actively stabilized at approximately 100°F (40°C). This protects the electronics from essentially all normal temperature fluctuations, but it is advisable that the Aethalometer NOT be located directly beneath the outlet vent of a cycling air-conditioner such as may be found in an instrument trailer in a field installation.

Secondly, consider the stability of the light sources, which are LED lamps. The lamp intensity is monitored by the reference detector, and the algorithm uses the signal ratios to compensate for changes in light intensity. Again, provided that these changes are SLOW in comparison with the measurement cycle, then the system can compensate to first order for intensity changes from one period to the next. If the intensity fluctuates rapidly, the sensing and reference beams will not be correlated and a certain amount of equivalent noise will be added to the measurement. As discussed below, the algorithm is such that measurement noise can be reduced by averaging together a larger number of short-timebase measurements to recreate the higher sensitivity of a longer-timebase measurement.

If, from one cycle to the next, the intensity of light reaching the central aerosol collecting spot was diminished by one part in ten thousand (100 PPM), the algorithm would be unable to distinguish this from the accumulation of 1 ng/cm² of black carbon on that spot. If the flow rate were 4 SLPM and the measurements were being made on a timebase of 5 minutes, this 1 nanogram of apparent black carbon would have been associated with the passage of 0.02 cubic meters of air, and so the measurement noise level would be equivalent to 50 ng/m³. Clearly, it is necessary to strive for extreme electronic and optical stability of the system, and the various models of Aethalometer can normally achieve this level of performance.

Having achieved a desired level of stability, we must now be able to measure the signal voltages with appropriate accuracy. The digitization is performed with an analog-to-digital system of resolution 22 bits (i.e. better than 0.3 parts per million). The nature of the algorithm is such that random excursions in measured voltages, impressed upon the 'true' signals as noise, result in a characteristic pattern of calculated BC concentration that may be readily recognized as a noise excursion event. This point is discussed in the following chapter.

9.2 STABILITY EXAMPLE – AE16

The following example shows data from a single-wavelength Aethalometer operating on a short timebase at low flow rate: 2 LPM flow, 1 minute timebase. Each data point is therefore calculated from the increment of optical attenuation gathered after the passage of 2 liters of air.   The instrument was operated in a closed, draft-free room with steady ambient temperature. The chart shows that the effective point-to-point noise level on any individual datum is equivalent to an excursion of approximately +/- 100 ng/m³ – i.e. 100 pg/liter – from the central mean. This implies that the optics and electronics can detect a signal change equivalent to the deposition of approximately **200 picograms** of BC on the filter spot, whose area was 0.5 cm² in this instrument. This is equivalent to a surface loading increment of 0.4 ng/cm², or a change in 'Attenuation' of 0.008 ATN units, slightly less than 1 part in 10,000 of the optical intensity.

Aethalometer Stability Test
Indoor Air, Closed Room
2 LPM flow, 1-minute timebase
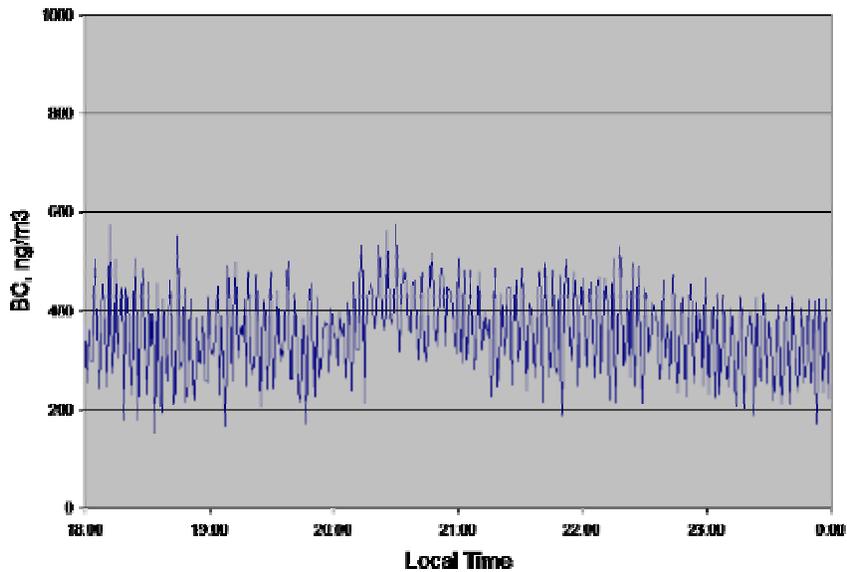
Aethalometer stability test: data chart and 'MF' report file

```
---
Aethalometer No. 367
---
14-mar-03  15:05:54  Measurements started
Starting voltages: sen(beam) =   2.161  sen(zero) =   0.020
.                   ref(beam) =   1.562  ref(zero) =   0.021
---
15-mar-03  01:56:47  Measurements ended
---
.                   Number of lamps (L) = 1
.                   Filter running time = 10.83 hours
.             Total airflow this filter = 1.3 cubic meters
.
Report for lamp 1:
. Ending voltages: sen(beam) =   1.832  sen(zero) =   0.020
.                  ref(beam) =   1.538  ref(zero) =   0.021
. Optical attenuation of filter deposit = 14
.  Total aerosol black carbon on filter = 448 ng
Mean aerosol black carbon concentration = 344 ng/m3
---
The limit of resolution of the analog/digital converter was equivalent
to a mean quantum of 95.4 ng/m3 on the measurement
---
The reference beam showed lamp intensity fluctuations of 25 ppm.
This was equivalent to 36.2 ng/m3 or .3 quanta of resolution.
Lamp stability is good.
---
```

10. INTERPRETATION OF DATA

10.1 GENERAL PRINCIPLES

Ideally, the data output from any measuring instrument would consist of a smoothly-varying analog voltage (or digital representation thereof) that instantaneously represented the value of the parameter being measured, without any corruption due to noise or other interference. In practice, realistic instruments present their measurements with some reductions from this ideal. The actual Aethalometer™ data output is affected to some degree by its mode of operation, inherent physical and electronic limitations, and the nature of the algorithm used to calculate the result.

The Aethalometer is set to operate on a certain timebase period, and calculates its data from the quantity of aerosol black carbon determined to have been collected on the filter during this period. Thus, the measurement is not presented until the *end* of the measurement period, and represents an arithmetic mean of the actual concentration during that period. The algorithm identifies the data with a date and time stamp that are displayed and recorded: the time shown is the time at the *start* of the measurement period. It is necessary either to know the length of the timebase period, or to examine the time value for the following data entry, in order to determine the *end* time for that period.

It is important to note that the analog voltage presented on the rear panel terminals represents the BC value from the **previous** timebase period. This value will be held until the end of the **next** timebase period. The analog output voltage is therefore always one period "behind" the current measurement.

In addition to the BC calculation, the system also records diagnostic signals to disk in case there is a need to examine the raw measurements from which the BC concentration was calculated. These additional data entries on the record line include: Sensing Beam signal with the lamp ON and OFF, Reference Beam signal with the lamp ON and OFF, the mean air flow rate, and the calculated optical attenuation. All of these quantities are measurements made at the *end* of the measurement timebase period, with the exception of the air flow rate which is the arithmetic mean of measurements taken continuously during the entire period. The BC number shown is the mean BC concentration for the period *starting* at the time and date shown.

The Aethalometer needs to measure extremely small changes in optical transmission in order to calculate BC concentrations with speed and accuracy. The optical transmission through a blank filter will change when vacuum is first applied to it, producing a pressure drop that compacts the filter fibers. This initial change would be interpreted by the algorithm as a large artifact 'BC' concentration, and so the software automatically provides a settling period before the first measurement on a fresh filter spot. Valid data are not produced until after at least *one* timebase. While the tape is advancing or the instrument is

subsequently initializing and equilibrating, the green 'Run' light will *flash* to signify that the instrument is functioning normally but there is no valid data. When the instrument is functioning normally, and valid data are being calculated, the green 'Run' light will be *steady*.

The major source of noise in the data is due to small, random fluctuations of digitized signals. These fluctuations have the effect of causing the calculated value of attenuation (ATN) to deviate from a smooth, monotonic increase with time: instead, individual values of ATN may be artificially higher or lower than would be predicted from the rate of accumulation of BC from the air stream. These isolated events give rise to a characteristic signature in the derivative calculation that yields the BC result. An error in one of the four fundamental signals will usually not be repeated the following measurement cycle, and the calculated ATN will revert to its 'correct' value: but with an intervening false number.

If the error condition produced an artificially high value of ATN for one measurement, the algorithm will interpret that large increase as a large value of the BC concentration for that period. This calculated value may be much larger than the preceding and following data, and the event will be obvious. However, this large value of ATN is used as the starting value for the calculation of the increment in the following cycle. The increase from this value to the 'correct' value at the end of the next period will be much smaller than it should be, resulting in a reduced value for the BC calculation. The result of the single error value of ATN in this case is an artificially <u>large</u> value of BC, followed by an artificially <u>small</u> value. The 'true' value is recovered by replacing the value for each of the periods with the arithmetic mean of the two distorted values. This is equivalent to simply ignoring the one bad signal measurement; determining the increase in ATN between the periods before and after the bad measurement; and calculating the increment in ATN and hence the mean BC concentration over a time interval of two periods rather than one.

In extreme cases, the error in voltage measurement may generate a value of ATN that deviates from the expected smooth progression by a large amount. The algorithm will process these deviations in the same manner: however, if the apparent value of ATN during the 'error' measurement exceeds the subsequent 'correct' value of ATN, the program is presented an optical attenuation value that is smaller than its predecessor. The mathematics will produce a <u>negative</u> apparent value of BC for this situation. This negative value will be adjacent to a slightly <u>larger</u> positive value: the arithmetic mean of the two numbers will still allow a recovery of the correct mean BC concentration for the double period. The derivative nature of the algorithm is such that a single error value in recorded signals produces a symmetrical plus-minus derivative event in the calculated BC result.

If the sign of the superimposed noise event were inverted, the signature in the final data would be reversed in order: a negative or reduced value will be followed by an enlarged positive value, and the BC data would show a characteristic minus-plus excursion.

Excluding data corruption events as described above, it is still clear that some noise of similar appearance will be present when attempting to measure extremely low concentrations of BC. At a very low level, small deviations in measured voltages will occur during each measurement cycle. If the actual increase in ATN is smaller than these fluctuations, due to actual very low levels of BC in the sampled atmosphere, the algorithm may produce positive and negative fluctuations in the same manner. Indeed, one of the tests that each Aethalometer is put through prior to release is to operate it sampling <u>filtered</u> air for 12 to 24 hours. The expected value of detected BC should be zero: in practice, small positive and negative fluctuations are observed. The negative values arise directly from the nature of the algorithm, as discussed above. The cumulative mean of these data values is usually observed to be close to zero: the parameter of interest is the standard deviation of the small fluctuations, as this will determine the effective noise level on the measurement of BC and the minimum detectable amount.

This effective noise level of BC is fundamentally a product of the ability of the detectors and electronics to resolve a very small increase in the amount of BC in the aerosol deposit on the filter. When translated to a BC concentration in the sampled air stream, factors of the air flow rate and sampling time are introduced. The 'usual' performance of an Aethalometer is to be able to resolve an increment of less than 1 nanogram of BC on the filter. If the instrument is operating at a flow rate of 4 liters per minute, this implies that the minimum resolvable concentration would be approximately 50 ng/m³ operating on a 5-minute timebase (i.e. 1 ng noise per 20 liters air flow), or approximately 5 ng/m³ if the timebase period were 1 hour. See the example shown in the previous section 9.2. In practice, we prefer to use more conservative figures for the instrument performance, and normally quote a limit of quantitation as 5 nanograms on the filter. The translation of this performance to a concentration figure will then depend on the sampling timebase period and the air flow rate. The greater either of these parameters, the lower the minimum detectable concentration of BC in the sampled air stream.

Note, however, that the appearance of 'negative' numbers for the deduced BC concentration is a natural consequence of the algorithm if either (i) there are occasional corrupting events on the voltages being recorded, or (ii) the instrument is being used to study extremely small concentrations of BC. These negative numbers do **not** imply malfunction of the instrument: they are the consequence of differentiating a quantity (ATN) whose increase with time is not perfectly smooth and monotonic. In subsequent data reduction, one must average the BC numbers appropriately until the negative numbers disappear: i.e., effectively increase the

averaging time until the increment of BC collected on the filter easily exceeds the minimum amount detectable by the electronics.

Considerations of the nature of the algorithm also lead to a suggested strategy for situations in which post-sampling data analysis is readily available: namely, to perform measurements with a timebase period that is considerably <u>shorter</u> than the final desired time resolution, and then to subsequently average and post-process the data. The reasons for this strategy are two-fold: firstly, to minimize the duration of the effect of any data 'glitches' (i.e. voltage measurement errors); and secondly, to allow the instrument to respond rapidly to 'real' events in the local atmosphere, while retaining the possibility of averaging the data into longer timebase periods during quiescent periods.

The first of these considerations attempts to minimize the 'damage' to the database due to one bad voltage reading. As discussed above, the effects of one bad voltage measurement will affect the measurements in the <u>two</u> contiguous periods. If an instrument is operating at a remote station with a timebase of one hour, a single voltage spike will affect two hours of data, although an average can be recovered. If, on the other hand, the instrument was being operated on a timebase of 5 minutes, with subsequent gathering of the data into one-hour averages, this isolated event would only affect 10 minutes of data and would in fact not affect the one-hour data at all. Although the individual 5-minute measurements have less inherent precision, due to the reduced volume of air sampled, their accumulation into one-hour averages is exactly equivalent to operating the instrument on a one-hour timebase. Nothing is lost by operating on a shorter timebase and post-processing the data into longer periods, if the laboratory data system can be programmed for these actions on the Aethalometer records.

The second advantage of operating on a shorter timebase is that occasionally, short-duration events of **actual** <u>BC concentration excursions</u> do occur. A vehicle may be operated upwind of the measurement site: a local recirculation pattern may bring emissions from one location into the sampling inlets. These events are identified in the database as those in which a large positive excursion is <u>not</u> followed by a compensating negative number.

For these reasons, Aethalometers are shipped from the factory with the timebase set to <u>5 minutes</u>. We recommend keeping this value unless considerations absolutely suggest otherwise: e.g., shorter timebases (1 or 3 minutes) for local-impact studies in areas of high concentration; very rapid timebases for source studies; or timebases of 10 or 15 minutes (maximum) for remote studies.

See also the chapter below on "Precise Timing"

10.2 INTERPRETATION OF UV DATA WITH VOLATILE ORGANIC SPECIES

The UV measurement responds to optical absorption by both elemental carbon and any aromatic organic species that exhibit the onset of optical absorption in this region of the spectrum, as discussed in chapter 2.2. However, some of these UV-active species may be (semi-) volatile, existing in equilibrium with filterable particles. In well-aged ambient air samples, these volatile organics will be found almost exclusively in the gas phase, and the UV response of a multi-wavelength aethalometer will show little enhancement over the BC response. However, combustion exhaust streams may contain filterable particles at high concentrations together with semi-volatile UV-active material that will be temporarily retained on the filter tape, leading to a distinct increase in UV absorption, for as long as the sampled air stream contains the high concentrations of other species that lead to equilibrium. If the exhaust 'event' then terminates, and the aethalometer is then drawing relatively clean air through the filter tape, the equilibrium conditions will no longer exist and the organics will *desorb* from the filter fibers into the passing clean air stream. This will result in a *loss* of UV-absorbing material from the filter deposit, which the algorithm will interpret as a *negative* signal in the UV data.

Such an example is shown above: after the sampling probe was removed from the

UVPM "Overshoot Recovery" : Desorption of Organics
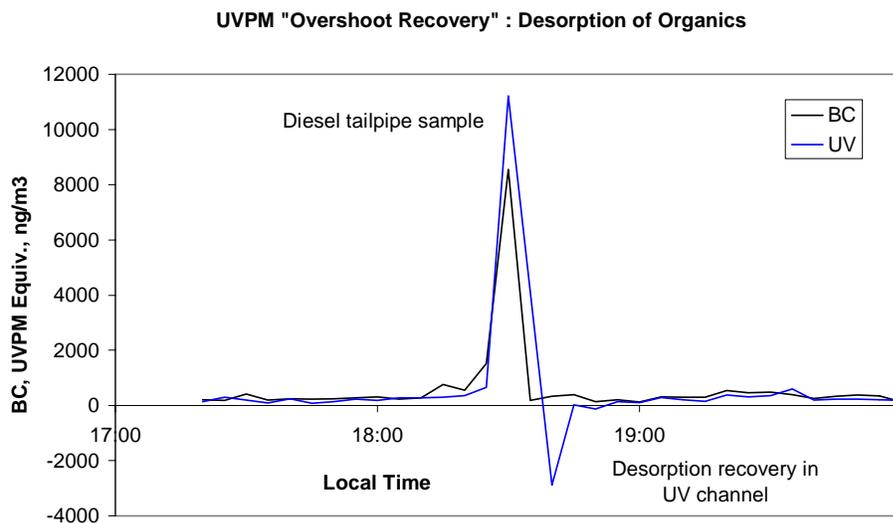
vicinity of a diesel engine tailpipe, the UV data showed a 'negative' recovery. This is not an instrumental error, but indicates that UV-absorbing material was deposited on the filter spot during the sampling event, and then desorbed from the filter spot afterwards.

10.3 DATA DISPLAY TEMPLATES

Convenient templates for processing and creating charts of Aethalometer data may be downloaded from the Magee Scientific website at http://www.mageesci.com/#Template . These are spreadsheets using Microsoft Excel, that allow for 24-hour day files of data to be displayed. The spreadsheet includes a smoothing function that uses an auto-regressive algorithm. Raw data may be imported and displayed: the smoothing function may then be gradually increased until the desired signal-to-noise ratio is achieved. Three templates are available, for 1-, 2- and 7-wavelength data.

10.4 THE 'WASHINGTON UNIVERSITY' DATA PROCESSOR

Professor J. Turner of Washington University, St. Louis MO, has developed a program for the post-processing of Aethalometer data. This program checks the diagnostic data columns for instability issues, gathers averages, and flags 'valid' or 'non-valid' hours. Complete details are posted on-line at http://www.seas.wustl.edu/user/jrturner/aethalometer .

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11.   UNPACKING AND SETTING UP THE INSTRUMENT

11.1   SHIPMENT CONTENTS

A complete Aethalometer™ installation requires the following items:

(a)   In shipping box:

- Aethalometer instrument, including power cord; sample inlet tubing; selection of fittings for sample inlet connection;

- Roll of Filter Tape, installed in instrument;

- This operations manual;

- Factory documentation: Final Inspection Record; CE Certificate; Calibration Test Document;

- Original Program Diskette for backup;

- Optical Test Strip;

- Box of 3.5" floppy diskettes, IBM-PC formatted for 1.44 MB.

(b)   If the instrument is configured for <u>External Pump</u>, the user must either provide the vacuum pump or have ordered it concurrently from us. In this case, check also that vacuum pump tubing and connectors are provided.

Check that all items are present and appear to be in good condition. In case of any damage in shipment, <u>notify your transport carrier first</u>, in order to protect your shipping insurance. Notify *Magee Scientific Company* for investigation.

The following label is attached inside the Aethalometer door when it is shipped from the factory:

Important Note…Read before Operating
THE AETHALOMETER

BEFORE USING INSTRUMENT:

1.) INSERT IBM-PC FORMATTED **DISKETTE** IN DISK DRIVE.

2.) REMOVE THE CAP PLUG FROM THE SAMPLE INLET PORT ON THE REAR PANEL AND USE A CONNECTION ADAPTER TO YOUR SAMPLE INLET TUBING.

3.) REMOVE THE FILTER PROTECTION STRIP FROM THE OPTICAL ANALYSIS HEAD BY HOLDING **TAPE ADVANCE** AND PULLING RIGHT GENTLY. DO NOT TEAR TAPE.

IN CASE OF ANY PROBLEMS OR QUESTIONS,
SEE *WWW.MAGEESCI.COM* FOR FURTHER INFORMATION

The 'Filter Protection Strip' is inserted between the filter tape and the optical head when the Aethalometer is shipped from the factory. **Be sure to remove this strip before operation of the instrument!** (see next section).

	REMOVE FILTER PROTECTION STRIPS BEFORE USING INSTRUMENT **PULL OUT TO RIGHT**

11.2 HARDWARE SET-UP

Connect the Aethalometer™ to an AC power outlet, switch it on briefly, and ensure that the instrument powers up. Note that there is an on/off switch at the rear panel power entry point, together with the fuse holder. Normally, this power switch is not used: however, you should check that it is in the 'On' position. For normal use, switch the Aethalometer 'On' and 'Off' using **only** the <u>Front Panel Switch</u>.

Remove the '<u>Filter Protection Strip</u>' that is installed at the factory for protection during initial shipping. Switch the instrument 'On'; press the 'Tape Advance' switch in the <u>upwards</u> direction; pull the filter protection strip out to the right; switch the instrument 'Off'.

Remove the red threaded plug from the 'Sample Inlet' port and install one of the ¼" fittings provided, according to the type of sample inlet line that will be used. If the instrument is configured for '<u>External Pump</u>', plug in the pump, check that it is running correctly, and connect it to the 'Vacuum Pump' suction connector on the rear panel.

The <u>sample inlet tubing</u> is inserted into the ¼" fitting on the rear panel, and should then be led to the sample inlet stack, the sampling point, etc

Insert a blank, formatted 3.5" disk into the drive.

Switch the power to the Aethalometer 'On'. The display screen will illuminate: for the first half-minute the computer is performing its program loading and initialization procedure, and the screen will only show a flashing cursor block. After a while, the screen will display the opening dialog.

Verify that the pump is drawing air through the Aethalometer, so that the suction can be felt at the end of the sample inlet tubing.

The instrument can (in principle) begin operation automatically from this point, and **will do so** after 60 seconds if none of the keypad keys are pressed.

11.3 SOFTWARE SET-UP

When an Aethalometer™ is first received and is being set up, we recommend that you follow a certain sequence of procedures in order to make sure that the software is correctly configured. Each system is shipped from the factory with most of the specifications set to typical values. However, we recommend that you run through the following procedures first before operating the Aethalometer.

(a)   Set computer date and time. This will ensure that all subsequent data and message entries are correctly identified.

(b)   Install permanent titles from disk: using a text editor, write two lines as plain text and save them under the file name 'TITLES.TXT' onto a floppy disk. These titling lines may now be loaded into the Aethalometer from the floppy disk, and will accompany <u>all</u> message files and printouts. Usually these two lines show the name of the institution or project, and other information that will remain the same from one measurement to the next. These lines must be written to a TITLES.TXT file on disk from an external editor using another computer, and loaded into the Aethalometer afterwards. The titles are loaded into the system using the "Operate" main menu selection, then responding "NO" to the prompt 'Go To Automatic Operation?'. (See software instructions in section 14.5.2).

(c)   Check specification of parameters. Items that can be specified include:

- Measurement timebase. This may be selected from one hour to one second (AE16), one hour to one minute (AE21), one hour to two minutes (AE31).

- Sample air flow rate.

- Analog output voltage scaling. This sets the correspondence between calculated BC concentrations, and the voltage presented at the Analog Output terminals on the rear panel.

- Communications parameters for the COM port data output;

- Etc.

11.4 "QUICK SET-UP SUMMARY GUIDE"

1. To Start: Plug in and switch on. Connect external pump if required. Instrument starts automatically without any operator attention. Data collection will begin after about 5 minutes.

    Note: instrument takes about 30 minutes to warm up and stabilize.

2. To Stop Quickly: Simply switch off. Data file on disk will be current up to this time.

3. To Exit Cleanly with Data Summary: Press STOP key, observe screen. Press STOP key again. Enter "Security Code" (factory default = 111). Summary file will be written to disk.

4. Data Diskette may be removed and exchanged at any time with a fresh disk: does not interfere with data collection.

5. Flow Rate is set in software. Flow may be set to read out in "Standard" units (sea level) or "Volumetric" units (adjusted for altitude and temperature).

6. To Change Settings:

    *   Switch on, observe opening countdown screen. Press any key to get top item in Main Menu, 'Operate'. Press down-arrow for next menu item 'Change Settings'. Press Enter.

    *   Scroll through settings list with down-arrow. Press Enter to access an item.

    *   First item is Date & Time.

    *   Next item is Timebase – usually set to 1 - 5 minutes, depending on need.

    *   Next item is Flow Rate – usually set to 2 to 4 LPM.

    *   To change an item, use arrow keys, make selection, press Enter to confirm, press Esc to escape from the systems-settings menu. Confirm change.

7. Data Tradeoffs:

    *   Shorter timebase = better response to rapid changes in concentration, but noisier data.

    Note: data can always be smoothed afterwards to reduce noise.

- Suggest running initially at 5 minute timebase.

Note: electronic digitzation noise is drastically reduced at timebases >= 5 minutes.

- Higher flowrate = less noise, but shorter lifetime of tape spot. When spot saturates, tape automatically advances, data will be interrupted for few min.

- Increase flowrate to reduce noise on data, if tape advance intervals are acceptable.

12. FILTER TAPE INSTALLATION

12.1 GENERAL INFORMATION

The Aethalometer™ determines the concentration of aerosol Black Carbon in the sampled air stream by measuring the rate of increase of optical attenuation due to the increasing deposit of particles collected on a spot on the filter tape. For most purposes, the spot itself has **no** individual identity and the progression of spots on the tape is simply the means to perform the measurement.   When the optical density reaches a pre-set value, the instrument advances the tape in order to provide a fresh collection surface. The filter tape merely provides the medium on which the aerosol is deposited, and is usually discarded when used.

The instrument is shipped with a fresh roll of quartz fiber sampling tape installed on the left-hand 'supply' spool. This roll provides 1500 sampling spot locations. Each spot lasts from a few hours in cities to as long as several months at remote locations, and so changing the tape roll is only required occasionally. The display screen shows an **estimate** of the percentage of the tape roll that remains: when this falls below 10%, the 'Check' lamp on the display panel will be lit.

Note that the 'Tape Remaining' percentage is a **software-based estimate**, not an actual measurement of the tape spool. Under some conditions, the estimate can become inaccurate and reach zero even though there is filter tape remaining on the supply spool. Even if the yellow 'Check' lamp is lit, and a warning message is displayed on the screen, the instrument **will continue to provide valid data** until the filter tape actually runs out.

- When the tape is eventually all used, it is necessary to install a fresh roll, according to the procedures set out below. The menu option '*Install New Tape*' offers an abbreviated set of sequential instructions with prompts to guide the user through the necessary steps. This software procedure also re-sets the tape supply percentage counter to 100%.

- For this reason, the '*Install New Tape*' software procedure *must* be used when installing a fresh roll of tape. If you are familiar with the procedure, you may bypass the screen instructions, but you must use the procedure in order to re-set the counter.

The 'Install New Tape' procedure is 'protected' and requires the Security Code as a password.

The first list describes the actual procedures. The second list shows the prompts displayed on the screen by the '*Install New Tape*' procedure.

12.2   INSTALL NEW TAPE – OPERATOR ACTIONS – RACK-MOUNT MODELS

(a)   Stop measurements, turn off the pump (if external). Do not switch off the instrument power.

(b)   Select *"Install New Tape"* from the Main Menu.

(c)   Remove the two thumb screws securing the analyzer chamber center cover plate.

(d)   Remove the two thumb screws securing the clear plastic front spool flanges.

(e)   Pull out the gray plastic guide rod (with banana jack) on the left side of the analyzer chamber.

(f)   Use scissors, cut the tape on the left hand (supply) side. Leave a few centimeters.

(g)   Remove the unused portion of the previous roll of tape from the supply side spindle. Open the box of new tape, take out the new roll.

(h)   Put the new roll of tape on the supply side spindle.

(i)   Using adhesive tape, stick the start of the new filter tape to the end of the old filter tape on the left side of the analyzer chamber.

(j)   Press and hold the "Tape Advance" button with your left hand. The inlet assembly will lift about 2 mm - just enough to release the clamping force on the tape.

(k)   With your right hand, pull the old tape out to the right, with the new tape stuck to it. Pull about 20 cm. of new tape through. Cut off the old tape.

(k)   Remove the filled spool of used tape from the right-hand (take-up) side. Unroll it in order to retrieve the brass spring clip and the cardboard center. Discard the used filter tape, retain the clip and the cardboard center.

(m)   Be sure not to dislodge the o-ring which is behind the cardboard center.

(n)   Put the empty cardboard center onto the take-up hub.

(o)   Take about 10 cm. of the new tape, and thread it under the swinging roller arm that controls the tension. Clamp it under the spring clip onto the cardboard center. Turn the cardboard center counter-clockwise to roll up the slack tape onto itself.

(p)   Replace the clear flange on the supply spool side. Tighten the thumb screw firmly but not excessively. Check by pulling on the unrolling portion on the left, that the supply roll can turn against a little friction. Plug the guide rod back in to its banana jack.

(q)   Replace the clear flange on the take-up spool side. Tightening the thumb screw clamps the cardboard hub against the o-ring behind it, which provides the grip to pull the tape.

(r)   Press the "Tape Tension" switch, roll up any slack tape on the right-hand side.

(s)   Replace the analyzer chamber cover plate and its two thumb screws.

12.3 INSTALL NEW TAPE – SOFTWARE PROCEDURE PROMPTS

The first screen asks '***List Instructions ?***'. If *NO* is selected, the instrument assumes that the operator is familiar with the tape installation procedure, and will not require guidance. The software skips the detailed instructions, re-sets the tape counter to 100%, and returns to the *Main Menu*.

If *YES* is selected, the display screen guides the user through all the operations required for changing the tape. After each phrase, the user must press any key to proceed to the next:

(a)   Remove spool screws

(b)   Remove cover screws

(c)   Pull out guide rod

(d)   Cut old tape

(e)   Remove supply roll

(f)   Remove takeup roll

(g)   Install new roll

(h)   Lift up chamber 2 mm

(i)   Push tape through

(j)   Lift up chamber 2 mm

(k)   Pull 10 cm tape

(l)   Install takeup hub

(m)   Clip tape to hub

(n)   Push in guide rod

(o)   Replace cover

(p)   Replace spools

(q)   Tighten spool screws

The screen then asks: 'Is the tape properly replaced?'. Entering *YES* will re-set the tape counter to 100% and finish the process.

13. OVERVIEW OF AUTOMATIC OPERATION

The nature of the Aethalometer™ algorithm makes it a very straightforward matter for the instrument to operate automatically, to acquire the raw numerical data, and to process it into a result as the concentration of aerosol Black Carbon. The combination of optical analyzer, digitizing interface, computer and software is combined in one instrument to perform these functions.

The program is stored on a 'solid-state disk' permanent memory. Operation of the Aethalometer does not require high-speed computation, and the embedded computer performs all necessary functions using only a fraction of its capacity.

The Aethalometer operating software is equipped with a large number of error-anticipating traps to identify and recover from a variety of hardware and software problems that may arise in actual operation. These are described in more detail in the sections below. A selection and overview follows:

- The program automatically starts when the instrument is switched on. The same sequence occurs if power fails, and then resumes. The first screen allows time for an operator to respond. If the operator is absent, measurements will proceed using the same parameters as previously saved.

- If the pump fails, or the plumbing or aerosol inlet becomes blocked, the instrument stops and will not re-start until an operator has checked and verified the equipment.

- If the light source(s) fail, or the performance of the optical detectors becomes questionable, the instrument stops.

- If a 'division by zero' or other internal error occurs, the system will automatically re-start.

- If the computer "freezes up" and stops executing code, the watchdog timer will automatically force a re-boot.

A number of other checks are performed, specific to the nature of the equipment. 'Problem' conditions are categorized as *serious* or *non-serious,* and the program will either halt or display a warning message as appropriate.

The software system generates two data files which are written to disk. One of these is the *BC Data File* of numerical data, including date, time, signals, air flow rate and calculated aerosol black carbon concentration. This file is written with 'comma-separated variables' so that it may be directly imported by most common data processing spreadsheets. The file name for this data file is compounded from the letters 'BC' (Black Carbon), six digits representing the date, and the extension '.CSV' .

The second data file is the *Message File*. This is intended to provide a permanent record suitable for a laboratory notebook. Its file name is constructed in a similar way: the first two characters are the letters 'MF', the next six digits represent the date, the extension type is '.TXT'. The file contains ASCII text in a human-readable format. The messages include: title of experiment or measurement program; date and time of sampling starting and ending for each filter; signal voltages at start and finish; total filter running time, total air flow, total BC collected on the filter and the overall average BC concentration for the filter period; an analysis of the stability of the instrument during the measurement period; and an estimate of the amount of data recording time remaining on the disk.

The software is designed to be self-explanatory, with enough text on each screen to allow the operator to make appropriate decisions without needing to refer to this literature. Almost all operator input is in the form of menu item selection. The available choices are scrolled using the up-down arrow keys, and then selected by pressing 'Enter'.

The computer and program operates the system completely automatically. Upon power-up, the first screen allows the operator time to press any key to gain control and proceed to the menus for parameter selection. If no key is pressed, the system will run using the parameters previously stored. The instrument automatically performs measurements of aerosol black carbon with a minimum of decision-making required of the on-site technician.

14. SOFTWARE

14.1 GENERAL PRINCIPLES

The Aethalometer™ is an analytical instrument that uses a differential-ratiometric optical transmission technique to determine the concentration of aerosol 'Black Carbon' particles suspended in the sampled air stream. The 'full-size' (19" rackmount) instrument is available in three principal versions: the "AE1-" series, performing the measurement at a single wavelength of 880 nm; the "AE2-" series, combining the 880 nm measurement with analysis in the near-UV at 370 nm; and the "AE3-" series, in which absorption is determined simultaneously at many wavelengths to yield the absorption spectrum (e.g. Model AE31, 7 wavelengths from 370 to 950 nm). Identical optical analysis and electronics are used in the 'Portable' instruments, the "AE4-" series, which is available with 1, 2 and 7-wavelength optical sources.

Each of these models of Aethalometer is controlled by an embedded 486-class single-board computer with 4M dynamic RAM and 2M solid-state disk for program storage. Its digital I/O is used to acquire signals from the electronics and to control internal functions. One of its serial ports is used to communicate with the display panel, which has a 4-line 20-character backlit display screen, a 25-button keypad and 5 programmable LED lamps to indicate instrument status. The other serial port provides digital data output to a connector on the rear panel.

The Aethalometer has a 3.5-inch floppy disk drive for data recording. Optionally, a PCMCIA solid-state memory card drive may be substituted for the floppy disk drive. A digital-analog converter is connected to terminals on the rear panel and provides an output voltage proportional to the measured BC concentration, or a programmable alarm function. The computer with its permanently stored program will start operation automatically upon power-up without any operator intervention necessary.

The software is written as an executable program file, accompanied by parameter files. These are stored in the computer's permanent memory and do not need to be accessed for routine operation.

The program is operated almost entirely by selection from menus. Choices are presented sequentially in a scrolling list, representing the various appropriate actions at any stage. The choices are selected by moving the up- and down-arrow keys. The first choice is the 'preferred' selection - i.e. the most likely response, the current state of a selection that is logical to preserve, and so forth. To maintain this choice, simply press the 'Enter' key. The instrument can be run through a complete operation to measure aerosol black carbon by always selecting the presented items, using no key other than 'Enter'.

At some points in the program, there may be a need for numerical input from the operator. A flashing underscore cursor (_) is shown on the screen at the input

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position. As numbers are typed, they are added to the input line. When the line is complete, press 'Enter'. If a typing error occurs, press the backspace key BKSP to erase the error.

The menu selection and parameter input program units incorporate a timer. The purpose of this timer is to handle the possibility that the operator is called away or distracted by other demands while in the middle of interacting with the Aethalometer. If a menu of items is displayed with the instruction to select just one, or if a numerical parameter is required, the computer will start to beep after 10 to 30 seconds if no keyboard activity occurs. This is a reminder that some input is required. This beeping will continue for 10 minutes, at which time the system will execute an automatic re-start. This is designed to take care of situations where the instrument was ready to run, parameters were being set up, and the operator was called away by the telephone in the middle of selecting choices.

In the case of system halts due to 'SERIOUS' problems, the timer is disabled so that the screen displays the fault condition message indefinitely until the operator presses a key to acknowledge the problem.

14.2 START-UP

Most Aethalometers incorporate an internal pump. The instrument will operate automatically when plugged in to a suitable power outlet and switched on. After power-up, the instrument loads its operating system and the program and automatically starts by resetting the instrument hardware and the display panel. For Aethalometers that use an <u>external</u> pump, it is necessary to connect the tubing for the vacuum pump, plug it in and switch on, so that the pump will run continuously during all use of the instrument

NOTE! - If the *Warm Up Wait* option had been previously selected from the *Settings* menu, the instrument will **<u>not</u>** start gathering measurement data immediately. Instead, it will display signal voltages while stabilizing for 30 minutes before measurements proceed automatically. The user may press the ESC key to enter manual-mode operation sooner.

Otherwise, the *Countdown Screen* is shown. This allows 60 seconds for the user to press any key to gain access to parameters set-up screens, test routines, etc.: otherwise, hands-off *automatic operation* starts, and the instrument will begin measurements to gather data.

Automatic operation requires no user intervention at all. By pressing the *STOP* key during measurements, the user may interrupt and stop the measurements, and access the *manual mode* functions.

In *automatic mode,* no keypad input is necessary at all.

Manual operation menus offer various utilities to change system settings and to test and calibrate hardware: the menus are shown and explained below.

14.3 USE OF THE KEYPAD

- To scroll through the menus, use the UP and DOWN arrow keys. Some menus (e.g. *Time & Date*) also use the LEFT and RIGHT arrow keys.

- To enter a selected menu, or to confirm a setting, press the ENTER key.

- To escape from a selected menu, press the ESC key.

- When entering parameter values in *Change Settings* sub-menus, allowable selections are shown by scrolling with the UP and DOWN arrow keys; entries are confirmed by pressing the ENTER key, or canceled by the ESC key.

- When the instrument is running, use the STOP key to return to the *Main System Menu*.

Response Time-Out: In most menus where user input is required, an automatic time-out feature allows the instrument to recover and resume operation if the operator is called away or fails to respond for whatever reason. After 30 seconds, the beeper sounds: if the user does not respond within 10 minutes, the instrument reboots and runs in *automatic operation mode*.

14.4 MENU TREE

The following chart shows the complete tree of Aethalometer software commands: they are described in detail in the subsequent sections of this chapter.

1.   Operate

1.1   Go to Automatic Mode? [YES] → 1.3

1.2   [NO]

1.2.1   Flow stabilization period (30 sec.)

1.2.2   Titles

1.2.2.1 Retain old titles

1.2.2.2 Read new titles
              → insert diskette with new titles

1.2.3   Verify timebase : OK / Change

1.2.4   Display flowrate for verification

1.2.5   Check diskette data capacity

1.2.5.1 Continue (= use existing disk)

1.2.5.2 New disk entered

1.2.5.3 Delete oldest files (use if insufficient space on disk)

1.3   Advance Tape, start measurement sequence

2.   Change Settings

2.1   Time & Date

2.1.1. Use Left/Right arrow keys to move blinking cursor

2.1.2. Use Up/Down arrow keys to change selected value

2.2   Set Flowrate

2.3   Timebase

2.3.1. Use Up/Down arrow keys to change value

2.4   Tape Saver

   2.4.1   Off

   2.4.2   X3

   2.4.3   X10

2.5   Analog Output Port

   2.5.1   Signal Output

          2.5.1.1 Enter scaling factor

   2.5.2. Alarm

          2.5.2.1 Alarm On/Off

          2.5.2.2 Alarm setpoint

2.6   Warm Up Wait

2.7   Communications Parameters

   2.7.1   Communication mode

          2.7.1.1 Dataline

          2.7.1.2 Gesytec

          2.7.1.3 GPS

          2.7.1.4 Off

   2.7.2   Baud rate

   2.7.3   Data bits

   2.7.4   Stop bits

   2.7.5   Parity

2.8   Overwrite Old Data

2.9   Filter Change Period (note! Set to ZERO for automatic tape advance)

2.10   Security Code

2.11   Date Format

   2.11.1 US (MMDDYY)

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3. Signals + Flow

 3.1 Use Up/Down arrow keys to control lamps

 3.2 Use Left/Right arrow keys to control flow bypass valve

4. Self test

 4.1 Lamp test (1, 2 or 7 lamps)

 4.2 Pump and Bypass Valve test

 4.3 Analog Output Port test: allows for testing external analog dataloggers

 4.4 COM Porrt test: allows for testing external digital dataloggers

 4.5 Display Screen test

 4.6 Tape Advance test

5. Calibrate Flowmeter

 5.1 Air volume units

  5.1.1 Standard

  5.1.2 Volumetric

   5.1.2.1 Barometric Pressure (millibars)

   5.1.2.2 Ambient Air Temperature (ºC)

 5.2 Flowmeter Calibration? [NO] → return

 5.3 [YES]

  5.3.1 Measure zero offset (wait for pump to stop – 2 minutes)

  5.3.2 Measure active flow (use external flow calibrator, enter factor)

6. Software Upload

7. Optical Test

    7.1   Insert floppy disk

    7.2   Remove filter tape

    7.3   Insert Optical Test Strip

8. Install New Tape

    8.1   List Instructions?

        8.1.1   [YES] $\rightarrow$ list of tape installation instructions

14.5   MAIN SYSTEM MENU UPON POWER-UP

14.5.1 Main Menu Overview

The opening screen displays an opening "Aethalometer" logo; the software version number; a countdown from 60 seconds for the *automatic start*; and the prompt to "Press Any Key for Main Menu"

If any key was pressed during the 60-second *Countdown*, the ***Main System Menu*** starts at the top of the list (i.e. *Operate*). The *Main Menu* offers the following selections:

1.   **Operate**

2.   **Change Settings**

3.   **Signals + Flow**

4.   **Self Test**

5.   **Calibrate Flowmeter**

6.   **Software Upgrade**

7.   **Optical Test**

8.   **Install New Tape**

Each of these menu items is discussed below.

14.5.2 <mark>Operate</mark>

<mark>This option of the *Main Menu* allows for automatic operation or for manual input while preparing the instrument to run. The first screen display asks "*Go To Auto Mode?*". The default response *Y* is displayed. If ENTER is pressed, the instrument immediately proceeds with fully-automatic operation, and no further operator interaction is required.</mark>

If *N* is selected with the down-arrow key, and then ENTER is pressed, the program provides the following interactions:

- The program asks the user if new titles should be read from the floppy disk (e.g. for a new experiment name). These titles will appear in the 'MF' message files. To enter new titles, use any plain-ascii text editor to write two separate lines title1 and title2 in a text file TITLES.TXT, and insert into the floppy disk drive at the prompt. These titles will be saved for future runs of the same experiment.

- The program prompts the user whether the data disk should be replaced, even if it is not full yet. Note that the option Overwrite Old Data, if set to "YES" in the Change Settings menu, will simply overwrite the oldest data when the disk becomes full (see also Overwrite Old Data menu).

- The screen will show a Flowrate display. This allows the operator to verify the air flow rate desired for the experiment or sequence of measurements.

Aside from these user inputs, operation is identical as for *automatic mode* described below. The *manual input mode* features simply allow the user to check parameters before running the instrument.

Firstly, the air flow rate is checked after a 30-second countdown that allows the flowmeter to stabilize. If (for example) the instrument was configured for 'External Pump', yet this was not connected or working, an error message would be given "WARNING .. FLOW < 1 LPM".

- Titles confirmation, "Title 1" ; "Title 2" .. "Retain Old Titles" / "Read New Titles". This allows new titles to be uploaded to designate new experiment, location, etc.

- Flowrate Display   This provides an opportunity for the flowrate to be adjusted by the user to suit the needs of the measurements. After the flowrate is accepted, press any key.

- Disk Data Space checking   This checks the free space remaining on the diskette and provides an opportunity to insert a fresh disk. "Continue" / "New disk entered" / "Delete oldest files"

After this question, no further user input is necessary.

Measurements will start automatically after the following two screen displays:

- "Advancing tape, wait"

- "Waiting for start time".

The screen displays a countdown to the start of the next integral timebase period.

14.5.3 Change Settings

This menu allows the system settings to be changed according to the user's needs. The following parameters may be altered:

- Time & Date

This menu allows the user to change the current time and date. If the *date* is changed, the *time* must be re-set also. Using the left- and right-arrow keys, position the cursor over the item to be changed. Using the up- and down-arrow keys, change the value. Note that the new time value is not written until the change menu is completely exited and saved. For this reason, it is advisable to set the time to the *next* minute with zero seconds, exit the change menu to the point of "Write System Settings?", and press ENTER at exactly the actual minute roll-over.

- Flow Rate: Usable range 1 – 6 LPM.

This allows the user to set the sample air flow rate in Liters Per Minute (LPM). The computer and electronics automatically control the variable-speed pump to maintain the desired flow rate based on the signal from the air mass flow meter.

- Timebase: Valid values: 1 sec - 60 min. (AE-2 models, 1 min - 60 min; AE-3 models, 2 min – 60 min; AE-4 'Portable' models, depending on optics).

This defines the time period over which the aerosol is collected and analyzed. At the end of each timebase, the data is written to disk and the display is updated. We <u>strongly</u> recommend using timebases <u>no longer than</u> 5 minutes in urban ares, or 15 minutes at very remote locations.

- Tape Saver: Selections: 'OFF', 'X3', 'X10' (not available on "Portable" models)

This parameter controls the flow bypass valve to prolong the lifetime of each filter tape spot, and thus to reduce the consumption of tape in locations of high BC concentration. Bypassing is disabled if this parameter is set to 'OFF'. If Tape Saver is set to X3 or X10, the instrument periodically switches the air flow to bypass the filter tape spot for a certain fraction of the time, although still passing through the flow meter. The fraction of active-collection time is automatically scaled by the program according to the BC concentration. The X3 setting varies the aerosol collection time from 50% at low BC concentrations (tape saving factor of 2) to 30% at high BC concentrations (tape saving factor of 3). The X10 setting varies the aerosol collection time from 50% at low BC concentrations (tape

saving factor of 2) to 10% at high BC concentrations (tape saving factor of 10).   All other functions of the instrument are identical, and the operation of this feature is not perceived by the user.

- Analog Output Port: Selections: SIGNAL OUTPUT / ALARM.

This function allows the analog voltage output connector either to provide a data output, for connection to an analog datalogger or chart recorder, or to operate as an alarm switch.

- If SIGNAL OUTPUT is selected:

Output Scale Factor: Valid values:

1 - 100,000 (ng BC /m3) / V, when the BC Display Unit is set to **ng/m3**;
1 - 1000 (μg BC /m3) / V, when the BC Display Unit is set to **ug/m3**.

This parameter defines the scaling factor of the analog voltage on the output connector that represents the measured black carbon concentration in "Signal Output" mode. This output voltage is swung to the value of -5 V to indicate "No Valid Data" during periods of instrument warm-up, operator intervention and menu selection, and also during the tape advance process. The analog output voltage is scaled with its factor from 0 to +5 V to represent data when it is valid. Note that when BC concentrations are extremely low, instrumental noise can lead to computed values of BC that are slightly negative (see text in main manual). These noise values will be presented as slightly negative analog output voltages, but still represent valid data.

- If ALARM is selected:

Alarm On/Off allows the alarm function to be enabled or disabled

Alarm Setpoint allows for entering the *Alarm Value Limit*. Valid values are 0.01 - 100,000 μg/m3.

If the measured BC concentration is lower that the Alarm Value Limit, the voltage output on the connector is zero. If the BC concentration exceeds the limit, the voltage output is +5 VDC. This allows triggering of a solid-state relay or other logic-level device to indicate the overlimit condition. If "ON" is selected, the screen will request an input value (in micrograms per cubic meter) of the Alarm Value.

- Analog Out Channel:

This is used only on multiple-wavelength models (AE2- and AE3-), and selects which wavelength's data will be used to control the output of the analog port.

- Warm Up Wait: Selections: YES / NO

If this parameter is set to "YES", the instrument displays optical sensing and flow voltages for 30 minutes at the start or restart of the program, before proceeding with automatic operation. The lamp and flow bypass valve may be tested by pressing the Up/Down arrow keys to turn the lamp on and off, or the Left/Right arrow keys to turn the flow bypass valve on and off. Press the ESC key to enter manual-mode operation. Use of this option allows the instrument to be thoroughly warmed up before data is gathered and recorded. This is recommended for routine aerosol monitoring programs with stringent QA/QC requirements. Note, however, that if the electrical power is interrupted even momentarily, 30 minutes of data loss will be introduced at every power-up automatic restart.

- Communication Parameters: COM mode, COM settings.

This menu controls the activity of RS-232 port on the rear panel of the instrument.

- The COM Mode sub-menu selects the type of data transmission: 'DATALINE', 'GESYTEC', 'GPS' or 'OFF'.

In 'DATALINE' mode the instrument transmits a replica of the data line that is written to floppy disk, once every timebase period.

'GESYTEC' mode is used primarily by the German National Network protocol, and allows for interrogation of the instrument to trigger a data stream.

Note: 'Portable' (AE4- series) instruments allow for GPS position data to be *input* by RS232 connection to the COM port. These instruments have an additional 'Comm. Mode' setting of 'GPS' that is not available on 'Rack-mount' (AE1-, AE2- and AE3- series) instruments.

'OFF' disables the COM port activity.

- The COM Settings sub-menu sets the communications parameters:

BAUD (9600, 4800, 2400, 1200);
DATA bits (8 or 7);
STOP bits (1 or 2);
PARITY (None, Even, Odd).

Default settings are 9600, 8, 1, N.

Note! If DATA BITS is set to **8** then PARITY **must** be set to **None**

- Overwrite Old Data:

Selections: YES / NO.

If this parameter is set to "YES", then the instrument automatically overwrites the oldest files on the data disk when the disk becomes almost full. It deletes both BC files and MF files. The number of files deleted depends on their size: the program removes old files until there is enough data disk space free for the BC and MF files that will be produced in the following 24 hours.

- Filter Change At: Valid values: 0-30 hours.

(**Important!** - set value to **0** to allow *automatic filter tape advancing*).

This parameter affects the triggering of filter tape advances at fixed time intervals, if the 'Filter Change At' value is greater than zero. If the Filter Change At value **is set equal to zero**, then the tape is automatically advanced when optical saturation of the filter spot is reached. If the Filter Change At value is **greater than zero**, then the tape is advanced **only** when the determined time period expires. **NOTE! – optical saturation of the filter spot may occur!** – leading to error-based automatic restarts. This feature was designed to allow for forced filter spot changing to coincide with 4-, 6-, 8- or 12-hour sampling periods of other analyses. Non-zero time values are combined with the Timebase parameter so that the first measurement on a new filter spot is exactly an integral number of hours after the previous filter spot's first measurement. Note that due to the time taken by the tape advance process, using low values of the 'Filter Change' parameter may result in loss of time coverage of data. If fixed times of filter spot durations are **not** required, and automatic tape advancing **is** required, then we **strongly** recommend that this feature should **not** be used, and the parameter should be set to **zero**.

- Security code:

  Important - remember this code! It is the password for access to the following protected functions:

  - Exit from Operate to the Main System Menu after pressing the STOP key.

  - Upload a software upgrade.

  - Change certain 'protected' setup parameters.

  In all cases the user must enter the correct security code within 10 seconds. If this time-out expires, the program reverts to the previous menu item.

When changing the security code the user must first enter the old security code, next enter the new security code, and then repeat for verification. There is also a special 'master' security code known to authorized maintenance support in case the user forgets the instrument's individual security code.

The security code is initially set to 111 when the instrument is shipped from the factory.

- Date Format: Selections: U.S. / Euro

This parameter controls the conversion of the date to a 6-digit number for the purposes of constructing file names for the 'BC' and 'MF' files written to disk. The date is written in 'Microsoft' format e.g. "12-jan-97" in lower case.

In 'U.S.' mode, the filename date is constructed as MMDDYY.
In 'Euro' mode the filename date is constructed as DDMMYY.

- BC Display Unit: Selections: Nanograms / Micrograms

This selects the concentration unit for the screen display. 'Nanograms' displays no decimal fractions (i.e. XXXX ng/m3) and is recommended for use in remote or unpolluted locations; 'Micrograms' displays 2 decimal fractions (i.e. XX.XX ug/m3) and is recommended for use in urban or polluted locations.

- Data Format: Selections: Expanded / Compressed

This option controls the format in which data is written to disk and sent to the COM port. In 'Expanded' format, the data record consists of numeric fields, each separated by commas. The file 'DATACOLS.CSV' is written to the floppy disk to identify the data columns for the various instrument options. Many of the columns represent internal signal parameters that are only required for performance verification: the measurement data of value to the user are represented by 'Date', 'Time' and Concentration'.

In 'Compressed' format, the data record consists of a reduced number of columns. The first entries are 'Date', 'Time' and 'Concentration', while the following column(s) are string(s) of alpha characters whose coding represents all the internal signals. For routine operation, this codeword may be discarded: it will appear as the final column(s) if the data is imported to a spreadsheet in '.CSV' format. If required, the codeword may be decompressed for instrument diagnosis using the 'COMDECOM' program available from Magee Scientific.

- UV Channel ON/OFF:

Selections: ON / OFF   (no longer used)

- Hardware Configuration

This allows the user to correctly specify the various hardware options, so that the software will function correctly. The sub-menu items are as follows:

- Instrument Type (Optics)

Selections are:

'AE1x – Standard' (e.g. AE16 single wavelength, BC only) ;

'AE2x - UV+LED' (e.g. AE21 combination BC + UV absorption) ;

'AE3x - 7 x LED' (e.g. AE31 multiple-wavelength "spectral" measurement).

Note: - use the appropriate optics selection for a 'Portable' AE-4 instrument.

- Instrument Type (Chassis Type)

Selections are 'Stationary' (i.e. rackmount chassis) and 'Portable'.

- Spot Size

Choices are 'Extended Range' ("larger" 1.67 cm² spot) and 'Standard Range' ("smaller" 0.5 cm² spot for higher sensitivity)

- Instrument Serial Number

The first three digits of the instrument's serial number must be entered before a software upgrade can be performed. This is a precaution that ensures that the software will operate correctly with the electronics hardware, which is routinely improved and enhanced at the circuit board level. This parameter identifies the hardware to the software, and is set at the factory to the correct value. Verify that it is indeed equal to the serial number printed on the instrument. If this is correct, **do not change it** unless specifically advised.

- PCMCIA Enablement

Select this option if the instrument is equipped with a PCMCIA 'Memory Card' in place of the standard 3½" floppy diskette drive.

- Gesytec ID

This parameter is only used by the German Network Protocol. The instrument responds to a data acquisition interrogation only if the Instrument ID that was sent as a request from the host computer matches the Instrument ID written in the setup file. The Gesytec protocol is very rarely used for the current series of Aethalometers.

- Sigma for Lamps

This permits changes to the proportionality constant 'sigma' that is used to convert optical attenuation to a mass of absorbing material. This may be used to 'tailor' the optical response, or to switch between 'Magee BC' and 'Harvard EC' calibrations.

- Spots Per Advance: Selections: 1 / 2

This allows the user to control the spacing of the spots collected on the filter tape. If '1' is selected, the spots will be close together and essentially touching. This minimizes the use to filter tape. It is possible that the spots may actually overlap by a very small amount: this does **not** affect the accuracy of the measurement, due to the nature of the algorithm. However, there may be situations in which the spots are to be collected afterwards for analysis or archiving. If touching of spots would be unacceptable for these requirements, select the value of '2' for this parameter. In this case, the tape advance mechanism will perform two complete cycles each time a tape spot advance is called for.

- Maximum Attenuation:

This allows the user to specify the maximum value of optical attenuation that defines the point at which an automatic tape advance is triggered. For conservative use, set this parameter to a value of **75**. However, if the instrument is operated in an urban area of high aerosol concentrations, it may be desirable to minimize the frequency of tape advances. In this case, set the value of *Maximum Attenuation* to **125** or **150** (highest value allowed).

- Return to Main

This concludes the *Change Settings* menu, and asks if the user wishes to save the changes by writing the parameters to an internal file.

14.5.4 Signals & Flow Display

This selection allows the user to check the optical signals and the flowmeter response. It is useful for checking the optics or verifying a desired flowrate.

The **lamp(s)** may be turned ON and OFF by toggling the UP/DOWN arrow keys. The lamp condition is shown on the right-hand side of the top line of the display screen as follows. AE2- and AE3- series instruments allow for testing of the additional lamps:

"Lamp=0" : lamp(s) OFF

"Lamp=1" : 880-nm lamp turned ON : "wavelength 1" BC measurement

"Lamp=2" : 370-nm UV lamp turned ON : "wavelength 2" UV measurement in AE-2 series instruments

"Lamp=3" to "Lamp=7" : other wavelength lamps turned ON for testing AE-3 series instruments.

The **bypass valve** may be turned ON and OFF by toggling the LEFT/RIGHT arrow keys. The air flow path is shown on the right-hand side of the second line of the display screen as "Filter" or "Bypass".

Press ESC to exit this selection and return to the *Main Menu*.

14.5.5 Self Test

This selection activates a sequence of tests of the instrument hardware. The series of tests are performed automatically: any error messages are shown on the screen.

- Lamp test: The lamp(s) are turned on and off, and measurements are made of the optical signals in the sensing and reference detectors. For multiple-source instruments, this procedure is repeated. Comparison of the signals allows for the following fault analyses:

- LAMP is burned out (OFF all the time)

- LAMP is ON all the time (electronics fault)

- TAPE torn or ended (signals too large)

- LAMP TEST PASSED.

- Pump & bypass test: This test measures the air flow: the user is prompted to connect the pump (in case the instrument is configured for 'External Pump'). The air flow is calculated using the flowmeter zero voltage and the flow scale factor that were set by the Calibrate Flowmeter routine. If the flow rate is smaller than 1 LPM, an error message is displayed. The flow rate is compared for both positions of the bypass valve, to make sure that it is not blocked in either position.

- Analog output test: The analog output connector on the rear panel is presented with a sequence of voltages to allow an external data logger or alarm relay to be tested. The sequence is: V = 0 ; +1 VDC; +2 VDC; +5 VDC

- COM port test: This routine allows the user to test the transmission of RS232 code from the COM port on the rear of the instrument, in order (for example) to test communications with a data logger or other receiver. This routine first allows the user to change COM parameters (baud rate, etc.) if desired. The screen then prompts "ENTER to send data". Press ENTER to transmit one data line using the COM parameters. This may be repeated as often as desired. Press ESC to escape.

- Screen test: This routine tests the display screen as follows:

- All LED's are turned ON.

- All LED's are FLASHED.

- All LED's are turned OFF.

- The screen is filled with characters.

- The screen backlight is turned OFF.

- The screen backlight is turned ON.

- <u>Tape advance test</u>: The tape feeder is activated: the user is prompted to watch the mechanism to verify correct operation. A countdown timer indicates the approximate duration of the test.

14.5.6 Calibrate Flowmeter

The program first allows the user to switch between 'Standard' and 'Volumetric' flow units. (If 'Volumetric' flow units are selected, it is necessary to input the barometric pressure and ambient air temperature). This function is <u>not</u> password protected. The program next allows the user to re-calibrate the flowmeter: this function *is* protected.

- <u>Flow Volume Units</u>:

The program allows the flow to be expressed in terms of either Standard Units or Volumetric Units.

Standard Units report the air flow rate as SLPM, i.e. volume occupied by a given mass of air at a temperature of 20°C and a pressure of 1013 mb. This mass flow rate is the signal that is provided by the mass flow meter in the instrument. The Aethalometer data is reported as ng/m³ or µg/m³, where the "m³" is understood to be a *standard* cubic meter.

Volumetric Units convert the *mass* of air to a *volume* calculated at certain specified ambient conditions of *temperature* and *pressure*. These conditions must be entered by the user – they are <u>not</u> measured by the instrument. The mass flow rate signal provided by the mass flow meter is scaled by proportionality factors for *temperature* (input in degrees C) and *pressure* (input in millibars). When *volumetric* units are selected for the flow, the flow rate display on the screen is shown as vLPM, and the BC calculation is presented as ng/vm³ or µg/vm³.

The *volumetric* calculation requires user input of ambient *temperature* and *pressure*. These factors may be entered <u>without</u> going through the flowmeter re-calibration procedure. This allows for entering different mean ambient temperatures, or different pressures if the instrument is moved to a location of different elevation, <u>without</u> disturbing the fundamental calibration of the mass flow meter response.

<u>Note</u>: the 'Portable' series of instruments use a different type of flow sensor whose output is not a representation of air <u>mass</u> flow, but is intrinsically dependent on ambient pressure. For precise operation at reduced ambient pressure, the 'Portable' instrument should be re-calibrated under ambient conditions.

- Flowmeter Re-Calibration

This is a 'protected' function and requires the Security Code as a password.

This procedure calibrates the flowmeter response by measuring the *flowmeter zero voltage* and determining the *flow scale factor*. These two factors are used during measurements to calculate the actual *air flow* through the flowmeter.

- You will need a standard external flowmeter or calibrator capable of reading air flow rates in the range of 2 to 10 slpm, with a low resistance to flow. Connect this calibrator firmly to the Sample Inlet Port with no possibility of an air leak (see sections 5.8, 7.2).

- **Only perform this re-calibration if you have serious reason to believe that the flowmeter response is incorrect**.

- Allow the instrument to warm up for at least 30 minutes with power and air flow 'on', before performing the re-calibration.

The internal pump is controlled by the computer and electronics, and this allows the program to set 'zero' and 'span' flows. All that is required of the operator is to connect a standard external flow calibrator, and observe its reading.

The routine first automatically reduces the pump speed slowly to zero, while measuring the signal from the internal flowmeter. When this has reached a steady low value as determined by no more change in voltage output, the value of the reading is used as the *flowmeter zero voltage*. The pump is then re-started and run up to its previous speed. When the flowmeter signal is steady, the screen displays the flowrate in liters per minute derived from the new *zero* and the previous *scale factor*. The user must then compare the displayed value of flow with the actual value as measured by the external standard. Pressing the keypad UP- and DOWN-arrow keys will change the *flow scale* factor. Press these keys until the displayed value agrees with the measurement from the external calibrator. Press ENTER when the displayed value is correct.

Upon return to the *main system menu* the user is asked to confirm writing the newly measured response factors to the setup file. The previous flow calibration values are <u>not</u> replaced until this confirmation is made. In case of any doubt, repeat the procedure.

14.5.7 Software Upload

This is a 'protected' function and requires the Security Code as a password.

The *Software Upgrade* selection provides a convenient means to load new software from floppy disk. This software may be derived from a disk physically provided by the factory or Magee Scientific, or from files sent either by e-mail or downloaded from the Magee Scientific website, and copied onto a diskette.

First, check the file names by inserting the diskette into another computer and viewing the files on its 'A:\' drive. If there are numerous files and a sub-directory named 'A', then the files are ready for upload. If there is only a single compressed file 'AExxxZIP.EXE', then this must first be de-compressed to recover the individual files. This is done by double-clicking on 'AExxxZIP.EXE' to launch the self-extraction process. When completed, the individual files will also be found on the 'A:\' directory.

Insert this disk into the Aethalometer, and proceed through the Main Menu selections to reach this item.

The user must type in the *security code* as a password, and also the first three digits of the instrument's *serial number*. If correct, the upgrade procedure is run. Before the upgrade is performed, internal parameter files are saved to the upgrade disk. The internal memory is erased, and files are re-loaded from the floppy disk. ***Remember to remove the upgrade disk from the floppy drive at the conclusion of the upload!***

The upload process allows the user to preserve the previous setup parameters, i.e. all operating variables such as timebase, analog output scaling, etc., as well as all hardware specification parameters such as flowmeter calibration, spot size, etc. We ***strongly*** recommend choosing to preserve parameters unless the instrument must be re-configured from a completely 'blank' start.

NOTE: Use only the upgrade disk provided from the factory, an exact replica, or a diskette created exactly according to instructions from the website. Do not use this disk for any other purpose: do not add files to it, nor delete anything. Do not change the setting of its 'write-protect' lock tab: the upgrade disk must not be write-protected, because some files are temporarily written to the disk.

14.5.8 Optical Test Procedure

This is a 'protected' function and requires the Security Code as a password.

This procedure performs a routine QC/QA check on the correct operation of the photodetectors, whose signals are the fundamental basis of the measurement. It uses the *Optical Test Strip* provided with the instrument. **Do Not Lose This Strip! Keep the Test Strip Clean, Flat and Smooth !** Contact Magee Scientific if a replacement is required, but be informed that the test is only relevant when repeatedly performed with the same *Test Strip*.

The *Optical Test Strip* consists of laminated material whose optical density at one end is greater than that at the other. The test procedure automatically determines the optical densities measured by the photodetectors, and writes the results to disk as a human-readable ASCII text file. The significance of the test is to be sure that the readings remain constant over time, i.e. from one test to the next. The actual numerical values of the calculated parameters are intrinsically meaningless: it is their constancy when measuring the same *test strip* that assures consistent performance of the instrument. The Optical Test Procedure guides the user through the various actions that are necessary, with prompts on the display screen.

- The Optical Test Strip has a serial number printed at one end that should match the serial number of the instrument. Enter this number when prompted. Check that there is a floppy disk in the disk drive.

- Open the door, and remove the two thumb screws that secure the rectangular metal cover over the sampling chamber in the center of the instrument. This provides access to the area where the filter tape passes through the analysis system.

- Cut the filter tape on the left side of the chamber with scissors. Press ENTER when prompted. The remaining tape will be pulled out onto the right-hand spool.

- When prompted, insert the test strip from the left-hand side. Its printed serial number should be facing upwards on the right-hand side. Push it in from the left until the tip of the arrow printed on it is just visible in alignment with the edge of the base block. Press ENTER when ready.

- The first phase of the test will proceed automatically: the lamp will turn ON and OFF to determine the optical transmission signals for the 'front' portion of the test strip.

- At the end of the first set of measurements, the transmission values will be displayed. It is not necessary to write them down, as they are saved to disk. Press ENTER to proceed. The mechanism will go through three tape-advance cycles in order to pull the test strip forward, taking approximately 5 minutes. Please be patient.

- The second phase of the test will cycle the lamps again and measure the optical transmission signals for the 'rear' portion of the test strip. The program will then calculate the quantities 'S Density', 'R Density', and 'Balance'. The signals, results and other information will be written to a file on the disk under file name 'OTxxxxxx.TXT' where 'OT' represents Optical Test, and 'xxxxxx' is the date coded in either 'US' or 'EURO' format, i.e. MMDDYY or DDMMYY. This text file provides the definitive report on the optical transmission signals and the balance between the Sensing and Reference signals. This text file should be printed out and saved in the laboratory records book.

- The display screen will then prompt the user to re-insert the filter tape from the left-hand side. After pulling it through, re-attach it to the tape on the right-hand take-up spool. Replace the rectangular metal cover with its two thumb screws.

14.5.9   Install New Roll of Tape

This is a 'protected' function and requires the Security Code as a password. See Chapter 12 for full details.

The Aethalometer™ determines the concentration of aerosol Black Carbon in the sampled air stream by measuring the rate of increase of optical attenuation due to the increasing deposit of particles collected on a spot on the filter tape. For most purposes, the spot itself has **no** individual identity and the progression of spots on the tape is simply the means to perform the measurement.   When the optical density reaches a pre-set value, the instrument advances the tape in order to provide a fresh collection surface. The filter tape merely provides the medium on which the aerosol is deposited, and is usually discarded when used.

Each 15-meter roll of tape provides approximately 1500 spots. Each spot lasts from hours in cities to as long as several months at remote locations, and so changing the tape roll is only required occasionally. The display screen shows an estimate of the percentage of the tape roll that remains: when this falls below 10%, the 'Check' lamp on the display panel will be lit.

The menu item '*Install New Tape*' contains an option to display an abbreviated set of sequential instructions with prompts. This not only guides the user through the necessary steps, but also re-sets the tape percentage counter to 100%.

For this reason, the software procedure *must* be used when installing a fresh roll of tape, even if the user is very familiar with the procedure.

The first screen asks '**List Instructions ?**'. If **NO** is selected, the instrument assumes that the operator is familiar with the tape installation procedure, and will not require guidance. The software skips the detailed instructions, re-sets the tape counter to 100%, and returns to the *Main Menu*.

If **YES** is selected, the display screen guides the user through all the operations required for changing the tape. After each phrase, the user must press any key to proceed to the next:

(a)   Remove spool screws

(b)   Remove cover screws

(c)   Pull out guide rod

(d)   Cut old tape

(e)   Remove supply roll

(f)   Remove takeup roll

(g)   Install new roll

(h)   Lift up chamber 2 mm

(i)   Push tape through

(j)   Lift up chamber 2 mm

(k)   Pull 10 cm tape

(l)   Install takeup hub

(m)   Clip tape to hub

(n)   Push in guide rod

(o)   Replace cover

(p)   Replace spools

(q)   Tighten spool screws

The screen then asks: 'Is the tape properly replaced?' Entering **YES** will re-set the tape counter to 100% and conclude the process.

14.6   'OPERATE' PROCEDURE

This procedure automatically performs all measurements, calculates the aerosol Black Carbon concentration, and passes the information to the screen display, the analog voltage output connector and the BC and MF disk files. The procedure has a number of steps:

- **Starting initialization:** In *manual operation mode* the user is asked to confirm the displayed parameters or data disk replacement: in *automatic operation mode* this is not required. The filter tape is advanced, and a report is started in the MF file.

- **Measuring Flowrate:** This display shows a continuous readout of the flow meter response. After the flow rate is verified, press any key to proceed. Note that if '*Volumetric'* flow units had been selected in the "Flowmeter Calibrate" routine, the flow display will show 'vLPM' as the units. If '*Standard'* units are selected, the display will show 'LPM'.

- **Overwrite Old Data:** The display will prompt for a decision of what to do if the data disk becomes full.

- **Initializing measurements**: Optical measurements are made with the light sources ON and OFF.

- **'Reference' flow measurement**: The system first measures the air flow and denotes this initial value to be the 'Reference' flow value. If the value is lower than 1 LPM, an error message is displayed and measurements are stopped. During data-taking operation the measured air flow is always compared to this initial 'reference' air flow. If the difference is greater than 10%, a warning message is generated and the LED's start to blink: it is presumed that the pump is failing, or a leak has developed. However, this warning does **not** cause the instrument to stop making valid measurements. If the actual air flow drops below 1 LPM, data-taking is stopped and an error message is displayed.

- **Data file names** are constructed from the current system date: two files are written to disk. The file BCxxxxxx.CSV contains the aerosol black carbon concentration results and accompanying instrument signals, written in 'comma-separated data' format for direct import into a spreadsheet. The message log file MFxxxxxx.TXT reports the instrument's operation in plain text (start and end of measurements, tape advance time, error warnings, etc.). The file names are coded with the date, according to either *'U.S.'* or *'Euro'* formats i.e. "BC*MMDDYY*.CSV" (U.S. format) or "BC*DDMMYY*.CSV" (Euro format), where *MM* stands for month number, *DD* for day of the month and *YY* for the last two digits of the year, with leading zeros inserted if needed.

- The initial tests detect any instrument malfunctions. If serious errors are found, the instrument stops and an error message is generated. If not, the program waits to the end of the rounded clock time according to the *timebase* parameter, and then begins.

14.7   BC ANALYSIS CYCLE

The aerosol sample is collected continuously on the filter spot. The *analytical procedure* is subdivided into 'inner' and 'outer' cycles depending on the *timebase* setting. Note that almost all Aethalometers are operated at timebases of 5 minutes or less: i.e. the analytical procedure is almost always based on 'short' timebases.

For <u>short</u> timebases, i.e. T ≤ 5 minutes, the instrument performs only the 'inner' cycle in which the optical signals are acquired. Each cycle generates a single analysis of the amount of BC collected during that time interval.

For <u>longer</u> timebases, i.e. T > 5 minutes, the values allowed for the *timebase* setting are restricted to multiples of 5 minutes. The instrument performs the 'inner' optical analytical cycle every 5 minutes, and gathers the average of those 5-minute measurements over the desired length of the 'outer' cycle. This averaging further reduces the effective noise, and also eliminates the missing data entries that occur when short timebases are selected, during the few minutes taken up by the tape advance process.

'Inner' optical analytical loop: The time cycle of this loop is defined by the *timebase* parameter. For T ≤ 5 minutes, the inner loop time is equal to the *timebase* time value. For longer timebases, the inner loop is fixed at 5 minutes, and a number of these data are averaged for the outer loop result. The inner optical analytical measuring loop is divided into three parts:

- At first, the lamp is off and no measurements are made. The air flow may pass through the filter for aerosol collection on the spot, or it may bypass the filter, depending on the Tape Saver function. If this function is enabled, the program adjusts the fraction of bypass time to prolong the tape spot lifetime.

- Next, optical measurements are made with the light source turned on, off, and on again, to determine the detector 'zero' and 'optical beam transmission' signals in both the 'sensing' and 'reference' detectors. The air flow always passes through the filter spot in this part of the measurement process.

- Next, the algorithm calculates the BC concentration. For short timebases, this result constitutes the measurement output. For long timebases, this result is gathered into an average for the outer loop. When the timebase end is reached, the program updates the D/A converter producing a voltage at the analog output connector, transmits a digital data stream to the COM port if set, updates the screen display to show the BC concentration and other parameters, and writes the data to disk.

- Finally, the program checks if the attenuation (optical density of the collected spot) has reached the saturation maximum. If so, the automatic tape advance procedure is invoked. Tape advances are also performed independent of

aerosol spot density if the Filter Change At parameter is non-zero and the hour counter has elapsed.

- After a tape advance, the program resumes execution at the Initialize point.

14.8   PRECISE TIMING

The computer algorithm performs the optical measurement sequence once every timebase period, or at least once every 5 minutes, as described above. The concentration of BC that is calculated and displayed, represents the average over the time interval between this measurement point and the previous. The result is recorded just before the 'zero seconds' rollover of the timebase minute and is flagged as if originating from [Minute Previous, Zero Seconds] to [Minute Present, Zero Seconds]. However, the *actual* optical measurements are made some seconds *prior* to the rollover of the minute, to allow time for calculation, recording to diskette, updating the screen display etc. In cases of very rapid fluctuations of concentration, or precise time synchronization with other instruments, this offset may be noticeable.

The time offset amount depends on the number of wavelengths in use and the timebase setting. At longer timebases, repeated analog/digital converstions and data acquisitions are performed, to improve accuracy and reduce electronic noise. Generally, for single-wavelength instruments, the time offset is about 20 seconds at a 5-minute or longer timebase, reducing at shorter timebases. For dual-wavelength instruments, the offset on a 5-minute timebase is approximately 90 seconds for the UV data and 60 seconds for the BC data. For 7-wavelength instruments, the offset ranges from approximately 120 seconds for the shortest wavelength to 60 seconds for the longest.

Note that although the time offsets may differ for differing wavelength data, the **interval** between successive measurements is always precisely equal to the timebase period. This value multiplies the measured flowrate to calculate the volume of air from which the particles have been collected, and will be identical for all wavelengths in use.

14.9   DATA FILE FORMAT

The full data set is written to the disk file "BCxxxxxx.CSV" : two formats are offered. Both are written in a single line as 'Comma-Separated Variable' data, to allow for immediate import into a spreadsheet:

14.9.1 Format Types

- **Expanded Data Format**: *"date", "time", BC concentration (ng/m3), sensing zero signal, sensing beam signal, reference zero signal, reference beam signal, air flow (LPM), bypass fraction, optical attenuation.*

A typical line in the data file might look like:

"01-may-99", "09:40", 866, .0213, 2.1956, .0241, 3.1455, 4.2, 1.00, 1.974

Note that the recorded time corresponds to the starting time of the measurement cycle.

Only the date, time and black carbon concentration are used in normal circumstances: namely the **first three columns** of data as shown **bold** in the above example. The other columns of data only verify correct operation of the instrument. For this reason, the data may also be written in a *'compressed' mode* which preserves the diagnostics but in a more compact form:

- **Compressed Data Format**:   *"date", "time", BC concentration (ng/m3), "codeword"*

In 'compressed' format, the same line in the data file might look like:

"01-may-99", "09:40", 866, "fpXeoenmRBqlaYdh"

The *codeword* is a 16-element string of upper- and lower-case alpha characters whose ASCII codes represent the numerical data exactly. No diagnostic data is lost in the compression process: it is simply compacted into a coded format. The data line may be decoded using the utility program COMDECOM available from Magee Scientific. This decoding program produces a new file in the full 'Expanded' data format. However, in many situations the internal diagnostic data represented by the *codeword* are unnecessary: all that is needed are the date, time and BC concentration. In those cases, the fourth column of CSV data, namely the *codeword*, may be simply discarded for the purposes of data analysis and display.

Note also that since the 'compressed' data format contains fewer characters per data line, the data capacity of a floppy diskette is greatly increased if the data is written in *compressed mode*. This is particularly true for multiple-wavelength instruments.

- **Data Continuation**

The *Tape Advance* process takes a few minutes before the instrument is re-initialized and valid data are again being produced. If the *Timebase* value is 10 minutes or longer, there is always at least one valid 'inner-loop' measurement and so the data file record is continuous. However, if the *Timebase* value is shorter than 10 minutes, there will be some timebase starting times for which no valid data exists. If these start times were simply ignored, the continuous data record would contain 'missing' values that would require manual editing to identify if the BC data were to be aligned with any other measurements.

To avoid these 'missing' entries, the software automatically writes blank data lines to disk at values of the start time that correspond to the *Timebase* sequence. These blank 'filler' lines contain valid values of date and time, but the remainder of the data entries consist of ASCII nulls enclosed in double quotes, separated by commas. This allows the entire data record to be imported into a spreadsheet in CSV format, and to yield blank (not numeric-zero) entries.

14.9.2 Data File Format - Dual wavelength Instruments

The AE-2 series dual wavelength Aethalometers measure optical absorbance at two optical wavelengths: BC (880 nm) and UV (370 nm). The data are reported on a single line written to disk as follows:

- Expanded Data Format: *"date", "time", BC concentration (ng/m3), UV data result (BC + 'UVPM', expressed as ng/m3), air flow (LPM), bypass fraction, BC sensing zero signal, BC sensing beam signal, BC reference zero signal, BC reference beam signal, BC optical attenuation, UV sensing zero signal, UV sensing beam signal, UV reference zero signal, UV reference beam signal, UV optical attenuation.*

A typical line in the data file might look like:

"01-may-99", "09:40", 866, 1013, 4.2, 1.00, .0213, 2.1956, .0241, 3.1455, 1.974, .0213, 1.5721, .0241, 2.9752, 2.652

Note that the time corresponds to the starting time of the measurement cycle.

Only the date, time, black carbon (BC) and UVPM equivalent concentrations are really important: namely the first four columns of data as shown **bold** in the above example. The other columns of data represent internal diagnostics and are represented by two 'codewords' when written in *'compressed' mode*:

- Compressed Data Format*: "date", "time", BC concentration (ng/m3), UV result (BC + 'UVPM', expressed as ng/m3), "BC codeword", "UV codeword"*

In 'compressed' format, the same line in the data file might look like:

"01-may-99", "09:40", 866, 1013, "fpXeoenmRBqlaYdh", "hLieoenfAsoRnYdh"

For routine use, the codewords may be discarded as discussed above.

14.9.3   Data File Format - Seven wavelength Instruments

The AE-3 series seven wavelength Aethalometers measure optical absorbance at seven optical wavelengths from 370 to 950 nm. The data are reported on a single line written to disk as follows:

- Expanded Data Format: *"date", "time", UV [370 nm] result, Blue [470 nm] result, Green [520 nm] result, Yellow [590 nm] result, Red [660 nm] result, IR1 [880 nm, "standard BC"] result, IR2 [950 nm] result, air flow (LPM), bypass fraction,*

and then the following columns of data repeated for the seven measurement wavelengths:

sensing zero signal, sensing beam signal, reference zero signal, reference beam signal, optical attenuation, air flow (LPM), bypass fraction.

The 'air flow' and 'bypass fraction' columns are repeated to allow for easy visual identification of the separation between the seven sets of data columns.

A typical line in the data file might look like:

"24-jul-00","16:40", 610 , 604 , 605 , 612 , 617 , 611 , 641 , 3.131 ,-.9812 ,-.9814 , 1.1881 , 1.8384 , 1 , 6.4 , 2.704 ,-.9812 ,-.9814 , 4.2483 , 2.7373 , 1 , 6.4 , 2.45 ,-.9812 ,-.9814 , 2.1716 , 1.9438 , 1 , 6.4 , 2.232 ,-.9812 ,-.9814 , 2.854 , 3.5259 , 1 , 6.4 , 1.957 ,-.9812 ,-.9814 , 3.3428 , 2.596 , 1 , 6.4 , 1.452 ,-.9812 ,-.9814 , 4.6719 , 3.3935 , 1 , 6.4 , 1.396 ,-.9812 ,-.9814 , 2.705 , 2.438 , 1 , 6.4

Note that the time corresponds to the starting time of the measurement cycle.

The date, time, and the seven wavelength results are the most significant: namely the first nine columns of data as shown **bold** in the above example. The other columns of data represent internal diagnostics and are represented by seven 'codewords' when written in *'compressed' mode*:

- Compressed Data Format: *"date", "time", UV [370 nm] result, Blue [470 nm] result, Green [520 nm] result, Yellow [590 nm] result, Red [660 nm] result, IR1 [880 nm, "standard BC"] result, IR2 [950 nm] result, UV [370 nm] codeword, Blue [470 nm] codeword, Green [520 nm] codeword, Yellow [590 nm] codeword, Red [660 nm] codeword, IR1 [880 nm, "standard BC"] codeword, IR2 [950 nm] codeword.*

In 'compressed' format, the same line in the data file might look like:

"24-jul-00", "16:40", 610, 604, 605, 612, 617, 611, 641, fmGdNdLiMGlrJYbo, feedNdLuYIoWxYbo, eYadNdLmJqlNNYbo, eTHdNdLpuPsfjYbo, eOhdNdLrsDotkYbo, eEcdNdLwJtrDKYbo, eCVdNdLoQanMFYbo

For routine use, the codewords may be discarded as discussed above.

14.10 PARAMETER SETUP FILE

The Parameter Setup File 'AE-SETUP.TXT' is a plain text file that is written to disk each time the instrument starts or the parameters are changed by the operator. This file provides an easily-readable summary of the parameter setup that is useful for record-keeping purposes. This information is also <u>essential</u> if it is ever necessary to contact Magee Scientific to discuss operational questions. The exact file structure will vary according to the software version installed in the instrument. A typical example is shown on the next page:

```
--- AE-SETUP.TXT ---
Created : 06-feb-04 13:29:19
.
Instrument serial number: 427
Software version: 984v9
Instrument type (0..U (1X), 1..UV+LED (2X), 2..7xLED (3X)): 2
Instrument (Portable/Stationary) : Stationary
Selected Pump Flow : 4.0 LPM
Flow scale factor : 1.97 LPM/V
Flow zero : .076V
Date format (0=US, 1=EU): 0
Tape saver: 0
Spots per advance: 1
Filter change interval: 0
Maximum attenuation: 125
Over old data: 1
Warm up wait: 0
Spot size: Extended Range
BC Unit (0..ng, 1..ug): 0
.
Serial comm. mode (1..OFF, 2..Dataline, 3..Gesytec): 2
Serial communication parameters:
   Speed(bps) : 9600
   Data bits  : 7
   Parity bits: N
   Stop bits  : 1
.
Gesytec parameters:
   Network Scale Factor: 10
   Instrument ID for Gesytec:333
.
Dataline parameters:
Alarm mode (0..Analog out, 1..Alarm): 0
Alarm ON/OFF : 1
Alarm value limit: 10
Alarm channel selection (channel number): 1
.
Data format (0..Extended, 1..Compressed): 0
.
UV channel OFF (0..UV ch. ON, 1..UV ch. OFF): 0
.
Sigma values:
   Sigma  1  : 39.5
   Sigma  2  : 31.1
   Sigma  3  : 28.1
   Sigma  4  : 25.9
   Sigma  5  : 22.2
   Sigma  6  : 16.6
   Sigma  7  : 15.4
Volumetric unit settings:
   Volumetric units (0..Standard,  1..Volumetric): 0
   Air Pressure(mbars): 1013
   Temperature(C): 20
```

14.11 'MESSAGE FILE' INFORMATION

14.11.1 'Message' File Contents

The message file name is constructed from the characters "MF" followed by six digits compounded from the date on which the file was opened, followed by the extension ".TXT". The file entries are all ASCII text strings that may be directly viewed by any word processor. Entries posted at distinctly different times contain the date and time as the first lines. The entries generally provide the following information:

- Date and time of measurements starting

- Optical signals at start

- Date and time of measurement ending

- Optical signals at end

- A summary of the run of a filter spot, including

  o Total aerosol black carbon collected on filter

  o Total filter spot running time

  o Total sampled air volume

  o Mean BC concentration during filter running period

  o Standard deviation of BC measurements

- Comments on the performance of the instrument, and the stability of the lamp

- An estimate of the remaining data disk capacity

If any instrument problems are encountered, additional messages are posted. 'Serious' problems cause measurements to halt until operator attention is provided, with a warning message displayed on the screen. These occurrences are also posted to the message file to provide a record in case the entire system goes down. Serious problems include: loss of air flow, due to pump failure or blockage of the plumbing; failure of the lamp, or other problem with the lamp control; etc. In addition, a message is posted each time the tape advances one spot. Other messages that are self-explanatory may occasionally be generated by particular conditions.

We recommend that the message files be saved in the station electronic logbook as a permanent record that will preserve some information even if the data disk is lost.

14.11.2 'Message File' Example : Single-Wavelength Instruments

```
---
MAGEE SCIENTIFIC
AE16 AETHALOMETER
---
Aethalometer No. 177
---
23-sep-00  15:54:54  Measurements started
Starting  voltages:  sen.(beam) =     3.067     sen.(zero) =
0.021
.                        ref.(beam) =    4.733    ref.(zero) =
0.021
---
23-sep-00  19:43:32  Measurements ended
---
.                      Number of lamps (L) = 1
.                      Filter running time = 3.74 hours
.               Total airflow this filter = 1.11 cubic meters
.
Report for lamp 1 (white):
. Ending voltages: sen(beam) =   2.871  sen.(zero) =   0.021
.                  ref(beam) =   4.809  ref.(zero) =   0.021
. Optical attenuation of filter deposit = 8
.  Total aerosol black carbon on filter = 400 ng
Mean aerosol black carbon concentration = 368 ng/m3
---
The limit of resolution of the analog/digital converter was
equivalent
to a mean quantum of 7.7 ng/m3 on the measurement
---
The reference beam showed lamp intensity fluctuations of 221
ppm.
This was equivalent to 32 ng/m3 or 4.1 quanta of resolution.
Lamp stability is good.
---
Disk  space = 1452544  bytes  free: One  entry  at  every  5
minutes.
There is space for 2631 hours ( 110 days) more data
```

14.11.3 'Message File' Example : Dual-Wavelength Instruments

```
---
MAGEE SCIENTIFIC
AE21 AETHALOMETER
---
Aethalometer No. 249
---
21-sep-00  10:57:54  Measurements started
Starting voltages:
.                    sen(zero) =   0.020 ref(zero) =   0.020
.  Lamp 1 (880 nm): sen(beam) =   1.611 ref(beam) =   2.147
.  Lamp 2 (370 nm): sen(beam) =    .673 ref(beam) =    .941

---
21-sep-00  19:59:00  Measurements ended
---
.                    Number of lamps (L) = 2
.                    Filter running time = 9.01 hours
.             Total airflow this filter = 2.54 cubic meters
.
Report for lamp 1 (880 nm):
. Ending voltages: sen(beam) =    .979  sen(zero) =   0.020
.                  ref(beam) =   2.105  ref(zero) =   0.020
. Optical attenuation of filter deposit = 47
.  Total aerosol black carbon on filter = 1441 ng
Mean aerosol black carbon concentration = 567 ng/m3
---
The reference beam showed lamp intensity fluctuations of 107
ppm.
---
Report for lamp 2 (370 nm):
. Ending voltages: sen(beam) =    .254  sen(zero) =   0.020
.                  ref(beam) =    .934  ref(zero) =   0.020
. Optical attenuation of filter deposit = 100
.  Total aerosol black carbon on filter = 1267 ng
Mean aerosol black carbon concentration = 498 ng/m3
---
The reference beam showed lamp intensity fluctuations of 295
ppm.
---
Disk  space  =  1414656  bytes  free:  One  entry  at  every  1
minutes.
There is space for 337 hours ( 14 days) more data
---
21-sep-00  19:59:02  Tape feeder mechanism advancing for 1
spot(s).
---
```

14.11.4 'Message File' Example : Seven-Wavelength Instruments

```
   ---
MAGEE SCIENTIFIC
AE31 AETHALOMETER
---
Aethalometer No. 268
---
03-sep-00  13:09:54  Measurements started
Starting voltages:
.                     sen(zero) =   0.023 ref(zero) =   0.023
.  Lamp 1 (370 nm): sen(beam) =    .905 ref(beam) =   1.697
.  Lamp 2 (470 nm): sen(beam) =   3.541 ref(beam) =   4.658
.  Lamp 3 (520 nm): sen(beam) =    .754 ref(beam) =   4.371
.  Lamp 4 (590 nm): sen(beam) =    .948 ref(beam) =   4.270
.  Lamp 5 (660 nm): sen(beam) =   2.693 ref(beam) =   5.447
.  Lamp 6 (880 nm): sen(beam) =   2.444 ref(beam) =   5.484
.  Lamp 7 (950 nm): sen(beam) =   1.087 ref(beam) =   4.535


---
03-sep-00  22:00:00  Measurements ended
---
.                     Number of lamps (L) = 7
.                     Filter running time = 8.83 hours
.              Total airflow this filter = 1.28 cubic meters
.    Mean BC concentration of all lamps = 1049 ng/m3
.
Report for lamp 1 (370 nm):
. Ending voltages: sen(beam) =    .429  sen(zero) =   0.023
.                  ref(beam) =   1.687  ref(zero) =   0.023
. Optical attenuation of filter deposit = 75
.  Total aerosol black carbon on filter = 1253 ng
Mean aerosol black carbon concentration = 988 ng/m3
---
The reference beam showed lamp intensity fluctuations of 112
ppm.
---
Report for lamp 2 (470 nm):
. Ending voltages: sen(beam) =   1.915  sen(zero) =   0.023
.                  ref(beam) =   4.661  ref(zero) =   0.023
. Optical attenuation of filter deposit = 60
.  Total aerosol black carbon on filter = 1283 ng
Mean aerosol black carbon concentration = 1012 ng/m3
---
The reference beam showed lamp intensity fluctuations of 25
ppm.
---
Report for lamp 3 (520 nm):
. Ending voltages: sen(beam) =    .439  sen(zero) =   0.023
.                  ref(beam) =   4.387  ref(zero) =   0.023
. Optical attenuation of filter deposit = 55
.  Total aerosol black carbon on filter = 1300 ng
Mean aerosol black carbon concentration = 1025 ng/m3
---
The reference beam showed lamp intensity fluctuations of 35
ppm.
---
Report for lamp 4 (590 nm):
. Ending voltages: sen(beam) =    .585  sen(zero) =   0.023
.                  ref(beam) =   4.275  ref(zero) =   0.023
```

```
. Optical attenuation of filter deposit = 49
.  Total aerosol black carbon on filter = 1303 ng
Mean aerosol black carbon concentration = 1028 ng/m3
---
The reference beam showed lamp intensity fluctuations of 117
ppm.
---
Report for lamp 5 (660 nm):
. Ending voltages: sen(beam) =   1.696  sen(zero) =   0.023
                   ref(beam) =   5.431  ref(zero) =   0.023
. Optical attenuation of filter deposit = 45
.  Total aerosol black carbon on filter = 1351 ng
Mean aerosol black carbon concentration = 1066 ng/m3
---
The reference beam showed lamp intensity fluctuations of 229
ppm.
---
Report for lamp 6 (880 nm):
. Ending voltages: sen(beam) =   1.714  sen(zero) =   0.023
                   ref(beam) =   5.484  ref(zero) =   0.023
. Optical attenuation of filter deposit = 35
.  Total aerosol black carbon on filter = 1416 ng
Mean aerosol black carbon concentration = 1117 ng/m3
---
The reference beam showed lamp intensity fluctuations of 112
ppm.
---
Report for lamp 7 (950 nm):
. Ending voltages: sen(beam) =    .785  sen(zero) =   0.023
                   ref(beam) =   4.538  ref(zero) =   0.023
. Optical attenuation of filter deposit = 32
.  Total aerosol black carbon on filter = 1406 ng
Mean aerosol black carbon concentration = 1108 ng/m3
---
The reference beam showed lamp intensity fluctuations of 230
ppm.
---
Disk  space  =  1317888  bytes  free:  One  entry  at  every  5
minutes.
There is space for 578 hours ( 24 days) more data
---
03-sep-00   22:00:03   Tape feeder mechanism advancing for 2
spot(s).

---
```

14.12 STOP MEASUREMENTS

This is a 'protected' function and requires the Security Code as a password.

The *Operate* procedure can be interrupted by pressing the STOP key: the screen will display the message "-- STOP key PRESSED --" .. "STOP again to exit". The user must then **PRESS THE STOP KEY AGAIN**. However, the measurements will only actually terminate if the user can enter the correct *security code* within a 10-second time window. If the correct *security code* is entered, the program returns to the *main system menu*: if the code is not correct, measurement operations simply continue.

These precautions are implemented to prevent accidental or unauthorized stopping of the measurements.

Note: the security code is initially set at the factory to the value **111.**

14.13   SCREEN DISPLAY: NORMAL OPERATION

14.13.1   Display Screen

1st line:	Left:	system time
	Right:	system date
2nd line:	Left:	(Tape:) estimated amount of tape roll remaining
	Right:	(Saver:) 'Tape Saver' feature activation status
3rd line:	Left:	(Disk:) free space on disk, expressed as **h**ours, **d**ays or **we**e**k**s.
	Right:	(Flow:) air flow in LPM: 'vLPM' indicates use of **v**olumetric units.
4th line:		Last value of BC concentration in μg/m3 or ng/m3.

14.13.2   Status Indicator Lamps

The front panel has 5 programmable lamps to indicate the instrument status:

- **RUN** (green):

    - Steady: Normal operation, measurement data is valid.

    - Flashing: Normal operation, but there is no valid data because the instrument is performing a tape advance or (re-) initializing.

- **PAUSE** (yellow): Indicates that the instrument is ready for measurements, but was stopped by the operator pressing the STOP key. Also lit in *manual mode* in the *operate procedure* until all operator interactions are completed

- **CHECK** (yellow): Flashing - something must be checked - data disk almost full, tape almost all used, or air flow rate has changed more than 10%.

- **ERROR** (red): Flashing - a serious error has occurred, the instrument has stopped.

- **STOP** (red): Instrument is not ready to run: stopped either by a serious error or when operator is in a menu/setup mode.

14.13.2   Measurement Screen Display: Dual-Wavelength Instruments

For AE-2 series dual-wavelength instruments, the fourth (lowest) line of the screen display shows two results. On the left, 'BC' indicates the calculation from the 880-nm BC measurement. On the right, the result from the UV calculation is shown as the <u>total</u> UV response, i.e. [BC + UVPM] in the terminology of section 4.2 of this book. The result shown should be close to or larger than the BC result. The difference between these quantities may have any value, from zero (if the aerosol sample does not contain any aromatic UV-absorbing material) up to a large value (if the aerosol sample contained, for example, a large amount of tobacco smoke). Negative values of this quantity do <u>not</u> indicate an error condition: they may arise due to the subtraction of two large and slightly noisy signals that are almost equal to each other.

14.13.3   Measurement Screen Display: Seven-Wavelength Instruments

For AE-3 series instruments, the fourth (lowest) line of the screen display shows a numerical and a graphical result. On the left, a 'BC' number represents the average result calculated from all seven wavelengths. On the right, a seven-unit-width graphic represents the spectral deviations from uniform absorbance, representing the wavelengths from 370-nm-UV (leftmost) to 950-nm-IR2 (rightmost). This bar chart is calculated as follows:

Firstly, the average result is calculated; secondly, the maximum excursion of data at any wavelength relative to this average is calculated by subtraction, to set a scale for the deviation from average. Finally, the result at each wavelength is compared to the average and expressed as a fraction of the maximum deviation. Each wavelength's relative deviation is represented by a bar whose vertical position can have one of 5 values: uppermost, highest positive deviation (i.e. this wavelength's result is in the highest percentile of the comparison of the 7 results); upper, moderate positive deviation; center, no significant deviation from average; lower, moderate negative deviation; lowest, greatest negative deviation. This provides a crude representation of the 'absorption spectrum' for the aerosol sample: if the bar chart has a large peak on the leftmost (UV) side, it may represent the presence of UV-active material such as tobacco smoke or fresh diesel smoke.   If the bar chart has a uniform slope from lower left to upper right (i.e. UV data suppressed, IR2 data enhanced), it may represent the presence of large-particle-size absorbing material.

15. PRESENTATION OF DATA

15.1 DATA MODES OVERVIEW

The measurement data are made available to the user in four different modes:

Display screen:

The most recent BC concentration is displayed in units of μg or ng BC/m³.

BC files and MF files on disk:

The measurement data are written in the BC files, and the instrument operation messages are logged in the MF files. If the *Overwrite Old Data* parameter is set to YES, old data is overwritten by new data when the disk is almost full. The structure of the BC and MF files is described in the *Operate procedure* section.

Analog Output Voltage on rear panel terminals:

A digital-analog converter connected to the rear panel terminals provides a voltage that can represent the value of the black carbon concentration. The proportionality between this output voltage (0 to +5V) on the terminals and the BC concentration is set by programming the *Output Scale Factor*. The default value of this scaling factor is set to 1 mV = 10 ng/m³ BC (i.e. 1 Volt = 10 μg/m³ BC), but can be changed in the *Change Settings* menu. The analog voltage output is forced to -5V to indicate 'data not valid' during tape advance, instrument initialization, etc. This connection can also be configured as an alarm to turn ON or OFF according to the BC concentration. See the following sub-section for more details.

Digital Data at COM port:

If the *COM Mode* parameter is set to 'DATALINE', the COM port will produce a single line of data once per timebase period that is a replica of the data line written to disk. The transmission parameters (baud, parity etc.) are set by the *COM settings* menu.

15.2 ANALOG OUTPUT PORT

15.2.1 Principle

The analog output port is connected to a D/A converter operated by the embedded computer. It is intended as an indicative signal voltage output only. It is not intended to be the primary definitive data output of record: this is the digital data either on diskette or transmitted by the COM port. The analog voltage output range is –5 to +5 volts DC. It has 3 modes of operation. The operator can choose between "Signal Output" and "Alarm" in the software setup. The –5 volt "Data Not Valid" flag is always active.

(i)   Data Valid / Not Valid : the output is driven to –5 volts whenever the instrument is initializing, warming up, re-initializing after a tape advance, paused or stopped by the operator, etc.

(ii)   Data Signal Representation: the output goes from 0 to +5 volts to represent the BC data generated by the computer. The scaling factor is set up in software under a heading in *Change Settings*. The units of scaling are [nanograms/m³] per [mV] which is equivalent to [micrograms/m³] per [volt].

(iii)   Alarm Mode: the output stays at zero until the BC concentration exceeds a threshold set in software, at which point the output goes to +5 volts. This can be used to signal an 'alarm' condition, or turn on an external device, etc. The output has enough power to directly drive a <u>solid-state</u> relay, but <u>does not</u> have enough power to drive a <u>mechanical</u> relay.

NOTE: when in "Signal Output" mode, remember that the computed BC concentration *can* go slightly 'negative' due to instrumental noise, artifacts etc., especially in locations of very low concentration. Thus, the output voltage *may* occasionally go negative by a few millivolts.   This does not indicate a fault condition, and is always very different from the full-scale –5 volts indicating 'Data Not Valid'.

15.2.2 Testing

The menu selection *Self Test* includes a routine that exercises the analog output terminals through –5, zero, +1, +2 and +5 volts. This allows the operator to verify that the analog output is working correctly in conjunction with externally-connected equipment.

To access this test:

Main Menu :

press DOWN-ARROW repeatedly to reach *Self Test*. Press ENTER.

Self Test :

press ENTER repeatedly to reach the *Analog Output* portion of the test.

Press ENTER to proceed from one voltage to the next.

15.2.3 Set Up Scaling Factor

The menu selection *Change Settings* has a routine to set up the operation mode ('Signal' or 'Alarm'), and then the scaling factor (or threshold).   To access this menu:

Main Menu :	Press DOWN-ARROW once. Screen will show *Change Settings*.
Change Settings:	Press DOWN-ARROW repeatedly to reach *Analog Output*.

Select mode (SIGNAL / ALARM) : use UP/DOWN arrows, press ENTER.

Enter scaling factor. Units are ng/m3/mV.

For example: 1000 ng/m³/V is equivalent to 1 volt = 1 μg/m³.

Recommendation: set to 10000 ng/m³/V: this scaling is 1 volt = 10 μg/m³

Press ENTER when done, press ESC to escape from settings, save setting with YES.

15.2.4 Programming of External Analog Voltage Datalogger

The Aethalometer provides an analog voltage output on the rear panel. This voltage may be scaled in software to represent any reasonable measurement range, in terms of [output volts] per [ng/m³ or μg/m³].   The output voltage ranges from 0 to +5 volts DC to represent the signal: small negative excursions may be produced if the signal is very small compared to the instrumental noise. An output of -5 VDC is generated when the instrument is first initializing, or re-initializing after a filter tape advance, to represent 'Data Not Valid'. The analog datalogger must be setup to perform one-minute voltage scans, and to void minutes with any individual voltage scans that are more negative than -2 volts. However, it must be able to collect small negative voltages e.g. -0.3 volts or so.

The standard rule for a valid hour is to contain at least 45 minutes of valid data. For the Aethalometer datalogger channel, this must be reduced to 40 minutes to avoid an invalid hour report every time the filter changes. This does not really violate the 45 minute rule, since no more than 15 minutes of data are lost when the filter changes. However, since the datalogger and Aethalometer clocks are unlikely to be exactly synchronized, the datalogger's 1-minute data capture might be only 43 valid minutes.

The datalogger's input range and the Aethalometer's analog output range must be set to [a] provide sufficient data resolution and [b] not go 'offscale' during short term [5-minute] events that may be well below the 1-hour mean. For some sites this could be as high as 40 to 50 µg/m³; many sites can use 20 µg/m³ as a full scale limit.

15.3   DIGITAL DATA OUTPUT PORT

The rear panel of the instrument is fitted with a 9-pin socket that provides a standard COM port output for digital data reporting. The only connections that are used are pins 2, 3 and 7 (ground). This port may be connected to a data recorder such as a commercial digital datalogger or a computer running a 'terminal' program. The transmitted data line is an exact replica of the data line written to diskette, as described in Section 14.8 above.

Note: the Aethalometer <u>outputs</u> data once per timebase period, at the end of the period when the data line is written to diskette. The data is not stored internally, and can not be retrieved upon command from an external interrogator. Thus, any data capture system must be set for continuous reception. It is <u>not</u> possible to connect a device to the Aethalometer's COM port and download data upon command.

Note: for connection to a standard PC computer, a 'null-modem' cable must be used. This cable interchanges the connections to pins 2 and 3.

15.4 GPS POSITION DATA CONNECTION TO COM PORT

The rear panel COM port may also be configured to <u>receive</u> data input from a GPS. This is intended for use with the Portable Aethalometer, to permit mapping of carbon particulate concentrations during mobile use. In this mode, the latitude and longitude coordinates are read from the GPS receiver, and appended to the data file by means of two additional columns at the end of the data string.

Most GPS receivers have a standard data output format named 'NMEA V1.5APA'. The GPS set must have its data transmission enabled, and its baud rate set to 1200. Use a suitable cable to connect it to the 9-pin COM port on the aethalometer. The aethalometer COM port parameters must then be set as follows:

- Change Settings Menu

- Communication Parameters sub-menu

- Comm. Mode: **GPS**

- Baud Rate: **1200**

- Data Bits: **8**

- Stop Bits: **1**

- Parity: **None**

and the 'Communications Mode' must be set to **GPS**.

Save the settings and exit to Operate mode. Two additional columns of data will be written to the disk files.

16.   FLOWMETER RE-CALIBRATION

The program first allows the user to switch between 'Standard' and 'Volumetric' flow units. (If 'Volumetric' flow units are selected, it is necessary to input the barometric pressure and ambient air temperature). This function is not password protected. The program next allows the user to re-calibrate the flowmeter: this function *is* protected.

- **Flow Volume Units:**

    The program allows the flow to be expressed in terms of either Standard Units or Volumetric Units.

    Standard Units report the air flow rate as SLPM, i.e. volume occupied by a given mass of air at a temperature of 20°C and a pressure of 1013 mb. This mass flow rate is the signal that is provided by the mass flow meter in the instrument. The Aethalometer data is reported as ng/m³ or µg/m³, where the "m³" is understood to be a *standard* cubic meter.

    Volumetric Units convert the *mass* of air to a *volume* calculated at certain specified ambient conditions of *temperature* and *pressure*. These conditions must be entered by the user – they are not measured by the instrument. The mass flow rate signal provided by the mass flow meter is scaled by proportionality factors for *temperature* (input in degrees C) and *pressure* (input in millibars). When *volumetric* units are selected for the flow, the flow rate display on the screen is shown as vLPM, and the BC calculation is presented as ng/vm³ or µg/vm³.

    The *volumetric* calculation requires user input of ambient *temperature* and *pressure*. These factors may be entered without going through the flowmeter re-calibration procedure. This allows for entering different mean ambient temperatures, or different pressures if the instrument is moved to a location of different elevation, without disturbing the fundamental calibration of the mass flow meter response.

    Note: the 'Portable' series of instruments use a different type of flow sensor whose output is not a representation of air mass flow, but is intrinsically dependent on ambient pressure. For precise operation at reduced ambient pressure, the 'Portable' instrument should be re-calibrated under ambient conditions.

- **Flowmeter Re-Calibration**

This is a 'protected' function and requires the Security Code as a password

This procedure calibrates the flowmeter response by measuring the *flowmeter zero voltage* and determining the *flow scale factor*. These two factors are used during measurements to calculate the actual *air flow* through the flowmeter.

Notes:

- You will need a standard external flowmeter or calibrator capable of reading air flow rates in the range of 2 to 10 slpm, with a low resistance to flow Connect this calibrator firmly to the Sample Inlet Port with no possibility of an air leak.

- **Only perform this re-calibration if you have serious reason to believe that the flowmeter response is incorrect**.

- Allow the instrument to warm up for at least 30 minutes with power and air flow 'on', before performing the re-calibration.

- See above for discussion of standard vs. Volumetric units.

The internal pump is controlled by the computer and electronics, and this allows the program to set 'zero' and 'span' flows. All that is required of the operator is to connect a standard external flow calibrator, and observe its reading.

The routine first automatically reduces the pump speed slowly to zero, while measuring the signal from the internal flowmeter. When this has reached a steady low value as determined by no more change in voltage output, the value of the reading is used as the *flowwmeter zero voltage*. The pump is then re-started and run up to its previous speed. When the flowmeter signal is steady, the screen displays the flowrate in liters per minute derived from the new *zero* and the previous *scale factor*. The user must then compare the displayed value of flow with the actual value as measured by the external standard. Pressing the keypad UP- and DOWN-arrow keys will change the *flow scale* factor. Press these keys until the displayed value agrees with the measurement from the external calibrator. Press ENTER when the displayed value is correct.

Upon return to the *main system menu* the user is asked to confirm writing the newly measured response factors to the setup file. The previous flow calibration values are <u>not</u> replaced until this confirmation is made. In case of any doubt, repeat the procedure.

17. ROUTINE MONITORING PROCEDURES

The Aethalometer™ does not require the regular attention of a specialized technician in order to operate it. Any keypad operations can be kept to a minimum, and can be explicitly written out. As described in the following sections, we suggest certain routine procedures for regular monitoring use of the instrument. The total workload does not exceed a few minutes, especially if pre-printed standard blank forms are used for filling in the various items.

17.1 RECORD KEEPING

We recommend that the message files be printed out during initial operation, even if it they will <u>not</u> be used routinely during measurements. Remove the disk, transfer it to another computer with a text processor, and print out the contents of the 'MF' files. Save these summaries in a report file book until you have acquired familiarity with the various operating parameters and the typical behavior of the system in your particular situation. If routine operations permit, we recommend that the message file be saved routinely, as a summary backup in case of loss of data on the magnetic media.

Occasionally, the stability of the lamp may be slightly below specifications and a message may be posted suggesting that the lamp performance be monitored. We suggest that you develop some familiarity with the instrument and its performance before interpreting this message absolutely literally. The threshold criteria are quite stringent, and in locations of fairly high concentrations of aerosol black carbon these minor instabilities may be completely insignificant. At first, simply make a note of the reference beam lamp stability report (in the summary text at the end of the message file), but do not develop concern about the lamp stability unless measurement performance is distinctly unacceptable.

Once you are familiar with use of the Aethalometer, manual record keeping can be performed at any level compatible with routine operations at your location. All <u>essential</u> information is maintained in the data and message files: if it can be guaranteed that these are recovered, very little 'pencil-and-paper' work is actually necessary although it is always a good precaution to maintain detailed records. We recommend keeping separate records of the following quantities taken from the message files: a sample blank form page is at the end of this chapter, although your own reporting requirements may call for more or less accounting.

17.2   SUGGESTED STANDARD LOG FOR DETAIL RECORDING OF MF FILE EXCERPTS

- Date

- For each filter spot:

    o Time of start of measurements

    o Time of end of measurements

    o Mean aerosol black carbon concentration (nanograms per m³)

    o Stability of reference beam (PPM, also expressed as ng/m³)

- End of each day:

    o Capacity remaining on data disk (hours or days) - floppy disk.

    o Any comments on external conditions, meteorology, activity, etc.

The mean BC value preserves some measurement information even if all else is lost. The stability number (usually a few tens or hundreds of PPM) indicates the general internal performance of the instrument: occasional fluctuations may be acceptable, but a systematic deterioration may require attention. The expression of this quantity in terms of an equivalent aerosol black carbon concentration gives an indication of the accuracy of the BC measurements, although the actual accuracy of any individual measurement is higher due to the compensating nature of the algorithm and the manner in which measurements are taken before, during and after the lamp-on period. The record of data disk capacity is advisable when floppy disks are used. Operator comments are always illuminating, and we strongly recommend that all operators be encouraged to use their own perceptions and to record their personal observations.

17.3 'STANDARD OPERATING PROCEDURE' FOR RACK-MOUNT AETHALOMETER

The following Standard Operating Procedure for use of a Rack-Mount Aethalometer was prepared by G. Allen of the Harvard School of Public Health, April 1999: modified by A. Hansen for this manual, March 2005, to reflect changes in hardware of recent Aethalometer models.

This protocol is for Black Carbon (BC) (soot) measurements using the Magee Scientific dual wavelength Aethalometer™ with a 4-LPM Harvard Impactor (HI) PM2.5. Additional text entries refer to operation with a PM2.5 sharp-cut cyclone operating at 5 LPM. The instrument is run with tape-saver mode off and flow reported at 20° C.

Any times that data are not valid while the system is "on-line" should be noted in the site logbook, along with any comments or notes. If at all possible, avoid doing any procedure that causes loss of data during periods with BC concentrations higher than about 5 μg/m^3.

Once Each Week:

1. Check the system date and time on the Aethalometer display and on the external data logger. Both times should be within 5 minutes of the correct time. If the time is reset, record the time error before changing the time, and the date and time you changed the time. The Aethalometer must be "stopped" to change the time, but does not need to be taken "off-line" from the data acquisition system, since the -5 volt output in this state automatically flags the data as void in the data logger. A security code must be entered to stop the Aethalometer and perform certain other system operating tasks; the default code is 111 and should not be changed. If there is a clear trend in the system time error, set the time somewhat off in the opposite direction of the trend to reduce the need for frequent system time changes.

2. Check the sample flow on the Aethalometer display and record it in the log. For correct operation of the Harvard Impactor inlet it should be 4.0 ± 0.3 lpm. For correct operation of the PM2.5 Sharp-Cut Cyclone inlet it should be 5.0 ± 0.3 lpm.

3. Check the display screen for normal operation (reasonable readings, no error messages, etc).

4. (Harvard Impactor) Change both impactor plates on the inlet. Plates can be reused at least 5 times by field cleaning before being throughly cleaned in the lab. Wipe the deposit off the plates with a Kimwipe, apply one drop of mineral oil on each plate, and blot dry after 30 seconds to remove any excess oil.

5. Check the filter tape supply. Re-tension the tape roll take-up spool if needed. Inspect the used filter tape spots that are visible: look for distinct and uniform borders between the exposed and unexposed areas. If obvious poor seals are noted, contact management.

Once Each Month:

1.   While the Aethalometer is in its normal run mode, perform an external flow check. Do not stop data collection on the Aethalometer to do this test, since that can change the flows. The "tape-saver" function must be off to perform this flow check procedure.

   1a.   Measure the sample flow at the inlet of the fine mass impactor using a BIOS flow meter, dry test meter, rotameter, or other calibrated volumetric (e.g, not STP) flow measurement device with a range of 3 to 6 LPM. Wet flow devices are not recommended since they can not be used below freezing, and have a RH dependent error due to water vapor. The external flow meter must be at ambient temperature for readings to be valid. An STP flow device can be used if the temperature is 20 °C; in this case skip the next step.

   1b.   Record the flow from the Aethalometer display, that is based on a mass flow meter calibrated for STP at 70 °F. Correct the volumetric flow measured by the external device to conditions of 20°C and 29.92" Hg as follows:

   STP flow = actual flow * [293 / (273 + ambient T in °C)] * [Barometer (inches Hg) / 29.92]

   Use barometric pressures and air temperatures reported from the nearest standard weather station (e.g. airport), if there is doubt about local sensors.

   1.c.   Calculate the % error of the Aethalometer flow compared to the external flow standard.

   % error = 100 x (Aethalometer display - external STP flow) / external STP flow

   If the flow difference is more than 10%, contact management.

2.   Change the Aethalometer data disk. The Aethalometer does not need to be interrupted to do this as long as the change is done during the first three minutes of any five minute measurement cycle [based on the Aethalometer's internal clock]. Before changing the disk, start by labeling a new disk with the site and start date/time (local standard time). Remove the old data disk and insert the new disk. Immediately put the write protect tab on the old disk, and record the end date/time on the disk label. Return the disk to the main office.

Aethalometer Instrument Log

G. Allen, HSPH Rev. 0, April 1999; A. Hansen, Rev. 1, March 2005

Date: _____   Site: _____   Operator: _____

Once Each Week:

Date (m/dd/yy)							
Time chk (✔)							
Flow (lpm)							
Tape supply (✔)							
Operator initials							

Record any changes to Aethalometer or datalogger time here: _____

Once each month: Date: _____   Operator: _____

Flow check:

Flowmeter Mfg. & S/N _____   Date last calibrated: _____

External flow reading at impactor inlet _____ ALPM

Ambient Temp.   _____ °C   Station Barometric Pressure _____ " Hg

External flow (20 °C): _____   Flow (from Aethalometer display) _____

Flow % difference: _____ (<10%)

17.4 'STANDARD OPERATING PROCEDURE' FOR PORTABLE AETHALOMETER

The following Standard Operating Procedure for use of a Portable Aethalometer was prepared by G. Allen of NESCAUM, April 2002

Portable Aethalometer™ "Black Carbon" Analyzer Field Operating Protocol

G. Allen, NESCAUM April 23, 2002

This protocol is for using the Magee Scientific Model AE-42 Portable 2-wavelength Aethalometer™ in field studies; it covers routine operation but not any problem situations. Full documentation for the analyzer and a "quick-start" guide with additional basic info are at: www.mageesci.com

The box contents are as follows; please be sure that all components are included when the system is returned after use.

Aethalometer main chassis
6-foot black sample line with hose-barb to quick-connect fitting in one end
AC power supply
AC power cord for above
Automobile Cigarette lighter power adaptor
Battery clamp power adaptor
Keypad
"Dynamic-zero test" Filter (Balston BQ green cartridge filter)
This operating protocol

1. **Environment**.

   The AE42 needs to be in a reasonably climate controlled environment, not outside. Suggested temperature limits are 50 to 85 degrees F. Rapid or large temperature fluctuations will affect the sensitivity. Avoid extreme vibration if possible; that will also degrade the sensitivity.

2. **Physical setup**.

   The AE42 comes with a six-foot inlet line, so the instrument must be placed near where the measurement is going to be made. Longer lines up to about 15 feet can be used if necessary. Attach the end of the inlet line that has the plastic barb fitting to the quick connect fitting on the rear of the AE42. Be sure it's fully seated. To release, push in on the inner ring while pulling out on the tubing. For unattended operation when sampling outdoor air, be sure that rain water can not enter the inlet.

3. **Startup**.

   A.   Before turning the unit on, insert a blank formatted floppy disk (3.5") into the disk drive on the front of the instrument.

   B.   If you want to change or confirm the instrument parameters, plug the external keypad into the connector on the rear of the instrument before turning it on (if the keypad's use is only temporary, it is not necessary to

tighten the connector's screws), and follow the on-screen prompts. Other than "clock time", the most likely change would be the 'timebase' – how often it writes the data to disk. Usual choices here are 1 or 5 minutes, depending on the application. For ambient or inside use, 5 minutes is usually preferred. For bus studies or other "close to the source" studies, the 1-minute timebase is recommended; those short-term data can always be averaged or smoothed later if needed.

C.   The instrument starts automatically when powered up; this process takes up to 25 minutes before valid data is available. If you know the instrument is configured as you want to run it, there is no need to use the keypad; simply turn on the front panel power switch. The filter tape advances each time the instrument is started, and when BC loading exceeds a predefined amount. After approximately 25 minutes, only the green LED should be on and non-zero values for BC and UV-C should be displayed (ng/m³). Any other status lights at any time during startup or operation are indications of problems. In this case, turn off the instrument power, wait several seconds, and turn it back on.

D.   Check the "spots" that are visible on the filter tape coming out of the front of the instrument. Sequential spots should at most just barely touch each other; there should be no significant overlap. The edges of the spot circle should be well defined. Cut off excess used tape with scissors when needed. Do not try to tear it off!

E.   Check the flow displayed on the AE42 screen. It should be 4.0 LPM; a range of 3.7 to 4.3 is OK. Outside of that range the flow should be adjusted by turning the small screw underneath the front panel flow meter. The flow shown on the flow meter tube should be somewhat close to the 4 LPM mark also. Check that the date and time shown on the screen are correct. The first measurement cycle will show 0 for concentrations; this is normal. The first several minutes of reported data are often invalid, especially when the 1-minute timebase is used.

4.   **Operation**.

A.   For studies that use both AE42s as a 'matched pair', it's critical that at the start and end of each study or study period the two instruments are run side-by-side for at least several hours to be sure that they report concentrations that are essentially the same on average. This test can be done on indoor air if the BC concentration is at least 500 ng/m³ (> 1000 is preferred though). If indoor BC is too low for this test, run the inlet line outdoors. Morning rush hour (before 9 am) is usually the time of day when BC is highest. Open the data files from both instruments into a spreadsheet and calculate the mean for both datasets. There should be no more than 5% difference between the means. If it's substantially greater than that, flow and leak and "dynamic zero" tests should be done. If those test results are OK, then it is possible to run the instruments "as-is" as long as the difference is less than 20%.; the study data should be "normalized" based on the pre- and post-study comparison test results to remove any "instrument bias" from the data analysis.

B.   The internal battery should run the unit for 3 hours on a full (overnight) charge. If longer battery operation is needed, a small external sealed lead-acid or marine 12 volt battery can be used; an external battery power cable is supplied with the instrument for this purpose. The

instrument can also run off of a cigarette lighter with the supplied adaptor cable.

C.   The disk has room for 7 days of 1-minute data, and more than a month of 5-minute data. It is recommended that the disk is backed up or changed after each day of use in intensive 'vehicle' studies, and at least once each week for indoor or outdoor studies. The disk can be changed without turning the instrument off; just be sure to change the disk during the first 30 seconds of any minute to avoid the period when the instrument writes to the data disk.

D.   Note that for situations where BC concentrations are high (more than 2 or 3 µg/m³), the filter tape will advance (automatically) more frequently. At 8 µg/m³ BC, it advances about once each hour. Several minutes of data are lost each time the tape advances. It is possible to run the system at a lower flow (2 LPM for example) if high BC concentrations are expected; this would minimize data loss.

5.   **Shutdown**.

The instrument can simply be turned off, but avoid doing this during the last 30 seconds of any minute to avoid the period when the instrument writes to the data disk. The instrument can generate summary info and performance stats, but that only occurs if the keypad is used to stop the measurements. Press the stop button twice, then when prompted enter "111" (the security code). Then turn the power off.

6.   **Data Format**.

The data on the disk are ASCII text, comma separated variable (csv) format, and are readily opened in most spreadsheet programs. Data filenames are BCmmddyy.CSV. An example data record is: "17-apr-02","15:50", 311, 496, 4.1

This example is truncated after the first 5 data fields; the remaining fields are internal raw instrument parameters that are only used for diagnostic purposes. The file "DATACOLS.CSV" on every data disk contains the field label information for all fields. Date and time are reported for the beginning of the averaging interval, not the end. The next 3 fields are BC and UV-C (ng/m³), and the sample flow (LPM). A new data file is created each day the instrument is used. Within the same day, the file is appended to. When the instrument is run overnight, a new file is created at midnight each day. Note that for long-term continuous operation, when the data disk is changed there are two data files with the same name but not the same data! There usually are also "Message Files" on the data disk that begin with "MF"; these are only used for diagnostic purposes.

7.   **Data interpretation**.

The BC concentration is highly correlated to elemental carbon (EC) measurements made by chemical methods. BC is approximately 30% lower then DRI's TOR-EC, and about 30% higher than the NIOSH method used by Sunset Labs. UV-C is a qualitative measurement that includes enhanced optical absorption by some "fresh" volatile organic particles such as wood smoke, nicotine and Diesel (but only when you can "smell it"). In theory, UV-C should always be equal to or higher than the BC; the difference between BC and UV-C is the "fresh organic" carbon signal."

18. OPTICAL TEST STRIP

The Aethalometer™ measurement does not depend on any <u>absolute calibration</u> of the detectors' response signals, but instead relies upon their ability to determine very small <u>changes</u> in optical transmission. This is an intrinsic feature of the detectors' response linearity, depending only on the proportionality between *photons absorbed* and *electrons generated*.

In normal operation, the Aethalometer does not require optical <u>calibration</u> *per se*: only an occasional check of the accuracy of the air mass flow meter is called for. Use of the *Optical Test Strip* is a simple means of verifying the ratiometric performance of the photodetectors as part of a routine QC/QA program.

The *Optical Test Strip* procedure can be completed in less than 15 minutes. No tools are needed, but some manual dexterity is required. The procedure is performed automatically by the software, and the results are recorded to disk, as described in the section above. We recommend that the results be printed out and saved in the instrument's permanent QC/QA log.

Optical Test Strip Algorithm

This calculation uses six signals measured during the *Optical Test Strip Procedure.* These signals are denoted SEN0, REF0, SEN1, REF1, SEN2, REF2.

The following quantities are calculated using natural logarithms:

Sensing Beam Test Value $= 100 * ln ((SEN1 - SEN0) / (SEN2 - SEN0))$

Reference Beam Test Value $= 100 * ln ((REF1 - REF0) / (REF2 - REF0))$

Optical Test Ratio $=$ (Sensing Beam Test Value) / (Ref. Beam Test Value)

These test values should be positive numbers in the region of 30 to 50, depending on the individual Optical Test Strip itself: the Optical Test Ratio should be close to unity.

The actual values of these unit-less numbers, and their exact relationship one to the other, are irrelevant. Fixed inequalities of +/- 20 percent in inter-relationship (i.e. fixed values of the Optical Test Ratio from 0.8 to 1.2) are acceptable, and are a consequence of the fabrication of the *Optical Test Strip* itself. The important issue is to ensure that the numbers *do not change appreciably:* changes from one measurement procedure to the next should be less than 10 percent of the Test Values, less than +/- 0.1 in the Test Ratio.

QC/QA Reporting Procedure

The appropriate QC/QA procedure is to perform the *Optical Test Strip Procedure* at routine intervals and to print out the Optical Test File written to the diskette as OTxxxxxx.TXT. If any of the signals, Test Values or the Test Ratio <u>change</u> appreciably over time, contact Magee Scientific Company.

19. ROUTINE MAINTENANCE

In normal operation the Aethalometer™ requires very little maintenance or attention. It is designed to operate automatically after power-up: an interruption of power does not mean that a visit from the site operator is required before valid data collection can resume. If the sample air flow rate varies somewhat, the data will still be valid, although a warning message "Air Flow Getting Low" may be displayed on the screen. Suggested 'Routine Monitoring Procedures' and the QC/QA procedures of the Optical Test Strip have been described in the previous two chapters. Many Aethalometers have been in continuous everyday use for ten years or more. Nevertheless, as with any scientific instrument, certain procedures are recommended or required to maintain the equipment in good condition and ensure the quality of the data.

19.1 DISASSEMBLY AND CLEANING

We recommend that the optical sampling and analysis cylinder should be removed and cleaned once every year or two, or at any time if there has been the possibility that foreign material such as insects, macroscopic dust or fluff has been drawn into the instrument by suction. This schedule may be accelerated in situations of high aerosol loading: a good guideline is to perform the cleaning every <u>second</u> time a roll of tape is installed. The disassembly and cleaning procedure takes less than 30 minutes; requires no special tools; requires no special skills; and the instrument may be re-assembled without any concerns about critical alignment or re-positioning of any components. The procedure is as follows:

(a) Remove the top and bottom instrument cover plates (4 screws each). Note the electrical grounding wires on tab connectors. The <u>lower</u> cover plate has a layer of black rubber thermal insulation.

(b) Remove the light shield covering the analysis chamber (2 thumb screws).

(c) Turn the instrument over to its underside. Remove the hose clamps that secure the sampling hose to the tube on the aerosol inlet fitting - use a small screwdriver to slide apart the two sets of gripping teeth. Disconnect the angled flexible black tubing that goes from the inlet port up and through the chassis plate to the analysis chamber.

(d) Push the inlet tube through the slot in the chassis plate to the upper side, so that it is loose.

(e) Turn the instrument back to its upper side. From the front, unscrew the knurled cap on top of the analysis chamber: note the electrical ribbon cable passing through.

(f) Lift up on the knurled cap, gently push approximately 1 cm. of ribbon cable through the grommet in the cap.

(g) Note the 10-pin flat cable connector inside on the right. Pull up on the cable GENTLY to pull the connector plug out of its socket. This is the power to the optical source assembly. In some cases, the optical source assembly may lift up on the end of the cable and come out of the top of the cylinder. If so, it is not necessary to disconnect the plug.

(h) Move the knurled cap to one side, with the cable passing through it and the connector (and possibly also the optical source board) dangling.

(i) Remove the spacer ring from UNDER the lifting frame: this is approximately 4 cm. in diameter but only 3 mm. thick.

(j)   There is now enough vertical clearance to lift up and pull out the optical analysis cylinder: the inlet tubing will follow behind like a tail.

(k)   The optical source assembly is in the top on a small gold-plated circuit board, or possibly loose. Clean it lightly with a soft cloth and alcohol. The sample analysis cylinder is underneath, with two quartz glass windows. The upper window is sealed; the lower window has an opening in the center fitted with a metal ring that defines the collection spot size. The sample air stream enters from the side. Clean the windows (inside and outside) with some alcohol and a soft cloth or cotton stick. Run solvent through the tubing and blow it out with light compressed air. If the optical cylinder is extremely dirty (for example, if sampling concentrated diesel exhaust), wash the optical cylinder in warm soapy water, then rinse and dry thoroughly with warm air.

(l)   Check the bypass filter cartridge (see next section)

(m)   Make sure everything is clean, re-assemble in the reverse order. Replace the optical cylinder; next, re-insert the spacer ring; finally, re-insert the optical source and/or reconnect its cable. Check the orientation of the optical source assembly: if it had been loose, be sure to re-locate it on the two small pins. Observe the tab on the cable plug to the sources, it only goes in one way round. All components are rugged, and there is NO critical alignment, provided that the source assembly is located on its pins.

(n)   When replacing the knurled cap, feel that the threads are properly engaged before tightening: don't strip them by being mis-aligned. Check that the optical cylinder and spacer ring are tight against the lifting frame.

(o)   Push the sample inlet tube down through the chassis plate. Turn the instrument over to its underside and reconnect the tube to the fitting on the rear panel. Replace and tighten the hose clamps.

(p)   Before putting the cover plates back on, run the instrument in 'Signals + Flow' test mode. Verify that you get good optical signals with the lamps ON and OFF by using the UP and DOWN arrow keys.

10.3   REPLACEMENT OF BYPASS FILTER CARTIDGE

The bypass filter cartridge is located at the rear of the upper chassis, above the sample inlet port. Its flow path is between a side connection to the sample inlet, and the bypass valve. When the bypass valve is not activated, pump suction is applied to the filter support grid in the analytical cylinder base, and the sample air stream is drawn from the inlet port through the filter tape. When the bypass valve is activated, pump suction is disconnected from the filter, and is instead connected directly to the sample inlet port, through the filter cartridge attached to a side fitting on the inlet. The purpose of the filter cartridge is to remove any particles from this air stream that might otherwise contaminate the bypass valve, the air mass flow meter and the pump.

The condition of the bypass filter cartridge does not affect the analytical operation of the Aethalometer™, provided it is not completely blocked. Even if it becomes visibly dark, it will not compromise the validity of the Aethalometer data. The flow resistance of the bypass filter cartridge is always much less than the flow resistance of the quartz fiber filter tape. Therefore, even if the cartridge becomes substantially loaded with collected particles, it will not affect the air flow. The reason for changing the bypass filter cartridge is simply to prevent it from becoming completely blocked with dust or other aerosol particles.

The bypass valve is activated only under the following conditions:

during filter tape advances. This removes suction from the underside of the filter tape, while it is being pulled across the support grid. This reduces the drag on the tape and reduces the probability of scraping quartz fibers from the tape.

during operation of the 'Tape Saver' mode. This applies a time fractionation to the sample air stream during each timebase period, to reduce the number of liters of air from which BC is collected. This reduces the rate of BC accumulation and prolongs the lifetime of each filter spot under conditions of high concentration.

If 'Tape Saver' is <u>not</u> used, very little air flow passes through the bypass filter cartridge: only during tape advances. In this case, the filter cartridge will last a long time before it starts to become visibly dark. If 'Tape Saver' <u>is</u> used, sample air will flow through the filter cartridge for a substantial fraction of the operating time, and the filter cartridge will collect a greater deposit of particles. If the bypass filter cartridge is visibly dark, replace it during the routine process of cleaning the inlet cylinder.

To replace the Bypass Filter Cartridge:

The Bypass Filter is a standard cartridge filter with ¼" (6 mm.) diameter smooth connection stems for press-fit. Its diameter is 1" (25 mm.) and its overall length is 3 ¼" (83 mm.). It may be replaced with any equivalent: alternatively, contact Magee Scientific for a replacement at no cost.

Press on the release ring of the fitting to allow the cartridge stem ends to be pulled out. When inserting the new cartridge, be sure to press the stems firmly into the fittings, to seal them in the internal o-rings.

10.4   FLOW AUDIT: FLOWRATE ERROR SCALING

The relationship between an increase in optical attenuation (as defined precisely by the ratio of photodetector signals), and a collected quantity of carbon in a specific 'elemental' form, is defined by an absorption cross-section per unit mass that is an intrinsic property of the carbonaceous material. This relationship is defined by the 'sigma' factor used in the Aethalometer algorithm but does not require periodic calibration or verification. However, knowledge of the number of liters of air from which these nanograms of BC were filtered _is_ required to calculate the concentration result. The mass flow meter used in the instrument returns a voltage signal proportional to the flow rate of air passing through it, and its recalibration in case of erroneous response is described in Section 14 above.

This recalibration should **only** be performed if it is believed that the actual flowmeter response itself is inaccurate. However, air flow reporting errors may occur as the result of leaks or blockages: the flowmeter may be reporting its signal correctly, but this may differ from the true flow rate of aerosol sample entering the instrument through its rear-panel sampling port. For example: if the hose connecting the inlet port to the sampling chamber were broken or disconnected, air would be drawn from the interior of the instrument chassis through the filter tape spot and thence through the flowmeter. The flowmeter might correctly report a flowrate of (say) 4 SLPM, but there would actually be no sample flow at all through the rear panel connector. It is therefore a wise precaution to verify the sampling flowrate by means of a flow audit at periodic intervals.

The **Flow Audit** is performed by simply connecting a standard flow measuring device to the inlet port, and comparing its reading of air flow entering the Aethalometer to the internal flowmeter signal as reported in the 'Signals + Flow' menu mode. (see section 12.3.3). Under 'normal' operating conditions, the internal flowmeter reading may differ by some percent (e.g. up to 0.5 LPM) due to minor internal leaks, especially air flowing tangentially through the edges of the filter tape. Thus, for example, the internally-reported flowrate used by the algorithm may be 4.0 LPM, while actually only 3.8 LPM are entering the sample inlet port on the rear panel: 0.2 LPM of leakage are occurring internally, adding to the flow through the flowmeter but not representing external air sampled. In such a case, the algorithm is dividing the determined number of nanograms of BC by 4.0 instead of 3.8: the reported data is too low by a simple scaling factor of (3.8 / 4.0) i.e. 5%. Correct data will be recovered by simply increasing the reported values by a correction factor of 5% : the scaling is directly proportional to the flowrate error factor.

Even if the flowrate scaling factor differs from unity, the sampling and analytical capability of the Aethalometer is not impaired. The optics and electronics still perform an accurate measurement of the increment of BC collected: the only error lies in the assignment of this increment to a certain number of liters of air. If this

error can be corrected by simple numerical scaling, the correct result will be recovered.

Recommendation: perform an external flow audit at least once per year, and also _before_ and _after_ any critical study period.

20.   USE OF PURE QUARTZ FIBER FILTER TAPE

The Aethalometer is an analytical instrument that measures the concentration of optically-absorbing 'Aerosol Black Carbon' particles in the sampled air stream by a differential-ratiometric optical transmission method. The particles are collected on a quartz fiber tape whose deep mat of optically-scattering fibers ensures that the instrument responds **only** to optically-*absorbing* particles, **not** to optically-*scattering* particles.

The optical response of the system has been calibrated against a chemical determination of the 'elemental' carbon content of the sample, using a protocol of extraction of inorganic and organic content using solvents of increasing polarity, followed by temperature-programmed thermal desorption of the remaining material in an oxygen stream. This analysis can **<u>only</u>** be performed on a material whose intrinsic carbon content is **<u>zero</u>**: namely ***pre-fired pure quartz fiber***. The definitive publication on this topic is:

L.A. Gundel, R.L. Dod, H. Rosen and T. Novakov, "The relationship between optical attenuation and black carbon concentration for ambient and source particles", *Sci. Total Environ.* **36**, 197 (1984).

Copies of this reports are available from *Magee Scientific Company*. Numerous reports since this early work have compared Aethalometer measurements with the results of other analyses in laboratory and field studies.

Pre-fired pure quartz fiber filters were used in all the earliest Aethalometers to collect and analyze the samples. However, this material is very fragile, and is not well suited to the mechanical stresses of tape transport as required for an automatically-changing instrument for continuous unattended operation. Nevertheless, a proprietary pure quartz fiber tape was developed, and success was achieved with a mechanism specially designed for moving the brittle tape through the machine. However, this mechanism was not suitable for the large rolls of tape required for long-term monitoring applications.

Consequently, *Magee Scientific Company* developed another proprietary product, namely web-reinforced quartz fiber tape. This uses the same quartz mat material, and retains the identical optical characteristics of the original filtration medium on which the instrument was developed. The addition of a thin reinforcing web underlayment allows the tape to be pulled through a feeder mechanism and spooled up after use without breaking.

However, the reinforcing underlayment is cellulosic: and the result is that the filter tape no longer has a <u>zero</u> carbon content. This renders it unsuitable for post-Aethalometer chemical analysis for speciation of the carbonaceous component of the aerosol sample.

For situations in which chemical analysis *is* required, pure pre-fired quartz fiber tape may be used: but with special handling conditions required, since the tape can **not** be spooled.

Instructions for Use of Pure Quartz Tape

Remove the 'normal' reinforced tape, following the 'Tape Change Instructions'. Install the roll of Pure Quartz Tape on the left-hand 'tape supply' side. Pull it through the analyzer unit when the "Tape Advance" button is pressed.

Do Not attach the loose end of the pure quartz tape to the right-hand take up hub: instead, allow it to hang free.

Collect the samples by normal operation of the instrument. Whenever a tape advance is called to prevent optical saturation of the sample collection spot, the loose end of the tape will be ejected forward another centimeter into the instrument front compartment.

To Recover Tape Spots for Subsequent Chemical Analysis :

Push the "Tape Advance" button, pull on the loose end of the tape about 3 inches until the collected spot becomes visible. Cut off with scissors the portion of tape holding the spot, punch out the spot for analysis.

Revert to use of Reinforced Tape as soon as chemical analysis procedures are no longer required. **Do Not** run the instrument for extended periods of unattended monitoring operation, using the non-reinforced pure quartz fiber tape.

21. HARDWARE REFERENCE INFORMATION

21.1 PROCUREMENT SPECIFICATIONS

The following text may be used to define a formal procurement specification for use by Purchasing Officers:

General Specifications:

Magee Scientific Aethalometer™ to include the following:

1. Complete, self-contained chassis
2. Dimensions: 19" Wide, 11" High, 12" Deep
3. Weight not to exceed 40 Pounds
4. Filtration and Analysis Chamber to provide continuous filtration with optical transmission analysis to measure elemental carbon
5. Automatically advancing quartz fiber filter tape
6. Internal sample aspiration pump
7. Air mass flow rate control
8. AC power cord
9. Sample inlet tubing
10. Sample inlet fittings
11. Roll of filter tape
12. Floppy disk drive 3.5"
13. Box of 3.5"disks
14. <0.1 micrograms/meter-cubed sensitivity
15. 5% Accuracy
16. 100-240 VAC 50-400Hz power input, auto switching
17. One (1) digital output
18. One (1) analog output
19. Environmental Technology Verification evaluated

Additional Terms and Conditions:

20. Delivery shall be within 45 days after receipt of order.
21. Equipment shall be new, of current production, and shall include the manufacturer's standard parts and accessories.
22. Operating Manual and Quick Start Guide shall be included with each instrument. The manual shall include complete operating instructions, theory of operation, location of controls and switches, software commands, schematic drawings.
23. Warranty period: Complete coverage of system, software, parts and labor for a minimum of one (1) year from date of acceptance.
24. The goods or materials ordered with this request will be subject to acceptance testing upon receipt.
25. Payment will be made within 30 days after receipt of goods or invoice, whichever is later.

21.2   REAR PANEL CONNECTIONS

<u>Electrical Signals</u>

(a)   Analog Output Voltage: (+) and (-) banana jack / clamp terminals.

(b)   Communications Connector: 9-pin D-sub

         This connector features the standard pins for the IBM-PC COM functions. Note that for connection to a standard computer, a <u>*null-modem cable*</u> **must** be used.   The baud rate, parity, etc. are set up in the operating software parameters.

Power

(c)   Standard IEC-320 receptacle incorporating slow-blow 2 amp fuse and secondary on-off switch

Air Flow

(d)   Suction Connection for External Pump (if required)

Sample Inlet

(e)   ¼" FPT threaded receptacle into which any standard fitting may be threaded, including the selection of fittings provided with the instrument, and a block-off cap to prevent entry of debris during shipping.

21.3 **FACTORY TESTING AND CERTIFICATION PROCEDURES**

Every Aethalometer™ is subjected to two independent sets of technical and scientific performance testing before being shipped from the factory.

21.3.1 Technical Performance Certification

Each Aethalometer is tested rigorously after assembly at the factory, to ensure that all supply and signal voltages are within specifications. These results are documented on the Performace Testing Report that is included with each instrument's documentation. These tests ensure that the electronic, optical and mechanical components are functioning correctly.

21.3.2 Scientific Performance Certification

It is, however, irrelevant for the signal voltages to be within specification, if the scientific performance – i.e. the actual data when measuring aerosol particles – is unsatisfactory. Therefore, every instrument is certified by an independent scientific laboratory after completion at the factory and before shipping. This certification is performed by the Analytical Chemistry Department of the National Institute of Chemistry of Slovenia, according to the following protocol:

**Standard Aethalometer™ Testing and Calibration Protocol
as performed by the National Institute of Chemistry, Ljubljana, Slovenia**

M. Bizjak, Ph.D., Head, NIC Analytical Laboratory

Aethalometer Testing and Calibration

1.   Flow Integrity Testing

Each instrument is tested with a standard setup consisting of two "low-impedance" mass flow meters (Sierra Instruments Model 730), whose calibration may be traced to the U.S. National Institute of Standards. One is connected to the Inlet Port, the other to a pumping connection. The air mass flow rates in and out of the sampling head are compared, in order to detect any internal leaks in the instrument. The results of this test are recorded on the Final Inspection Record and Certification Sheet for each instrument.

2.   Flow Response Calibration

The Aethalometer™ software includes an internal calibration feature that allows the system to perform a two-point calibration for the response of the internal mass flow meter or controller. The instrument must first be allowed to stabilize under normal 'power-on' operating conditions for a minimum period of one hour before this calibration is performed.

Firstly, the pump is turned off or disconnected. The internal flowmeter is allowed to stabilize to this condition for a minimum of 30 seconds. The software then records its internal response to a zero-flow condition. This represents any offsets in the electronics, analog-digital converters, etc.

Secondly, the external standard low-impedance mass flow meter is connected to the instrument's inlet port, and a standard value of operating flow (5.0 SLPM) is produced by connecting the pump and adjusting the flow rate using either the pump motor speed controller or an external flow control valve (depending on the instrument model). This condition is maintained for a minimum of 30 seconds prior to measurement, to allow both mass flow meters to stabilize.

Some instruments incorporate a Mass Flow Controller, whose set point may be adjusted from the front panel. In these cases, the setpoint is adjusted to an inlet flow of 5.0 SLPM (i.e. calculated for conditions of 1017 mb pressure, 20 °C temperature).

The computer system is then activated to record the response. It assigns the signal to the value of flow indicated by the external standard, representing the sample air flow entering the instrument.

The computer algorithm then calculates the response factors such that a signal from the analog-digital converter can be accurately interpreted as an actual inlet sample flow entering the instrument, using a linear interpolation from the 'zero' and 'span' calibration points. Completion of this test is indicated on the Final Inspection Record and Certification Sheet.

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3.   Clean Air Dynamical Test

The instrument is connected to a manifold that is flushed with particle-free air at ambient temperature, pressure and humidity. Ambient air from the outdoor urban environment is pumped at a flow rate of approximately 20 SLPM through a quartz fiber filter (Pallflex 2500QAT-UP, filtration efficiency > 99.9% for particles of aerodynamic diameter > 0.1 micrometer, performance traceable to measurements performed by the U.S. National Institute of Standards). This particle-free air stream enters a long manifold tube, whose distant end is vented to the ambient atmosphere. This ensures that that the manifold absolute pressure is identical to the laboratory atmospheric pressure. The sample inlet port of the Aethalometer™ under test is connected to the manifold, and the instrument is operated for a period of 24 hours to sample air that is free of BC particulates. The response of the instrument is recorded and calculated as a 'Zero Air Mean' and 'Zero Air Standard Deviation'. Under ideal circumstances these values would be 0.0 ng/m³ +/- 0.0 ng/m³. In practice, there may be an extremely small bypass or infiltration of particle-laden ambient air from the laboratory, where the BC concentrations are normally in the range of 1000 -3000 ng/m³. Thus, the 'Zero Air Mean' value may be slightly above zero. We allow an acceptable limit of 20 ng/m³. However, higher values of 'Zero Air Mean' response would indicate an internal leakage of particle-laden ambient air into the internal plumbing. This is therefore a more sensitive test of leakage than the input-versus-output flow rate test mentioned above.

In addition, instrumental electronic noise will result in a small fluctuation of each individual reading. Thus, the 'Zero Air Standard Deviation' represents the noise level of the instrument under the stated conditions of timebase and air mass flow rate. An acceptable limit is +/- 30 ng/m³ computed for a time base of 5 minutes at an air flow rate of 5 LPM. The results of this test are recorded on the Final Inspection Record and Certification Sheet.

4.   Ambient Air Test and Intercomparison with Standard Reference Instrument

The Aethalometer™ under test is next connected to a second manifold that is flushed with realistic, representative particle-laden ambient air from the external urban environment. Concentrations of BC in this atmosphere are highly variable, usually ranging from 1000 ng/m³ to 20000 ng/m³, depending on season and weather conditions. The instrument is connected to a manifold port that is adjacent to a port from which a Standard Reference Aethalometer™ also draws its sample. The two instruments are operated in parallel for a period of 24 hours. During this period, it is usual that the concentration of BC in the sampled air stream will vary by at least one order of magnitude. The data from the instrument under test are displayed versus the data from the Standard Reference Instrument. The regression of the two data sets is calculated to display the response of the instrument under test. This is reported on the Final Inspection Record and Certification Sheet as a response ratio and standard deviation over a BC concentration range.

22. FIGURES

Identification of Major Components

Flow Schematics

'Portable' chassis model diagrams
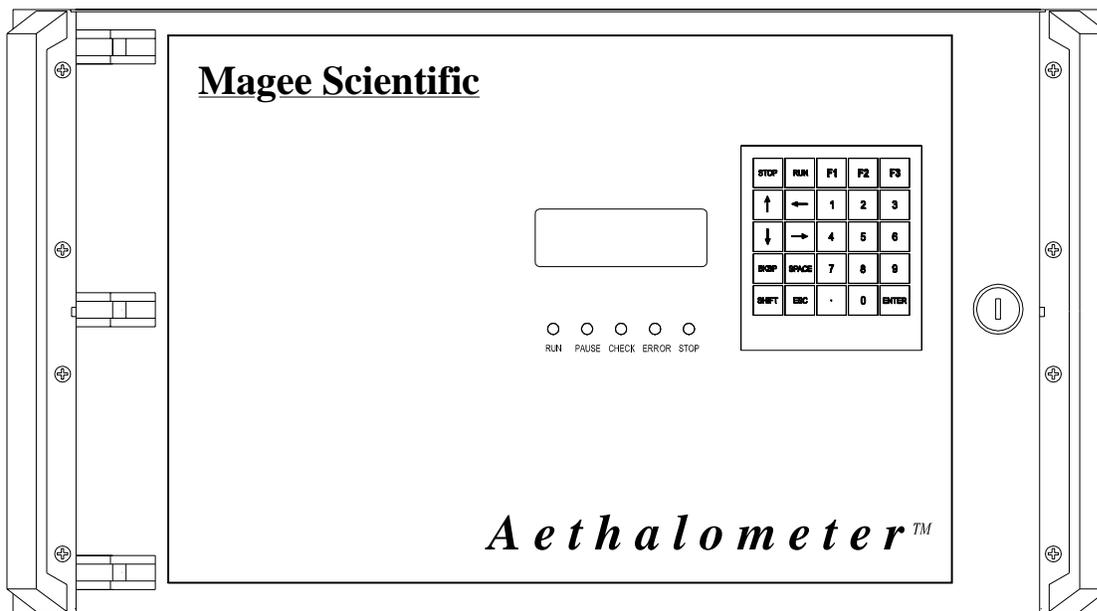
Figure 1 : Front Panel
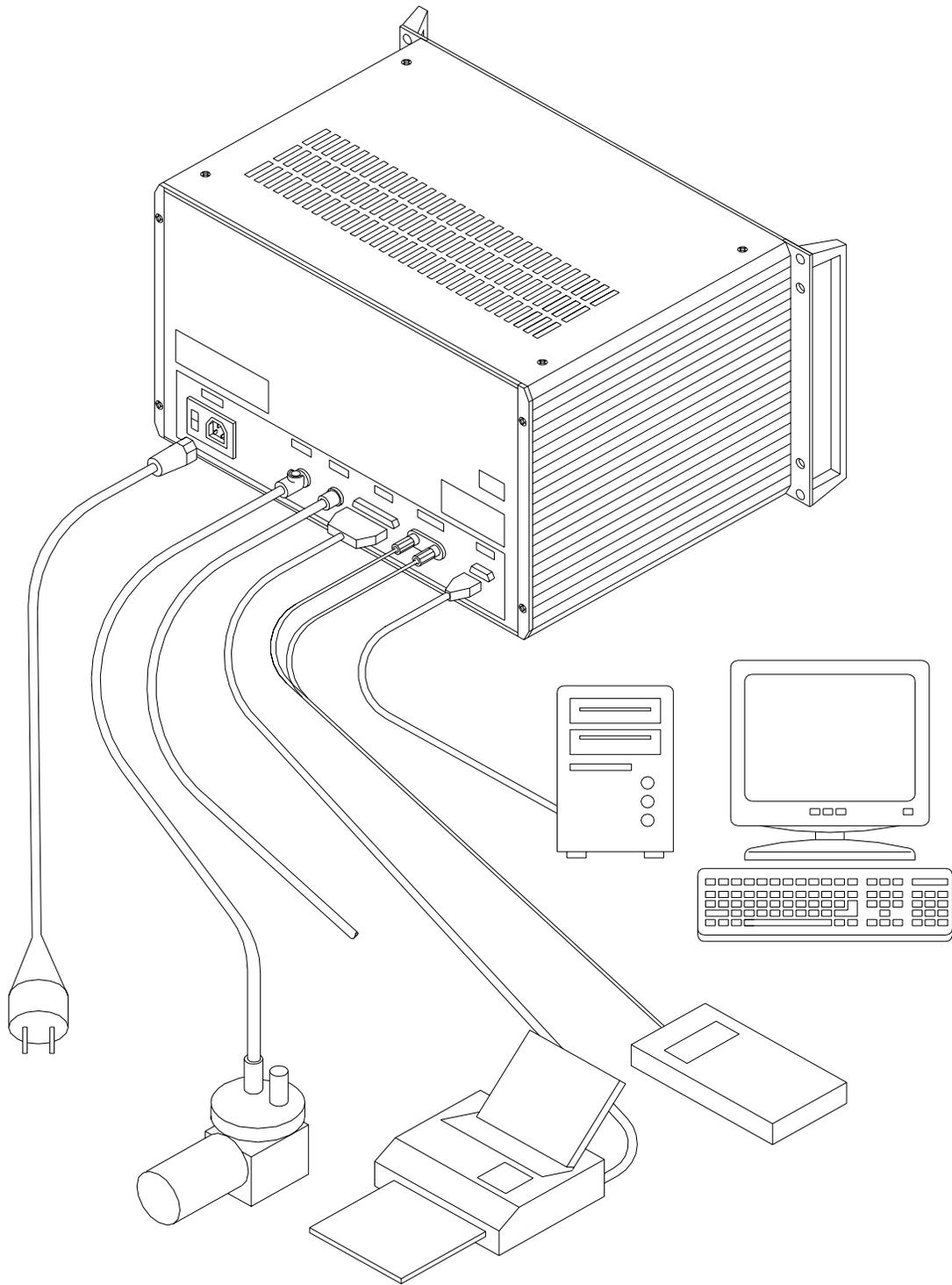
Figure 2 : External connections
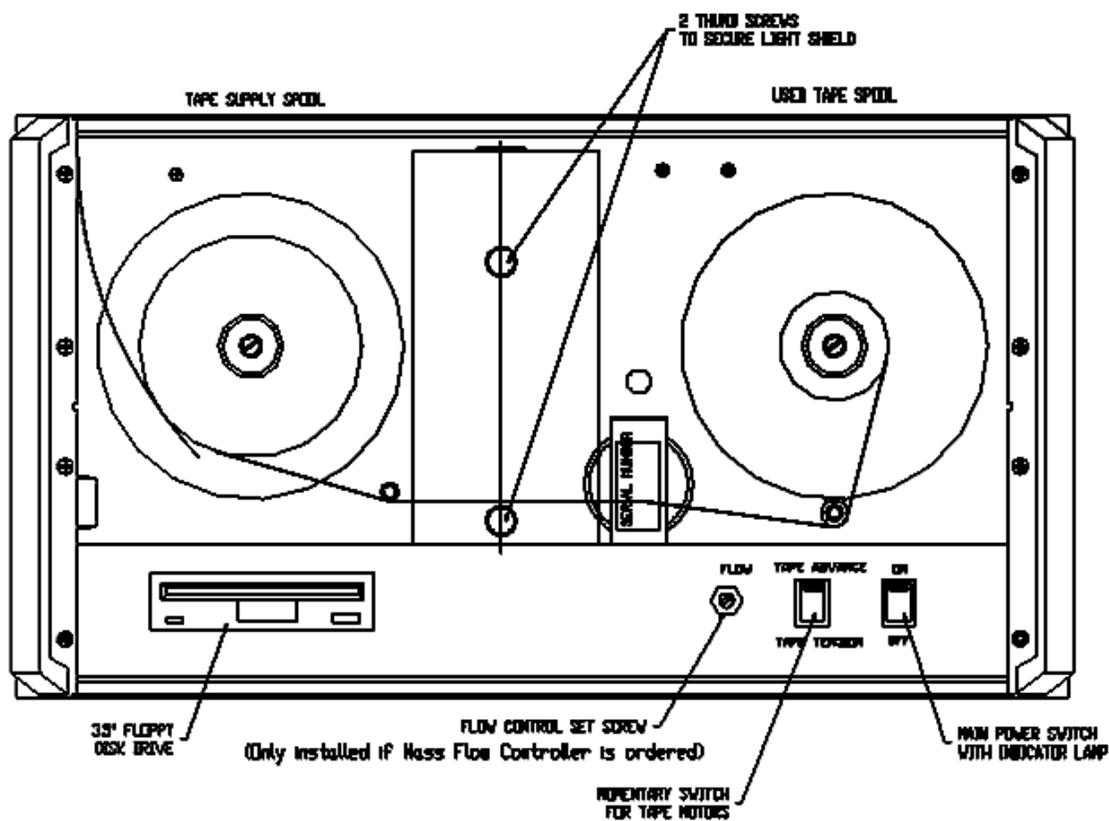
Figure 3 : Front View, interior
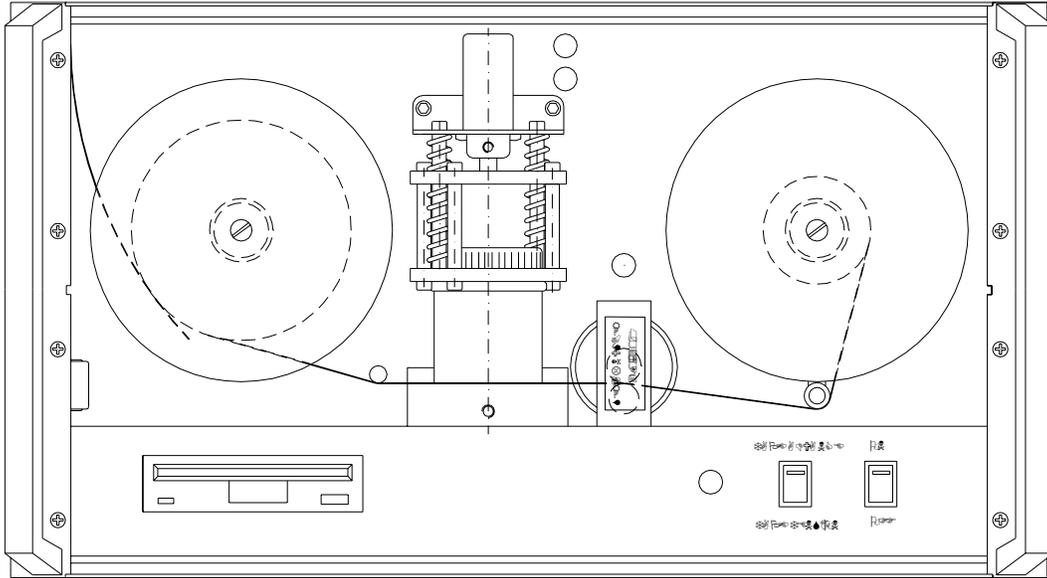
Figure 4 : Front View, Interior, Light Shield Removed
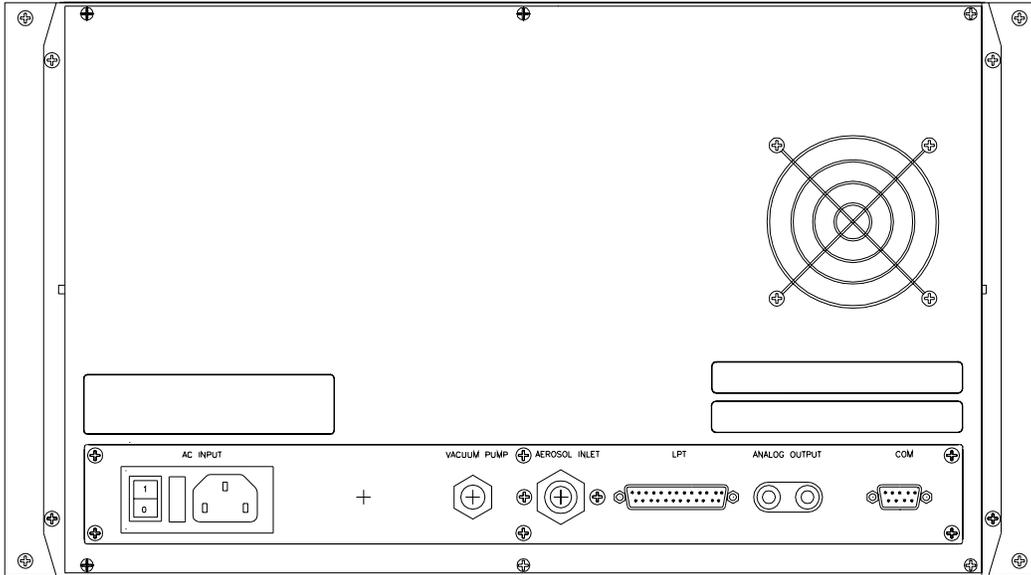
Figure 5 : Rear Panel
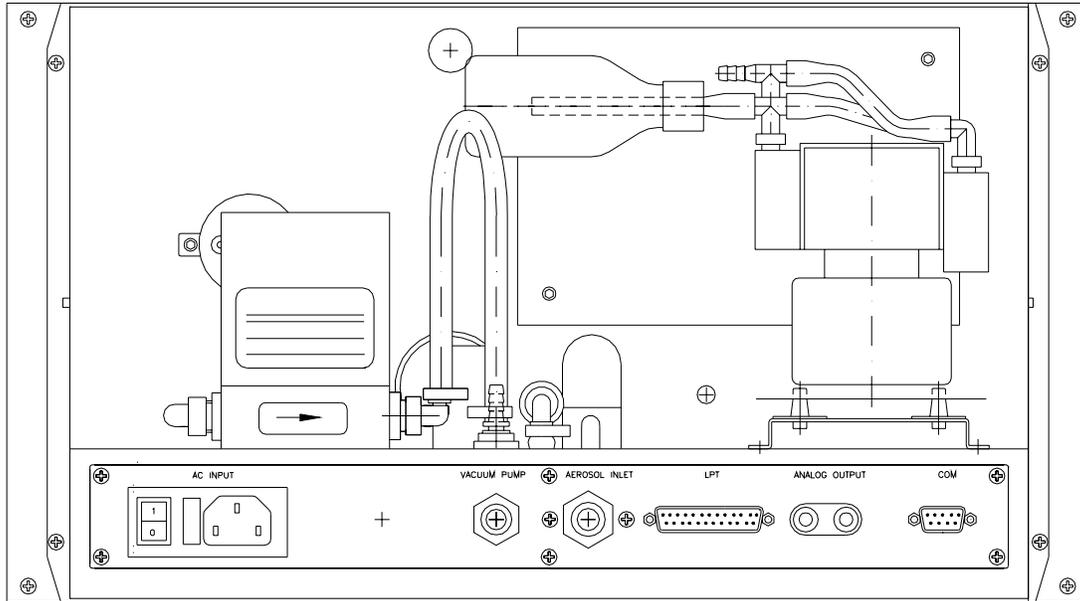
Figure 6 : Rear View – Interior – instrument configured for 'External Pump'
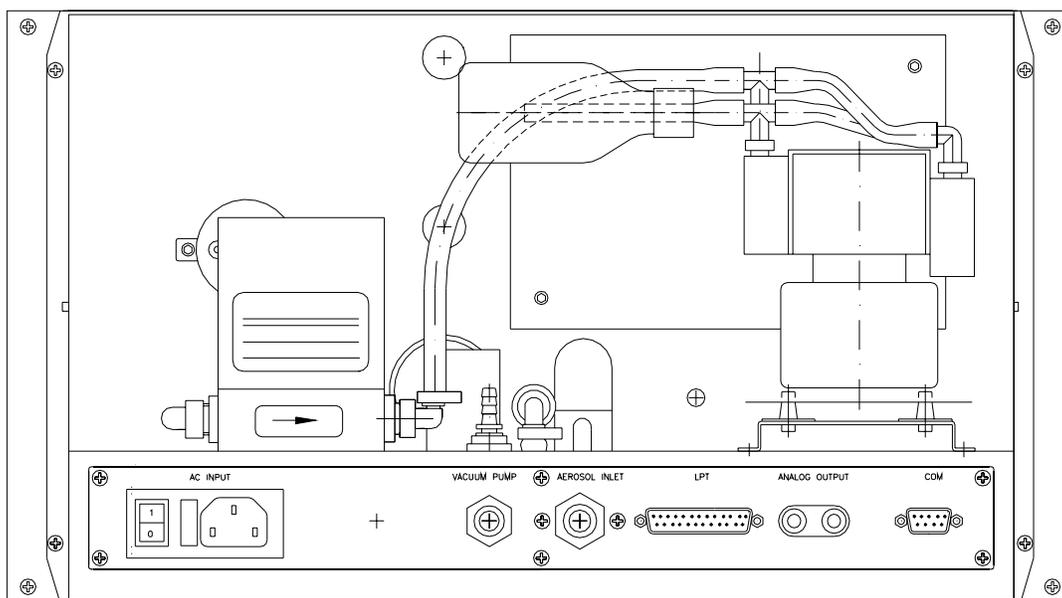
Figure 7 : Rear View – Interior – instrument provided with Internal Pump
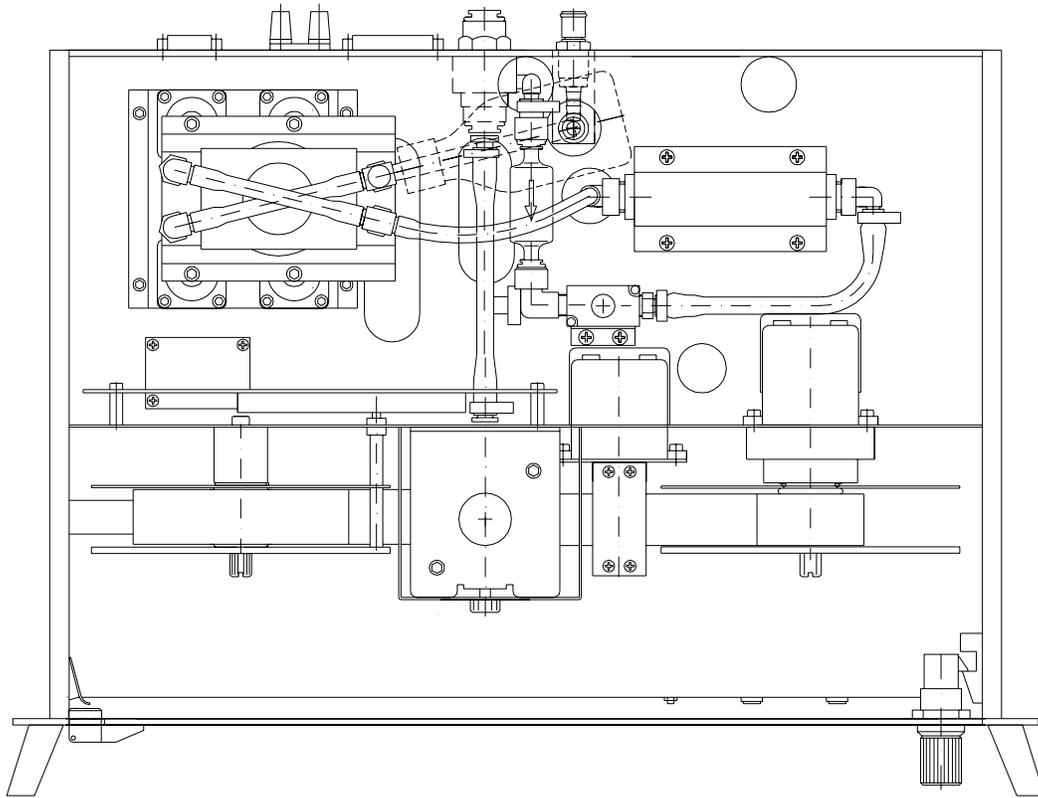
Figure 8 : Top View – Interior – instrument fitted with Internal Pump
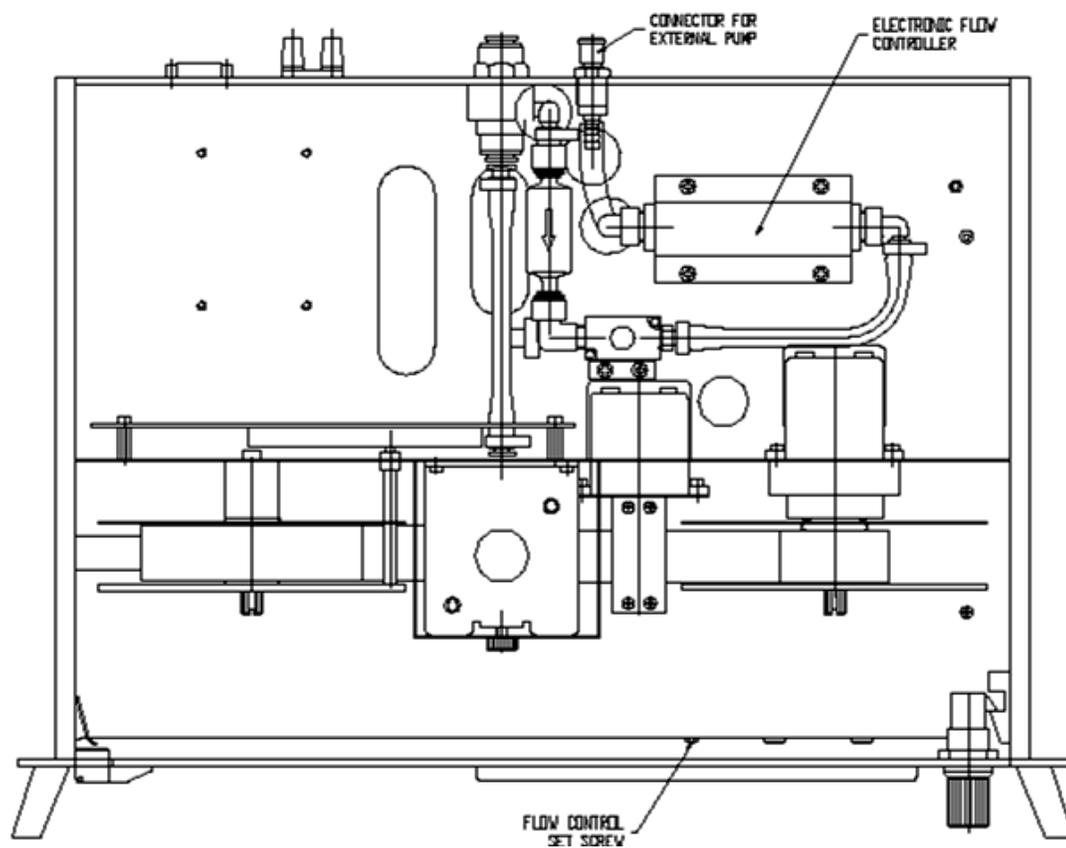
Figure 9 : Top View – Interior – instrument fitted with Electronic Mass Flow Controller (requires External Pump)
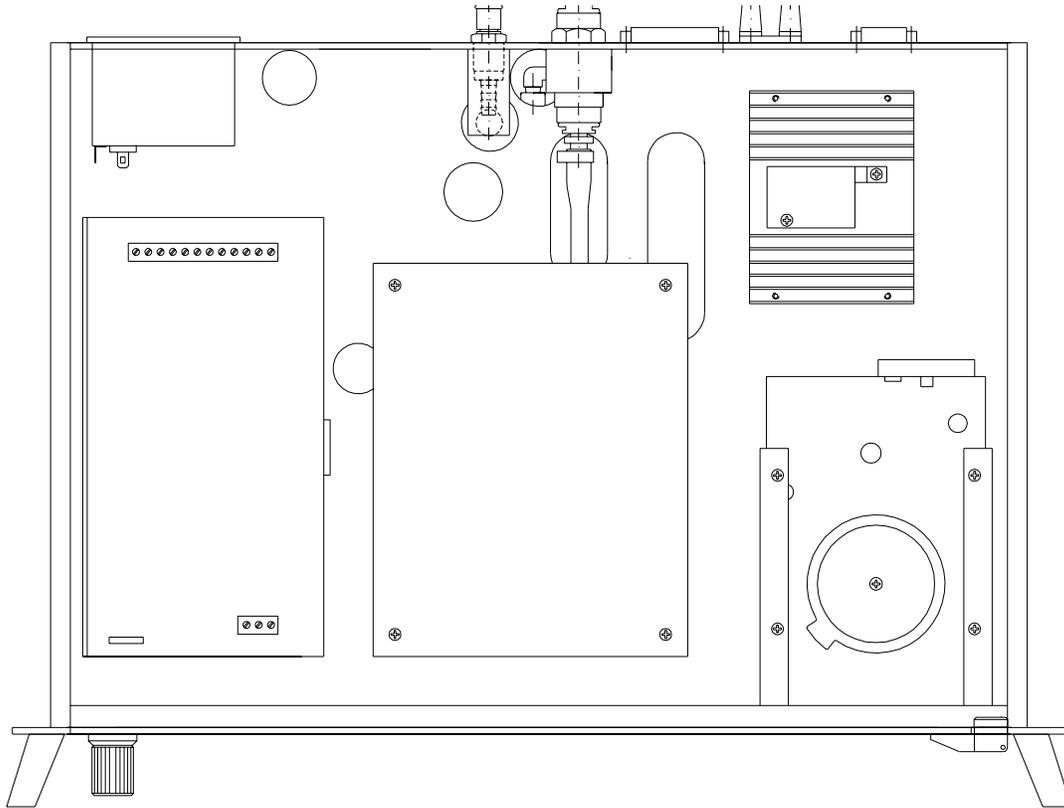
Figure 10 : Underside View – Interior
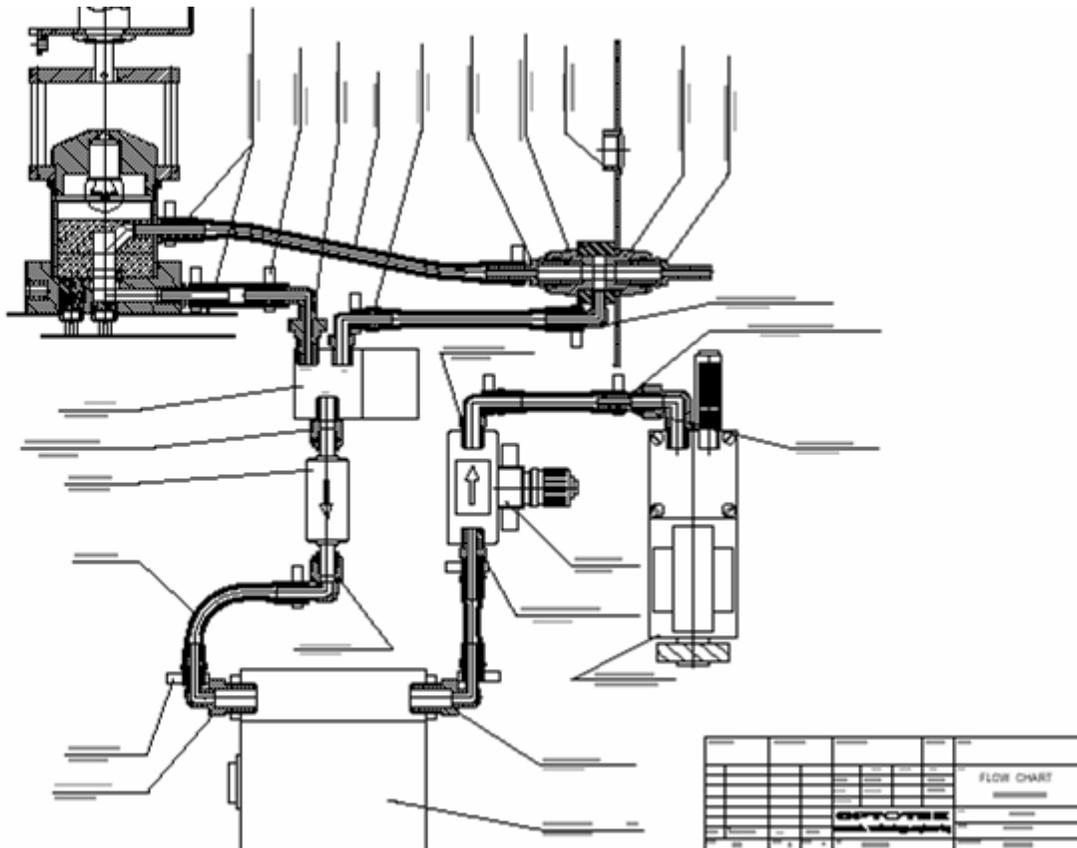
Figure 11 : Air Flow Schematic – Internal Pump
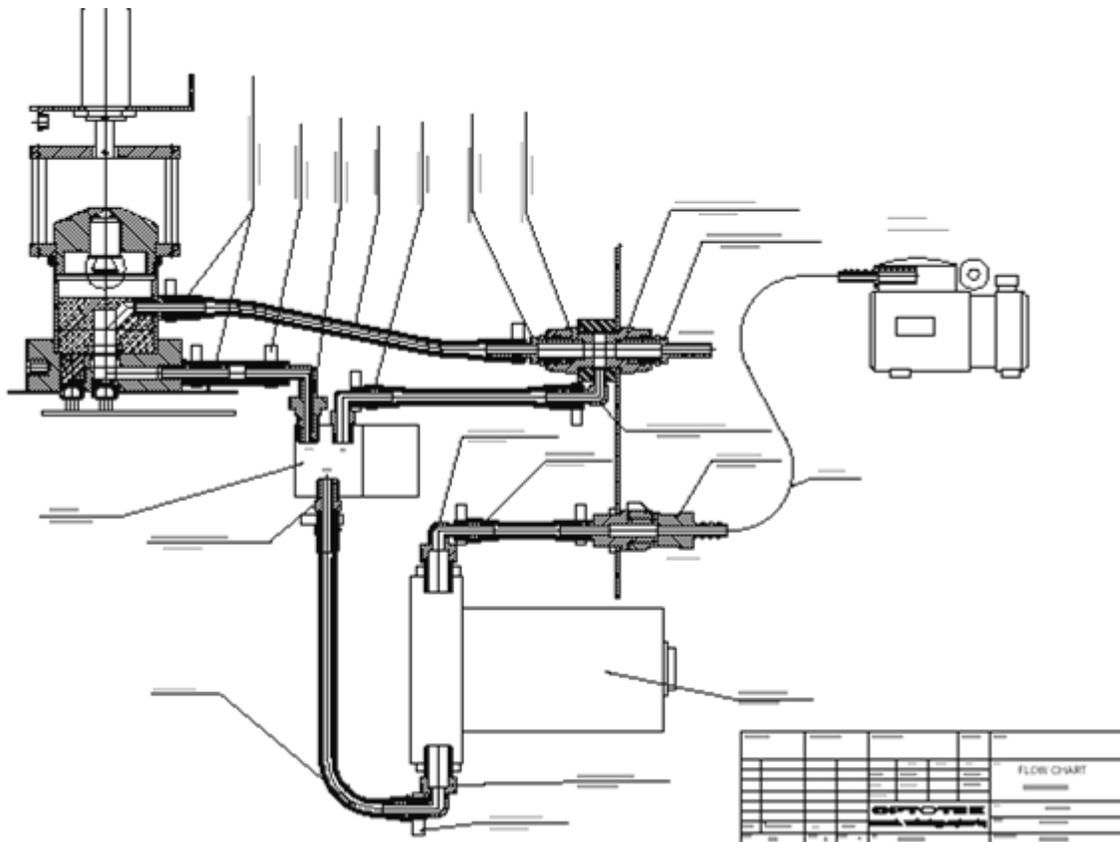
Figure 12 : Air Flow Schematic – External Pump
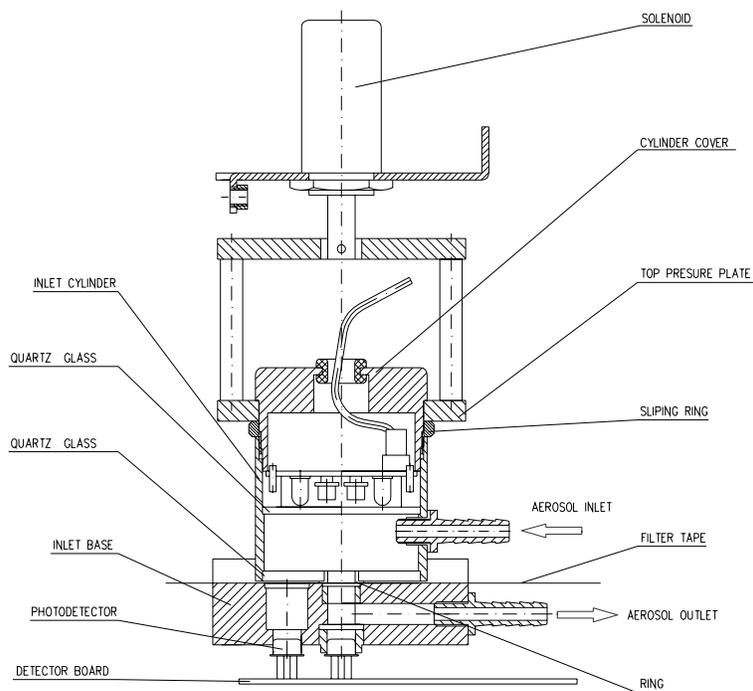
Figure 13 : Cross-Section of Optical Analysis Head (diagrammatic only)
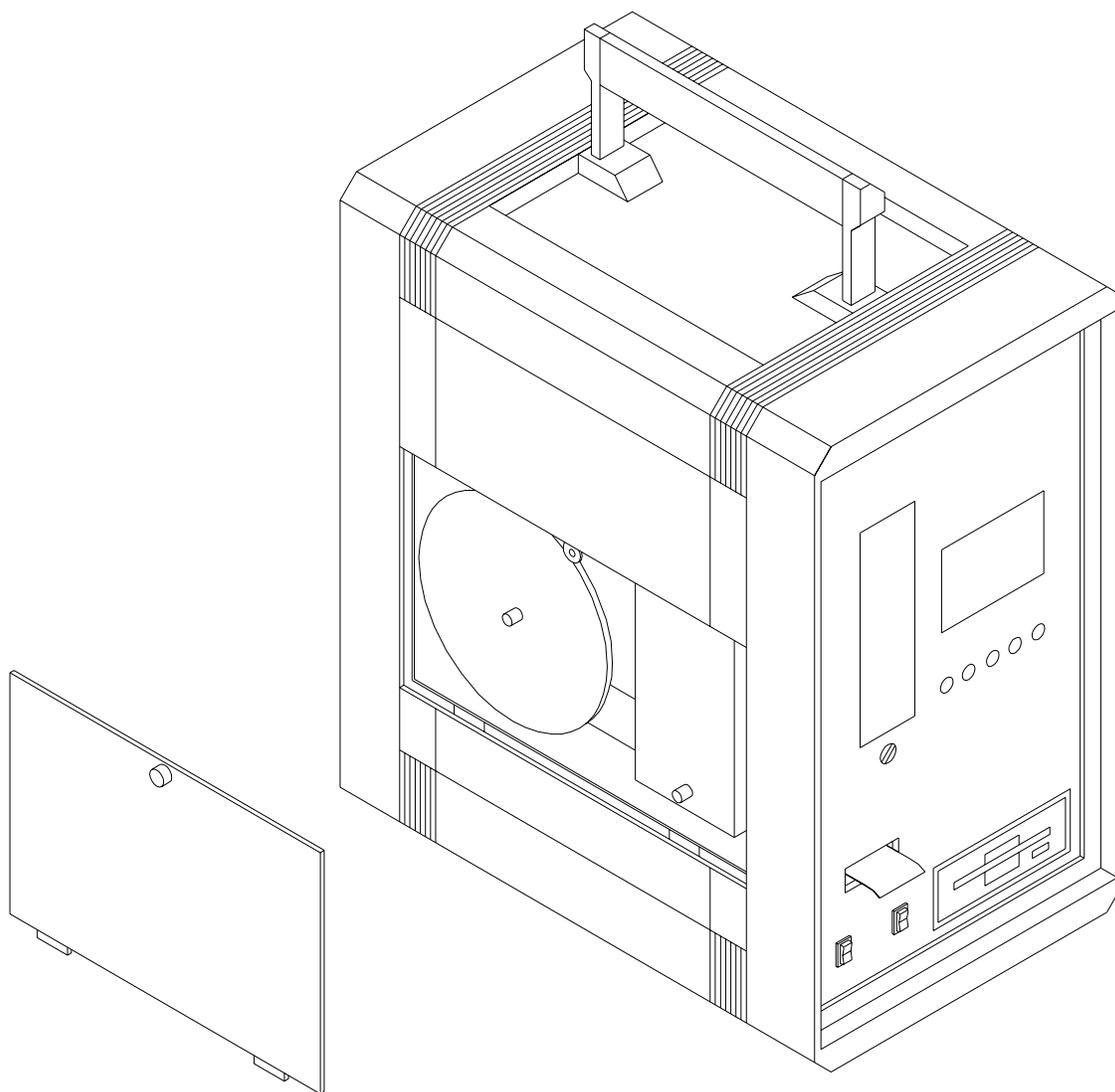
Figure 14 : 'Portable' Aethalometer™ - left side front view, access door open
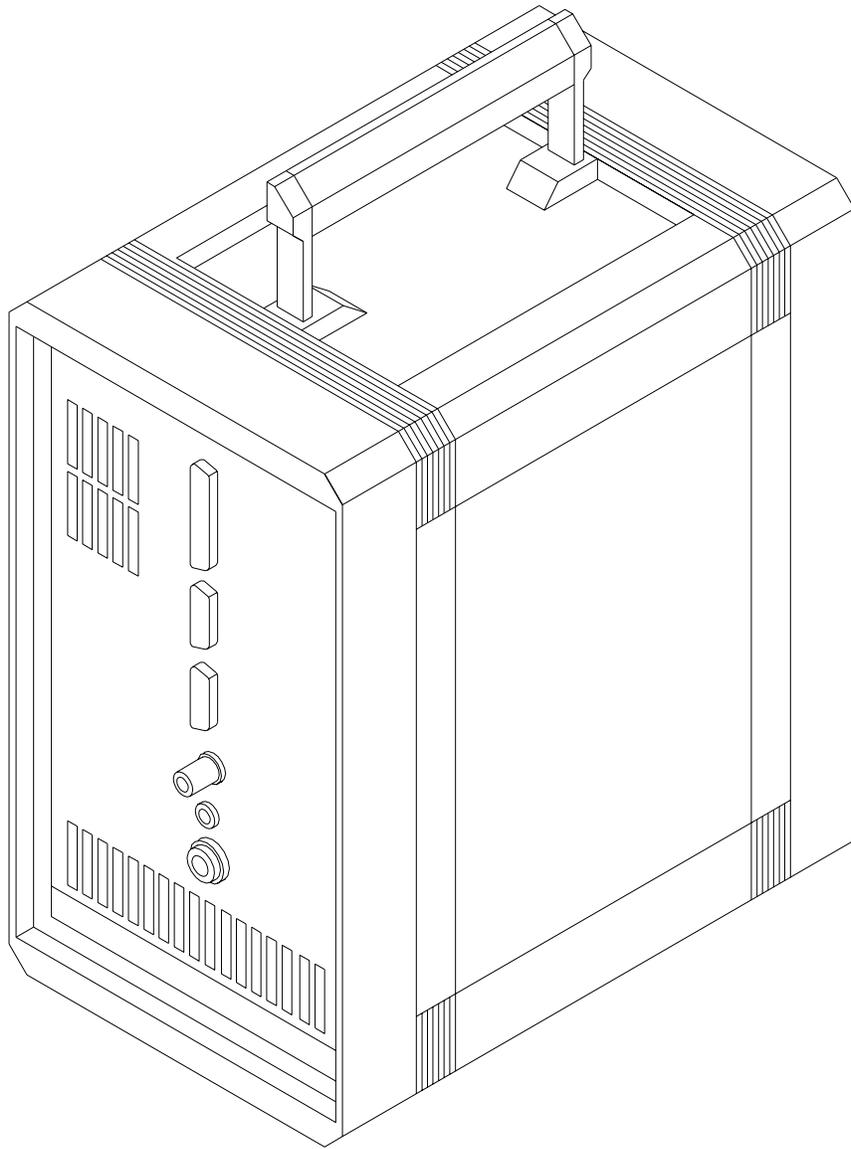
Figure 15 : 'Portable' Aethalometer™ - left side rear view
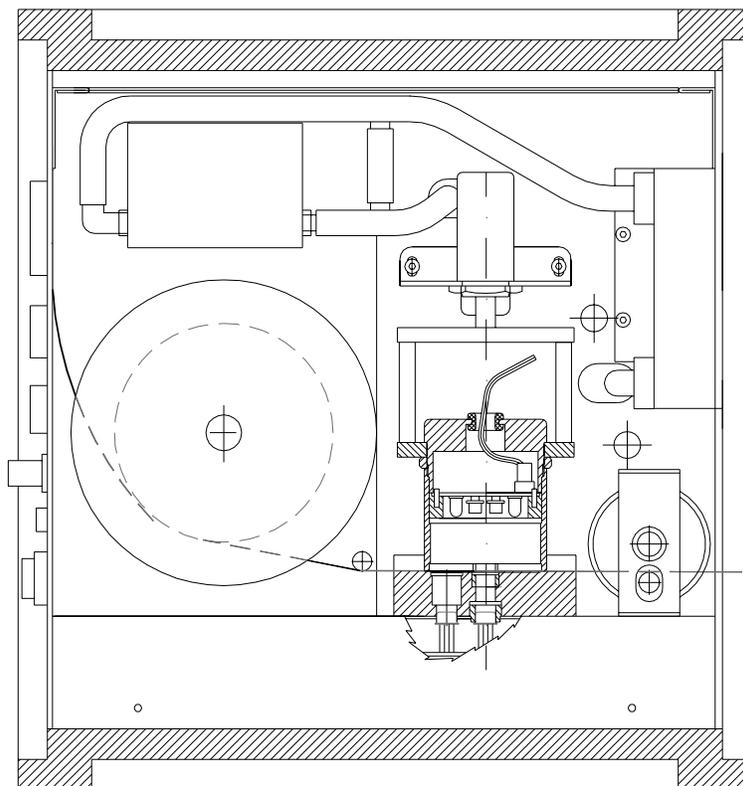
Figure 16 : 'Portable' Aethalometer™ - left side interior
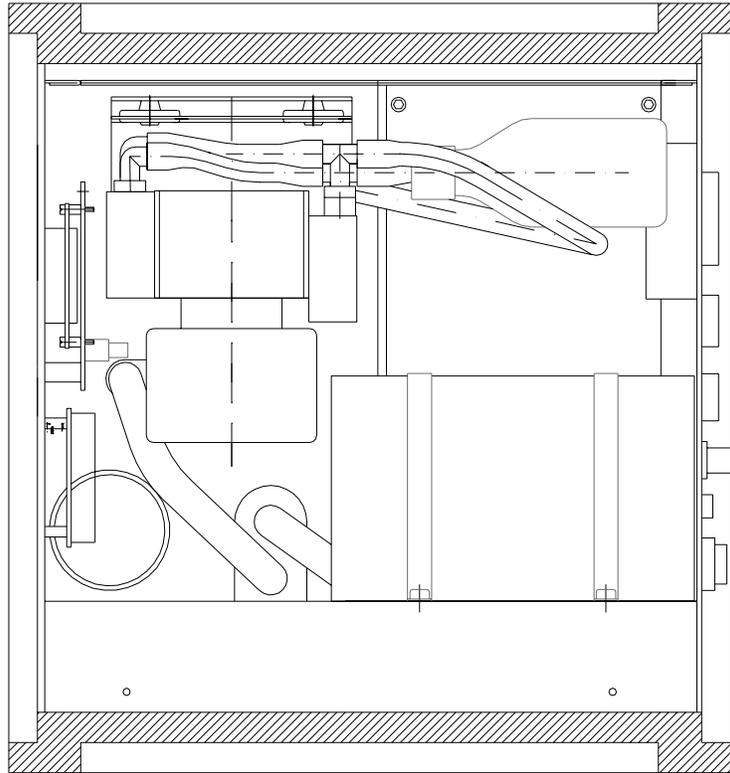
Figure 17 : 'Portable' Aethalometer™ - right side interior
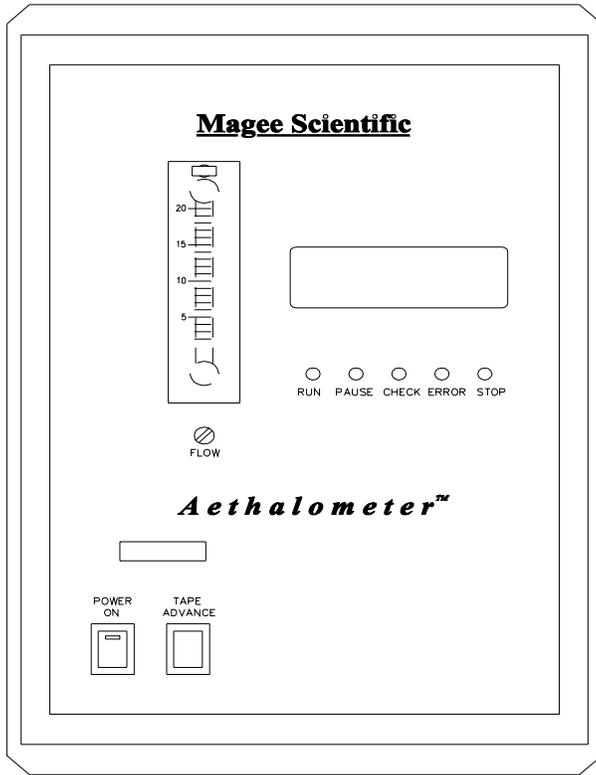
Figure 18 : 'Portable' Aethalometer™ -fromt view
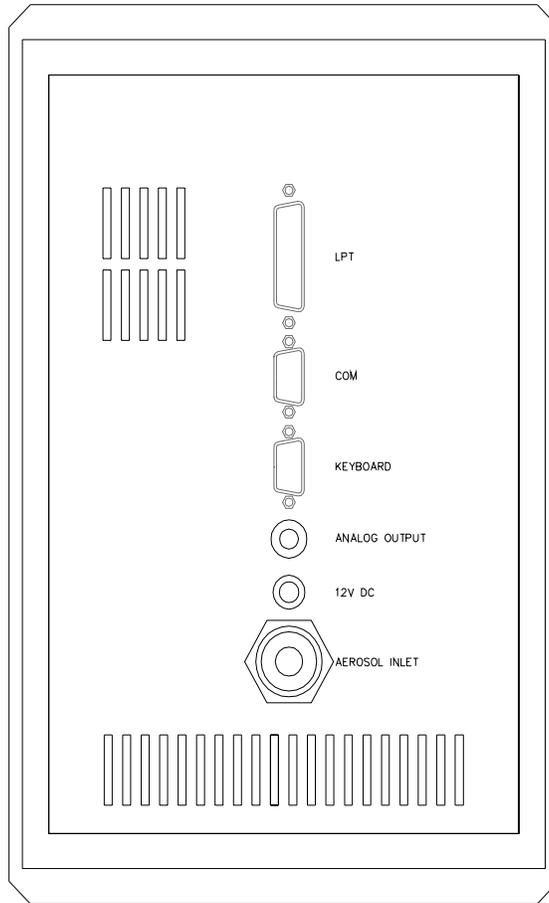
Figure 19 : 'Portable' Aethalometer™ - rear view

23.   MAGEE SCIENTIFIC COMPANY

Research into methods for the real-time measurement of optically absorbing aerosols began in Berkeley in approximately 1978. The first-ever Aethalometer™ was deployed in a field study in the summer of 1980: the first aircraft measurements were made in 1982, and in 1986 an Aethalometer started making measurements of aerosol black carbon at the most remote location on the planet, the South Pole Observatory. Magee Scientific Company was established that same year to develop the Aethalometer further and make it available to the aerosol research and monitoring community. From 1999 to 2001, the instruments were also distributed by *Andersen Instruments Inc.* as identical hardware, but with the chassis painted in 'Andersen' colors and name. Distribution by Andersen has now been discontinued.

Aethalometers have been used in increasing numbers over the years: a large number of reports have been published in the open scientific literature. For further scientific or technical information, please contact the Magee Scientific office as shown below, or see the Magee Scientific web site at ***http://www.mageesci.com*** . This site provides a wealth of information on Aethalometers, examples of Aethalometer applications, downloadable documentation and software upgrades, and other related material.

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Berkeley, CA 94703, USA	e-mail:	Mail@MageeSci.com

24. LITERATURE AND REFERENCES

24.1 ARTICLES IN PRINTED FORM

Copies of the following publications in printed form may be requested free of charge from our offices:

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