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To be presented at the Second International Conference on Carbonaceous Particles in the Atmosphere, Linz, Austria, September 11-14, 1983

THE AETHALOMETER - AN INSTRUMENT FOR THE REAL-TIME MEASUREMENT OF OPTICAL ABSORPTION BY AEROSOL PARTICLES

A.D.A. Hansen, H. Rosen, and T. Novakov

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THE AETHALOMETER — AN INSTRUMENT FOR THE REAL-TIME MEASUREMENT OF OPTICAL ABSORPTION BY AEROSOL PARTICLES*

A.D.A. HANSEN, H. ROSEN, and T. NOVAKOV
Applied Science Division, Lawrence Berkeley Laboratory, University of California, Berkeley, California 94720, USA

ABSTRACT

We describe an instrument that measures the concentration of optically absorbing aerosol particles in real time. This absorption is normally due to black carbon, which is a good tracer for combustion emission. The minimum resolving times range from seconds in urban environments to minutes in remote locations. We present results obtained during operation on an aircraft. Due to the time resolution capability, we can determine the spatial distributions of absorbing aerosol. From the Greek word "αιθαλουν," "to blacken with soot," we have named this instrument the aethalometer.

INTRODUCTION

Aerosol particles emitted from combustion sources contain many different carbonaceous compounds and structures. One of these components is carbon in a microcrystalline graphitic form (ref.1), which, due to its strong optical absorption, is termed "black carbon." This material can only be produced by incomplete combustion: there are no secondary mechanisms known for its production from airborne precursors. It is also inert to transformation in the atmosphere and therefore possesses qualities that make it a good tracer for combustion emissions. Chemical techniques (ref.2) for the determination of the black carbon content of aerosol samples collected on filters are generally complex and time consuming. In contrast, optical measurements are often simple and rapid. Since most ambient aerosols do not contain large amounts of other noncarbonaceous absorbing particulate material, a measurement of optical absorption of the filter deposit corresponds very closely to the black carbon determination. These methods and results are discussed in detail by Gundel et al. (ref.3). Here we describe an instrument that uses an optical technique to measure the concentration of aerosol black carbon in real time. From the Greek word "αιθαλουν," "to blacken with soot," we have named the instrument the aethalometer.

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*This work was supported by the Director, Office of Energy Research, CO$_2$ Research Division of the U.S. Department of Energy under contract DE-AC03-76SF00098 and by the National Oceanic and Atmospheric Administration under contract NA81RAG00254, Mod. 1.

PRINCIPLE OF OPERATION

The aethalometer operates on the principle of continuous measuring of the attenuation of a beam of light transmitted through a filter (ref.4), while the particle-laden air is being drawn through the filter. At a constant airstream velocity, the rate of deposition of black carbon on the filter is proportional to its concentration in the aerosol and gives a corresponding rate of increase of optical attenuation. Measurement of this last quantity constitutes the basis of this method. The aerosol particles are retained on the filter and are available for subsequent analysis by other physical and chemical means. Some of these results are used for calibration of the instrument.

INSTRUMENTAL DETAILS

A block diagram of the instrument is shown in Fig. 1. A transparent mask with a 5-mm diameter hole covers the filter, which is usually prefired quartz

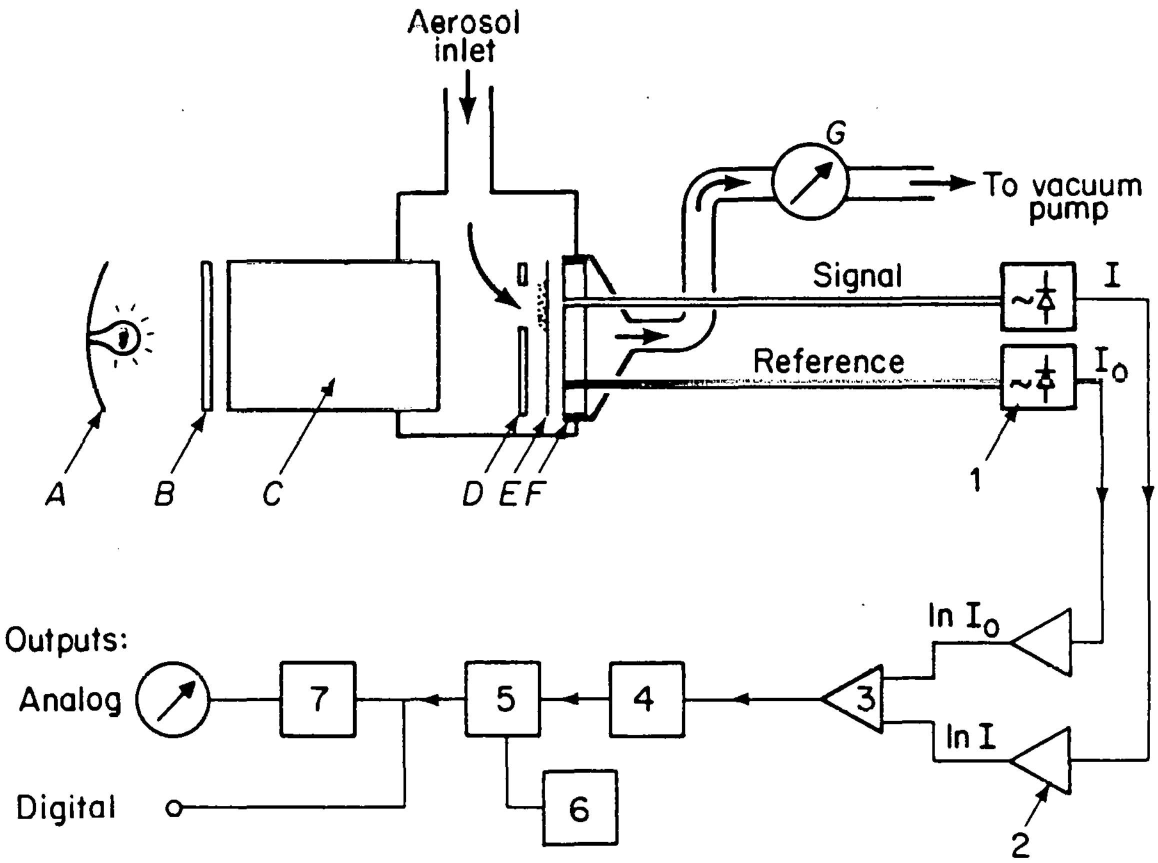

Fig. 1. Block diagram of the instrument. Optical and aerosol collection components: A, light source; B, 530-nm bandpass filter; C, quartz light guide; D, transparent mask; E, filter with particles collected on portion underneath hole in mask; F, filter support with optical fibers set in; G, flowmeter. Electronic system components: 1, silicon photodetectors; 2, logarithmic amplifiers; 3, difference amplifier giving output proportional to $\ln(I/I_0)$; 4, A/D converter; 5, storage and subtraction; 6, variable time base; 7, D/A converter.

fiber. The air stream is therefore drawn through only a small part of the filter, on which the particles are collected. The remainder of the filter is used as a reference for the optical measurement and as a blank for chemical analyses. The filter is uniformly illuminated by a stabilized incandescent (530 nm) lamp, and two optical fibers set into the filter support under the collecting and reference portions of the filter convey the transmitted light to a pair of matched photodetectors. The attenuation of the intensity I transmitted through the collecting part of the filter relative to the intensity I_0 through the reference part is $A = 100 \ln(I_0/I)$ and is proportional to the surface concentration of black carbon. The detector outputs are coupled to a logarithmic ratiometer (ref.5) that produces a voltage proportional to the optical attenuation A. The rate of increase of this voltage is proportional to the rate of deposition of black carbon on the filter. Since this rate may be slow, we use digital methods at discrete time intervals to perform the differentiation. Input via a 12-bit analog to digital converter gives a resolution of 0.025%, enabling us to detect an increase in optical attenuation of 0.075 units. This corresponds to the deposition of 3 ng/cm^2 of black carbon on the filter. The minimum resolving time t_{min} is the time necessary to collect this quantity Q_{min} of black carbon from the air stream, whose velocity at the filter face is denoted v.

If the concentration of black carbon in the aerosol is C, then $t_{min} = Q_{min}/Cv$. Using quartz fiber as the filtering medium, the aethalometer can operate at filtering velocities of up to 5 m/sec, giving a minimum resolving time of 6 seconds for a black carbon concentration of 1 μg/m^3. A variable time base determines the actual interval over which the digitization and differentiation are performed. We may select longer time base periods to improve the accuracy of the concentration measurement at the expense of its time resolution.

To avoid the effects of optical saturation, a maximum loading Q_{max} of 8 μg/cm^2 of black carbon on the filter is allowed before a filter change is required. At constant filtering velocity v and average aerosol black carbon concentration C, this occurs after a time $t_{max} = Q_{max}/Cv$. At maximum flow rate with C equal to 1 μg/m^3, this time is approximately 4-1/2 hours. In situations that do not require maximum time resolution or sensitivity, the time between filter changes may be extended by reducing the air-flow rate.

CALIBRATION

The aethalometer is calibrated by performing quantitative chemical analysis for black carbon (ref.3) on the quartz fiber filter removed from the instrument at the end of a sampling period. The result is compared to the integral of the real-time output to give the calibration factor. A calibration based on the optical attenuation measurement as an intermediary agrees closely and may be used for routine work; when the greatest accuracy is required, we chemically analyze each individual filter.

AEROSOL ABSORPTION COEFFICIENT

The optical scattering coefficient of an aerosol may be measured by the integrating nephelometer (refs.6,7). The aethalometer provides a complementary measurement from which we may estimate the aerosol's optical absorption coefficient. The optical absorption cross section of suspended aerosol particles depends markedly on their microscopic composition (ref.8). Different configurations of the mixing of absorbing (black carbon) and scattering components (sulfate, water, organics, etc.) can result in large changes in the absorption cross section. A value of 10 m^2/g is compatible with other reported work (refs. 9,10). The optical absorption coefficient may then be calculated from the relation [absorption coefficient (units 10^{-6} m^{-1})] = [concentration (units $\mu g/m^3$)] × [cross section (units m^2/g)]. At maximum sensitivity, the aethalometer can detect in a few seconds an aerosol having an absorption coefficient of 10^{-5} m^{-1}.

RESULTS

In previous ground-level studies (ref.11) of the black carbon content of ambient aerosols, the aethalometer measurement showed detailed time-dependent behavior. Here we present results emphasizing the time resolution capability as a means of determining spatial structure. As part of the NOAA "AGASP 1983" project (ref.12), the aethalometer was operated on board an aircraft. Figure 2 shows the output during a pass at 900 m altitude through a plume from agricultural burning. The time-base period was 4 seconds, giving a horizontal resolution of approximately 500 m and a measurement accuracy of approximately 5% of peak. Figure 3 shows the output during a descent profile from 6000 m altitude to sea level in the Norwegian Arctic. A 1-minute time-base period was used, and we obtained a vertical distribution of aerosol black carbon with a resolution of approximately 200 m.

CONCLUSION

We have developed and refined an instrument that is capable of yielding a highly sensitive measurement of the concentration of aerosol black carbon in real time. This measurement may be directly calibrated by means of chemical analysis and may be interpreted in terms of an aerosol absorption coefficient. The instrument has sufficient sensitivity to perform this measurement in remote locations with a time resolution of minutes, and in plumes, within seconds. Its capabilities suggest applications in many areas of atmospheric sciences as well as combustion research.

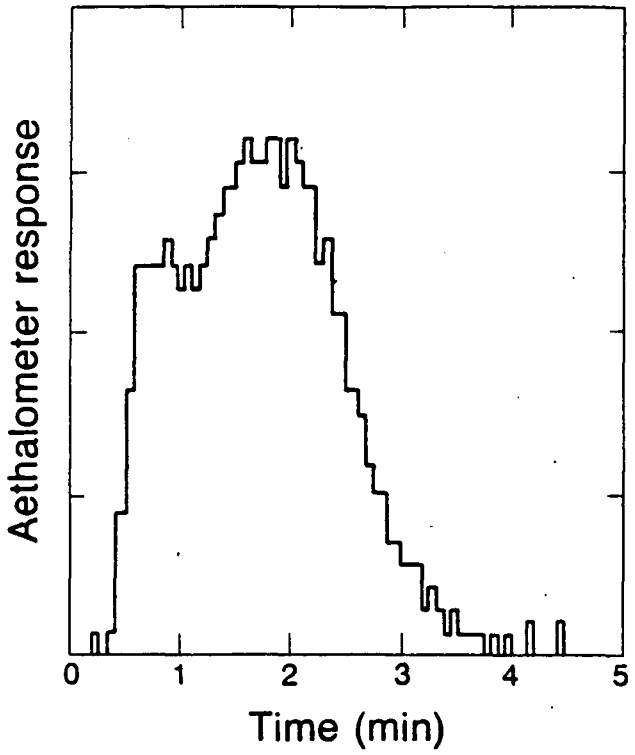

Fig. 2. Aethalometer response during transit of a plume from agricultural burning over the Bahamas. The aethalometer time-base period of 4 seconds gives a horizontal resolution of approximately 500 m.

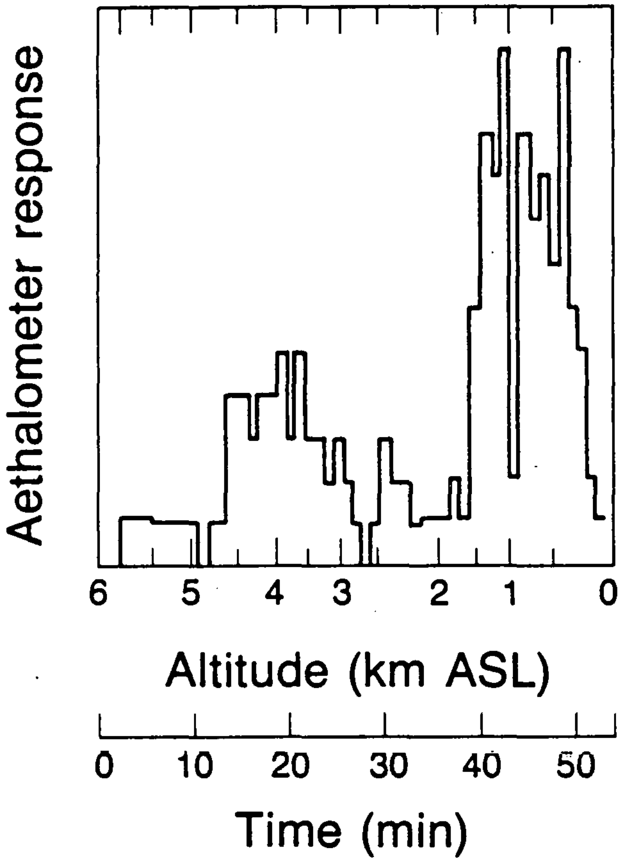

Fig. 3. Aethalometer response during descent profile near Spitzbergen. A separate record of flow rate vs. altitude is also kept, which must be factored into these data to yield the aerosol black carbon concentration. The aethalometer time-base period is 1 min.

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