Lecture 9. Ground-based Measurements

1. Mass Concentration

1.1. Filters

Filters collect liquid and solid particles by mechanisms including diffusion, impaction, interception, electrostatic attraction, sedimentation onto filter while allowing the gas to pass through. The high-volume (*hi-vol*) filter is used by US EPA to monitor total suspended particles in ambient air. Air is drawn (at 40 to 60 ft^3/min) through a glass fiber filter by means of a blower, and suspended particles having a diameter between 0.3 and 100 micro-meters are collected. The total suspended particulate is calculate by dividing the net weight of the particulate by the total air volume samples and is reported in $\mu g.m^{-3}$. For PM10 and PM2.5, pumped air is drawn into different cyclones.

Figure 1. Hi-vol particulate sampler.

Figure 2. Filter of Hi-vol sampler.

1.2. Inertial collections

1.2.1. Cyclones

Cyclones are used for aerosol measurement where specific cut-off diameters for Respirable, PM 10, PM 2.5 (Fine), and most recently PM 1. The US Environmental Protection Agency (EPA) and world health air quality agencies use cyclones for size selective sampling.

An air sampling cyclone brings a sample of air and particles into a tangential nozzle or jet which forces the flow against the inner circular wall. Shaped like a tapering cylinder, the air forms streamlines that follow the wall and spiral clockwise with a downward swirl direction, hence, the name cyclone. When the spiral reaches the bottom it reverses and a smaller diameter vortex ascends spinning in the opposite direction.

If the flow rate remains constant, then due to centrifugal, gravitational and inertial principles the particles of a calculated cut-off diameter spiral downward and out of the flow stream to drop into a dust collection cavity (grit pot). The smaller diameter particles reverse direction and spiral upwards near the cyclone axis to an exit tube.

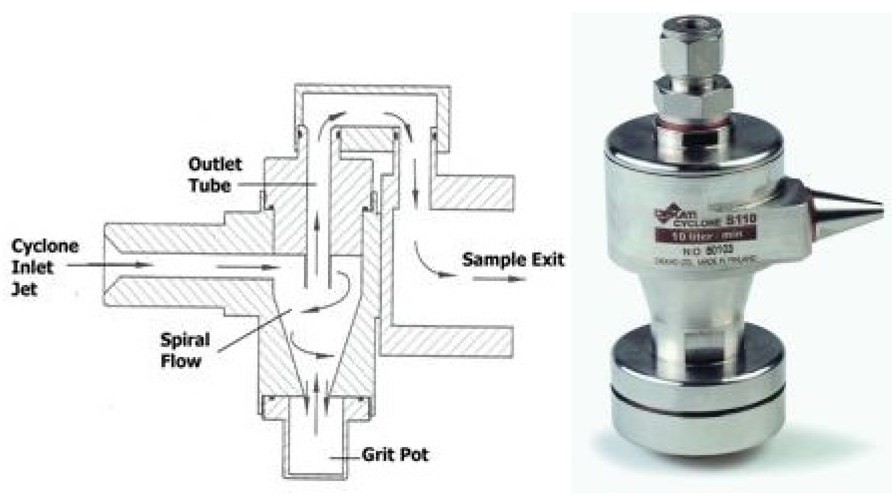
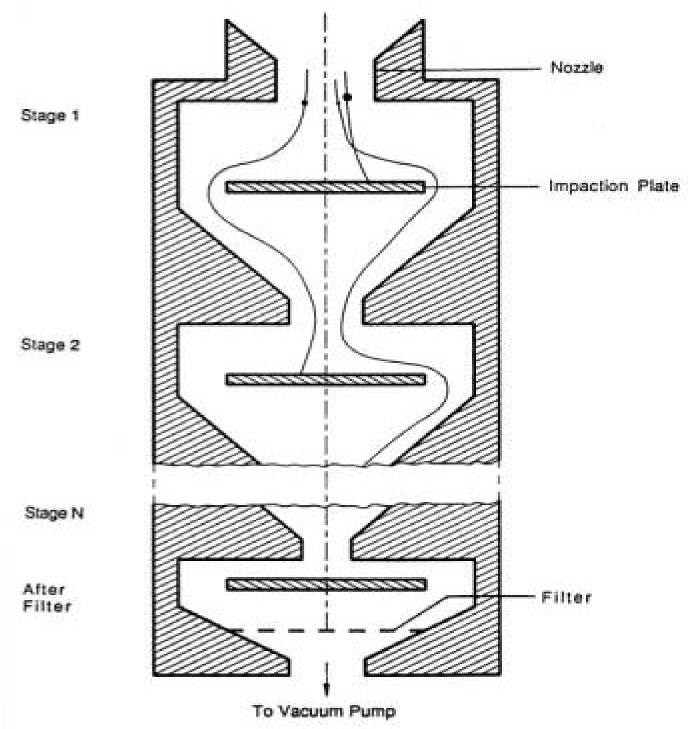


Figure 3. PM10 cyclone.

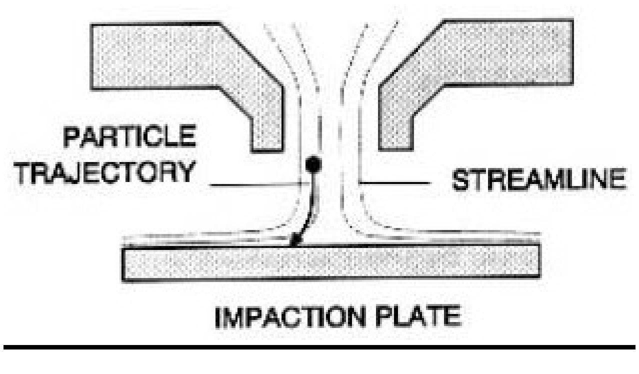
1.3. Impactors

Impactors are based on the principle that particles in airstreams will tend to continue in a straight line due to their inertia when the flow of air bends sharply. A collection plate is placed in the air flow causing the gas flow to stream around the obstacle, while large particles may strike the plate and stick. The larger the particles the greater is its inertia and the greater the impaction on the plate. The impaction efficiency is given by

$\eta = \frac{D_p^2 V \rho_p}{18\mu D_b}$ where D_p is the particle diameter, V the flow velocity, μ the air viscosity, ρ_p the particle density, and D_b is the inlet nozzle diameter.



Schematic Diagram of Cascade Impactor.



Cascade impactors are consists of a number of impactor stages connected in series with smaller and smaller cut-off diameter. The cut-off diameter in each stage depends on the air velocity and geometry of the stage (i.e. the distance from the nozzle to the impaction plate). Cascade impactors often have up to some ten stages ranging from a cut-off diameter on the first stage of 10 – 30 μm to a diameter of 0.1 μm or lower on the backup filter in the end. This gives the opportunity to analyse (e.g. chemical or gravimetrical) a number of small size intervals. Some drawbacks are the risk of bounce off from one stage to the next (i.e. particles of wrong size at some of the stages) as well as the problem of obtaining sharp cut-off diameters in the last stages (cut-off diameter less than 0.1 – 0.2 μm). Coating the impaction plates with oil or some other sticky substance, which catches the particles more effectively, can reduce the risk of bounce off. This will then prevent or severely complicate direct mass concentration calculations of the different stages.

Monitoring Networks

US ENVIRONMENTAL PROTECTION AGENCY (EPA) The EPA is requires to http://www.epa.gov/ttn/airs/airsaqs/

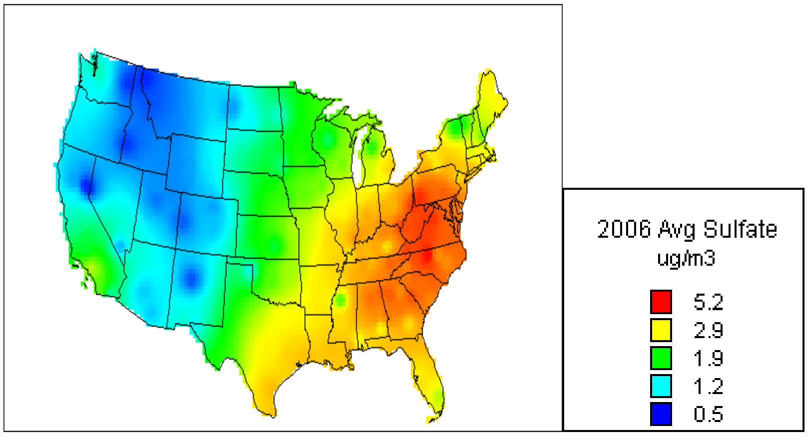
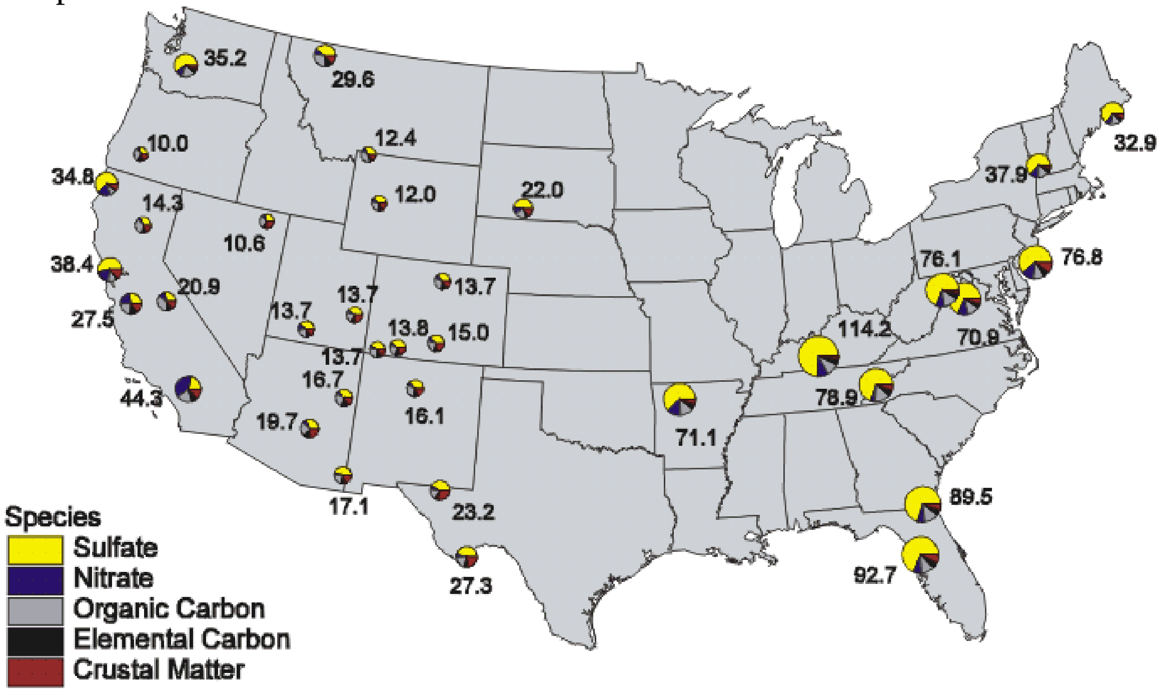


Figure 4. Sulfate average concentration for 2006 [ug.m-3].

IMPROVE: http://vista.cira.colostate.edu/improve/Data/data.htm

The Interagency Monitoring of Protected Visual Environments (IMPROVE) monitoring network consists of aerosol, light scatter, light extinction and scene samplers in a number of National Parks and Wilderness areas.



EMEP: http://www.nilu.no/projects/ccc/

The concentration of PM10 sulfate has been monitored by the European Monitoring and Evaluation Program (EMEP) since 1977 at 102 stations spread across 27 countries in Europe [Hjellbrekke, 2005]. The monthly climatological concentrations are calculated by averaging valid data over the entire records. From July 2002 to July 2003, 13 European countries participated in the measurements of OC and BC.

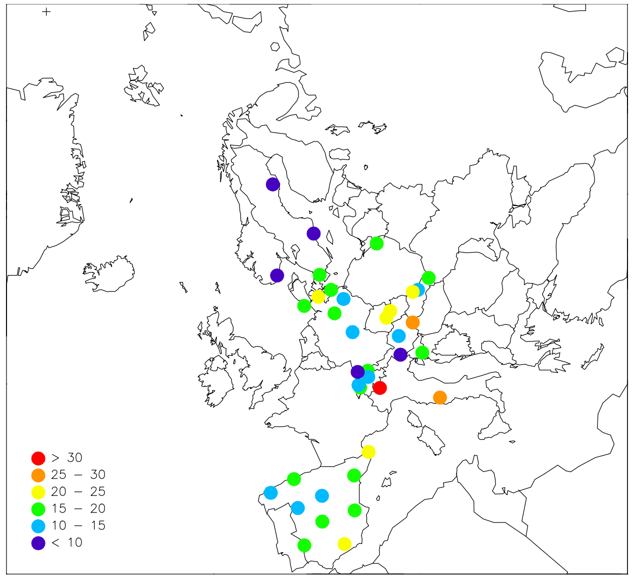


Figure 5. Annual mean concentrations of PM10 for 2005 [ug.m-3].

• U. Miami Ocean Aerosol Network

http://gacp.giss.nasa.gov/data_sets/Joseph_Prospero.html

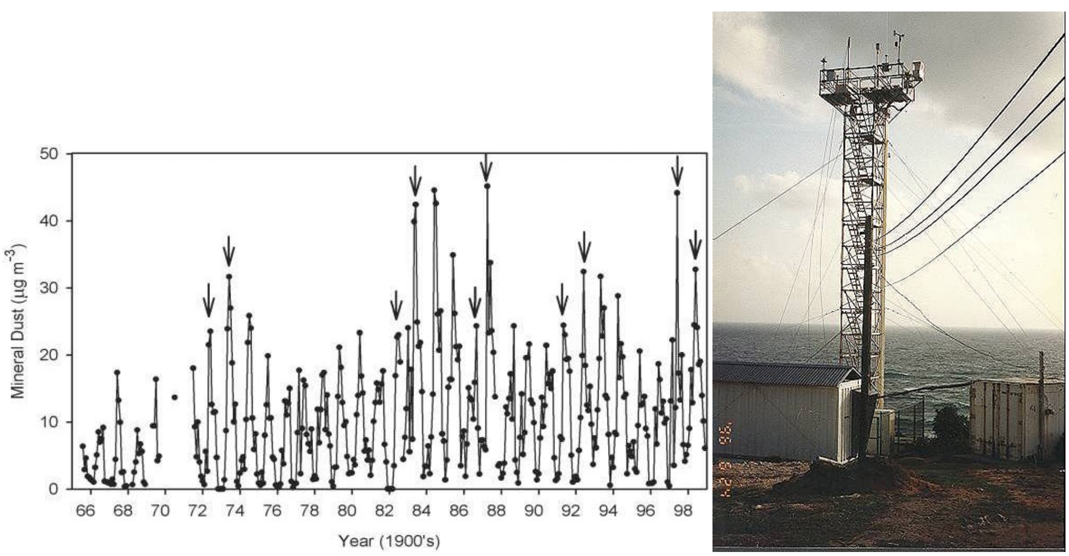


Figure 6. Aerosol sampling facility in Barbados island operated by University of Miami.

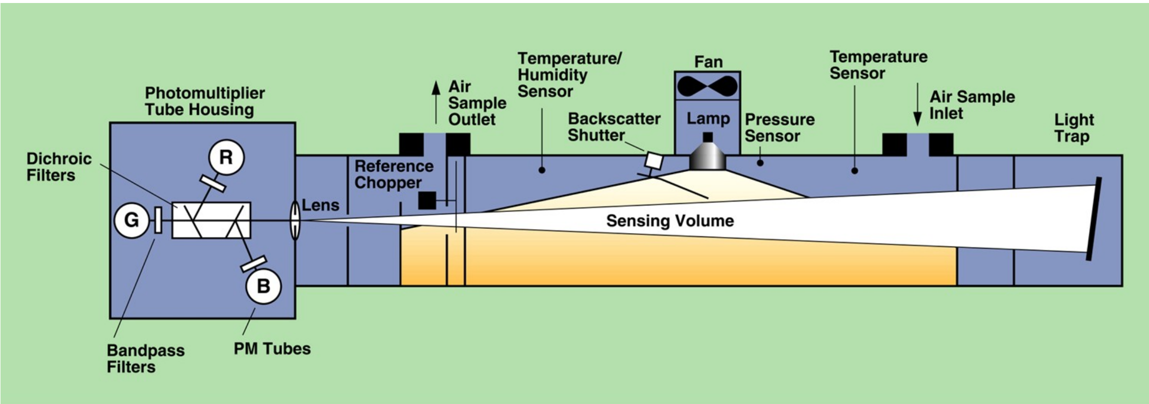
The mass concentration of major aerosol components (e.g. sulfate, dust, sea salt, nitrate) have been collected continuously by the University of Miami at 30 stations, mostly on islands, over the past 2 or even 4 (in the case of the

Barbados station) decades Aerosols are collected by high-volume filter samplers. All samples are analyzed for the major aerosol species: nss-SO4=, NO3-, NH4+, sea-salt components. Another large subset of samples is analyzed for mineral dust either through the analysis for Al and/or other trace elements) or by ashing the filter at 500°C (after extracting water soluble species) and weighing the ash. At some sites, in order to minimize the impact from local aerosol sources, the samplers are controlled by a wind sensor system which activates the pumps only when the wind is blowing from the open-ocean sector and when the wind velocity is greater than 1 m/s. The data set has commonly been used for the evaluation and intercomparison of models [e.g., IPCC 2001 http://www.ipcc.ch/ipccreports/tar/wg1/192.htm]).

1. Optical properties

1.1. Nephelometer

The nephelometer is an instrument that measures aerosol light scattering. It detects scattering properties by measuring light scattered by the aerosol and subtracting light scattered by the gas, the walls of the instrument and the background noise in the detector.



The main body of the TSI 3563 nephelometer is a 10 cm diameter aluminum tube, 90 cm long. Along the axis is an 8 cm diameter tube set with aperture plates. The plates range from 7 - 170^{o} on the horizontal range of the lamp. The backscatter shutter allows blocking of the angles from 7 - 90^{o} so that only backscattering is measured. The light trap provides a dark reference against which to measure the scattered light. The receiving optics is located on the other side of the tube from the trap. The reference chopper is used for calibration of the nephelometer.

The nephelometer measures the scattering by both particles and air molecules ε_{scat} and by air molecules only $\varepsilon_{a\ scat}$ and subtracts them to get particle scattering $\varepsilon_{p\ scat}$. The equation derived by Middleton (1958) and Butcher and Charlson (1972) that governs the instrument is

$$B = \frac{I_0}{z}\frac{\varepsilon_{scat}}{2\pi}$$

Where *z* is the vertical distance from light source to sensor and *B* is light flux detected by the sensor. The nephelometer counts photons using the photomultiplier tubes. The photon counts are converted into scattering coefficients using calibration constants. The calibration is performed by measuring the scattering of a known gas, e.g. the scattering coefficient of $H_e=3x10^{-7}$ $[m^{-1}]$. This instrument is used by NOAA ESRL to measure total scattering (between 7 and 170 degrees) and backscattering (between 90 and 170 degrees) by aerosol particles at three wavelengths: blue (450 nm), green (550 nm) and red (700 nm) (see details at http://www.esrl.noaa.gov/gmd/aero/instrumentation/neph_desc.html)

1.2. Sunphotometer

Sun photometer measures the directional solar irradiance in discrete wavelength channels along a vector from the instrument detector to the solar disk. The irradiance at the observer height *h* for a solar zenith χ is given by

$I_h = I_{TOA}\exp(-\int_h^\infty \alpha_{ext}\,\rho\sec\chi\,dz)$, where I_h is the irradiance at the observer height *h* above sea level, I_{TOA} is the irradiance at the top of the atmosphere, α_{ext} is the mass extinction coefficient due to aerosol and molecular absorption and scattering. The integration along z follows the ray in its refracted path through the atmosphere. Generally, α_{ext} is not constant through air column, and is replaced by an effective mass extinction coefficient $\overline{\alpha_{ext}}$, given by

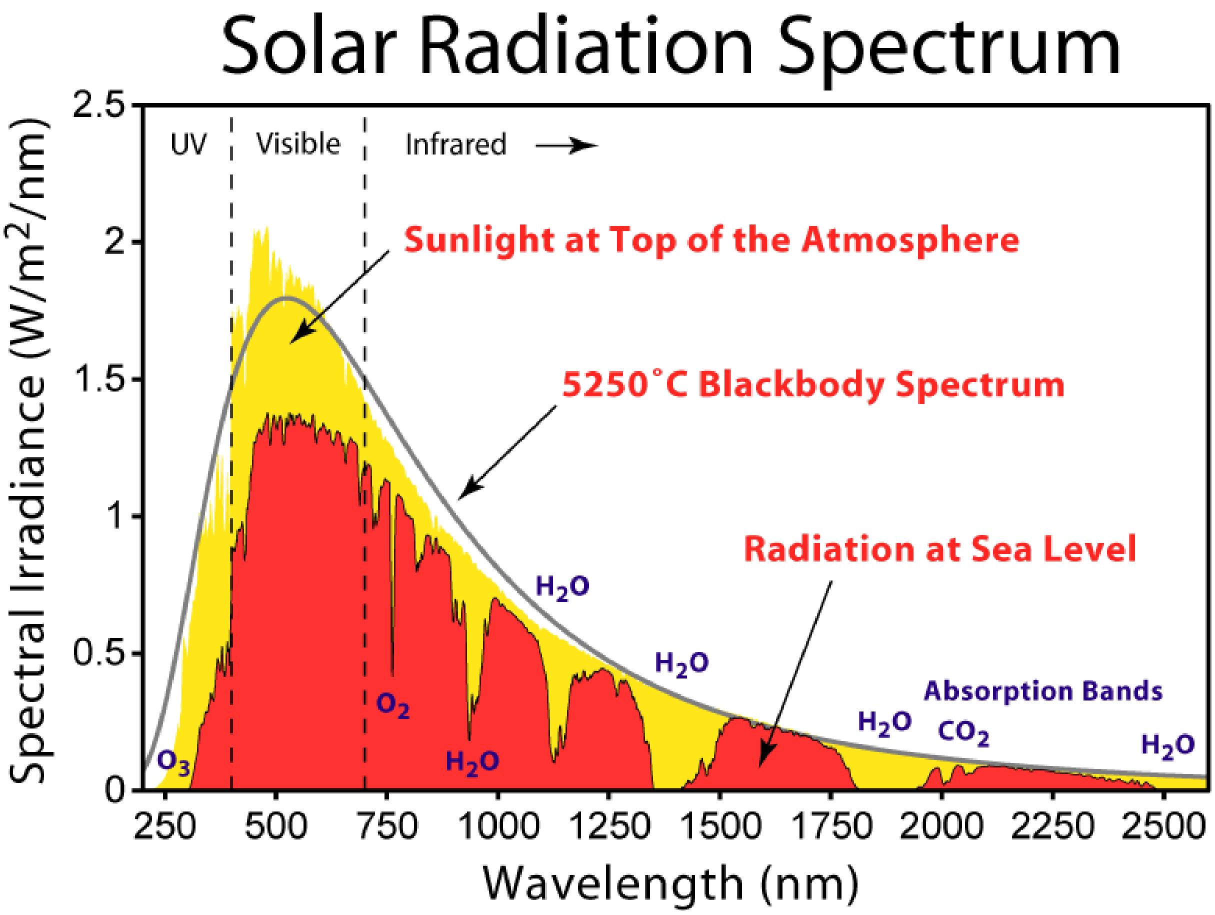
$$\int_h^\infty \alpha_{ext}\,\rho\sec\chi\,dz = \overline{\alpha_{ext}}\int_h^\infty \rho\sec\chi\,dz = \tau\frac{\int\rho\sec\chi\,dz}{\int\rho\,dz} = \tau\,m(\chi)$$

Where $m(\chi) = \dfrac{\int\rho\sec\chi\,dz}{\int\rho dz}$ is defined as the air mass.

The irradiance becomes $I_h = I_{TOA}e^{-\tau m(\chi)}$ which is analog to Beer-Lambert equation.

The solar irradiance at the top of atmosphere I_{TOA} is the solar constant modulated by earth-sun distance:

$I_{TOA} = I_0 / r^2$ where I_0 is the mean solar irradiance at top of the atmosphere r is the ratio of the earth-sun distance to its mean value and is given by $r = 1 - \varepsilon \cos(\frac{2\pi}{365.3}(J-4))$, with the orbit eccentricity ε =0.01673 and *J* is Julian day.



The air mass (also called atmospheric mass) $m(\chi)$ is a function of the earth's curvature and atmospheric refraction. For $\chi \leq 70^o$, *m*=sec χ within 1%.

By assuming that the different scattering and absorption processes are independent to each other, the total extinction (or optical thickness) is the sum from all contributors. In the visible the most important contributors are aerosol scattering (τ_A), Rayleigh scattering (τ_R) and ozone absorption (τ_{O3}). Considering only these 3 processes, the irradiance becomes:

$$I_h = \frac{I_o}{r^2}\exp(-(\tau_A + \tau_R + \tau_{O3})m(\chi))$$

The Rayleigh scattering can be computed by theoretical formulation, using tables or empirical equation as:

$$\tau_R = \left(\frac{p}{p_o}\right)[0.008569\lambda^{-4}(1+0.0113\lambda^{-2}+0.00013\lambda^{-4})]$$

where ($a1$, $a2$, $a3$, $a4$) = (117.2594, -1.3215, 0.00032073, -0.000076842), p is the atmospheric pressure [hPa], p_0=1013.25 hPa, and λ is the wavelength (in μm).

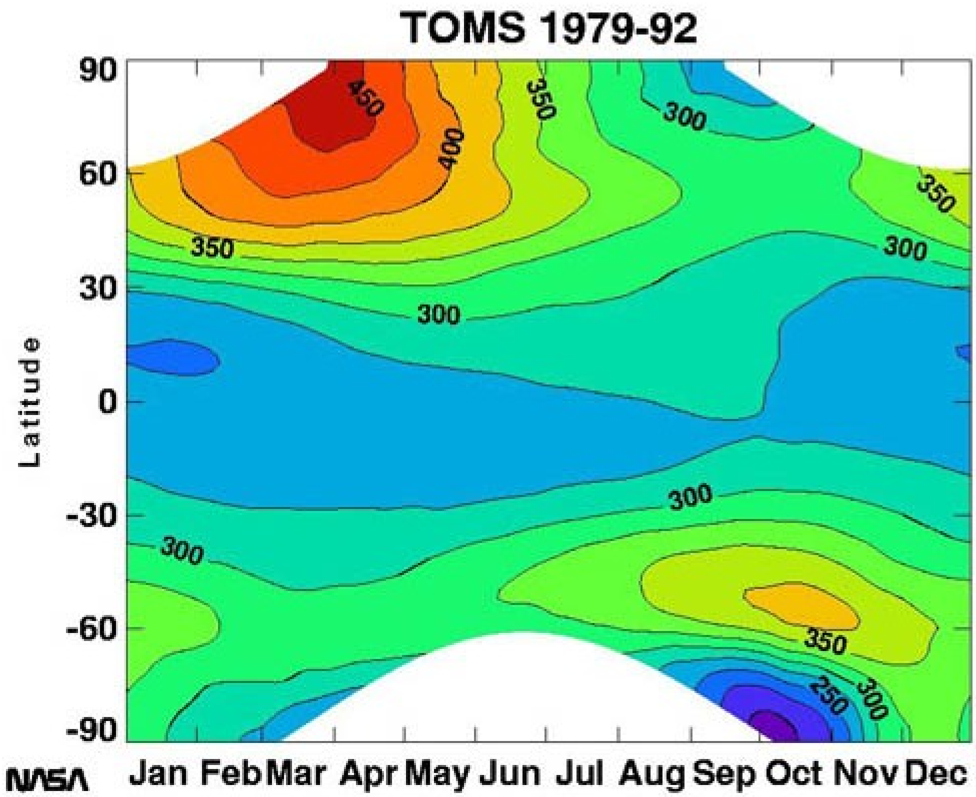


Figure 7 Seasonal variation of zonal mean ozone column (DU) of TOMS 1979-1992 data.

Ozone optical thickness τ_{O3} is estimated by multiplying the ozone column abundance in Dobson units (a 1 Dobson Unit (DU) is defined to be 0.01 mm thickness at 0^o Celsius and 1 atm; the ozone layer over US is around 300 DU or matm.cm) obtained from satellite data (e.g. TOMS or OMI http://toms.gsfc.nasa.gov/ozone/ozone_v8.html) or climatological charts (i.e., the standard relationship between ozone abundance, latitude and time of year) by the absorption coefficients tabulated below:

Wavelength	Ozone Absorption Coefficients in

	[matm^-1][cm^-1]
441	3.36E-6
522	4.8E-5
557	9.73E-5
613	1.19E-4
671	4.55E-5
781	4.61E-6
872	6.17E-7
1030	0.0

If the sunphotometer responds with a voltage ***V*** for an incident radiance ***I*** as in ***I = KV***, where ***K*** is a constant, thus, implying linearity in the instrument response, Equation (1) becomes, after some manipulation,

$$m(\chi)\tau_A = \ln\left(\frac{V_o}{r^2}\right) - \ln V - m(\chi)\tau_{O3} - m(\chi)\tau_R$$

For a measurement of voltage (***V***) at a known airmass *m* all the terms on the right-hand side of the above equation are known, and therefore aerosol optical thickness τ_A can be estimated, once the calibration coefficient $\boldsymbol{V_o}$ has been obtained. The Langley method consists to plot m versus $\ln(I)$ an extrapolate to m=0 to derive $\boldsymbol{V_o}$.

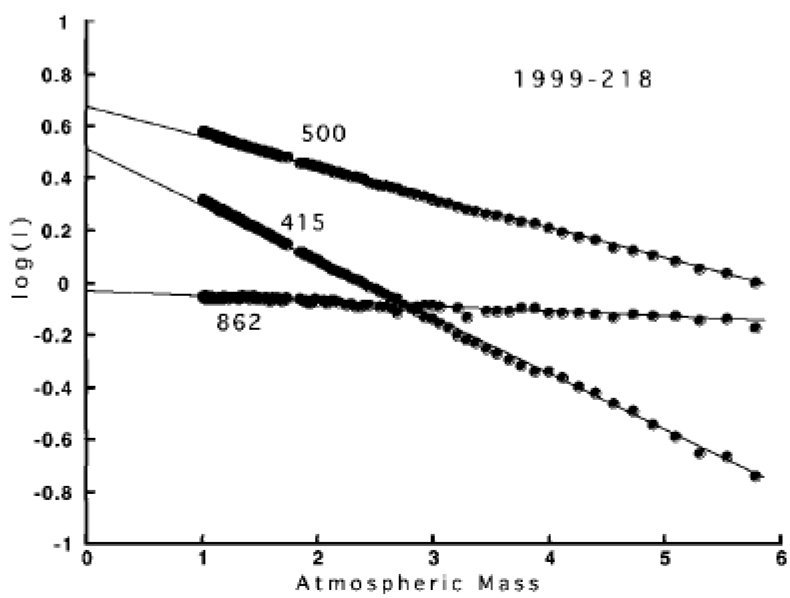


Figure 8. Langley plot for calibration of sunphotometer measurements at 415, 500 and 862 nm, realized at Mauna Loa in 1999.

Sun-photometer designs

Two sun photometer designs are commonly used: a narrowbeam sky radiometer mechanically pointed in the direction of the sun or a wide-field-of-view radiometer with a solar occulting apparatus:

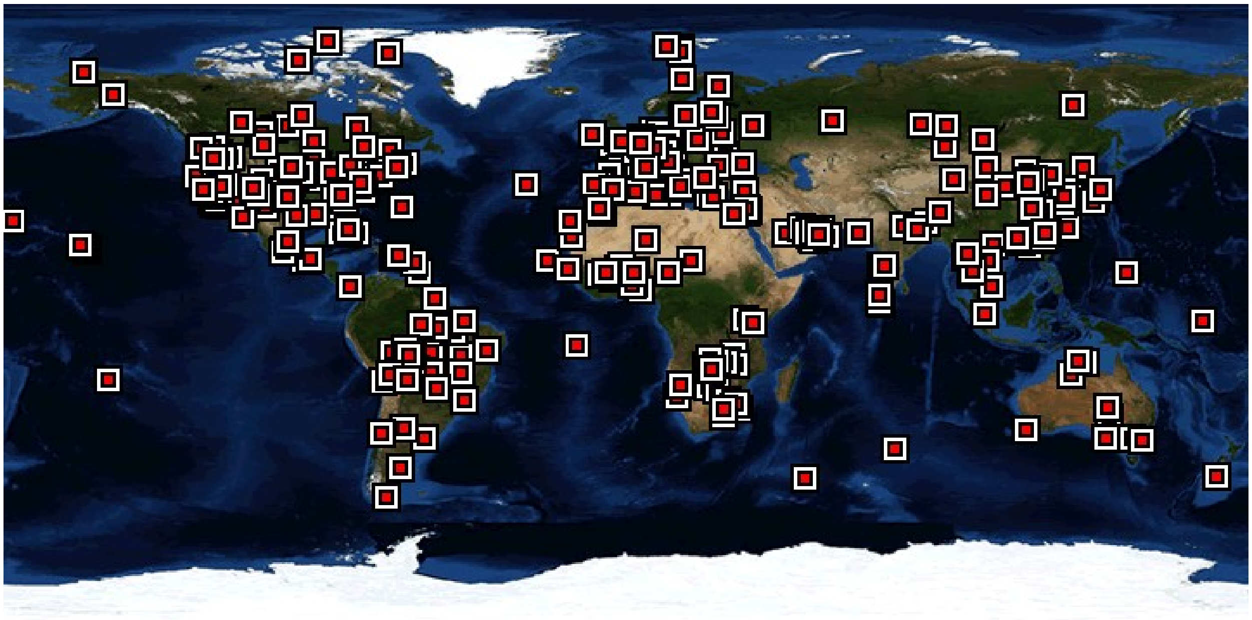
1. Sky radiometer requires careful angular positioning but can provide additional information on forward scattering phase function and thus help characterize the aerosol constituents.

a. Instrument type:

CIMEL instruments operate automatically without operator assistance. It measures direct solar irradiance by first pointing the collimator toward the approximate position of the sun (provided it is aligned properly) based on an in-built program that takes into account the time of the year and the coordinates of the location that are input to the CIMEL control box prior to operation. A 4-quadrant detector then positions the sun at the center of the fields of view of the collimators by using a feedback control loop. The filter wheel rotates in front of the detector to obtain a measurement sequence. A sequence takes about 10 seconds. In order to discriminate against the presence of thin cirrus clouds, which may be non-uniform, three measurement sequences are performed (called as a triplet), lasting about 35 seconds. During a data analysis procedure, the measured voltages are compared to eliminate non-uniform scenes. Almucantar sky radiance is obtained by scanning the sky at the solar zenith angle but different azimuth angles to obtain the angular variation of skylight in 4 filters. Solar principal plane sky measurement is obtained by scanning the sky in a plane containing the sun and the instrument and normal to the surface. Data are taken more frequently near the sun since the intensity varies rapidly in the solar aureole. The sky brightness data is inverted by radiative transfer routines to derive aerosol size distribution and phase function.

b. Monitoring network of Sky-radiometer

The AERONET (**AE**rosol **RO**botic **NET**work) program is a federation of ground-based remote sensing aerosol networks established by **NASA** and **LOA-PHOTONS** **(CNRS)** and is greatly expanded by **collaborators** from national agencies, institutes, universities, individual scientists, and partners. The program provides a long-term, continuous and readily accessible public domain database of aerosol optical, mircrophysical and radiative properties for aerosol research and characterization, validation of satellite retrievals, and synergism with other databases (http://aeronet.gsfc.nasa.gov/)



2. Shadowband radiometer measures the diffuse and global irradiance and compute the solar beam irradicance as the difference between the two.

   a. Type of instruments

Multi-Filter Rotating Shadowband Radiometer: The MFRSR is a portable instrument that determines nearly simultaneous global and diffuse components of the solar spectral irradiance. From these an estimate of the imaginary part of the aerosol refractive index and an average surface Lambertian reflectance can be found. It uses independent interference filter-photodiode combinations that are mounted in a temperature-controlled enclosure for measurement of spectral irradiance at six wavelengths and one broadband channel. A rotating shadowband moves to four positions, blocking the instrument entrance aperture occulting the direct solar beam plus adjacent aureole components, observations on either side to correct for excess blocked sky during the sun occultation, and a rest position.

a. Monitoring Radiation with Shadowband Radiometers

The NOAA Global Monitoring Division is involved in empirical and theoreticalSurface radiation network (SURFRAD) was established in 1993 to objective is to support climate research with accurate, continuous, long-term measurements of the surface radiation budget over the United States (http://www.srrb.noaa.gov/surfrad/index.html).

Figure 9. Desert Rock (NV) SURFRAD station, including (clokwise from left center) radiometer platform, met tower, TSI and solar tracker.

The US Department of Agriculture (USDA) has supported a UV-B monitoring and research program (http://uvb.nrel.colostate.edu/UVB/uvb_program_overview.html) to provide information on the geographical and temporal trends of UV-B radiation in the US. This information is important to assess the potential impacts of increasing UV radiation at the surface. The instruments are UV multi-filter rotating shadowband radiometer.

b. Network of radiometers

The **Baseline Surface Radiation Network** (BSRN) operates cavity radiometers to monitor short and longwave surface radiation fluxes worldwide through 35 stations. (http://bsrn.ethz.ch/)

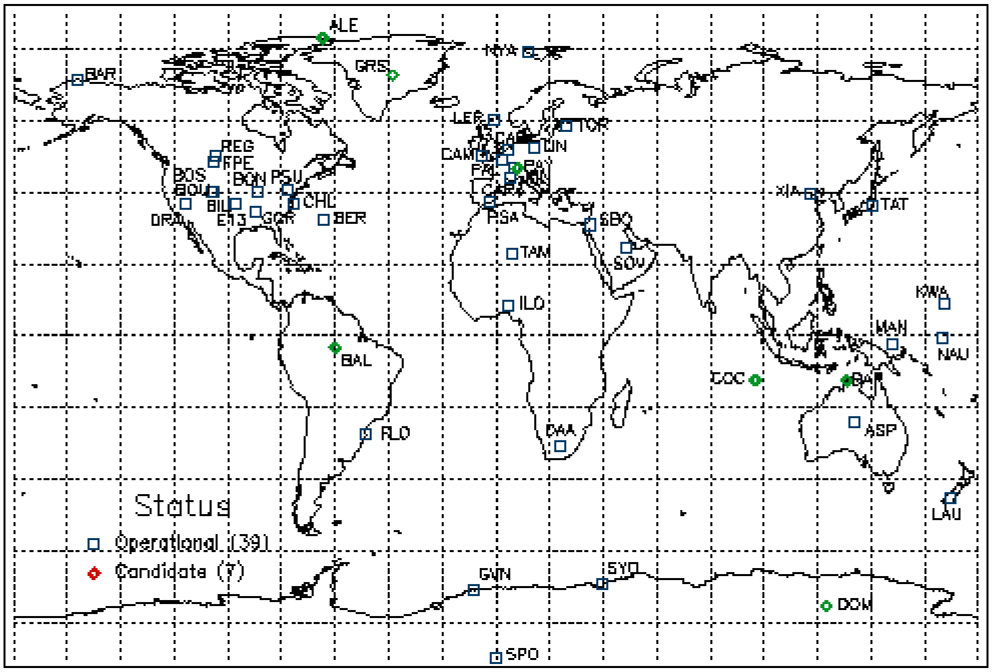


Figure 10 Operational and candidate sites of BSRN.