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Atmospheric Aerosols Monitoring: Ground and Satellite-Based Instruments

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Abstract

Aerosols are submicron particles suspended in the atmosphere which affect Earth's energy balance directly by scattering and absorbing the of solar radiation. In addition, they can indirectly affect radiation balance by changing the micro-physical and optical properties of the cloud. The difficulties in accessing the contribution of aerosols to radiative balance are caused partly due to incomplete knowledge of spatiotemporal variabilities in physicochemical and optical properties of aerosols on regional to global scale. Several state-of-the-art instrumentation techniques for ground-based measurements and satellite remote sensing technologies have been developed in past three decades to monitor physicochemical and optical properties of aerosols for a better understanding of radiative balance and feedback mechanisms. Satellite retrievals of moderate resolution imaging spectroradiometer (MODIS), ozone monitoring instrument (OMI), multi-angle imaging spectroradiometer (MISR) are used for this purpose. Ground-based measurements of aerosol properties provide a basis for validation of atmospheric correction procedures and can be used for validation of aerosol models used in atmospheric correction algorithms. This chapter describes in details about the widely used ground- and satellite-based remote sensing instruments for aerosol monitoring.

Keywords: aerosols, AOT, satellite, MODIS, particle, size, remote sensing, OMI, MISR

1. Introduction

Aerosols are a two-phase colloidal system, consisting of the particles (solid or liquid) and the gas in which they are suspended. An individual aerosol particle can either cause cooling or warming depending on its size, refractive index, composition and mixing state in the atmosphere

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[1–3]. The interaction of aerosol particles with radiation further depends on their origins and subsequent atmospheric processing. The size of aerosols particles is an important parameter to study their chemical or optical properties. On the basis of particle size distribution the aerosols are broadly classified into three main categories: (1) Aitken particles or nucleation mode (0.001–0.2 μm diameter), (2) large particles, or accumulation mode (0.2–2 μm diameter) and (3) giant particles, or coarse particle mode (>2 μm diameter). Aerosol size distribution may be represented by number or volume density [4] (**Figure 1**). The particles of size less than 0.04 μm exhibit greater coagulation and hence their number is greatly reduced. Particles bigger than 10 μm are removed more effectively from the atmosphere either by sedimentation or by rain-wash.

Atmospheric aerosols have sizes, shape, and a chemical composition mainly due to their different emission sources and heterogeneous nature. Since the size, as well as composition of aerosol particles vary by orders of magnitude, no single instrument or technique is adequate for entire characterization of aerosols. The selection of a particular method for characterization of aerosols depends primarily on the particular type of application and scientific objectives. Aerosol optical thickness (AOT) is the most fundamental parameter for determining optical properties of aerosols which is the degree to which aerosols prevent the transmission of light in the atmosphere either through scattering or absorption. Measuring AOT at different spectral wavelengths (mostly visible range) helps in deriving information on the optical properties and to understand their impact on radiation balance while aerosol size distribution and mass concentration are crucial for understanding source strength, visibility and several environmental including fog-haze formation, cloud condensation nuclei (CCN), etc., and ecological impacts.

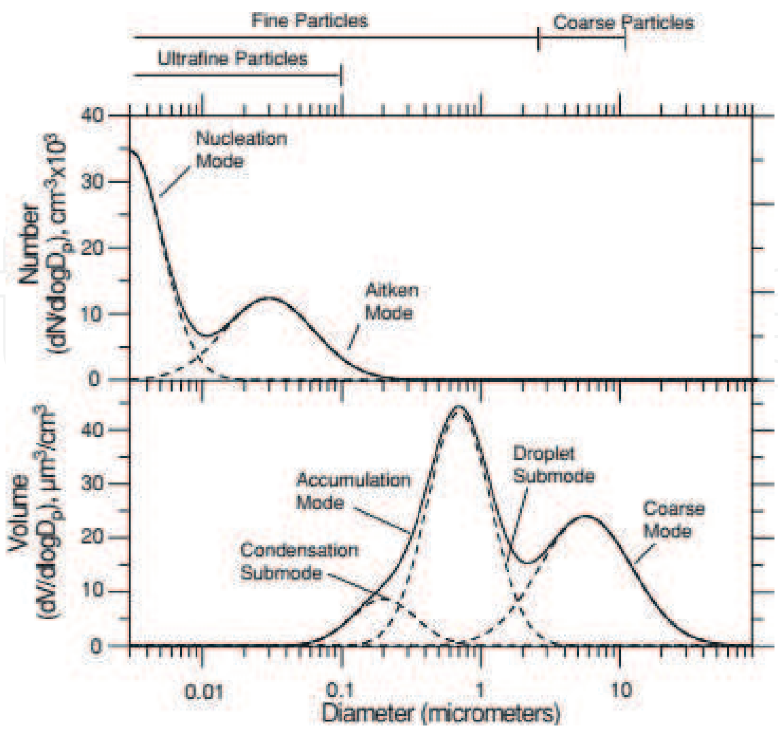

Figure 1. Typical volume and number distribution of atmospheric particles with different modes [4].

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Three different kinds of data are available for the study of aerosols: (1) point data from ground locations equipped with sunphotometers (highest accuracy, but periods of missing data are frequent) [5]; (2) gridded data from space observations (low accuracy, with frequent missing data) [6]; and (3) gridded data from monthly climatologies (low to intermediate accuracy, no missing data) [6, 7].

Ground and satellite-based remote sensing are two important ways for monitoring aerosol optical properties [8]. The ground-based and satellite aerosol optical measurements contribute to our understanding of the Earth's systems by not only characterizing the ambient aerosol but validate satellite retrievals and numerical modeling algorithms. This also provides information on environmental pollution and investigates aerosol and cloud effects on radiative fluxes [8, 9].

More importantly, they provide a wider spatial as well as temporal (e.g., long-term variability) coverage of aerosol properties on a regional to global scale. Nonetheless, the resolution of measurements is rather poor for local observations and thus, these methods do not provide adequate information over a given site. In contrast, real-time measurements of chemical and optical properties are advantageous to study several physical and chemical processes on a finer spatial scale but fail to provide information about these processes on a regional scale. Therefore, a blended approach of simultaneous real-time ground-based measurements in tandem with ground and satellite-based remote sensing techniques is a need for better understanding of aerosol properties and their impact on the environment, ecology weather and climate.

The present chapter discusses several established as well as recent instruments in the field of atmospheric aerosol measurements with a particular focus on the measurements of aerosol optical depth and size. The brief description of instruments for aerosols along with their measurement techniques and working principles are discussed in details.

2. Ground-based aerosols instruments

Different types of ground-based instruments are used for monitoring aerosols such as spectroradiometers, multichannel radiometers, and broadband radiometers. Spectroradiometers present today provides excellent spectral performance across a full range of solar irradiance spectrum. Though, they are very expensive and thus, most ground-based stations generally prefer to deploy multichannel and broadband radiometers. Data from the ground are mostly used as ground truth to validate and optimally combine data from the other sources. Ground-based multi-wavelength sunphotometric measurements are the most accurate source of AOT data [9].

In multichannel and broadband radiometers, the wavelength integrated quantities are reproduced as accurately as in the spectroradiometers. This section further discusses in details about the ground-based aerosols measurement instruments. The brief description of sunphotometer for AOT and aerosol spectrometer for size distribution measurements are described in Sections 2.1 and 2.2.

2.1. Sunphotometer

Sunphotometer is capable of measuring AOT (AOT) and direct solar irradiance in different wavelength bands generally in 6 narrow spectral bands ranging from 360 to 1000 nm. It uses the Langley method for deriving optical thickness of the atmosphere by measuring direct sun irradiance. A correction for Rayleigh scattering as well as selected atmospheric gases such as ozone, water-vapor, etc., is needed. After subtraction of the Rayleigh optical thickness and the ozone optical thickness, the aerosol optical thickness is obtained. In the following section, we describe MICROTOP II sunphotometer as an example for sunphotometers.

2.1.1. MICROTOP II

Sunphotometer MICROTOP II (Model 540) is a five-channel small portable, handheld sunphotometer manufactured by solar light [10]. This is particularly useful for taking ground-based measurements at different locations (**Figure 2**). This instrument can give total column aerosol optical thickness spectra together with total column ozone content and precipitable water vapor within the atmosphere. The instrument is equipped with five accurately aligned optical collimators, with a full field of view of 2.5°, while the full width at half maximum (FWHM) bandwidth at each of the AOT channels is 2.4 ± 0.4 nm. It is a Voltz-type radiometer and measures the intensity of direct solar irradiance at five narrow-band spectral channels centered at 440, 500, 675, 870 and 936 nm. Each channel is fitted with a narrow-band interference filter and a photodiode suitable for particular wavelength range. The collimators are encapsulated in a cast aluminum optical block for stability. A sun target and pointing assembly is permanently attached to the optical block and laser-aligned to ensure accurate alignment with the optical channels. When the image of the sun is centered in the bulls-eye of the sun target, all optical channels are oriented directly at the solar disk. Radiation captured by the collimator and bandpass filters radiate onto the photodiodes, producing an electrical current that is proportional to the radiant power intercepted by the photodiodes. These signals are first amplified and then converted to a digital signal by a high-resolution A/D converter. The signals from the photodiodes are processed in series. However, with 20 conversions per second, the results can be treated as if the photodiodes were read simultaneously [11].

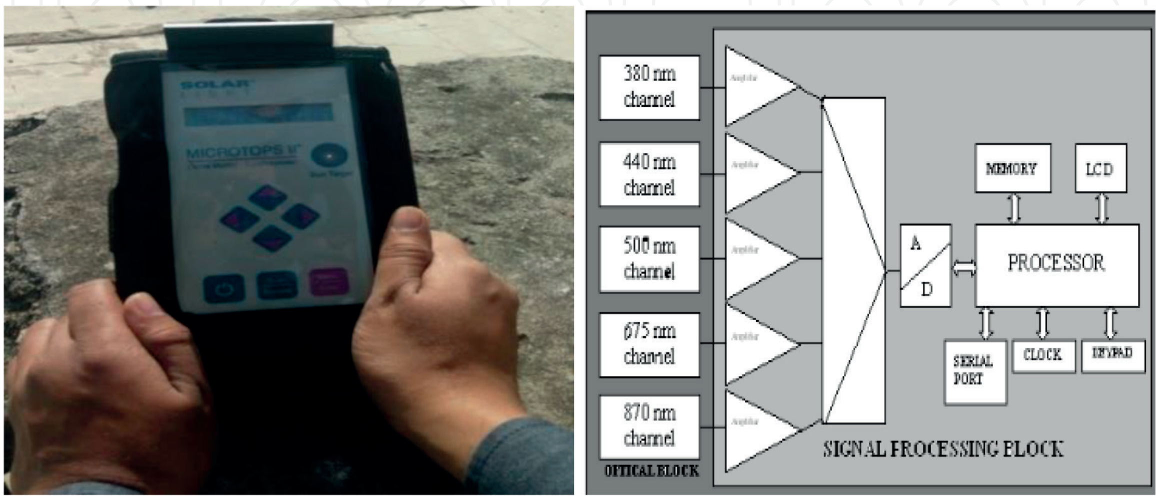

Figure 2. Operational block diagram of MICROTOP II [12].

Optionally the MICROTOP is capable of deriving the water vapor column. AOT and water vapor column are determined to assume the validity of the Bouguer-Lambert-Beer law. At a wavelength λ, the total optical thickness recorded by a sunphotometer can be expressed as the sum.

$$\tau_{\lambda} = \tau_{A\lambda} + \tau_{R\lambda} \tag{1}$$

where $\tau_{A\lambda}$ is AOT and $\tau_{R\lambda}$ is Rayleigh optical thickness.

The MICROTOPS II calculates the AOT (τλ) value of each wavelength based on the channel's signal, its extraterrestrial constant, atmospheric pressure (for Rayleigh scattering), time and location. Solar distance correction is automatically applied. The AOT formula is

$$\tau_{\lambda} = \frac{\ln(V_{0\lambda}) - \ln(V_{\lambda} \times SDCORR)}{m} - \tau_{R\lambda} \times \frac{P}{P_0} \tag{2}$$

where the index λ references the channel's wavelength, $\ln(V_{0\lambda})$ is the AOT calibration constant, V_{λ} is the signal intensity in mV, SDCORR is the mean Earth-Sun distance correction, m is the optical air mass, $\tau_{R\lambda}$ is the Rayleigh optical thickness and P and P0 are station pressure and standard sea level pressure (1013.25 mB) respectively [9].

Young [13] has given one approximate formula to calculate air mass (m) from true solar zenith angle (θ) that accounts for the effects of refractive index and curvature of the Earth.

$$m = \frac{1.002432 \times \cos^2(\theta) + 0.148386 \times \cos^2(\theta) + 0.0096467}{\cos^3(\theta) + 0.149864 \times \cos^2(\theta) + 0.0102963 \times \cos(\theta) + 0.000303978} \tag{3}$$

where θ represents the solar zenith angle at the time of measurement. The optical thickness due to Rayleigh scattering is subtracted from the total optical thickness to obtain AOT. Optical thickness from other processes such as O_3 and NO_2 absorption are ignored in MICROTOPS II. The combined error in the estimated AOT due to errors like entering of the diffuse radiations, computational error calculating the air mass, calibration coefficient estimation error and uncertainty in deriving optical depth due to Rayleigh scattering and absorption is in the range of 0.009–0.011 at different wavelengths (which is 2–10% of the total AOT). Typical errors in AOT measurements from MICROTOP-II are ~0.03 [14].

In 1961, Scientist named Angstrom proposed an empirical formula to estimate the spectral dependence of atmospheric extinction (scattering and absorption) caused by aerosols:

$$\tau_{\lambda} = \beta^{*} \lambda^{-\alpha} \tag{4}$$

where τ_{λ} is the spectral AOT, λ is the wavelength in μm; α is the Ångström exponent and β is the turbidity coefficient (equivalent to AOT at 1 μm) provides a measure of columnar aerosol loading. The values of α and β were calculated by evolving a linear least square fit between τλ and λ (in μm) in log-log scale over the entire wavelength range. The Ångström exponent (α) is a measure of the relative dominance of small particles while the coefficient β depends on the aerosol loading associating more with coarse aerosols.

2.1.2. CIMEL sunphotometer

The CIMEL (CE318) sunphotometer is also a multi-channel, automatic sun-and-sky scanning radiometer that measures the direct solar irradiance and sky radiance at the Earth's surface (**Figure 3**). The CIMEL sunphotometer is developed by French company Cimel Electronique [15].

CIMEL works on Rayleigh scattering principle and measures the total aerosol load in the atmosphere. AERONET (AErosol RObotic NETwork) is an optical ground-based aerosol monitoring network and data archive consisting of sunphotometers. This network provides globally distributed near real-time observations of aerosol spectral optical depths, aerosol size distributions, and precipitable water in diverse aerosol regimes. Measurements through CIMEL are taken at pre-determined discrete wavelengths in the visible and near-IR (i.e., at 340, 380, 440, 500, 675, 870, 1020 nm) parts of the spectrum to determine atmospheric transmission and scattering properties. The CIMEL sunphotometer takes measurements of the direct sun and diffuse sky radiance with 1.2° full field of view within the spectral range 340–1020 nm [16].

The direct sun measurements are done for all eight spectral channels with triplet observations per wavelength and sky radiance measurements at following four spectral channels (440, 675, 870, and 1020 nm). The instrument performs direct spectral solar radiation measurements within a 1.2 full field of view every 15 min. This data set is in the form of Level 2.0 quality assured product after cloud screening and necessary post calibration. The AOT is retrieved at all channels [16] other than the 940-nm channel, which is used to retrieve atmospheric water vapor content. The CIMEL sky radiance measurements together with the direct sun measurements of optical depths are used to retrieve optical equivalent aerosol size distributions and refractive indices. This instrument is weather-proof and requires little maintenance during periods of adverse weather conditions. It takes measurements only during daylight hours (sun above the horizon). It provides the quantification and physical-optical characterizations of the aerosols. CIMEL fully meets the operational requirements of continuous monitoring in terms of reliability, long lifetime and very low maintenance cost The large range of parameters that are derived and calculated from the measurements and from the atmospheric physics equations make the CE318 photometer a worldwide benchmark device for many applications like characterization and quantification of aerosols and aerosol types, bias correction for satellite aerosol retrievals,

Figure 3. The CIMEL Sunphotmeter instrument.

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detection of volcanic ash plumes in real time, deriving parameters (i.e., aerosol optical depth, fine mode AOD, coarse mode AOD, optical properties), volume size distribution, air quality monitoring, etc. The types of error that instrumentation of sunphotometer faces are described in [17–19] These studies reveals that, the overall error in the AOT can be due to (a) error associated with the uncertainty in the optical thickness due to Rayleigh scattering and absorption by O_3 and water vapor (b) deviation of the calibration coefficient with time (c) diffuse radiation entering the optical channel and (d) computation error in relative air mass (a geometrical term to account for the relative increase in optical path length as solar zenith angle increases).

2.2. Aerosol spectrometer

The aerosol spectrometer is a device that is used for continuous measurement of airborne particles as well as for measuring the particle's number and volume concentration.

2.2.1. GRIMM aerosols spectrometer

The GRIMM (model 1.108) is a compact portable instrument developed by GRIMM Aerosol Technik Ainring contains an integrated gravimetric filter on which all particles are collected after the optical measurement [20]. GRIMM aerosol spectrometer measures the number of particles per unit volume of air using light-scattering technology. This instrument operates in four modes: count distribution, mass distribution, occupational health and environmental mode. The instrument measures particle concentrations in an optical size of 0.3–20 μm in 15 channels with differently sizes with a concentration range of 1–2,000,000 particles/L (for count distribution mode) or a mass concentration range of 1–1,00,000 μg/m^3 (for mass distribution, environmental and occupational health modes) [21]. The sensitivity of the spectrometer is 1 particle/L or 1 μg/m^3, whereas reproducibility of the instrument is ±2%. Ambient air is drawn into the unit via an internal volume-controlled pump at a rate of 1.2 L/min. The instrument initiates a system self-test (≈30 s) and zero calibration check at the start of each measurement. Afterward the actual measurement starts and the LCD-display shows data continuously every 6 s. A stainless-steel tube is utilized as the spectrometer inlet (**Figure 4**).

2.2.1.1. Measuring principle

The sample air is led directly into the measuring cell via the aerosol inlet. The particles in the sample air are being detected by light scattering inside the measuring cell. The scattering

Figure 4. GRIMM aerosol spectrometer (model 1.108).

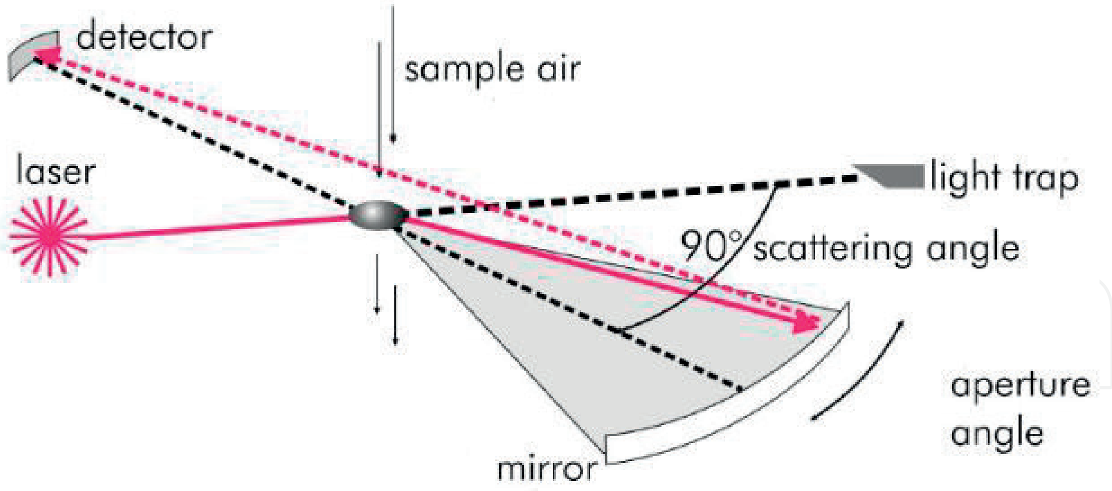

Figure 5. Measuring principle of GRIMM aerosol spectrometer [23].

light pulse of every single particle is being counted and the intensity of its scattering light signal classified to a certain particle size. The measuring principle is schematically shown in **Figure 5** [22].

The spectrometer uses a light-scattering technology for single-particle counts, whereby a semiconductor-laser is used as the light source. The wavelength for laser light is in the infra-red ranges, i.e., 780 nm. The aerosol particles can be detected over a very wide size range from 0.3 up to 20 μm. The scattered light is picked up directly as well as via a specific wide-angle optical system with a reflector at a scattering angle of 90°. The signal of the detector is classified into size channels after amplification subject to its intensity. This way, the dependency of the refraction index on the measured signal is low and scattered light intensity permits a precise determination of the particle size. The measured particles are deposited on a removable 47 mm polytetrafluoroethylene (PTFE) filter inside the instrument and are thus available for further gravimetric analysis as well as chemical analysis for detection of metals and non-metals, etc. **Figure 5** shows the assembly of the laser-measuring chamber. The sample air duct occurs perpendicular to the perspective into the measuring volume [23]. The advantages of ground-based instruments are better accuracy and precise measurements. However, the main disadvantage is that data are sparsely available due to highly expensive instruments. Also, one problem which the scientific community faces is data sharing. The benefits of data sharing are improving our understanding of the results or analysis, the accuracy of the research, can also strength collaborations.

3. Satellite-based remote sensing instruments

The high spatial and temporal resolution of satellite remote sensing data is more valuable in most atmospheric studies. The application of these new technologies to different satellite data have led to the generation of multiple aerosol products, such as spatial distribution, temporal variation, a fraction of fine and coarse modes, vertical distribution, light absorption, and some

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spectral characteristics. These can be used to infer sources of major aerosol emissions, the transportation of aerosols, interactions between aerosols and energy and water cycles, and the involvement of aerosols with the dynamic system. A series of space missions with instruments capable of making observations of backscattered solar radiation emerging at the top of the atmosphere (TOA) have been launched since the late 1970s.

The current satellites orbiting the Earth are either in geostationary or polar orbits and are described below.

1. Geostationary orbits

   Geostationary satellites are orbiting the Earth in the equatorial plane at a distance of about 36,000 km above the surface. The satellite's rotational velocity is identical to that of the Earth, and this enables the monitoring of dynamic meteorological phenomena such as major dust clouds, volcanic eruptions, smoke plumes or regional pollution events as they evolve throughout the day.

2. Polar orbits

   Polar satellites are orbiting the Earth in a plane that passes through the two poles. The orbit is adjusted to about 100 km above the Earth's surface and this corresponds to a full rotation every 90 minutes. Due to the low orbit, each consecutive rotation samples only a swath of the Earth's surface that is at most 3000 km wide. Each swath is incremented such that the polar orbit is sun-synchronous, i.e., the sensor will always observe the sunny side of the Earth at the same local time of the day. But this limits the polar-orbiting satellite to only one measurement or observation per day over any given location on the Earth's surface. The low orbit allows sensors to have higher spatial resolution and geolocation accuracy. Most quantitative aerosol datasets and climatologies are derived from polar orbiting satellites carrying a variety of sensors. There are two basic observation modes for satellite instruments depending on the observation geometry, i.e., vertical and horizontal observation modes (**Figure 6**). In vertical (or nadir viewing) observation mode, the satellite instrument faces to nadir or near-nadir to detect and measure the radiation coming from the Earth. A number of satellite instruments use the vertical observation concept to provide column integrated products. Observations in a horizontal direction including Limb-viewing and occultation sounding probe the Earth's limb at various depths in the atmosphere. Horizontal observations are characterized by altitude and geo-location of the tangent point. Sun occultation instruments can retrieve aerosol extinction profile from measurements of solar extinction through the atmospheric limb during sunrise and sunset.

Some of the polar orbiting satellites providing long-term and continuous sets of aerosol data are described below:

3.1. The ozone monitoring instrument (OMI)

Ozone monitoring instrument (OMI) onboard the NASA's Aura spacecraft has a high spectral resolution UV and visible (270–500 nm) spectrum. OMI is a nadir-viewing, wide-field-imaging UV and visible spectrometer designed to monitor ozone and other atmospheric species

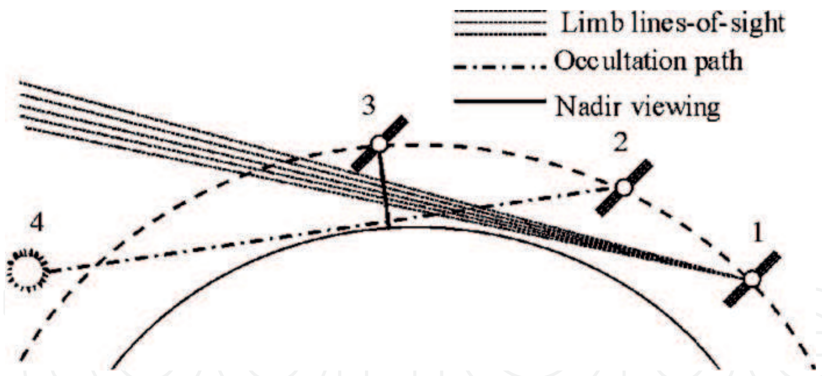

Figure 6. Observation modes of different satellites (1) nadir (vertical), (2) limb, (3) occultation (horizontal), and (4) Sun [24].

including aerosols. It derives its heritage from the descendant TOMS and the European Space Agency (ESA) Global Ozone Monitoring Experiment (GOME) instrument (on the ERS-2 satellite). This instrument has the capability to categorize aerosol types and also measures cloud pressure and coverage. The sensor provides data to derive tropospheric ozone and other important parameters related to climate and ozone chemistry. It uses a push broom technique to measure backscatter in the visible and UV spectrum and has a self-calibration mechanism. The measurements are accurate and precise of total ozone concentration due to its hyperspectral capabilities. OMI instrument has telescope field of view (FOV) 115° wide in across-track dimension. The orbital inclination of Aura Satellite is 98.1 degrees, providing latitudinal coverage from 82° N to 82° S.

3.2. Multi-angle imaging spectroradiometer (MISR)

The multi-angle imaging spectroradiometer is a satellite sensor onboard the NASA's Terra satellite. This scientific instrument was designed to measure the intensities of reflected and absorbed solar radiations by Earth in various directions and spectral bands. It has nine different digital cameras each having four spectral bands (blue, green, red, near infrared), and views the Earth at nine different angles. Out of these 9 cameras, one is towards nadir, other cameras as tilted forward and afterward view angles, at the Earth's surface, of 26.1, 45.6, 60.0, and 70.5°. When it is over the Earth surface each region is imaged by all nine cameras in four spectral bands. It can measure the amount and type of aerosol particles produced due to natural and anthropogenic activities. It can also measure the type and height of clouds. In addition, it also can distinguish different land surface types (snow and ice fields, vegetation, etc.). Owing to nine different angles it covers equator coverage in 9 days and Polar coverage in 2 days.

3.3. Moderate resolution imaging spectroradiometer (MODIS)

This is a key instrument onboard the Terra and Aqua satellite. Terra satellite orbits around the Earth during the morning at 10:30 local time in the north to south direction (descending) while Aqua orbits during the afternoon at 13:30 local time in the south to the north direction (ascending). Both of these instruments capture the same area on Earth. Though, they are approximately 3 hours apart. They observe the earth surface every 1–2 days. MODIS measures

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various aerosol optical properties, e.g., AOT, types of aerosols, aerosol size-distribution which enable us to understand complex atmospheric processes and varying climate dynamics over land and oceans. Different algorithms are used nowadays for the dark surface as well as bright surface (deep blue). It is providing a long-term and continuous measurement of different aerosol properties from a very long time. This sensor is playing an important role in validating and developing new models to predict climate change. Out of 36 spectral bands, first 19 are used for land, cloud, aerosol (properties and boundaries) as well as for ocean color, atmospheric water vapor, and biogeochemistry, etc., and the remaining are used for surface, cloud, atmospheric (temperature, altitude) as well as cloud water vapor, etc.

Information regarding the general characteristics (Platform, Resolution, Swath Width, Channels, Launch Date, etc.) of OMI, MISR and MODIS are provided in **Table 1**. The list of websites providing design specifications, principles of satellite instruments used for aerosol retrieval can be found elsewhere [25–27]. MODIS and MISR work on Rayleigh scattering principle whereas OMI works on both Rayleigh as well as Mie scattering principles. Both MODIS and OMI have wide spatial coverage (2330 and 2600 km) whereas MISR has narrow coverage (380 km). MODIS and OMI are single view sensors whereas MISR is multi-view sensor (nine cameras). Advantages of all these satellite sensors are wide spatial and temporal coverage. The disadvantage is only one or two retrievals possible in a day.

Sensor	OMI	MISR	MODIS
Platform	NASA EOS-AURA	NASA Terra	NASA Terra/Aqua
Spatial resolution at Nadir (km)	13 km × 24 km at nadir for UV2 (307–383 nm) and visible spectrum (349–504 nm) 13 km × 48 km for UV-1 spectrum (264–311 nm)	0.275	0.25 (bands 1–2) 0.50 (bands 3–7) 1.0 (bands 8–36) Pixel resolution 10 km
Swath width (km)	2600	380	2330
Channel and spectral range(wavelength nm)	270–500 nm with spectral resolution of 0.5 nm	Four wavelengths in each camera Centered at 446, 558, 672, and 867 nm Giving image in red, green, blue and near infrared	620–965 nm and 3.6–14.385 μm 36 spectral bands
Launch	15th July 2004	18th December 1999	18th December 1999/4th May 2002
Equator crossing time and mode	13:42 (ascending mode)	10:30 (descending mode)	10:30 (descending mode)/ 13:30 (ascending mode)
Multiview observations	No	9 (yes)	No
Altitude (km)	705	705	705

Table 1. General characteristics of instruments currently used for aerosol retrievals.

4. Conclusions

In this chapter, we discussed the principles and use of ground and satellite-based remote sensing instruments like CIMEL sunphotometer, MICROTOP, mass spectrometer. The remote sensing observations are commonly used to monitor and study the interaction of aerosols with solar radiation by measuring several aerosol optical properties on temporal and spatial variations on both local and global scales. Satellite based remote sensing owing to wide spatial and temporal coverage enables us to get retrievals or measurements at every spatial point. Sensors like OMI, MODIS, MISR have provided us long-term and continuous measurements of AOD and other selected optical parameters at every location with some bias factor. Although these instruments are sparsely available and also very expensive, these instruments yield reasonably good quality data, along with aerosol spectra, with a valid radiometric calibration. The vertical column aerosol load and aerosol types can be computed on basis of the aerosol spectra. These sensors have advantages and disadvantages though new techniques developed nowadays have enabled us to estimate air quality relatively better using a combination of satellite retrievals along with chemical transport model outputs.

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