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ATMOSPHERIC AEROSOL OBSERVATION DATA AT KYIV AERONET SITE: CONTRIBUTION TO THE ACME PROJECT

Background. An important direction of the ACME project is the collection of observational data characterizing the environment, in particular the transparency of the atmosphere, at astronomical observatories which are members of ACME. These data are also very important for meteorology and climatology. Aerosols are one of the components of the atmosphere that affect its transparency in a wide range of the continuous optical spectrum. The international network of automatic sun photometers AERONET provides observations of the content, dynamics, sizes and optical characteristics of aerosol particles almost over the entire globe. Additionally, the content of water vapor in the atmosphere above the observation site is measured. The observation sites of this network have been operating in Kyiv since March 2008, providing observational data on aerosols and the content of water vapor in the atmospheric column above the city.

Methods. Observations in the AERONET network are carried out using automatic CIMEL CE318 sun photometers, which measure the spectral optical thickness of the atmosphere caused by aerosol particles, recording the irradiance of the photosensitive element by the direct radiation from the solar disk, as well as the distribution of the sky radiation. Measurements are made in separate spectral channels with a width of approximately 10 nm, in the range from 340 nm to 1640 nm. The set of spectral channels depends on the photometer model. To determine the water vapor content, a channel with a wavelength of 940 nm is used. These data are processed by the AERONET standardized algorithms. The particle size distribution, single scattering albedo, complex refractive index, particle concentration, and their extinction and absorption coefficients are determined by solving the appropriate inverse problem. Based on these data, the spectral and integral downward fluxes at the Earth's surface of direct and scattered by the atmosphere solar radiation, and the upward fluxes at the upper boundary of the atmosphere of radiation reflected by the surface and the atmosphere, are calculated in the spectral range from 0.2 μm to 4.0 μm . The climatic effect of aerosols (radiative forcing) is estimated based on the magnitudes of these fluxes.

Results. Datasets of the observation results collected at Kyiv site since March 2008 contain data on spectral optical thickness in spectral channels with wavelengths of 440 nm, 675 nm, 870 nm and 1020 nm, on the water vapor content, and on the aerosol particles properties and radiative fluxes. These data series are available via the AERONET website, and may eventually be available via the ACME website.

Conclusions. Data on the aerosol particles properties contained in the database of the AERONET, may be of interest for analyzing the results of optical observations performed at astronomical observatories that are part of the ACME project infrastructure. Aerosols extinction data can be used when processing the results of observations of Cherenkov radiation which are carried out at observatories Auger, H.E.S.S., MSAGIC, VERITAS, HAWC, and at the new-generation gamma-ray observatory, the Cherenkov Telescope Array (CTA). The data of aerosol observations at Kyiv site can be used within Work Package 7 (WP7) of the ACME project for the processing of astrophysical observations of celestial objects made with small telescopes, particularly by amateur astronomers.

Keywords: ACME, the Earth's atmosphere, AERONET, sun photometers, aerosols.

Background

Astronomical observatories and institutes participating in the Astrophysics Centre for Multi-Messenger Studies in Europe (ACME, <https://www.acme-astro.eu/>) collect large volumes of observational data characterizing the surrounding environment. In particular, these include data on the composition and transparency of the Earth's atmosphere at observation sites. An important direction of the ACME project is the dissemination of these data to researchers and specialists in fields related to the environment, such as meteorology and climatology. On the other hand, these data are valuable for the processing and analysis of astronomical observations, since the state of the Earth's atmosphere significantly affects astronomical measurements performed from the ground. This is especially relevant for the short-wavelength part of the electromagnetic spectrum, which includes the ultraviolet, visible, and infrared ranges.

The strongest influence, of course, comes from the scattering of electromagnetic waves by atmospheric molecules – the most evident result of which is the blue color of the daytime sky. The effect of this Rayleigh scattering is relatively easy to account for, since its intensity depends on the concentration of the so-called major atmospheric gases (nitrogen, oxygen, and inert gases). Their concentration at an observatory site can be calculated with sufficient accuracy using meteorological data. The global content of these gases in the Earth's atmosphere is stable, and local variations due to meteorological processes are relatively minor. However, the atmosphere also contains other components – both gaseous and in the form of liquid droplets and solid

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particles (aerosols) – whose concentrations vary greatly on both local and global scales. These components also have a significant impact on atmospheric transparency across different spectral ranges. As an example, Fig. 1 depicts the influence of the absorption properties of individual gaseous components on atmospheric transparency as a function of altitude.

The main atmospheric constituents that limit the transparency of a cloudless atmosphere at short wavelengths, besides Rayleigh scattering, are ozone, carbon dioxide, and aerosols (mainly due to scattering). In the visible part of the spectrum, atmospheric transparency is determined primarily by Rayleigh scattering and aerosols (see Fig. 2). However, apart from their impact on conditions for astronomical observations, these components also play a crucial role in meteorological processes and in the formation of both global and regional climate (Szopa et al., 2013). Therefore, the scientific community devotes substantial attention to monitoring the composition and dynamics of these atmospheric components (see, for example, (Gulev et al. 2021)).

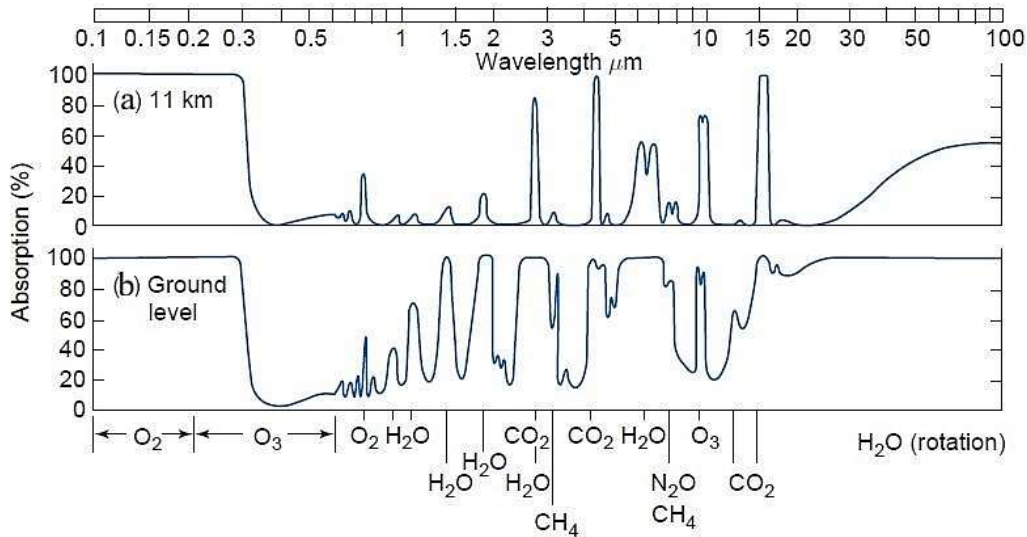


Fig. 1. Spectrum of monochromatic absorption of the part of the atmosphere that lies above the 11-km level (a); spectrum of monochromatic absorption of the entire atmosphere (b). Adapted from (Wallace, & Hobbs, 2006)

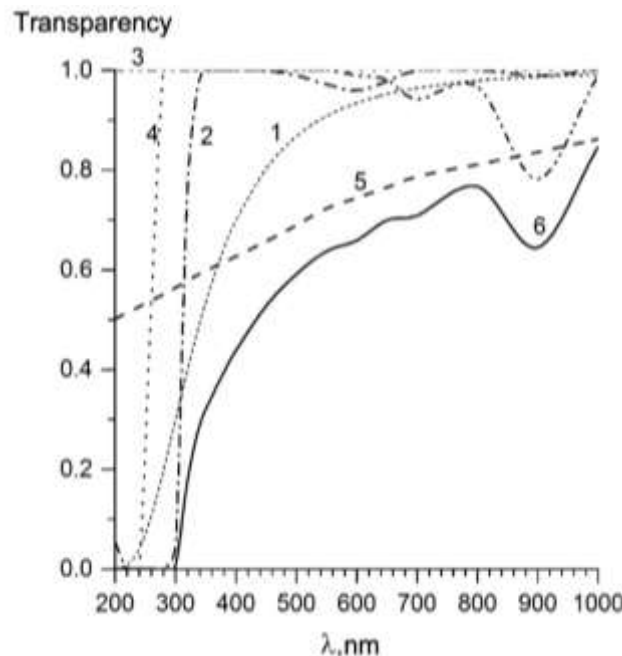


Fig. 2. Spectral transparency of the Earth's atmosphere in the absence of clouds (constructed using data from (Cox, 2002)): 1 – molecular (Rayleigh) scattering; 2 – ozone; 3 – water vapor; 4 – CO₂; 5 – aerosol; 6 – total transparency

Scientists of the Taras Shevchenko National University of Kyiv (TSNUK) have been performing long-term observations of the content and dynamics of aerosol particles, water vapor, and ozone in the atmospheric column above Kyiv. These studies include measurements of aerosols and water vapor within the framework of the AERONET (AERosol RObotic NETwork) international network of sun photometers, as well as ozone observations using a Dobson spectrophotometer, which is part of

the network coordinated by the World Meteorological Organization (WMO). The data obtained from these observations can be used within Work Package 7 (WP7) of the ACME project for the processing of astrophysical observations of celestial objects made with small telescopes at the Astronomical Observatory of TSNUK (AO TSNUK), at the Main Astronomical Observatory of the National Academy of Sciences of Ukraine (MAO NASU), as well as by amateur astronomers. This article discusses the methods used at TSNUK for monitoring aerosols and water vapor, and characterizes the datasets which contain the results of observation data and their processing.

Methods

Studies of the optical properties of the Earth's atmosphere caused by aerosols, as well as of the content, dynamics, and characteristics of aerosol particles in the atmosphere over Kyiv – and later over other regions of Ukraine – began at TSNUK in 2008 with the establishment of a Kyiv observation station of the AERONET/PHOTONS network. This was accomplished through the joint efforts of the Department of Astronomy and Space Physics and the AO TSNUK, together with the MAO NASU, with the assistance of the Laboratoire d'Optique Atmosphérique (LOA) at the University of Lille 1, France.

PHOTONS (from the French PHOTométrie pour le Traitement, l'Observation et la Normalisation Satellite) is the European branch of AERONET (<http://loaphotons.univ-lille1.fr/photons/>), recognized as a National Observatory for Aerosol Research. It supports the operation of about 100 observation stations located mainly across Europe, as well as in Africa, Asia, and even Antarctica. However, in the eastern part of Europe, such stations were very limited. To address this gap, the necessary equipment was installed at the main building of the MAO in the Holiiv Forest, about 10 km from the city center. Continuous measurements began in late March 2008 and have been ongoing ever since.

The AERONET instruments, observation procedure and data transfer. The AERONET is a federation of ground-based remote sensing aerosol networks established by NASA and a French organization PHOTONS. PHOTONS is supported by the University of Lille 1 (<https://www.univ-lille.fr/>), Centre National D'Etudes Spatiales (CNES, <https://cnes.fr/>), and l'Institut national des sciences de l'Univers (INSU, <https://www.insu.cnrs.fr/fr>) du Centre national de la recherche scientifique (CNRS, <https://www.cnrs.fr/>). AERONET is also expanding through networks, calibration centers and other partners from national agencies of many countries, institutes, universities, individual scientists (a full list of these organizations can be found on the AERONET website). For more than 25 years, the project has provided continuous, and readily accessible public databases of aerosol optical, microphysical and radiative properties for aerosol studies, validation of satellite retrievals, and synergism with other databases. The network provides standardization of instruments and their calibration, processing and distribution of data. In such a way, AERONET maintains globally observations of spectral aerosol optical depth (AOD), optical and microphysical properties of aerosol particles, and water vapor content in different aerosol regimes in the atmosphere column over the observational site. The AERONET offers high-precision measurements of aerosol optical parameters and water vapor content over about 1700 stations globally, many of which have long-term measurements for one or more decades.

The AERONET instruments for the aerosol and water vapor observations are the CIMEL Electronique CE318 sun photometers which perform measurements of spectral sun irradiance and sky radiances in different wavelength bands from near UV to near IR. The sun photometer is an autonomous and portable instrument. It consists of a sensor head provided with 25 cm collimators that is attached to a 40 cm robot base which points the sensor head at the Sun, the sky and the moon according to a preprogrammed procedure. The optical head has two channel systems: the sun collimator, and the sky collimator without lenses. The sun tracking is equipped with a 4-quadrant detector. The electronic control box contains two microprocessors for real time operation of the robot motion control and data acquisition by the optical head. The electronic box performs the computation of the Sun coordinates, and the robot rotates the optical head by step-by-step motors in the zenith and azimuth planes and directs it to the Sun or the certain point of the sky. Accuracy of the optical head pointing is better than 0.1° . Also, the control box operates a wet sensor that detects precipitation and in automatic mode forces the instrument to park and to protect the optics. Internal batteries are used for the optical head operation, and external batteries for the robot. The batteries are rechargeable by solar panels. The Cimel control unit and batteries are usually deployed in a weatherproof plastic case. The solar panels are usually located on the case door. The operating temperature of the sun photometer is -30 to $+60^\circ\text{C}$.

The observational data collected in the AERONET database are obtained with sun photometers of different models, whose characteristics and potential of measurements developed greatly during more than 25 years. Design, parameters and characteristics of the sun photometer of various models can be found in the sections "System Description" of the AERONET site. The sun photometer's manuals and operation rules are contained in the "Logistic" section. Sun photometers perform measurements in the single bands of the spectrum with a full width at half maximum (FWHM) of 10 nm in the range from 340 to 1640 nm. The interference filters at each wavelength are located in a filter wheel which is rotated by a direct drive stepping motor. The number of the spectral filters depends on the photometer model. Modern CE318 photometers can have from 5 to 9 spectral channels. For example, the base model of the CIMEL CE 318 sun photometer has 5 filters of 440, 670, 870, 936, 1020 nm, but the latest CE318-T models which also perform nighttime measurements of the spectral lunar irradiance have 9 filters with wavelengths of 340, 380, 440, 500, 675, 870, 937, 1020, and 1640 nm. The CE318-T models spectral filters also have the FWHM of 2 nm at 340 nm, 4 nm at 380 nm and 25 nm at 1640 nm. The sun photometers of the newest models also have polarization analyzers in each of these channels to measure the polarization parameters of the solar radiance scattered by the Earth atmosphere.

The field sun photometers are calibrated against an AERONET reference instrument both before deployment in the field and post-deployment. Analysis suggests an uncertainty of approximately 0.01 – 0.02 in AOD (wavelength dependent) due to calibration uncertainty for the field instruments. For the sky radiance measurements, calibration is performed at a calibration facility using a calibrated integrating sphere to an accuracy of $\pm 5\%$.

Photometers perform measurements by observing the Sun and the Moon in automatic mode according to a special algorithm controlled by a microprocessor. In addition, the distribution of sky brightness is measured along the Sun's almucantar in the range of $\pm 180^\circ$, and along the circle of its altitude from the solar disk through the zenith to the horizon (i.e. in the principal plane). Special measurement sequences have been created to measure sky and sun radiance. Different

scenarios are used to make various kinds of measurement automatic. A preprogrammed sequence of measurements is taken by these instruments starting at an air mass of 7 in the morning and ending at an air mass of 7 in the evening. Optical depth is calculated from spectral extinction of direct beam radiation at each wavelength based on the Beer-Bouguer Law. This parameter depends on the content of particles in the atmospheric column, and on their optical characteristics:

$$\tau(\lambda) = \int_0^H \int_{r_{\min}}^{r_{\max}} \sum \left(\frac{2\pi r}{\lambda}, m(\lambda) \right) \cdot \frac{dN(r, h)}{dr} \cdot dr \cdot dh,$$

where λ is the wavelength of radiation; H is the height of the upper boundary of the aerosol layer above the observation site; r_{\min} , r_{\max} are the minimum and maximum sizes of aerosol particles; Σ is the scattering cross-section area of an aerosol particle, which depends on the ratio between the particle size r and the radiation wavelength (size parameter), and on the complex refractive index of the particle m , which also depends on the radiation wavelength; dN/dr is the size distribution of particles in the atmospheric column, which generally varies with height, as do other particle parameters.

Attenuation due to Rayleigh scatter, and absorption by ozone, and gaseous pollutants is estimated and removed to isolate the AOD. Measurements of the sky radiance are performed by the sun photometer in four spectral bands (440, 670, 870 and 1020 nm) along the solar principal plane up to nine times a day and along the solar almucantar up to six times a day. The approach is to acquire aureole and sky radiances observations through a large range of scattering angles from the sun through a constant aerosol profile to retrieve size distribution, phase function and aerosol optical depth. More than eight almucantar sequences are made daily at an optical air mass of 4, 3, 2 and 1.7 both morning and afternoon.

To characterize the AOD wavelength dependence the Angström parameter is used in the AERONET. It is parameter that is determined by empirical formula:

$$\tau(\lambda) = \tau(\lambda_0) \cdot \lambda^{-\alpha},$$

where $\lambda_0 = 1 \cdot \mu m$, and which in AERONET data processing algorithms is determined from AOD measurements in different spectral channels. To interpolate AOD from the spectrum in AERONET algorithms, the Angström exponent determined at wavelengths of 440 and 870 nm is usually used.

Observed data may be downloaded automatically from the Cimel sun photometer and stored on the local computer. This computer can run software to automatically transfer data files to the AERONET processing system through the Internet. Also, data can be transmitted from the memory of the sun photometer via the Data Collection Systems (DCS) to either of geosynchronous satellites GOES, METEOSAT or GMS and then retransmitted to the appropriate ground receiving station. The special satellite transmitter module with antenna is used, collocated with the sun photometer. The transmitter system is battery operated and charged by a solar panel. The Model T instrument has the capability of uploading data directly from the instrument to a cellular network using the modem inside the control box with a SIM card instead of a PC. After collection in the processing server the data are converted to the unified format and are placed in the database. Data are also copied to a backup system and cloned on several other workstations.

The AERONET data processing and distribution. Observational data are filtered and processed using special standardized algorithms. The processing consists of several algorithms applied to the raw data. They are: 1) Aerosol Optical Depth (AOD) retrieval; 2) AOD cloud screening; 3) Inversion of Sky Radiance data measured on Almucantars and Principal Planes. The processing algorithms have evolved from Version 1.0 to Version 2.0 and now Version 3.0. The Version 3 databases are available from the AERONET and PHOTONS web sites. Version 2 data may be downloaded from the web site through 2018 and thereafter upon *special request*. Version 3 AOD data are computed for three data quality levels: Level 1.0 (unscreened), Level 1.5 (cloud-screened and quality-controlled), and Level 2.0 (quality-assured) (Giles et al., 2019; Sinyuk et al., 2020). These data can also be reprocessed to implement new parameters (e.g., calibration). Inversion results (i.e. aerosol particles properties), precipitable water content, and other AOD-dependent products averaged over an atmosphere column are derived from data of these levels. Documents and publications for the algorithms of data processing and inversion can also be found on the AERONET web-site. New AERONET products will be released as new measurement techniques and algorithms are adopted and validated by the AERONET research community.

AERONET data are distributed via the internet through a web tool and FTP. The primary distribution method of AERONET data is the AERONET web download tool. This tool provides access to most AERONET data products (e.g., aerosol optical depth and inversion products). For special requests and products not available through the download tool (e.g., data for specific instruments), an FTP transfer can be set up to update remote systems. AERONET uses the ASCII text format for data dissemination. These data are provided within compressed zip files to improve data transfer between systems.

The AERONET website also provides AERONET-related news, a description of research and operational activities, data visualization, web services, related Earth Science links, and links to other data related to the Earth atmosphere research. Particularly, the AERONET – Ocean Color (https://aeronet.gsfc.nasa.gov/new_web/ocean_color.html) that is another component of the AERONET program, provides the additional capability of measuring the radiance emerging from the sea (i.e., water-leaving radiance) with sun photometers installed on offshore platforms like lighthouses, oceanographic and oil towers. Similarly, the Maritime Aerosol Network (https://aeronet.gsfc.nasa.gov/new_web/maritime_aerosol_network_v3.html) component of the AERONET program provides ship-borne aerosol optical depth measurements from the Microtops II sun photometers. These instruments have been deployed periodically on ships of opportunity and research vessels to monitor aerosol properties over the World's Oceans. The Solar Radiation Network (https://aeronet.gsfc.nasa.gov/new_web/maritime_aerosol_network_v3.html) provides high-frequency solar flux measurements and is collocated with AERONET sites. Some of the satellite instruments data (i.e., MODIS) are available on the AERONET web-site.

AERONET Inversion Methodology. The final product of AERONET is data on the aerosol content in the atmospheric column above the observation site and properties of aerosol particles, averaged in the atmospheric column, and the water vapor content in it. The content of aerosol particles is characterized by the AOD of the atmosphere. The characteristics of

aerosol particles are determined from the AOD observations and the distribution of sky brightness along the almucantar and the circle of the solar altitude by solving the corresponding inverse problem (Holben et al., 1998; Dubovik, & King, 2000; Dubovik et al., 2000; 2002; 2006). These are the following characteristics: 1) particle Volume Size distribution (VSD) in 22 size bins approximated by two-modal (fine and coarse modes) lognormal function, 2) volume concentration (VC), 3) volume median radius, 4) standard deviation and effective radius for total, fine and coarse modes; 5) relative content (in %) of spherical particles; 6) spectral Phase function (PF) of the light scattered by particles; 7) spectral Asymmetry Parameter of the Phase function (APPF); 8) spectral Extinction Optical Depth (ExtAOD); 9) spectral Absorption Optical Depth (AbsAOD); 10) spectral Single Scattering Albedo (SSA); 11) spectral Complex Index of Refraction (real ReRI and imaginary ImRI); 12) lidar and depolarization ratios.

Based on these data, the AERONET algorithms calculate the spectral flux of solar radiation at the Earth's surface, the flux at the upper boundary of the atmosphere of radiation scattered by the atmosphere and reflected by the Earth's surface, and the contribution of scattering by aerosol particles to these fluxes (the so-called radiative forcing). The following radiative fluxes are calculated. 1) Spectral downward flux for each of the sun photometer spectral channels at the bottom of atmosphere (BOA), and upward fluxes at the top of atmosphere (TOA). 2) Downward flux at the BOA and upward flux at the TOA in the broad spectral band in the spectral range from 0.2 to 4.0 μm . 3) Radiative forcing at TOA and BOA. 4) Radiative forcing efficiency at TOA and BOA.

Also, a special algorithm determines the AOD for the fine and coarse modes of aerosol particles at a light wavelength of 500 nm (O'Neil et al., 2003; O'Neill et al., 2023).

The inversion algorithm is based on integration of the radiative transfer equation downward from TOA to BOA and upward to TOA with some assumptions on the atmosphere and aerosol particles properties. The first, the atmosphere is assumed to be plane-parallel. Gaseous absorption by ozone, nitrogen dioxide and water vapor are accounted for in the inversion of the sky radiances. Total column water vapor amount is determined from the AERONET sun photometer measurements at 940 nm spectral channel. Total ozone optical depth is determined from the total column monthly average climatology (1978–2004) of O₃ concentration data collected by the Total Ozone Mapping Spectrometer (TOMS) instrument aboard set of satellites (EarthProbe, Nimbus-7, Meteor-3) and The Ozone Monitoring Instrument (OMI), aboard the Aura satellite (July 2004 – current). Measurements were performed at $1^\circ \times 1.25^\circ$ spatial resolution, and the O₃ spectral absorption coefficient was used. The nitrogen dioxide optical depth is calculated using the total column OMI monthly average climatology of NO₂ concentration at $0.25^\circ \times 0.25^\circ$ spatial resolution and the NO₂ spectral absorption coefficient.

Vertical distributions of aerosol concentration are adopted from MERRA-2 reanalysis, which uses aerosol vertical profile from measurements made by Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) instrument. CALIOP was installed aboard the joint NASA/French Space Agency Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) satellite that was in operation from April 28, 2006 to December 15, 2023. Aerosol particles are assumed to be partitioned into spherical and non-spherical. The spherical component is modeled by an ensemble of polydisperse, homogeneous spheres. The non-spherical component is a mixture of polydisperse, randomly-oriented homogeneous spheroids. The spheroid aspect ratio distribution is retrieved by Dubovik et al. [2006] and fits to the scattering matrix of mineral dust measured in the laboratory. The volume particle size distribution ($dV(r)/d\ln r$ ($\mu\text{m}^3/\mu\text{m}^2$)) is simulated by a bimodal log-normal function, and is retrieved for 22 logarithmically equidistant discrete points (r_i) in the range of sizes $0.05\mu\text{m} \leq r \leq 15\mu\text{m}$. The inversion algorithm finds the minimum of the bimodal function within the size interval from 0.439 to 0.992 μm . This minimum is used as a separation point between fine and coarse mode particles. Using that separation, the algorithm simulates AOD, phase function and single scattering albedo of fine and coarse mode separately. Furthermore, the retrieval provides estimates of effective radius, volume median radius, Standard Deviation and particle volume concentrations ($\mu\text{m}^3 / \mu\text{m}^2$) for both fine and coarse modes of the retrieved size distribution.

The complex index of refraction is assumed to be the same for particles of all sizes. The real for ($1.33 \leq \text{ReRI}(\lambda) \leq 1.6$) and imaginary ($0.0005 \leq \text{ImRI}(\lambda) \leq 0.5$) parts of the complex refractive index are retrieved for the wavelengths from the sky radiance measurements.

Surface Reflectance (surface albedo) is modeled by the bidirectional reflectance distribution function (BRDF) (Breon, & Maignan, 2017). The BRDF parameters for land sites are adopted from MODIS measurements. The land and water BRDF models are mixed using the percentage of land and water within a 10 km diameter circle centered at AERONET site.

The statistically optimized inversion algorithm is applied to retrieve the aerosol particles properties listed above. The particle parameters retrieval and errors estimate are obtained under the assumption of uncorrelated log-normally distributed errors. This optimization accounts for different levels of accuracy in the measurements. For example, the standard deviation for error in $\tau(\lambda)$ is assumed 0.01, and the standard deviation for error in sky radiance measurements is assumed 5 %). The details see in (Dubovik, & King 2000; Dubovik et al., 2000; 2002; 2006). The output provides estimates for both random and possible systematic (resulted from possible biases in measurements) errors for most of the retrieved parameters. According to those estimates, 68 % confidence intervals are presented for most retrieved characteristics.

The almucantar sky radiance scans made by the CIMEL instruments are performed at fixed elevation angles equal to the solar elevation with $\pm 180^\circ$ azimuthal measurements made sequentially at seven wavelengths (380, 440, 500, 675, 870, 1020 and 1640 nm). In the standard retrieval product only the data from 440, 675, 870 and 1020 nm are input to the inversion algorithm. All sky scan retrievals in the AERONET Version 3 database were only inverted for these wavelengths since these are the common wavelengths for all instruments and all sites.

Almucantar directional scan radiance data are combined with measured AOD data at identical wavelengths as inputs to retrieve optically equivalent column-integrated volume size distributions and aerosol refractive indices utilizing the algorithms as developed by Dubovik and King (2000) and Dubovik et al. (2006). The Dubovik and King (2000) inversion algorithm in AERONET makes no assumptions about the spectral variation of AOD. The inversion fits the measured AOD to within 0.01 consistent with the measurement accuracy of the direct sun measured AOD, and along with the retrieved size distribution and complex refractive indices computes the radiative transfer calculated sky radiances with residual errors of

maximum of 5–8 % (lower value at higher AOD). These retrieved aerosol properties are used to derive additional parameters such as asymmetry parameter, single scattering albedo, and phase function. The percentage particles of spheroidal and spherical shape required to give the best fit to the measured angular distribution of spectral sky radiances is also determined by the AERONET retrieval algorithm. Dubovik et al. (2006) provides further details on these retrieval algorithms. The nominal uncertainty of AERONET SSA at AOD (440) is ~0.03, and the SSA uncertainty decreases as AOD increases (Sinyuk et al., 2020).

Results

This section will provide a description of the aerosol properties data obtained from observations at Kyiv AERONET/PHOTONS site. To access these data, use the Download Tool option on the AERONET website on the left side of the screen. The following datasets of three data quality levels are available for download for Kyiv: Level 1.0, Level 1.5 and Level 2.0. Observational data are collected in the dataset of all measurements, and daily and monthly averaged datasets. But all measurements datasets of Level 1.5 are described here because these data contain all basic information about aerosol properties and observation conditions. Also, these datasets have a larger size. Download Tool options propose to download the following data sets.

AEROSOL OPTICAL DEPTH (V3)-SOLAR Download Tool option allows access to datasets containing the following parameters.

1) Spectral AOD with Precipitable Water (i.e., water vapor amount) and Angström Parameter. This dataset contains for each observation time the AOD value for each spectral channel and SD estimations from triplet measurements; the precipitable water layer thickness (in cm) and SD from triplet measurement; the Angström Parameter values determined for the spectral intervals 380–500 nm (if available), 440–675 nm and 440–870 nm. Also, other data are available in this dataset, such as the observational site coordinates, the Sun zenith angle, optical air mass, O₃ and NO₂ content in the atmosphere column (in Dobson unit), the sun photometer temperature and exact wavelength of each spectral channel, and other relevant information.

2) Total Optical Depth based on AOD Level contains an optical depth of the entire atmosphere and optical depths of each atmosphere component in the atmosphere column: Rayleigh scattering, O₃, NO₂, Water Vapor and CO₂. Also, all relevant data are available in this dataset like as in the previous dataset.

3) Spectral Deconvolution Algorithm (SDA) Retrievals: Fine Mode AOD, Coarse Mode AOD, and Fine Mode Fraction in the AOD. SDA is O'Neill's algorithm (O'Neill et al., 2003; 2023).

AEROSOL INVERSIONS (V3) Download Tool option allows access to all inversion product datasets. The aerosol particle properties are available in the following datasets of data quality Level 1.5 and Level 2.0.

1) Raw Almacantar, Raw Principal Plane and Raw Polarized Principal Plane (with degree of polarization). These data are the Sky radiance data Level 1.0 in $\mu W/(cm^2 \cdot sr \cdot nm)$ measured by the sun photometer scanning along the Almacantar of the Sun and in the Principal Plane, at each spectral channel. The Almacantar radiance dataset contains the radiance data for each mean time moment of scanning at the azimuth angle series from the solar disk to 180° in both directions: the eastward and the westward. The step of measurements is 0.5° in the range of azimuth from 2° up to 4°, 1° in the azimuth range from 4° to 10°, 2° from azimuth 10° to 20°, 5° from azimuth 20° to 50°, 10° from azimuth 50° to 100° and 20° from azimuth 100° to 180°. Corresponding zenith angles of the Sun and scattering angles are also given, together with exact wavelength values, and the sun photometer number.

2) The Sky radiance data Level 1.0 of measurements in the principal plane are given for each mean time moment of scanning from the Sun through zenith to the maximum scattering angle that is equal to 150°. The step of measurements is 0.5° in the range of scattering angle from 2° up to 4°, 1° in the scattering angle range from 4° to 6°, 2° from 6° to 16°, 4° from 16° to 20°, 5° from 20° to 70° and 10° from the scattering angle 100° to 150°. Relevant data on the Sun zenith angles and the sun photometer information are given too.

3) Volume Size Distribution (VSD) is the Dataset of the aerosol particle size distribution averaged in the atmosphere column over the observational site, determined as the particle volume distribution, $dV(r)/dr$ ($\mu m^3/\mu m^2$). This means the integral volume of all particles in the atmosphere column with section equal to 1 μm^2 . These data are given for each of the almucantar radiance dataset of Level 1.5. Particle radii are in the range from 0.05 to 15 μm . The VSD data are given for 22 discrete values r_i which logarithmically equidistant in the range of sizes $0.05 \mu m \leq r \leq 15 \mu m$. Also, the r value corresponding to inflection point of the bimodal lognormal function are given in this dataset, and relevant data on the Sun zenith angle, number of the scanning, coincident AOD at 440 nm, values of the Earth surface albedo and other relevant parameters of the sun photometer and observational site.

4) Size Distribution Parameters dataset contains parameters of the Total Volume Distribution and both Fine mode and Coarse mode distribution: Volume particles concentration, Effective radius, Modal radius and Standard Deviation of the distribution. Also, the relevant parameters are given, such as the Sun zenith angles at the time moment of scanning and moment of start scanning, coincident AOD (440 nm), the surface albedo for each spectral channel, the observational site coordinates and other.

5) Coincident AOD dataset contains the AOD measured with the direct Sun at the time of almucantar scanning for each spectral channel 440, 675, 870 and 1020 nm. Also, the Angström exponent values determined for 440–870 nm are given together with the Sun zenith angles, surface albedo and other relevant parameters of the observational site.

6) Extinction AOD dataset contains AOD values caused by absorption and scattering solar radiation by aerosol particles, determined from almucantar scanning, for total aerosol content in the atmosphere column, and for both aerosol fine and coarse mode. Also, the Angström exponent values of extinction determined for 440–870 nm for total aerosol content in the atmosphere column are given together with the Sun zenith angles, surface albedo and other relevant parameters of the observational site and observation conditions.

7) Absorption AOD dataset contains AOD caused only by absorption of the solar radiation by the aerosol particles at for total aerosol content in the atmosphere column, and for both aerosol fine and coarse mode. Also, the Angström exponent values of absorption determined for 440–870 nm for total aerosol content in the atmosphere column are given together with the Sun zenith angles, surface albedo and other relevant parameters of the observational site and observation conditions.

8) Refractive Index dataset contains the real and imaginary parts of aerosol particles RI determined from almucantar measurements for spectral channels of 440, 675, 870 and 1020 nm, averaged in the whole atmosphere column, together with the Sun zenith angle and other parameters of the observational site and observation conditions.

9) Single Scattering Albedo contains the SSA values of the aerosol particles determined from almucantar measurements for spectral channels of 440, 675, 870 and 1020 nm, averaged in the whole atmosphere column, together with the Sun zenith angle and other parameters of the observational site and observation conditions.

10) Uncertainty Estimates – are the standard deviation of SSA and RI data retrieved from Almucantar measurements.

11) Phase Function (PhF) dataset contains values of PhF for 83 scattering angles from 0° to 180° at wavelengths corresponding to sky radiance measurements: 440, 675, 870 and 1020 nm. Also, the relevant parameters of the observational site and conditions of observations.

12) Asymmetry Factor dataset contains the factor of phase function asymmetry values for the same wavelength as the PhF. Also, the particle sphericity factor (in %) is given in this dataset. The relevant parameters of the observational site and conditions of observations are given too.

13) Spectral Flux (SF) dataset contains values of SF in W/m^2 at the wavelengths of spectral channels corresponding to the direct Sun irradiance and sky radiance measurements. SF are determined from both the direct Sun irradiance measurements (direct Sun SF) and the Sky radiance measurements (diffuse SF). Correspondingly, downward SF at the top of the atmosphere ($F_{\downarrow TOA}(\lambda)$) and bottom of the atmosphere ($F_{\downarrow BOA}(\lambda)$) and upward SF at the bottom of the atmosphere ($F_{\uparrow BOA}(\lambda)$) and at the top of the atmosphere ($F_{\uparrow TOA}(\lambda)$) of direct Sun SF and diffuse SF are also calculated and given in this dataset. Also, all relevant data on the Sun zenith angles, coincident AOD (440 nm), surface albedo spectral values and other parameters of the observational site and condition of observations are given in this dataset.

14) Radiative Forcing (RF) dataset contains values of the downward direct Sun flux and diffuse flux at TOA and BOA, and the upward direct Sun and diffuse fluxes at BOA and TOA. These fluxes are integral in the spectral range from 0.2 μm to 4 μm . They are calculated on the basis of the corresponding spectral fluxes which are given in the previous datasets using the data on the spectral properties of the atmosphere constituents. Also, the direct RF values for the BOA and TOA, and diffuse RF at TOA are given in this dataset together with altitudes of the bottom and top atmosphere layers used for calculation of the BOA and TOA fluxes and RF. All relevant data on the Sun zenith angles and parameters of the observational site and condition of observations are given in this dataset too.

15) Lidar and Depolarization Ratios dataset contains lidar ratio and the particle linear depolarization ratio values for the wavelengths 440, 675, 870 and 1020 nm at each time of the almucantar scanning of the sky. Also, all relevant data on the Sun zenith angles, coincident AOD (440 nm), surface albedo spectral values and other parameters of the observational site and condition of observations are given in this dataset.

The data presented in the above datasets are obtained from observations made since the end of March 2008. In total, for the period from March 29, 2008 to May 30, 2024, the Spectral AOD with Precipitable Water and Angström Parameter datasets provide aerosol data values for 91193 observation times. There are a total of 113 values for each observation time. In total, the data in the Spectral AOD with Precipitable Water and Angström Parameter, Total Optical Depth and Spectral Deconvolution Algorithm Retrievals datasets are approximately 432 MB in size.

To solve the inverse problem and determine the optical and microphysical characteristics of the particles, a sufficient number of sky brightness observations are required, which are contained in the Raw Almucantar and Raw Principal Plane datasets. These observational data are used in solving the inverse problem after filtering. Accordingly, the amount of data in the Raw Almucantar and Raw Principal Plane datasets is the largest. From March 29, 2008 to May 30, 2024, the Raw Almucantar dataset contains 129717 scan cycles, which are assigned to a single moment of time. Each scan cycle contains 164 values. The Raw Principal Plane dataset has 107274 scan cycles, and each of them contains 51 values. In the datasets containing characteristics of aerosol particles, fluxes and RF values, data are provided for a total of 10705 moments of time. In total, the data in datasets containing raw data and aerosol particles properties have a total size of approximately 495 Mb.

Discussion and conclusions

The article describes a data series of the characteristics of aerosol particles contained in the database of the International network of the automatic sun photometers AERONET, which may be of interest for analyzing the results of optical observations performed at astronomical observatories that are part of the ACME project infrastructure. Since aerosol particles affect the transparency of the atmosphere in a wide range of the optical spectrum due to their content, optical characteristics, and dynamics in the atmosphere, these data can be used when processing the results of observations of Cherenkov radiation, which is measured to record fluxes of high-energy cosmic particles and gamma rays. In particular, such observations are carried out at observatories Auger, H.E.S.S., MAGIC, VERITAS, HAWC. Such research will also be carried out at the new-generation gamma-ray observatory, the Cherenkov Telescope Array (CTA), which is under construction and should become a particularly powerful tool for studying high-energy cosmic rays.

Although AERONET sun photometers use sunlight to study aerosols and perform measurements during the daytime, these data can be used to determine atmospheric transparency at astronomical observation sites. As aerosol particles can be transported by air masses over significant distances when they enter the atmosphere in a large number, sun photometer observations can also be useful for tracking particle transport trajectories and assessing their impact on atmospheric transparency at night. Large amounts of aerosol particles enter the atmosphere during large-scale wildfires, dust storms or volcanic eruptions. Analysis of observational data, including data from sun photometers, has revealed that aerosol particles that entered the high atmosphere as a result of such phenomena can spread thousands of kilometers from the site where they enter the atmosphere. For example, smoke particles from wildfires in Canada in 2023 were observed in Europe (Evgenieva et al., 2025), and aerosol particles from the eruption of the Hunga Tonga-Hunga Ha'apai volcano in the Tonga archipelago in the southwest Pacific were observed on Reunion Island in the Indian Ocean, near Madagascar (Baron et al., 2023). Also, dust from the Sahara spreads across the Atlantic and reaches the Caribbean islands (Rittmeister et al., 2017).

The AERONET database (<https://aeronet.gsfc.nasa.gov/>) contains data on the dynamics of the content and characteristics of aerosol particles, determined from observations with sun photometers at more than 1700 sites in various regions of the globe. Such aerosols parameters as the spectral AOD of the atmosphere, caused by the scattering and absorption of sunlight

by aerosol particles in the atmospheric column above the observation site, as well as the particle sizes averaged in the atmospheric column, their complex refractive index, scattering and absorption coefficients, and other parameters affecting the transparency of the atmosphere are determined from the observation data. In particular, these data are used to assess the impact of aerosols on meteorological processes and climate by calculating the solar radiation fluxes integrated over a wide range of the optical spectrum: descending to the Earth's surface (BOA) and ascending to the upper boundary of the atmosphere (TOA). Radiation flux at BOA takes into account both the direct radiation from the solar disk and the radiation scattered by the atmosphere from the entire hemisphere of the sky, while flux at TOA takes into account fluxes of the radiation reflected from the surface and scattered by the atmosphere. Estimates of the radiative forcing at the BOA and TOA generated by aerosol particles are also provided. All these properties are given as separate datasets together with additional data on the values of the parameters characterizing the sun photometers used for the measurements and the circumstances under which these measurements were made. Sun photometers are characterized by precise wavelengths of their spectral channels. Circumstances of the observations are characterized by the moments of measurements, the zenith distance of the Sun, the albedo of the Earth's surface, and some others, depending on the aerosol particles properties in the dataset. The coordinates of the observation site are also given in the datasets.

Observations with the AERONET sun photometer have been carried out in Kyiv since March 29, 2008. During this time, a significant amount of data has been accumulated on the content and characteristics of aerosol particles and the content of water vapor in the entire atmospheric column. All of this data is available to interested scientists through the AERONET website. Over time, access to these data may be provided through the ACME research infrastructure, in particular through the Center for Collective Use of Scientific Equipment "Laboratory of High Energy Physics and Astrophysics" of Taras Shevchenko National University of Kyiv, as a component of ACME infrastructure.

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ДАНІ СПОСТЕРЕЖЕНЬ АТМОСФЕРНИХ АЕРОЗОЛІВ НА КИЇВСЬКІЙ СТАНЦІЇ AERONET: ВНЕСОК ДО ПРОЄКТУ АСМЕ

Вступ. Важливим напрямом проєкту АСМЕ є збір даних спостережень, які характеризують навколишнє середовище, зокрема і прозорість атмосфери, в астрономічних обсерваторіях – членах АСМЕ. Також ці дані дуже важливі для дослідників і фахівців у галузях, пов'язаних із навколишнім середовищем, таких як метеорологія та кліматологія. Аерозолі є однією зі складових атмосфери, що впливають на її прозорість у широкому діапазоні неперервного оптичного спектра. Міжнародна мережа автоматичних сонячних фотометрів AERONET забезпечує спостереження за вмістом, динамікою, розмірами й оптичними характеристиками аерозольних частинок практично над усією землею кулею. Додатково вимірюється і вміст водяної пари в атмосфері над місцем спостережень. Спостережна станція цієї мережі працює у Києві з березня 2008 р., забезпечуючи дані про аерозолі та вміст водяної пари у стовпі атмосфери над містом.

Методи. Спостереження у мережі AERONET виконують за допомогою автоматичних сонячних фотометрів CIMEL CE318, які вимірюють спектральну оптичну товщину атмосфери, спричинену аерозольними частинками, реєструючи опроміненість світлочутливого елемента промінням від сонячного диска, а також розподіл яскравості неба. Вимірювання виконують в окремих спектральних каналах завширшки приблизно 10 нм, у діапазоні від 340 нм до 1640 нм. Набір спектральних каналів залежить від моделі фотометра. Для визначення вмісту водяної пари використовують канал із довжиною хвилі 940 нм. Зазначені дані опрацьовують стандартизованими алгоритмами AERONET, і шляхом розв'язування оберненої задачі з них визначають розподіл частинок за розмірами, альbedo одноразового розсіяння, комплексний показник заломлення, концентрацію частинок, їхні коефіцієнти екстинкції та поглинання. За цими даними обчислюють спектральні й інтегральні у діапазоні спектра від 0.2 мкм до 4.0 мкм низхідні потоки прямого та розсіяного атмосферою сонячного проміння на земній поверхні, і висхідні потоки відбитого поверхнею і атмосферою проміння на верхній межі атмосфери. За величинами таких потоків оцінюють кліматичний ефект аерозолів (радіаційний форсинг).

Результати. За спостереженнями у Києві з березня 2008 р. одержано ряди даних про спектральну оптичну товщину у спектральних каналах із довжинами хвиль 440 нм, 675 нм, 870 нм і 1020 нм, про вміст водяної пари, про характеристики аерозольних частинок і про променеві потоки. Ці ряди даних доступні через інтернет-сторінку AERONET, а із часом можуть бути доступні й через інтернет-сторінку АСМЕ.

Висновки. Дані про характеристики аерозольних частинок, що містяться в базі даних AERONET, можуть бути корисними для аналізу результатів оптичних спостережень, що проводяться в астрономічних обсерваторіях, які входять до інфраструктури проєкту АСМЕ. Дані про аерозольну екстинкцію можна використати під час оброблення результатів спостережень черенковського випромінювання, які проводяться в обсерваторіях Auger, H.E.S.S., MAGIC, VERITAS, HAWC, а також у гамма-обсерваторії нового покоління – масиві черенковських телескопів (СТА). Дані спостережень аерозолів на київській станції можна застосувати в межах Робочого пакету 7 (WP7) проєкту АСМЕ для оброблення астрофізичних спостережень небесних об'єктів, виконаних за допомогою малих телескопів, зокрема й астрономами-аматорами.

Ключові слова: АСМЕ, земна атмосфера, AERONET, сонячні фотометри, аерозолі.

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