

New satellite project Aerosol-UA: Remote sensing of aerosols in the terrestrial atmosphere

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ABSTRACT

We discuss the development of the Ukrainian space project Aerosol-UA which has the following three main objectives: (1) to monitor the spatial distribution of key characteristics of terrestrial tropospheric and stratospheric aerosols; (2) to provide a comprehensive observational database enabling accurate quantitative estimates of the aerosol contribution to the energy budget of the climate system; and (3) quantify the contribution of anthropogenic aerosols to climate and ecological processes. The remote sensing concept of the project is based on precise orbital measurements of the intensity and polarization of sunlight scattered by the atmosphere and the surface with a scanning polarimeter accompanied by a wide-angle multispectral imager-polarimeter.

Preparations have already been made for the development of the instrument suite for the Aerosol-UA project, in particular, of the multi-channel scanning polarimeter (ScanPol) designed for remote sensing studies of the global distribution of aerosol and cloud properties (such as particle size, morphology, and composition) in the terrestrial atmosphere by polarimetric and spectrophotometric measurements of the scattered sunlight in a wide range of wavelengths and viewing directions from which a scene location is observed. ScanPol is accompanied by multispectral wide-angle imager-polarimeter (MSIP) that serves to collect information on cloud conditions and Earth's surface image. Various components of the polarimeter ScanPol have been prototyped, including the opto-mechanical and electronic assemblies and the scanning mirror controller. Preliminary synthetic data simulations for the retrieval of aerosol parameters over land surfaces have been performed using the Generalized Retrieval of Aerosol and Surface Properties (GRASP) algorithm. Methods for the validation of satellite data using ground-based observations of aerosol properties are also discussed. We assume that designing, building, and launching into orbit a multi-functional high-precision scanning polarimeter and an imager-polarimeter should make a significant contribution to the study of natural and anthropogenic aerosols and their climatic and ecological effects.

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1. Introduction

The knowledge of the distribution and properties of atmospheric aerosols is still poor known to be useful in comprehensive climate modeling. Aerosol climate impacts are estimated to be comparable to those of the greenhouse gases, but are more difficult to measure, especially with respect to aerosol microphysical properties and estimates of the anthropogenic component. This makes it difficult to provide accurate climate change modeling and formulate scientifically justified social and economic programs. Currently, there are many satellite missions studying aerosols distribution in the terrestrial atmosphere, such as MISR/Terra, OMI/Aura, AVHRR, MODIS/Terra/Aqua, CALIOP/CALIPSO (see e.g., [1]). To improve the quality of data and climate models as well as to reduce aerosol climate forcing uncertainties, several new missions are planned. The NASA's Aerosol Cloud Ecosystems (ACE) mission is expected to reduce the uncertainty regarding the climate forcing via aerosol–cloud interactions and ocean ecosystem carbon dioxide uptake [2]. The ACE mission is expected to be launched in 2024, preceded by the Pre-ACE mission in 2019 or later. After successful nine years of operation of the CNES POLDER/PARASOL aerosol space mission an advanced aerosol polarimeter in the framework of the project 3MI/EPS-SG is planned for launch in 2020 or later [1]. Two more instruments/missions are contemplated, namely, the Multiangle SpectroPolarimetric Imager (MSPI) as a possible instrument for ACE mission [3] and the SPEX instrument [4] designed in the NWO–SRON Netherlands Institute for Space Research. The several planned aerosol space missions, including the Ukrainian project Aerosol-UA, are briefly described in the review paper [5].

After the failed launch of the Glory mission [6] in 2011, the temporal gap in aerosol orbital instruments has emerged because the scheduled launches of similar types of instrument are planned for 2019 or later. This is one of the reasons that we propose to consider a scientific space project with an aerosol photometer-polarimeter accompanied by a wide-angle multispectral imager-polarimeter to study detailed physical parameters of natural and anthropogenic aerosols and estimate their chemical composition (via refractive index). A detailed analysis of an aerosol remote sensing concept based on precise orbital measurements of the intensity and polarization of sunlight scattered by the atmosphere and the surface shows that an orbital multi-functional high-precision polarimeter can provide an essential contribution to the study of natural and man-made aerosols and their climatic and ecological effects [6]. The instruments of the mission will collect data on the spatial and temporal distribution of the chemical, microphysical and optical properties of atmospheric aerosols.

In this paper we describe the development of the Ukrainian space project Aerosol-UA which has the following three main objectives: (1) to monitor the spatial and temporal distribution of key parameters of terrestrial tropospheric and stratospheric aerosols; (2) to provide a comprehensive observational database enabling accurate quantitative estimates of the aerosol contribution to the energy budget of the climate system; and (3) to quantify the contribution of anthropogenic aerosols to climatic and ecological processes [7]. The Aerosol-UA platform will be launched on a sun-synchronous near-polar orbiting satellite with an inclination of 98° and an altitude of 670 km.

2. Design of the opto-mechanical unit for ScanPol

2.1. ScanPol polarimeter

The ScanPol polarimeter serves to register spectral polarimetric characteristics of the reflected atmospheric radiation at about 200

viewing directions over each observed scene. The retrieval of aerosol and cloud properties is based on multiangular, multispectral and polarization measurements. The state of polarization of light scattered once by an aerosol or cloud particle contains more and geometrically sharper features as a function of the scattering angle (i.e., the angle between the incident solar and scattered light) than features in the total intensity. These features in the state of polarization are much more sensitive to the microphysical properties of particles (shape, size, and composition) than the corresponding features in the total intensity. Moreover, the single-scattering sensitivities of the state of polarization to particle properties are much better preserved in the presence of multiply scattered light than the corresponding sensitivities of the total intensity.

The design of the ScanPol polarimeter provides a rather comprehensive characterization of the angular distribution of both total and polarized components (the Stokes parameter I , Q , and U) of solar radiation reflected in the direction of the spacecraft. Observations in spectral atmospheric windows, where the effects of absorption by atmospheric gases are minimal, are used for aerosol retrievals. Therefore, the instrument spectral channels were chosen at the following wavelengths: 370, 410, 555, 865, 1378, 1610 nm.

A high accuracy measurement of the degree of linear polarization is provided by on-board calibration of the ScanPol polarimeter. Onboard calibration is performed for each scan of the mirror scanning system. A set of calibrators is viewed during the part of the scan range when the ScanPol polarimeter looks in the direction opposite to the Earth's surface. These reference assemblies provide calibration of the zero of the polarimetric scale (unpolarized reference assembly) and the scale factor for the polarimetric scale (polarized reference assembly). The zero of the radiometric scale is provided by the dark reference assembly.

2.2. Optical layout

The scanning polarimeter (ScanPol, as the name implies) of the Aerosol-UA mission is based on the concept of the NASA's Glory satellite mission, the purpose of which was monitoring the spatial and temporal distribution of the main characteristics of tropospheric and stratospheric aerosols and clouds in the atmosphere using the Aerosol Polarimetry Sensor (APS) [6]. ScanPol is a continuous scanning polarimetric sensor designed to make along-track, multi-angle observations of the Earth surface and atmospheric scene spectral polarization and radiance. This multi-channel instrument has the capability to collect polarized radiometric data scattered from aerosols and clouds in a wide spectral range. The number of spectral channels in ScanPol is reduced to six as compared with the APS, but a new spectral channel at 370 nm is added. ScanPol allows the measurement of the Stokes parameters I , Q , U within the spectral range from the near ultraviolet-visible (NUV-VIS) to the near-infrared (NIR) spectral band in a wide range of phase angles with a photometric accuracy of about 4% and a polarimetric accuracy of about 0.2%.

The ScanPol polarimeter module is composed of two major modules: the mirror scanning system and the optical module (Fig. 1). The two-mirror scanning system is designed for the transmission of solar radiation scattered by the investigated area of the atmosphere–surface system to the exit pupil of the optical units simultaneously. Scanning system has a pair of mirrors which form a neutral polarization combination that rotates at a speed of about 40 revolutions per minute (rpm) in the plane of the spacecraft orbit. The ScanPol viewing angle range at the Earth is +50°/–60° from the nadir direction.

The optical module includes four optical units: NUV-VIS-1, NUV-VIS-2, NIR-1, and NIR-2 (Fig. 1). Each VIS unit has three

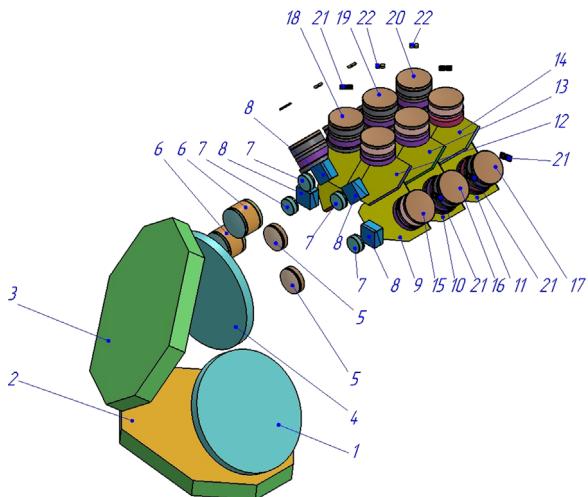


Fig. 1. ScanPol polarimeter optical layout: 1–4 – mirror scanning system, 5 – input lens of NUV–VIS spectral channel, 6 – input lens of the NIR spectral channel, 7 – collimator, 8 – Wollaston prism, 9–14 – dichroic mirrors, 15–20 – camera lens and interference filters for spectral channels, 21 – NUV–VIS sensors, 22 – NIR sensors.

spectral channels in the spectral range 370–555 nm and each NIR unit has 3 spectral channels in the spectral range 865–1610 nm (see Fig. 1 and Table 1).

The spectral channels of the NUV–VIS units are used to estimate the tropospheric aerosol absorption capacity, the aerosol over the ocean and the land surface, and the color of the ocean. The optical NIR units have spectral channels required for sensing aerosols over ocean and land, to separate the signals from cirrus clouds and stratospheric/tropospheric aerosols, to separate stratospheric aerosols caused by major volcanic eruptions and to assess the contribution of the Earth's surface to the measured signal over land. The central wavelengths at the maximum of the filter passband and their bandwidths $\Delta\lambda$ (i.e. the full-width at half-maximum) for each channel are presented in Table 1.

The optical layout of the instrument is shown in Fig. 1. Each of the optical units consists of the following optical elements (sequenced starting from the beam scanning system): an input lens which forms an intermediate image of the object; a field diaphragm (Fig. 1, not shown); a collimator; a Wollaston prism splitting rays into two components with the S and P orthogonal polarizations and thereby performing the function of analyzer; a system of dichroic mirrors and interference filters that cut out the required narrow spectral range $\Delta\lambda$; and camera lenses forming two images (S and P) on the detector.

2.3. The opto-mechanical unit

The final dimensional and aberrational calculation of the ScanPol optical layout has been performed using the Zemax software. We performed a detailed analysis and computer simulation of the ScanPol opto-mechanical unit using calculated parameters and the CAD software for the mechanical design. The design

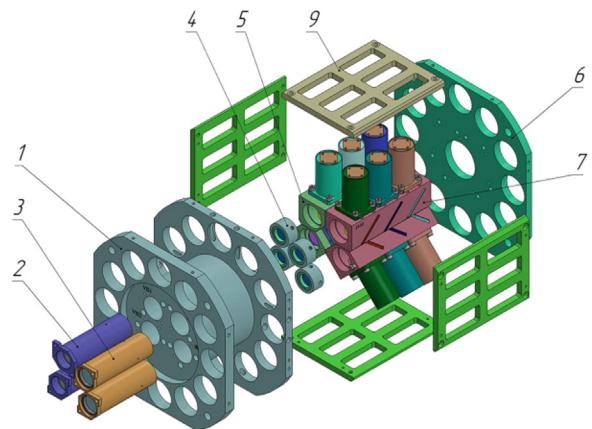


Fig. 2. ScanPol optical-mechanics unit general layout: 1 – body, 2 – input lens and collimator of the NUV–VIS channel, 3 – input lens and collimator of the NIR channel, 4 – Wollaston prism, 5 – spectral selection unit and camera lens of the NUV–VIS channel, 6 – spectral selection unit and camera lens of the NIR channel, 7 – flange, 8 and 9 – side plates.

parameters of each optical element were obtained. Fig. 2 shows its design, which meets the relevant requirements of compactness and rigidity. The main requirement for the ScanPol polarimeter is to achieve convergent fields of view for each of the four optical units. A monolithic frame with concentric holes, which carry four input lenses and collimator units, is proposed to achieve this goal. In Fig. 2, the basic elements are separated for better visibility.

The unit of the input lens and the collimator lens (Fig. 2) performs two functions: (i) to form the necessary instantaneous field of view by the field diaphragm which is mounted in the focal plane of the input lens; and (ii) to collimate the rays propagating to the Wollaston prism. The specific design of the unit allows for the assembly and alignment of each unit separately with a clear fixation of the requisite angular field of view of the system.

The Wollaston prism units of each optical unit is also mounted in the frame (Fig. 2) and can be accurately positioned on the angle of rotation around its own axis in the preparation alignment of the opto-mechanical unit. Initial technical requirements have been formulated for the spectral selection of elements namely the dichroic mirror and interference filters. Spectral selection unit and chamber lens of the NUV–VIS and NIR optical blocks are designed for allocation of the required narrow spectral channels with a half-width $\Delta\lambda$.

Fig. 3 is a sketch of the spectral selection and the camera lenses unit of the NUV–VIS optical unit. The unit is a mechanical block in which dichroic mirrors are fixed and camera lenses are attached. During the assembly, the opto-mechanical unit is fixed by side plates (see Fig. 2) that act as stiffeners. The design documentation of the ScanPol polarimeter is ready for replication.

The ScanPol general layout prepared for laboratory test is shown in Fig. 4. A preliminary investigation of the scanning mirror unit (shown in Fig. 4b) has been performed as well. The results show that the proposed combination of mirrors indeed compensates polarization in reflection from the metal coatings. The

Table 1

Central wavelengths of ScanPol spectral channels and their bandwidths.

Channel	Central wavelength, λ , nm	Bandwidth, $\Delta\lambda$, nm	Measurement purpose
NUV–VIS	370	10	Tropospheric aerosol and top of clouds
	410	20	Aerosol over ocean and Earth's surface
	555	20	Aerosol over ocean and Earth's surface, ocean color
	865	40	Aerosol over ocean and Earth's surface
NIR	1378	40	Thin cirrus clouds, separate troposphere and stratosphere aerosol in case of volcanic eruption
	1610	40	Separation surface signal from aerosol over Earth's surface

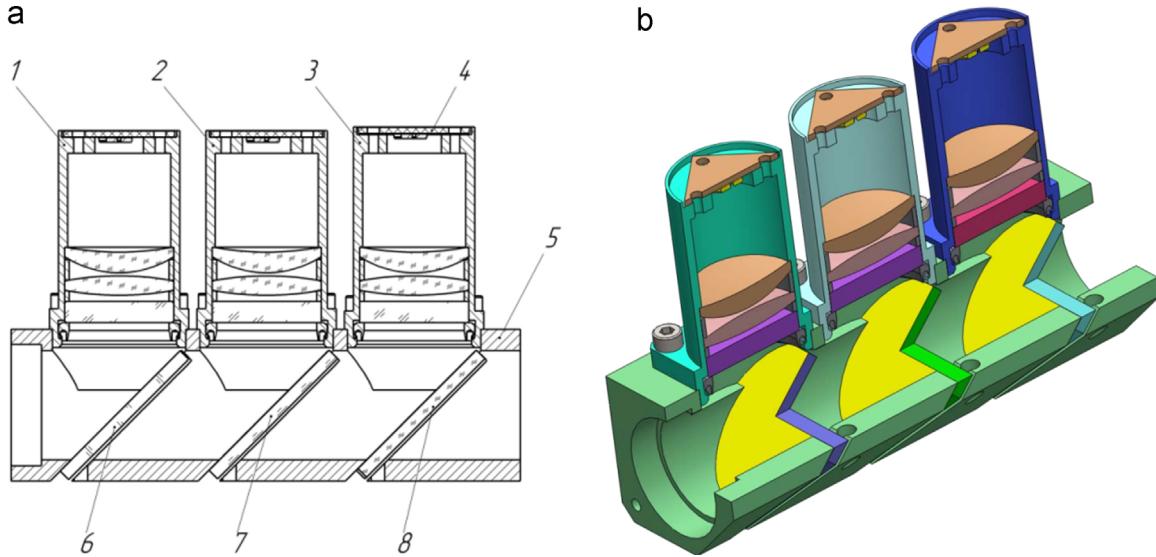


Fig. 3. Draft and outline in cross-section of spectral selection unit and camera lens of the NUV-VIS channel: 1 – camera lens of the 370 nm spectral channel, 2 – camera lens of 410 nm spectral channel, 3 – camera lens of 555 nm spectral channel, 4 – the multichannel module of the optical information reader, 5 – body, 6–8 – dichroic mirrors.

residual polarization depends on the wavelength (in the blue spectral range it increases by 0.6%), and the angular of field of view (up to 0.15%). This can be taken into account during the calibration maintenance.

The design of the ScanPol polarimeter provides a rather comprehensive characterization of the angular distribution of both total and polarized components (the Stokes parameter I , Q , and U) of solar radiation reflected in the direction of the spacecraft.

2.4. Multichannel optical information reader

The multichannel reader for the collection of the optical information is intended for the conversion of the optical information into the electrical signal for further transfer to the data processing facility. For conversion of the optical information, the silicon

photodiodes SI0356-01 and InGaAs PIN photodiodes G8941-01 of the HAMAMATSU PHOTONICS (Japan) are used in the spectral range from 370 nm to 555 nm and from 865 nm up to 1610 nm, respectively. The distance between the sensitive surfaces of the photodiodes, which are placed in pairs on modules of the channel light transformers, significantly affects the functionality of the polarimeter. The choice of photodiode types was made according to the requirement of ensuring respective electrical parameters with consideration of its implementation.

The modules are built using photodiodes from the input side of the optical information and their inverted side. The composition of the elements and the construction of the channel modules provide a convenient connection with other parts of the reader, which is important on bread boarding stage. The specific design of the printed boards of module pairs of the photo receivers ensures

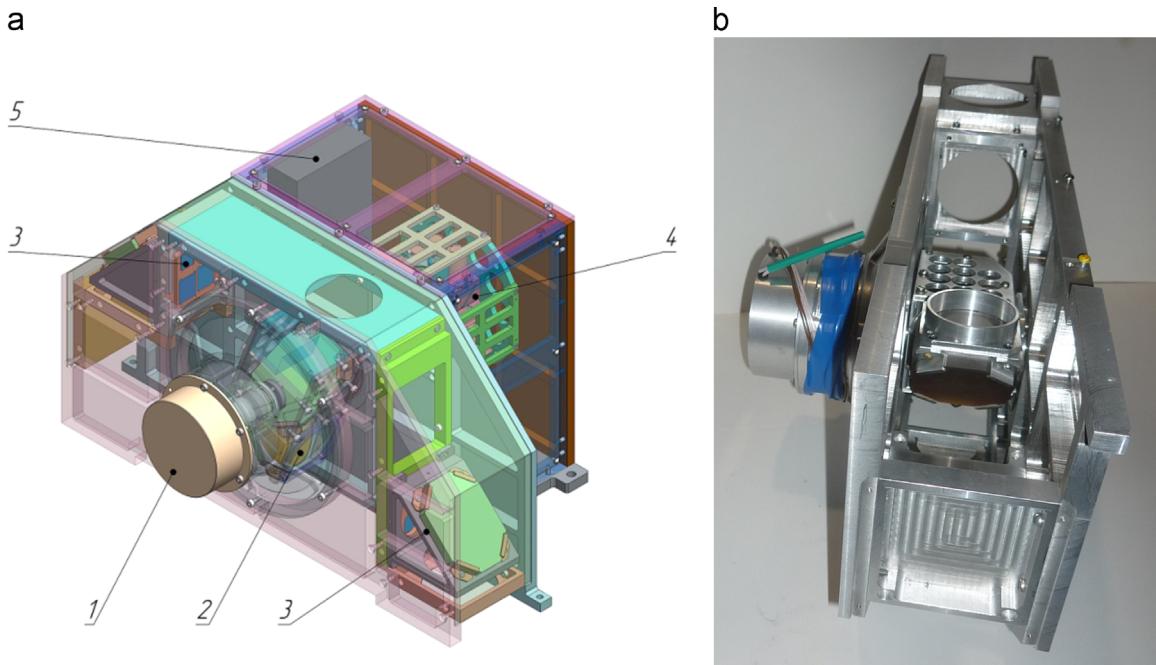


Fig. 4. ScanPol (a) general layout: 1 – motor; 2 – scanning mirror unit; 3 – unit for onboard calibration; 4 – opto-mechanics unit; 5 – multichannel optical information reader; (b) photograph of the scanning rotated mirror unit with motor (on left) that serves also to produce the synchronizing impulses for ScanPol data.

small sizes ($13 \text{ mm} \times 13 \text{ mm}$) and a high accuracy of photodiode positioning.

A laboratory test of the channel modules has demonstrated that their sensitivity provides the signal-to-noise ratio at the level of 200 with the light flux about 2 nW and the range of frequencies 0–1 kHz. In the test circuit the photodiode operates in the photovoltaic mode. The optical signal that reaches the photodiode is easily determined as $P_w = (U_s/R_{oc})/S$, where U_s is the output signal at the amplifier, R_{oc} is the resistance feedback amplifier of the photodetector, and S is the photosensitivity in amper/watt (AW^{-1}) units for each photodiode ($S=0.57 \text{ AW}^{-1}$ for the Si S10356-01 photodiode and $S=0.95 \text{ AW}^{-1}$ for the G8941-01 InGaAs PIN photodiode).

The presented characteristics are ensured by the respective scheme including photodiodes with the use of the amplifiers MAX9945AUA by the MAXIM Company. The digitization of the analog signal outputs of the module channels is provided by the E14-440 AD/DA module converter. The optical information from the multichannel reader has been tested using the processing software developed for the reader.

3. Wide-angle multispectral imager-polarimeter

The information on cloud conditions and Earth's surface image including determination of the scene, location are need for the correct interpretation of ScanPol data. In the concept of the Aerosol-UA mission the multispectral wide-angle imager-polarimeter (MSIP) was included for that purposes. Four channels of the MSIP will collect images on the state of the atmosphere (cloud distribution) and surface (surface homogeneity, land surface, sea surface) in the area of the ScanPol polarimeter measurements to retrieve aerosol optical depth and polarization properties of aerosol by registration of three Stocks parameters simultaneously in three spectral channels 410, 555 and 865 nm ($\Delta\lambda=20-40 \text{ nm}$). The fourth channel of the MSIP is the intensity channel that serves to obtain images in four spectral wavebands 410, 555, 865 and 910 nm ($\Delta\lambda=20-40 \text{ nm}$) to retrieve the aerosol optical depth. The main feature of the MSIP channels is the splitting of the image by a special prism-splitter for four images on the same CCD detector in each channel. In that way we can measure simultaneously four polarization components 0° , 45° , 90° and 135° as images in each of three polarization channels and four images in four spectral bands in the intensity channel (see Fig. 5).

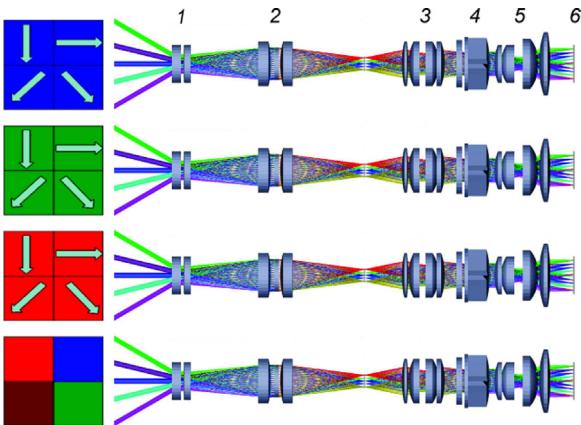


Fig. 5. The wide-angle multispectral imager-polarimeter MSIP field of view of three polarization channels and one intensity channel (left), the direction of linear polarization is shown by arrows, each FOV is divided on four images; preliminary optical design of three spectral polarization channel and one intensity channel of the MSIP (right): 1–2 – input lens; 3 – collimator; 4 – polarization unit and image division system; 5 – camera lens; 6 – detectop plane.

Four independent identical camera units (three for polarization and one for intensity) will collect images of the undersatellite scene with a field-of-view of $60^\circ \times 60^\circ$ ($770 \times 770 \text{ km}^2$) and a spatial resolution of 0.5–0.2 km. The preliminary optical design of the MSIP imager-polarimeter is shown in Fig. 5. The technical parameters of the MSIP are as follows: the aperture diameter is 22 mm, the total length is 300 mm, and the detector size is $20 \times 20 \text{ mm}^2$. The unit of the polarization analysis in MSIP is based on birefringent prisms or polarizing films. We expect that the polarization accuracy of MSIP should be better than 1% and will be achieved by using intercalibration within ScanPol data onboard the satellite.

4. The concept of the inversion algorithm for the retrieval of aerosol and cloud properties

4.1. ScanPol data

The majority of satellite aerosol retrievals use look-up tables of simulated satellite signals pre-computed for some limited selected scenarios of aerosol and underlying surface combinations. The modeled scenario that provides the best match of the observed radiances is accepted as the retrieved solution. However, the required comprehensive look-up tables of the observations may have larger dimensions and thus be less suitable for operational use. As a result, most look-up table based algorithms rely only on the selected sub-sets of the observations with the highest sensitivity to the aerosol parameters and retrieve a reduced set of characteristics.

On the other hand, a new approach was proposed as an optimization concept that improves the retrieval accuracy relying on the knowledge of the measurement error distribution [8]. Based on this strategy, the GRASP Generalized Retrieval of Aerosol and Surface Properties (GRASP) algorithm is driven by a larger number of unknown parameters and is aimed the retrieval of an extended set of parameters affecting the measured radiation [9]. The GRASP algorithm has been developed in the Laboratoire d'Optique Atmosphérique of University Lille1 and published by Dubovik et al. [8]. The GRASP algorithm derives an extended set of aerosol parameters including detailed particle size distribution, spectral refractive index, single scattering albedo and the fraction of non-spherical particles. The algorithm uses an elaborated model of the atmosphere and fully accounts for all multiple interactions of scattered solar light with aerosol, gases and the underlying surface [10,11]. The algorithm is very flexible in utilization of various types of *a priori* constraints on the retrieved characteristics and in the parameterization of the surface-atmosphere system.

The GRASP algorithm consists of two main independent modules. First, the numerical inversion includes general mathematical operations not related to the particular physical nature of the inverted data (in this case, remote sensing observations). The second module, the forward model, is intended to simulate various atmospheric remote sensing observations. During three last years the GRASP algorithm and its operational retrieval environment have been significantly optimized, improved and adapted for processing extended sets of observational data [8,9].

4.2. Forward model of the ScanPol and MSIP observations

It is assumed that the light observed at the top of the atmosphere is only linearly polarized [10]. In the polarized channels, besides the total reflected radiance, I , the measurements provide the Stokes parameters Q and U referred to axes perpendicular and parallel to the local meridian plane, i.e. $Q=I_p \cos 2\alpha$ and $U=I_p \sin 2\alpha$ where I_p is the polarized component of the reflected radiance and

α is the angle between the meridian plane and the polarization direction [12].

In the following consideration, $\mathbf{I}=(I, Q, U, V)^T$ and $\mathbf{E}_0=(E_0, 0, 0, 0)^T$ stand for the Stokes vector of the observed electromagnetic radiation and of the incident unpolarized solar radiation (T stands for “transposed”; V is assumed to be negligible). The Stokes vector $\mathbf{I}=(I, Q, U, V)^T=\mathbf{I}(\mu_0, \mu_1, \varphi_0; \varphi_1; \lambda)$ depends on the solar zenith angle ϑ_0 ($\mu_0=\cos \vartheta_0$), the observation zenith angle ϑ_1 ($\mu_1=\cos \vartheta_1$), the solar and observation azimuth angles φ_0 and φ_1 , and wavelength λ . The reflected radiance can be written as follows:

$$\mathbf{I}(\mu_0, \mu_1, \varphi_0, \varphi_1; \lambda) = \mathbf{L} [\mathbf{M}_{\text{scat}}(\theta; \lambda) + \mathbf{M}_{\text{refl}}(\mu_0, \mu_1, \varphi_0, \varphi_1; \lambda)] \mathbf{E}_0 \\ + \text{mult. scat.}, \quad (1)$$

where the terms \mathbf{M}_{scat} and \mathbf{M}_{refl} correspond to the light reflected as a result of single interaction of the incident solar light with the atmosphere and surface, respectively. In Eq. (1) it is envisaged that polarized light is referred to axes perpendicular and parallel to the scattering and reflection planes (here, both formed by the solar and viewing directions); and the matrix \mathbf{L} transforms the Stokes vector into the plane of observations [13]. Under the assumption of a plane parallel multi-layered atmosphere, the single-scattering term, \mathbf{M}_{scat} , at the top of the atmosphere can be expressed as:

$$\mathbf{M}_{\text{scat}}(\theta; \lambda) = \frac{\mu_0}{\mu_0 + \mu_1} \sum_{i=1, \dots, N} \left(e^{-m\tau_{i-1}} (1 - e^{-m\Delta\tau_i}) \frac{\omega_0^i}{4\pi} \mathbf{P}_i(\theta; \lambda) \right), \quad (2)$$

where $\Delta\tau_i$ is the optical thickness of the i -th atmospheric layer ($i=1, \dots, N$ numbered from the top to the bottom of the atmosphere) and τ_i is the optical depth of the bottom of layer i (i.e. $\tau_i = \sum_{k=1, \dots, j} \Delta\tau_k$); $\mathbf{P}_i(\theta; \lambda)$ and ω_0^i denote the phase matrix and single-scattering albedo of the i -th atmospheric layer, $m = 1/\mu_0 + 1/\mu_1$.

The optical properties τ_i , $\mathbf{P}_i(\theta; \lambda)$ and ω_0^i in each atmospheric layer include the contributions of aerosols (characterized in i -th layer by $\Delta\tau_{i,a}$, $\omega_{0,i}^a$ and $\mathbf{P}_i^a(\theta; \lambda)$), gaseous scattering (characterized in i -th layer by $\Delta\tau_{i,mol}$, $\omega_{0,i}^{\text{mol}}=1$ and $\mathbf{P}_i^{\text{mol}}(\theta; \lambda)$) and atmospheric gases (characterized in i -th layer by $\Delta\tau_{i,gas}$ and $\omega_{0,i}^{\text{gas}}=0$). The resulting single-scattering albedo ω_0^i and phase matrix $\mathbf{P}_i(\theta; \lambda)$ of the i -th atmospheric layer are:

$$\omega_0^i = \frac{\omega_{0,i}^a \Delta\tau_{i,a} + \Delta\tau_{i,mol}}{\Delta\tau_{i,a} + \Delta\tau_{i,mol} + \Delta\tau_{i,gas}}, \quad (3)$$

and

$$\mathbf{P}_i(\theta; \lambda) = \frac{\omega_{0,i}^a \Delta\tau_{i,a} \mathbf{P}_i^a(\theta; \lambda) + \Delta\tau_{i,mol} \mathbf{P}_i^{\text{mol}}(\theta; \lambda)}{\Delta\tau_{i,a} + \Delta\tau_{i,mol} + \Delta\tau_{i,gas}}, \quad (4)$$

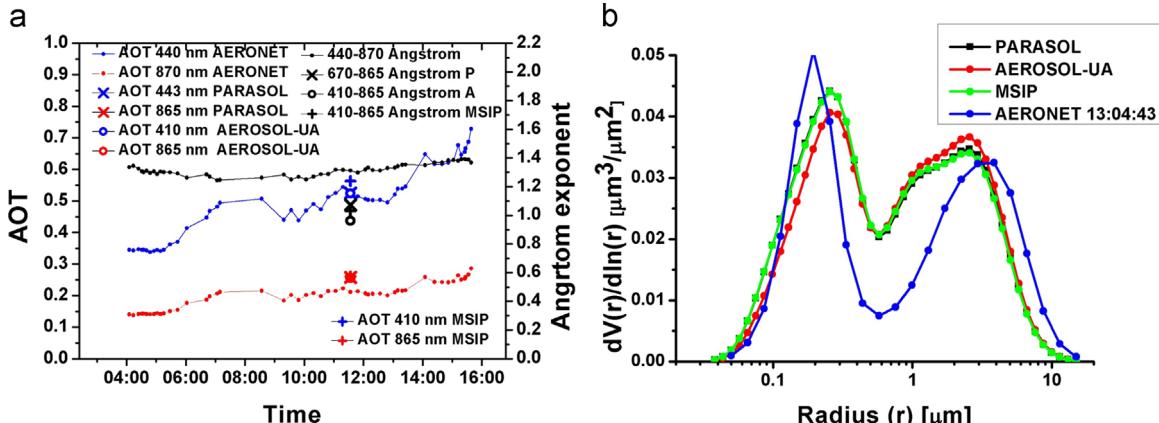


Fig. 6. The comparison of POLDER/PARASOL, AERONET observations and the Aerosol-UA synthetic data retrieved aerosols parameters: (a) aerosol optical thickness (AOT) and Angstrom exponent; (b) size distribution.

and the extinction optical thickness τ of the atmosphere is the sum of the corresponding components:

$$\tau = \tau_a + \tau_{mol} + \tau_{gas}. \quad (5)$$

The properties of gaseous scattering τ_{mol} and $\mathbf{P}^{\text{mol}}(\theta; \lambda)$ are known and can be calculated with sufficient accuracy [12]. The absorption of atmospheric gases τ_{gas} has rather minor contribution in the ScanPol channels and can be accounted for using known climatologies and the MSIP observations, as well as using data from satellite instruments (for example, OMPS, OMI). Thus, the most challenging part in modeling the single-scattering properties of the atmosphere is the modeling of aerosol contribution, i.e., the aerosol extinction τ_a , single-scattering albedo ω_0^a , and phase matrix $\mathbf{P}^a(\theta; \lambda)$. These properties depend on aerosol microphysics: particle size, shape, and composition (refractive index) [14]. All these characteristics are driven by the parameters included in the vector of unknowns and correspondingly they are retrieved from the observations.

The single reflection \mathbf{M}_{refl} at the top of atmosphere can be calculated as:

$$\mathbf{M}_{\text{refl}}(\mu_0, \mu_1, \varphi_0, \varphi_1; \lambda) = \frac{\mu_0}{\pi} e^{-m\tau} \mathbf{R}(\mu_0, \mu_1, \varphi_0, \varphi_1; \lambda), \quad (6)$$

where the reflection matrix $\mathbf{R}(\mu_0, \mu_1, \varphi_0, \varphi_1; \lambda)$ describes the surface reflection properties in the plane formed by the solar and viewing directions. For the ocean surface, the reflection $\mathbf{R}(\mu_0, \mu_1, \varphi_0, \varphi_1; \lambda)$ is mainly governed by the wind speed at sea level as suggested by the Cox–Munk model [15]. In contrast, the reflection matrix of the land surface may vary very strongly from scene to scene. Therefore, the key properties of the land surface reflectance are included in the set of unknowns and retrieved from the observations.

As follows from Eq. (1), once the single scattering terms \mathbf{M}_{scat} and \mathbf{M}_{refl} are defined, one needs to account for multiple interactions of scattered light with the atmosphere and surface. In the GRASP algorithm these interactions are accounted for by rigorous solving the vector radiative transfer equation [8]. Thus, the forward model of the reflected radiances measured by ScanPol and the MSIP instruments contains three main components: aerosol single scattering, surface reflection, and solving the vector radiative transfer equation to account for multiple scattering.

4.3. Preliminary results of synthetic data simulation

Originally the GRASP algorithm was developed for the POLDER/PARASOL multi-viewing imager [16] and later adapted to a number of other satellite sensors. We adapted this algorithm for the ScanPol and MSIP instruments synthetic data simulation. The

retrieved aerosol parameters using GRASP for POLDER/PARASOL measurements were used for modeling the Aerosol-UA synthetic observation. The geometry of observation for the Aerosol-UA was configured over Kyiv, Ukraine on 14 August 2010. This date was chosen due to high AOT values that correspond to wildfires in the center of western Russia and transportation of biomass burning particles to Kyiv [17,18]. The comparison of POLDER/PARASOL, AERONET and Aerosol-UA retrieved aerosols parameters are presented in Fig. 6. Moreover, the simulation was performed for the MSIP separately and combines ScanPol with the MSIP (Aerosol-UA).

The simulated aerosol parameters, obtained from the Aerosol-UA, are in good correspondence to parameters retrieved from POLDER/PARASOL and AERONET measurements. This preliminary analysis has shown that the number of “independent” measurements (obtained by Aerosol-UA simulated data for each pixel: ~2400 for ScanPol and ~126 for the MSIP) is enough for retrieving aerosol characteristics correctly. The synthetic Aerosol-UA signals were not perturbed by random noise prior to applying the retrieval algorithm. More comprehensive studies for testing and tuning the GRASP algorithm are planned in the near future.

5. Data processing facility

The data processing facility is being developed for data processing obtained from the ScanPol and MSIP instruments of the Aerosol-UA project. The data processing facility consist of physical and logical structures. The physical structure is a cluster of three servers which are connected by channel with a bandwidth of 1 Gbit/s (see Fig. 7). Due to several system controllers each server has the possibility of reserving power supply blocks and data storages at the physical layer. The possibility of increasing maximum data capacity by including additional servers is a key feature of the system.

Logical structure of the cluster can be represented as three physical servers. At the main server there are three virtual machines. The first one is the application server, the second one is the processing unit, and the third one is the database node 0. The second physical server is a replica of the storage data node 1. The third one is a replica of the storage data node 2. The data are written and read from the main data base node 0 synchronously. But in the replica storages the write/read operations are asynchronous. This structure provides the possibility to add a new physical server for data storage scaling. The replication is used for data redundancy and availability since one portion of information is saved on different physical servers simultaneously. All of the replica sets should be on different physical servers.

The logical structure of the data storage and processing is represented as a block structure in Fig. 8. The data obtained from the Aerosol-UA satellite are proceeded to database Level 0 where they are kept for further processing. By the command of user or according to the planned tasks in the automatic mode, the data are forwarded to the processing and sorting unit. This block contains software to convert the primary signal into the differential signals of ScanPol and the MSIP instruments in appliance with a spectral channel with a geolocation, satellite coordinates, and time binding.

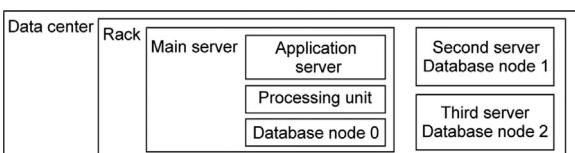


Fig. 7. The data processing facility general structure.

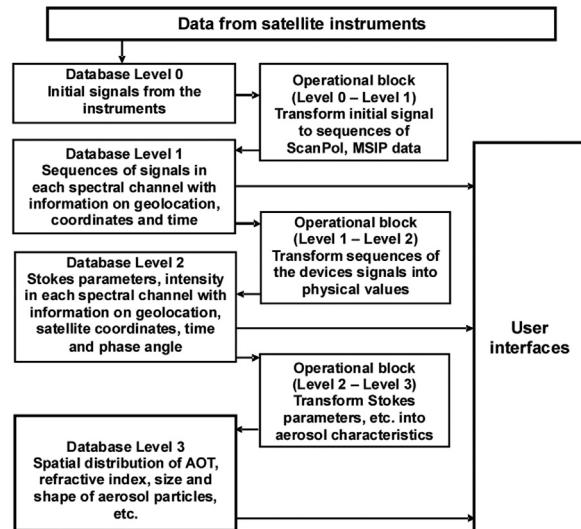


Fig. 8. The logical structure of the data storage and processing represented as blocks with description of the type of data and processing.

There is a calibration of signals according to the parameters have got from a satellite about the instrument status in the same block. It is tested by internal calibration directly on the satellite. Then this information proceeds to database Level 1 where are kept for further processing. If the command of user is received or according to the planned tasks in automatic mode the information proceed to the data processing unit from Level 1 to Level 2 (see Fig. 8).

This block contains the software to convert the data of Level 1 to Level 2 – the sequence of physical parameters of the ScanPol and MSIP measurements – the Stokes parameter vector, intensity in appliance with the spectral channel with the geolocation, satellite coordinates, time, and phase angle binding. So in this way the database Level 2 is formed with restricted access. The data obtained from the database Level 2 can be proceed to block of algorithms which transform data in Level 3 by the command of user or according to the planned tasks in automatic mode. This block contains the package of algorithms and software for converting the data Level 2 into the data Level 3. It is properly scientific product of the project in the sequence of physical parameters such as refractive index, particle size, AOT aerosol linked to geographic coordinates, spectral channel, and time. The access to database Level 3 is possible only if the procedure of authentication, authorization and accounting is done. Besides, there is a possibility in providing privileged access to get more detailed information about the status and dynamics of aerosol within a well-defined sampling data, or provide the access to data center capacity to formulate the problem with some restriction to dedicated capacity for processing.

6. Ground-based validation of the experiment

Validation of the Aerosol-UA mission data by ground-based measurements is based on algorithms, equipment and experience of the sunphotometer AERONET network [19]. The AERONET was created as the facility for validation of satellite data on aerosol properties on the global scale. Using AERONET network, international scientific community will be involved to participate in the Aerosol-UA mission support and validation. Validation of the ScanPol space-born polarimeter data will be performed by comparison of the columnar spectral aerosol optical depth (AOD) and columnar aerosol particles properties obtained from simultaneous measurements of the optical characteristics of the same air mass

by both the orbital ScanPol polarimeter and ground-based sunphotometer. The “simultaneity (coincidence)” criterion of the space-born and ground-based measurements has been determined, for example, in [20–24], and this method was used for validation of the data obtained by satellite instruments with a large field of view as POLDER/PARASOL, MODIS and MISR instruments [18–24]. But there are specific problems in coincident ground-based and satellite measurements of the same air mass optical properties in the case of the ScanPol, similar to case of the Glory/APS and CALIOP, due to a very narrow field of view of these instruments [25,26] and low probability of such coincident and/or low number of simultaneous measurements. To ameliorate this situation the imager-polarimeter MSIP allows expanding the Aerosol-UA effective field of view. Also the data of all suitable AERONET sites over the world will be used for Aerosol-UA data validation at various aerosol and underlying surfaces types during time of the mission operation. The columnar spectral AOD, particles sizes distribution, single-scattering albedo and refractive index will be retrieved from ScanPol and MSIP observations simultaneously with AERONET sunphotometers CIMEL CE318N-EDPS9 polarimetric measurements using GRASP algorithm [8,9].

In order to maximize the amount of data it is possible to use the CIMEL sunphotometers for mobile ground-based measurements of the aerosol properties in the sites located close to Aerosol-UA ground trace and close to its passage time. Using the mobile AERONET site will allow us to perform coincident space-born and ground-based measurements very close to the Aerosol-UA ground trace and to enhance the satellite data accuracy. Also, the portable sunphotometer Microtops II can be used for mobile spectral AOD measurements in accordance to AERONET program. This portable sunphotometer is used successfully for aerosol measurements from ships in various sites of the planet as a part of AERONET [27]. Experiences in aerosol properties mobile measurements acquired earlier in various regions of Ukraine (see [28,29]) allow us to fine-tune experimental technique for ground-based validation of aerosol studies in the Earth's atmosphere by the Aerosol-UA mission instruments. We will propose as well to provide the mobile measurements techniques for the validation of the Aerosol-UA data over the world as the mission begins.

Also the *in situ* measurements of the aerosol particles properties with special instruments such as integrating nephelometers and particle size spectrometers will be useful in the locations close to the Aerosol-UA traces, particularly installed on the flying vehicles which allow performing measurements on various heights over the land. The ground-based validation program for Aerosol-UA mission is based on the proposals earlier stated for NASA Glory mission project validation [30].

7. Conclusions

Preparations have been made for the development of the instrumentation suite for the aerosol space experiment Aerosol-UA, in particular, of the ScanPol polarimeter intended for remote-sensing studies of the global distribution of aerosol and clouds properties in the terrestrial atmosphere by polarimetric and spectral measurements of the scattered sunlight in the broad range of spectrum and viewing directions. Various components of the ScanPol polarimeter have been computer-designed and prototyped, including the optical-mechanical and electronic assemblies and the scanning mirror controller. Initial technical requirements are developed to the elements of the spectral selection, particularly, dichroic mirrors and interference filters. The ScanPol polarimeter optical-mechanical unit equipped with a multichannel optical information reader has been built and prepared for a laboratory test. To obtain the different phase angles it is easiest to

scan the scene along satellite track by rotating the scanning mirror. However, a mirror gives additional linear polarization, which distorts the measuring result. This distortion can be compensated by another mirror with reflective plane mounted normally to the first mirror plane. This system of orthogonally installed mirrors has been examined to determine the quality of compensation. We have found that the additional polarization is compensated almost completely. The residual stray polarization is 0.15%.

The optical layout of the multispectral wide-angle imager-polarimeter MSIP has been modeled. The imager will monitor weather conditions and maintain the measurements scene along the ScanPol polarimeter ground track. The data processing facility, its physical and logical structures, is being developed for data processing obtained from the ScanPol and MSIP polarimeters. Preliminary synthetic data simulations have been performed using the GRASP algorithm for ScanPol and MSIP instruments. The simulations were designed to mimic satellite observations over the AERONET ground-based sunphotometer located in Kyiv, Ukraine. The preliminary results of the synthetic data test showed that we can robustly derive Aerosol-UA aerosol parameters that are in good agreement with the parameters retrieved from POLDER/PARASOL and AERONET measurements.

Methods for the satellite data validation using AERONET network, mobile sunphotometer station and *in situ* measurements have been discussed. Validation of the Aerosol-UA mission data can be performed on global and regional scales using aerosol ground-based remote sensing measurements by AERONET sunphotometers, mobile and portable sunphotometers used in the Maritime Aerosol Network [26], and *in-situ* measurements data. International scientific community will be involved to participate in the Aerosol-UA mission support and validation. Using the GRASP algorithm the columnar properties of the aerosols layer and particles characteristics will be retrieved from ScanPol and MSIP measurements coincident with the ground-based observations.

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