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Passive Remote Study of the Aerosol in the Upper Atmosphere of the Earth

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ABSTRACT

Climate changes on planet Earth are mainly caused by disturbances in the energy balance of the Sun-Earth system. This process is the result of both natural changes in nature and the influence of anthropogenic factors. The combined effect of these factors can lead to threatening phenomena for mankind - a decrease in the power of the ozone layer, the formation of "ozone holes" and global warming on the planet and other disasters. The study of the causes of these factors and the determination of their relative contribution is one of the pressing problems of our time.

To clarify these reasons, the Main Astronomical Observatory of the National Academy of Sciences of Ukraine (MAO NASU) proposed to conduct a satellite polarimetric experiment in the ultraviolet region of the spectrum on passive remote sensing of the upper atmosphere of the Earth in order to obtain information about the physical properties of the stratospheric aerosol according to the results of polarimetric and photometric measurements. To implement this experiment, the joint efforts of three organizations (the Main Astronomical Observatory of the National Academy of Sciences of Ukraine, the National Technical University of Ukraine "KPI" and the Lviv Polytechnic National University) developed and created a working model of the onboard miniature polarimeter (UVP) operating in the ultraviolet spectral range of wavelengths. Compared with other similar experiments, the proposed method for remote study of aerosol from space allows to cut off the influence of the tropospheric component of the atmosphere and the Earth's surface and, as a result, to isolate the polarization component of the stratospheric aerosol for research in its pure form.

To confirm the correctness of the chosen research ideology, the model created of the current on-board UVP was created and carefully examined at a specially designed and manufactured stand, and then adapted for ground-based observations and mounted on the AZT-2 astronomical telescope (MAO NASU). On September 26, 2017, cloudless sky observations were conducted on the AZT-2 telescope in the MAO NAS of Ukraine and data on changes in the Stokes polarimetric parameters were obtained. Processing the obtained data showed that the polarization on the phase curve varies from -3 to 32%. A comparison analysis of the observational data with the calculation results shows that our observations best fit the calculations for the particle size ro = 0.16 μm and the real part of the refractive index nr = 1.33 in the troposphere and up to 1.42 for the stratosphere.

Therefore, it can be concluded that even such an approximate analysis of polarization observations of a cloudless sky under terrestrial conditions, both during the day and after sunset, indicates the possibility of studying the physical characteristics of the aerosol in the troposphere and stratosphere, respectively. And conducting a space experiment to study changes in the polarization component of the stratospheric aerosol in the ozone layer of the Earth will allow us to obtain data, the analysis of which will make it possible to judge the causes of the change in the thickness of this layer in the Earth's atmosphere.

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Introduction

Many the cataclysms occurring in nature are interrelated with changes in the weather and climate of the Earth [1, 2]. Often, they are the source of aerosol formation in the atmosphere. This process is the result of both natural changes in nature and the influence of anthropogenic factors. The combined effect of these factors can lead to threatening phenomena for mankind - a decrease in the power of the ozone layer, the formation of "ozone holes" and global warming on the planet and other disasters. A special place in the atmosphere is occupied by the stratosphere and its ozone layer which protects the Earth from hard ultraviolet (UV) radiation [3-6]. Stratospheric aerosol at altitudes of more than 30 km can be in the atmosphere for years and play an important role in the formation of the thermal regime and the thickness of the ozone layer. Moreover, the aerosol can participate in atmospheric processes both actively and passively. Thanks to spectrophotometric studies data ware obtained on the optical thickness of the aerosol at these heights [7-10]. At the same time, its nature (real part of the refractive index) (particle size, particle size distribution function, optical thickness of the aerosol and its horizontal structure, the upper boundary of the ozone layer in the stratosphere, etc.) have been little studied. Among remote methods, polarization measurements that make it possible to determine these characteristics most correctly. Such measurements can be carried out both from a spacecraft (SC) (measurements "from above") and from a ground-based telescope complex (measurements "from below"); and it is better to use both methods together, complementing each other. It is more efficient to carry out with spacecraft in the ultraviolet wavelength range. This approach allows you to study the stratospheric aerosol, projects of polarimetric experiments in the ultraviolet spectral region were proposed [5, 6]. Another method for obtaining data on the physical properties of an aerosol in the upper atmosphere of the planets [11-15] was considered using the results of polarimetric measurements of a cloudless sky [16, 17]. As a modification of the process of polarimetric observations of the sky, it was proposed to install the telescope not to the zenith, but to the declination coordinate of the Sun [9]. In this case, by changing the hour angle of the telescope, one can extend the interval of the observed phase angles. In addition, there is also possibility of planning it in advance for obtaining the necessary information for a selected altitude in the Earth's atmosphere, above which scattering is recorded during such observations. These measurements are complemented by photometric measurements [18-21]. The generalization of the main results by the middle of the 20-th century showed that on different days the degree of polarization (P) of the sky at the zenith was 30-50%, which is significantly less than the polarization value of the pure gas atmosphere [22]. Moreover, the dependence of P on the height h of the scattering layer indicates the absence of systematic changes in the degree of polarization. A slight decrease in the degree of polarization may be due to the depolarizing effect of the sky background; as the sun's zenith distance increases by more than 90°, the degree of polarization decreases; an increase in the degree of polarization with increasing wavelength is also observed. Later it was noted that the influence of a significant amount of aerosol in the troposphere significantly increases at wavelengths greater than 760 nm, and the degree of polarization at a phase angle of 90° was nearly 20% [23]. Then the amount of stratospheric aerosol was estimated as small, but from the end of 2006 its increase began. This manifested itself in a decrease in the degree of polarization at $\lambda = 525$ nm at the solar zenith distance of 91–94 °. Such a drop in the polarization value can be explained as a consequence of the eruption of Rabaul volcano in New Guinea in October, 2006 and the release of significant amounts of dust [24].

Device and Research Technique

The Main Astronomical Observatory (MAO) of the National Academy of Sciences of Ukraine (NASU) proposed in 2004 to conduct a space experiment to study the physical characteristics of the stratospheric aerosol from the spacecraft [21]. For this a working model of an on-board ultraviolet polarimeter (UVP) was developed and created together with Igor Sikorsky KPI and Lviv Polytechnic National University [25, 26]. This optoelectronic device can receive polarimetric data during remote sensing of a stratospheric aerosol from a spacecraft. The photodetector is a photomultiplier R1893, operating in photon counting mode; thermal sensors monitor the ambient temperature and radiation detector; the polarizer is a Glan prism that is rotated by a miniature hollow-rotor piezoelectric motor.

All data of the photodetector, temperature sensors and other parameters are recorded and prepared for transmission to the operator for further analysis by the specially designed control unit. It was built as the single chip control unit which additionally contains the motor driver unit for polarizer rotation and stabilized power source for powering all internal elements in wide range of input power voltage. Together with the motor control function this control unit works as data gathering and formatting device for providing all the measured information in time tagged packages through USB interface to PC (Figure1).

Figure 1: The onboard UVP device

Considering the tasks that executed by the UVP control unit, its functional diagram can be represented as on (Figure 2).

Additionally, the PC based software application for communication with this control unit and storing all incoming data to local Microsoft© Access database for further data processing and manipulations was developed. It is also possible to change mode settings of the control unit with this application.

The firmware of the control unit provides functions of the positioning of the polarization plane of the polarization element depending on the selected task. This model of UVP is close to the flight model and proved the possibility of setting up a space experiment to study the stratospheric aerosol. A special stand has been developed for setting up and studying the UVP and its individual blocks (Figure 3) [25].

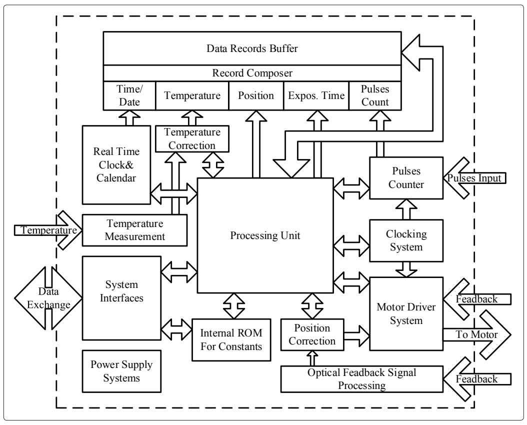


Figure 2: Functional diagram of the UVP control unit.

With the help of the stand the wide range of the radiation receiver – the photomultiplier R1893 of the HAMAMATSU company- studies were carried out. There were obtained its spectral pulse-counting characteristics, light and dark pulses to powering voltage dependencies in range of 1050 to 1500V, and so on. For example, the "flat" of counting characteristics both light and dark is situated near 1250V, note that at the variation of high powering voltage range the deviation of dark impulses did not exceeded 2-4 pulses per second (Figure 4). The presence of such a threshold and the minimum hysteresis, equal to 0.5 pulses per second, made it possible to confirm the correctness of the chosen operating voltage of the device.

Also, special attention was paid to studying the stability of the readings of the output signal of the polarimeter by measuring dark pulses and the useful signal.

To test the proposed methodology for carrying out polarization observations of a cloudless sky (measuring from "bottom") from a telescope a modification of the UVP model was used [11,25,26,28,29].

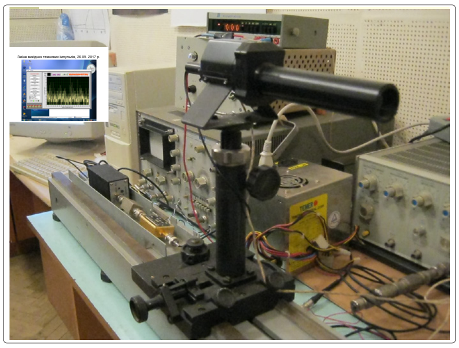
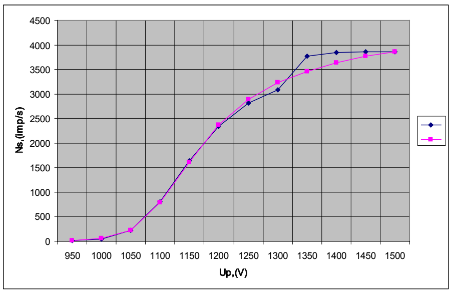
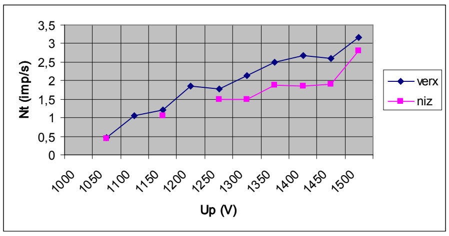


Figure 3: Stand for research and verification of UVP



a) The light pulses dependence



b) The dark pulses dependence

Figure 4: The photomultiplier R1893 pulses dependance (a – light; b – dark; rhombs - top squares - bottom)

This model was carefully studied on the above-mentioned stand, specially adapted for this purpose. Particular attention was paid to the stability of the readings of the output signal of the polarimeter at the measuring dark pulses and the useful signal. It was showed almost the absence of their changes for up to three hours (Figure 5).

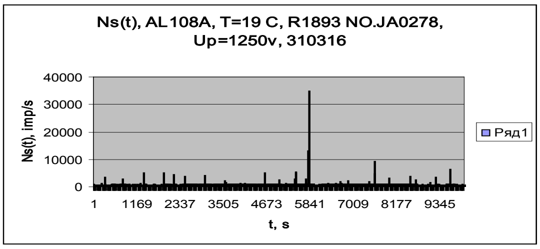


Figure 5: The dark pulses time dependence

Methodology Study

Polarimetric observations were carried out on September 26 and September 27, 2017 in the MAO NAS of Ukraine. UVP was installed on the AZT-2 telescope with a mirror diameter of 70 cm and a focal length of 15 m (Figure 6).

The telescope was aimed at a part of the sky with the Sun declining $\delta \approx °$ to the hour angle -1h to the central meridian. The work began with the engine turned off at 14:00 Kyiv time and observations were carried out until 20:00. In the observations, a filter with λ equal to 362 nm was used at the border of the visible and ultraviolet parts of the spectrum; a diaphragm with a diameter of 0.5 mm cut out the area in the sky.

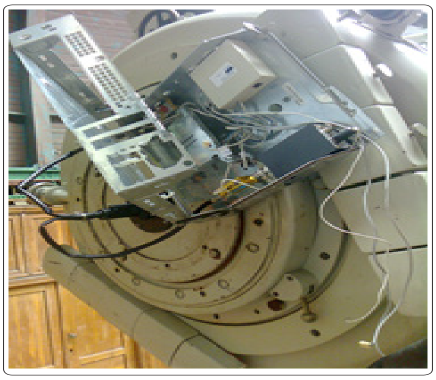


Figure 6: Modernized UVP on the AZT-2 telescope

The piezo motor turned the modulator with the phase plate at a constant angle of 45°. Therefore, one rotation was realized during 8 steps. An exposure time of 2 seconds was selected. The useful signal at the beginning of operation was about 300,000 pulses per second with a dark flux of 10–20 pulses per second.

The calculations performed according to the chosen method yielded polarization values on the phase curve, which vary from +8 to + 32% for the daytime sky and from +2 to -3% for the twilight sky (column 4, table 1) [21,28,29]. The accuracy of each measurement was about ±0.7%.

There were estimated changes in the relative radiation intensity of a cloudless sky (in two filters: 362nm (rhombuses) and 552nm (squares)) over two days (September 26 and September 27, 2017 from 12-00 to 20-00 hours) (Figure 7).

The results of observations were compared with the results of calculations (tab.) of polarization phase curves for spherical particles given in with the normal logarithmic law of size distribution, size dispersion equal to 0.1, mean geometric particle size r0 and the real part of the refractive index nr [11,30].

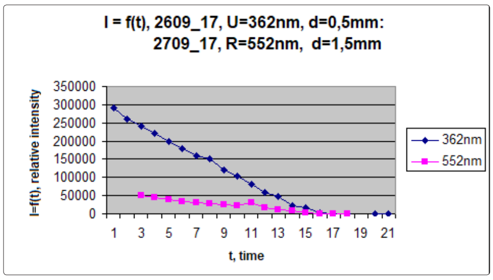


Figure 7: Changes in the relative radiation intensity

Observational data were compared with the results of calculations in shows that the daytime observations coincide with the calculations with particle size r0 equal to 0.16 µm and the real part of the refractive index nr equal to 1.33 (column 4, of table 1) [11,30]. Thus, the obtained polarimetric data in the ultraviolet region of the spectrum at λ equal to 362 nm indicate the presence of aerosol in both the troposphere and the stratosphere. Indeed, according to the calculations, the size of aerosol particles is r0 equal to 0.16µm, the real part of the refractive index nr equal to 1.33 is in the troposphere, and there is a slight increase in the value of the refractive index in the stratosphere, possibly to the value nr equal to 1.42.

In the future it is necessary to choose the dimensions of the diaphragms convenient for this type of observations and the filters that cover the visible part of the spectrum more fully in the future. For a more reliable interpretation of the estimate of the imaginary part of the refractive index, polarization observations should be supplemented with studies of the reflectivity of areas of a cloudless sky [30].

The researchers show that even an approximate analysis of polarization observations of a cloudless sky, both during the day and after sunset, makes it possible to study the physical characteristics of the aerosol in the troposphere and stratosphere.

Table 1: Comparison of the values of the degree of Polarization for a pure gas atmosphere (PR) and An aerosol (PA) with different values of Nr and R0 (µM) [11], and our observations on 09/26/2017 (Column 4)

Angle, degree	PR, %	P_a									
		n_r =	1.33-1.42	1.33		1.33		1.55		1.55	
		λ =	362 nm	360 nm		650 nm		360 nm		650 nm	
		r_0 =	0.16	0.06	0.16	0.06	0.16	0.06	0.16	0.06	0.16
1	2	3	4	5	6	7	8	9	10	11	12
105			-3								
100	+89		-2	+77	+12	+91	+54	+59	–12	+87	+25
95			+2								
90	+95		+8	+89	+18	+99	+62	+69	–11	+97	+25
80	+89		+16	+92	+24	+96	+66	+74	–11	+96	+23
70	+75		+30	+84	+29	+83	+62	+70	–11	+84	+17
60	+57		+32	+76	+31	+64	+52	+58	–14	+66	+ 7
50	+40		+27	+48	+29	+44	+36	+41	–21	+46	–4
40	+25		+17	+30	+18	+28	+21	+25	–35	+29	–14
30	+14		+ 9	+16	+ 1	+15	+ 9	+13	–55	+16	–16

Conclusion

The developed method for remote study of the stratospheric aerosol using an ultraviolet polarimeter in practice has confirmed the possibility of implementing the proposed space experiment.

It was shown that even such an approximate analysis of polarization observations of a cloudless sky in terrestrial conditions, both during the day and after sunset, indicates the possibility of studying the physical characteristics of the aerosol, respectively, in the troposphere and stratosphere.

After studying the polarimeter on a specially designed stand made by MAO, on September 26, 2017, the performed calculations polarimetric observations of the cloudless sky showed that the polarization on the phase curve varies from -3 to +32%. Comparison of experimental data showed the best agreement with the results of calculations for particle sizes r0 equal to 0.16 µm, the real part of the refractive index nr equal to 1.33 in the troposphere and 1.42 in the stratosphere.

The possibility of studying the physical characteristics of the aerosol in the troposphere and stratosphere through polarization studies has been shown. The accumulated experience will allow to choose the best option and reduce the time for setting up remote satellite research of the Earth's stratosphere.

The current prototype of the miniature onboard UV ultraviolet polarimeter UVP is considered as the basic model for the space experiment on the topic: "The study of the influence of variations in the physical characteristics of the stratospheric aerosol on the global and local climate of the Earth." The device is designed in such a way that it is possible to upgrade it depending on the variations of the tasks when setting up such a complex experiment. So, the use of scanning parallel to the equator (Fig. 8) or the use of a group of artificial Earth satellites created on the basis of picosatellites - polarimeters that are oriented to one site (object of study) (Fig. 9) will significantly improve the accuracy of research.

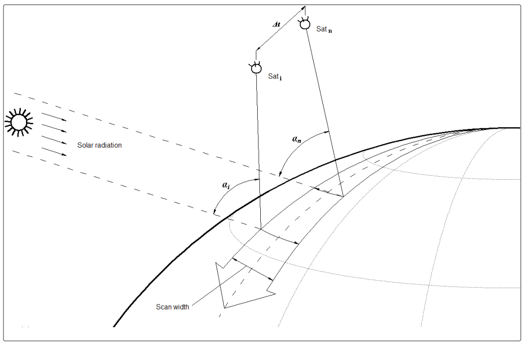


Figure 8: Space experiment model with scanning UVP

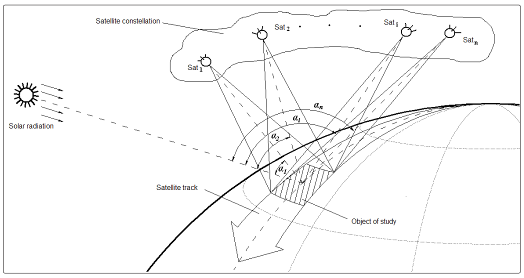


Figure 9: Space experiment model with the group of scanning UVP

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