Study of atmosphere characteristics using ultra-high energy cosmic rays and $\lambda = 532\,\mathrm{nm}$ LIDAR

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***Abstract*— A collaborative study of lower atmospheric layers are being carried at the Yakutsk complex EAS array using LIDAR and registration of ultra-high energy cosmic ray rate. The aim of these studies is to obtain the information on a distribution of aerosol over the altitude in the atmosphere, to estimate a transmission factor of the atmosphere and to study the effects of atmospheric conditions on registration rate of EAS with energies $E \leq 10^{16}$ eV.**

I. Introduction

The study of atmospheric physics on the territory of Russia is usually associated with atmospheric observations at various stationary points of the State Hydrometeorological Service. Recently, in Siberia there appeared observational points which are involved in the international AERONET [1], [2] network. Such an interest is connected not only with obtaining of long-term and short-term forecasts but with the problem of a thermal regime changing on the whole. The so-called “Global Warming” effect noted by many authors [3]–[5] may seriously affect the environment, especially, in polar and circumpolar regions.

Cosmic rays with high- and ultra-high energies ($10^{12} - 10^{16}$ eV) may also contribute to the “swing” of the troposphere. For example, ultra-high energy cosmic rays (UHECR) ionizing the medium (in the cores of extensive air showers (EAS) with different energies $10^{11} - 10^{17}$ ions are generated), may form clusters from hydroxyl groups in the air thus to open channels for the solar energy supply to the Earth surface [6]. In this sense, the study of atmosphere characteristics using a stratospheric laser (LIDAR) and cosmic rays may reveal new mechanisms for the transfer of solar energy to lower atmosphere layers.

II. The climate of Central Yakutia

The polygon for EAS observation is situated in the valley of river Lena, at a distance of 50 km south-east-ward of Yakutsk, at 110 m above sea level. By its geographical coordinates ($61^\circ\,39'$ N, $129^\circ\,22'$ E) the polygon refers to Central Yakutia. The climate of Central Yakutia is sharp-continental: the temperature may reach 35° C in July and often drops to -55° C in winter. In the region where the array is located the westward and north-west-ward winds predominate. The annual precipitation is 247 mm. In winter, especially during the frost period ($t^\circ \sim -40^\circ$ C), a frosty fog appears, spreading over the valley. Usually, the thickness of the fog doesn’t exceed $5-50$ m from the surface. The period of low night temperatures in the area of the array complex lasts for 8 months, from October to May. A minimum quantity of precipitation (in the form of fine needle-shaped crystals) also falls on the period of winter.

III. Brief description of the EAS array and LIDAR

A. The EAS array

The array consists of several instruments [7]. All of them are aimed at simultaneous observation of electron, muon and Čerenkov components of the shower. For measurements in the range of optic wavelengths, integral and Čerenkov light tracking detectors are used. As a receiver in such a detector a photo-multiplier tube (PMT) of model “49B” is used; this PMT is sensitive in the wavelength range of $360 - 800$ nm with a maximum sensitivity at $\lambda = 430$ nm. The receivers are located in the area of $6\ \mathrm{km}^2$ in the hermetic trunks and observe the nightsky withing 60° in vertical direction. There are 50 integral detectors in total and one tracking Čerenkov detector with the angle of view 2° per PMT. Event selection system has a good resolution in frequency up to 2000 Hz. Synchronous measurements of a laser radiation with both the LIDAR telescope and Čerenkov light detectors showed that such equipment resolves single laser pulses quite well. Later on the Čerenkov tracking detector was used as a receiver of scattered laser radiation for a mutual calibration and estimation of fog and mist distribution height at temperatures below 40° C.

B. Atmosphere laser probing point

Continuous atmosphere observations in the area of the Yakutsk EAS array last 35 years. There are no any industrial installations or significant mining of minerals in this region. As a rule, scattered settlements are small and are located at large distances from each other. This fact creates favourable conditions for the atmospheric monitoring at the polygon.

Since November 2004 at the Yakutsk EAS array a stratospheric LIDAR is used for the atmospheric monitoring (see Fig. 1). As a transmitter we use a solid-state laser based on the neodymium-doped yttrium aluminium garnet (Nd:YAG) crystal with a power of 300 mJ and pulselength of 13 ns in the monopulse regime, working at frequency 20 Hz. The laser can operate in two regimes: with $\lambda = 532$ nm and $\lambda = 430$ nm. Receiver is a Newton system telescope with a diameter of 0.6 m and a focal length of 2 m. The observation is controlled by a computer through a special block connected via USB 2.0 port, using an interface program developed with the virtual instrument package LabView 6.1.

Fig. 1. Atmospheric monitoring using LIDAR laser

Measurements start at twilight and last all night with a duty factor which is about one measuring per one hour. The season of atmospheric observation falls on autumn-winter and the spring periods of the year. During summer period observations are performed with SE 318 and SP-4 photometers involved in the international AERONET system.

IV. Observation results

A. Joint atmosphere condition control using UHECR's and LIDAR

The triggering system singling out air shower events at the small Čerenkov array is a matrix, where a coincidence of signals from any three non collinear Čerenkov detectors forms a controlling signal that initiates a recording of information from detectors into the memory of observational station, interlocks of input devices during processing of the signal and then a transmission of the complete set of data to the computer center.

Since Čerenkov light from a shower is generated throughout the atmosphere and actually isn't absorbed in clear atmosphere, then the rate of such showers depends on the atmosphere conditions where EAS develop [9].

As the first joint measurements of scattered laser radiation with a wavelength $\lambda = 532\,\mathrm{nm}$ with a tracking Čerenkov detector and LIDAR telescope, one can control not only the optical state of the atmosphere but also to determine the altitude of aerosol layers scattering a laser light. Fig.2 shows the value of response (number of photons) of LIDAR versus the altitude measured on April 8, 2005. Measurements have been performed under transparency of 5 balls. The pattern practically corresponds to exponential decrease of signal that is typical to Rayleigh photon scattering (nights with a high transparency).

Fig.3 demonstrates a signal formed by reflections from several aerosol layers distributed in hight; such conditions correspond to the night with a transparency of $2-3$ balls. As seen from Fig.3, the main contribution is made by aerosol layers located at 800 and $1600\,\mathrm{m}$ from the Earth surface. This

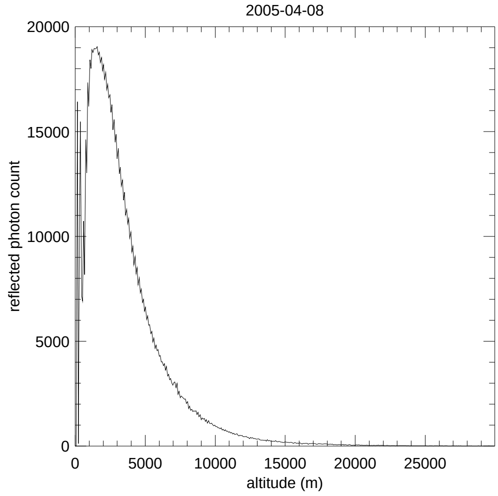

Fig. 2. The Yakutsk complex EAS array LIDAR measurements. The cloudiness is 5 balls

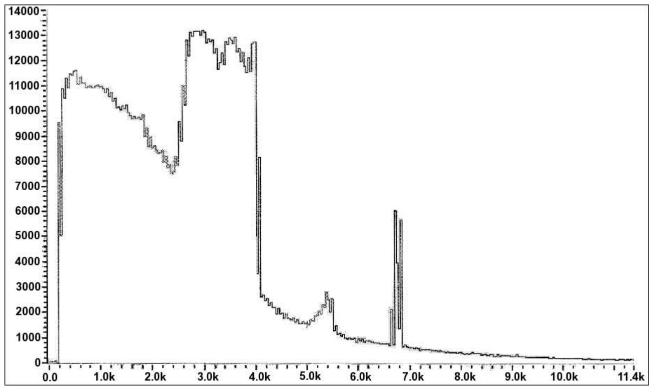

Fig. 3. The same exposure but only small altitudes are shown

aerosol layer is an obstacle for the EAS Čerenkov light, whose maximum is at $\sim(5-7)\,\mathrm{km}$ heigh.

One can estimate the value of light flux absorption by the registration of Čerenkov radiation with the Yakutsk EAS array integral an differential detectors relative to the night with a high transparency. Fig.4 shows the result of registration of scattering laser radiation with a wavelength $\lambda = 532\,\mathrm{nm}$ with a differential Čerenkov detector. It is seen from Fig.4 that no distortions in the time-base of signal connected with the reflection from aerosol layers are observed. At the same time, in the signal time-base (see Fig.5) there are distinctive signals caused by reflection from one or even several aerosol layers. Moreover, the signal distortion differs in magnitude and is in a good agreement with the atmospheric transparency scale adopted at the array. We have estimated the location altitude of aerosol layers using the registration of laser radiation performed with Čerenkov tracking detector located at $300\,\mathrm{m}$ from the LIDAR location point.

It is seen that with the help of tracking Čerenkov detector it is possible to estimate the aerosol layer altitudes with a good accuracy starting from hundreds and up to $2-3\,\mathrm{km}$ where the altitude resolution of LIDAR used is obstructed due

TABLE I

OBSERVATION RESULTS FOR GEOPHYSICAL AND OPTICAL ATMOSPHERIC FEATURES

Method	Date	Time	Balls	$(F/F_0)^{-1.6}$	$P_\lambda = 430$	$P_\lambda = 532$	h_{low} (m)	$h_{\mathrm{upper}}(m)$	$T,^\circ$ C	P, μb
	11.12.04	05:16:09	4, lf	0.68	0.69	0.81	10, lf		-49	1023
	11.12.04	06:36:15	4, lf	0.67	0.69	0.80	10, lf		-49	1024
Č.T.D.	12.02.05	22:37:44	$4-5$	0.71	0.73	0.86	335, f	665, f	-40	1011
	13.02.05	01:28:27	$4-5$	0.69	0.71	0.83	645, f		-41	1012
	11.03.05	21:13:28	$3-4$	0.60	0.60	0.71	1850, cl		-14	1011
	24.12.05	18:34:08	3	0.57	0.55	0.68	505, cl		-39	1014
	28.01.06	22:34:11	3	0.58	0.56	0.68	< 10, hf		-40	1016
	08.04.05		5	0.75	0.73	0.85			-11	1009
	09.04.05		$3-2$	0.55	0.52	0.63			-6	1002
	05.03.06		$4-5$	0.72	0.70	0.82			-34	1010
	11.12.04	05:16:09	4, lf	0.67	0.69	0.81	12000	13000	-49	1023
	12.02.05	22:37:44	$4-5$	0.71	0.73	0.86			-40	1011
LIDAR,	13.02.05	01:28:27	$4-5$	0.69	0.71	0.82			-41	1012
$\lambda = 532$	08.04.05		5	0.75	0.73	0.85				
	09.04.05		$3-2$	0.51	0.52	0.64				
	05.03.06		$4-5$	0.72	0.70	0.82			-34	1010
	30.03.06		$4-5$	0.74	0.72	0.84			-20	997
	01.04.06		$4-5$	0.76	0.70	0.81			-9	991

Here: lf — low light fog, f — fog, hf — hard fog, cl — cloud.

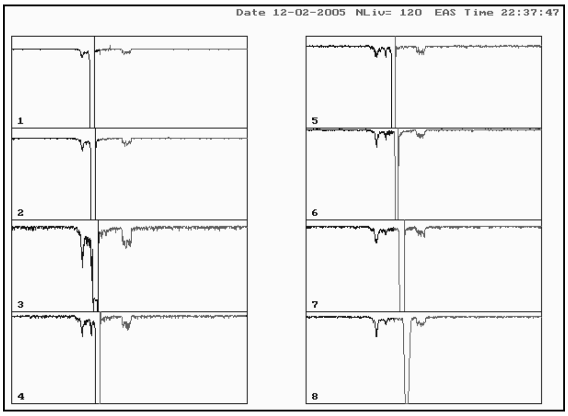

Fig. 4. Visual estimate of the transparency is two balls, 09-04-2005 (on the right: controlling signal from LED)

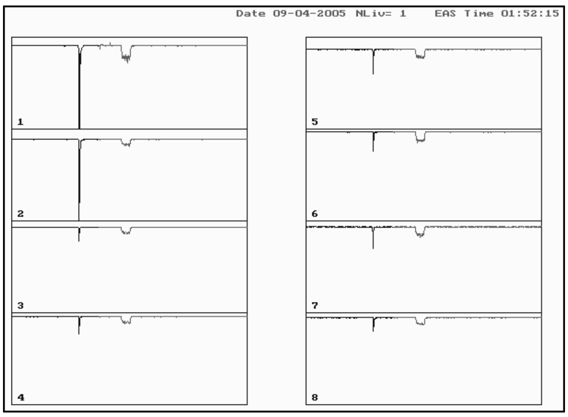

Fig. 5. Visual estimate of the transparency is five balls, 12-02-2005 (on the right: controlling signal from LED)

to the structural peculiarities. The atmosphere higher 3 km is controlled with a good accuracy by LIDAR measurements.

Table I demonstrates a spectral transparency of the atmosphere for $\lambda_1 = 430\,\mathrm{nm}$ and $\lambda_2 = 532\,\mathrm{nm}$ together with the atmosphere transmission function $\left(\frac{F}{F_0}\right)^{-1.6}$ obtained from measurements of $10^{15} - 10^{16}$ eV EAS events rate. Ibidem, an estimate of the atmosphere state in balls used at the array is shown. The data have been obtained at low temperature and increased atmospheric pressure. One can see from table I that there is a good correlation between atmosphere transparency measured with the LIDAR and UHECR events rate registered with the differential Čerenkov detector.

B. *Optical features of the atmosphere*

Since summer 2004 at the Yakutsk EAS array complex atmosphere observations with solar spectrophotometers have been carried out [2]. Observations are carried out during the April to October period in the automatic mode. The following characteristics are reconstructed: atmospheric optical thickness (AOT) $\tau(\lambda)$, single aerosol scattering albedo Λ and particle volume distribution. It follows from the data that in the Yakutsk area the monthly moisture content is low in summer. During this period the minium of atmosphere dimness is observed, the AOT value is lower than in other regions of Siberia by factor $1.5 - 2$. For Yakutsk the maximum of AOT spectral course selectivity is typical giving evidence for a relatively high content of fine aerosol in the atmosphere. High values of Λ are also typical for Yakutsk, indicating a low amount of absorbing matter in the aerosol. Aerosol dispersion composition shows that in the area the content of practically all particles is much lower than in the regions of Tomsk and Ekaterinburg. Thus, the atmosphere over the area of the Yakutsk array (near Yakutsk) during a summer period is favourable for optical observations.

In Fig.6 an aerosol optical thickness data are presented. It is seen from the Figure that absolute value of aerosol optical thickness during the summer period is larger than those at the beginning of the Yakutsk winter. This fact confirms again our conclusions about clear winter atmosphere in the area of the Yakutsk complex array.

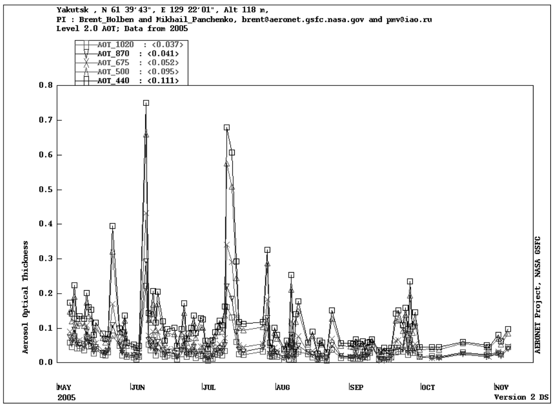

Fig. 6. Aerosol optical thickness distribution [1]

C. *Classification of the cloudless atmospheric features by SAT and SAOT values*

For a prompt estimation of the atmosphere conditions by visual observations of the firmament for many years and by UHECR registration an ball system for cloudless atmosphere conditions was developed. Further, this estimation was improved with an instrumental method, i.e. a measurement of relative rate of the EAS events with $10^{15} - 10^{18}$ eV energy [9]. The ball system on the atmosphere state classification was in agreement with the system proposed in the work [10], where the classification of the atmosphere conditions was made by a spectral atmosphere transparency (SAT) P_λ and a spectral optical thickness (SAOT) δ_λ of aerosol.

The adopted classification system for the lower atmosphere layers is currently improved by patrolling LIDAR measurements.

TABLE II

DIFFERENT VALUES FOR P_λ AND δ_λ IN DIFFERENT SCALES OF THE ATMOSPHERE TRANSPARENCY

Atmospheric transparency	P_{530}	δ_{530}	P_{369}	δ_{369}	P_{430}
low (2 balls)	0.60	0.180	0.35	0.260	0.48
decreased (3 balls)	0.70	0.080	0.46	0.120	0.56
normal ($3-4$ balls)	0.75	0.060	0.50	0.080	0.60
increased (4 balls)	0.80	0.040	0.52	0.060	0.68
high (5 balls)	0.85	0.020	0.56	0.030	0.72

V. CONCLUSIONS

Since measurements of Čerenkov light from EAS are carried out in winter at clear, dark, moonless nights, then the study of the atmosphere is of interest in this period. In particular, it is connected with the comparison of atmosphere characteristics obtained during different seasons of the year. In Central Yakutia winter conditions are being kept from October to April and are characterized by stable low temperatures. During this period a thermal inversion occurs in the atmosphere, low haze and frost fog also often happen (see Fig.1). It is not yet entirely clear how these atmosphere phenomena affect the passage of optical waves. A seasonal trend of the atmosphere transparency during the transition from winter to spring and from summer to autumn have been marked in the data of atmosphere observations using cosmic rays [5]. We hope that with LIDAR measurements it will become possible to study this effect not only qualitatively but also quantitatively. Besides, with the LIDAR one may study the air mass transport both of local and of global character.

Another problem solvable using the LIDAR method is studying of the atmosphere transmission as a function of altitude. This feature is required for the correct solution of the inverse problem of longitudinal EAS development reconstruction.

Preliminary results of LIDAR measurements for two winter periods of 2004-2005 and 2005-2006 indicated that at the Yakutsk array the atmosphere conditions mostly prosper for optical observations. During separate periods of 2004-2005 season a stationary aerosol layer was detected at altitudes of 13, 17 and 22 km which, as it is proposed, have origins outside Yakutia.

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