STATE OF THE ART AND PROSPECTS FOR THE DEVELOPMENT OF THE BALKAN SERIES SPACEBORNE LIDARS

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Comparative analysis of specifications and measurement capabilities of lidars harnessing elastic scattering and intended to operate onboard piloted and automatic space stations has been made. The BALKAN-1 lidar is now placed in orbit as part of the SPEKTR module of the MIR station. Other lidars of this series are under development now. Methodical and engineering principles of Russian spaceborne lidars are discussed.

High practical significance of the study of the Earth from onboard satellites provides the basis for design and development of new devices that increase the number of measurable parameters of the environment. In particular, it is possible now to obtain the information on the atmosphere, ocean, and underlying surface from the data of laser spaceborne sounding in the optical range of electromagnetic waves.[1–3] Lidar is the active mean of sounding characterized by very high spatial resolution. It is among few devices capable of analyzing the vertical structure of the atmosphere and subsurface layer of the ocean. Inviting prospects for spaceborne lidar applications stimulate a number of lidar projects, including Doppler lidars, in different countries. They are LITE[2] and LAWS[4] in the USA and ATLID[5] and ALADIN[6] in the European Space Agency.

Russia is one of the first countries that began to develop spaceborne lidars. The BALKAN-1 lidar destined for mounting onboard the SPEKTR module of the MIR station was produced in 1989. A module with the BALKAN-1 lidar placed onboard it was put into orbit on May 20, 1995. Experiments on laser sounding of the Earth from space were carried out July–October after a test. Together with the spaceborne experiment conducted with the LITE lidar during 9 days in September of 1994 onboard the Shuttle, these investigations are the first experience in spaceborne lidar application.

Preparation of the ALISA Russian-French spaceborne lidar[1] for the PRIRODA module of the MIR space station is being finished now. The development of the BALKAN-2 aerosol lidar has been started for the ALMAZ-2B automatic station.[7] Projects of the BALKAN-3 aerosol–gas lidar and Globwind Doppler lidar are at the stage of technical proposals. The capabilities of the BALKAN series Russian lidars are analyzed below, and their further development is discussed.

The feasibility of laser sounding of the Earth from space was substantiated many times.[8,9] The first spaceborne lidar experiments (LITE and BALKAN-1) are technological and methodical in character rather than research. However, in the design of the first lidars the users' requirements for the data obtained were taken into account.

First of all, meteorological, ecological, and environmental protection services as well as institutions that explore natural resources should be mentioned among the users. Meteorologists use the satellite data during many years, and they have formulated their own more particular requirements for the global data obtained from space. The requirements for measurements from space are given in Table I from the standpoint of their meteorological and climatological applications. These requirements are the results of a special discussion of the experts joined by the European Space Agency[10] and cover the most important parameters.

The parameters presented in Table I determine and characterize the thermodynamics of planets and are used for weather forecasting models. Capabilities of the lidars that have already been produced or are planned in Russia for the study of weather forming processes are illustrated by the last columns of Table I and are mainly related to the study of cloud and aerosol formations. Only the BALKAN-3 lidar is capable of measuring atmospheric ozone. At the same time, the spaceborne lidars are promising for estimating some other characteristics of the underlying surface and ocean, such as elevations of the surface, the height of plant canopies, depths of bottom in shallows, elevations of energy transferring waves in the ocean, and turbidity of the subsurface layer of water areas as well as detecting zones of enhanced bioproductivity in the ocean, floating impurities of water basins, and space debris. The above-indicated characteristics can be interesting for other nonmeteorological applications. The parameters measured by spaceborne lidars are analyzed in detail below.

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TABLE I. Requirements for measurements of the global distribution of the parameters from space in the interests of meteorology and climatology and the capabilities of the BALKAN series lidars.

Parameter	Error (3)	Data sampling interval	Lidar capabilities		
			BALKAN-1	BALKAN-2	BALKAN-3
Wind velocity field (4, 5)	2 m/s	3 h			
Temperature (4)	0.5 j	3 h		(8)	(8)
Relative humidity (4)	10 %	3 h			
Temperature of oceanic surface (4)	< 0.25°q	12 h			
Land temperature (4)	0.5°q	6 h			
Snow cover (4)	3%	24 h			
Soil moisture	10–20%	12 h			
Surface albedo (4)	1%	week	(10)	(10)	(11)
Vegetative index	5%	week			
Cloud cover and temperature (4)	3%,1j	1 h			
Heights of upper and lower cloud boundaries (4)	< 1 km	(2)	(6)	(6)	(6)
Water content of clouds	10%	(2)	(7)	(7)	(7)
Size and phase composition of cloud particles	20%	(2)		phase	phase, (9)
Precipitation	10%	(2)			
Aerosol depth and vertical profile	5%	24 h		+	+
Radiative budget at the upper boundary of the atmosphere	1 W/m^2	(1)			
Friction stress above the ocean surface	10%	6 h			
Oceanic topography (circulation)	2–5 cm	24 h			
Color of the ocean	-	2 h			
Ice in the ocean (4)	3%	12 h			
Total ozone content	2%	24 h			+

Notes: Figures in parentheses mean:
(1) Surface resolution and data sampling interval of different satellites must be compatible with the desired accuracy in determining the mean values of the parameters.
(2) Sufficiently short data sampling interval must meet the requirements for model averaging.
(3) The error in measuring the parameters over extended regions of the surface is given for areas 10^3–10^4 km^2.
(4) Data are continuously used for numerical models of weather forecast.
(5) Some data on the wind are obtained by geostationary satellites.
(6) Lower boundary is determined only for thin clouds.
(7) Only for thin clouds under additional assumptions.
(8) In the stratosphere.
(9) For particle size about 1 μm.
(10) At a wavelength of 532 nm.
(11) At wavelengths of 355, 532, and 1064 nm.

BALKAN-1 LIDAR

The BALKAN-1 lidar developed for the SPEKTR module of the MIR station implements the methods for investigating the environment based on the elastic scattering of a laser beam and is destined for identification of scattering objects (clouds, for example) against the underlying surface background, determination of the upper boundary height and optical properties of clouds, and investigation of the statistical structure and optical parameters of the underlying surface (especially of the sea and ocean surfaces). The feasibility of the study of the structure of the ocean subsurface layer can be evaluated (down to depths of 10–30 m), because the wavelength of radiation used in the lidar (532 nm) falls within the water transparency window and is absorbed insignificantly. Capabilities of the lidar for solving the meteorological problems are clear from Table I and are related to the monitoring of the spectral albedo and the parameters of cloudiness.

The lidar was developed by the Joint Institute of Atmospheric Optics and the Scientific-Production Association "Radiopribor" to order of the Russian Space Corporation “Energiya.B The specifications of the BALKAN-1 lidar are given in Table II together with the specifications of the BALKAN-2 and BALKAN-3 lidars being developed now. As is seen from Table II, the BALKAN-1 lidar has minimum overall dimensions, mass, and power supply. Lidar return signals are transmitted through a telemetric channel to ground-based stations where they are finally processed. The lidar was described in more detail in Ref. 11.

TABLE II. Specifications of lidars.

Parameter	BALKAN–1	BALKAN–2	BALKAN–3				
	Laser transmitter						
Wavelength, nm	532	532	1064	532	355	266	299
Output energy, J	0.15	0.2	0.15	0.35	0.2	0.15	0.15
Pulse duration, ns	12	10	3	3	3	3	3
Beam divergence, mrad	0.15	0.15	0.25	0.20	0.20	0.20	0.25
Pulse repetition rate, Hz, no more than	0.18	1	50	50	50	50	50
Transmitting collimator diameter, mm	100	115	120	120	120	120	120
	Optical receiver						
Bandwidth of interference filter, nm	2.8	2.8	4.0	3.0	1.5	1.0	1.0
Polarization analysis	–	+	–	+	–	–	–
Receiving telescope diameter, mm	275	275	300	300	700	700	700
Angle of the field of view, mrad	0.45	0.45	0.5	0.5	0.5	0.5	0.5
	Photodetectors						
Current mode	+	+	+	+	+	+	+
Photon counting mode (PCM)	–	+	–	+	+	+	+
	Signal recording system						
Bandwidth of amplifier, MHz	40	40	40				
Amplitude resolution of the analog-to-digital convertor (ADC), bit	6	6	10				
Temporal resolution of ADC, ns	20	20	20				
Strobe duration in PCM, μs	–	2.0 6.67 20	2.0 6.67 20				
Number of strobes	–	26	26				
	Operation characteristics						
Scanning, degrees	–	± 10	–				
Power, requirements W	200	600	1500				
Mass, kg	88	165	1200				
Maximum number of radiation pulses	$3\cdot10^4$	$2\cdot10^5$	10^8				

Notes: Here the plus sign indicates feasibility of technical realization, and the minus sign indicates its unfeasibility.

BALKAN-2 LIDAR

Development of lidar systems is expedient for unpiloted space stations that play a leading role in monitoring of the Earth's state, because a lot of automatic satellites are used for observations from space. In particular, one of the heaviest station[7] known as KOSMOS-1870 (1987) and ALMAZ-1 (1991) is periodically launched into space in Russia. The ALMAZ stations are equipped with scientific instrumentation including radars, radiometers, and multisprectral and stereo-TV cameras. This instrumentation is effective for the study of the Earth's surface, but significant part of phenomena in the atmosphere and ocean subsurface layer is beyond its capabilities. Taking into account the great significance of atmospheric and oceanic measurements, the next ALMAZ-1B satellite is planned to be equipped with a lidar.

The BALKAN-2 lidar created for the ALMAZ-1B station utilizes a lot of know-how tested for the BALKAN-1 lidar. Its specifications are also given in Table II. However, the capabilities of the BALKAN-2 lidar are considerably expanded in comparison with the BALKAN-1 lidar due to increased laser pulse repetition rate, scanning, and photon counting mode of detecting lidar return signals. In addition, the polarization analysis of the lidar return signals is made. The proposed innovations essentially increase the number of problems to be solved by the BALKAN-2 lidar (Table III). Due to scanning, it becomes possible to study the space debris whose fine fraction (particles with size less than 1–10 cm) cannot be detected by radars.

TABLE III. Parameters determined by the BALKAN–2 lidar.

Range of sounding	Parameters
Stratosphere (night side of the Earth)	Aerosol backscattering coefficient, scattering ratio, tropopause altitude, temperature and density profile
Troposphere (night side of the Earth)	Aerosol scattering coefficient, planetary boundary layer (PBL) altitude, PBL optical depth
Heavy ecological catastrophes in the troposphere and stratosphere (day and night sides of the Earth)	Backscattering coefficient, geographic distribution
Clouds (day and night sides)	Altitudes of upper and lower (for transparent clouds) boundaries, extinction coefficient profile, phase composition, geographical distribution, albedo
Ocean (day and night sides)	Albedo, upper layer turbidity, depths of shallows, detection of zones of enhanced bioproductivity (fish schools, plankton)
Surface (day and night sides)	Mean height of plant canopies in forests, elevations of barkhans in desert, albedo, true altitude of the orbit

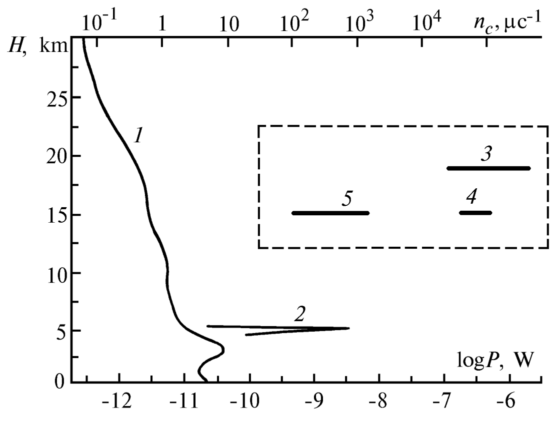

FIG. 1. Model estimates of the power P and photon count rate n_c of lidar return signals for the BALKAN-2 lidar (the orbit altitude is 300 km*): 1) cloudless atmosphere, model of Ref. 13; 2) cloud*[9] *with extinction coefficient* 10 km^{-1} *at an altitude of* 5 km*; 3) range of variation of signals reflected from the dry land; 4) range of variation of signals reflected from the rough sea surface; 5) range of variation of daytime background illumination within the lidar filter bandwidth at a Sun elevation angle of* 60° *counted off from the zenith (maximum background level).*

Determination of the parameters listed in Table III was tested in practice for ground-based and airborne lidars as well as on the basis of theoretical estimates and simulation of spaceborne lidar operation.[8,9,12] The estimated lidar return signals of the BALKAN-2 lidar are shown in Fig. 1 for sounding of different formations. It is seen from the figure that signals from the underlying surface and clouds can be detected in the current mode (thereby, sounding can be carried out on day and night sides of the Earth). Signals from the aerosol atmosphere are much weaker and can be detected only on night side in the photon counting mode. In this case, a signal should be integrated over 50–100 sounding pulses (depending on the altitude and strobe duration), which corresponds to horizontal resolution of 400–800 km.

BALKAN-3 LIDAR

As part of the project of the ALMAZ-2 multifunctional space laboratory aimed at the solution of ecological problems, the BALKAN-3 lidar that can be called the aerosol-ozone lidar was proposed for its equipment.

The atmospheric ozone problem is considered now as one of the main ecological problems. It can be investigated by such an aerosol-ozone spaceborne lidar that is capable of analyzing the three-dimensional fields of ozone and aerosol. The latter can be considered as one of ozone sinks.

For simultaneous measurement of aerosol and ozone parameters, the BALKAN-3 lidar is assumed to operate at the following wavelengths: 1064, 532, 355, 266, and 299 nm with pulse powers of 0.15, 0.35, 0.2, 0.15 and 0.15 J, respectively.

A receiving system will comprise two mirrors, 700 and 300 mm in diameter, and will be capable of analyzing the polarization state of lidar return signals at a wavelength of 532 nm. The detailed lidar specifications are given in Table IV. The lidar with such parameters is promising for global monitoring of ozone and aerosol from orbits at altitudes 300–400 km. The potentialities of the lidar are not exhausted by the analysis of aerosol and gas composition of the atmosphere. It is also capable of investigating the underlying surface, upper layer of the ocean, clouds, and atmospheric stratification. The full list of measurable parameters is given in Table IV. Quantitative characteristics of measurable parameters are confirmed by physical and mathematical modeling and results of airborne tests. They are estimated for a laser pulse repetition rate of 50 Hz (see Ref. 14).

TABLE IV. Parameters determined by the BALKAN–3 lidar (parameters marked by asterisk are measured at the night side of the Earth).

Parameter	Range of variability	Error	Spatial resolution vertical/horizontal, m
	Cloudiness		
Upper boundary altitude	50...12000 m	50 m	3/320
Vertical profile of the scattering coefficient	5...100 km^{-1}	20%	3/320
	Atmospheric aerosol		
Altitudes of upper and lower boundaries of aerosol plumes	50...5000 m	50 m	3/320
Vertical profiles of the scattering coefficient (mass concentration for the visible wavelength range in the lower troposphere)*	2...10 km^{-1} (0.5...5 mg/m^3)	30% 40%	300/16000
Particle size spectrum in the upper troposphere and the stratosphere*	0.4...1.5 mkm	50%	300/16000
	Atmospheric gases*		
Density fluctuations of the atmosphere at the orbit altitude	50%		5000/16000
Vertical profile of ozone concentration	0.13...10 ppm	10...60%	500...5000/16000
Air density and temperature*	20...0.003 g/m^3 − 100... + 50°C		200...2000/16000
	Underlying surface		
Spectral albedo for 1064, 532, and 355 nm	0.3...0.9	15%	–/320
Elevations of barkhans	5...50 m	+ 0.5 m	–/320
Height of plant canopies	5...50 m	+ 0.5 m	–/320
Vegetation state	–		
Depths of shallows	3...30 m	+ 0.5 m	0.5/320
Elevations of energy transporting waves	0.7...8 m	+ 0.5 m	0.5/320
Extinction index of the upper sea layer at 532 nm	0.5...0.15 m^{-1}	30%	–/320
Presence of chlorophyll in the upper sea layer with concentration higher than the threshold level	yes/no		–/320
Presence of oil products on the sea surface	yes/no		–/320

Considering above-enumerated spaceborne lidars as measuring devices, one should mention the field tests of the techniques for measuring some atmospheric parameters from space by means of lidar systems. The case in point is the use of laser rangefinders that have been regularly placed in orbit as parts of Russian geodesic satellites since 1982 for determining the upper boundary and optical density (related to the water content) of dense clouds.[11,15] The peculiarities of recording systems of these rangefinders that are capable of measuring not only the time delay of lidar return signals but also their duration at several levels made it possible to test the lidar methods and to determine the profiles of the optical radiation extinction coefficient at the upper boundary of clouds. Comparison of the statistical distribution of the cloud extinction coefficients with the data available in meteorology showed their satisfactory agreement for cumulus. The last fact encourages us for implementation of the program of investigations by means of the BALKAN series lidars.

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