Radiation Experiment in Support of the Atmospheric Radiation Measurement Program

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The objective of this work is to test and improve the radiation models under clear sky, homogeneous, and broken cloud conditions. The effort will produce data of field measurements of the atmospheric radiation taken simultaneously with measurements of the atmospheric parameters which determine the radiative transfer under three meteorological conditions mentioned above. These measurements provide a basis for the detailed testing and verification of the radiation models in GCMs and are applicable in various scientific centers.

Experimental investigations of the dependence of radiation fields on the parameters describing the physical state of the atmosphere will be carried out as part of this program. The experiment will include measurements of the following characteristics of the radiation field and the parameters of the "atmosphere-underlying surface" system:

- meteorological measurements—pressure and temperature as functions of the altitude and the three-dimensional field of wind velocity
- atmospheric composition—concentration and phase composition of water; content of the greenhouse gases; size distribution and optical parameters of aerosol and cloud particles
- surface properties—albedo and effective radiative temperature
- geometric structure of clouds—cloud fraction, location, shape, vertical and horizontal size
- radiation measurements—spectral radiance, broadband and net fluxes, relative fluxes, and polarization state.

A unique instrumentation complex, which is a reliable base for carrying out the radiation experiment, has been developed at the Institute of Atmospheric Optics of the Siberian Branch of the Russian Academy of Sciences. A number of the atmospheric parameters are measured by several methods by means of devices. This approach is important for intercalibration and increasing the reliability and the accuracy of the data obtained. Figure 1 illustrates the principal instrumentation of the conceptual project. The capabilities of the instrumentation are briefly described below.

The meteorological and aerological stations situated in the vicinity of Tomsk are also presented in Figure 1. The data from these stations will be used for planning and carrying out the experiment and for interpreting the results.

Atmospheric Parameter Measurements

The detailed study of various physical effects associated with laser radiation propagation in the scattering and absorbing media provides a methodological basis for lidars. The lidars are capable of obtaining the quantitative information about the vertical profiles with high spatial resolution, and in some cases about the spatial distribution of the atmospheric parameters.

The **multifrequency lidar** is used for measuring the ozone and aerosol concentration profiles and for retrieving the aerosol size distribution function. At present, the multifrequency lidar operates better at night, when it can cover the 5-30 km height range; in the day, the height range is 5 to 15 km. The principal parameters of the multifrequency lidar are given in Table 1.

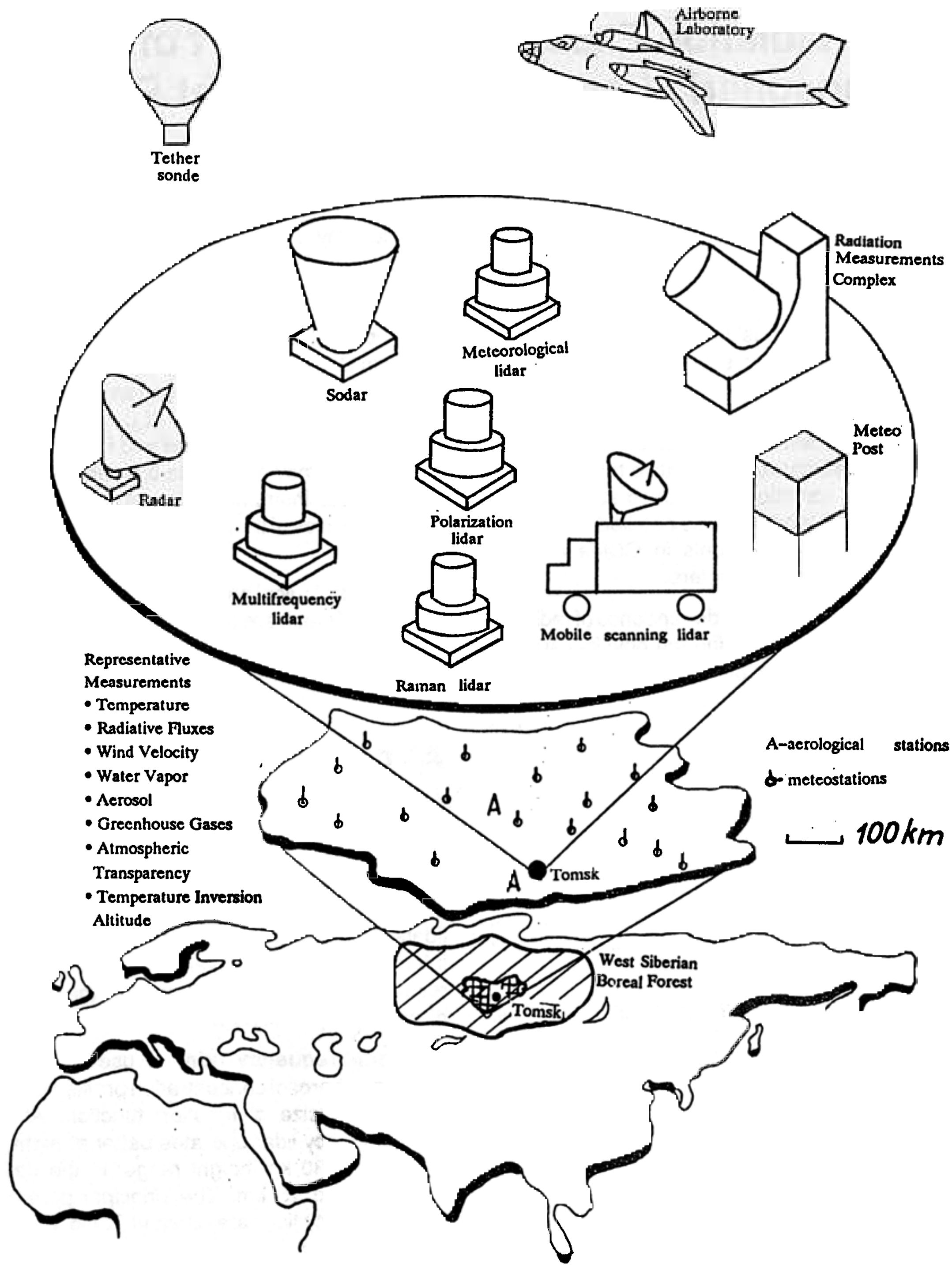

Figure 1. Conceptual design for the Complex Radiative Experiment.

Table 1. Parameters of the multifrequency lidar.

Parameters of sounding	Ozone, Aerosol, Temperature
Range of sounding heights	5-40 km
Temporal resolution	15-30 min
Spatial resolution	50-500 m

	Transmitter			
Laser	λ, nm	*E*,mJ	P_{mean}, W	*f*, Hz
Cu(578 mn)+frequency doubling	289		0.2	5•10³
XeCl	308	50		50-100
XeCl+Raman-cell(H_2)	353	30		50-100
Nd:YAG	1064	150		10
Nd:YAG+frequency doubling	523	50		10
Nd:YAG(532 nm)+Raman-cell(H_2)	683	30		10
Sr+	431		1	2.5•10³
Cu	511		2	2.5•10³
Au	628		2	2.5•10³
Pb	723		1	2.5•10³
	Receiver			
Telescope diameter, m	2.2			0.35
Telescope focal length, m	10			1
Telescope viewing field, mrad	0.5			2
Wavelengths, nm	308, 353, 1064, 532 683, 431, 511, 628, 723			289, 308
	Registration			
Detector-photomultiplier	PMT-79, PMT-130, PMT-142			
Number of gates	512			
Computer	IBM PC AT			

The **"LOZA-3" mobile aerosol lidar** measures the following atmospheric parameters:

- the scattering coefficients and estimated aerosol mass concentration along the vertical, horizontal, and slant paths
- spatial and temporal variations of the lower boundary and the optical depth of clouds
- wind velocity in the boundary layer
- height of the mixing layer, the size and velocity of the thermal plumes under various convective conditions, and the temperature inversion height.

The lidar can operate in the scanning regime (Table 2); thus, it can obtain quantitative data on the spatial distribution of the enumerated parameters. In addition, the lidar can be situated at the basic site of the experiment, can be placed at the necessary distance, and can operate in an independent regime.

Table 2. The "LOZA-3" mobile aerosol lidar.

Parameters of sounding	optical-physical parameters of aerosol and cloud formations
Range of sounding distances	
Clear sky	3-4 km
Cloud fields	7-10 km
Temporal resolution	1-3 s
Spatial resolution	7.5 m
Angular resolution	20'
Operation regime	round-the-clock, cycle

Transmitter

Laser	λ, nm	*E*,mJ	P_{mean}, W	*f*, Hz
	0.532	30	1-25	15

Receiver

	Diameter, m	Focus, m	Field of view
Lens telescope	0.3	1	0.5-5

Scanning column

	Azimuth	Elevation	Scanning rate range
Two-coordinate platform	0-340°	-10-90°	0.5-10 grad/s

System of control and registration

Computer	IBM PC/AT
Photoreceiver	photomultiplier
Analog-digital convertor	8 digits; 20 MHz
Number of gates	1024

The **"MAKREL-2" airborne lidar** measures the horizontal size and spatial variations of the upper boundary of the cloud fields, the optical depth and the phase composition of clouds, and the statistical parameters describing the vertical geometrical structure of cumulus clouds. The lidar is used onboard the "OPTIK-E" AN-30 Aircraft Laboratory. It can operate over the basic site or fly along the selected routes. The principal parameters of the lidar are given in Table 3.

Table 3. Parameters of the airborne polarization lidar.

Parameters of sounding	Cloud upper boundary altitude; phase state of clouds; atmospheric aerosol		
Sounding distance	0.2-7 km		
Temporal resolution	0.1 s		
Vertical resolution	1.5-30 m		
Horizontal resolution	10-100 m		
Aircraft	AN-30; IL-18		
Transmitter			
Laser	λ, nm	*E*,mJ	*f*, Hz
Bd:YAG+frequency doubling	532	100	1-15
	(1064)	60	1-15
Receiver			
Telescope diameter, m	0.15		
Focal length, m	0.75		
Field of view, mrad	1-20		
Polarization	linear		
Analyzer	Wollaston prism		
Registration			
Detector	Photomultipliers PMT-84, PMT-141, PMT-83		
Analog-digital converter	4 channels, 10 ns, 7 digits		
Computer	Data processing onboard the aircraft and on the ground		

The **"STRATOSFERA-1M" polarization lidar** is designed to measure the profiles of the backscattering coefficient, Stokes parameters, scattering matrix of cirrus clouds, and aerosol and molecular components of the atmosphere (Table 4a). The lidar operates at night. The relative error in measuring the backscattering coefficient is 15% to 20%. The scattering matrix elements are measured with an absolute error of ±0.04.

The additional lidar channel (Table 4b) measures the scattering ratio

$$R = \frac{\sigma_m}{\sigma_m + \sigma_a}$$

where σ_m and σ_a are the molecular and aerosol backscattering coefficients, respectively. The lidar also measures the temperature and humidity profiles.

Table 4a. Parameters of the "STRATOSFERA-1M" polarization lidar.

Parameters of sounding	backscattering coefficients, Stokes parameters; scattering matrices of cirrus clouds; aerosol and molecular atmospheric components
Range of sounding heights:	
for measuring the backscattering coefficient only	5-30 km
for measuring the scattering matrix elements	5-20 km
Spatial resolution (depends on the height)	24-480 m

	Transmitter			
Laser	λ, nm	*E*,mJ	*P*, W	*f*, Hz
Nd:YAG	532	50		25
	Receiver			
Antenna diameter, m	0.5			
Detector-photomultiplier	PMT-130			
Dark current	102 Hz			
	Registration			
Maximum photon counter rate	100 MHz			
Computer	IBM PC/AT			

Table 4b. Parameters of the lidar channel of temperature and humidity measurements.

Parameters of sounding	Temperature	Humidity	Scattering ratio
Range of sounding heights	1.5-10 km	1.5-8 km	1.5-12 km
Spatial resolution (depends on the height)	48-480	48-480	48-480

	Transmitter			
Laser	λ, nm	*E*,mJ	*P*, W	*f*, Hz
Nd:YAG	532	80		14
	Receiver			
Antenna diameter, m	2.2			
Focal length, m	10.07			
Field of view, mrad	0.4			
Spectral width of the momochromator, nm	0.6			
Detector-photomultiplier	PMT-104			
Dark current	10^2 Hz			
	Registration			
Maximum photon counter rate	100 Hz			
Computer	IBM PC/AT			

The **Meteorological lidar** employs the correlation method to measure the wind parameters and the differential absorption method to measure temperature, humidity, and pressure. The lidar measures the following parameters (Table 5):

- the profiles of wind velocity in the lower troposphere up to the altitudes of 1 to 2 km. The error in measuring the wind speed is ±7%, the error in measuring the wind direction is ±7°
- the profiles of temperature (±5°), humidity, (±10%), and pressure (±7 mbar) up to a height of 1 km
- the height of the lower cloud boundary and the cloud fraction
- the height and the thickness of temperature inversions
- the statistical characteristics of aerosol inhomogeneities.

The **Raman lidar** measures the profiles of temperature, humidity, and the extinction coefficient in the 0.05-1.5 km height range with a spatial resolution of 0.015 km (Table 6).

Table 5. Parameters of the meteorological lidar.

Parameters of sounding	wind velocity, temperature, humidity, aerosol			
Range of sounding heights	1-2 km			
Temporal resolution	3-10 min			
Spatial resolution	50-200 m			
	Transmitter			
Laser	λ, nm	*E*,mJ	*P*, W	*f*, Hz
Nd:YAG	1064	250	5	5-30
Nd:YAG+frequency doubling	532	100	2	5-30
Nd:YAG(532 nm)+$A1_2O_3$:Ti^3+	725±3	20	0.3	5-30
	Receiver			
Telescope diameter, m	0.3			
Telescope focal length, m	0.64			
Telescope viewing field, mrad	1			
Wavelengths, nm	1064, 532, 725±3			
	Registration			
Detector-photomultiplier	PMT-83, PMT-84			
Number of gates	128			
Computer	IBM PC/AT			

Table 6. Parameters of the raman lidar.

Parameters of sounding	temperature, humidity, extinction coefficient.
Range of sounding heights	0.05-1.5 km
Spatial resolution	15 m

Transmitter

Laser	λ, nm	E,mJ	P, W	f, Hz
Cu	511		2	$5 \cdot 10^3$

Receiver

Antenna diameter, m	0.4
Detector-photomultiplier	PMT-104
Dark current, Hz	10^2
Spectral width of the monochromator, nm	1.2

Registration

Maximum photon counter rate	100 MHz
Computer	IBM PC/AT

The **meteorological acoustic sensor** identifies the stratification type (class of atmospheric stability) and determines the height of the mixing layer, the structural characteristics of the temperature field, the height and thickness of temperature inversions, and the wind velocity up to a height of 1 km.

The sensor's specifications are as follows:

Altitude range	35-300 m
Currier frequency	1650-1850 Hz
Electric power	65 W
Antenna (diam)	paraboloid, 1.0 m
Beam width	<15°
Noise-cancelling shield	frustum
Height	1.55 m
Pulse repetition period	4.0 s
Pulse duration	150 ms
Vertical resolution	25 m
Recording system	echo sounder, PC
Power supply	220 V, 50 Hz
Power consumption,	
Electronic equipment	300 W
Antenna heater	1000 W

The **"OPTIK-E" AN-30 Aircraft Laboratory** is equipped with the instrumentation for acquiring data on the meteorological parameters, gas composition, and aerosol content of the atmosphere at the altitudes of flights, as well as for measuring characteristics of the radiation field and underlying surface. The maximum altitude of flights is 8000 m; the speed of flights varies from 250 to 400 km/h; the maximum range of flights is about 2400 km; sufficient runway length is 1300 m.

The aircraft carries the following instrumentation:

- meteorological complex
- aerosol complex
  - photoelectric counter
  - diffusion battery
  - nephelometer supplied by thermo- and hydro-optical devices
  - filters
- gas analyzing complex

- "MAKREL-2" lidar
- spectro-photo-radiometric complex
- TV-03 thermal imaging camera
- onboard recording system
- navigation complex.

The instrumentation measures the following parameters:

- air temperature and its fluctuations
- humidity
- pressure
- wind velocity and its fluctuations,
- cloud microphysics
- number density and/or mass concentration of aerosol
- aerosol particle size distribution in the range from 0.005 to 10.0 µm
- chemical composition of aerosol ions:

- F^-	- SO_4^{2-}	- NA+
- NH_4^+	- As^{5+}	- K^+
- NO_3^-	- Cl^-	- Cd^{2+}

elements

- Al	- Mg	- Si
- Cr	- Ga	- Ba
- Mo	- Ca	- Cu
- Ti	- Sb	- Sn
- B	- Be	- Mn
- Ag	- Co	- Fe
- Br	- Mo	- W
- Pb	- Ni	- Hg
V	- Zn	- In

- aerosol scattering coefficient (at the scattering angle of 45°, at $\lambda = 0.42, 0.52$, and 0.61 µm) and the polarization degree of scattered light at these wavelengths
- content of aerosol volatile components at temperatures 10° to 400°C
- gases:

- ammonium	- nitric oxide
- acetylene	- nitrogen peroxide
- acetone	- carbon monoxide
- benzine	- sulfur anhydride
- benzene	- hydrogen sulfide
- xylene	- toluol
- ozone	- chlorine
- carbon dioxide	

- extinction coefficient of water (at depths down to 25 m)
- extinction coefficient of clouds ($\lambda = 0.53$ µm)
- vertical profile of the aerosol scattering coefficient ($\lambda = 0.53$ µm)
- intensity of upwelling and downwelling radiation in the atmosphere—underlying surface system at wavelengths $\lambda = 0.44, 0.63, 0.67, 1.05, 1.20, 1.60$, and 8 to 15.0 µm
- upwelling and downwelling fluxes of solar and thermal radiations
- temperature of the underlying surface in the range from -40° to 60°C
- onboard recording system (based on IBM PC/AT with a streamer) records the flight course, the air and actual speed of flight, drift angles, barometric altitude, bank and pitching angles, overload, presence of thunderstorms (radar indicator).

The aircraft-laboratory has been used in the DUNA USA-USSR Experiment (Dushanbe), ODAEX (Odessa), "Vertical 86 and 87" (Tomsk), and the SATOR Experiment (Subprogramme of TOR EUREKA). In addition, this aircraft/laboratory has been used to inspect the air quality over the cities of Alma-Ata, Balkhash, Pavlodar, Ust'-Kamenogorsk, Khabarovsk, Komsomol'sk-on-Amur, Ulan-Ude, Nizhnevartovsk, Nizhnii Tagil, and Petropavlovsk-Kamchatskii.

Other possible applications for the aircraft/laboratory include

- investigating the transboundary transfer
- studying air pollution over urban areas with indication of the emission sources

- measuring water turbidity in the upper 25 m layer of the oceans
- determining chlorophyll and hydrosol content in water
- detecting oil films on the water surface
- measuring height of plants and their spectral albedo.

The **radar** will determine the vertical and horizontal cloud size, cloud water amount and phase composition. Its specifications are

Wavelength	0.8 and 3.2 cm
Field of view	44'
Diameter of the receiving antenna	3 m
Pulse duration	1 and 2 ms
Pulse repetition rate	600 and 30 Hz
Range of operation	300 km.

The **radiosonde** measures the profiles of temperature, humidity, pressure, and wind velocity up to 30 km with spatial resolution of 50 to 150 m. In addition, special sensors installed on the radiosonde can measure the ozone profiles and upwelling and downwelling fluxes of the longwave radiation.

The standard meteorological parameters (temperature, relative and absolute humidity, wind velocity) are measured at several heights in the 0.5 to 10 m range. The fluxes of heat, humidity and momentum are determined from data on gradient measurements.

The **aerosol ground-based complex** of instruments measures the particle size distribution function in the range d = -0.006-10 μm and collects the aerosol samples for subsequent chemical analysis. (The list of the elements and ions to be determined is the same as for the aircraft laboratory.)

Optical properties of the aerosol particles are studied by the following devices:

1. The **aureole nephelometer** (λ = 0.63 μm) measures the scattering phase function within the angle 20'-10° and simultaneously with the inverse problem solution provides data on the concentration of particles with the size d = 2-20 mm.
2. The **nephelometer with local scattering volume** measures the scattering coefficient at three wavelengths in the visible spectral range (λ = 0.42, 0.52, and 0.62 μm). Thermo- and hydro-optical devices provide for the measurement of the aerosol parameter of condensation activity λ and estimation of the volatile components in the aerosol composition (by heating up to 300°C). If necessary, the local volume nephelometer can be additionally equipped with a device for estimating the soot content in aerosol particles.
3. The **multiwave measurer of transparency** determines atmospheric transmission at extended horizontal paths in 22 spectral intervals in the range λ = 0.44-12 μm. Solution of the inverse problem makes it possible to estimate the size distribution function of the aerosol particles in the range d = 0.1-10 μm, and statistical correction of the data makes it possible to determine the extinction caused by the continuous absorption by water vapor in the transparency window at λ = 8-12 μm.
4. The **aerosol complex** (analogous to the one for the airborne laboratory) is also used to determine the gaseous composition. The complex includes chromatographic and hemiluminscent devices for determining the content of greenhouse gases and of the ozone cycle gases (see the description of the gas measured by the aircraft laboratory).
5. The **all-sky camera system** is used to study the geometrical structure of the cloud fields.

Radiation Measurements

The **complex of standard devices** will measure the integral and broadband fluxes of the incident, scattered, and total solar radiation, as well as the integral and broadband fluxes of the longwave radiation at the ground surface.

The **solar spectral photometer** is designed for measuring the radiation intensity in the sun's direction and for determining the aerosol spectral optical thickness (in the transparency windows λ = 0.3-12 μm) and the total content of some greenhouse gases (H_2O, CO_2, CO, O_3, CH_4, N_2O, CFC) by the solar spectrophotometric method with low resolution ($\Delta\lambda$ = 10-40 μm).

Specifications for the photometer are

• angular resolution	0.3°
• wavelength range	0.3-12 mm

- the number of the spectral channels 16
- error in determining the optical depth rel. units 0.01-0.03
- error in following the sun ±0.1°
- time of recording the individual spectrum 0.5-2 s
- data storage on IBM PC/AT.

The **stellar spectral photometers** with analogous functions is used instead of the solar photometer at night.

The **scanning filter spectrophotometer of the daytime sky** measures the spatial-angular structure of the sky and underlying surface brightness in the wavelength range 0.4-1.06 μm. Scanning is controlled by a special program. The instrument's specifications are

- angular resolution 1°
- the number of the spectral channels (filters) 6
- error in photometering 1-3%
- scanning range of the elevation angle ±90° of the azimuth ±180°
- wavelength resolution 5-20 nm
- time recording the individual 0.1-1 s
- data storage on IBM PC/AT.

The filters can be installed centered on the absorption bands of atmospheric gases.

The **scanning filter radiometer** measures the spatial-angular structure of brightness (radiative temperature) of the sky, clouds and the surface in the transparency windows at λ = 4-12 μm. Scanning is controlled by a special program. Specifications for the radiometer are

- angular resolution 0.5-1°
- number of spectral channels (filters) 6
- error in absolute measuring the radiative temperature 0.1°
- scanning range of the elevation angle ±90° of the azimuth ±180°
- wavelength resolution 0.1-0.2 μm
- radiative temperature resolution (λ = 10 μm) 0.05°

The filters can be matched to the absorption bands of atmospheric gases.

The **spectrophotometer** recording the weak fluxes of the atmospheric radiation is designed to measure the cloud optical depth. Its specifications are

- field of view 20'
- the number of the spectral channels 5
- wavelengths 0.63 μm, 0.91 μm, 3.7 μm, 10.8 μm, 12 μm
- wavelength resolution: in the range 0.63-0.91 μm 0.1 μm in the range 3.7-12 μm 0.2 μm

The photometer is calibrated in absolute units and is compatible with any kind of computers.

At present, monitoring atmospheric parameters and radiation fields to solve the problems of global nature and climate change is one of the principal scientific directions of the Institute of Atmospheric Optics. The geophysically significant series of observations of some atmospheric parameters (for example, aerosol optical and microphysical parameters, including the antropogeneous aerosol, ozone, etc.) have been obtained by means of the instrumentation complex described above.

These observational series can be used to improve the available regional radiation models and to create new models. The latter is especially important for modeling regional climatic change. The available instrumentation complex is permanently modernized, as are the methods of retrieving the atmospheric parameters from the observational data. However, the Institute of Atmospheric Optics cannot carry out the radiative experiment without financial support.