THE "OPTIK–É" AN–30 AIRCRAFT–LABORATORY FOR ECOLOGICAL INVESTIGATIONS

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Aircraft–laboratory for ecological monitoring of the atmosphere and the underlying surface including that of water is described. The specifications of the complexes included in it are given. The problems of correctness of airborne measurements are discussed. The operations of the modernized aircraft-laboratory are listed in conclusion.

Aircrafts have long been in use for investigation of the atmosphere. Apparently, the use of a meteorograph onboard the aircraft in Frankfurt am Main in 1912 may be considered as the first case.[1] The rapid development of aviation in the 30's gave impetus to airborne sounding. This process is still in progress.

The aircraft has attracted attention of investigators in the field of atmospheric physics primarily because it is capable of carrying out the investigations *in situ*, i.e., directly at the point in space we are interested in. In this case numerous instruments, which are combined, as a rule, into a unified complex connected with an onboard recording system on the basis of a computer, can be delivered at the given point in space. The advantages of this method are the integrated character of measurements, which are carried out simultaneously, and the possibility of tracking the examined phenomenon.

This method has been occasionally used at the Institute of Atmospheric Optics of the Siberian Branch of the Russian Academy of Sciences since the early 70's.

Airborne sounding has become regular since 1981. It was carried out from aboard the IL–14 aircraft–laboratory. A detailed description of this aircraft and of the complexes included in it was presented in Ref. 2. In connection with the fact that this aircraft was written off after completion of its prolonged service life, we began to master a new type of carrier –– the AN–30 aircraft –– in 1988. This aircraft essentially differs from the IL–14 aircraft by its tightness resulting in the need of new technical solutions for placing the scientific instrumentation onboard it. In addition, some complexes were substantially modernized. In 1989 this process was accomplished by the issuance of engineering specifications in the O.K. Antonov Design Bureau and by mounting the instrumentation.

This paper is devoted to the description of the specifications of the developed aircraft–laboratory and the problems to be solved by it.

Taking into account severe ecological situation in many regions of our country and the absence of means for obtaining the objective data on it at the regional scale the main purpose of creation of the aicraft–laboratory was production of the instrumentation complex destined to measure the amount of pollutants in air and on the underlying surface. Such an approach essentially differs from the others in that the other aircrafts, which implement different programs, are called ecological without changing their instrumentation and their sounding techniques. The created "OPTIK–É" AN–30 aircraft–laboratory is a new type of the aircraft–laboratory, since the remote active (lidar) and passive (spectrophotometric and radiometric) sounding techniques are used onboard it along with the conventional contact measurement techniques. This makes it possible to obtain not only linear (at the flight altitude) and two–dimensional (on the underlying surface) but also the vertical sectional views. The "OPTIK–É" AN–30 aircraft–laboratory is capable of solving a large class of problems from investigation of the transboundary and regional transport of air polluttants to certification of the individual sources of polluttants in cities and regions and identification of the sites of polluttants on the sea and underlying surfaces.

Before describing the instrumentation complexes let us dwell briefly on the specifications of the AN–30 aircraft. This aircraft was created especially for aerophotography. In the floor it has five hatches protected by glasses and intended for input and output optical radiation. Its passenger cabin is free of armchairs that facilitates placing of the measurement instrumentation. There are a sideboard and a dark room in it. The aircraft is equipped with special navigation instrumentation and radar, and is capable of flying in severe meteorological conditions and holding the selected heading accurately. The electric circuit developed in the O.K. Antonov Design Bureau allows us to make connections with this instrumentation and to record on a computer the navigation characteristics in addition to the measurable physical parameters. Further this facilitates the interpretation of the data and makes it possible to correct the results of remote sensing. The aircraft has sufficient power supply. The devices having a total power of 12 kVA can be connected to the electric dashboard of an operator arranged in the cabin. The main specifications of the aircraft–laboratory are the following:

maximum take–off mass	24 ton
range of working speed	250–450 km/h
maximum flight distance (with filled tank and endurance two hours)	2400 km
maximum flight time	5.5 h
range of working altitudes	100–8100 m
meteorological minimum	50/700
runway (ground or concrete) length	1300 m

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GENERAL DESCRIPTION OF THE MEASURING COMPLEX

Figure 1 shows the arrangement of scientific instrumentation on the covering and in the cabin of the "OPTIK–É" AN–30 aircraft–laboratory.

Air samples for gas analyzers, photoelectric counter, and other devices embodying the contact principle are installed in the forepart of the aircraft on the special table *1* in the undisturbed zone in front of the propellers. Diffusers creating the vacuum for vent of the air after its passage through the analyzers and specially protected (with fairings) meteorological sensors are mounted on the same table *1*. Such an arrangement of the contact means was chosen because of the design features of the AN–30 aircraft. Its nose is glassed and is the work station of a navigator. The radar antenna is in the lower part of the nose. This gives no way of conventional installation of the samplers and sensors on the rod clamped on the nose of the aircraft.

The rack *2*, on which the gas analyzers, the photoelectric counter, and the filter–ventilator are mounted, is installed near the base of samplers and sensors in the pilot cabin. This arrangement makes it possible to shorten substantially the length of the supply air communications to the devices and to minimize the destruction and sedimentation of polluttants in them.

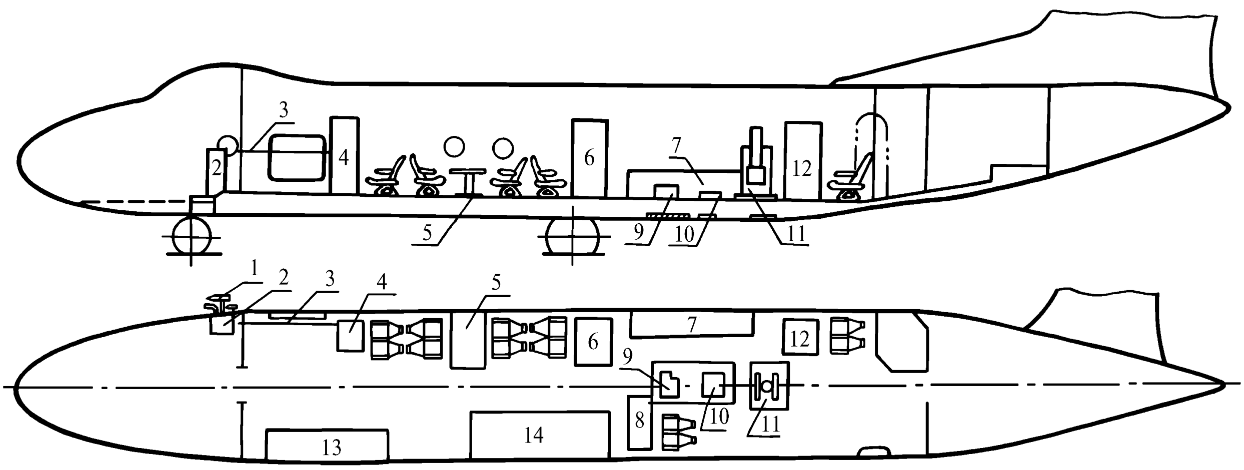

FIG. 1.

The rack *4*, on which a nephelometer with thermo– and hygro–optical means is mounted, for reason of space is situated in the passenger cabin 1.5 m apart from the pilot cabin. The outboard air is conveyed to and carried away from the nephelometer by means of the air duct *3*. This position of the nephelometer is caused by the fact that a cargo hatch, which is simultaneously the emergency exit, is here. The relocation of the rack *4* is impossible for reasons of the safety engineering requirements.

The work station of the flight leader is shown by the reference number *5* (Fig. 1). It is equipped with an intercommunication system.

The reference numbers *6* and *11* denote the "MAKREL'–2" airborne lidar. A recording system of the lidar is mounted on the rack *6*. The lidar *11* is situated above the photohatch, which makes it possible to carry out sounding in the nadir.

The spectrophotometer *9* and the radiometer *10* are mounted above the first and second photohatches, respectively. The spectrophotometer operates through the standard photohatch glass, while the radiometer is enclosed in a hermetic container placed above the photohatch, which has no glass, since it is opaque to the IR radiation. Recording instrumentation of the spectrophotometer and the radiometer is mounted on the rack *8*.

Feeders with automatic circuit–breakers, related navigation devices, radio intercommunication means, and recapitulator of direction indicator are on the dashboard *7*.

A main recording system, which receives the current data on the flight characteristics and measurable physical quantities through the CRATE–CAMAC, is mounted on the rack *12*. A piece of information is processed immediately in flight. Initial and processed data are stored on a floppy disk. The sideboard *13* and the dark room *14* are the service elements.

CONTACT MEANS OF THE AICRAFT–LABORATORY

Meteorological system, gas analyzers, and aerosol complex are the contact means. Before the description of their specifications, let us dwell on the peculiarities of contact measurements from aboard the aircraft. This primarily concerns the correctness of air sampling for the analysis.

To avoid the distortion of the sample properties, the isokinetic condition[3] must be satisfied. It means that the speed of the airflow outside the sampling tube and at its input cross section must be equal, and this input cross section must be perpendicular to the flight direction.

As it has been mentioned above, the draught of the air through the device is provided by the velocity head appearing in flight due to difference in the action of this mechanism (Fig. 2). Theoretical substantiation of this approach was presented in Ref. 4. The sampler shown in Fig. 2 operates in the following way. An airflow passes through the nozzle *1*, supply tube *2*, filter *4*, and gas counter *5*. Then it is thrown overboard through the Venturi tube (diffuser) *6*. The shutter *3* cuts off both input and output airflows when changing filters, thereby keeping the tightness of the cabin (figure *7* denotes the aircraft covering).

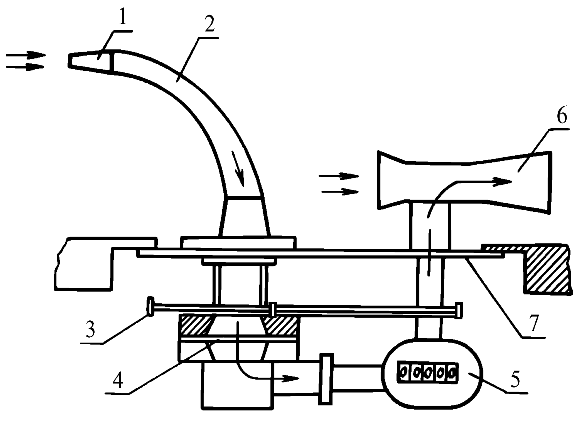

FIG. 2.

According to Ref. 4, for this arrangement of the airduct the isokinetic condition, when it is satisfied at the input of the nozzle *1*, will be preserved in the case of variations of the altitude and speed of flight over a wide ranges. As our operating experience onboard the IL–14 aircraft showed, for the produced and mounted air–duct shown in Fig. 2 we must correctly select the input cross–sectional area of the nozzle *1* for the isokinetic condition to be fulfilled. We have done this job during several flights. The nozzles with different cross sections were selected by the rules given in Ref. 5. For air sampling one should use a thin–walled tube which satisfies the following requirements: the ratio of the external diameter to the inner one is no more than 1.1 %, or, if it is sharpened at the angle $\le 15^{\circ}$, the thickness of its leading edges should be less than 5% of its inner diameter.

The design of all the air ducts for the contact means follows the same pattern. In addition, the distorting effects can appear in the samplers for aerosol investigation due to the sedimentation of particles in the communications. The formula for taking these effects into account was proposed in Ref. 6

$$M/M_0 = (1 - \alpha)(V/V_0) + \alpha ,$$

where M is the mass of a particle which enters the sampler with the speed V, M_0 is the mass of the particle with the speed V_0, and α is given by the relation

$$\alpha = [1 - \exp(L/d)]/(L/d) .$$

Here L is the distance from the end of the sampler to the place, where the bends appear due to nonisokinetic passage of the gas flow, d is the distance at the end of which particle comes to rest and is given by the relation

$$d = \rho V_0 D^2/18\mu.$$

Here ρ is the density of particle, D is its diameter, and μ is the gas viscosity. From the above reasoning the curvature radius of the supply tubes *2* (Fig. 2) was calculated from the condition that the particles whose size is ≤ 100 μm passed without sedimentation on the communications. The calculated results were taken into account in the design of the input part of the air samplers.

Since the contact means used onboard the aircraft–laboratory are described in detail in Ref. 2, we will only briefly describe them.

The meteorological system was destined to measure the vertical profiles of meteorological parameters and their values along the flight line in real time. Air temperature and its fluctuations were measured by resistance thermometers, humidity was measured by the sensor taken from a MARZ radiosonde, pressure was measured by a DD–15 aircraft sensor. Wind velocity was calculated from the data of a Doppler drift velocity indicator (DDVI) and from the navigation characteristics. The measuring ranges and the errors are presented in Table I.

TABLE I. Physical characteristics of the air measured by contact means of the "OPTIK–É" AN–30 aircraft–laboratory.

Parameter	Range or threshold	Error
Air temperature	–70°C...50°C	±0.5°C
Air humidity	10...100%	±5...7%
Air pressure	800..200 mm Hg	±1 mm Hg
Wind speed	0...300 km/h	±10 km/h
Wind direction	0...360°	±10°
Aerosol number density ($r \ge 0.2$ μm)	0...300 cm^{-3}	±20%
Particle size distribution	12 parallel channels	–
Aerosol mass concentration	0.01...2000mg/m^3	±25%
Aerosol scattering coefficient	0.001...1 km^{-1}	±10%
Wavelengths	0.42, 0.52, 0.61 μm	–
Content of volative components in aerosol particles in the range of temperatures	10...400°C	±1°C
Ozone concentration	2...500 μg/m^3	±10%
Carbon oxide concentration	1..100 ppm	±5%
Carbon doixide concentration	10...1000 ppm	±10%
γ – background	1...1000 μR/h	±20%

The aerosol complex was destined to determine microphysical and optical characteristics of the atmospheric aerosol, its mass concentration, and chemical composition. All the characteristics, excluding the chemical composition, were obtained in real time. Chemical composition and mass concentration were determined in the laboratory after the flight. The following ions: F^-, NH_4^+, NO^-, SO_4^{2-}, Cl^-, Na^+, K^+, Cd^{2+}, and As^{5+} and the following elements: Al, Co, Cr, Mo, Ni, Ti, Zn, B, Si, Ag, Ba, Br, Cu, Pb, Sn, V, Mn, Mg, Fe, Ga, W, Ca, Hg, Sb, In, and Be are identified in the aerosol composition.

An AZ–5 photoelectric counter, or more exactly, its optical head, modernized taking into account the recommendations of Ref. 7, was used for determining the particle number density. Since its electric part was developed for successive measurements of the particle size spectrum, it was replaced by the parallel spectrum analyzer. The analyzer was made in CAMAC and set in CRATE of the central recording system. Particle size distribution was measured in the same ranges as in the AZ–5 counter.

The optical aerosol characteristics were determined by means of a FAN photoelectric nephelometer equipped with the devices of thermo– and hygro–optics. Block diagram of the nephelometric complex is shown in Fig. 3. The complex is capable of measuring the coefficient of aerosol scattering at an angle of 45° and three wavelengths (0.42, 0.52, and 0.61 μm), the degree of polarization at the same wavelengths at an angle of 90°, the content of the volatile components in the atmospheric aerosol particles in the temperature range 10...400°C, and the variations of the optical properties of the particles due to their moistening in the range 10...100%.

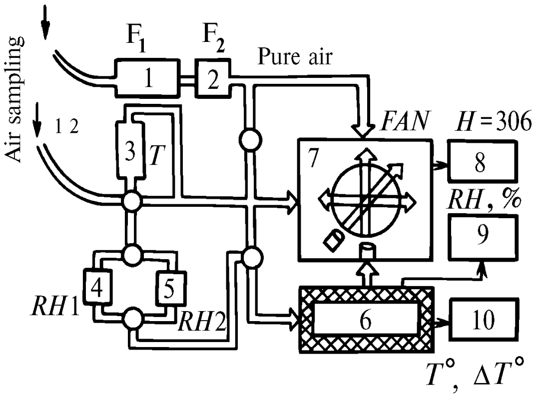

FIG. 3. Nephelometer with thermo– and hygro–optical devices: 1) filter of coarse purification, 2) filter of fine purification, 3) heater, 4) and 5) humidifiers, 6) stabilization chamber, 7) FAN nephelometer, 8) recorder, 9) hygrometer, and 10) thermometer.

The aerosol complex included also the filter–ventilator consisting of three identical devices. The diagram of one of the devices is shown in Fig. 2. They were destined for concentration of the aerosol on the AFA–VP (HA or HP)–20 filters and provided the airflow rate through them in the range 100–250 l/min.

The principal parameters measured by the aerosol complex are presented in Table I. The method employed is described in detail in Ref. 2.

Gas analysis complex was destined for determination of the concentration of the gaseous components of the pollutants.

Taking into account a variety of gases of interest for ecological monitoring, we overvelmingly employed the technique of sampling into the containers onboard the aircraft–laboratory with subsequent gas chromatography analysis. This makes it possible not only to increase the number of recorded components, but also to raise the upper threshold of their determination. By the way, the majority of foreign aircraft–laboratories follow the same pattern.[8–10] Only ozone and carbon oxide and dioxide were measured immediately onboard the aircraft by means of chemiluminiscent and opto–acoustic analyzers. Ammonium, acetylene, acetone, benzine, benzol, xylone, nitrogen oxide and dioxide, sulphur dioxide, toluene, hydrogen sulphide, and chlorine were determined in the containers by means of the gas chromatograph. Techniques for increasing the number of recorded gases are being devised.

REMOTE MEASUREMENT MEANS

Both active and passive remote means were available onboard the "OPTIK–E" AN–30 aircraft–laboratory. The active means included the "MAKREL'–2" lidar and the passive ones – the spectrophotometer operating in the visible and near–UV ranges and the radiometer receiving the radiation in the 8–15 μm band.

By virtue of the fact that they were modernized only slightly in going from the IL–14 aircraft to the AN–30 aircraft and were described in detail in Ref. 2, let us only recall their specifications here.

The "MAKREL'–2" lidar was destined for investigation of atmospheric aerosol, clouds, upper layer of water, and underlying surface. When sounding clouds, it was capable of measuring the distance from them, their optical depth, and their phase state. In studies of industrial emissions, the lidar determined the aerosol optical scattering coefficient depending on the aerosol mass concentration and asphericity of particles. When sounding the upper layer of water, the lidar measured the extinction coefficient (turbidity), identified the presence of optical anomalies in the water column (hydrosol and plankton), and measured the height of the wind–driven waves (≥ 0.4 m) and the laser–induced luminescence.

The "MAKREL'–2" lidar has the following specifications:

working wavelength of the laser	532 nm
transmitted pulse energy	50 mJ
pulse duration	15 ns
beam divergence	1 mrad
diameter of the receiving lens	0.15 m
angle of the field of view of the receiver	1.3 ...13mrad
center of the band of the luminescence reception	680 nm
bandwidth of the interference filters	3 nm
depth of sounding of water	2 ... 30 m
depth resolution	2.2 m
measuring range of water extinction coefficient	0.1–0.5 m^{-1}±20%
depth of sounding of clouds	50...300 m
scattering coefficient of clouds	0.005–0.07 m^{-1}±20%
aerosol mass concentration	17–1700 μg/m^3±20%

The spectrometer and the radiometer are destined for record of the spatial–angular components of the upwelling radiation of the "atmosphere–underlying surface" system taking into account the current angular position of the aircraft. The data can be used for determining the background characteristics of the ground–based objects and IR radiation fields of the underlying surface, reconstructing the optical depth, the vertical transparency of the atmosphere, and the radiant temperature of the underlying surface.

The spectrometer has the following specifications:

light diameter of the lens	0.2 m
focal length	0.4 m
angle of the field of view	0.4°
rate of angular scanning	0–20°/s
range of scanning in the elevation angle	0–90°
working wavelengths (half–bandwidth of the filter)	400(0.008)
	0.487(0.006)
	0.551(0.008)
	0.630(0.008)
	0.670(0.008)
	1.060(0.015)
	1.221(0.016)
	1.620(0.020) μm

Radiometer has the following specifications:

light diameter of the lens	28 mm
focal length	56 mm
angle of the field of view	1°
working wavelength range	8–15 μm
center of the band (halfwidth) of the light filters	
	8.1(0.22)
	9.1(0.24)
	10.2(0.24)
	12.1(0.48)
	14.8(0.56)μm
rate of angular scanning	0...20°/s
angle of scanning	0–90°
range of measurable radiant temperatures	250–320 K
temperature threshold sensitivity	0.2 K
time constant	1 s

RECORDING SYSTEMS

They were assembled from the elements produced by national industry. The principal component of each of three systems was a DVK–2M microcomputer. All systems were stand–alone. The first was destined to service the "MAKREL'–2" lidar, the second maintained in operation the spectrophotometer and the radiometer, and the third was a multiaccess system. A meteorological system, aerosol and gas analysis complexes, sensors of navigation parameters, and sensor of γ–background were connected with it through the CRATE–CAMAC.

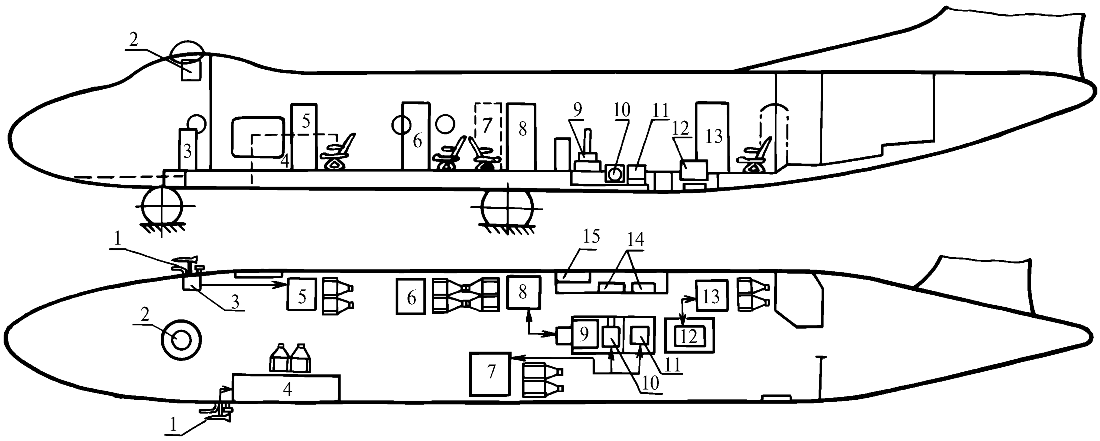

FIG. 4. Arrangement of instrumentation onboard the "OPTIK–É" AN–30 aircraft–laboratory: 1) units of air samplers and sensors, 2) solar spectrophotometer, 3) rack of preliminary transformes of gas and aerosol complex, 4) chromatograph, 5) nephelometric complex, 6) central computer, 7) recording instrumentation of the spectrophotometric complex, 8) recording system of the lidar, 9) lidar, 10) spectrophotometer, 11) radiometer, 12) thermal imager, 13) recording system of the thermal imager, 14) electric dashboard, and 15) navigation complex.

A number of ecological inspections of several cities and regions, such as Kamchatka, Baikal Lake, Buryat, Niznii Tagil, Nizhnevartovsk, Pavlodar, Ust'–Kamenogorsk, Khabarovsk, Komsomolsk–on–the Amur, and Ulan–Ude, have been carried out aboard the "OPTIK–É" AN–30 aircraft–laboratory for three years. The "OPTIK–É" AN–30 aircraft–laboratory was rewarded with gold and two silver medals of the pavilion "Protection of Nature" of the Exibition of National Economic Achievement of the USSR.

In addition, the experience of operation of the aircraft–laboratory revealed a number of drawbacks in its application. For this reason in 1990 we decided to modernize it. Its specifications have been improved, and the number of measurable parameters has been increased.

A dew–point hygrometer and thermodynamic complex destined to measure the wind velocity along three coordinates and temperature fluctuations along three directions with the sampling frequency up to 100 Hz were included into the meteorological system. A diffuse aerosol spectrometer (DAS) aimed at expanding the range of measurement of the dispersed composition (3...200 nm) and multiangular nephelometer capable of recording the aerosol scattering matrix were included into the aerosol complex.

A solar spectrophotometer for determining the total content of gas pollutant in the atmospheric column was included into the gas analysis complex.

An HPM–4 gas chromatograph for the in–flight analysis was used onboard the aircraft.

A new lidar combining the advantages of the previous ones was developed taking into account the experience of operation of the "MAKREL'–2" and "SVETOZAR" airborne lidars. It included the Raman channel for determining the concentration of polluttants in the emissions of enterprises.

The optical and mechanical units of the spectrometer and the radiometer were modernized in order to image the underlying surface in different wavelength ranges. In addition, a TV–03 thermal imager for monitoring of thermal polluttants was included into the aircraft–laboratory instrumentation.

The recording systems were also modernized. The IBM PC/AT–286 series computers integrated in the ARCNET local network with the IBM PC/AT–386 central computer became a principal element of the recording system.

The NAVSTAR navigation system is target for use onboard the aircraft in order to improve the geodetic tie of the data.

The introduction of the additional instrumentation in the "OPTIK–É" AN–30 aircraft–laboratory called for replanning the arrangement of the devices in the cabin. This job was done in 1991 in collaboration with the O.K. Antonov Design Bureau.

A new variant of arrangement of instrumentation in the "OPTIK–ÉM" modernized AN–30 aircraft–laboratory is shown in Fig. 4. This figure does not require any comments.

In conclusion we list the operations of the "OPTIK–ÉM" modernized AN–30 aircraft–laboratory. Among these are:

– investigation of regional and transboundary transfer of gas and aerosol air polluttants;

– monitoring of urban polluttants with their bridging to the enterprises, studying the scattering of polluttants and the areal of their spreading around the city, and calculating the budget of urban polluttants;

– ecological examination of regions;

– measuring the thermal air pollution;

– monitoring of gas and petroleum products in the atmosphere;

– determining the radiant temperature of the underlying surface;

– sounding of the ocean surface including the determination of the turbidity of the upper 30–m layer, the presence of chlorophyll in it, the presence of discharges of polluttants into water, the film of petroleum products on the water surface and its thickness, and the measurement of the bottom depth of shallows; and,

– sounding of the forest areas including the measurement of the height of the trees and study of the spectral albedo of the forest in order to identify the areas of plant diseases.

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