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Central Eurasia: Earth Sciences

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SCIENCE & TECHNOLOGY

CENTRAL EURASIA: EARTH SCIENCES

CONTENTS

Oceanic Acoustic Research

927N0029A Moscow ZEMLYA I VSELENNAYA in Russian No 4, Jul-Aug 91 pp 58-63

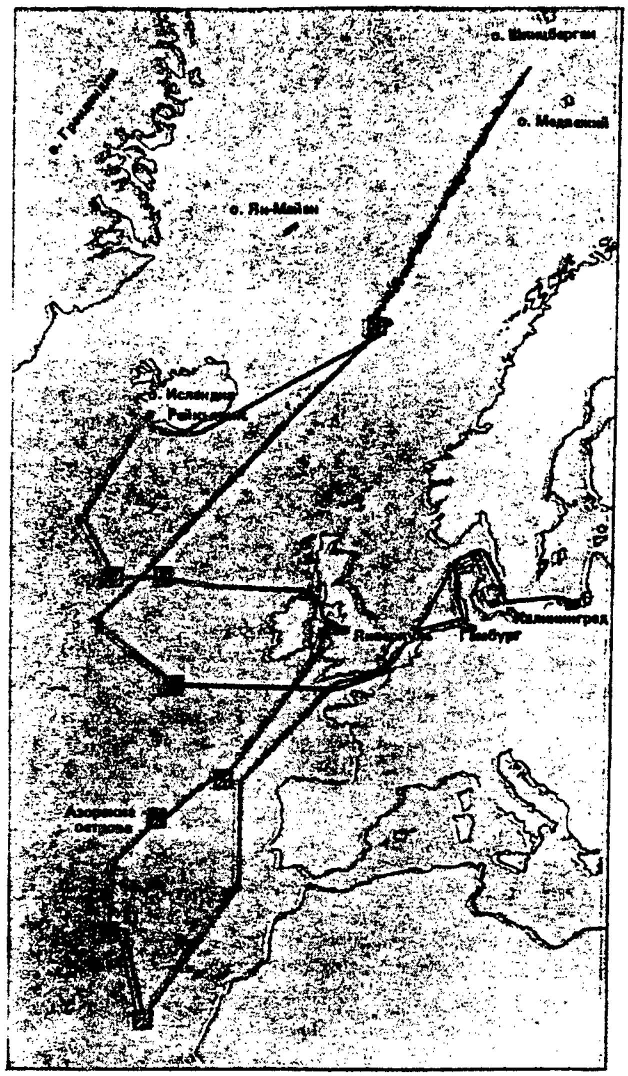
[Article by A. G. Voronovich, doctor of physical and mathematical sciences, Oceanology Institute imeni P. P. Shirshov, USSR Academy of Sciences]

[Text] New Scientific Research Ships

An expedition to the North Atlantic was carried out in March-July 1990 on two scientific research ships of the Oceanology Institute, USSR Academy of Sciences, the Akademik Sergey Vavilov and the Akademik Ioffe. The objective of the expedition was acoustic research in the ocean. But before telling of the expedition, we will familiarize the reader with these two ships, which were added to the scientific fleet of the USSR Academy of Sciences in 1988-1989. Constructed in the yards of the Finnish Hollming Company, these twin ships with a displacement of 6600 tons were each intended for oceanic research, primarily by acoustic methods.

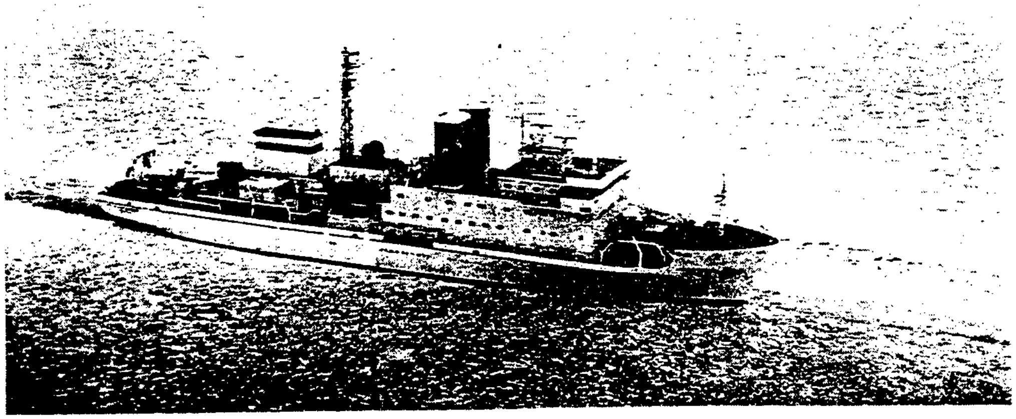
It is well known that acoustic waves in the ocean are in actuality the only presently known type of radiation which can be propagated in the water for great distances without significant absorption (ZEMLYA I VSELENNAYA, No 5, p 3, 1990 -- Editor's note). However, many purely hydrodynamic waves, such as surface gravity waves, have the same property, but it is virtually impossible to transmit information using them. In navigation use has long been made of the echo sounder, an entirely ordinary standard hydroacoustic instrument. The arsenal of scientific acoustic equipment is now being rapidly supplemented by new types of instruments and the technical specifications of traditional instruments are being sharply improved. It would probably be no exaggeration to say that practical civil hydroacoustics is now undergoing a boom due to the new capabilities of electronics and especially computer technology. Their broad use in hydroacoustics is related to the fact that the characteristic frequencies of acoustic signals are usually not greater than a few KHz, but since the speed of computations by modern computers is hundreds of thousands and millions of operations per second, computers are able to carry out complex processing of acoustic signals directly in the course of their receipt.

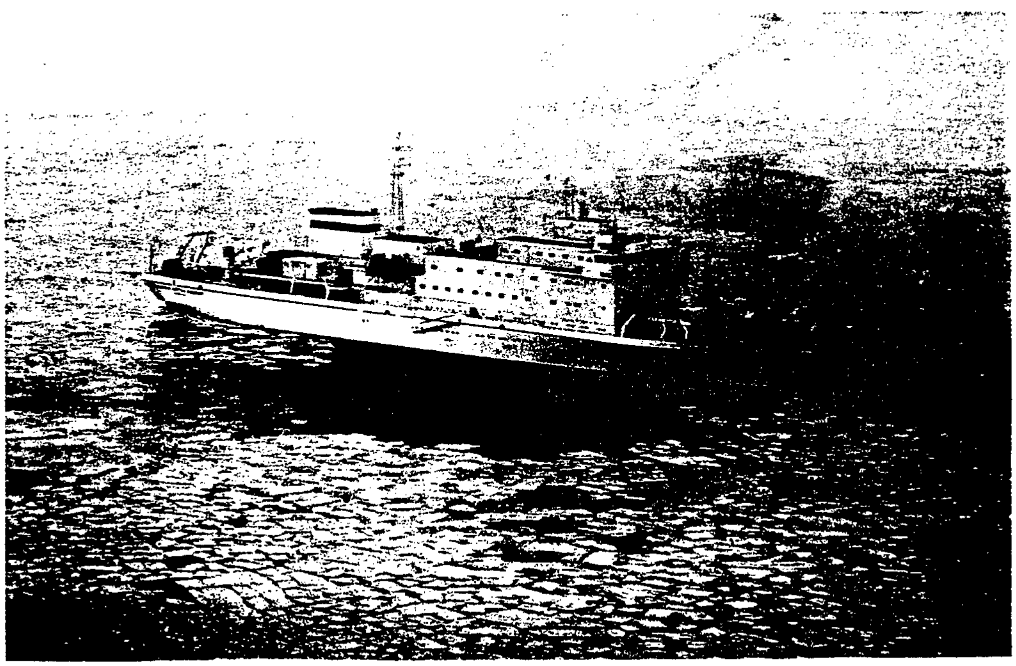
The ships Akademik Sergey Vavilov and Akademik Ioffe are outfitted with more than a dozen computers, connected into an integrated network. Among them there are both specialized computers, used, for example, in reception and processing of satellite information, and general-purpose computers employed for the collection of information, all kinds of scientific computations and numerical simulation. On the ship Akademik Sergey Vavilov acoustic information is assimilated by means of a "fast collection" system supplied with high-productivity processors (it differs considerably from a "slow collection" system intended for the accumulation and processing of standard oceanological information -- data on the vertical profiles of temperature and salinity obtained using STD probes measuring salinity, temperature and pressure, meteorological information, etc.).



Expedition track. The squares represent test ranges within which research was carried out.

Due to the use of computers there has been a substantial change in the very appearance of hydroacoustic experiments. Whereas earlier an analog magnetic recorder was "No 1" in any experiment, it now dominates only in self-contained measuring instruments, such as bottom stations.





Scientific research ships Akademik Sergey Vavilov and Akademik Ioffe.

We will enumerate only some of the hydroacoustic systems carried aboard the Akademik Sergey Vavilov ship. These include, first, a multiray echo sounder which draws a picture of the sea floor in a strip with a width of two ocean depths (other than the multiray echo sounder, a relatively new instrument, the ship carries a family of traditional echo sounders and sonars). Second, the "Parasaund" parametric echo sounder, capable of creating a pencil beam of low-frequency radiation which can penetrate many tens of meters into the depth of sedimentary bottom layers. By using a Doppler current meter it is possible to determine the vertical profile of currents to depths of about 500 m. And finally, we will mention a special hydrophone array which is installed in the bottom of the ship and can perform the function of a singular retina of the "acoustic eye."

When experiments are carried out constant use is made of information obtained from a station for the reception of satellite data, an automatic weather station, STD probes, etc. Both these and many other measuring systems -- their simple listing would take up more than one page -- are connected to the shipboard computer network. The measurement results are stored in data banks in the ship's computer center, but some of these data are constantly displayed in laboratory rooms on television monitors.

We see that the research capabilities of "acoustic" ships are extremely great: many experiments can be carried out simply using their standard equipment. Nevertheless, scientists are constantly developing, testing and using new instruments in research.

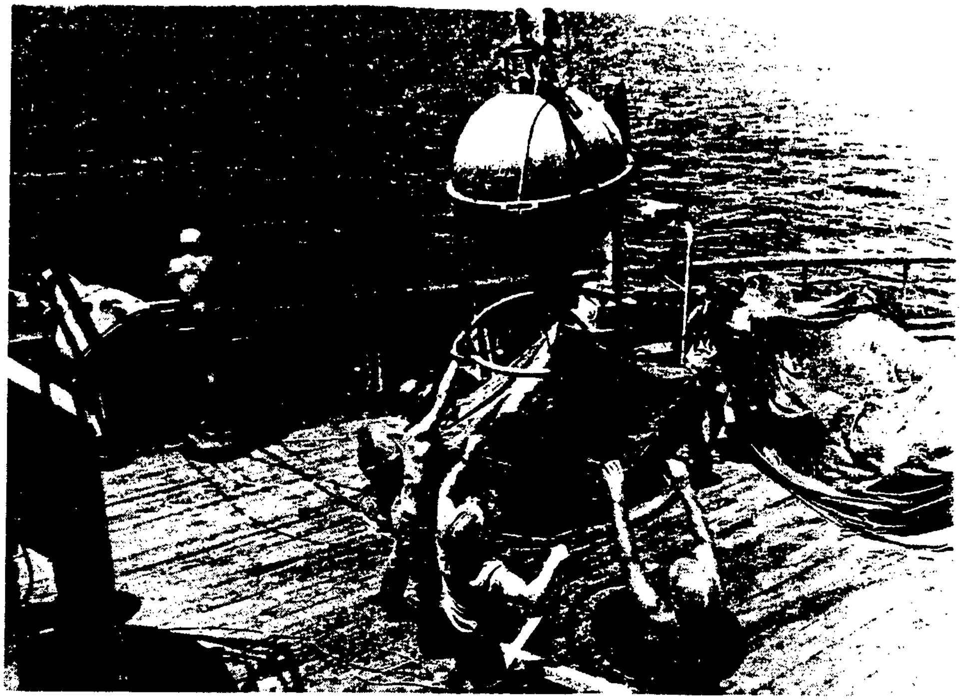
Experiments

The expedition began on 29 March 1990 with the departure of the ships from Kaliningrad. Although both ships operated under independent programs (the research test ranges were located from the western coast of Africa to ocean areas lying to the south of Spitsbergen), for about a month joint experiments were carried out with the participation of both ships.

The natural noise of the ocean was measured in the first series of these experiments. The cracking and clicking, gurgling and "heavy breathing" which can be heard with lowering of a hydrophone (the most widely used pickup of acoustic signals) is still not the natural noise of the ocean. During its registry interference is generated by noise from the ship, whose auxiliary motors operate even at the time of drift, as well as inevitable tuggings of the cable connecting the measuring hydrophone and the ship (these tuggings are due to the constant rolling of the ship). The cable tuggings result in noise from streamline flow around the hydrophone. Naturally, in many cases the noise may be the noise of a motor and therefore on the ship Akademik Sergey Vavilov in order to supply power to systems there is a special noise-suppressed generator which is insulated to the greatest degree possible from the hull. There also are definite methods for contending with the noise of streamline flow around the hydrophones, although it is impossible to be entirely free of it.

A radical method for avoiding these difficulties is the use of a self-contained (not connected to the ship) instrument. For example, the atomic bottom stations developed at the Oceanology Institute, USSR Academy of Sciences, serve as such a device. They are lowered to the bottom, operate in conformity to a stipulated program, and finally, by releasing ballast, float up to the surface.. Thereafter they send signals that they have surfaced, thereby assisting in their detection. In order to accomplish all this the self-contained bottom stations have a rather intricate "life support" system which together with a power source is situated within a sturdy spherical capsule capable of withstanding pressure at depths as great as 6000 meters. Within the sphere there also is a magnetic recorder which registers the received acoustic signals.

In the first variants of self-contained bottom stations the natural noise of the ocean was picked up by a single hydrophone. Later considerably more information began to be received by reception using an array extending tens of meters above or below the bottom station. The processing of these data makes it possible to compute noise directivity in the vertical plane.



Self-contained bottom station.

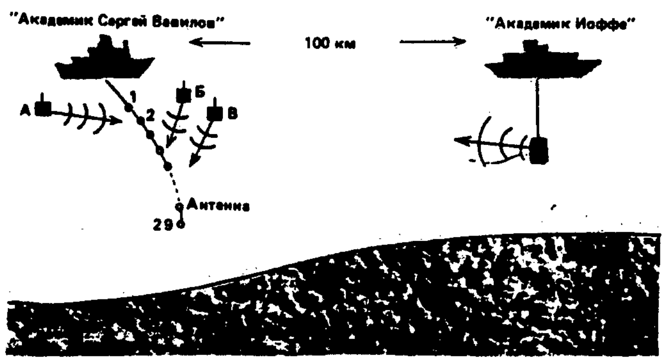
Why is the natural noise of the ocean studied? The initial interest in it was probably purely practical because the statistical characteristics of noise are among the principal initial parameters when developing hydroacoustic instruments. But as time passed it was learned that noise carries interesting information on the state of the ocean and even on the structure of sedimentary layers of the ocean floor. In any case it is necessary to study the noise sources, which are usually concentrated at the water surface; these are turbulent wind pulsations, surface waves and shipping. In addition, the formation of the noise field also is greatly influenced by sound propagation conditions because noise, especially low-frequency noise, arrives from enormous areas -- many hundreds of kilometers (we recall that sound is relatively slightly absorbed in sea water).

There are now two principal models of noise field formation: "stratified" and "unstratified." In the first, the ocean is considered horizontally homogeneous; in the second it is of fundamental importance to take its horizontal inhomogeneities into account. The "stratified" model predicts that on the axis of the underwater sound channel (the depth at which the speed of sound in sea water is minimal) the noise intensity should have a minimum.

The objective of one of the experiments in the first series was measurement of the directivity and level of oceanic noise at different depths, including on the axis of the underwater sound channel. We note that such experiments are extremely difficult and in the scientific literature there are only a few brief communications on such measurements. On our expedition for this purpose we used a controllable buoyancy buoy. Outwardly it is very similar to a self-contained bottom station, but in contrast to it there is a special device making possible precise regulation of system buoyancy. Since sea water density does not increase greatly with depth, it is possible to force a buoy with an array to "hover" at definite depths, in conformity to a stipulated program. A self-contained bottom station for measuring the "reference" noise level is positioned at the same time in the region of lowering of the buoy. These data make it possible to take the natural variability of noise into account.

Akademik Sergey Vavilov

Akademik Ioffe



Antenna array

Diagram of experiment in which a study was made of the distant propagation of sound. The extended vertical array consists of 29 detection modules. A, B, C -- emitters of acoustic pulses used in determining spatial configuration of array (with an accuracy to several meters).

KEY:

1. Akademik Sergey Vavilov
2. Akademik Ioffe
3. Array

The experimental results revealed that on the axis of the underwater sound channel, where the "stratified" model predicts a minimal sound intensity, in actuality a noise minimum is not observed, especially at low frequencies. Thus, one of the principal predictions of the "stratified" model is not justified. So that it must be admitted that horizontal inhomogeneities of the water layer exert a substantial influence on formation of the noise field in the ocean. One of the mechanisms of "cluttering" of the underwater sound channel may be, for example, the reflection of shipping noise by the shore slope; another possible cause may be the scattering of sound on internal waves in the ocean. In other words, any scattering process, changing the direction of sound propagation, may carry the noise radiated from the surface into the underwater sound channel.

As already mentioned, the noise received during an experiment by an array is registered by a magnetic recorder placed within a strong spherical capsule. But in this case the received signals are greatly distorted. Even an extremely small time shift between the two channels into which the record of different array hydrophones is divided considerably distorts the directional diagram of the measured noise field. How can this be avoided? A radical solution for this problem is as follows: a microcomputer can be placed within the housing of a self-contained bottom station and the arriving signals would be processed directly in the course of the experiment. In such a case the already averaged characteristics of the signals, whose volume is immeasurably smaller than the volume of the primary unaveraged data, are entered in the computer memory.

A copy of a self-contained bottom station of a new generation, having within it a microcomputer and with on-line signal processing, was tested during our expedition.

The next series of experiments carried out on the expedition was related to distant sound propagation (both ships participated in the experiments). In one of the experiments measurements were made of the vertical sections of the intensity of the sound field along a path 900 km in extent in the Norwegian Sea. The sound source was the standard emitter on the Akademik Ioffe and reception was aboard the Akademik Sergey Vavilov using the special "Triada" probe. The "emitting" ship was kept steady near one point, whereas the "receiving" ship withdrew from it along the intended path, heading for Spitsbergen. The theoretically computed and experimentally measured vertical profiles of sound intensity (in other words, the dependence of intensity on depth) were compared. The computations were made using special programs on a computer and the initial data for them were the vertical speed-of-sound profiles measured along the acoustic path. And although the profiles at different points on the path are similar to one another, there is nevertheless some difference between them.

In those cases when the difference can be neglected (the ocean is considered horizontally homogeneous), the sound field is computed relatively simply, using virtually finalized formulas. The sound field is represented in the form of the finite sum of so-called normal waves or modes (the parameters of normal waves are determined when solving some differential equation). However, when the oceanic medium is variable along the path numerical methods for computing sound fields will virtually always be approximate. The following conclusion can be drawn from these measurements: the accuracy in predicting the nature of the sound field in the ocean is dependent on the completeness of our information on the ocean medium. If the information is adequate, the sound field can be predicted with a high accuracy at extremely great distances.

Still another experiment with sound propagation which was carried out on the expedition seemed to us to be of fundamental importance. This was an attempt by a direct method to measure the parameters of normal waves, which was already mentioned. In principle such an experiment can be carried out using an extended vertical array. The number of hydrophones in such an array must not be less than the number of normal waves and the length must be about a kilometer in order for the array to be able to cover a considerable part of the oceanic waveguide. The difficulty of an experiment is that such an array cannot occupy a rigorously vertical spatial position; it will bend because the ship virtually always is subject to drift. It is necessary to control the position of the array in space with an accuracy to fractions of the wave length, that is, to several meters.

A special extended vertical array 560 m long (approximate height of the Ostankino television tower), supplied with a special acoustic system for control of its position in the ocean relative to a ship, was developed at the Oceanology Institute, USSR Academy of Sciences. The operating principle of the system is measurement of the time required for the propagation of short high-frequency acoustic pulses between special emitters and hydrophones of the array let out from the ship's side. In the course of the work we demonstrated that the mentioned high accuracy in monitoring the spatial position of the hydrophones can be attained under real conditions. Then using this array the modal composition of the sound field was measured, which, as before, was generated by the standard emitter on the Akademik Ioffe. The amplitudes of the measured modes approximately corresponded to those obtained from theoretical computations. We hope that the further development of such work will make it possible in the future to realize one of the variants of acoustic tomography of the ocean: research on its properties using acoustic signals.

The expedition ended on 11 July 1990 with arrival of the ships in Kaliningrad.

Cruises of Scientific Ships (July-December 1990)

927N0029B Moscow ZEMLYA I VSELENNAYA in Russian No 4, Jul-Aug 91 pp 64-67

[Unsigned]

[Text]

1. Akademik Kurchatov, Professor Shtokman (Oceanology Institute imeni P. P. Shirshov, USSR Academy of Sciences (OI)
Geographical region: Northwestern part of Atlantic Ocean
Expedition objective: Hydrophysics: study of role of energy-active zones in world ocean in short-period climatic changes, study of thermohydrodynamic, acoustic and optical properties of oceanic medium
Notes: "Atlanteks-90" (Atlantex-90), "Razrezy" (Cross Sections), "Front" (Front), "VOCE" (WOCE)

2. Akademik Ioffe (OI)
Geographical region: North Atlantic, Norwegian and Barents Seas
Expedition objective: Hydroacoustics: research on sound scattering and propagation in ocean, relationship between acoustic fields in ocean and characteristics of bottom and water layer
Notes: "Akustika" (Acoustics), "Diagnostika" (Diagnostics). Meetings with foreign scientists in ports of Dover, Liverpool and Kiel

3. Akademik Sergey Vavilov (OI)
Geographical region: North Atlantic, Norwegian Sea
Expedition objective: Hydroacoustics: research on oceanic noise under different geological-geophysical conditions, study of sound propagation on extended paths
Notes: "Akustika" (Acoustics)

4. Gidrobiolog (OI)
Geographical region: Black Sea, Sea of Azov
Expedition objective: Biology: measurement of flows of oxygen, biogenous elements and trace metals at water-bottom interface in river mouth sectors
Notes: Scientific contacts with Bulgarian scientists at Varna

5. Shelf (OI)
Geographical region: Baltic Sea
Expedition objective: Geology: study of sedimentary mantle; tracing of ancient shore levels and formations in southeastern Baltic

Notes: "Mirovoy okean" (World Ocean). Polish scientists in work of the expedition

6. Vityaz (OI)
Geographical region: Southeastern part of Atlantic Ocean
Expedition objective: Geology, geophysics, hydrobiology: multisided research on near-bottom layer in active geological-biochemical zones of ocean, evaluation of influence of bottom relief, marine biota and flows of matter in water-bottom system on its formation
Notes: "Pridonnaya okeanologiya" (Near-Bottom Oceanology). Scientific contacts with Namibian scientists at Luderitz

7. Akademik Mstislav Keldysh (OI)
Geographical region: Northern part of Pacific Ocean
Expedition objective: Hydrobiology: study of structure of biological associations in entire thickness of ocean, influence of active tectonovolcanic and hydrothermal activity on fauna and bottom ecosystems
Notes: "Ekosistema" (Ecosystem). American and Mexican scientists participated in expeditionary work.
Notes: "Ekosistema" (Ecosystem). American and Mexican scientists participated in the expedition

8. Akademik Kurchatov (OI)
Geographical region: Eastern part of Atlantic Ocean, northern and central parts of Pacific Ocean
Expedition objective: Hydrodynamics: study of oceanic eddies arising at junctures of differently directed currents, in frontal zones with current flowing around bottom irregularities and shoreline
Notes: "Mikrostruktura" (Microstructure). American scientists participated in the expedition

9. Akademik Sergey Vavilov (OI)
Geographical region: Northern part of Atlantic Ocean, Barents Sea
Expedition objective: Hydroacoustics, geology, geophysics: study of influence of inhomogeneity of water medium on variation of acoustic signals, research on sound backscattering by bottom, characteristics of fields in underwater sound channels
Notes: "Akustika" (Acoustics), "Diagnostika" (Diagnostics). Contacts with British, Icelandic and American scientists at Aberdeen, Reykjavik and Boston

10. Akademik Nikolay Strakhov (Geology Institute, USSR Academy of Sciences) (GI)
Geographical region: Equatorial Atlantic
Expedition objective: Geology, geophysics: multisided geological-geophysical research for detecting differences in development of riftogenic structures and transverse faults
Notes: "Mirovoy okean" (World Ocean), "Litos" (Lithos), "Sediment" (Sediment). West German, American and Israeli scientists participated in the expedition

11. Akademik Boris Petrov (Geochemistry and Analytical Chemistry Institute imeni V. I. Vernadskiy, USSR Academy of Sciences) (GACI)
Geographical region: Central part of Mediterranean, Barents, North and

Baltic Seas
Expedition objective: Hydrophysics: study of spatial-temporal variability of hydrophysical fields, study of interaction between medium parameters and characteristics of surface waves by radar methods
Notes: "Mikrostruktura" (Microstructure). Scientific contacts with Greek, West German and Swedish scientists in ports of Piraeus, Hamburg and Goteborg

12. Dalniye Zelentsy (Murmansk Marine Biological Institute, USSR Academy of Sciences (MMBI)
Geographical region: Barents, Norwegian, Greenland, North and Baltic Seas
Expedition objective: Ecology: study of influence of hydrological-hydrochemical regime on formation of structure of bacterio-, phyto- and zooplankton, research on dynamics of feeding of zooplankton
Notes: "Ekosistema" (Ecosystem). Polish scientists participated in the expedition

13. Pomor (MMBI)
Geographical region: Barents, Norwegian, Greenland, North and Baltic Seas
Expedition objective: Ecology, geophysics: study of modern genesis of sediments on coast of Spitsbergen, estimate of distance of transport of sedimentary material by icebergs and coastal shore ice
Notes: "Ekosistema." Polish scientists participated in the expedition

14. Zarya (Leningrad Division, Institute of Terrestrial Magnetism, Ionosphere and Radio Wave Propagation) (LO IZMIRAN)
Geographical region: Baltic Sea
Expedition objective: Geophysics: research on spatial-temporal structure of geomagnetic field, running of vectorial geomagnetic survey
Notes: "Baltika-magnit" (Baltic-Magnet). Scientific contacts with West German, Finnish and Sweden in ports of Helsinki and Stockholm

15. Arnold Veymer (Ecology and Marine Research Institute, Estonian Academy of Sciences) (EMRI)
Geographical region: Baltic Sea
Expedition objective: Hydrobiology, hydrophysics: research on optical and biological fields and hydrological characteristics of water masses during summer. Research on hydrophysical processes, study of their influence on chemical-biological fields
Notes: "Mirovoy okean" (World Ocean), "Baltika" (Baltic). Scientific contacts with West German scientists in Kiel

16. Akademik Vernadskiy (Marine Hydrophysics Institute, Ukrainian Academy of Sciences (MHI)
First geographical region: North, Central and Tropical parts of Atlantic
Expedition objective: Hydrology, hydrochemistry: research on circulation of waters, collection of data on parameters of hydrological and geochemical structures, interrelationships among them
Notes: "Kosmos" (Cosmos), "Razrezy" (Cross Sections). Scientific contacts with American scientists in Boston
Second geographic region: Western part of Tropical Atlantic

Expedition objective: Hydrodynamics, ecology: research on large-scale anomalies of thermal state of upper layer of ocean, analysis of mechanisms of meridional transport of heat, dynamics of fronts in ocean-atmosphere system
Notes: "Razrezy" (Cross Sections), "Kosmos" (Cosmos), "Mikrostruktura" (Microstructure), "Ekosistema" (Ecosystem).

17. Professor Kolesnikov (MHI)
Geographical region: Equatorial part of Atlantic Ocean
Expedition objective: Geology, hydrology: study of structure of sedimentary mantle to depths 80-100 m, types of bottom formations, conditions for genesis of sediments on shelf and at river mouths, bedrock in coastal exposures, their petrography, mineral composition
Notes: "Granitsa okean-kontinent" (Ocean-Continent Boundary). Guinean scientists participated in the expedition

18. Gidrooptik, Leda (MHI)
Geographical region: Eastern part of Mediterranean Sea
Expedition objective: Hydroacoustics: research on spatial structure of sound-scattering layers.
Notes: "Akustika" (Acoustics)

19. Mikhail Lomonosov (MHI)
First geographical region: Black Sea
Expedition objective: Geology, geochemistry: geological-geochemical investigation of canyons in regions of volcanism, their role in sediment- and ore-formation processes
Notes: "Chernoye more" (Black Sea)
Second geographical region: Tropical Atlantic
Expedition objective: Hydrophysics: research on large-scale oceanic circulation, mechanisms of formation of meridional heat flows and variability of frontal formations, fine structure of hydrological and hydrooptical fields
Notes: "Razrezy" (Cross Sections), "Mikrostruktura" (Microstructure). Scientific contacts with scientists of Istanbul University at Istanbul

20. Professor Vodyanitskiy (Biology of Southern Seas Institute, Ukrainian Academy of Sciences) (BSSI)
Geographical region: Eastern part of Tropical Atlantic, Black Sea
Expedition objective: Hydrobiology, hydrochemistry: in situ observations in different frontal zones, detection of relationship between dynamics of waters and bioproduction characteristics of associations and, accordingly, indices of abundance of plankton, fish and shellfish. Research on the hydrogen sulfide mechanism of waters
Notes: "Ekosistema" (Ecosystem)

21. Akademik Kovalevskiy (BSSI)
Geographical region: Black Sea
Expedition objective: Hydrobiology: study of frontogenesis, eddy formation, turbulence and diffusion processes, fine structure and circulation of waters processes. Evaluation of principal components of plankton associations, their evolution
Notes: "Chernoye more" (Black Sea), "Bioshelf" (Bioshelf). Contact with Bulgarian scientists at Varna

22. Akademik Aleksandr Vinogradov (Far Eastern Department, USSR Academy of Sciences) (FED)
First geographical region: Northern part of Pacific Ocean
Expedition objective: Hydrology, hydroacoustics, hydrochemistry: research on synoptic eddies and mesoscale inhomogeneities, collection of hydrological and hydrochemical data for research on climatic changes in subarctic waters, making of acoustic remote observations in upper layer of ocean.
Notes: "Front" (Front), "Vestpak" (Westpac), "VOCE" (WOCE), "Akustika" (Acoustics). Contacts with Canadian scientists at Vancouver
Second geographical region: Eastern part of Pacific Ocean
Expedition objective: Geology, geophysics: study of Earth's crust, mineralogical composition of basement and sedimentary mantle within limits of principal morphological elements
Notes: "Vestpak" (Westpac), "Granitsa kontinent-okean" (Continent-Ocean Boundary)

23. Akademik Aleksandr Nesmeyanov (FED)
Geographical region: Southwestern part of Pacific Ocean
Expedition objective: Geology, geophysics: multisided geological-geophysical study of structure, mineralogical composition, conditions for formation and evolution of arc-trench system and adjacent morphostructures
Notes: "Lotos" (Lotus), "Granitsa kontinent-okean" (Continent-Ocean Boundary), "Rudoobrazovaniye" (Ore Formation), "Sediment" (Sediment)

24. Akademik M. A. Lavrentyev (FED)
Geographical region: Eastern part of Indian Ocean, southwestern part of Pacific Ocean
Expedition objective: Hydrophysics, hydroacoustics: research on flux of cosmic muons at different depths in ocean, perfection of method for registry of cosmic particles. Use of acoustic methods for study of spatial structure of volume scattering field
Notes: "Dyumand" (DUMAND), "Akustika" (Acoustics), "Front" (Front), "Razrezy" (Cross Sections).

25. Professor Bogorov (FED)
First geographical region: East China. South China Seas, Northern part of Indian Ocean, Red, Mediterranean Seas
Expedition objective: Hydrobiology, ecology: evaluation of influence of anthropogenic impact on vital functioning of sea organisms, development of principles for monitoring of marine biota and fields of prediction of biological productivity under different anthropogenic impact
Notes: "Sreda" (Medium), "Abissal" (Abyssal), "Vestpak" (Westpac). Vietnamese, Egyptian and West German scientists participated in expedition. Participation at 21st International Conference on Cosmic Rays at Adelaide
Second geographical region: Southwestern part of Pacific Ocean, Sea of Japan
Expedition objective: Geology: seismic research on structure of lithosphere, study of structure of upper part of Earth's crust
Notes: "Geopol" (Geopol), "Vestpak" (Westpac), "Granitsa okean-kontinent" (Ocean-Continent Boundary). Japanese scientists participated

in the expedition.

26. Professor Gagarinskiy (FED)
Geographical region: Sea of Japan, South China Sea
Expedition objective: Geophysics, geology: study of gravity, magnetic and heat fields as a basis for solving problems in tectonics, magnetism and geological activity of marginal seas, long-range prediction of minerals
Notes: "Granitsa okean-kontinent" (Ocean-Continent Boundary), "Yuzhno-Kitayskoye More" (South China Sea). Vietnamese and Korean scientists participated in the expedition

27. Akademik Oparin (FED)
Geographical region: Indian, Pacific, Atlantic Oceans
Expedition objective: Hydrobiology, biochemistry: search for physiologically active substances and their biological sources for use as biochemical preparations and medicinals
Notes: "Mirovoy okean" (World Ocean). American and Australian scientists participated in expedition. Contacts with Spanish, Italian and Seychellian scientists in ports of Las Palmas, Trieste and Victoria

28. Vulkanolog (FED)
Geographical region: Pacific Ocean, Barents Sea
Expedition objective: Geology, geophysics: geological and geographical research in regions of abyssal drilling. Study of underwater volcanism and processes associated with it
Notes: "Vestpak" (Westpac), "TPI-Okean" (TPI-Ocean), "Granitsa okean-kontinent" (Ocean-Continent Boundary)

29. Morskoy geofizik (FED)
Geographical region: Pacific Ocean, South China Sea
Expedition objective: Geophysics, geology: research on structure of Earth's crust, nature of relief, magnetic, gravity and heat fields in Pacific Ocean transect zone
Notes: "Geotraverzy" (Geotraverses), "Geopol" (Geopol). American scientists participated in work of the expedition

Overview of Remote Sensing Methods

927N0042A Moscow ZEMLYA I VSELENNAYA in Russian No 6, Nov-Dec 91 pp 15-20

[Article by O. V. Kopelevich, doctor of physical and mathematical sciences, Oceanology Institute imeni P. P. Shirshov, USSR Academy of Sciences; "Light Assists in Studying the Ocean." The first paragraph is an introduction.]

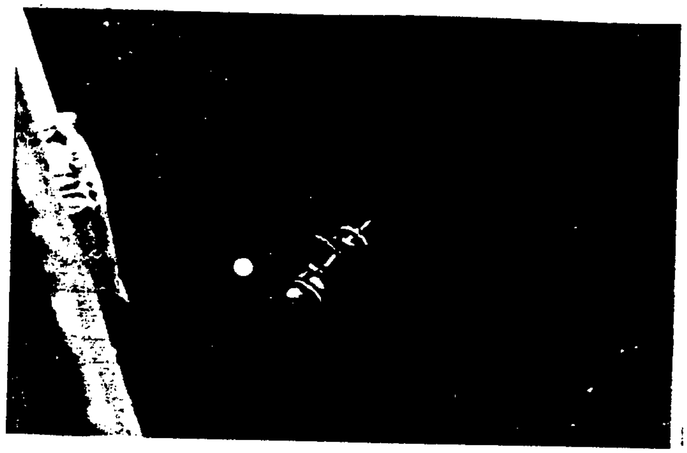
[Text] Man is penetrating increasingly deeper into the oceanic abyss, still cameras and motion picture cameras are being sent to these depths and TV cameras are being lowered beneath the water. In order to work with this highly complex equipment it is necessary to have a good knowledge of the optical characteristics of sea water and to understand the physical laws of light propagation in the sea. More than twenty years ago our journal published an article entitled "Light in the Sea" (ZEMLYA I VSELENNAYA, No 2, 1968) which familiarized the readers with the principles of a science which was only then gathering strength -- hydrooptics. Today hydrooptics has taken great strides forward. The article which follows tells of the modern stage in study of the ocean by means of light rays.

Advantages of Optical Measurements

The first attempts at using optical methods for studying the ocean were already undertaken at the beginning of the last century. Naturally, at that time reliance was solely on visual evaluations of phenomena. For example, the scales of the British hydrographer F. Beaufort (1805), and later, already at the beginning of our century, H. Douglas (1921), making it possible to estimate wind speed from the appearance of the sea surface, were used. The famed Russian navigator O. Ye. Kotzebue, during an expedition on the Ryurik in 1815-1818, was the first to estimate the transparency of sea water, lowering ordinary dishes on a cable over the ship's side and noting the depth of their disappearance from view. In 1865 the Italian astronomer A. Secchi made numerous observations of water transparency in the Mediterranean Sea with white and colored disks and the white disk ("Secchi disk") became solidly entrenched in practical oceanologic work. Until recently the Forel-Uhle scale was employed in evaluating sea color; this is a set of test tubes with solutions of different color for comparison with the apparent color of a water body. These methods afforded scientists the possibility of obtaining useful oceanologic information relatively easily.

But simplicity is by no means the sole merit of optical methods. In what way are they attractive for oceanology? First, the possibility for making measurements without "impact" on the medium; after all, the research tool is a light ray. To be sure, the light may cause some biological, chemical and physical changes in the water, but with a low intensity of the light radiation and a short time of the experiments these changes are negligible.

Optical methods also make it possible to make measurements without contact with the investigated medium, at a distance. (Light beams enter the water and emerge from it with small losses, whereas, for example, in the case of acoustic waves almost all the acoustic energy is reflected at the water-air interface.) Optical instruments measure the characteristics of the surface layer without submerging these instruments into the water: from aboard a ship, helicopter, aircraft or from satellites.



The "Gelios-Ye" instrument, an automatic instrument for measuring underwater irradiance, is lowered over the side.

An important merit of optical methods is that they are virtually without inertia. Measurements can be made continuously in time and space. The time resolution of such measurements is determined only by the parameters of the registry instrument and this makes it possible to investigate processes with frequencies on the order of tens and hundreds of Hz. A unique capability of optical methods is a high spatial resolution: in case of necessity a light beam is focused to a very tiny spot -- as small as 1 μm!

Optical methods yield a great volume of diverse information. They make it possible to register both the absolute strengths of the optical signals and the spectral angular dependencies, both the polarization characteristics and the dependence of the registered light pulse on time. All these characteristics together quite fully characterize the properties of the studied object.

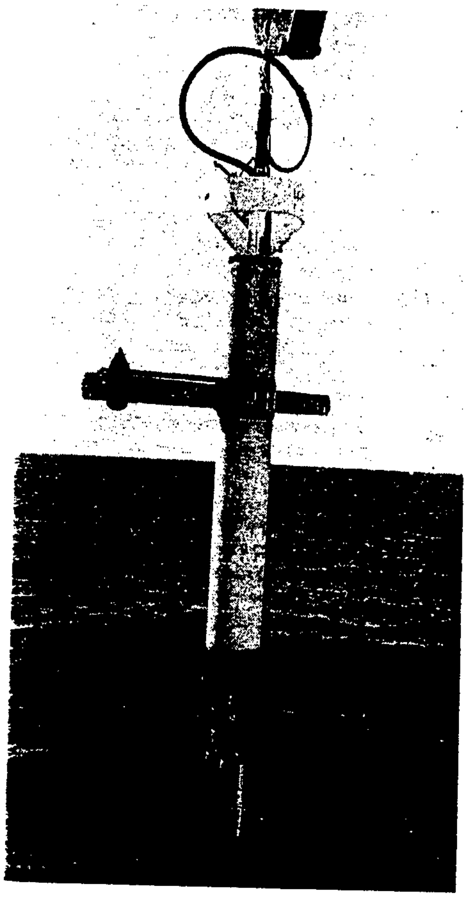
Analytic Methods

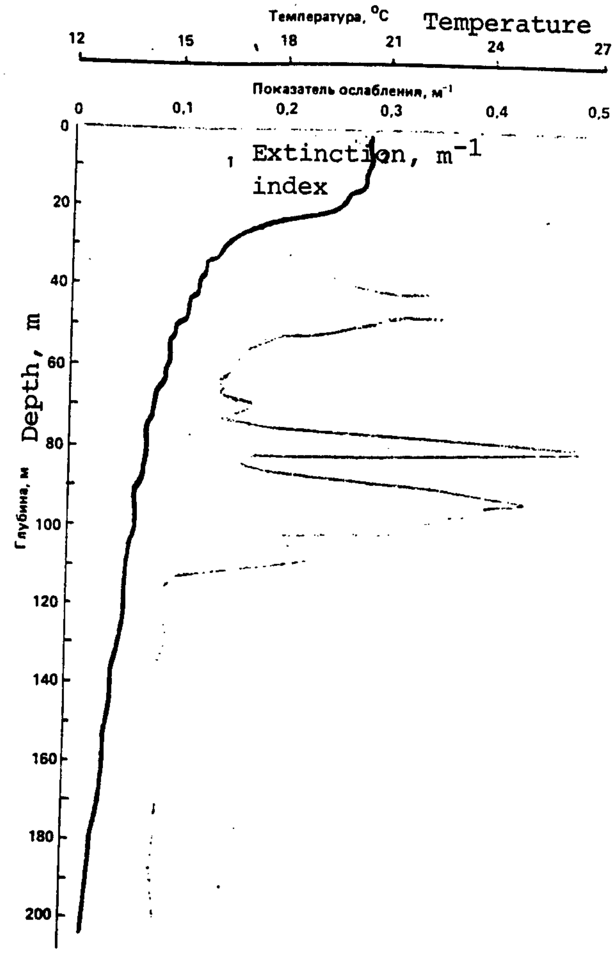
Optical measurements have long been used in biology, geology, chemistry and geochemistry of the ocean. Using these it is possible to study virtually any component of matter in sea water, but in many cases it is first necessary to prepare samples, concentrating or segregating the investigated component in order to attain the concentrations necessary for detection.

We will tell about methods which do not require such preparation in which the optical characteristics of the water itself are measured. Now optical methods have been developed for determining the concentration and distribution from the sizes of the particles suspended in sea water. Use is made of the measured characteristics of light scattering by sea water, particularly the scattering phase function, describing the dependence of the intensity of scattered light on the scattering angle. In order to find the size distribution of particles through the measured scattering phase function it is necessary to solve the "inverse problem" (it essentially involves solution of an integral equation). This is not a simple problem. It belongs to the class of "incorrect" problems (this term was introduced early in the century by the French mathematician J. Adamar for designating problems in which the inevitable small errors in initial data may lead to a considerable change in the answer -- a "swaying of the solution"). The well-known Leningrad physicist K. S. Shifrin proposed several productive methods for solving the inverse light scattering problem.

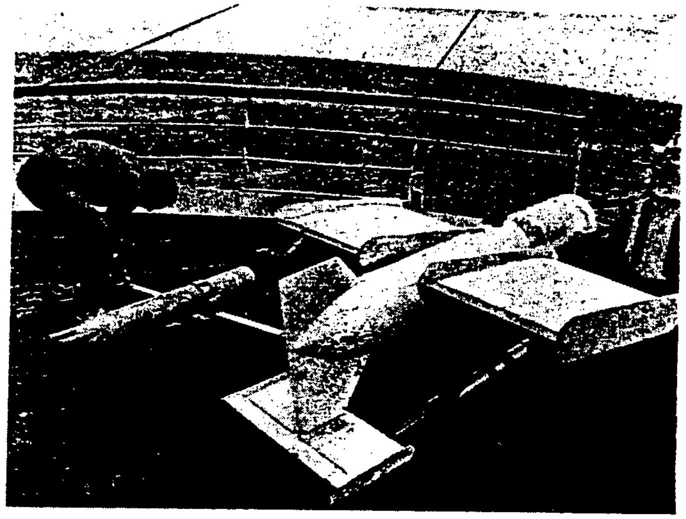
What is the advantage of measuring light scattering over traditional methods for counting particles of sea suspended matter which are used by geologists? First of all, the light scattering method makes it possible to estimate the number of fine particles measuring less than 1 μm which are not visible when using an ordinary microscope. They also cannot be detected with the Coulter counter employed in practical oceanology. Moreover, fine particles not only dominate in sea suspended matter with respect to quantity, but also make a substantial contribution to the volume and weight concentration. Still another advantage of the light scattering method is that here we are dealing directly with sea water, which need not be filtered first, and this means that we avoid the complications involved in filtering. It also is impossible not to note the great promise of the method: obtaining additional information on the polarization characteristics of scattering, which will make it possible to judge the material of the suspended particles, their configuration and internal structure.

The chlorophyll concentration and content of colored organic compounds (yellow substance) in sea water are estimated by optical methods. This is done by using the spectral dependence of the light absorption index of sea water. The method developed at the Oceanology Institute, USSR Academy of Sciences, makes it possible to determine the chlorophyll concentration with an accuracy to about 0.1 mg/m^3. We note that the accuracy is incomparably greater than in the tedious standard method for determining chlorophyll with filtering and extraction, which is not greater than several hundredths of a mg/m^3.





The "Delfin" transparency meter, an instrument for registry of the light extinction index in sea water. The vertical profiles of light extinction (1) and temperature (2) (expedition on the Akademik Kurchatov scientific research ship in the Mediterranean Sea in 1988) measured with the "Delfin" are shown at the right. Several peaks are shown on profile 1. These are thin light-scattering layers in which there is a sharp increase in light extinction (water transparency decreases sharply). Such layers are virtually undetectable on the basis of temperature measurements (profile 2).



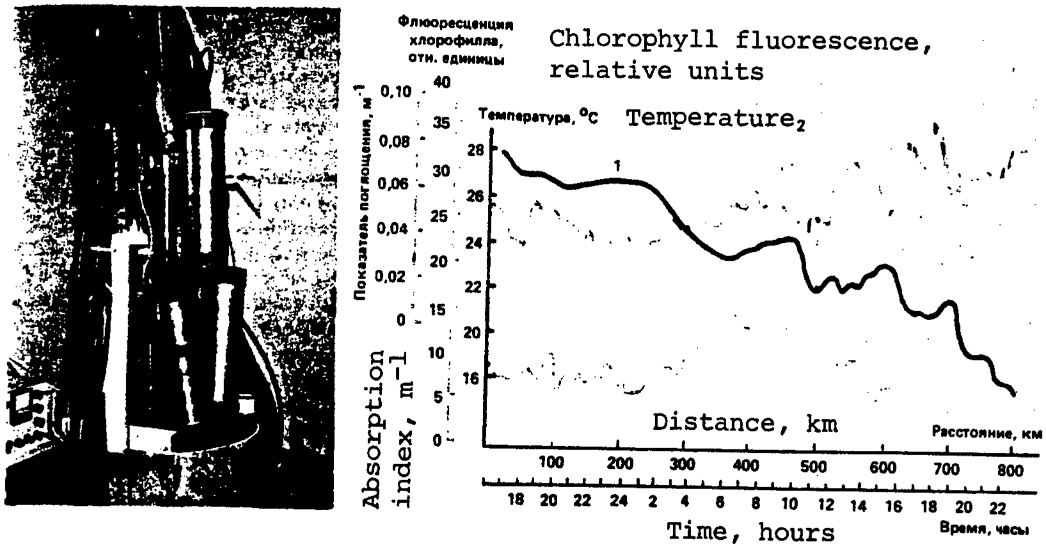
Controllable carrier (hydroplane) aboard scientific research ship. The "Delfin" is attached to it for use in a towing mode (the towing depth can be changed by command from a control panel located in the ship's laboratory).

Optical methods give particularly valuable information on the sea water content of yellow substance because it is extremely difficult to segregate it chemically. Moreover, optical data made possible a reliable estimate of the range of changes of yellow substance in oceanic and coastal waters, to establish that it is only a small part (several percent) of the total quantity of organic matter and is formed primarily in the ocean itself in an early stage in degradation of dissolved organic matter.

Research on Spatial-Temporal Variability

Optical measurements are now used particularly frequently for studying the content of different components of matter in the ocean, changing in space and time, and in the detection of hydrodynamic processes. Submersible and remote measuring instruments are used for this purpose.

Such information is difficult to obtain by standard biological or geological methods, making it possible to carry out measurements only at individual points. Continuous optical measurements are virtually the sole method for investigating the thin-layered stratification of the distribution of the concentration of suspended particles, phytoplankton and chlorophyll cells. Such a stratification, it was found, is frequently expressed rather sharply. Here is one of the results obtained using the submersible scattering measuring instrument, the "Poseydon" instrument, outfitted with a special bathometer-attachment (it is triggered by command from a control panel). In the central part of the Atlantic, in a water sample taken in the light-scattering layer at the



Shipboard lidar mounted in special shaft in bottom of hull of Dmitriy Mendeleyev research ship (the instrument was developed at the Oceanology Institute, USSR Academy of Sciences). Data obtained using this instrument in a section through the subequatorial front in the Eastern Atlantic are shown at the right: absorption index at a wavelength 532 nm (curve 3) and chlorophyll fluorescence at a wavelength 680 nm (curve 2). The temperature change at the horizon 6 m (curve 1) is shown as a comparison. Horizontal inhomogeneity is expressed best of all in a change in chlorophyll fluorescence. There are sharp peaks 5-30 km in width associated with cold fronts; they are evidently related to the local upwelling of cold waters enriched with biogenous elements.

horizon 113 m, a concentration of phytoplankton cells 3800 cells/liter was registered. However, at the standard horizon 100 m (difference 13 m) the concentration was only 7 cells/liter -- less by a factor of 540! The entire explanation here lies in the thin-layer stratification: the concentration changes sharply in a narrow depth range -- from one thin layer to the next.

It is interesting that in the light-scattering layers increased concentrations of biogenous elements also are detected: phosphorus, nitrogen and silicon, necessary for the development of phytoplankton. For example, a silicon concentration 2.1 μg-at/liter was registered in the central part of the Atlantic Ocean in a narrow light-scattering layer at a depth of 49 m, whereas at the standard horizon 50 m (a difference of only 1 m) it was about half as great -- 1.1 μg-at/liter.

Optical sensors are evidently the sole instrument for continuous registry of change in the content of matter both in time and in space. Such sensors can be set at stipulated horizons in the ocean and register these changes. True, during prolonged measurements, when self-contained instruments mounted on buoys are necessary, the problem arises of power supply to the instruments. In these cases, in place of instruments with power-consuming radiation sources it is feasible to use optical sensors registering natural solar radiation. A vertical string of such sensors, attached to a self-contained buoy, performs a time-continuous (true, only for a day) layer-by-layer "probing" of sea water. Such measurements yield information, first of all, on the matter on which is dependent the transmission of light radiation by the water layer, and second, on change on the light regime in the euphotic water layer (where primary production is formed in the photosynthesis process) and on the absorption of solar energy in the ocean. The latter is especially important for many problems related to model computations of energy exchange in the ocean, prediction of the thermal structure and dynamics of the near-surface layer. (Here it must be taken into account that solar energy is absorbed not only in the thin surface layer, but also lower -- to a depth of tens of meters.)

By studying the horizontal variability of the optical characteristics it is possible to detect in the ocean nonuniformities in the distribution of bioproductivity, to detect pollution, to map the propagation of fluvial sediments in sea water and to judge hydrodynamic processes in the water layer. In these cases towed instruments or flowthrough units are used in measurements from ships.

Remote Measuring Instruments

These are divided into passive and active. First we will tell about passive optical measuring instruments which register the solar radiation reflected from the sea surface and emanating from the water as a result of backscattering. The depth reached by the radiation is dependent on water turbidity and radiation wavelength; it may be tens of meters. The emanating radiation may carry information on the optical properties of the water layer through which it has passed, on the composition of the matter present in the water and on hydrodynamic processes. This information is present in the spectral composition of the emanating radiation, which determines the characteristic color of the sea, and also in its absolute brightness values.

The brightness of ascending radiation in the green and yellow spectral ranges is dependent primarily on the concentration of suspended matter. By registering it continuously, for example, from aboard a ship, it is possible to obtain a picture of hydrological fronts in the ocean and to investigate processes of mixing of different waters. Sometimes on the records of the radiation brightness coefficient, changing during the ship's movement, some periodic structure is traced which is associated with internal waves (ZEMLYA I VSELENNAYA, No 4, p 40, 1984 -- Editor). Its appearance is evidently attributable to the influence of internal waves on the vertical distribution of the optical characteristics or to interaction between the internal waves emerging at the surface and surface waves. The latter is clearly traced at the sea surface in the form of contrasting bands -- light bands, where smoothing of the waves occurs, and dark bands, where waves are being generated. On the basis of the characteristics of these bands it is possible to determine the parameters of the internal waves. Using optical apparatus specialists at the Applied Physics Institute, USSR Academy of Sciences (Nizhnyy Novgorod) were able to register interesting characteristics of the interaction between trains of internal waves and surface waves. For example, the presence of a "precursor" was discovered: an anomaly of surface waves already appears at the observation point prior to the arrival of a train of internal waves.

Laser Sounders - Lidars

Active methods for optical sounding of the ocean, where laser sounders - lidars [See Footnote 1] are used, have definite advantages over passive methods. They make it possible to work not only during the daytime, but also at twilight and at nighttime. It is true that for the time being lidars are not being used when making observations from space, whereas passive optical measuring instruments with their small power consumption are being successfully carried aboard satellites.

How does a lidar work? A short light pulse with a duration about 10 ns (10 billionths of a second) is transmitted from a powerful laser into the water. This light blob -- its length at the beginning of the path is a little more than 2 m -- being propagated in the water, is deformed, part of it is backscattered and returned. The backscattered pulse or echo signal is registered by a photodetector, positioned alongside the radiating laser, and is analyzed. Important information on the medium is provided, in particular, by the shape of the registered pulse, that is, the change in its power with time (the duration of the backscattered pulse is no longer tens of nanoseconds, as for the initial pulse, but hundreds of nanoseconds).

Several types of oceanologic lidars have now been developed. One of these, developed at the Oceanology Institute, USSR Academy of Sciences, makes it possible to determine the absorption indices of sea water, to judge the content of yellow substance in the layer 20-100 m, and also to estimate the chlorophyll concentration in a surface layer with a thickness of several meters.

In lidars of another type, designed in a shipboard variant at Moscow State University under the direction of V. V. Fadeyev and developed for an aerial carrier by the American specialists F. Hoge and R. Swift, the spectral composition of the backscattered pulse is registered. However, what does the spectrum look like if the initial pulse is monochromatic and its spectral width is only a fraction of a nanometer? Its appearance is governed primarily by the fluorescence of organic matter present in sea water, pigments of phytoplankton and petroleum pollutants. And the fluorescence characteristics provide useful information on the oceanic medium. Another reason for the appearance of the spectrum is scattering with a change in frequency, Raman and Mandelshtam-Brillouin scattering (the relative Raman scattering value is considered constant -- this is a singular internal reference point for the calibration of other echo signal components -- and this considerably increases the accuracy of this type of lidars).

At the Ecology and Marine Research Institute, Estonian Academy of Sciences, a fluorescent lidar has been developed in which the excitation spectrum, as well as the radiation spectrum, is registered. In order to be able to change the wavelength of the sounding radiation dye lasers with a tunable frequency are used here into which energy is "pumped" from a powerful ultraviolet laser.

A new type of lidar was recently developed at the Oceanology Institute, USSR Academy of Sciences. This is an airborne polarization lidar which makes it possible to determine the change in the light scattering index with depth, related to the vertical distribution of the concentration of suspended matter. The essence of the method, whose idea was proposed by A. P. Vasilkov, involves measurement of the polarization components of the backscattered pulse. Tests of this lidar from a helicopter were carried out over the Black Sea. The retrieved profiles of the scattering index were compared with profiles of the extinction index measured with a "Delfin" transparency meter. The comparison gave extremely similar results.

Lidars also are used in laser bathymetry, making it possible to determine the bottom profile in shallow waters. In transparent waters during the dark time of day and in calm weather by using a bathymetric lidar carried by an aerial carrier it is possible to determine the bottom profile at depths of several tens of meters (with an accuracy to 1 m).

Study of Sea Waves

This is still another field of applicability of optical methods in which measurements are made, in particular, of the high-frequency component of sea waves, including capillary waves (small waves arising under the influence of surface tension). Passive and optical methods are used here. Passive methods include photographing of the sun's track with a subsequent spectral analysis of the registered images. An optical spectrum analyzer, operating in coherent light, making it possible to evaluate the wave spectrum on an on-line basis without recourse to the processing of photographs, was developed at the Applied Physics Institute, USSR Academy of Sciences. Active methods make use of narrow beams generated by laser sources. One of such successfully operating instruments, measuring the distribution of sea surface elements from the radii of curvature in the range from 4 to 150 mm, was developed under the direction of V. N. Nosov.

Laser scanning outfits, intended for measuring the spectrum of sea surface rises, were developed at the Oceanology Institute and have already been installed aboard the new scientific research ships Akademik Sergey Vavilov and Akademik Ioffe. The outfit constitutes a laser rangefinder which measures the difference in the arrival times of laser pulses from the crests and troughs of waves and on that basis evaluates the amplitude of sea waves. The sensitivity of the method is on the order of several centimeters. However, its technical realization is by no means simple; it is necessary to overcome a great many difficulties related to stabilization of the laser beam sighting axis during the time of the ship's rolling, stray illumination and other external factors.

Due to the new, modern instruments developed during recent decades optical methods have firmly taken their place in practical oceanologic research.

FOOTNOTE

1. A lidar is a light sounder (The word LIDAR is an English abbreviation of the words Light Detection and Ranging).

Laser Monitoring of Atmosphere

927N0031A Moscow PRIRODA in Russian No 8, Aug 91 pp 24-33

[Article by V. Ye. Zuyev, academician, chairman Tomsk Scientific Center, Siberian Department, USSR Academy of Sciences, general director of Atmospheric Optics Institute Scientific-Technical Complex]

[Text] Man's industrial activity is exerting a strong impact on nature and is affecting an ever-increasing number of people on the planet. Simultaneously with this, in all countries of the world scientists are increasing their attention to ecological problems, among which a special place is occupied by ecological monitoring of the environment, and especially the atmosphere, the medium occupied by man.

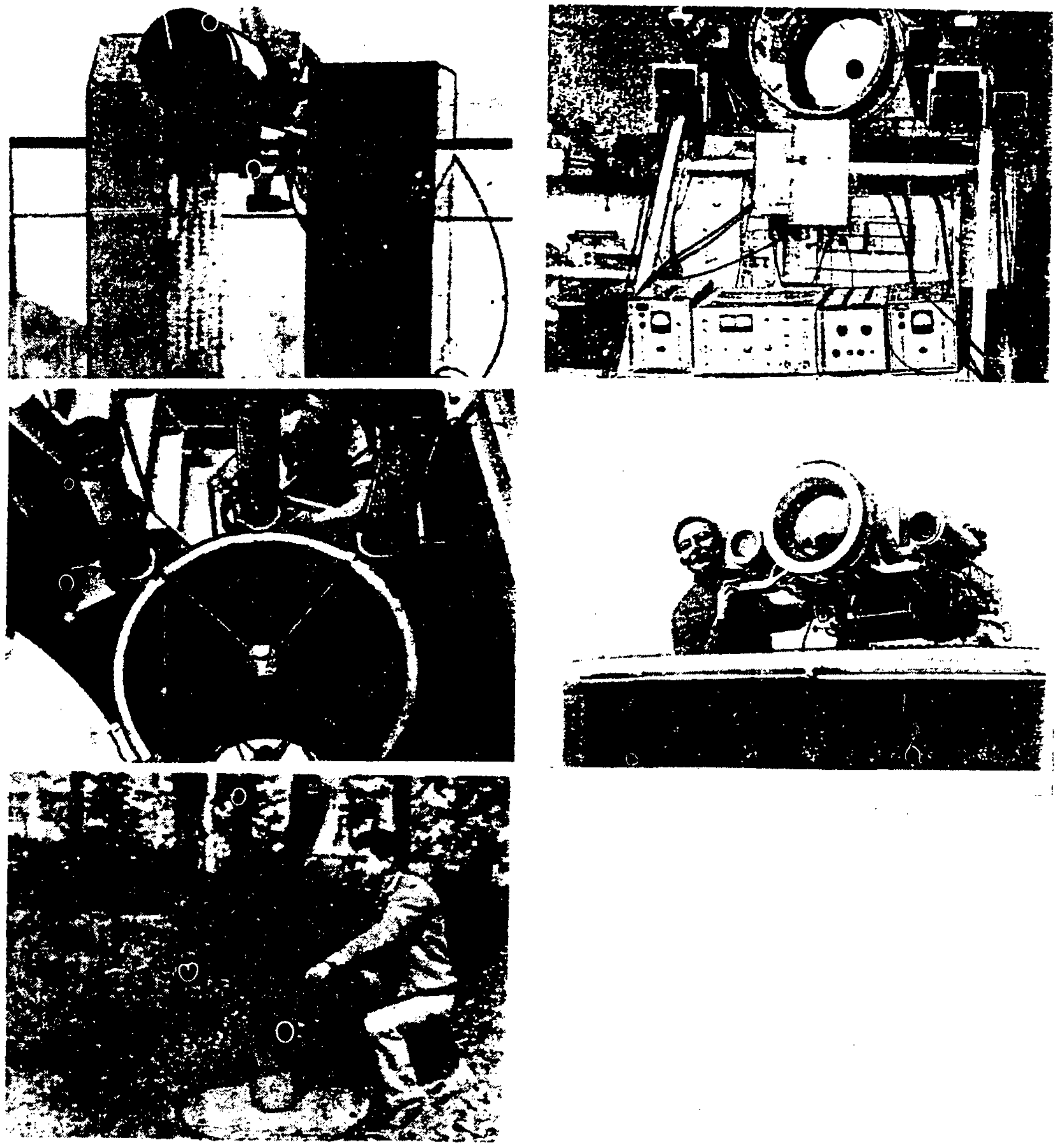
Among the presently known methods for remote sounding of the atmosphere it is the laser method which is indisputably superior. The possibilities of laser monitoring of components polluting the atmosphere are particularly great. It is scarcely possible to expect that in the next few years scientists will be able to develop reliable, economical, waste-free technologies for all types of large-scale production. It also is naive to expect that industrial development will turn back. This means that even now there is a need to think about how to decrease losses from harmful discharges into the atmosphere to the maximal degree possible.

This requires a detailed knowledge of the real processes occurring in the atmosphere, the nature and characteristics of migration of pollutants there. And the methods for laser remote sounding of atmospheric parameters from the ground, ships, aircraft, and especially from space, have no worthy competitors in solving such problems.

Laser Monitoring Method

Laser radiation, propagating in the atmosphere, experiences a great many transformations. The energy of this radiation can be absorbed by atmospheric gases and particles of aerosols and may be scattered on random inhomogeneities of air density and these same aerosols. Atmospheric turbulence causes random changes in laser ray amplitude and phase. Atmospheric Raman scattering of light results in the appearance of combined frequencies belonging to different gases in the spectrum of scattered radiation.

Without dwelling on the wide range of other phenomena related to interaction between laser radiation and the atmosphere, we note a characteristic feature which they have in common, having fundamental importance in developing the method as a whole. Reference is to the fact that the result of any interaction can be registered by corresponding instruments and in principle be interpreted.



Lidars for laser monitoring of atmosphere developed at Atmospheric Optics Institute STC, Siberian Department, USSR Academy of Sciences.

Thus, in order to obtain information on atmospheric parameters and their distribution in time and space it is necessary to develop corresponding apparatus and be able to interpret echo signals (returns) from the interaction between the sounding laser radiation and the atmosphere. In order to interpret the returns it is necessary to know solutions of problems related to influence of the atmosphere on the laser ray, or, as they are usually called, direct problems in atmospheric laser sounding.

The second highly important condition for success in interpreting returns involves solution of the corresponding inverse problems, in which information on atmospheric parameters is obtained on the basis of the registered influence of the atmosphere on the pulse sounding it. The success of the methods is determined by a highly precise solution of direct problems in atmospheric optics, the determinacy of the solution of inverse problems and corresponding sounding apparatus (laser sounders, or lidars).

Considerable progress has been attained in all three directions during the last 25 years. Hundreds of scientific teams and groups which are engaged in different aspects of laser sounding of the atmosphere are now working throughout the world. Fourteen international and 10 national symposia have been held. In July 1990 the Atmospheric Optics Institute, Siberian Department, USSR Academy of Sciences (Tomsk), organized the 15th International Symposium, the first in the USSR.

A wide range of corresponding research and development work has been carried out at the Atmospheric Optics Institute and the Optika Special Design Bureau for Scientific Instrument Making, Siberian Department, USSR Academy of Sciences, now joined into the Atmospheric Optics Institute Scientific-Technical Complex (STC). We will tell briefly about the results obtained here.

Lidars

Lidars are complex technical instruments which consist of mechanical and optical modules, laser equipment, electronic and automation systems. The principal components of any lidar are a laser, transmitting antenna, receiving antenna, narrow-band optical filter, receiver, amplifier and system for automated processing of returns.

It is clear that the greater the power of the sounding pulse, the area of the receiving dish (antenna) and the sensitivity of the receiving channel, the greater is the lidar potential when there is a definite interaction between radiation and the atmosphere (characterized by the interaction probability). On the other hand, the greater the probability, which may vary in a wide range, the greater is the effective range of the lidar.

The power and duration of radiation of the sounding laser pulses usually vary in the range 10^{-2}-10 J and 10^{-9}-10^{-6} s respectively (pulse repetition rate from a few to 10^3 and 10^4 Hz). The diameter of the dishes of the transmitting and receiving antennas of the lidar most frequently falls in the range 200-600 mm.

We will cite a specific example of the sounding ceiling of a lidar whose receiving antenna has a diameter 1 m; the radiation pulse power at a wavelength 0.7 μm is equal to 1 J, the remaining parameters are mean statistical. If such a lidar is used for the registry of returns from aerosols and due to molecular scattering, in the cloudless sky it is possible to obtain the profile of returns from each pulse to altitudes 20-km. With summation of the returns from a group of sounding pulses the sounding ceiling may attain 100 km.

At the Atmospheric Optics Institute STC different types of completely automated lidars have been developed which are intended for obtaining on-line information on the state of the atmosphere, as well as a mobile lidar having no analogues elsewhere in the world. This is a so-called spectrochemical lidar using radiation pulses of a CO_2 laser with a wavelength 10.6 μm and a power 200-300 J, which by means of an optical system can be focused at a stipulated distance up to 300 m and form a laser spark. It can be used in remote determination of the concentration of atoms and ions arising in the laser spark as a result of the evaporation of aerosol particles, dissociation of the formed molecules into atoms, their partial ionization, and finally, excitation of both atoms and ions. Molecules of the gases present in the air volume occupied by the laser spark are entrained into these same processes. In addition, the acoustic waves formed from the laser spark make it possible to determine the water vapor concentration, temperature, wind speed and other parameters.

Taking into account that a laser spark can be generated with the focusing of the sounding pulse energy on a water surface or on a solid body (minerals, soils, etc.), the spectrochemical lidar also can be used in remote sounding of condensed media, in particular, ecological monitoring of the Earth's surface or a search for minerals.

Our institute also has developed a multichannel fluorescent laser for monitoring a water surface by means of which corresponding data were obtained for the surfaces of the Atlantic Ocean, Baltic and North Seas, and Sea of Japan.

Direct Problems in Atmospheric Optics

The atmospheric propagation of laser radiation is accompanied by a wide range of phenomena, not one of which occurs all by itself. On the basis of qualitative criteria they can be divided into the following principal groups: refraction of laser beam rays; absorption of beam energy by atmospheric gases; its scattering by aerosol particles on air density fluctuations, etc.; fluctuations of laser beam parameters caused by atmospheric turbulence.

Each of such interactions between laser radiation and the atmosphere has specific characteristics which must be taken into account in corresponding theoretical and experimental investigations.

Laser radiation is highly monochromatic and spatially limited. It makes it possible to obtain great powers, energies and short pulses. Hence there are rigorous requirements on formulation of theoretical and experimental investigations of the problem of atmospheric propagation of laser radiation. It was found that the information on atmospheric propagation of optical waves accumulated over a period of many years is unsuited for corresponding quantitative evaluations applicable to lasers.

The widely developing research under a multisided program for study of the atmospheric propagation of laser radiation stimulated the appearance of new directions in science and technology, among them remote sounding of the atmosphere and superhigh-resolution laser spectroscopy. Nonlinear atmospheric optics, taking shape during the last 15-20 years, can be rightfully assigned to the new directions.

In order to realize this vigorous undertaking it was necessary to formulate new theories and develop new experimental research methods, as well as corresponding equipment, whose use ultimately ensured success in solving numerous direct problems in atmospheric optics. For example, the appearance of supersensitive laser spectroscopy with high and superhigh resolution made it possible to develop methods for laser analysis of trace gas components which it had been impossible to detect by classical absorption spectroscopy methods.

The new methods also were of fundamental importance for molecular spectroscopy itself. For the first time they made it possible to register an enormous number of earlier unknown lines in the spectra, and even entire vibrational-rotational absorption bands of different atmospheric gases, including polluting components.

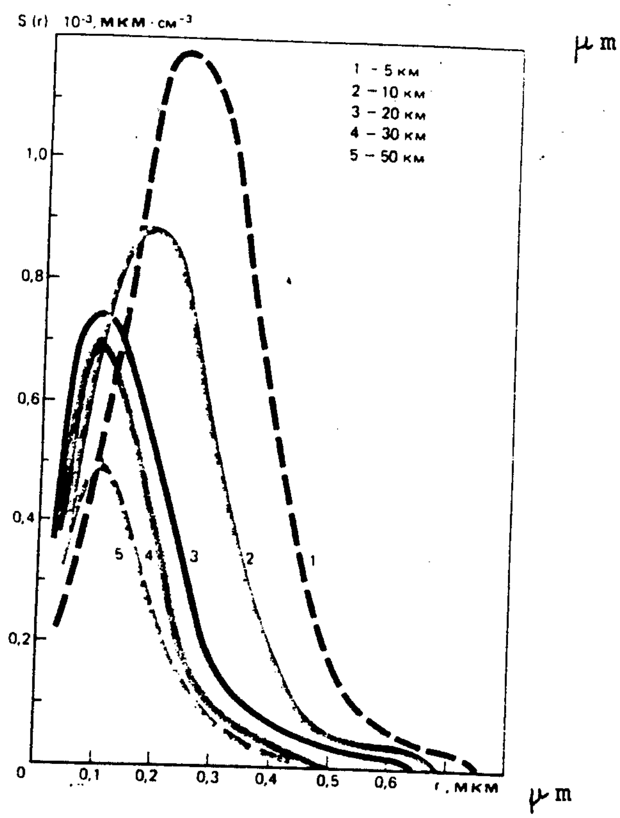
An entire series of high-resolution laser spectrometers, having superhigh response, exceeding the response of classical spectrometers by three-five orders of magnitude, was developed for research on the absorption spectra of different molecular and atomic gases. Particular mention should be made of intraresonator and optoacoustic spectrometers with different lasers, as well as a fluorescent spectrometer.

All these instruments can now be employed effectively for obtaining spectroscopic data (position of the centers of absorption lines, their intensity and half-width) for numerous atmospheric gas pollutants, whose spectra for the time being are lacking in the scientific literature.

As already mentioned, by "direct problems" are meant those related to study of the influence of the atmosphere on radiation propagating through it. This influence is caused by the absorption of laser radiation by atmospheric gases, its attenuation by aerosol systems (clouds, fogs, haze, smoke, dust) and the effect of a turbulent atmosphere on random changes in the parameters of laser beams.

We have obtained reliable results in all the mentioned directions. These ensure corresponding quantitative evaluations of the considered phenomena for any parameters of the laser sources, as well as any realistic atmospheric models, also including components of anthropogenic origin.

In the laser spectrometers which we developed the resolution attains thousandths and ten-thousandths of a cm^{-1}, which made it possible to obtain completely undistorted absorption spectra of a great number of atmospheric gases, including those of anthropogenic origin, and for the first time to register simultaneously many thousands of absorption lines.



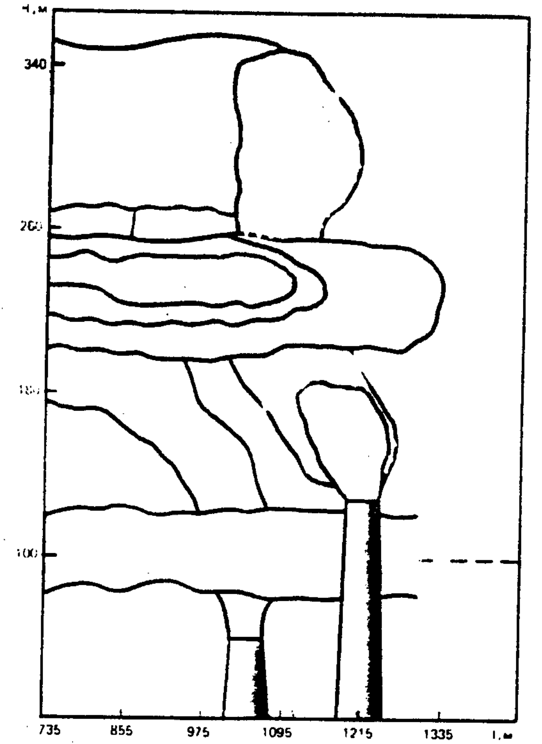
Distribution of particles of S [r] of coastal haze by size r with different values of meteorological range of visibility obtained using results of multiyear research.

Inverse Problems in Atmospheric Optics

Most inverse problems in laser sounding are incorrect. They have a great many solutions, from which it is necessary to select a correct one. The mathematical principles for solving such a class of problems were brilliantly developed by A. N. Tikhonov and his school. However, for each type of specific problems it is necessary to have a specific solution algorithm. This work was done at the Atmospheric Optics Institute.

The multifrequency laser sounding method, ensuring a possibility of remote determination of such microphysical parameters of aerosols as the size and concentration distribution of particles measuring about 1 μm or less at different altitudes, is the best developed and in the widest practical use.

The specific results of laser sounding of atmospheric parameters, based on solution of direct and inverse problems in atmospheric optics and obtained using corresponding lidars, are described below.

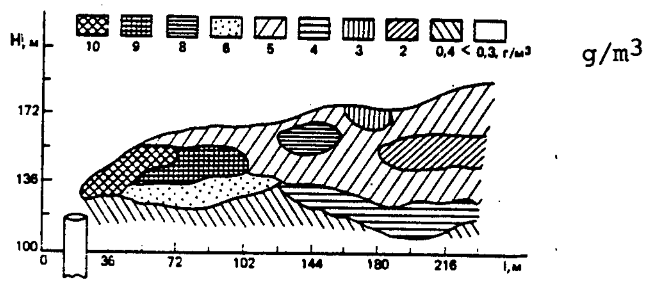


Altitudinal section of aerosol pollutants from localized sources: dashed curve -- level of lidar positioning; I -- distance from lidar. Pollution sources -- effluent from stacks 120 m high [thermal electric power plant] and 60 m [black-liquor recovery furnace]. Aerosol concentrations are clearly visible at heights 100, 220 and 300 m. These are caused by a temperature inversion or an inverse dependence of temperature on height at the corresponding heights. It is known that a mean statistical temperature profile indicates its monotonic decrease in the lower atmospheric layers. The density of the shading corresponds to the degree of concentration of aerosols.

Aerosols

Aerosols play an enormous role in the formation of weather and the atmospheric radiation field in different physicochemical transformations, including those associated with atmospheric pollution by the products of man's industrial activity. Aerosols to a considerable degree determine atmospheric albedo, that is, atmospheric capacity for the reflection of solar radiation.

Laser sounding makes possible reliable detection of layers with a temperature inversion, which constitute a barrier for the upward penetration of pollutants. Accordingly, a system for the monitoring of pollutants must without fail include the sounding of temperature inversions.



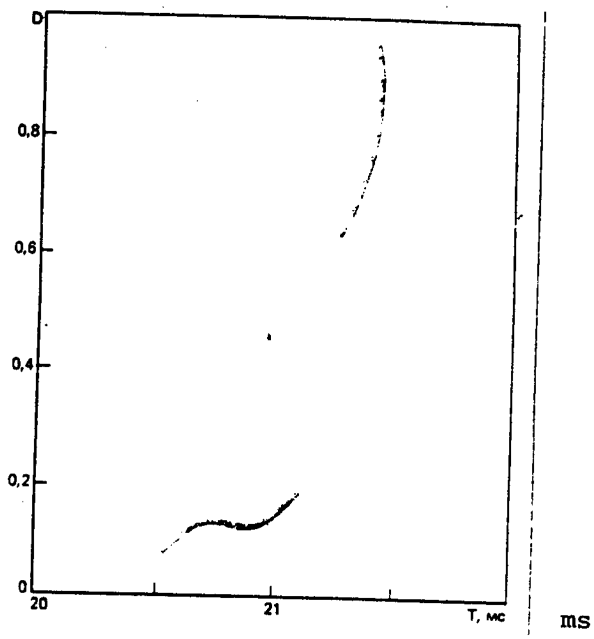
Vertical section of mass concentration of aerosols (in g/m³) in smoke plume of one of thermal electric power plants in Moscow obtained using LOZA-3 lidar during time of Moscow Olympics. Different mass concentrations of aerosols in the smoke plume of the thermal electric power plant, changing at a distance from its stack of approximately 220 m by a factor of 10 (H is height, I is distance), are represented by different shaded patterns.

Research on the dynamics of propagation of volcanic aerosol clouds in the atmosphere is of fundamental importance. A shining example of this type of experiment is one in which data for a whole series of laser sounding stations, located at different latitudes and longitudes in the northern and southern hemispheres, for the first time were used in constructing a real model at a global scale describing the behavior of dynamics of a cloud forming during the eruption of El Chichon volcano (Mexico, 1982). Today there are no other methods which make it possible to solve such a problem. This model was used in developing a three-dimensional model of the impact on climate from the eruption and reliable data were obtained on the total mass of aerosols ejected into the stratosphere.

Humidity

All the processes transpiring in the atmosphere, including the dynamics of aerosol filling, formation of clouds, atmospheric pollution, etc. are very substantially dependent primarily on the humidity field. For that reason so much attention is devoted to the development of methods for determining humidity. By "humidity field," like the field of any other atmospheric component, we mean the spatial distribution of the concentration of water vapor molecules. For obtaining the humidity field it is necessary to have a set of profiles which characterize its distribution along the line of a linearly propagating laser sounding pulse. If the sounding direction in space is changed, we obtain a set of profiles from which it is easy to construct the humidity profile.

Among the methods for the laser sounding of humidity it is the differential absorption method which must be assigned first place. One of its variants was developed at the Atmospheric Optics Institute; it provides data on humidity profiles to altitudes of about 10 km with standard deviations of several tens of percent. The idea of the method has long been known and its essence is as follows. If two sounding pulses are directed into the atmosphere, the frequency of one of which coincides with the absorption line of water vapor, whereas the frequency of the second is in the adjacent microwindow of atmospheric transparency, then by writing two laser sounding equations and taking their ratio it is easy to derive a very simple expression for the humidity profile. A distinguishing feature of our method is that a multisided approach is used.



Measured values of degree of polarization D of returns of sounding pulses of ruby laser from smoke plumes of two thermal electric power plants, one of which burns gas (lower curve) and the second which burns coal. It is shown that the discharge of aerosols from the stacks of the thermal electric power plant burning coal results in a substantially higher degree of depolarization D of the reflected laser pulse. The data were registered in one of the joint Soviet-Bulgarian expeditions in Sofia. They indicate the possibility of using measurements of the degree of depolarization of the sounding pulse return for identifying the sources of atmospheric pollution. An inexpensive polarization attachment is added to the lidar in order to obtain data on the D value.

First a highly monochromatic ruby laser with a width of the emission line not greater than 0.01 cm^{-1} was developed for solving this problem. A laser spectrophone, having a very high response to the absorption coefficient, developed at our institute, was used for the precise tuning of one of the sounding pulses to the center of the water vapor absorption line, whose width in the atmospheric surface layer is equal to approximately 0.06 cm^{-1}. In addition, an algorithm was used supplying unambiguous data on the corresponding inverse problem. The values of the water vapor absorption coefficients entering into the working formula for the two wavelengths also were obtained at our institute as a result of careful laboratory measurements carried out under corresponding controllable conditions.

The described multisided approach ensured a considerable increase in differential absorption response and the accuracy in retrieving the humidity profiles. The humidity profiles were determined to altitudes 10 km with standard deviations of about several tens of percent. It must be remembered that at an altitude of about 10 km the concentration of water vapor molecules is, in order of magnitude, millionths of the concentration of air molecules.

Temperature

Temperature is related by analytical expressions to two other atmospheric physical parameters: pressure and density. Thus, a determination of temperature on the basis of sounding results automatically makes it possible to obtain pressure and density data. Pressure and density insignificantly change with time at a definite altitude, whereas temperature is an extremely variable characteristic, especially in the atmospheric boundary layer. At heights of about several tens and hundreds of meters it is common to encounter layers with a temperature inversion, giving rise, as we have already mentioned, to barriers for the upward transport of masses and causing the accumulation of pollutants. In this connection the sounding of temperature profiles in the lower atmospheric 1-km layer is especially timely, particularly since a knowledge of the profiles, and especially the temperature fields in this layer, is important for numerous applications.

A method proposed in its time in the United States by J. Kuehne proved to be the most promising. It is known that the intensity of the lines of the two branches of the purely rotational spectra of spontaneous Raman scattering (SRS) of the principal atmospheric gases, molecular nitrogen and oxygen, whose concentration in the air is 99%, have an inverse dependence on temperature. Thus, if measurements of SRS returns are made in the indicated N_2 and O_2 branches, in principle it also is possible to extract information on temperature. For this purpose at our institute we developed reliable apparatus, especially a SRS lidar. In this work it was necessary to solve a number of technically difficult problems. It was necessary to develop a special dual monochromator in order to protect the returns against strong noise. In addition, for collecting reliable data it was necessary, on the one hand, to have a sufficiently powerful laser, and on the other hand, to have a mode of high-speed accumulation of lidar returns. A Cu-vapor laser with a mean power 8-10 W, developed at our institute, was used as a sounding source. We also developed a corresponding receiving channel.

In the next few years, when using SRS lidars with a high potential, it will be possible to increase the ceiling for sounding of the lower atmospheric layers to 3-5 km. However, the range of altitudes to approximately 30 km, with respect to the laser sounding of temperature, can now still be considered virgin territory.

Laser sounding of temperature at altitudes greater than 30 km is based on the assumption of a negligible contribution of aerosol scattering to the return pulses. Then, depending on the potential of the lidars, it will be possible to sound temperature profiles at altitudes from 30 to 50-100 km.

Wind Speed

A knowledge of the wind speed fields is of exceptional importance in predicting the development of atmospheric processes, primarily weather and the diffusion of pollutants. When we speak of wind speed fields, we also have in mind the dynamics of their changes, that is, dependence on time.

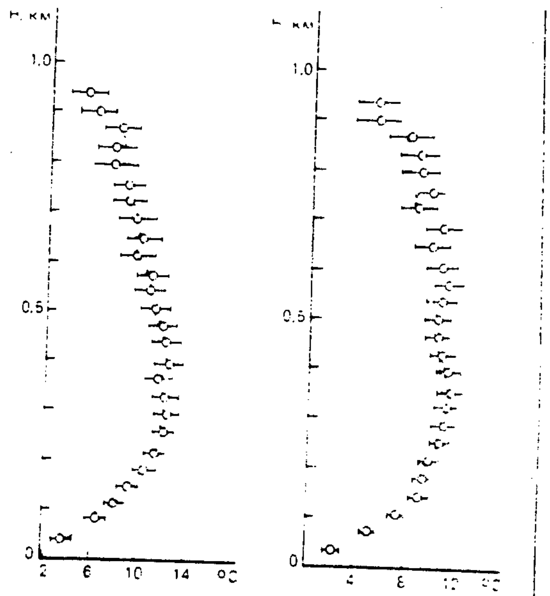
The solution of this problem today is unthinkable without using remote methods for sounding the atmosphere, including with the use of lidars, at the most different scales: from local to global.

Methods for the laser sounding of wind speed are developing in two principal directions: Doppler and correlation. The first are based on use of the well-known Doppler effect (dependence of the frequency of the received return signal on the velocity of movement of the sounded atmospheric volumes). The idea of correlation methods involves a statistical analysis of returns from the different volumes through which these signals are carried by the wind.

Unique results from sounding wind speed by Doppler methods were obtained at the NASA Wave Propagation Laboratory (Boulder, Colorado) by a group headed by M. Hardesty. The Doppler coherent lidar with heterodyne reception which they developed, and which has no analogues, makes it possible to sound wind speed to altitudes 20 km.

The best results were attained at our institute using correlation methods, especially for the atmospheric boundary layer, which to a considerable degree determines the diffusion of its pollutants.

On the one hand, the data which we obtained on the wind speed profiles describe its change with altitude in detail; on the other hand, they reveal a substantial difference in the change in wind speed with altitude in an anticyclonic situation even in the presence of an arctic front. In speaking of the spatial resolution of the registered data we note that for the investigated ranges of altitudes traditional measurements by means of radiosondes would give only one point, characterizing some mean wind speed.



Vertical temperature profiles obtained simultaneously at same place using SRS lidar based on Cu-vapor laser and using radiosondes (solid curves). The horizontal segments on the profiles characterize the rms errors. Comparison of the two profiles indicates their quite good agreement.

Atmospheric Gases

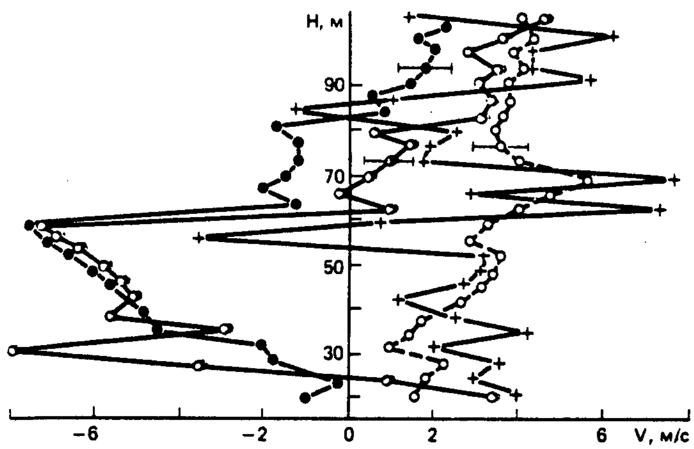
In order to measure the concentration of any atmospheric gas it is necessary that the laser used for these purposes radiate frequencies in the region of the absorption line of this gas. In this connection the good prospects for using frequency-tunable lasers or lasers with a great many emission lines at different frequencies for gas analysis is becoming clear.

Among the most widely used lasers it is CO_2 lasers which best satisfy the mentioned requirements. They emit tens of lines in the spectral range 9-11 μm.

Over a period of years work has been done at the Atmospheric Optics Institute in developing lidars with CO lasers for a gas analysis of the atmosphere by the long paths method, constituting one of the modifications of the differential absorption method described above. The essence of this modification is as follows. If the transparency of a definite layer of the atmosphere is measured at two close wavelengths, one of which falls in the absorption line of the sounded gas, whereas the second falls in the closest microwindows of atmospheric transparency, then, writing two expressions of the Bouguer law [See Footnote 1], well known from school curricula, it is easy, by jointly solving these equations, to obtain the mean gas concentration on the investigated path. We make the proviso that the absorption coefficients at the two wavelengths must be known in advance.

The concentration response of the described method is the greater the greater the difference in the absorption coefficients. It is clear that the best conditions are realized when one of the laser emission lines falls at the center of the absorption line of the sounded gas, but for the second line the absorption coefficient is close to zero. Further, the greater the difference between the absorption coefficients, the easier it is to obtain the required reliability of the measurement data with a lesser path length.

An analysis of the data available in the scientific literature on the absorption spectra of gases polluting the atmosphere indicated that the range from 4.5 to 5.5 μm, covered by the second harmonic of a CO_2 laser, is richest in the absorption lines of different gases. In this connection, in collaboration with the Siberian Physical Technical Institute at Tomsk University, we made attempts at developing an appropriate nonlinear crystal for obtaining the second and other harmonics of the fundamental frequency of radiation of a CO_2 laser.



Vertical profiles of wind speed in presence of arctic front for height interval 25-100 m obtained using correlation method with spatial resolution 3 m at 1118 hours (black circles), 1148 hours (colored circles), 1218 hours (plus symbols) and 1248 hours (open circles) local time respectively on 14 April 1987 at Tomsk, that is, after a time interval of a half-hour. The figure shows a substantial change in the wind speed value and direction in the entire interval of the sounded layers (at the right -- angles 0-180°, at the left -- 180-360°).

As a result a technology was developed for growth of the corresponding crystals and they have been used in obtaining the second harmonic of a CO_2 laser with a high efficiency linearly dependent on the intensity of the transformed radiation and the length of the nonlinear crystal. This result, together with the possibility for generating harmonics higher than the second, as well as the summation of the transformed frequencies with the stabilized frequency of another laser, is today affording a fundamentally new approach not only for the long paths method, but also for many other methods for laser sounding of the atmosphere, including from space.

In 1986 a record result was obtained in transforming (using $ZnGeP_2$ crystals) the fundamental frequency of radiation of a CO_2 laser with a radiation power 1 GW and a pulse duration 2×10^{-9} s into the second harmonic with an efficiency 83.3%. On the basis of the new approach to laser gas analysis the Atmospheric Optics Institute developed the "TRAL" path measuring instrument, which included two CO_2 lasers, one CO laser, a $ZnGeP_2$ crystal and all other components, and having full automation of work in processing measurements at a real time scale.

The use of pulsed CO_2 lasers affords still more impressive possibilities for use of the described method because in this case at a real time scale it will be possible to obtain data not only on the mean concentrations of any gas polluting the atmosphere, but also its spatial distribution. The sounding can be carried out from the ground, from a ship or from aircraft, or, finally, from space.

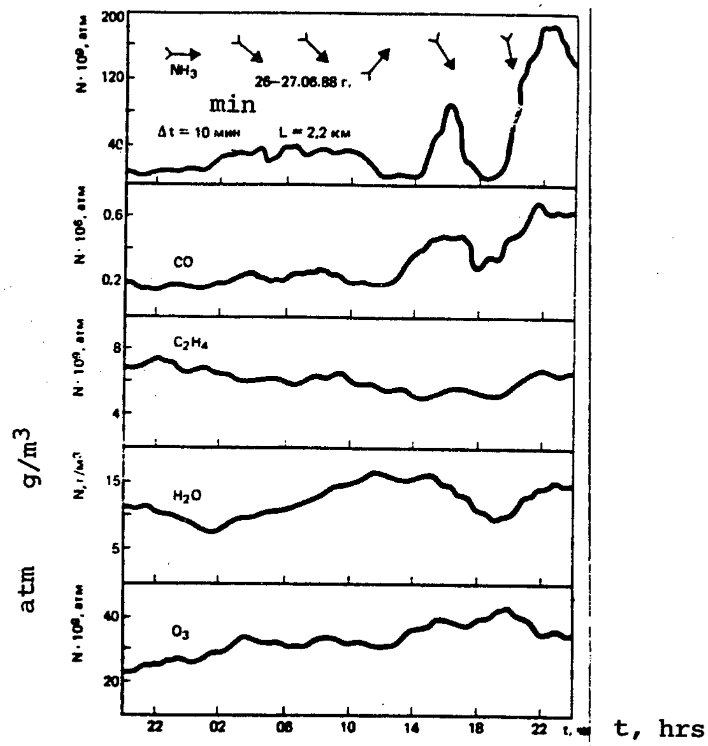
In conclusion we will discuss one other method for laser gas analysis also developed at our institute. Reference is to local gas analysis using laser spectrophones. This method, first of all, does not require two radiation wavelengths for determining the concentration of any gas and second, it makes possible reliable determination of the concentration of gases in extremely limited volumes (of about several cubic centimeters), which in many cases is of fundamental importance. Very low concentrations of analyzed gases are determined by this method.

The laser spectrophone which we developed has a very high response relative to the absorption coefficient. It is a quantity 10^{-9} cm^{-1}/W or 10^{-9} cm^{-1}/J, depending on whether we work with continuously modulated or pulsed laser radiation. With such a high response the method makes it possible to measure the background concentrations of different atmospheric gases, including polluting components.

LP Lidars

Still another unique and highly sensitive method for laser remote gas analysis, developed at our institute, is based on the functional matching of the lidar transmitter and receiver modules when the reflected echo signal is received by a laser, which also plays the role of both a filter and an amplifier (LP lidar, or lidar with laser reception).

Four copies of LP lidars with the use of ruby and glass-Nd solid-state lasers and gas CO and Ar lasers were designed and fabricated. The LP lidar with a ruby laser is intended for the sounding of H_2O, NO_2 and CN. It ensures a record response on a path with a length 100 m of 1.5×10^{-8} cm^{-1} for the absorption coefficient. Such a response makes it possible to determine the concentration of saturated water vapor at an air temperature 50°C. The lidar was awarded a Gold Medal at the Leipzig Fair in 1986.



Temporal behavior of concentration of ammonia NH_3, carbon monoxide CO, ethylene C_2H_4, water vapor H_2O and ozone O_3, obtained using "TRAL" outfit at Kemerovo. An analysis of collected data made with allowance for wind direction (indicated by arrows), as well as location of objects polluting the atmosphere, makes it possible to relate with certainty the change in concentration of gases to the change in wind speed.

In a coherent CO_2 LP lidar a response in the reception of returns was attained which exceeds the response of cooled IR detectors by a factor of 10. The use of 60 CO_2 laser transitions in the range 9-11 μm ensures the sounding of H_3, C_2H_4, C_2H_2, O_3, H_2O and a number of other gases with a record concentration response.

In conclusion we emphasize the unquestionable superiority of the LP lidar over other lidars using interference filters. The advantage is that in this case the width of the filter coincides with the width of the line of the sounding laser pulse. Accordingly, the best values of the signal-to-noise ratio are thereby attained. The latter circumstance is therefore of fundamental importance for daytime laser gas analysis of the atmosphere.

Conclusion

Thus, the advances in atmospheric laser sounding from the Earth's surface are evident. The next step, which could substantially broaden our possibilities, is putting lidars into space for obtaining data on the dynamics of filling of the atmosphere with the products of man's industrial activity, as well as components of natural origin, such as from the eruption of volcanoes.

The principal technical difficulties in the practical realization of methods for laser space sounding of the atmosphere are related primarily to the unusually requirements imposed on lidar technology, which are further aggravated by the shortage of energy on space vehicles and corresponding limitations on the weight and size of shipboard systems.

Accordingly, despite the fact that space lidars have already been in development in the United States for more than 10 years, until now not one has been put into space, although as early as 1979, at the Ninth International Symposium on Laser Sounding of the Atmosphere (Munich) one of the sessions was devoted to the results of detailed development work already carried out on variants of space lidars for sounding different atmospheric parameters.

At the same time the results of the numerical simulation which we carried out indicate high possibilities of laser sounding of both humidity profiles and fields in the troposphere and stratosphere using CO and CO_2 lasers operating in the region 3 μm.

Similar results also must be expected for cases of laser sounding of other atmospheric gas components, including atmospheric pollutants.

In summarizing what has been said we emphasize that in the next few years it is necessary to expect the launching of the first space lidars, whose routine use ultimately is destined to bring about a revolution in atmospheric research on a global scale. This revolution, in turn, should make a substantial contribution to solution of such very important problems as that of reliable weather forecasts, routine diagnosis of atmospheric pollutants on a global scale, including their transboundary transport, as well as many other problems for which a reliable knowledge of diverse processes transpiring in the atmosphere is very necessary.

Footnote

1. According to this law, the intensity of light with the wavelength λ, passing through an absorbing layer of the thickness L, is proportional to its intensity with incidence of light on a layer and the base of the natural logarithm in a power which is equal to the product of the absorption coefficient and the L value.

- END -

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