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SPECTROTOMOGRAPHY, A NEW METHOD FOR STUDYING THE INTERNAL STRUCTURE OF POLYCHROMATIC OBJECTS

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A survey of spectrotomographic experiments, discussion of the advantages and limitations of spectrotomographs, and also the future development and application possibilities in various branches of science and technology are provided.

Key words: *optical tomography, spectrometry, spectrozonal exposure.*

The problem of spectral analysis for polychromatic two-dimensional objects (colored images) arises in different fields of human activity, i.e., from space observation of the earth's surface, planets, astrophysical formations, to studying the structure of fluorescing biological macro-objects. Instruments for spectral analysis of images have been given the name of image spectrometers or videospectrometers. The overwhelming majority of videospectrometers may be separated into two groups with respect to operating principle. The main operating principle for instruments of the first group is spectral filtration of an optical signal. In order to obtain spectrally separated images of a test object at different wavelengths absorbing or interference filters are substituted or acoustic-optical filters are rearranged. Use of a finite number of light filters leads to marked discretization with respect to spectrum and as a consequence to loss of information about the spectral components of an object.

Instruments of the second group are close in operating principle to a traditional spectroscope. By means of an optical system and an entrance slit, a narrow band is cut off from the image of the test object that is projected on a diffraction grid and is broken down into a spectrum. In order to obtain a collection of spectrally-separated images, it is necessary to scan the test object with the slit and to synthesize its monochromatic images by means of a computer. These instruments are used for spectrozonal recording of the earth's surface from space. Scanning is accomplished with movement of airborne equipment [1].

The fact that they accomplish scanning of a test object with respect to spectrum or with respect to spatial coordinate is common for both types of videospectrometers. This is connected with the fact that a two-dimensional colored image is a three-dimensional object $f(x, y, \lambda)$ in a phase space (X, Y, λ), where λ is optical radiation wavelength, and x and y are spatial coordinates. The function f itself describes the spatial distribution of illumination brightness. Currently there are recorders such as the CCD-matrix or photographic film that make it possible only to record the two-dimensional distribution of brightness. Scanning of an object with a videospectrometer makes it possible to reduce the dimensionality of single-moment recorded information to two-dimensional. Here individual cross sections of an object are recorded for λ_i = const or x_i = const. This discretization of an information record with respect to space or spectrum leads to loss of information, a limitation on time for the stability of a test object, and worsening the signal to noise ratio.

However, it is possible to reduce the dimensionality in recording images of unidimensional objects by means of integrated probing described by a Radon transform [2].

Development of thermodynamic probing methods in space changing with a different physical nature, such spatial and spectral, makes it possible to create a new class of instruments for spectral analysis of images. In studying a two-dimensional polychromatic object $f(x, y, \lambda)$ in these instruments for a single moment there is recording not of the individual cross

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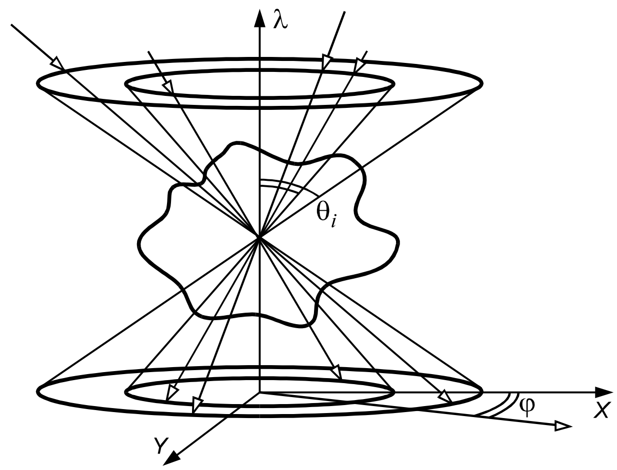

Fig. 1. Combined spectrotomographic scheme for probing with replacement and rotation of the dispersing element.

sections of the object, but two-dimensional tomographic projections carrying integral information about all of the cross sections of a test object. This approach suggested the start of a new scientific direction at the junction of two divisions of contemporary optics, i.e., optical tomography and spectroscopy, and it has been given the name "spectrotomography" (ST) [3]. The principle of ST is recording of a collection of projections containing integral information about the spectral and spatial properties of a test object, and subsequent tomographic reconstruction of its internal structure [4].

Experiments for Spectrotomography. In order to obtain a collection of ST projections of a polychromatic object, it is necessary to carry out probing of the test object with beams lying not only in spatial plane (X, Y), but also in spatial-spectral planes (X, λ) or (Y, λ). The physical process that may be described by this procedure is "transmission" of the image of a polychromatic object $f(x, \lambda)$ through a dispersing element, i.e., a prism or diffraction grid. As a result of this, a series of images superimposed on each other forms in the recorder corresponding to different wavelengths. The shift of spectral dispersion D is determined whose value may be correlated with the probing angle in the space-spectral plane $D \sim \tan\theta$. By changing the dispersion, it is possible to change the probing angle and thus to obtain a collection of projections of the spatial-spectral object $f(x, \lambda)$ and then reconstruct its structure by means of computer tomography. The reconstructed structure may be visualized in the form of a cross section $\lambda = \text{const}$ or $x = \text{const}$. A drawback of the ST scheme for probing described above is the requirement of mechanical changing of the dispersing elements. Subsequently, a system was suggested for data collection within which the dispersing element was not changed but rotated with respect to the optical axis of the system. Recording of projections is accomplished through specific intervals of rotation angle. Here the probing beams are described in space (X, Y, λ) of cones whose axis coincides with axis λ. In order to increase the number of projections, a combined scheme is used within which both replacement and rotation of the dispersing element are carried out (Fig. 1). In this case, the probing beam forms several cones with different slopes of the generating line.

In order to check the feasibility of spectrotomography, an experiment was performed for obtaining an ST projection of a real polychromatic spatially-spectral object, i.e., an alcohol burner flame. Prisms with different dispersion were used as the dispersing element. Nine ST projections were obtained by means of prism substitution. Reconstruction of the space-spectral of the test object was carried out by means of a Herschberg iteration algorithm on a grid 64×64. Five iterations were carried out. Comparison of the reconstructed space-spectral structure of an alcohol burner flame with the results of spectrometric experiments showed that the error of determining the coordinates of the spectral peaks is not more than 2%, and the error of determining the amplitude of peaks is not more than 18%. This error corresponds to an error of the tomographic reconstruction algorithm for this number of projections obtained as a result of mathematical modelling [4]. Thus, the possibility has been demonstrated by experiment for the first time of ST reconstruction of a space-spectral structure for a polychromatic object.

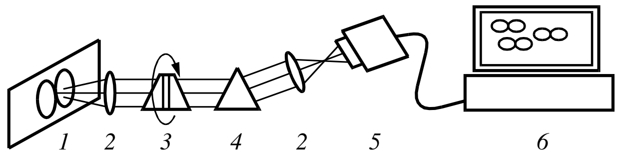

Fig. 2. Optical scheme of a spectrotomograph for studying the space-spectral structure of artificial ionosphere formations: *1*) model AIF; *2*) confocal optical system; *3*) rotary mirror analog of a Dove prism; *4*) dispersing element; *5*) CCD-camera; *6*) PC.

A spectrotomographic experiment with a similar probing scheme is described in [5]. In the optical channel for image recording, two crossed transmission diffraction grids were introduced accomplishing diffraction of the category +1 and –1. Diffracted images were projected on a recorder. Thus, five projections were obtained including the 0 category. A slide with images of vegetables of different colors was used for the test. Reconstruction of the space-spectral structure of the object was accomplished by means of an algebraic tomographic algorithm. According to the authors' estimate the accuracy of reconstruction appeared to be low due to the small number of projections.

Spectrotomography in Geophysical Research. The first experiments in spectrotomography showed that spectrotomographs exhibit some advantages, such as simplicity of the optical path, absence of discretization in recording spectral information, high noise immunity, an intrinsic integral meter, and the possibility of operating under conditions of a weak signal. The optical path of the ST system may be made in the form of an attachment to a photo- and telerecorder used in different fields of science and technology. An ST attachment has been developed for terrestrial and airborne equipment used for recording artificial ionosphere formations (AIF).

These formations are a cloud of alkali or alkali-earth metals that are created in the upper layers of the atmosphere and near earth space by explosive injection from a geophysical rocket. Physicochemical properties of the upper layers of the atmosphere are assessed from the evolution of their shape, drift, brightness, and color [6]. During experiments in studying an AIF a requirement arose for recording the spatial distribution of their parts with different illumination color without marked changes in the existing equipment. Use of light filters appeared to be ineffective and it was decided to create the ST attachment.

In [7], an ST system is described that was developed for studying the space-spectral structure of AIF (Fig. 2) in which as a recorder there is use of a telecamera and in front of the camera objective there is a prism. Rotation of the image of the test object is accomplished by means of a mirror analog of a Dove prism. A series of experiments was carried out for ST research of an AIF model representing two diffusion disks each which shines at two wavelengths. Sixteen ST projections were obtained. Restoration of the space-spectral structure was carried out by means of an algebraic algorithm TOPAS developed in the Institute of Theoretical and Applied Mechanics of the Siberian Section of the Russian Academy of Sciences. Results of the restoration made it possible to recover the space and spectral structure of the model object.

Some researchers abroad concerned with improving videospectrometers with the aim of increasing the light power and improving the signal to noise ratio have removed the entrance slit of the videospectrometer and recorded a series of blurred images. Interpretation of these images and preparation of the spectrally separated images based on them is accomplished in the best way means of mathematical Radon transformation and algorithms for tomographic reconstruction. Further development of these methods has led to creation of ST systems used for probing the surface of the earth and they are close in structure to that described above.

An experiment was considered in [8] for ST reconstruction of spectrally separated images in the middle IR-range (3–5 μm). The image recorded in an optical channel entered a dispersing element that is two prisms glued together. The prism material was selected so that radiation with a wavelength of 4 μm was not deflected but radiation with wavelengths of 3 and 5 μm was deflected in different directions and dispersed. By means of prism rotation it was possible to obtain a collection of eight projections. Reconstruction was accomplished by means of an original combined matrix Fourier-algorithm in a computer. The authors managed to achieve a spectral resolution of 0.1 μm.

In order to increase the number of projections and expand the range of probing angles, an ST system was used in [9] within which apart form rotation of the image dispersion of the optical system was changed. Rotation of the image with respect to the dispersing element was accomplished by rotating the diffraction grid around the optical axis of the system. In order to change the linear dispersion of the system with an unchanged angular dispersion, the diffraction grid changed the scale of the image by means of a transfocal objective. It was possible to obtain 64 projections.

An attempt to expand the angular range of probing for ST systems in a spectral plane led to creation of an original construction of a videospectrometer within which the probing angle in the spectral plane was 90° [10]. Here the projection data recorded made it possible to carry out reconstruction of spectrotomograms, i.e., sections of the object λ = const for unidimensional projections, which made it possible to use it for reconstructng the structure of an object with a simple and rapidly operating Herschberg algorithm. In the course of an experiment, 36 projections were obtained for aero-photographs of agricultural areas from reconstruction of the spectral distribution of the images was carried out with a spectral resolution of about 5 nm and satisfactory spatial resolution.

Spectrotomography of Fluorescing Objects. There is a broad class of self-illuminating objects that relate to different forms of plasma, fluorescing crystals, and also various biological micro-objects. Enormous progress in studying the structure of cells and their protein components has mainly been achieved due to the development of optical microscope provisions, particularly in the field of observing the spatial distribution of fluorescent dyes, probes, and quantum points [11]. Equipment that resolves this problem is a confocal scanning microspectrometer [12]. This complicated and expensive equipment is only accessible for large scientific centers. In addition, the recording time for one specimen reaches 20 min and that makes it impossible to study the dynamics of intracellular processes.

In addition, in many biological and medical laboratories, treatment and educational establishments connected with the biomedical theme, there is an enormous stock of fluorescence microscopes giving access to fluorescence research of living cells to a broad circle of scientific workers. With the use of contemporary dye-fluophores and fluorescent markers, a cell shines with different colors and for the researcher it is necessary to accomplish spatial selection of a field with a different fluorescence color. The requirement arises of creating an attachment for fluorescence microscopes making it possible to carry out spectral selection of energies continuously with respect to spectrum and at a higher resolution level than for filters.

A scientist from the University of Arizona (USA) has managed to improve markedly the system of collection of projection data described in [5] using a complex system of diffraction grids and an increase in the number of projections to sixteen as a result of this [13]. Subsequently he managed to create a compact spectrotomograph synthesizing a complex holographic diffraction grid providing single-time preparation of 25 ST projections [12]. On the basis of this construction and an inverted fluorescence microscope Olympus IMT-2 an ST system was created by the authors for recording fluorescence of micro-objects [14]. In the recording channel, the image is introduced into a dispersing element synthesized by a holographic method. This made it possible to obtain in the recording plane a collection of 49 spectrotomographic projections. Reconstruction was accomplished by means of an iteration algebraic algorithm on a grid 29×29 with 31 spectral zones. The calculation time for a single iteration was about 20 sec in a Pentium 200 processor.

Another approach to creating an ST attachment to a fluorescence microscope is the use of a successive scheme of recording ST projections on the basis of image rotation [7]. A system has been suggested in [15] in which the change in ST probing angle is accomplished as a result of rotating the preparation by means of a rotating table that is fitted to the majority of microscopes. Here the cut-off spectral filter of the fluorescence microscope is replaced by dispersing element, i.e., a prism or diffraction grid. Then blurred colored images are obtained in the recorder that are ST projections. In order to obtain a collection of these projections, required in order to reconstruct the structure of a polychromatic object, rotation of the preparation is carried out with respect to the vertical axis of the instrument by mean of the rotary table to which the preparation is fastened. Spectrally-separated images of the test micro-object are obtained as a result of tomographic reconstruction of the projections in a PC. A collection of 30–60 projections is sufficient in order to achieve a spectral resolution of 3–5 nm.

Of considerable interest is the use of ST methods for analyzing the internal spatial and spectral structure of three-dimensional luminous polychromatic objects, for example various plasma formations. Analysis of the internal spatial structure of plasma objects is traditionally accomplished by means of three-dimensional optical low approach-angle tomography [16]. These objects are described by functions $f(x, y, z, \lambda)$ and they are four-dimensional. Use of the principles of spectroto-

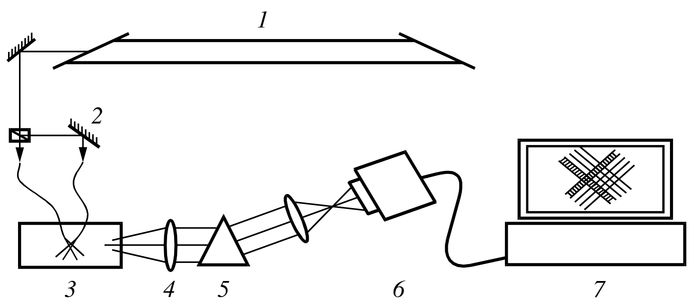

Fig. 3. Optical scheme of a spectrotomograph for studying the space-spectral of plasma jets: *1*) argon laser; *2*) light guide; *3*) cell with liquid; *4*) confocal optical system; *5*) dispersing element; *6*) CDD-camera; *7*) PC.

mography combined with three-dimensional optical tomography makes it possible to create a fundamentally new scheme for obtaining projections of a four-dimensional object within which single-time probing is carried out with respect to spectral and spatial coordinates. Here the row of the two-dimensional ST projection for this four-dimensional object is a Radon integral for the plane in three-dimensional space (X, Y, λ) [17]. According to [18] reverse Radon transformation in odd-dimensional space is local in nature, i.e., the reconstructed value of function of f at some point (x, y, z) is determined by the integral of the second derivative of the projection $F(s)$ for the small vicinity of point s. Due to this, resolution in the reconstruction field of interest may be increased considerably without increasing the computing power of the processor. On the basis of this principle, an ST system has been created accomplishing probing of a four-dimensional space-spectral over a plane, and a local algorithm has also been developed for tomographic reconstruction [17, 19]. A study of the space-spectral structure of a model jet of an argon plasma and also a fluorescing diamond has been carried out. The ST projections were obtained by means of a confocal optical system (Fig. 3). A collection of prisms was used as the dispersing element. The image was recorded by means of a telecamera and it was introduced to a PC with a resolution of 512×512 pixels. Rotation of the object with respect to the vertical axis provided a change in the azimuthal probing angle. The probing angle in the space-spectral plane was varied by changing the prism. From 30 to 50 projections were obtained in different experiments. Results of tomographic reconstruction made it possible to interpret the structure of the test objects. The reconstruction error did not exceed the value determined as a result of mathematical modelling taking account of error in projections data. Results obtained made it possible to conclude that use of local tomographic algorithms is successful and there are possibilities for extensive application of this method for creating ST systems.

Thus, analysis of work on spectrotomography indicates that the main disadvantage of ST systems is the low spatial resolution. This disadvantage is inherent for all small approach-angle tomographic systems. The main way of overcoming this is an increase in the number of projections.

Spectrotomographic systems realize the principle of constructing a measurement instrument within which the main information load is transferred from the equipment to the processing part. Therefore, the main advantage of these systems is simplicity and flexibility of the optical path. Use of ST systems is promising where low weight, compactness, and cheapness of the optical system are required. Spectrotomographic systems are preferred in carrying out non-traditional spectral measurements with the absence of a developed equipment base and also under conditions of a weak signal.

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