Videospectrometric devices built on the basis of Fourier transform spectrometry method for detection of trace gas impurities in the atmosphere

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Received May 24, 2007

Spheres of application of hyper-spectral videospectrometers and the basic advantages of the videospectrometers based on application of a Fourier transform method with the use of many-element receivers are considered. The Fourier-spectrometer, using the deeply cooling detectors having two rulers with 14 elements in each, is described. The device is intended for detection of trace gas impurities in the atmosphere.

Introduction

Remote sensing (RS) is one of the main methods of studying and monitoring the environment. Since the 80s, RS is rapidly developed as a unified multidisciplinary scientific and technical direction due to its high information efficiency and a possibility of many-time observation of vast territories. Relatively low cost of the method allows efficiently investigate new processes and phenomena in dynamics on the Earth surface and in the atmosphere.

RS is widely used in ecological monitoring and detection of emergency cases. Optical technologies form the basis for obtaining reliable information. A wide range of pollutants and the diversity of ways of their distribution and influence on the environment affected the structure of the equipment for environmental studies. According to environment protection organizations, there are three large groups of analytic methods (equipment) for instrumental monitoring: laboratory, express, and automated. Among these methods more than 50% fall on the laboratory analytic methods and between 40 and 100% on express and automated ones.

Development and application of multispectral (consisting up to several dozens of spectral decomposition elements) and hyperspectral (with the number of spectral decomposition elements up to 100 or more) videospectrometers,[1,2] which provide for detailed surface images within relatively narrow spectral ranges is of particular importance now.

Combination of multi- and hyper-spectral images of scenes in different spectral intervals with independent spatial and spectral (polarization) characteristics, high-quality radiometric calibration, simultaneous correction of atmospheric parameter influence on data measurements and analysis (compression and on-board processing) allows treating video-spectrometers as the most prospective RS instrumentation.

The first prototypes of hyper-spectral video-spectrometers were used as space-born instruments for obtaining hyper-spectral images of the Earth underlying surface; first, within spectral range from 0.4 to 2.5 μm and then in 3–5 and 8–12 μm ranges.[3]

The importance of development of such equipment is reflected, in particular, in the "Conception of development of Russian space system of the Earth remote sensing for the period up to 2025,"[4] in which "... development and application of supermulti-spectral survey (videospectrometric and hyper-spectral) with the number of channels higher than 256" is named as one of the leading directions.

The main element of multi- and hyper-spectral videospectrometers is the device for coding the spectral information, i.e., just the spectrometric unit. As a rule, this block is based on dispersion (surface and diffraction) polychromatic systems, which, being limited in luminosity and spectral resolution,[5] often can not provide accurate information, necessary for unique identification of the investigated objects. At the same time, the most intensively and dynamically developing branch of spectral optical instrument engineering is Fourier-spectrometry.[6,7] It is a high-end product combining the precision optics and mechanics, high-quality electronics and computing units with special algorithms and controlling and processing programs.

The well-known advantages of the Fourier-spectrometry (FS) as compared to classical spectral equipment,[8] become even more prominent when multielement photodetectors (MPD) are used, which favor the constructing of new types of highly efficient equipment for RS, i.e., Fourier-videospectrometers[9] and Fourier-spectrovisors.[3] Their basic advantages are the following:

– high aperture ratio (wide solid angle, in the range of which the investigated radiation at the same spectral resolution can be gathered to the whole light-sensitive area of the radiation detector), which, in some cases, gives a possibility to set FS

0235-6880/08/09 715-03 $02.00

interferometer in the convergent beams of the telescope, thus eliminating the additional focusing optics, which is necessary in front of the slit of the classical dispersion monochromator;

– the simultaneous recording of all spectral intervals (multiplexity) on each detector element. This significantly increases the signal-to-noise ratio in the spectrum under study and allows both coordinates of MPD to be used for building the investigated scene, as well as to use the special algorithm,[3] decreasing the influence of image distortion due to the carrier movement and increased time for recording a single interferogram;

– the accuracy of attachment of the wave number scale to an inner etalon, that significantly simplifies the equipment calibration, such increasing the reliability of the investigated objects identification;

– a possibility for wider variations of the spectral resolution, determined solely by the magnitude of the realized run difference of the interferometer arms. This allows constructing the video-spectrometer equipment with program-variable spectral resolution during the experiment depending on the investigated scenes (sea, forest, steppe, desert, snow, etc…) along the line of flight, such optimizing the obtained data[10];

– the absence of overlapping diffraction spectral orders and, consequently, a wide recorded spectrum, defined only by the light transmission of optical elements and by the area of the photodetector sensitivity, that allows a significant reducing of the number of developed and launched apparatus;

– the availability of the additional information received from the phase spectrum, which shows the change of the "source–detector" system radiation direction for each wavelength. This is particularly important for operation with an uncooled detectors in IR spectral region, because this gives a possibility to correct spectra and increase the reliability of the obtained information;

– a possibility to compensate the intrinsic radiation of interferometer's optical elements due to antiphase emission of units, set in front of the beam splitting layer and behind it[11];

– obtaining of additional information from phase spectra, which then can be used for detection of some moving radiating point object (in its field of view) and its income and outcome from the field of view[12];

– determination of direction to the point emitting object with an error not worse than one tenth of the size of a single photodetector pixel from calculation of the interferogram phase spectra[13];

– almost a full absence of the dispersed light influence;

– uniqueness of engineering and methodic solutions in the development of equipment in a wide spectral range.

Thus, just FS with MPD have maximal capabilities and prospects for future development and improvement of video-spectrometric equipment for RS.

The idea to use MPD in FS for simultaneous spatial and temporary resolution was first proposed in our country in 1977.[14] In 1991, a unique complex of space equipment for operation at geostationary orbits was developed, which combined both ideas of thermal direction-finder and multi-element FS.[15] However, FS using MPD and designed for operation in field conditions has not been developed until recently. Having quite high spectral resolution (less than $0.5\ \mathrm{cm}^{-1}$), such equipment is most useful in detection of minor gas impurities in the atmosphere and determination of their spatial variations.

To solve the latter problem, a two-channel FS was built, based on two cooled bars of detectors with 14 photosensitive elements (PSE) in each. The choice of the bar detector was stipulated by the absence of home-produced reliable and high-sensitive cooled matrices for long-wave spectral range. Working spectral range of the first channel covers the wavelength region from 3.0 to 5.5 μm, of the second channel – from 3.0 to 14.0 μm at the device spectral resolution no worse than $0.5\ \mathrm{cm}^{-1}$, total field of view of $6\times6°$, field of view of an isolated FSE of 13×26 angle min.

This device, in principle, is a classic FS, designed on the basis of Michelson interferometer, at each MPD PSE of which an interferogram is formed in the field of its view depending on spectral composition of radiation of the investigated space. The electric signal passes the corresponding amplification path, which consists of a broadband preamplifier and a band amplifier, then comes through a beam switching tube onto 14-discharge analog-digital converter, is quantized according to the run difference with the help of a reference channel signal. Then the information comes through the interface to computer, where arrays of all 28 interferograms are formed for their further processing and obtaining radiation spectra.

To reach high threshold sensitivity, a specially designed original photoresistive cooled MPD on the basis of Germanium, doped with mercury,[16] was used in FS. Application of this material for producing photosensitive elements has many advantages as compared to other materials (including CdHgTe): a wide operating range (3–14 μm) and a possibility to form several PSE bars in a single focal plane. These PSEs have different ranges of sensitivity, determined by optical filters, which are mounted directly on the PSE bars.

Besides, GeHg-detectors have a high detection capability (close to theoretical limit in each of the chosen spectral range), high quantum efficiency (more than 50%), high level of output signals (volt-watt sensitivity about $\approx 2.5\cdot10^6$ V/W, which makes easier suppression of interferences of vibrational, electrical, and electronic origin). They also allow a possibility to implement bars with PSE of any size between 30 and 200 μm. One more their advantage is a relatively low price. However, all these tasks can be solved only at low operating temperature (about 30 K), that requires the use of gas cryogenic units, which make the operation of the instrument more sophisticated and increase the power consumption.

As a result, the sensitivity threshold of FS with MPD in the first channel is equal to $9.3 \cdot 10^{-6}$ W/(m$^2 \cdot$ sr $\cdot$ cm^{-1}) (for 4.8 μm) and in the second channel – to $3.4 \cdot 10^{-5}$ W/(m$^2 \cdot$ sr $\cdot$ cm^{-1}) (for 11.8 μm).

Estimates of dynamic ranges of spectral radiance for summer and winter models of the atmosphere for ozone, water vapor, carbon dioxide and methane are presented in Ref. 16. Amplitudes of the spectral radiance change for these gases at one-percent change of concentration of the corresponding gas total profile lies in range $(3 \div 20) \cdot 10^{-4}$ W /(m$^2 \cdot$sr $\cdot$ cm^{-1}). These values of the threshold sensitivity of FS with MPD are close to variations of the spectral radiance at one-percent change of mean concentration of these gases in the corresponding spectral range in the atmospheric air column. This proves the fact that the device can be used in studies of similar minor gas impurities in the atmosphere and for obtaining spatial pattern of their distribution, as well as, sooner, for determination of the concentration of many anthropogenic gases, radiation spectrum of which falls in range 3.5–14.0 μm. In case of ground measurements at zenith observations the sensitivity can be increased even more due to accumulation and statistical processing of interferograms of the observed spatial region (a cloud or a gas trail).

Nowadays, a possibility of building a FS matrix with the number of PSE PDM up to 512×512 is under study, which will make possible to gain spatial and spectral resolutions of even a greater area of the investigated scene.

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