Some peculiarities in calculation and design of promising spectral-vision systems for remote sensing

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Peculiarities of design and methodological capabilities of promising spectral vision systems are considered, which are intended for aircraft or space remote sensing. The described system can be used in many scientific and applied tasks.

The remote sensing (RS) is a process of measuring characteristics of some object by means of sensors, which are not in immediate contact with the object.[1] Such sensors are mounted, as a rule, aboard aircraft or space carriers.

Multi-spectral RS methods are based on measuring and recording the energy in several ranges of the electromagnetic spectrum simultaneously, in which it is emitted or reflected from the studied objects[2] with different spectral brightness coefficients (SBC). The conducted thorough investigations of SBC of natural and anthropogenic formations have shown[1,2] that just small spectral variations are indicators of most important characteristics of objects and phenomena, in particular, of small-size ones.

During ground-based measurements, observations are usually conducted immediately above the studied object, as a rule, from a 1.0–1.5 m height, and comparatively seldom – from special towers. Therefore, a researcher is sure that the necessary object is chosen correctly (type of soil, rock formation, or vegetable) and can adequately estimate conditions of its location. In the aircraft or space observations, vice versa, the ground surface SBC are recorded and averaged over the device field-of-view, therefore, they can significantly differ from actual values, particularly, in the case of small objects on the surface. The results of both methods can differ drastically even in case of homogeneous elongated surface objects.[2] Thus, for vegetable and some rock formations, the ground-measured SBC values often overestimate the values, measured from the aircraft and space carriers, by 30–60%. This difference is rather large and, probably, caused by insufficiently proper accounting for the optical thickness of the atmospheric vertical column.[3]

Only the invention of new instruments with high spatial, spectral, and radiometric resolution (videospectrometers),[4] which provide for element-by-element simultaneous recording of both the SBC and the geometric structure of the studied remote objects, made it possible to extract in full measure the scientific and practical information from peculiarities of the SBC behavior. These instruments open wide possibilities for sensing the Earth and circumterrestrial space despite very refined natural and artificial ways of masking of the studied objects. They allow one to obtain data, which can be used both independently and together with visual data on the topology of the observed objects. Note that the processing of the spectral visual data can be easily automated.

Modern aerospace spectral vision instruments allow one not only to analyze in detail the obtained many-element images of the Earth surface, but also record the spectra of each element of the image, including those, which are at the very limit of the spatial resolution. Thus, the main peculiarity of the videospectrometers is their concurrent high spatial and spectral resolutions.

The first characteristic – spatial resolution – is determined by minimal sizes of the surface area under study, which this instrument can perceive as an individual element. At agreed characteristics of the videospectrometer optics and its receiving-recording block, the spatial resolution is commonly determined from the standard formula $R = h\tan\omega$, where R is the linear resolution on the terrain; h is the height of the flying carrier; ω is the angular resolution of the videospectrometer.[1]

The second characteristic – spectral resolution $\delta\lambda$ – is determined by the instrument capability to distinguish radiation from neighboring spectral ranges. In this case, the amount of spectral information H, which can be sent to the processing, is estimated as

$$H = Z\log_2(M + 1),$$

where $Z = \Delta\lambda/\delta\lambda$ is the number of recorded spectral ranges (spectral channels); $\Delta\lambda$ is the working range of the spectrum; M is the number of possible values of the measured intensities.[5]

The traditional complement of the videospectrometer includes the projecting objective and a spectral unit (polychromic one), consisting of the entrance slit, collimating objective, dispersing element (plane reflecting diffraction grating), camera objective, and matrix photoreceiver (MPR) of radiation.

The input projecting objective (analog of photo camera objective) builds the image of the studied remote object in the undecomposed light at the input of the polychromic unit in the plane of its entrance slit. Since the entrance slit is optically conjugated with the object plane, then its length (height) determines the length of the survey band on the surface plane, and the width determines the spectral and spatial resolutions. The same slit is conjugated also with the plane of MPR photo-sensitive elements, that allows a simultaneous spatial and spectral scanning.

Each MPR line located strictly crosswise the fly direction, records, in fact, the monochromic image of a narrow band of the ground surface (vision band) and provides for spatial development of this image, while spatial scanning is provided by the carrier movement. Scanning over spectrum performed by MPR electronics, as well as the maximal number of the recorded spectral intervals resolved by the videospectrometer, are determined by the number of MPR lines. The number of MPR lines, in principle, corresponds to the number of the recorded monochromic images of the terrain band passed by the flying carrier.

Videospectrometers combine a high spatial resolution, inherent to high-quality photo-cameras, and a high spectral resolution, characteristic of high-class spectral instruments.

The enumerated positive properties of videospectrometers, mounted aboard air or space carriers, fully unveil their potential in applied investigations, when high-quality monochromic images of natural or/and artificial objects are obtained with simultaneous visualization of the scene. This allows the measurement of spatial and spectral characteristics of the proper or reflected radiation of numerous objects, studied by different users.

In particular, the videospectrometers are efficient when using in different geological and geological-engineering surveys, for example, when designing and building gas pipelines.[6] In this case, the most amount of information is contained in the 500–600 nm and UV ranges. Here, when moving from deep-water areas to shoal, a complex scale of hue transitions from dark to light is traced. Light hues correspond to turbid waters. When the short-wave solar beams penetrate deep into the see water, the obtained video-spectral images characterize the turbid water distribution up to the boundary with shoal and elucidate the distribution of depths.

Besides, according to available data, video-spectral surveys allow visualization of lithodynamical processes, which can noticeably affect the silting of the bottom trenches (slits), the washout of the backfilling of the buried pipelines, the coastal line migration, as well as act dynamically directly on pipelines.

The videospectral methods are useful in solving many ecological problems, particularly, in biosphere investigations: they can detect harmful pollutants in the atmosphere, vegetation stresses under impacts of nitrates and precipitation of heavy metals, hydrocarbon leakages from pipelines, as well as instantaneous outbursts of pollutants. This is particularly important for on-line estimation of natural emergency consequences, technogenic catastrophes, forest fires, and other force-major situations.

The designing and improving of such instruments are of great importance also in military applications, when it is necessary to obtain high-quality distinct images and to distinguish masked objects of close colors and hues, that is impossible with the use of traditional methods of aerial surveying. The importance of constructing instrumentation for space visual reconnaissance has been marked in the review of military programs.[7]

Numerous results of testing videospectral instrumentation abroad,[8,9] as well as the home practice of its application[10–15] allow one to make a conclusion on considerable promise of such type of surveying for remote sensing problems solved in the optical spectral range.

The reaching of high characteristics of videospectrometer transmission, spatial and spectral resolutions are gained, first of all, due to obtained images of high quality. Consequently, the requirements to initial images, formed in the entrance quasi-illuminant block, should be sufficiently strong. This block cannot be referred to standard illuminants, since, operating as the projecting objective, it must have the properties, characteristic of the best present-day aerial-surveying objectives.

Evidently, a simple combination of the entrance projecting objective and polychromic device, calculated independently, cannot assure solving the above problems. In this connection, the concept of through joint calculation of the videospectrometer optics was worked out, based on strong mutual correction of aberrations of their projecting and spectral units.

The improvement of the image sharpness can be reached by decreasing the astigmatism, field curvature, and aberrations of wide slant (off the axis) beams, particularly, in the sagittal plane. This problem is not simple.

Note that the main requirement imposed on any videospectrometer objective is sufficiently elaborated correction of not only monochromatic aberrations, but chromatic as well, and sometimes in a more wide spectral range as compared to usual objectives – achromatic or apochromatic. The matching of this requirement allows one to overcome difficulties in designing videospectrometers, capable to operate in a wide working spectral range, but instrumental configuration of which keeps from the optics refocusing during the transition from one wavelength of the recorded radiation to another. At last, optical elements of instruments mounted aboard space carriers should be radiation-resistant, i.e., not subjected to darkening and destruction under impact of ionizing radiation.

All this severely hampers the choice of transparent optical media and mirror covers, having at the same time high reflectance and resistance to radiation.

The requirement of minimal size and mass of aircraft-born and space-born devices forces to use small-size mirror-lens systems with transparent mirror elements operating at significant angles of the radiation incidence. In this case, it is reasonable to take concentric optical systems as basic ones, because they are free of majority of simple aberrations (coma, astigmatism, distortion). This will help to correct effectively the residual aberrations. For example, in order to correct spherical aberrations, the way of calculations can be proposed, in which the analytical expression of the aberration obeys the condition of its minimization, and the chromatism can be corrected through fulfilling the condition of invariance of the equivalence of objective rear focal length on the lens material refractive index.

The above-enumerated peculiarities were taken into account in the videospectrometer scheme, presented in Fig. 1.

Entrance components of the scheme form a concentric telescopic system with angular (and visible) amplification equal to unit. They include the projecting objective made of convex *1* and concave *2* spherical mirrors (Kassegrain reversed system) and collimated objective of the polychromic element in the form of concave spherical mirror *4* with the same focal length. Such a system is free of coma and astigmatism; its spherical aberration is minimized; and the field curvature is compensated by the position of the device aperture diaphragm in the common curvature center of the three above spherical mirror surfaces. As the result, the telescopic system gives a beam of rays with a plain wave front, which provides for effective correction of aberrations introduced by the dispersing element, i.e., plane reflecting diffraction grating *6*.

The entrance slit *3*, located inside the coinciding foci of the projecting objectives *1*, *2* and the collimator objective *4* provides for the given spectral resolution (together with the diffracting grating and camera's mirror-lens objective *7*–*9*) due to the fact that the grating case serves as the device's aperture diaphragm. Besides, the entrance slit, as well as inner blinds and light traps, operating in cooperation, effectively eliminate the directed distorting emissions (spurious reflexes) and the scattered light. Due to the plain apertured mirrors *5* and *8*, the optical scheme becomes compact.

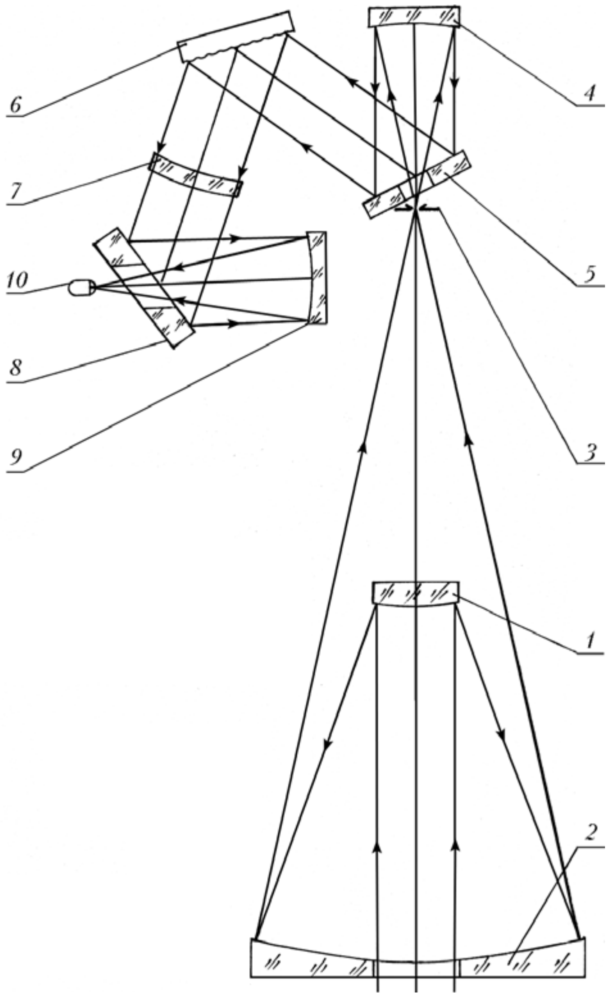


Fig. 1. Optimized optical scheme of videospectrometer.

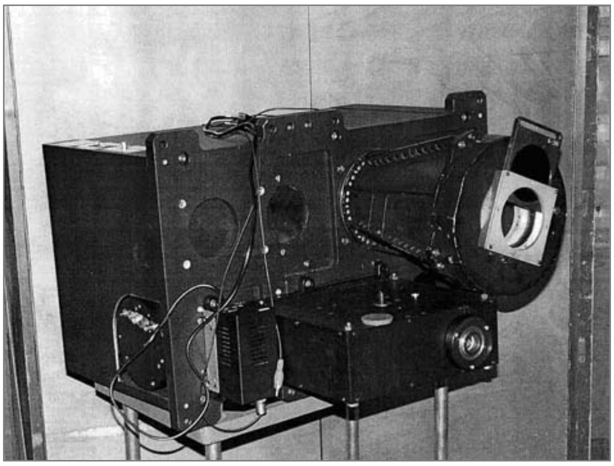
A peculiarity of this part of the optical scheme is a capability of meniscus *7* to eliminate significantly spherical aberrations both of the telescopic system and spherical mirror *9* in the camera objective. The corresponding radii of the meniscus spherical surfaces, its small thickness and location behind the diffraction grating provide for minimal spherochromatic aberration.

The field curvature at the device output is corrected by the Piaci–Smith lens, located at immediate proximity to the image, formed by the camera objective in MPR *10*. The same lens has an additional function, namely, the filtering of the highest diffraction orders, because it is made of two butt jointed half-lenses of differently colored glasses, where the joint is glued. The abutting sides of both half-lenses are oriented perpendicular to the device dispersion plane. The pointed properties of the device optical scheme provide for the required spatial resolution.

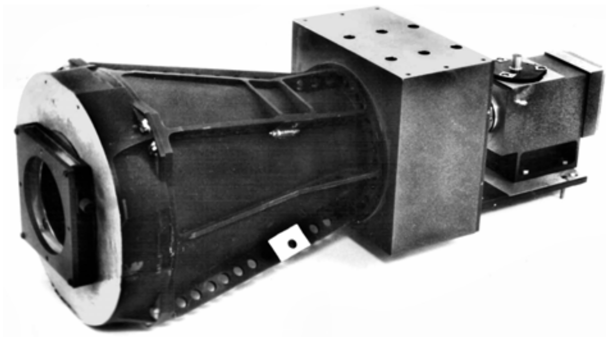
Figure 2 presents the home-made videospectrometers based on the described scheme.

Basic specifications of the spectrometers are the following:

– working spectral range, nm	200–350	400–1000
– focal length of projecting and collimating objectives, mm	98.76	98.76
– focal length of the camera objective, mm	95.57	97.03
– relative hole	≈ 1 : 2.5	≈ 1 : 2.5
– entrance slit sizes, mm × mm	0.037 × 13.824	0.019 × 9.4
– spectral resolution, nm	≈ 1.8	≈ 1.5
– spatial resolution (from a height of 500 km), m	≈ 100	≈ 95
– fast response, s/spectrum	0.04	0.04
– power expenditure, W	≤ 25	≤ 20



a



b

Fig. 2. Home-made spectrometers: *a* – for UV range; *b* – for visible and near infrared ranges.

In the first instrument (*a*), a high-sensitive hybrid TV device of UPZS-023 type, based on electron-optical inventor transformer with the entrance window made of MgF_2 or uviol glass UT-49, is used as a receiver; it also includes a solar-blind photocathode (CsTe), output fibre-optical plate, micro-channel plate as a brightness amplifier, and a screen of yellow-green luminosity.

The silicon PZS matrix "Kalimantan" with a 6.91 × 9.22 mm photosensitivity area serves as a receiver at the second instrument (*b*).

The conducted field and fly experiments[12,13,16] have justified the expected spectral-power and operational characteristics of the videospectrometers. The best results were obtained in the visible and near infrared spectral ranges. The experiments were conducted, taking into account intra-landscape migration relations allowing studies of harmful matter migration from the atmosphere to the underlying surface in the systems "soil – vegetation" and "soil – water reservoir."

References

1. P. Kronberg, *Remote Study of the Earth* (Mir, Moscow, 1988), 343 pp.
2. L.I. Chapurskii, *Reflecting Properties of Natural Objects in the 400–2500 nm* (Izd. Military Ministry of USSR, Moscow, 1986), 160 pp.
3. V.V. Belov and S.V. Afonin, *From Physical Grounds, Theory, and Modeling to Thematic Processing of Satellite Images* (Izd. IOA SB RAS, Tomsk, 2005), 266 pp.
4. V.M. Krasavtsev, A.N. Semenov, K.N. Chikov, and V.B. Shlishevskii, in: *Proc. of III International Congress "GEO-SIBERIA-2007"* (Novosibirsk, 2007), V. 4, P. 1, pp. 89–94.
5. N.N. Khrenov, *Foundations for Complex Diagnostics of Northern Pipelines. Aerospace Methods and Processing of Surveying Results* (Gasoilpress, Moscow, 2003), 352 pp.
6. V.D. Shinkov and I.A. Seleznev, Inf. i Kosmos, Nos. 1–2, 21–22 (2002).
7. L. Yablonskii, E. Voronin, and V. Kashin, Foreign Military Review, No. 7 (2002).
8. *Proc. of the Fourth Int. Airborne Remote Sensing Conf. and Exhibit: 21 Canadian Symp. on Remote Sensing* (Ottawa, Canada, 1999).
9. *Proc. of the Fourteenth Conf. and Workshops Applied Geologic Remote Sensing* (Las Vegas, USA, 2000).
10. V.V. Gud, V.M. Krasavtsev, A.N. Sandakov, and K.N. Chikov, Opt. J., No. 8, 67–71 (1995).
11. K.N. Chikov, V.V. Gud, V.M. Krasavtsev, and A.N. Sandakov, Izv. Vuzov. Priborost., No. 3, 5–10 (1998).
12. K.N. Chikov, V.V. Gud, and V.M. Krasavtsev, in: *Scientific Researches of Higher School on Ecology and Efficient Nature Management* (St. Petersburg, 2000), pp. 173–175.
13. P.V. Batyan, V.V. Gud, I.A. Konyakhin, et al., Izv. Vuzov. Priborostr., No. 2, 46–51 (2002).
14. K.N. Chikov, E.D. Pankov, L.F. Porfir'ev, et al., Izv. Vuzov. Priborostr., No. 9, 60–67 (2004).
15. A.S. Rafailovich, and V.B. Shlishevskii, in: *Proc. of Intern. Congress "GEO-SIBERIA-2006"* (SSGA, Novosibirsk, 2006), V. 4, pp. 31–34.
16. A.V. Markov, A.S. Rafailovich, V.B. Shlishevskii, et. al. in: *Proc. of Intern. Congress "GEO-Siberia-2006"* (SSGA, Novosibirsk, 2006), V. 4, pp. 34–37.