ISSN 2409-9066. Sci. innov. 2015, 11(6): 15—23 doi: http://dx.doi.org/10.15407/scine11.06.015

Lyalko*[1]*, V.I., Popov*[1]*, M.A.,
Stankevich*[1]*, S.A., Shklyar*[1]*, S.V., Podorvan*[1]*, V.N.,
Likholit*[2]*, N.I., Tiagur*[2]*, V.M., and Dobrovolska*[2]*, C.V.

[1] R&D Center for Aerospace Research of the Earth, the NAS of Ukraine, Kyiv
[2] *ARSENAL* SDP SE, State Space Agency of Ukraine, Kyiv

PHYSICAL SIMULATOR OF INFRARED SPECTRORADIOMETER WITH ENHANCED SPATIAL RESOLUTION USING SUBPIXEL IMAGE REGISTRATION AND PROCESSING

The mathematical and physical models of new frame IR spectroradiometer based on microbolometer detector array with subpixel image registration have been presented. The radiometer is planned to be incorporated into the onboard instrumentation of Sich satellite system for obtaining the earth surface physical parameters from the data of aerospace IR survey with enhanced spatial resolution.

Keywords: infrared satellite imaging, frame microbolometer array spectroradiometer, sub-pixel image registration, spatial resolution enhancement.

Aerospace survey in the visible and the IR bands is an important tool to address effectively the following tasks: to search the minerals and energy sources, to monitor the environmental situation and environmental pollution, to assess the heat losses in urban and industrial areas, to monitor the agricultural and forest plantations, to surveil the emergency situation zones, to detect the disguised objects and so on [1].

The majority of problems to be solved requires the data on physical parameters of the observed objects and the earth's surface, such as temperature and emissivity. Such information can be provided only by survey within the far infrared (thermal) range of 7–14 microns [2], but today the accuracy of temperature and heat radiation coefficient derived from the survey data does not always meet the requirements and conditions of problem to be solved. Therefore, worldwide, the researchers are working to improve means of infrared survey and to develop effective algorithms for processing of survey results and reconstruction of real values of the aforementioned physical parameters [3].

The purpose of this study is to develop mathematical and physical models for a new IR spectroradiometer based on microbolometer detector array with sub-pixel image registration, which ensures deriving the physical characteristics of terrestrial objects from the space survey data in order to address many problems of the Earth remote sensing (RS).

PHYSICAL PARAMETERS OF THE EARTH SURFACE BASED ON IR SURVEY

The remote measurement of physical parameters of the terrestrial objects and the earth surface (temperature and emissivity) is complicated by two factors. *Firstly*, in the case of real (not black) bodies, these parameters are interdependent. *Secondly*, the calculated emissivity of the object depends on the spectral range where IR radiation is recorded. Consequently, in the case of multispectral IR imaging, the number of unknown values in the equations of radiation transfer always exceeds by one the number of equations in the system. Thus, the problem of separation of temperature and spectral emissivity is incorrect in the general case [4].

It should be noted that the Earth surface parameters are remotely measured as average weighted by shares of different layers, provided the layer is materially inhomogeneous within the pixel of IR image. Therefore, emissivity differs for different pixels, even if their values have been measured for all types of layers. Hence, temperature T and emissivity ε should be found for each pixel of IR image separately.

The remote temperature control is based on the Planck law of thermal radiation:

$$L(\lambda, T) = \varepsilon(\lambda)\, M(\lambda, T) = \frac{\varepsilon(\lambda)\, c_1\, \lambda^{-5}}{\exp\left(\dfrac{c_2}{\lambda\, T}\right) - 1}, \quad (1)$$

where $L(\lambda, T)$ is spectral density of earth's surface radiance; $\varepsilon(\lambda)$ is spectral coefficient of thermal radiation; $M(\lambda, T)$ is spectral density of black body radiance; $c_1 = 2hc^2 = 1.191 \times 10^{-16}$ W × m^2 and $c_2 = \dfrac{hc}{k} = 1.439 \times 10^{-2}$ m × K are the first and the second constants of the Planck law; $h = 6.626 \times 10^{-34}$ J × s is the Planck constant, $c = 2.998 \times 10^{8}$ m/s is light speed in vacuum; $k = 1.381 \times 10^{-23}$ J/K is the Boltzmann constant; λ is wavelength of electromagnetic radiation [5]. Temperature can be derived from (1):

$$T = \frac{c_2}{\lambda \ln\left(\dfrac{\varepsilon(\lambda)\, c_1}{\lambda^5 L} + 1\right)}. \quad (2)$$

Thermal radiation is governed by the Wien displacement law

$$\lambda_{\max} = \frac{b}{T}, \quad (3)$$

where $\lambda_{\max}$ is wavelength corresponding to the maximum spectral density of radiance (1); $b = 2898$ μm × K – the Wien constant. For typical temperature of the Earth's surface $T = 25$ °C the maximum radiation is reported for $\lambda_{\max} = 9.72$ μm, i.e. for the far IR band.

The spectral density of radiance Li on the IR sensor aperture in the i-th spectral channel in the upper limit of atmosphere is described by integral equation of radiation transfer:

$$L_i = \varepsilon_i\, \tau_i \int M(\lambda, T)\, S_i(\lambda)\, d\lambda + \\ + L_i^{\uparrow} + (1 - \varepsilon_i)\, \tau_i\, L_i^{\downarrow}, \quad (4)$$

where ε_i is emissivity in the i-th spectral channel; τ_i is transmission coefficient of atmosphere in the i-th spectral channel; $S_i(\lambda)$ is normalized spectral sensitivity of the sensor in the i-th spectral channel; $L_i^{\uparrow}$ and $L_i^{\downarrow}$ are spectral densities of radiance of ascending and descending radiation in the i-th spectral channel [6].

The main cause of atmosphere effect on the radiation transfer in the far IR range is water vapors. In addition, τ_i and $L_i^{\uparrow}$, and, respectively, the recorded radiance temperature depend on the angle of sensor boresight. Hence, in order to determine the physical parameters of terrestrial surface on the basis of IR survey it is necessary to take into consideration the atmospheric, the angular, and the emission uncertainties in the radiation transfer equation. Unlike the first two factors that can be removed or reduced with the help of additional orbital or surface surveys, the uncertainty of spectral emissivity always requires certain *a priori* assumptions [7].

All known methods for determining temperature and emissivity are divided into the two different groups: *1*) the methods that use radiation transfer models and *2*) the methods that foresee the separation of temperature and emissivity. Both groups require knowledge of either emissivity of the surface or other parameters of the earth surface that enable to estimate it. The first group methods can be realized even for one spectral band, while the second group requires, at least, two different spectral ranges [8].

Since the studied array spectroradiometer is planned to be incorporated into the onboard optoelectronic instrumentation of *Sich* satellite system together with survey instruments of multispectral scanner operating in the visual and the near IR bands [9], it is feasible to develop two independent models for determining temperature and emissivity of the earth surface on the basis of IR survey data: the first one is for the combined application of IR spectroradiometer and survey instruments of multispectral scanner and the second one is for the separate use of IR spectroradiometer. Both models require additional models to make onboard calibration of IR spectroradiometer and to take into consideration the atmospheric effect. Also, it is necessary to have a database (spectral library) of spectral emissivity of typical surface layers in the far IR band in order to ensure information support of the models [10].

The most accurate and reliable method or determination of emissivity is the one based on the classification of surface layers and the use of respective databases followed by recalculation of radiance temperature of the surface measured by IR radiometer into the thermodynamic temperature [11]. However, the creation and the validation of huge databases of emissivity and other parameters of surface layers even for a small territory are very resource and time intensive processes [12]. Therefore, the most suitable method is the one based on Variable Atmospherically Resistant Index (VARI) [13]:

$$\varepsilon(\lambda) \approx a + b \ln \mathrm{VARI}, \qquad (5)$$

where $\mathrm{VARI} = \dfrac{\rho_{\mathrm{green}} - \rho_{\mathrm{red}}}{\rho_{\mathrm{green}} + \rho_{\mathrm{gred}} - \rho_{\mathrm{blue}}}$; ρ are spectral reflection coefficients of terrestrial surface in the respective ranges; $a \approx 1.1011$ and $b \approx 0.0857$ are regression coefficients.

Using the IR spectroradiometer without the data of multispectral survey in the visual and the near bands (for example, at night) the temperature and emissivity separation problem can be solved by joint processing of IR images recorded in several spectral bands at the same time. Insofar as the designed IR spectroradiometer is expected to be equipped with 3–5 separate spectral channels [14], it is feasible to use the TES (Temperature and Emission Separation) method, as the most advanced one [16], for processing the survey data [15].

The TES algorithm combines three groups of operations:

1) Normalization of emissivity in different spectral channels

$$\beta_i = \frac{\varepsilon_i}{\sum_j \varepsilon_j}, \qquad (6)$$

where β_i is normalized emissivity in the *i*-th spectral channel;

2) Calculation of MMD (Minimum Maximum Difference): $\Delta\beta_{\max} = \max_i \beta_i - \min_i \beta_i$;

3) determination of absolute value of minimum emissivity $\varepsilon_{\min}$ proceeding from empirical dependence

$$\varepsilon_{\min} \approx a + b\,(\Delta\beta_{\max})^r, \qquad (7)$$

where *a*, *b* and *r* are the coefficients of indicative regression to be obtain from experiments for each multispectral IR radiometer separately [17].

Having obtained $\varepsilon_{\min}$ one can calculate the absolute values of emissivity from (6):

$$\varepsilon_i = \beta_i \frac{\varepsilon_{\min}}{\min_j \beta_j}. \qquad (8)$$

With the help of (6)–(8), the temperature and emissivity separation has been made. Now, temperature can be easily calculated by the Planck formula (2).

CALIBRATION OF IR SPECTRORADIOMETER

The calibration of IR spectroradiometer means the determination of coefficients for recalculating the digital values *DN* of output image signal level into the absolute physical value, spectral density of radiance *L* on the sensor aperture measured in $\mathrm{W/(m^2 \times \mu m \times sr)}$. An important requirement for the calibration of spectroradiometer is linearity [18]. The linear calibration parameter can be described by the following dependence between input *DN* and output *L* [19]:

$$L = bDN + a, \tag{9}$$

where b and a are calibration coefficients of enhancement and shift.

For getting more accurate calibration coefficients during the flight, the satellite IR spectroradiometer is provided with a special calibration device incorporated into the far IR metallic emission element equipped with electric heating system with precision embedded thermometer [20]. The onboard calibration subsystem enables obtaining IR images of emission element in the whole radiometer view at known physical temperature of emitter, at closed input aperture. Having several, at least, 3 measurements at different temperature of the emitter, one can solve the uncertainty of calibration coefficients and emissivity of the emitter.

Hence, onboard calibration of IR spectroradiometer is based on a set of, at least, three measurements of emitter physical temperature, respective readings of spectral density of radiance L and DN. Insofar as direct onboard record of L is too complicated or impossible at all, it is calculated by formula (4), for which information on relative spectral sensitivity of the sensor in operating spectral range $S(\lambda)$.is required.

The calibration algorithm foresees two stages: firstly, to determine emissivity of the calibrating emitter from the equation (1):

$$\varepsilon = \frac{\Omega\, L}{M(\lambda, T)}, \tag{10}$$

where $M(\lambda, T)$ is the Planck spectral density of black body radiance; Ω is solid angle within which radiation spreads. This angle depends on the inner geometry of calibrating device; secondly, referring to the known values of L and DN, the calibration coefficients a and b in the equation system (9) are reproduced using the least square method [21].

IMPROVEMENT OF SPATIAL RESOLUTION OF IR IMAGES

Currently, the spatial resolution of far IR microbolometric spectroradiometers depends mainly on technological limitations of photo receiving arrays and is not sufficient. Nowadays, all over the world, the researchers are carrying out studies for developing techniques of sub-pixel digital imaging, which can ensure raising the spatial resolution of survey instruments without affecting the properties of photo receiving array [22]. The sub-pixel imaging significantly softens requirements for the number of photo detectors of multi-element photo receiver due to an increase in the time of record and a certain complication of the survey instrument design. The critical parameter is time per formation of image that is limited by requirement for uninterrupted imaging in the case of moving carrier of survey instruments, on the one hand, and by frequency of image formation and reading by the array photo receiver, on the other hand [23].

The proposed physical simulator of IR spectroradiometer enables enhancing the spatial resolution through restoration of resulting image on the basis of two images of lower spatial resolution displaced with respect to each other. The displacement is assumed to be the translational one, by non-integer number of pixels [24]. The Gauss regularization method based on transformation in sliding window has been implemented. For reducing the image noises the iterative image reconstruction method was used [25]. The method is based on the serial regularization of restored image and the removal of discrepancies and errors resulting from the substitution of restored image with simultaneous noise attenuation using the median filtration at the stage of decreasing the resolution of restored image [26].

The algorithm for processing the input images with low resolution enables the superposition of fragments of input images and their alignment, the calculation of auto-covariance matrixes and operators of window processing, and the above mentioned iterative regularization.

PRACTICAL REALIZATION OF THE PHYSICAL SIMULATOR

The testing and adjustment of engineering solutions with respect to design and functionality of IR array spectroradiometer were made using a physical simulator developed by researchers of

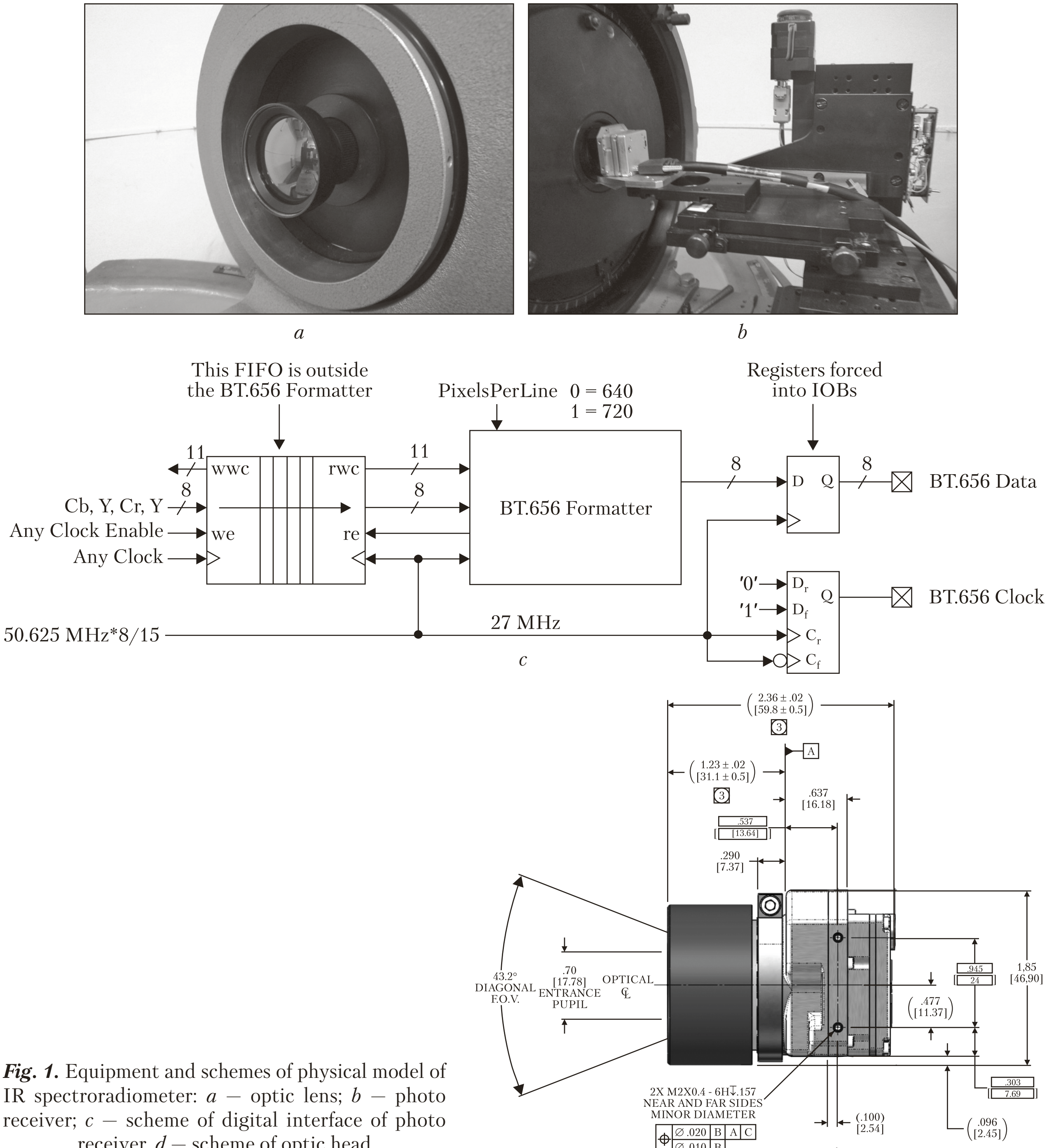
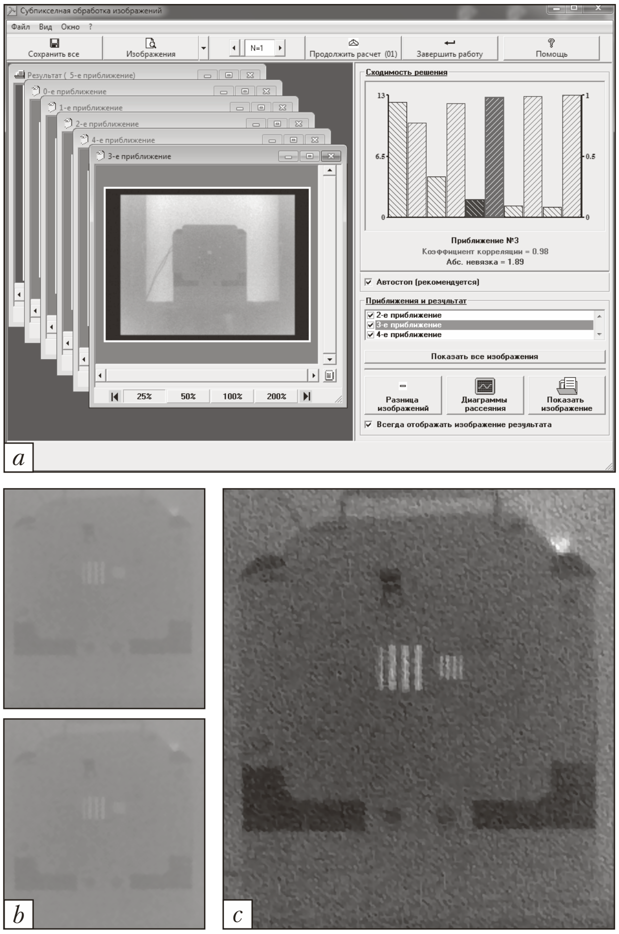


Fig. 1. Equipment and schemes of physical model of IR spectroradiometer: *a* — optic lens; *b* — photo receiver; *c* — scheme of digital interface of photo receiver, *d* — scheme of optic head

Arsenal corporation (Fig. 1 *a, b*). The simulator contains a microbolometric photo receiver, an IR lens, a splitter based on the system of IR filters enabling to create 3–5 operating spectral bands of spectroradiometer, as well as all necessary processing and service electronic devices [27]. The physical simulator was tested at a special stand designed at the *Arsenal* design office using the 4-groove



Приближение №3
Коэффициент корреляции = 0.98
Абс. невязка = 1.89

☑ Автостоп (рекомендуется)

☑ 2-е приближение
☑ 3-е приближение
☑ 4-е приближение

☑ Всегда отображать изображение результата

Fig. 2. Graphic interface (*a*) of software for sub-pixel processing of IR images and fragments of the input digital images having a poor resolution (*b*) with test patterns and the output digital image with enhanced resolution (*c*)

IR Foucault patterns with different spatial frequency and IR contrast as test images, a mirror optic collimator, and a precision positioning table.

The simulator was based on OEM-product of uncooled far IR microbolometric chamber of Tau series (http://www.flir.com/cores/display/?id=51981) manufactured by *FLIR Systems, Inc.* The schemes of digital interface and photo receiver are showed in Figs. 1 *c, d*. The products of FLIR Systems are widely used for aviation and specialized IR systems. The proposed physical simulator differs from counterparts [28] by the option of sub-pixel processing of digital IR images, which potentially is able to improve the resolution. The onboard sub-pixel IR imaging is done due to the special engineering solution [29] constituting a part of general technology proposed.

The sub-pixel processing of input series of IR images has been realized with the help of software developed by researchers of the R&D Center for Aerospace Research of the Earth under the Institute of Geologic Science of the NAS of Ukraine. The software enables obtaining IR images with enhanced resolution in a quick and easy manner. It has a modular architecture and advanced multi-window user interface (Fig. 2). It supports widespread formats of digital images. The software structure includes 10 separate computational modules [30].

RESULTS AND DISCUSSION

The proposed physical simulator of IR spectroradiometer was tested through obtaining several series of test IR images with different spectral bands, temperature, composition of optic patterns, and other parameters, processing and evaluating the spatial resolution, the IR contrast enabling reliable detection of test objects, the calibration coefficients, and the accuracy of restoration of temperature and emissivity.

During the tests, the following parameters have been assessed: enhancement of spatial resolution due to sub-pixel processing, minimum detectable temperature difference (MDTD), and minimum resolvable temperature difference (MRTD).

The statistical analysis of spatial resolution r^* by test images of IR patterns is based on calculating the significance of difference of respective areas of digital image [31]:

$$r^* = \frac{1}{\nu^*} \cong \frac{a\,\sigma}{|\Delta x|}\Phi^{-1}(P^*), \qquad (11)$$

where ν^* is threshold spatial frequency of image at which the object is recognized with sufficient prescribed probability P^*; a is size of photo detector of multi-element photo receiver; σ is total mean square deviation of noises in the image; Δx is difference of mean signal values in images of grooves and periods of the pattern; $\Phi(x)$ is the Laplace function [32].

The statistical analysis shows that the spatial resolution of physical simulator increases, at least, 1.66 times with 95% confidence, while MRTD grows 1.41 times, at average [33].

The accuracy of temperature and emissivity determined on the basis of IR survey data depends on many factors, in particular, on the errors caused by inaccurate definition of types of surface layers, the estimation of atmospheric parameters, as well as on the methods and computational algorithms. The majority of these uncertainties cannot be solved reliably. However, the accuracy of radiometer is determined mainly by the errors of calibration and can be estimated theoretically by propagating the errors through the computing lane of the determination of earth surface physical parameters.

The analytical solution of error propagation in the radiation transfer equations (1) — (4) for estimating the accuracy of earth surface temperature is complicated, therefore the statistic modelling by the Monte Carlo method has been used. The mean square deviations of temperature caused by the calibration errors of spectroradiometer physical simulator range within 0.08–0.37 K. Emissivity was accurately determined using the TES algorithm whose ratios (6) – (8) make possible to get an analytical solution with respect to the errors [34]. The calculated errors of emissivity vary from 0.005 to 0.02.

CONCLUSIONS AND PROPOSALS

Hence, during the project implementation, a physical simulator of frame IR spectroradiometer based on microbolometric detector array with sub-pixel imaging has been designed and studied. The device enables obtaining numerical physical parameters of earth surface objects on the basis of space survey data, with the use of satellite IR spectroradiometer in order to address problems of the Earth remote sensing (RS).

Among the project deliverables, there are a mathematical model and algorithms for determining thermodynamic temperature and zonal emissivity, algorithms and software for sub-pixel processing of IR images, and a panel for testing the physical simulator of IR spectroradiometer with enhanced spatial resolution. The developed simulator of IR spectroradiometer has been tested.

The implementation of project results will enable enhancing 1.4—1.8 times the spatial resolution of IR imaging due to sub-pixel processing, without any substantial complication of design.

The designed physical simulator has confirmed the possibility of creating a satellite array IR spectroradiometer with parameters that match the best world counterparts.

The project has created technological opportunities for implementing software and engineering solutions to be used for the design of first Ukrainian satellite IR spectroradiometer. As of today, the project results have been implemented at the *Arsenal*'s design office when developing and manufacturing an operating sample of array camera for RS system within the scope of assignments specified by target R&D space program of Ukraine for 2013–2017.

The further studies should be aimed at improving the models and algorithms for the determination of physical parameters of the earth surface on the basis of IR survey data in order to better the accuracy of temperature and emissivity measurements; at developing new methods and schemes for the sub-pixel imaging and restoration of IR images in order to enhance their spatial resolution and to improve MRTD; and at creating a prototype of satellite IR spectroradiometer having an enhanced spatial resolution with the help of sub-pixel image processing. The test bench for studying the physical simulator of spectroradiometer should be upgraded in order to ensure additional tests of calibration methods related to temperature and emissivity measurements under realistic conditions

The research was made within the framework of innovative R&D project of the Target Comprehensive Space Research Program of the NAS of Ukraine for 2012–2016, under financial support of the NAS of Ukraine (Resolution of the Presidium of the NAS of Ukraine no. 142 of 05.03.2014, grant no.13).

REFERENCES

1. *Bagatospektral'ni metody dystancijnogo zonduvannja Zemli v zadachah pryrodokorystuvannja*. Za red. V.I. Ljal'ko ta M.O. Popova. Kyiv: Nauk. dumka, 2006 [in Ukrainian].
2. Stankevych S.A. Vyjavlennja dodatkovyh rozpiznaval'nyh oznak ob'jektiv za rezul'tatamy bagatozonal'nogo dystancijnogo sposterezhennja v infrachervonomu spektral'nomu diapazoni. *Trudy akademii'*. Vyp.23. Kyiv: NAO Ukrai'ny, 1999: 92—99 [in Ukrainian].
3. Dash P., Gottsche F.-M., Olesen F.-S., Fischer H. Retrieval of land surface temperature and emissivity from satellite data: Physics, theoretical limitations and current methods. *J. of the Indian Society of Remote Sensing*. 2001, 29(1—2): 23—30.
4. Baranov V.L., Vodop'jan S.V., Gryshhuk R.V. Algorytm avtomatyzovanogo ocinjuvannja spektral'nogo koeficijenta teplovogo vyprominjuvannja. *Visnyk ZhDTU*. 2006, N 4(39): 77—83 [in Ukrainian].
5. Kriksunov L.Z. *Spravochnik po osnovam infrakrasnoj tehniki*. Moskva: Sovetskoe radio, 1978 [in Russian].
6. Tang H., Li. Z.-L. *Quantitative Remote Sensing in Thermal Infrared: Theory and Applications*. Berlin: Springer—Verlag, 2014.
7. Kealy P.S., Hook S.J. Separating temperature and emissivity in thermal infrared multispectral scanner data: Implications for recovering land surface temperatures. *IEEE Transactions on Geoscience and Remote Sensing*. 1993, 31(6): 1155—1164.
8. Wan Z., Dozier J. A generalized split-window algorithm for retrieving land-surface temperature from space. *IEEE Transactions on Geoscience and Remote Sensing*. 1996, 34(4): 892—905.
9. Popov M.A., Liholit N.I., Stankevich S.A. i dr. Obosnovanie tehnicheskogo oblika bortovogo optiko-jelektronnogo kompleksa srednego prostranstvennogo razreshenija perspektivnogo sputnika distancionnogo zondirovanija Zemli. *Sovremennye problemy distancionnogo zondirovanija Zemli iz kosmosa*. 2010, 2(7): 293—299 [in Russian].
10. Li Z., Li J., Jin X. et al. An objective methodology for infrared land surface emissivity evaluation. *J. of Geophysical Research*. 2010. V. 115. N D22: 308—322.
11. Snyder W.C., Wan Z., Zhang Y., Feng Y.—Z. Classification-based emissivity for land surface temperature measurement from space. *Intern. J. of Remote Sensing*. 1998, 19(14): 2753—2774.
12. Hulley G.C., Hook S.J., Baldridge A.M. ASTER Land Surface Emissivity Database of California and Nevada. *Geophysical Research Letters*. 2008. V. 35. N L13: 401—406.
13. Jiménez-Muñoz J.C., Sobrino J.A., Guaner L. et al. Fractional vegetation cover estimation from Proba/CHRIS data: Methods, analysis of angular effects and application to the land surface emissivity retrieval. *Proceedings of the 3rd ESA CHRIS/Proba Workshop*. Frascati: ESRIN, 2005: 161—170.
14. Popov M.O., Liholit M.I., Stankevych S.A. ta in. Mikrobolometrychna matrychna kamera dal'n'ogo infrachervonogo diapazonu dlja kosmichnoi' zjomky. *Tezy dopovidej XI Mizhnarodnoi' naukovo-tehnichnoi' konferencii' «Pryladobuduvannja: stan i perspektyvy»*. Kyiv: NTUU «KPI», 2012 [in Ukrainian].
15. Liang S. An optimization algorithm for separating land surface temperature and emissivity from multispectral thermal infrared imagery. *IEEE Transactions on Geoscience and Remote Sensing*. 2001, 39(2): 264—274.
16. Payan V., Royer A. Analysis of Temperature Emissivity Separation (TES) algorithm applicability and sensitivity. *Intern. J. of Remote Sensing*. 2004, 25(1): 15—37.
17. Liu H., Zhang C., Ye F., Zhang J. Temperature and emissivity separation methods based on TASI data. *Proceedings of International Conference on Remote Sensing, Environment and Transportation Engineering (RSETE 2013)*. Nanjing: Atlantis Press, 2013: 685—688.
18. Panfilov A.S., Burdakin A.A., Gavrilov V.R. i dr. Kachestvo radiometricheskih dannyh opticheskoj apparatury nabljudenija Zemli i postroenie rossijskoj sistemy obespechenija edinstva radiometricheskih izmerenij jetoj apparaturoj. *Sovremennye problemy distancionnogo zondirovanija Zemli iz kosmosa*. 2012, 9(2): 152—159 [in Russian].
19. Popov M.O., Stankevych S.A., Zjelyk Ja.I. ta in. Kalibruvannja spektral'noi' chutlyvosti sensora bagatospektral'noi' suputnykovoi' systemy «Sich-2» za nazemnymy spektrometrychnymy vymirjuvannjamy: poperedni rezul'taty. *Kosmichna nauka i tehnologija*. 2012, 18(5): 59—65 [in Ukrainian].
20. Liholit N.I., Tjagur V.M., Haritonenko E.V. IK-kamera kosmicheskogo bazirovanija s mikrobolometricheskoj matricej. *Materiali XI Mizhnarodnoï naukovo-tehnichnoï konferencïi «Avia—2013»*. Kyiv: NAU, 2013: 61—63 [in Russian].
21. Balyko I.A., Levashov S.V., Holodov D.V., Balyko A.K. Reshenie sistemy linejnyh uravnenij s izbytochnym chislom uravnenij. *Materialy Mezhdunarodnoj nauchno-tehnicheskoj konferencii «Fundamental'nye problemy radiojelektronnogo priborostroenija» (INTERMATIC-2012)*. Ch. 7. Moskva: MIRJeA, 2012 [in Russian].
22. *Super-Resolution Imaging*. Ed. by P. Milanfar. Boca Raton: CRC Press, 2010.
23. Stankevich S.A., Shklyar S.V., Tyagur V.M. Subpixel resolution satellite imaging technique. *Proceedings of the Ninth International Conference on Digital Technologies (DT'2013)*. Žilina: University of Žilina, 2013: 81—84.
24. Stankevych S.A., Shkljar S.V., Lubs'kyj M.S. Pidvyshhennja prostorovoi' rozriznennosti aeroznimannja na osnovi

subpikselnoi rejestracii zobrazhen. *Zbirnyk naukovyh prac Derzhavnogo naukovo-doslidnogo instytutu aviacii'*. Vyp.9(16). Kyiv: DNDIA, 2013: 110—117 [in Ukrainian].

25. Bannore V. *Iterative-Interpolation Super-Resolution Image Reconstruction: A Computationally Efficient Technique*. Berlin: Springer, 2009.
26. Popov M.A., Stankevich S.A., Shkljar S.V. Algoritm povyshenija razreshenija subpiksel'no smeshhjonnyh izobrazhenij. *Matematichni mashini ta sistemi*. 2015, N 1: 29—36 [in Russian].
27. Popov M.A., Stankevich S.A., Shklyar S.V. et al. Functional model of the new multiband infrared radiometer for «Sich» Earth observation satellite system. *Tezy dopovidej 14-oi' Ukrai'ns'koi' konferencii' z kosmichnyh doslidzhen'*. Uzhgorod: Instytut elektronnoi' fizyky NAN Ukrai'ny, 2014: 72.
28. Tatsumi K., Sakuma F., Kikuchi M. et al. A compact thermal infrared imaging radiometer with high spatial resolution and wide swath for a small satellite using a large format uncooled infrared focal plane array. *Proceedings SPIE 9241, Sensors, Systems, and Next-Generation Satellites XVIII*. Amsterdam: SPIE, 2014: 92411F.
29. *Pat. № 109181, Ukraina, MPK6 G01C 3/08, G01V 8/20, G06K 9/00, G06K 9/32, H04N 5/225*. Sposib pidvyshhennja prostorovoi' rozriznennosti pry dystancijnij zjomci z vykorystannjam subpiksel'noi' rejestracii' zobrazhen ta prystrij dlja jogo zdijsnennja. M.I. Lyholit, V.I. Ljalko, M.O. Popov, S.A. Stankevych, V.M. Tjagur, E.V. Harytonenko [in Ukrainian].
30. Popov M.A., Stankevych S.A., Tjagur V.M. y dr. Povishenye prostranstvennogo razreshenyja putëm subpyksel'noj obrabotky yzobrazhenyj. *Materialy Vosmoi Mizhnarodnoi naukovo-tehnichnoi konferencii «Problemy telekomunykacij—2014»* (PT-2014). Kyiv: ITS NTUU «KPI», 2014: 57—60 [in Ukrainian].
31. Stankevych S.A. Statystychnyj pidhid do vyznachennja porogovoi' moduljacii' cyfrovyh aerokosmichnyh zobrazhen'. *Kosmichna nauka i tehnologija*. 2005, 11(3/4): 81—84 [in Ukrainian].
32. Stankevych S.A., Shkljar S.V. Udoskonalenyj algorytm vyznachennja perehidnoi funkcii na cyfrovomu aerokosmichnomu zobrazhenni. *Uchenie zapysky Tavrycheskogo nacyonal'nogo unyversyteta ym. V.Y. Vernadskogo*. 2005. T. 18(57). N 2: 97—102 [in Ukrainian].
33. Ljalko V.I., Popov M.O., Stankevych S.A. ta in. Fizychna model' infrachervonogo spektroradiometra iz subpiksel'nym pidvyshhennjam prostorovoi rozriznenosti. *Materialy Ukrainskoi naukovo-tehnichnoi konferencii'«Aviakosmichne pryladobuduvannja»*. Kyiv: KP SPB «Arsenal», 2014: 33—35 [in Ukrainian].
34. Sabol Jr. D.E., Gillespie A.R., Abbott E., Yamada G. Field validation of the ASTER Temperature—Emissivity Separation algorithm. *Remote Sensing of Environment*. 2009, 113(11): 2328—2344.

В.І. Лялько[1]*, М.О. Попов*[1]*, С.А. Станкевич*[1]*,*
С.В. Шкляр[1]*, В.М. Подорван*[1]*, М.І. Лихоліт*[2]*,*
В.М. Тягур[2]*, К.В. Добровольська*[2]

[1] Науковий центр аерокосмічних досліджень
Землі ІГН НАН України, Київ
[2] Казенне підприємство спеціального приладобудування
«Арсенал» ДКА України, Київ

ФІЗИЧНА МОДЕЛЬ ІНФРАЧЕРВОНОГО СПЕКТРОРАДІОМЕТРА З ПІДВИЩЕННЯМ ПРОСТОРОВОЇ РОЗРІЗНЕННОСТІ ЗА ДОПОМОГОЮ СУБПІКСЕЛЬНОЇ ОБРОБКИ ЗОБРАЖЕНЬ

Наведено математичну та фізичну моделі нового кадрового інфрачервоного спектрорадіометра на основі мікроболометричного матричного приймача із субпіксельною реєстрацією зображень. Спектрорадіометр планується включити до складу бортового обладнання перспективної супутникової системи «Січ» для одержання фізичних характеристик об'єктів земної поверхні за матеріалами інфрачервоної космічної зйомки з підвищенням просторової розрізненності.

Ключові слова: інфрачервона космічна зйомка, кадровий мікроболометричний спектрорадиометр, субпіксельна реєстрація зображень, підвищення просторової розрізненності.

В.И. Лялько[1]*, М.А. Попов*[1]*,*
С.А. Станкевич[1]*, С.В. Шкляр*[1]*, В.Н. Подорван*[1]*,*
Н.И. Лихолит[2]*, В.М. Тягур*[2]*, Е.В. Добровольская*[2]

[1] Научный центр аэрокосмических исследований
Земли ИГН НАН Украины, Киев
[2] Казённое предприятие специального приборостроения
«Арсенал» ГКА Украины, Киев

ФИЗИЧЕСКАЯ МОДЕЛЬ ИНФРАКРАСНОГО СПЕКТРОРАДИОМЕТРА С ПОВЫШЕНИЕМ ПРОСТРАНСТВЕННОГО РАЗРЕШЕНИЯ ПРИ ПОМОЩИ СУБПИКСЕЛЬНОЙ ОБРАБОТКИ ИЗОБРАЖЕНИЙ

Представлены математическая и физическая модели нового кадрового инфракрасного спектрорадиометра на основе микроболометрического матричного приёмника с субпиксельной регистрацией изображений. Спектрорадиометр планируется включить в состав бортового оборудования перспективной спутниковой системы «Січ» для получения физических характеристик объектов земной поверхности по материалам инфракрасной космической съёмки с повышением пространственного разрешения.

Ключевые слова: инфракрасная космическая съёмка, субпиксельная регистрация изображений, кадровый микроболометрический спектрорадиометр, повышение пространственного разрешения.

Received 02.06.15