Simulation of satellite landmark navigation on the base of optoelectronic image processing technique

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ABSTRACT

Hybrid optoelectronic landmark navigation is proposed as backup navigation for Low Earth Orbit satellite. Optoelectronic navigation can use earth observation camera, originally not assigned for navigation purposes. The concept of the landmark navigation system is based on the onboard optical correlator application for real time matching of the earth images and pre-recorded images of landmarks with known coordinates. The software model of image processing by optical correlator has been developed to test the system operation in simulated experiments and to estimate the expected performance. The hardware model of the joint transform optical correlator has been manufactured and tested. The model uses commercially available optoelectronic components and works with PC, which performs all digital processing and data flow control. As a result of the model testing, the feasibility of the system concept and the adequacy of the software model have been proved. The image processing system which calculates satellite attitude and position on the base of correlation peaks measurements has been used for simulation of optoelectronic satellite landmark navigation. In the series of simulated experiments the navigation accuracy was estimated in presence of image distortions and noise for earth observation mission.

Keywords: optical correlator, image processing, landmark, Earth observation, satellite navigation

1. INTRODUCTION

Processing optical images represented by large two-dimensional data arrays is necessary for space monitoring problems. Real time image processing under the circumstances of onboard computing power shortage is a difficult problem. Usage of hybrid optoelectronic systems increases processing performance numerously[1]. Optical correlators fall into category of these systems. Optical correlator is an optoelectronic device, capable of fast producing the 2D function of correlation[2] between the image of landmark from database and current earth image from camera. Application of correlator for landmark recognition is useful for backup navigation of Low Earth Orbit satellite. Optoelectronic navigation can use earth observation camera, originally not assigned for navigation purposes. The concept of the landmark navigation system is based on the onboard joint transform optical correlator (JTC) application for real time matching of the earth images and pre-recorded images of landmarks with known coordinates. The system can be used for satellite position and attitude determination, precision camera pointing and for onboard georeferencing of the obtained images.

One of optical correlator applications is searching and recognizing textures and objects on Earth surface. Correlator can be used for automatic georeferencing of aerospace images obtained from ground receiver stations.

The general algorithm of operation for backup navigation system comprises the following steps:

- landmark imaging by an onboard camera;
- image processing and recognition of landmark (area which coordinates are known);
- transformation of landmark image coordinates to angular coordinates;
- estimation of the state vector of satellite motion using the landmark image data and additional measurements from magnetometer (with Kalman filter).

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2. INFORMATION SYSTEM OF IMAGE PROCESSING FOR OPTOELECTRONIC NAVIGATION

Information system of image processing for optoelectronic navigation is developed. The information system performs the following functions:

- modeling the image processing by JTC using the fast Fourier transformation algorithm[3];
- generation of test Earth surface images;
- geometric transformation of landmark images;
- calculation of satellite attitude and position determination on the base of correlation peaks measurements;
- selection of landmarks from database using rough position data from magnetometer.

The information system is useful for onboard navigation, estimation of characteristics of various navigation system modifications and investigation of image distortions effect on accuracy of navigation.

The software model of JTC (as part of the information system) has been created. The model has been developed to test the system operation in simulated experiments and to estimate the expected performance. The model is based on the Kirchhoff diffraction theory and takes into consideration the imperfections of the optoelectronic components, used in the optical system of the correlator. Optical Fourier transform of the image was imitated by fast digital Fourier transform with appropriate quadrants rearrangement to put the dark current component in the centre of the image. Input image for first Fourier transform was embedded in the middle of black square to enlarge the spectrum image. Output matrix was squared to obtain intensity distribution image. Limited dynamic ranges of TV camera and SLM were considered by truncating of real intensity values to integers in the range from 0 to 255.

Navigation algorithms are based on the mathematical model of the optoelectronic landmark navigation. The mathematical model considers the obtaining of images by Earth observation camera and the impact of navigation parameters on correlation peaks coordinates[4].

The following algorithms are created for information system:

- algorithm of satellite position determination with accurate attitude data available;
- algorithm of satellite attitude and position determination without accurate attitude data;
- algorithm of geometric transformation of landmark images from onboard database for given satellite attitude;
- algorithm of test current image generation for given satellite attitude and landmark image.

The landmark database does not include whole underlying Earth surface because of excess volume of such images and inapplicability of most of surface areas for landmarks.

Two measurements per orbital period are enough for backup navigation[5]. Volume of landmark database is less than 1 GB in this case. The database includes landmarks obtained from 2000-3000 images of separate Earth surface areas of 30×60 km size approximately (images of city and suburbs, for example). About 50-60 landmarks can be obtained from one area image.

Fig. 1 shows layout of landmarks on the area. Point O is center of rectangle ABCD that represents the area contains the set of landmarks. Landmarks are shown on Fig. 1 as small gray squares in three rows.

Structure of landmark database is given on Fig. 2.

Fig. 3 represents the algorithm of satellite attitude and position determination without accurate attitude data known. Attitude of satellite at any moment of time is described by three rotation angles – pitch θ, roll φ and yaw ψ; y-axis coincides to satellite velocity vector. When satellite came less than 10 km near the area (by magnetometer measurement), the landmarks from left row on Fig. 1 are checked if they belong to current image from camera. Correlation between the current image and each sixth landmark from the left row (these landmarks are darker on Fig. 1) is determined to check this condition. This operation is made for the subsequent images while the correlation peaks are detected.

After detecting the position of landmark center on current image (by the peak position measurement), three landmarks is chosen. These landmarks are used for navigation. The correlator processes each current image jointly with each of three chosen landmarks while it is detected that all three landmarks belong to one current image.

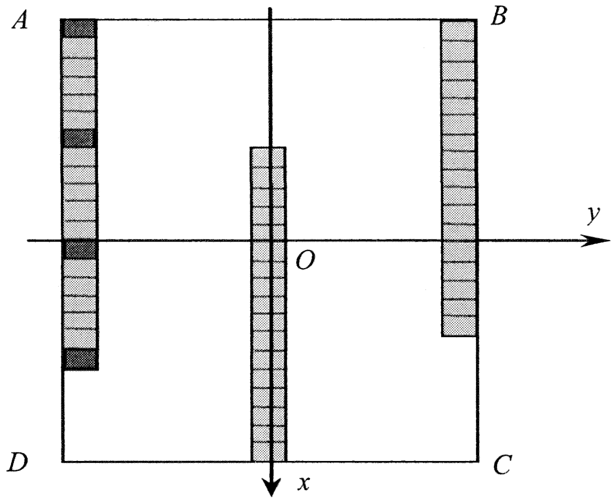

Fig. 1. Layout of landmarks on the area.

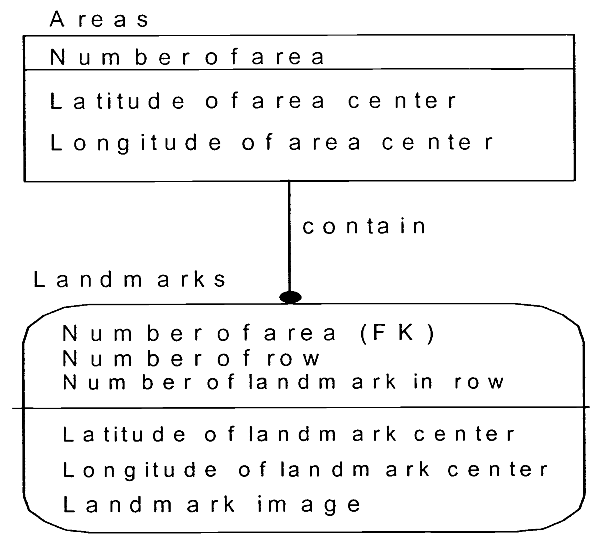

Fig. 2. Structure of landmark database.

Yaw ψ most affects peak determination accuracy, so it is necessary to adjust value of ψ. One of three landmarks is sequentially geometrically transformed for values $\psi = -1°,\ldots,+1°$ with step 0,5°, $\varphi = 0°$ and $\theta = 0°$. Then correlation between each transformed landmark and one current image are calculated sequentially. Value of ψ resulting in greater peak-to-noise ratio (PNR) is chosen. So the value of yaw is obtained with error not more than 0,25°. Then three landmarks are geometrically transformed for the chosen value of ψ, and coordinates of three transformed landmarks at the current image are found using correlation.

As latitude α_i, longitude β_i (from database) and vector $\mathbf{q}_{ivwu} = (\mathbf{q}_{iv}, \mathbf{q}_{iw}, f)^{\mathrm{T}}$ determining the coordinates of landmark image centre on focal plane (computed from correlation peak) are known for each of three landmarks, position and attitude of satellite can be determined by minimization of cost function G on the plane (θ, φ, ψ, α, β):

$$G = \sum_{i=1}^{3}\left(\left(\frac{\left(\hat{\mathrm{K}}\cdot(0,0,H+R)^{\mathrm{T}}\right)_{x^0} - R\sin\alpha_i}{\left(\hat{\mathrm{K}}\cdot\hat{\mathrm{M}}\cdot\mathbf{q}_{ivwu}\right)_{x^0}} - \frac{\left(\hat{\mathrm{K}}\cdot(0,0,H+R)^{\mathrm{T}}\right)_{y^0} + R\cos\alpha_i\sin\beta_i}{\left(\hat{\mathrm{K}}\cdot\hat{\mathrm{M}}\cdot\mathbf{q}_{ivwu}\right)_{y^0}}\right)^2 + \left(\frac{\left(\hat{\mathrm{K}}\cdot(0,0,H+R)^{\mathrm{T}}\right)_{x^0} - R\sin\alpha_i}{\left(\hat{\mathrm{K}}\cdot\hat{\mathrm{M}}\cdot\mathbf{q}_{ivwu}\right)_{x^0}} - \frac{\left(\hat{\mathrm{K}}\cdot(0,0,H+R)^{\mathrm{T}}\right)_{z^0} - R\cos\alpha_i\cos\beta_i}{\left(\hat{\mathrm{K}}\cdot\hat{\mathrm{M}}\cdot\mathbf{q}_{ivwu}\right)_{z^0}}\right)^2\right), \tag{1}$$

where H is orbit altitude, expression $(\mathbf{Q})_x$ means projection of vector $\mathbf{Q}$ onto x-axis, matrix $\hat{\mathrm{M}}$ depends on θ, φ, ψ, matrix $\hat{\mathrm{K}}$ depends on α, β, Earth radius is assumed to be

$$R = \sqrt{\frac{R_{\min}^2 R_{\max}^2 (\mathrm{tg}^2\alpha + 1)}{R_{\max}^2 \mathrm{tg}^2\alpha + R_{\min}^2}}, \qquad (2)$$

where $R_{\max}$ и $R_{\min}$ – major and minor semi-axes of Earth ellipsoid correspondingly[4].

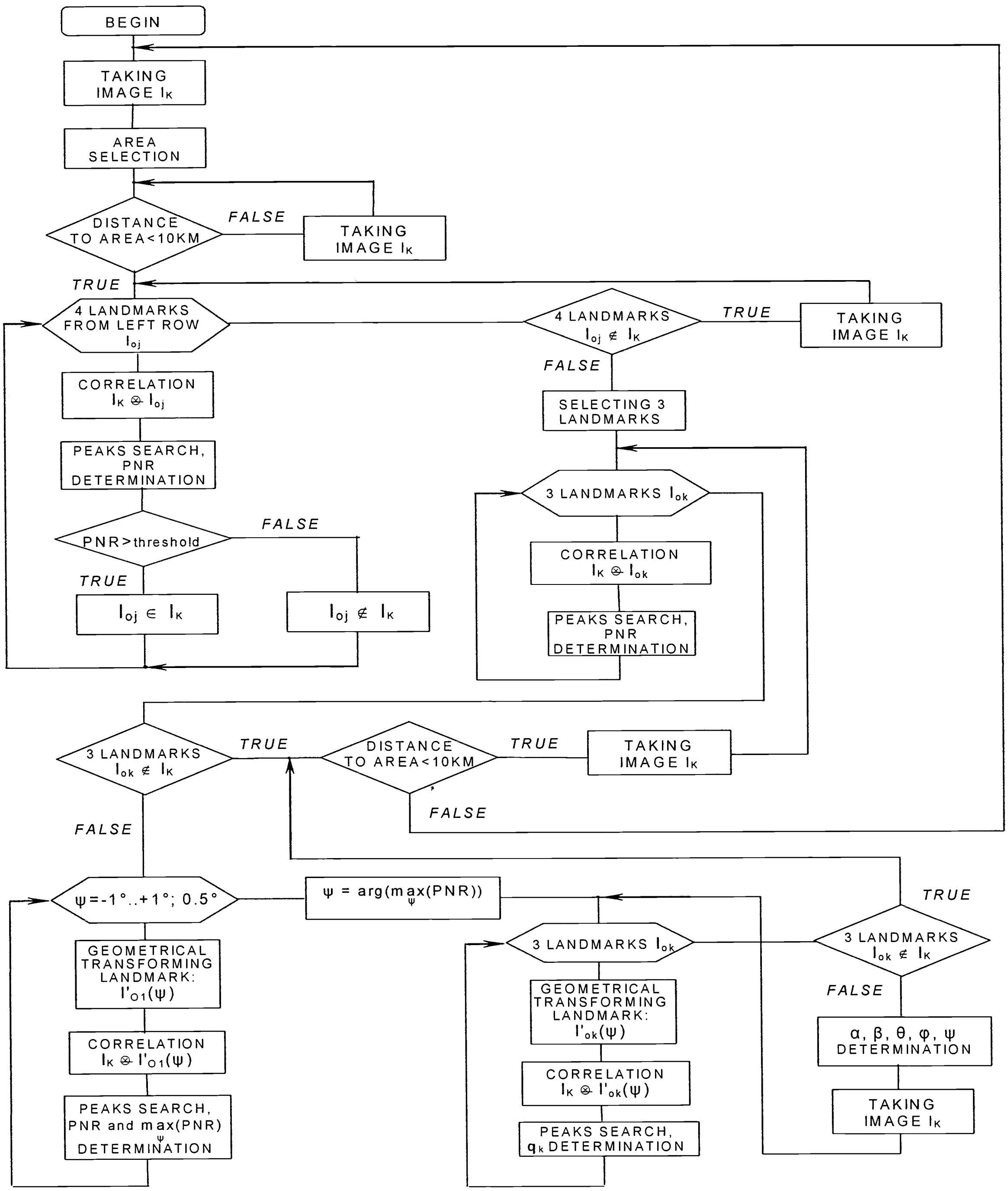

Fig. 3. Algorithm of satellite position and attitude determination.

3. EXPERIMENTAL SIMULATION

The hardware model of the joint transform optical correlator has been manufactured and tested[6]. The model uses commercially available optoelectronic components and works with PC, which performs all digital processing and data flow control. Due to the low data rate via standard parallel interface, the model does not have the real time performance, but represents the real system in terms of the accuracy of landmark position determination. As a result of the model testing, the feasibility of the system concept and the adequacy of the software model have been proved.

Close similarity between spectra of test images and correlation images obtained from hardware model of optical correlator and from information system of image processing are shown. Inappreciable distinction between the images are resulted by uncompensated reflections in optical system, inaccuracies in spectrum and correlation images detection and difference in size of images processed by hardware and software models. This distinction does not sensibly affect the accuracy of peak position determination.

Fig. 4 shows input image containing current and reference images. Spectrum and output correlation images obtained from hardware model of JTC are represented on Fig. 5 and Fig. 6 respectively. Spectrum and output correlation images obtained from information system of image processing are shown on Fig. 7 and Fig. 8 respectively.

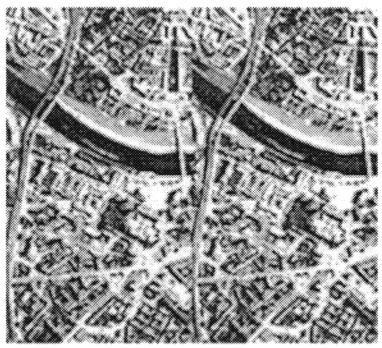

Fig. 4. Input image.

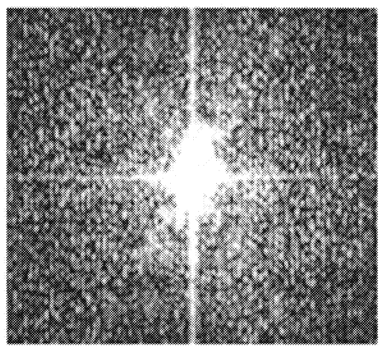

Fig. 5. Spectrum image obtained from hardware model of JTC.

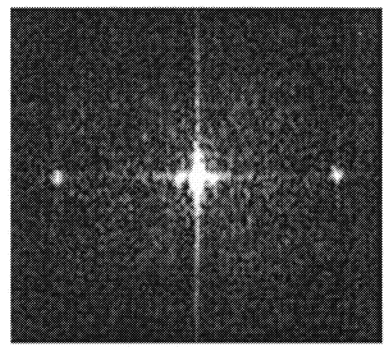

Fig. 6. Output correlation image obtained from hardware model of JTC.

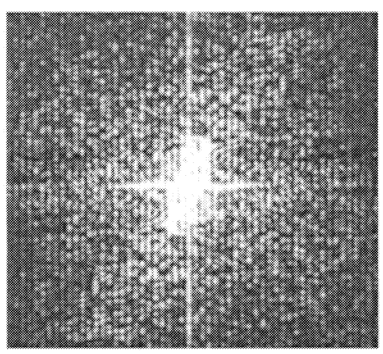

Fig. 7. Spectrum image obtained from software model of JTC.

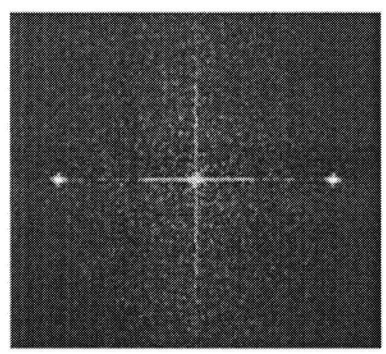

Fig. 8. Output correlation image obtained from software model of JTC.

The series of simulated experiments was performed to ascertain robustness of navigation system of Earth observation satellite to image distortions and noise.

The real satellite image of Ufa city and suburbs (Fig. 9) was used for simulated experiments with the information system software. The image has the ground resolution of 10 m per pixel. Areas of urban territory are used as landmarks because they result in better accuracy of peak detection. Satellite orbit is assumed to be circular one with 500 km altitude. The following image sizes (in pixels) are assumed: 1280×1024 – camera image for satellite position determination with accurate attitude data known; 2832×2124 – camera image satellite attitude and position determination by three landmarks; 256×256 – landmark image. Layout of the current and reference images in the input plane of JTC are shown on Fig. 10.

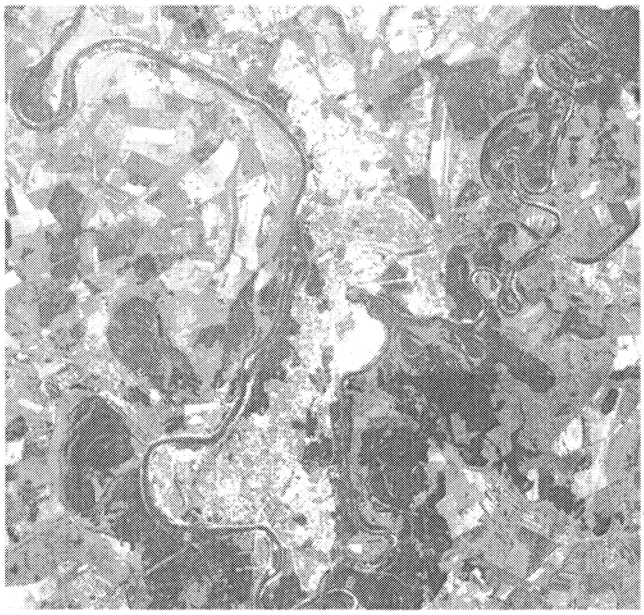

Fig. 9. The image used for simulated experiments.

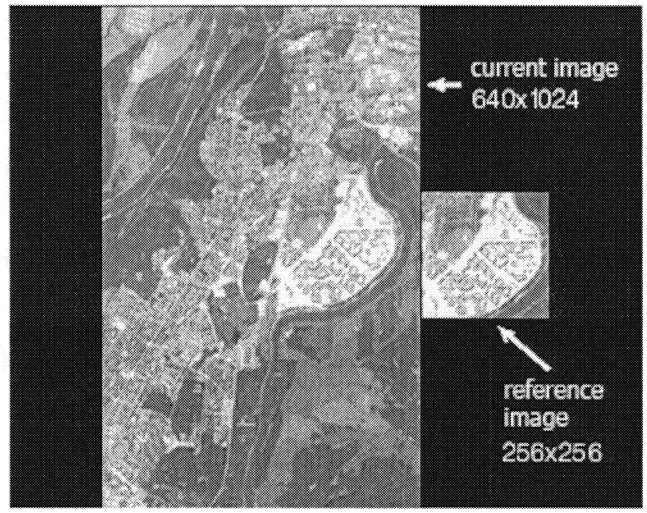

Fig. 10. Layout of the current and reference images in the input plane of JTC.

Fig. 11-18 represent distortion and noise characteristics influence on PNR. Peak discrimination is fully characterised by this PNR[6]. If PNR exceeds one thousand, high reliability of correlation peak detection and high accuracy of its position determination are reached.

Fig. 11 represents the correlation peak-to-noise ratio (PNR) in the output correlation plane of the optical correlator obtained for different amount of current image rotation relative to reference. If the angle of mutual rotation of the images is no more, than 0.35 degrees, the ratio exceeds one thousand.

Fig. 12 represents the effect of current image scaling on the correlation peak-to-noise ratio. To keep the ratio above one thousand, scaling factor should be limited to 1.005.

The effect of current image brightness changing is shown on Fig. 13. To keep the ratio above one thousand, change in brightness should be in the range –175…+135 (the average brightness of reference image used for simulation was +138).

Graph of PNR against the percentage of reference and current images superposition is shown on Fig. 14. It can be seen, that 60% superposition gives PNR more, than 1000. Practically it means that reliable landmark recognition and satellite position estimation is possible if at least 60% of reference image is visible within the current frame.

Perspective distortions arise, if the direction to the centre of landmark deviates from nadir.

First case considered for simulation is the whole camera deviation from nadir with the land-mark image situated in the centre of field-of-view. The simulation results are shown on the Fig. 15. The peak-to-noise ratio is above one thousand, if the deviation (tilt) angle is limited by 4.5 degrees.

Second type of perspective distortions occurs when the camera is oriented to nadir, but the landmark image is shifted from the centre of field-of-view. With orthoscopic optics the main source of distortions in this case will be the Earth sphericity. Fig. 16 represents the dependence of the peak-to-noise ratio on off-nadir angle of landmark. The effect of the off-nadir observation on correlation peak brightness is much less in this case: the peak-to-noise ratio is above one thousand, if the angular deviation from nadir is no more than 14 degrees.

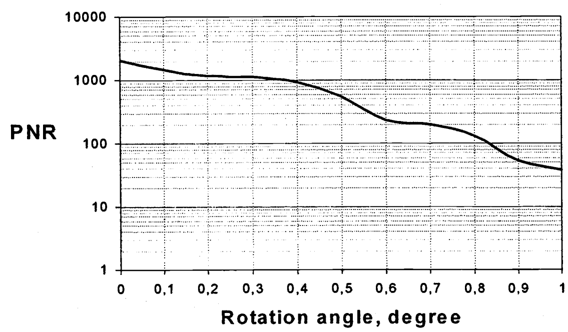

Fig. 11. Degradation of PNR with rotation of current image.

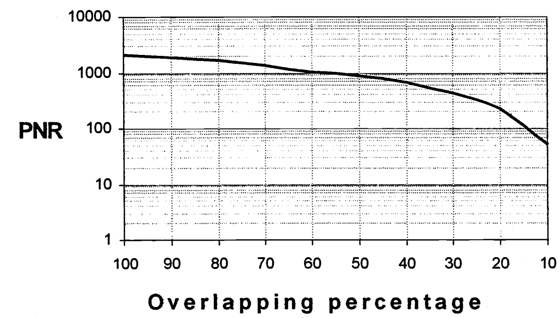

Fig. 14. Degradation of PNR with changing the current and reference images overlapping.

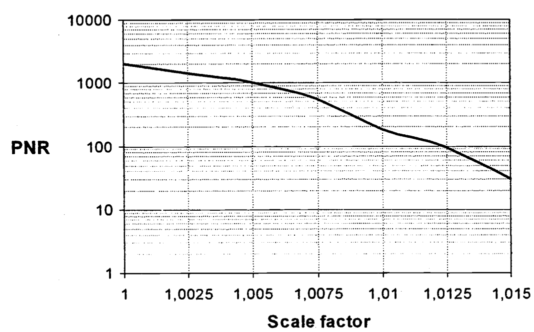

Fig. 12. Degradation of PNR with current image scaling.

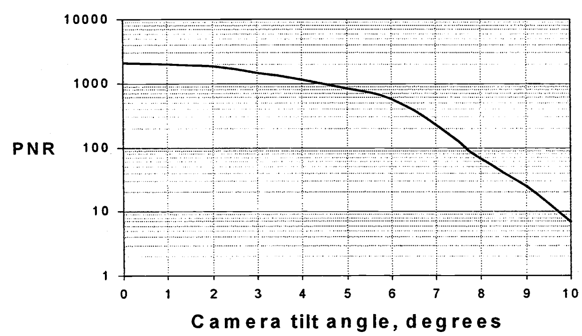

Fig. 15. Degradation of PNR with perspective distortions – camera axis is directed to landmark.

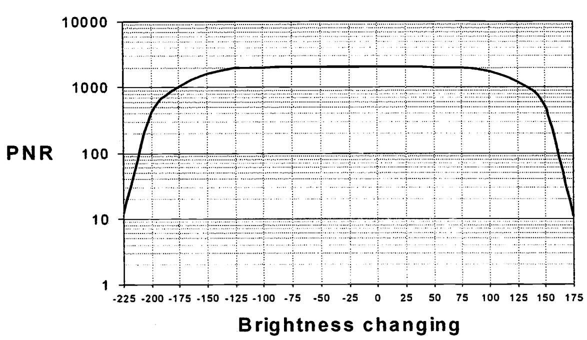

Fig. 13. Changing of PNR with changing brightness of current image.

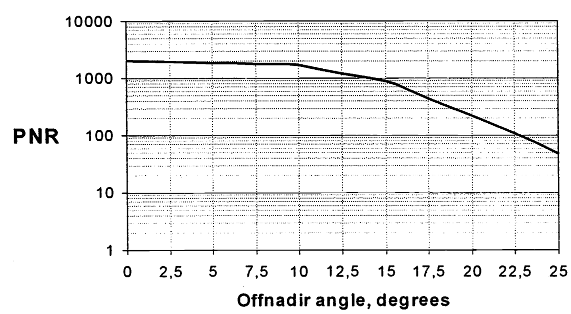

Fig. 16. Degradation of PNR with perspective distortions – camera axis is directed to nadir.

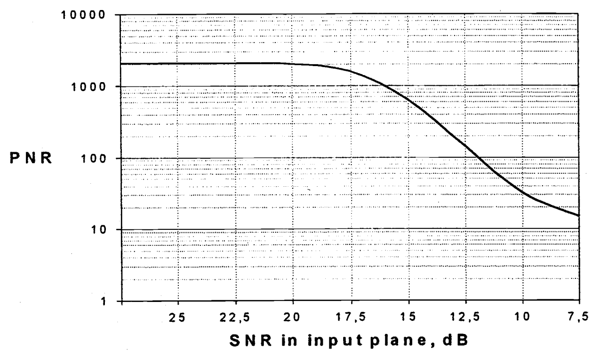

Fig. 17. Input noise influence on PNR.

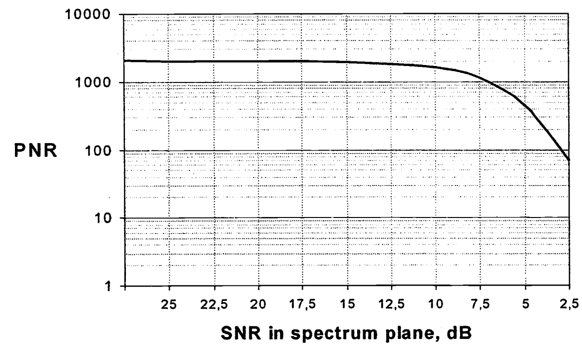

Fig. 18. Spectrum plane noise influence on PNR.

Low signal-to-noise ratio (SNR) is typical for the high-resolution satellite images due to limited exposure time. Video input/output devices such as SLMs and CCDs add also noisy components in data. However, the joint transform correlator is not so sensitive to additional noise in the input and intermediate planes.

Fig. 17 represents the effect of Gaussian noise in the input plane on the simulated JTC on the correlation ambient noise in the output plane. If the input image noise SNR is less, than 16 dB, the PNR exceeds one thousand.

Fig. 18 represents the effect of noise added to intermediary (joint spectrum) plane. The SNR of noise in intermediary plane can be increased up to 7 dB with the PNR remaining above 1000. These results show, that high accuracy of grey scale reproducing is not necessary for the SLMs to be used in JTC scheme and conventional devices can easily meet noise level requirements.

To make the first order estimation of the system accuracy in presence of image distortions and noise, series of simulated experiments was carried.

For the each pair of images the amount of mutual shift was calculated on base of analysis of optical correlator simulated output (measuring of the correlation peak coordinates) and compared with the real value used for corresponding reference image generation. From this comparison a set of differences was obtained and used for statistics calculation.

To take into account the effect of the image distortions the current image was rotated, scaled and perspective distorted before simulation of the optical processing. The amounts of distortions were fixed for each test with value of 0.35 degrees for rotation, 1.005 for scaling and 3 degrees for simulated camera axis deviation from nadir (perspective distortions). These values were chosen as having maximal acceptable impacts to measurements errors.

To imitate the effect of the noise, Gaussian noise was added to the input image, joint transform and the output correlation images. The amount of added noises corresponded to the SNR of 25 dB for input image, 40 dB for joint transform spectrum and 55 dB for the output correlation images.

As a result of the simulation root mean square error of 0.22 pixel was obtained for images shift measurements with mentioned above noise and distortions.

Estimation of the accuracy of spacecraft position and attitude determination was made using the developed image processing system for satellite landmark navigation. Of course, the image chosen for the simulated testing (Fig. 9) represents only one class of Earth scenes in terms of texture parameters and scale, so the test results will be most applicable to the urban territories imaged with resolution of 5-15 m per pixel. At the same time these results are a first-order estimation of expected system performance for various high- and medium resolution Earth images processing.

Expected accuracy characteristics of the system (as result of simulation) are:

- satellite position estimation error (with accurate attitude known) $\pm$ 30 m;
- satellite position estimation error (without accurate attitude known) $\pm$ 500 m;
- error of satellite attitude estimation $\pm$ 0.06°;
- error of pointing of Earth imaging camera $\pm$ 5 m.

4. CONCLUSION

The optoelectronic system for satellite position and attitude determination, precision camera pointing and onboard georeferencing of the obtained images is introduced. The JTC is proposed to be used for fast matching of the current landmark images from onboard camera with ones from pre-recorded landmark database to recognise the landmarks and measure landmark positions on the input images.

Information system of image processing for optoelectronic navigation is developed. The system realizes algorithms of satellite attitude and position determination. The information system is useful for onboard navigation, estimation of characteristics of various navigation system modifications and investigation of image distortions effect on accuracy of navigation.

The software model of JTC (as part of the information system) has been created to test the system operation in simulated experiments and to estimate the expected performance. The hardware model of the JTC has been manufactured and tested. As a result of the software and hardware models testing, the feasibility of the system concept and the adequacy of the software model have been proved.

The effects of the current image distortions on correlator performance were investigated for rotation, scale, perspective distortions, partial overlapping, brightness change, noise. As the results of the simulated experiments, the acceptable limits of image distortions and noise have been estimated.

The accuracy characteristics of optoelectronic navigation system were estimated using the developed information system. They show the possibility to use optoelectronic system for the satellite backup navigations in real conditions.

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