Optoelectronic image processing system for satellite landmark navigation

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ABSTRACT

Information system determining the satellite navigation parameters on the base of landmark image processing is considered. The concept of the optoelectronic navigation is based on the onboard optical correlator application for real time matching of the Earth images and prerecorded images of landmarks with known coordinates. The system is suitable for the low-orbit Earth imaging missions with 3-axis attitude stabilization and can be used for backup landmark navigation, precision pointing of the imaging payload and for onboard georeferencing of the obtained images. Mathematical model of the optoelectronic landmark navigation is considered. Compact optics design, the software and hardware models of the joint transform optical correlator have been developed. Experimental results obtained by using the image processing system are represented. The effects of the current image distortions on correlator performance were investigated. In the series of simulated experiments the accuracy of images matching was estimated in presence of image distortions and noise typical for high resolution Earth observation mission. The possibility to obtain the sub-pixel accuracy of images matching in real conditions under noisy environment is shown.

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

1. INTRODUCTION

Low Earth Orbit (LEO) Satellite Networks offer new commercial and technological potentials in the area of global information networking. Making LEO Satellite Networks generates quite new requirements on the producers and operators of such systems: the change from single to multispaceceraft production and operation under rigid commercial constraints. These requirements imply cost optimized solutions for both spacecraft production and spacecraft operation. This challenging task can be solved using novel concepts and techniques taking into account the specific characteristics of the low earth orbit and the satellite network scenario. The proposed system deals with novel concepts for the cost optimized realization of the mission critical function named onboard navigation for LEO-satellites. A reliable and accurate provision of satellite attitude and position is mandatory for the basic tasks of spacecraft attitude stabilization and control, spacecraft orbit control as well as for the general payload management (communication, earth observation, etc.).

Conventional implementations of the navigation function use specific equipment for each subfunction (position, attitude) and explicite hardware redundancy (i.e. at least two identical devices) to cope with equipment failures. These concepts offer the best performances in terms of accuracy, availability and operational freedom, but suffer from high overall cost in terms of monetary value, electrical power, mass, space, testing and engineering effort. Therefore creation of navigation system for commercial LEO-satellite using novel concepts is urgent problem.

2. CONCEPT OF OPTOELECTRONIC LANDMARK NAVIGATION SYSTEM FOR LEO SATELLITE

The concept is based on the maximum-use principle of any onboard equipment:
- hardware minimization by use of any single navigation equipment for both position and attitude determination;
- substitution of the conventional hardware redundancy by functional redundancy.

This principle reduces overall navigation cost[1].

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The secondary equipment (Earth observation camera), originally not assigned for navigation purposes, is used for backup navigation (optical secondary payloads may be interesting for LEO communication satellites, because they can provide additional information which can be distributed on a commercial basis by the network owners).

GPS/GLONASS receiver is used as the primary equipment for nominal operation[2]. To cope with failures of the primary navigation equipment, the combination of secondary sensors and advanced data processing will substitute the primary equipment. Backup navigation system is based on the fusion of geomagnetic and optoelectronic measurements.

The landmark navigation can be used for: precise pointing of the Earth observation equipment; precise attitude evaluation using the GPS position data; providing a backup for the GPS system, georeferencing the camera images.

The main low-level tasks of the landmark navigation are landmarks recognition and determination of navigation angles in spacecraft body fixed coordinate frame. This can be done by extracting the specific high contrast features of the landmark image (coastline, rivers, etc) and matching it with reference contours from the onboard database[3]. This method, however, limits the number of the Earth scenes, which can be used as landmarks and is sensitive to image distortions caused by natural reasons (changing of coastline, clouds covering) and errors of spacecraft attitude.

To improve the accuracy and reliability correlation analysis can be used to compare the current image of the landmark and reference image with known geographical coordinates. Correlation method has the advantages of high reliability of landmark recognition, even if some features of it are changed (e.g. due to season changes), the image is partially obscured by clouds or slightly geometrically distorted due to attitude instability. Correlation method also makes possible high accuracy for navigation angles determination and has low sensitivity to image noise. Practically, any Earth scene image can be used as landmark, this makes possible to use the image of the observation target itself. The main disadvantage of this method is large amount of digital image processing necessary to calculate 2D-correlation function for the current and reference images. This means large processing time and overload of the onboard computer.

Using the onboard optical correlator for fast recognition of the landmarks allows to save the digital processing resources onboard and to minimize the processing time. The optical correlator is an optoelectronic device, capable of fast optical determination of 2D correlation function of two images[4].

There are two main schemes of optical correlator: Vander Lugt scheme with the complex matching filter in the Fourier plane, and joint transform correlator, where reference and current images are jointly optically processed to form a correlation output. Vander Lugt correlator require complex digital processing of the reference image to produce the matching filter, so it is impossible to form the matching filters in real time onboard the satellite. Vander Lugt correlator is also much more sensitive to the optical elements misalignments[5]. Joint transform correlator (JTC) does not require any digital processing of the reference image and therefore can be used for real time operation. Thus joint transform scheme suits better for onboard matching of the Earth images for landmark navigation.

Fig. 1 shows the scheme of landmark navigation with optical correlator. The concept is based on the onboard optical correlator application for real time matching of the Earth images and prerecorded images of landmarks with known coordinates. The system is suitable for the low-orbit Earth imaging missions with 3-axis attitude stabilization. The system can be useful for missions to other planetary bodies, where no GPS data are available. The operational principle is based on analysis of the Earth images from the onboard camera in order to detect the landmarks with known coordinates (the landmarks images and their coordinates are stored in the onboard database). Selection of landmarks from database and its geometric transformation are made on the base of rough position data from magnetometer. Transformed landmark images and current earth surface image are entered to the correlator. Correlation peaks positions and peak-to-noise ratio (PNR) in the output correlation plane of JTC are obtained. This information as well as landmarks positions (its latitudes and longitudes from the database) is used by onboard computer for attitude and position calculation. Here PNR was assumed as a value of correlation peak tip divided by root power of ambient noise. This root power was calculated in the neighborhood of the detected peak and represents such a statistical characteristic of ambient noise as root mean square (rms), if mean of noise is accepted as zero.

The landmark navigation system can be used for satellite backup navigation in two modes:

- *with accurate attitude data known.* In this case the input data are satellite attitude (e.g. from star tracker, with error not more than 0,003°) and position (from magnetometer, with error not more than 10 km). Navigation system determines satellite position with error not more than 30 m relying on the measurement of landmark position on current image.

- *without accurate attitude data known*. In this case the input data is satellite position (from magnetometer, with error not more than 10 km)[2]. Navigation system determines satellite position with error not more than 500 m and attitude with error not more than 0,06° relying on the measurement of three landmarks positions on each image of the image series obtained during the flight over one triad of landmarks.

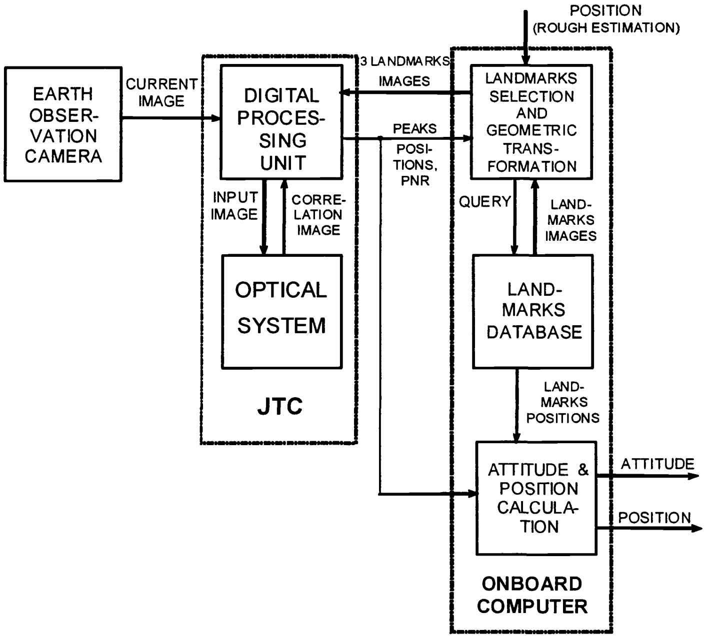

Fig. 1. Landmark navigation with optical correlator (without accurate attitude data)

3. JOINT TRANSFORM OPTICAL CORRELATOR BACKGROUND

Joint transform optical correlator (JTC) comprises of two almost identical optoelectronic modules – optical Fourier processors (OFP) – and employs the lens feature to produce optically 2D Fourier transform of the image (Fig. 2). Current and reference images (Fig. 3) are entered into the optical system of first OFP by the transparent spatial light modulator (SLM). After optical Fourier transform, the joint power spectrum (Fig. 4) is read by the Charge-Coupled Device (CCD) image sensor and loaded to the SLM of the second OFP. After the second optical Fourier transform, the correlation image (Fig. 5) is formed. If both input images are of the same region, the correlation image will contain two symmetric correlation peaks. If both OFPs are identical, the shift between correlation peaks will be equal to the doubled amount of shift between the current and reference images[6]. It means that if the SLM and CCD have equal size in pixels, the CCD of the second OFP must be off-axis shifted to accept the whole range of one correlation peak. The position of peaks and, therefore, the shift between current and reference images can be measured with sub-pixel accuracy.

4. IMAGE PROCESSING SYSTEM FOR OPTOELECTRONIC SATELLITE NAVIGATION

Image processing system for onboard optoelectronic satellite navigation is developed. The system realizes algorithms of satellite attitude and position determination.

Image processing system performs the following functions:

- modeling the image processing by JTC using the fast Fourier transformation algorithm;
- 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.

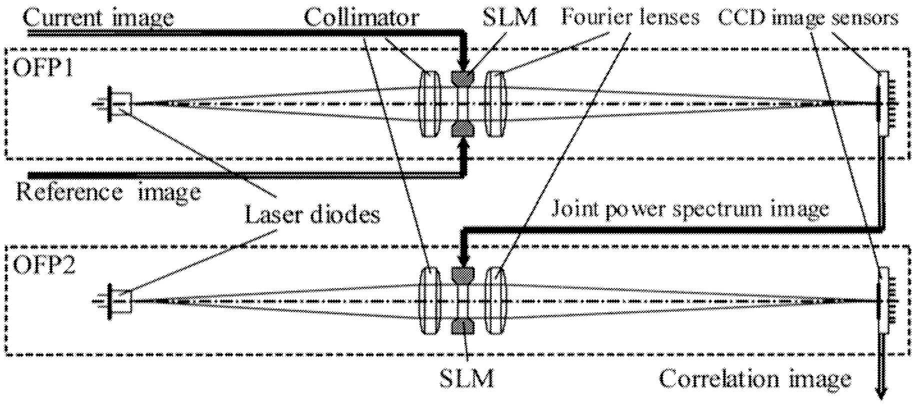

Fig. 2. Joint transform optical correlator

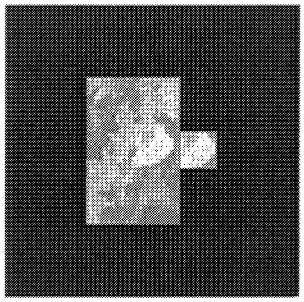

Fig. 3. Input – current and reference images

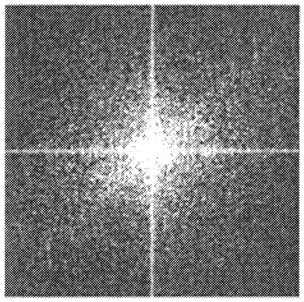

Fig. 4. Joint power spectrum image

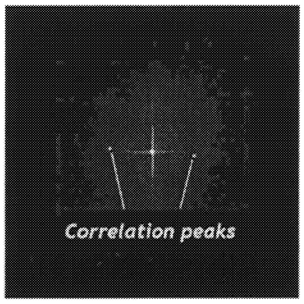

Fig. 5. Output – correlation image

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.

4.1. Mathematical model of the optoelectronic landmark navigation

The accurate determination of the spacecraft attitude respectively the attitude of the imaging device (observation camera) itself is of particular interest for spacecraft missions. This can give the overall system back-up capability with using the same camera as that for observation tasks.

Attitude of satellite camera at any moment of time is described by three rotation angles – pitch θ, roll φ and yaw ψ – Fig. 6. Rotated frame is tied with camera itself. The centre is centre of camera lens, *u*-axis coincides with optical axis, *v*-axis is parallel to line sensor and *w*-axis is perpendicular to line sensor. Plane *vw* is parallel to focal plane and aparted by focal length *f*. Here *u*-axis is the yaw axis, *v*-axis – pitch axis, *w*-axis – roll axis. The *xyz*-frame is fixed to the centre of planet, *z*-axis is headed to the satellite, *x*-axis is perpendicular to *z*-axis and velocity vector, *y*-axis is orthogonal complementary to *x* and *z*. Axes *z* and *y* lie into the plane of the orbit.

If all three angles are given, the matrix describing the relationship between frames *xyz* and *vwu* can be represented as

$$\hat{M}(\theta,\varphi,\psi)=\begin{pmatrix}1 & 0 & 0\\ 0 & \cos\theta & -\sin\theta\\ 0 & \sin\theta & \cos\theta\end{pmatrix}\cdot\begin{pmatrix}\cos\varphi & 0 & \sin\varphi\\ 0 & 1 & 0\\ -\sin\varphi & 0 & \cos\varphi\end{pmatrix}\cdot\begin{pmatrix}\cos\psi & -\sin\psi & 0\\ \sin\psi & \cos\psi & 0\\ 0 & 0 & 1\end{pmatrix}=$$

$$=\begin{pmatrix}\cos\varphi\cdot\cos\psi & -\cos\varphi\cdot\sin\psi & \sin\varphi\\ \sin\psi\cdot\cos\theta+\sin\varphi\cdot\cos\psi\cdot\sin\theta & \cos\theta\cdot\cos\psi-\sin\theta\cdot\sin\varphi\cdot\sin\psi & -\sin\theta\cdot\cos\varphi\\ \sin\theta\cdot\sin\psi-\cos\theta\cdot\sin\varphi\cdot\cos\psi & \sin\theta\cdot\cos\psi+\cos\theta\cdot\sin\varphi\cdot\sin\psi & \cos\theta\cdot\cos\varphi\end{pmatrix}. \tag{1}$$

Also $\mathbf{Q}_{xyz} = \hat{\mathrm{M}}\,\mathbf{Q}_{vwu}$, (2)

where $\mathbf{Q}$ – any vector.

Here an order of rotation must be the following: pitch θ, roll φ, yaw ψ.

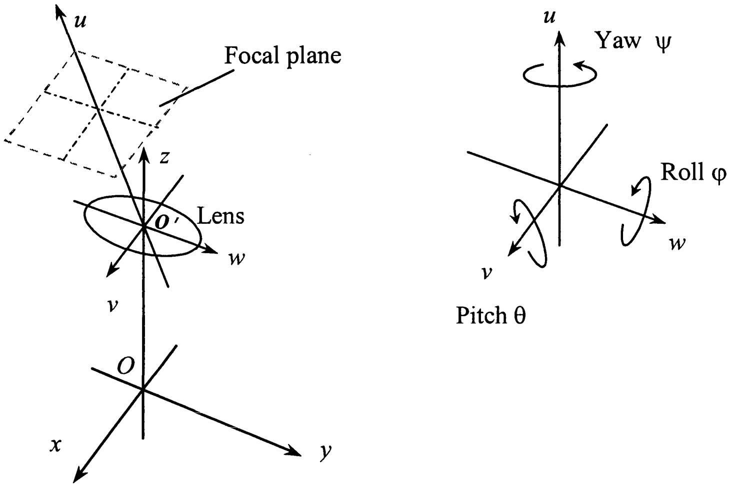

Fig. 6. Coordinate frames attitude representation used for satellite attitude description

Fig. 7 shows $x^0y^0z^0$-frame used for satellite latitude (α) and longitude (β) description. The centre of $x^0y^0z^0$-frame O is the centre of Earth. z^0-axis is headed to the point on Earth surface with α=0° and β=0°; x^0-axis is headed to the South Pole; y^0-axis is headed to the point on Earth surface with α=0° and β=0° of eastern longitude. Earth radius is assumed to be

$$R = \sqrt{\frac{R_{\min}^2 R_{\max}^2 (\mathrm{tg}^2\alpha + 1)}{R_{\max}^2 \mathrm{tg}^2\alpha + R_{\min}^2}}, \tag{3}$$

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

The matrix describing the relationship between frames xyz and $x^0y^0z^0$ can be represented as:

$$\hat{\mathrm{K}}(\alpha,\beta,\gamma) = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\beta & -\sin\beta \\ 0 & \sin\beta & \cos\beta \end{pmatrix} \cdot \begin{pmatrix} \cos\alpha & 0 & \sin\alpha \\ 0 & 1 & 0 \\ -\sin\alpha & 0 & \cos\alpha \end{pmatrix} \cdot \begin{pmatrix} \cos\gamma & -\sin\gamma & 0 \\ \sin\gamma & \cos\gamma & 0 \\ 0 & 0 & 1 \end{pmatrix} =$$

$$= \begin{pmatrix} \cos\alpha\cdot\cos\gamma & -\cos\alpha\cdot\sin\gamma & \sin\alpha \\ \sin\alpha\cdot\sin\beta\cdot\cos\gamma + \cos\beta\cdot\sin\gamma & -\sin\alpha\cdot\sin\beta\cdot\sin\gamma + \cos\beta\cdot\cos\gamma & -\cos\alpha\cdot\sin\beta \\ -\sin\alpha\cdot\cos\beta\cdot\cos\gamma + \sin\beta\cdot\sin\gamma & \sin\alpha\cdot\cos\beta\cdot\sin\gamma + \sin\beta\cdot\cos\gamma & \cos\alpha\cdot\cos\beta \end{pmatrix}, \tag{4}$$

where γ-angle depends on latitude, longitude and orbit parameters.
Also for any vector $\mathbf{Q}$:

$$\mathbf{Q}_{x^0y^0z^0} = \hat{\mathrm{K}}\,\mathbf{Q}_{xyz}. \tag{5}$$

Model of satellite attitude and position determination is developed. Latitude and longitude α_i, β_i (from database), vector $\mathbf{q}_{ivwu} = (\mathbf{q}_{iv}, \mathbf{q}_{iw}, f)^{\mathrm{T}}$ are known for each of three landmarks from one Earth surface image. Vector $\mathbf{q}_{ivwu}$ determines the coordinates of landmark image centre on focal plane (i.e. coordinates of point P_i on Fig. 8). These $\mathbf{q}_{ivwu}$ vectors are found by correlation peaks measurement.

The following equations set (in $x^0y^0z^0$-frame) determines the straight line drawn parallel to $\mathbf{q}_i$ vector through the centre of i-th landmark (point P_i on Fig. 8):

$$\begin{cases} \dfrac{x - R\sin\alpha_i}{\left(\hat{\mathrm{K}}\cdot\hat{\mathrm{M}}\cdot\mathbf{q}_{ivwu}\right)_{x^0}} = \dfrac{y + R\cos\alpha_i\sin\beta_i}{\left(\hat{\mathrm{K}}\cdot\hat{\mathrm{M}}\cdot\mathbf{q}_{ivwu}\right)_{y^0}} \\ \dfrac{x - R\sin\alpha_i}{\left(\hat{\mathrm{K}}\cdot\hat{\mathrm{M}}\cdot\mathbf{q}_{ivwu}\right)_{x^0}} = \dfrac{z - R\cos\alpha_i\cos\beta_i}{\left(\hat{\mathrm{K}}\cdot\hat{\mathrm{M}}\cdot\mathbf{q}_{ivwu}\right)_{z^0}} \end{cases} . \tag{6}$$

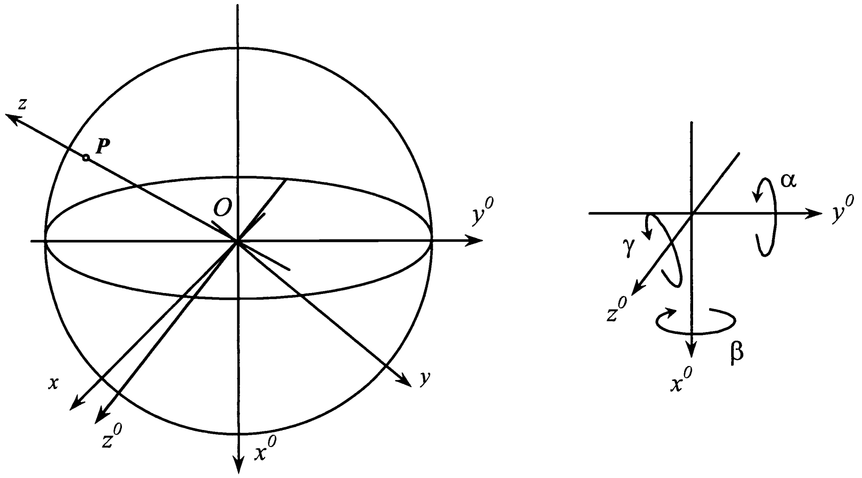

Fig. 7. Coordinate frames used for satellite latitude and longitude description

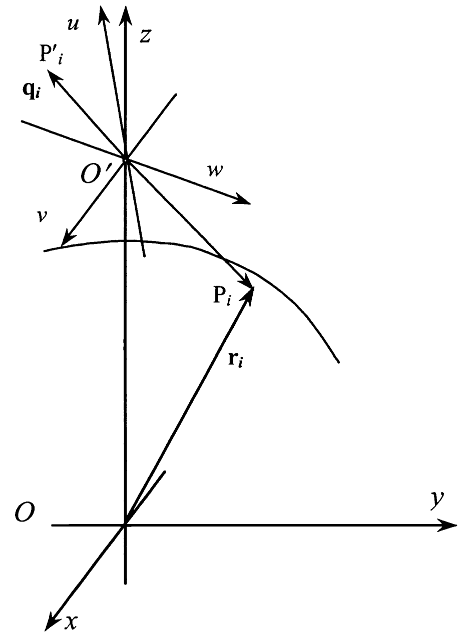

Fig. 8. Determination of satellite attitude and position by landmarks

Since the point O′ belongs to three straight lines determined by equations sets of kind (6), lets substitute coordinates of point O′ (that is defined by vector $\hat{K}\cdot(0,0,H+R)^{T}$) for *x, y, z* in (6). We shall get the set of six equations. Solution of this equations set gives us the values of satellite latitude, longitude and attitude angles. This equations set can be solved by minimization of cost function *G* on the plane (θ, φ, ψ, α, β):

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

$$\left.+\left(\frac{\left(\hat{K}\cdot(0,0,H+R)^{T}\right)_{x^0}-R\sin\alpha_i}{\left(\hat{K}\cdot\hat{M}\cdot\mathbf{q}_{ivwu}\right)_{x^0}}-\frac{\left(\hat{K}\cdot(0,0,H+R)^{T}\right)_{z^0}-R\cos\alpha_i\cos\beta_i}{\left(\hat{K}\cdot\hat{M}\cdot\mathbf{q}_{ivwu}\right)_{z^0}}\right)^2\right),\qquad(7)$$

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

The following algorithms are developed:

- algorithm of satellite position determination (with accurate attitude data known);
- algorithm of satellite attitude and position determination (without accurate attitude data known);
- algorithm of landmark image geometric transformation (for the satellite attitude given);
- algorithm of test current image generation (for the satellite attitude and landmark given).

4.2. Methods of reference images generation

The most straightforward way to generate the reference images is to take the image of the necessary landmark and send it to the ground station. The image is georeferenced by ground computer, than the exact coordinates of it are sent to satellite. With exact coordinates known, the image can be used as reference one during the following passes over the same region.

The reference image can be synthesised by ground computer on base of available Earth images and sent to the satellite.

The set of reference images can be also recorded prior to launch (using the available images of the region).

The reference image can be synthesised onboard the satellite using the geographic information system databases with slightly reducing performance of correlation.

In case of significant inclination of the line of sight from nadir or change of the orbit altitude, geometric transformation of the reference image is necessary to prevent the decreasing of the system performance due to the geometrical distortions.

4.3. Determination of spacecraft position and attitude

With the camera placement in spacecraft body and its focal length known, position of correlation peak on the output image can be calculated into the mutual shift vector between the current image and reference landmark image.

If the spacecraft attitude is known, this mutual shift vector can be recalculated to find the spacecraft position in the Earth fixed coordinate frame.

The exact position of the spacecraft can not be calculated in absence of accurate attitude information in the moment of determination of the mutual shift vector. One of the known procedures is to detect three images of separate landmarks on one main image. With mutual shift vectors for three separate landmarks known the attitude and position of the spacecraft in the moment of taking of main image can be calculated. With detecting a triad of landmarks on one main image the position of satellite in Geocentric Inertial Frame can be defined.

As latitude α_i, longitude β_i (from database) and vector $\mathbf{q}_{ivwu} = (\mathbf{q}_{iv}, \mathbf{q}_{iw}, f)^{\mathrm{T}}$ (computed from mutual shift vector) are known for each landmark from triad, position and attitude of satellite can be determined by minimization of cost function G on the plane (θ, φ, ψ, α, β).

Usual scheme of observation implies only one measurement in flying over one triad. However, with choosing a small triad it is possible to obtain several tens of mutual shift vectors during the flight over one triad. As this procedure increases an amount of information input to filter by several tens time, accuracy can be expected to be better. In order to avoid storing all sequence of successive images in onboard memory the onboard image processor must process them in real time. On each main image at least three operations of image matching must be performed within this interval. The processing rate is extremely high and can be provided by optical correlator only.

As the orbit parameters change very slowly, they can be determined with high accuracy by processing of the discrete position data (determined for the certain points over the available landmarks) with the Kalman filter. With the orbit parameters available, the accurate spacecraft position can be calculated for every moment.

The dissimilarities between reference and current images must be within an interval of correlator robustness. This means that they must be taken from the very close flight points with the very close attitudes. If it is not so, a pre-correction (geometric transformation) of the reference image is required. Such a pre-corrector must be provided with information about both positions and attitudes of satellite at taking of reference and current image. This information can be inaccurate in such a limit that final corrected images dissimilarities meet correlator robustness interval.

Due to correlation peaks degradation the system cannot work with significantly distorted landmark images, so initial 3-axis stabilisation of the spacecraft is required. At the same time, the system itself can provide the attitude information necessary for such stabilisation, by analysing of the Earth image motion in the focal plane of the camera. The local velocity vectors of Earth image motion can be calculated on the base of matching of Earth image fragments, produced by the image sensor with known time interval. With such vectors known for few separate points in the focal plane of Earth observation camera, it is possible to estimate the spacecraft attitude[7].

5. CORRELATOR DESIGN

Standard JTC has considerably long optical system and is sensitive to the optical system deformations. To make it more suitable for the onboard installation, compact single optical processor scheme of JTC (Fig. 9) has been developed[8] with up-to-date optoelectronic components and dimensions within 250x20x20 mm. Dimensions of digital processor unit and auxiliary circuitry are within 100x40x10 mm. Total mass of the optical system and electronics is within the limit of 300 g. Both optical Fourier transforms are performed by one OFP sequentially. Current and reference images are loaded to the SLM, then the laser gives a short light pulse to project the spectrum image on the image sensor array. The spectrum image is read from image sensor and directly loaded to the SLM. After finishing of the readout/loading the laser gives the second pulse and the correlation image is read from the image sensor.

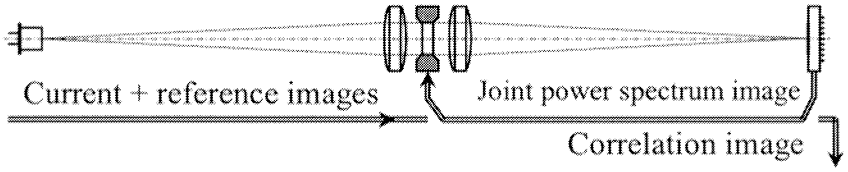

Fig. 9. Joint transform correlator with single optical processor.

The software model of JTC 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.

The hardware model of JTC (Fig. 10) has been manufactured and tested. The model uses commercially available optoelectronic components and works with personal computer (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.

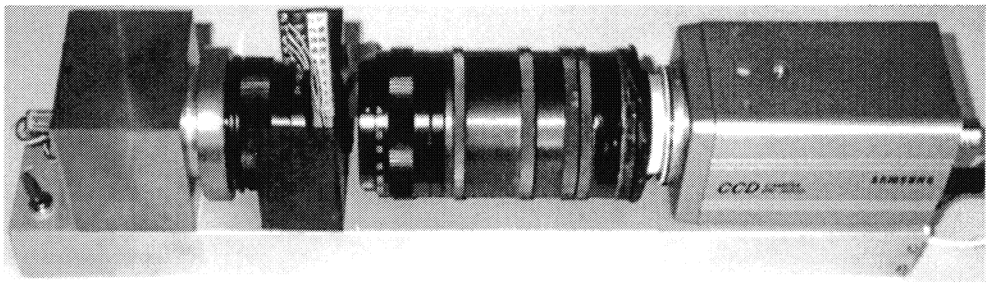

Fig. 10. Optical correlator hardware model

Expected characteristics of optical correlator are:

- image processing time (determination of landmark position on the image) – within 0.025 s (40 images per second);
- input image noise – SNR better, than 25 dB;
- dimensions of the optical system – within 250x20x20 mm;
- dimensions of the electronics – within 100x40x10 mm;
- mass of the optical system and electronics – within 300 g;
- power consumption – within 2 W.

6. EXPERIMENTAL SIMULATION

As a result of the model testing, the feasibility of the system concept and the adequacy of the software model have been proved. Fig. 3-5 show input, spectrum and output images obtained from software model. The errors of the landmark position determination on current images were within $\sigma = 0.22$ pixel.

6.1. The effect of the image distortions and noise on the system performance

The series of simulated experiments has been performed with hard- and software models of the system and simulated Earth images. The images were geometrically distorted (rotated, scaled and perspective distorted) to simulate the effect of the satellite attitude instability and off-nadir observations. To simulate the camera noise, the Gaussian noise has been added.

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. Peak discrimination is fully characterised by this PNR[8].

If the angle of mutual rotation of the images is no more, than 0.35 degrees, the ratio exceeds one thousand, what means high reliability of correlation peak detection and high accuracy of its position determination.

Graph of PNR against the percentage of reference and current images superposition is shown on Fig. 12. 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.

Fig. 13 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. 14. 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).

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. As the Earth spherical effect on the perspective image distortions depends on the orbit altitude, altitude should be specified for simulation. We considered 500 km orbit. 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. 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.

Low signal-to-noise ratio 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. If the input image noise is less, than 16 dB, the PNR exceeds one thousand. The noise in intermediary (joint spectrum) 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.

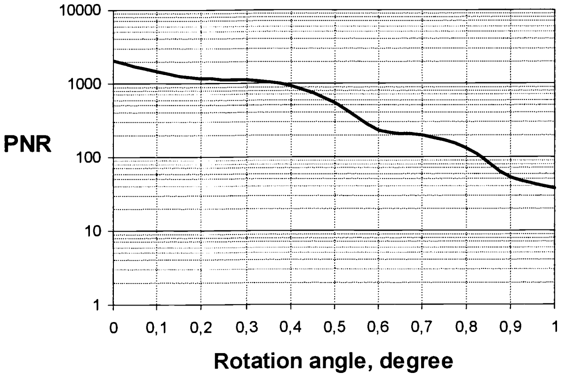

Fig. 11. Degradation of the correlation peak-to-noise ratio with rotation of the current image

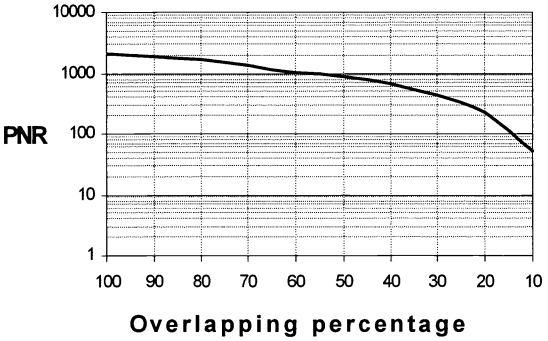

Fig. 12. Degradation of the correlation peak-to-noise ratio with changing of the current and reference images overlapping

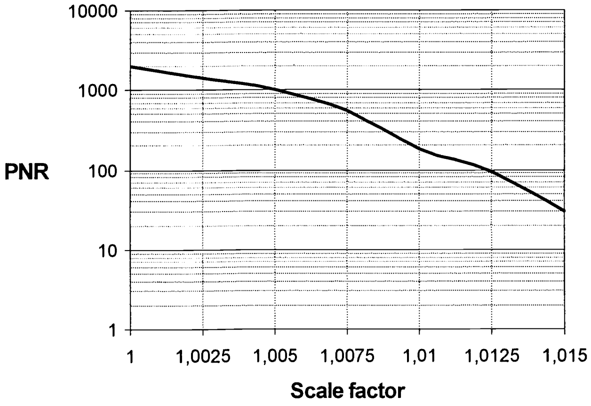

Fig. 13. Degradation of the correlation peak-to-noise ratio with scaling of the current image

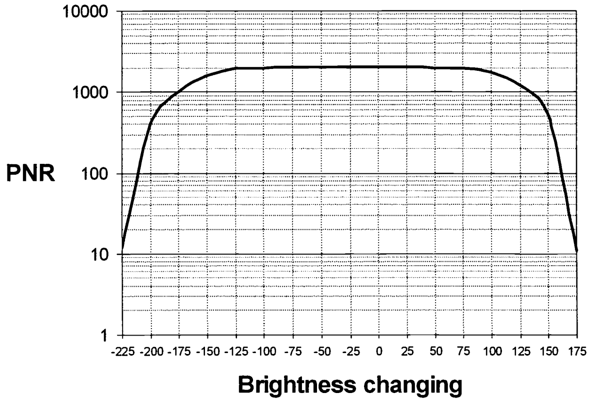

Fig. 14. Changing of the correlation peak-to-noise ratio with changing of the current image brightness

6.2. Estimation of the accuracy of the image matching in presence of image distortions and noise

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 signal-to-noise ratio (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.

6.3. Estimation of the accuracy of spacecraft position and attitude determination

Estimation of the accuracy of spacecraft position and attitude determination was made using the developed image processing system for satellite landmark navigation. The real satellite image of Ufa city with 10 m/pixel resolution was applied for simulation. The satellite with 500 km circular orbit is considered.

Of course, the image chosen for the simulated testing 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 are:

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

6. CONCLUSIONS

The concept of optoelectronic landmark navigation system for LEO satellite based on the maximum-use principle of any onboard equipment has been introduced.

The joint transform correlator 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.

Image processing system for onboard optoelectronic satellite navigation is developed. The system realizes algorithms of satellite attitude and position determination.

Mathematical model of the optoelectronic landmark navigation taking the obtaining of images by Earth observation camera and the impact of navigation parameters on correlation peaks coordinates to account is considered.

Compact optics design, the software and hardware models of the joint transform optical correlator have been developed.

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 averaged error of landmark position determination in presence of image distortions and noise was found to be σ=0.22 pixel. It shows the possibility to obtain the sub-pixel accuracy of images matching in real conditions under noisy environment.

The accuracy of spacecraft position and attitude determination was estimated using the developed information system.

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