Design concept for a secondary payload Earth observation camera

Klaus Janschek[a], Valeri Tchernykh[b], Sergei Dyblenko[b]

[a]Dresden University of Technology, Department of Electrical Engineering, 01062 Dresden, Germany
[b]Ufa State Aviation Technical University, K.Marx str.12, 450025 Ufa, Russia

ABSTRACT

The concept of the small, medium resolution Earth observation camera (14-20 m per pixel) using a joint transform optical correlator is proposed. The camera is intended to be used as a secondary payload for low orbit, 3-axis stabilised spacecraft, including ones with moderate attitude stability. The optical correlator is used for a real-time determination of the camera pointing motion for posteriori correction of the image distortions due to attitude unstability. A wide angle lens and long assembly of the line sensors in the focal plane permit to change the view direction without need to move the satellite or camera elements. A possible layout of the optoelectronic unit is described and the results of simulated experiments, expected performances and size estimations are given.

Keywords: satellite, camera pointing, secondary payload, remote sensing, optical correlator.

1. BACKGROUND

Today, there is a firm tendency to increase the resolution of Earth observation missions (some 1-meter resolution missions are planned). At the same time, the needs for global *medium resolution* Earth imagery (15-20 m) with high revisibility rates are still far from being satisfied. Such image data are essential for agriculture, environmental/ecological monitoring, forest monitoring, mapping and many other applications. A number of potential customers is, however, limited by the high cost of image data and large revisit times. *High cost* of imagery is determined mainly by the high cost of dedicated remote sensing satellites with precise and fast attitude control systems.

Large revisit time due to the relatively small number of Earth observation satellites is also the result of high cost of such missions. A considerable reduction of revisit times (by increasing the number of Earth observation missions) is of particular interest for the following applications:

1. Observations of the regions with generally bad weather conditions (Middle and Northern Europe, for example), especially autumn and winter time. For such regions, the periods of clear sky during the short winter day can be very limited, so it is essential to have at least one satellite above the desired region in the proper time[1].
2. Detection of short duration events, such as oil spills in water.
3. Floods monitoring and forecasting.
4. Up-to-date information on the sites of disaster.
5. Some agricultural applications requiring daily updating (irrigating control and planning).
6. Observations of the desired regions at different illumination conditions (or at different observation angles).

A solution for an improved situation in terms of increasing the number of such missions, of reducing the revisit time and enlarging the number of potential customers could be a considerable *cost reduction* of *medium resolution Earth observation missions* as outlined below.

For medium ground resolution and low orbit the cost of the imaging system is small with comparison to the cost of the satellite, so that reducing the cost of the imaging system (camera) alone will not help much in reducing the overall cost of the mission. Taking this into account, it is very attractive to *add* a sufficiently small and cheap Earth observation camera as a *secondary payload* to other purpose 3-axis stabilised satellites, e.g. communication satellites. In this case an imaging payload can share a lot of platform resources of host satellite. The important show-stopper for such a solution lies however in the diversity and incompatibility of the attitude accuracy requirements for communication and observation satellites. Fulfilling the attitude accuracies for state of the art imaging payloads on a communication satellite, would increase dramatically the complexity and realisation effort and in consequence the cost of the host (communication) satellite. This paper shows a camera concept, which can deal also with moderately stabilised host satellites and which avoids therefore a dedicated and increased host satellite design effort.

Part of the EUROPTO Conference on Sensors, Systems, and Next-Generation Satellites V
Florence, Italy • September 1999 SPIE Vol. 3870 • 0277-786X/99/$10.00

2. THE CONCEPT OF SECONDARY PAYLOAD CAMERA WITH OPTICAL CORRELATOR

Small secondary payload cameras can be installed on most of the 3-axis stabilised platforms. However, two problems arise, associated with using a satellite, not specially designed for Earth observation. First one is the impossibility of rotating the whole satellite to point the camera. The other option to include movable elements in the camera structure for pointing is also not desirable, as it increases cost, size and mass as well as it decreases the reliability of the imaging system.

The second problem is associated with the low accuracy of attitude stabilisation of a satellite, which is not specially intended for imaging mission. If a line (pushbroom) scanner is used, the attitude instability during frame scanning will result in image distortions. Figure 1 shows the simulated image distortion for a medium resolution camera (15 m per pixel) due to the attitude unstability typical for communication satellite (0.005 degrees vibrations amplitude, 0.005 deg/s angular drift rate).

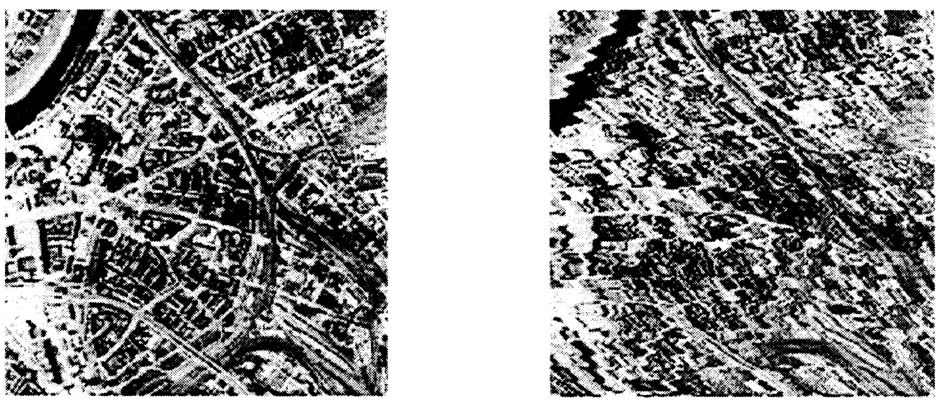


Fig. 1. Simulation of the image distortions due to the attitude instability during the image scanning. Left – original image, right – distortions simulation.

The main purpose of the proposed camera concept development is to overcome the two problems mentioned above resulting in a compact smart camera with *minimal size* and *without any moving parts*.

To avoid moving camera elements or a pointing (slewing) of the whole spacecraft to the specific observation region it is possible to use a *wide angle lens* and *long assembly of line sensors*. The line sensors are installed in the focal plane of the lens perpendicular to the flight direction, as it is shown on *Figure* 2. The assembly of line sensors covers the complete field of view (FOV) of the lens (40°). To produce the image of the desired region the output signal of the appropriate line sensor is recorded in appropriate time intervals. This permits an instantaneous change of the view direction by a simple commutation of the sensors or even recording the images of two different regions simultaneously. With a moderate aperture of the lens, the whole system can be realised as flat, compact unit. Using the line sensors, it is also easy to achieve multi-spectral capability (with colour line sensors or fixed filters).

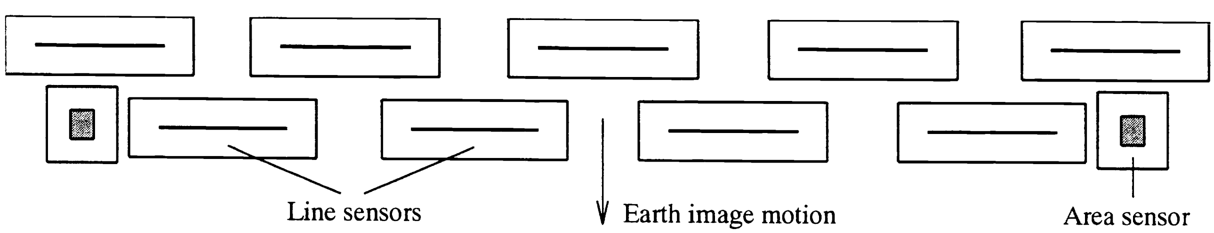


Fig. 2. Focal plane assembly of line and area sensors.

To make the camera usable onboard satellites with *moderate attitude stabilisation*, we propose to use an *onboard optical correlator* and small additional *area sensors* in the focal plane for *real time recording* of the ground track of camera pointing during scanning of the frame. The pointing record is transmitted to ground station together with image information. With this record a ground computer can restore the actual position of every line of the image (relatively to the first line) and is able to perform posteriori correction of possible image distortions resulting from short-term attitude changes during scanning.

To produce the record of camera pointing two additional area sensors are installed in the focal plane, as it is shown on the Figure 2. During the scan of the frame each area sensor produces a sequence of instantly obtained small images at certain time intervals. These images are processed in real time by an *optical correlator*. An optical correlator is an optoelectronic device capable of performing instantly the 2D correlation between two images[2,6,7]. If both images cover the same region, the shift of one image relatively to another can be measured. Using the first area sensor image (produced at the beginning of the image scan) as reference image and performing correlations of this image with all following (current) area sensor images sequentially, it is possible to produce the sequence of image shift readouts for every area sensor during the big frame scan. This sequence of readouts can be transformed by simple calculations into the record of the Earth image motion in the focal plane. If the axis of the optical system is approximately oriented to nadir (typical yaw, pitch and roll errors are within 0.5 degrees for most 3-axis stabilised platforms) and the lens has small geometrical distortions, the actual position of every line of the scanned Earth image can be calculated.

If the length of the scanned image exceeds the length of the area sensor, a new image must be used as a reference. The position of this new reference image relatively to the previous one is determined by the same correlation procedure. This, of course, will lead to some error accumulation for long images (when few changes of the reference images are required). However for image lengths within 2700 pixels, this error will be less than one pixel and spread over all image length. For many applications such a spread error is not critical. In any case, it can be removed easily during the geo-referencing procedure.

3. OPTOELECTRONIC UNIT DESIGN AND SIZE ESTIMATION

The *physical size* of the camera with a given resolution is determined by parameters of the optoelectronic components and the orbit. In the following are given the results of calculations, made for 20 m resolution and 700 km orbit. The parameters of the line and area sensors are consistent with the commercially available colour line sensor ILX533K and b/w area sensor ICX084AL from Sony[2]. The length of the line sensor is 2700 pixels, pixel size is 8 x 8 μm (8 μm pitch). The area sensor has the dimensions of 659 x 494 pixels, pixel size is 7.4 x 7.4 μm.

To obtain the ground resolution of 20 m for 700 km orbit and 8 μm pixels pitch the focal length of the camera, the lens should be 280 mm. For the 500 km orbit the resolution will be 14 m per pixel. The angular FOV of the lens determines the ground swath width, however, large values of FOV set high requirements to the lens characteristics, increasing its size and cost. Taking into account also a fast growth of the geometric distortions with increasing of the distance from nadir, we estimate the optimal FOV for this case as 2 x 20 = 40 degrees.
The length of the line sensors assembly in this case will amount to 191.5 mm, what requires using 9 devices (figure 2). Total swath width (for the whole assembly of line sensors) will be 510 km for 700 km orbit and 370 km for 500 km orbit.

To minimise cost and size of the lens its aperture should be as small as possible. The limiting factor here is the resolution degradation due to diffraction and decreasing of illumination in the focal plane. For the given line sensor parameters the aperture can be as small, as f/8, what amounts to 35 mm for given focal length. Such aperture provides sufficient illumination in the focal plane and small enough diffraction pattern. Approximate size of the lens with given above parameters can be within ∅ 50 x 40 mm.

The focal plane electronics (for driving the sensors scan and output signals amplifying) can fit into the volume of 210 x 50 x 20 mm, so the *whole camera size* (without the envelope) can be *320 x 210 x 50 mm*.

To determine the optical correlator layout and size it is necessary to choose its type, suitable for this particular application. There are two main types of optical correlators: VanderLugt and Joint Transform ones[2]. For this application the Joint Transform Correlator (JTC) suits better, as it does not require complex pre-processing of the reference images and has more tolerance to shocks and mechanical deformation[2,4]. The image processing in JTC includes joint optical Fourier transformation of reference and current images, readout of the resulting joint power spectrum with square law detector (CCD matrix), second optical Fourier transformation and readout of the resulting correlation image. The position of bright correlation peaks on the correlation image corresponds to the mutual shift of current and reference images. The complex operation of the mutual shift determination is therefore substituted by relative simple operation of the bright spot position determination. This operation can be performed in real time by small DSP-based digital processing module.

Optical Fourier transformations are made by optical Fourier processors (OFP). Each of them includes a laser diode, collimating and Fourier lenses, a spatial light modulator (SLM) for images input into the optical system and a CCD matrix for output image readout (Figure 3).

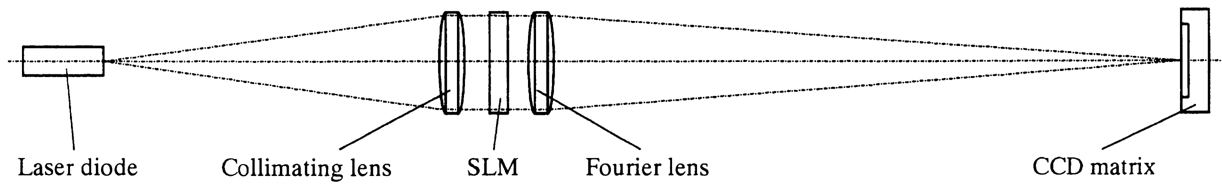


Fig. 3. Optical Fourier Processor

As each correlation requires two operations of optical Fourier transformations, it is better to have four OFPs for processing of two area sensors outputs. Usage of the up-to-date optoelectronic components permits a very compact realisation of the OFP. With a 320C device from Kopin Corp[5]. used as SLM and a CCD matrix ICX084AL from Sony[3], the focal length of the Fourier lens can be as small, as 90 mm and the whole OFP can fit into the volume of 12 x 15 x 180 mm. Such size makes it possible to realise the assembly of 4 OFP within the volume of 50 x 15 x 210 mm, perfectly fitting over the focal plane electronic module. The correlator electronics, necessary for control of image data flow and processing of the correlation images, can also be realised within the volume of 50 x 15 x 210 mm. The *total size of the optoelectronic unit*, including the *camera and correlator module* can be *350 x 210 x 50 mm*, as it is shown on the Figure 4.

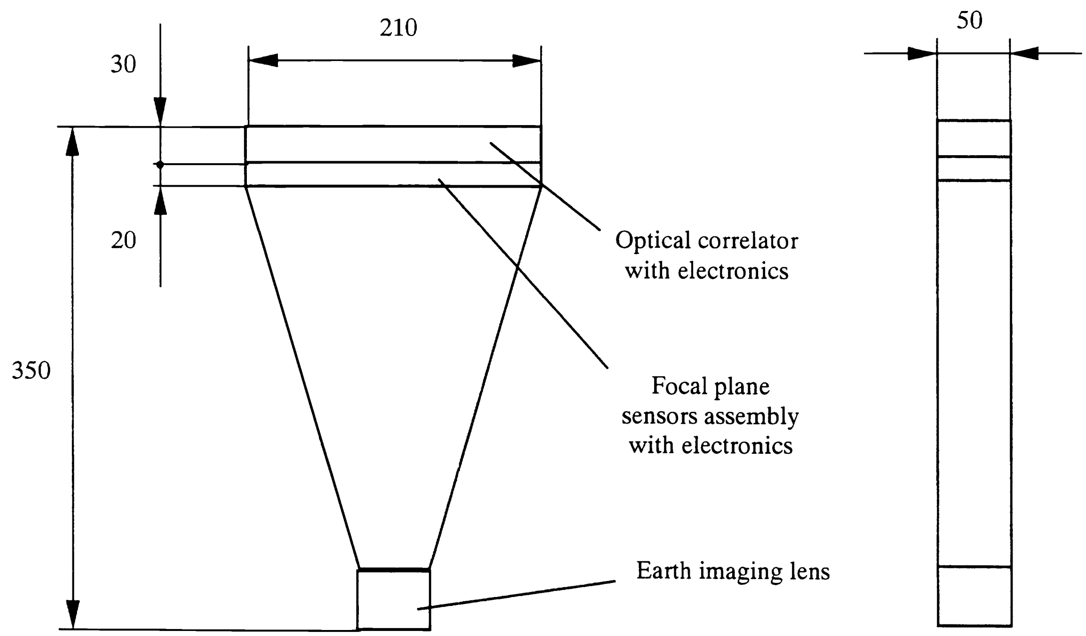


Fig. 4. Possible layout of Earth observation camera with optical correlator

Of course, a separate electronic unit is required for camera operation control, image data routing and for interfacing with he host satellite systems, but, as high data processing is not required for it, it can be realised within a very limited volume.

4. ACCURACY ESTIMATION.

4.1 Sources of errors

Main sources of errors of images shift determination with an optical correlator are:

- mechanical deformations of the optical system of the correlator;
- discrete structure of SLM and CCD;
- noise;
- low percentage of current and reference images overlapping;
- geometrical distortions of the current and reference images.

In the following subsections the effects of these error sources on the measurement accuracy is described. The error values were obtained in the series of simulated experiments. For the experiments a software model of a JTC was used. The parameters of the model were set accordingly to the parameters of the JTC optoelectronic components, mentioned in previous section. The adequacy of the model was proved by comparing of its output with results, obtained with JTC laboratory model (Figure 5).

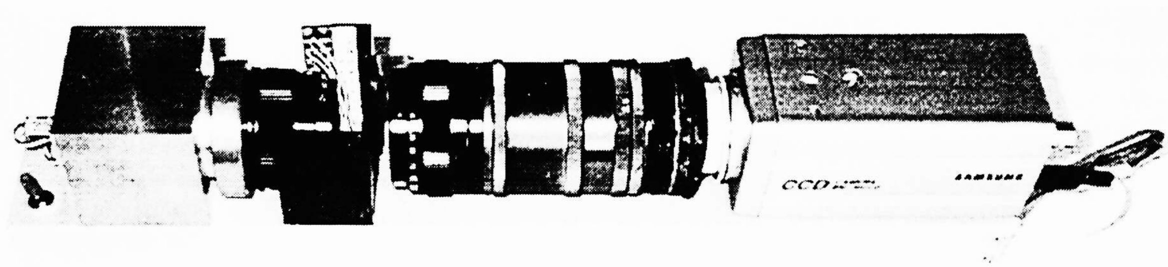


Fig. 5. Laboratory model of joint transform correlator used for testing of the software model

The results of testing has shown a good similarity of the correlation images obtained in software experiment and with a laboratory model. The picture, obtained with model, was a little smoothed due to imperfections of optics.

4.2 Mechanical deformations of the optical system

Mechanical deformations can result in correlation peak degradation and peak displacement. For a JTC the correlation peak intensity is less dependent on the optical system deformations (compared with VanderLugt scheme)[4]. The peak displacement is much more essential. With a 7.4 μm CCD pixel pitch even a small displacements will cause large errors. To avoid this, a special technique of shift measurement was developed, robust to the deformations of the optical system.

The effect of twisting of the optical system can be minimised by using the same OFP for both optical Fourier transforms necessary for one correlation. The joint power spectrum, obtained after the first transform, is flipped horizontally and forwarded to the same OFP for the second transform. If the SLM is twisted relatively to CCD, the joint power spectrum will be rotated by certain angle. After flipping this angle is reversed and compensated during the second transform, so the correlation image will not be rotated. Using the same OFP for both optical Fourier transforms also averts the scaling error in case of difference of the focal length of the Fourier lenses.

Bending of the optical system will cause a shift of the correlation image. To compensate this error, the shift between two symmetric correlation peaks is measured, rather than position of the single peak. For small angles of optical system bending this distance practically does not depend on the bend angle.

4.3 Discrete structure of SLM and CCD

The discrete structure of the SLM will result in the additional peaks emerging on the correlation image. However, for a properly designed correlator these peaks are situated outside the working zone and can not be mixed with correlation peaks. The discrete structure of the output CCD is much more essential, as it directly affect the peak position measurement. For a single bright point, the error can reach 0.7 pixel, but fortunately the real correlation peak is not pointwise. It has bell-like energy distribution shape with diameter of few pixels. Using a simple mass centre algorithm reduces the error to $\sigma = 0.05$ pixel (for given optical correlator parameters and high SNR).

4.4 Noise

A Fourier transform based system such as a JTC has a high tolerance to input noise. Input reference and current Earth images as well, as the intermediate joint power spectrum image can have low SNR without much effect on error of shift measurement.

Figure 6 represents the dependence of the correlation peak-to-noise ratio in the correlation plane on the SNR in the input plane (plot a), or in the plane of joint power spectrum (plot b). The noise was generated on the basis of maximal dynamical range of devices at given signal-to-noise ratio.

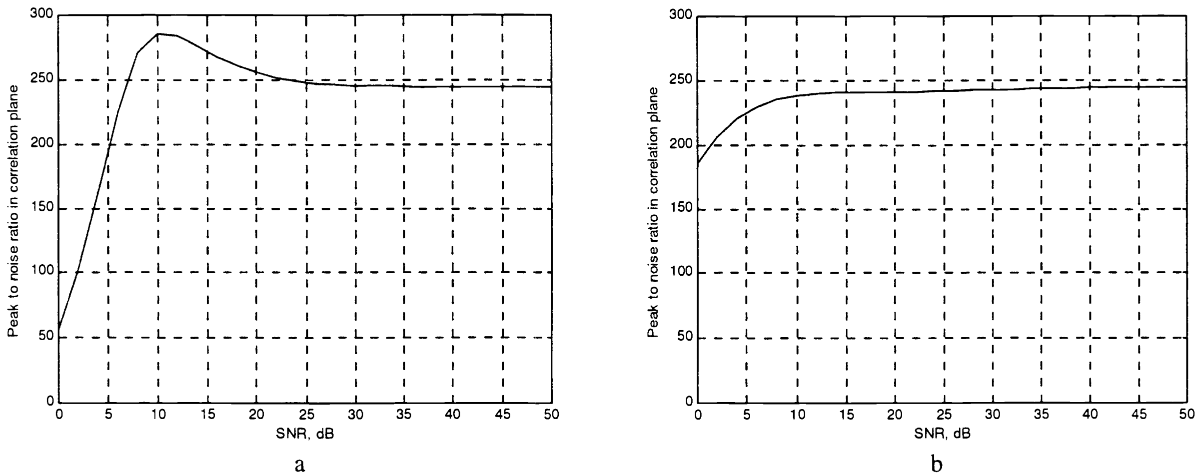


Fig. 6. Correlation peak-to-noise ratio in dependence on: a – SNR in the input plane, b – SNR in the plane of joint power spectrum.

The plots show little degradation of the peak-to-noise ratio in the correlation plane in presence of noise in the input and joint power spectrum planes. Degradation of peak-to-noise ratio by 40% (3 dB) corresponds to SNR of 4 dB in the input plane and 0 dB in the joint power spectrum planes. 4 dB SNR in the input plane means, that the images are practically unrecognisable by the human eye, but the correlation peak is still 150 times higher, than the background noise.

On the Figure 7 the effect of noise in different planes of JTC on error of peak position estimation is shown.

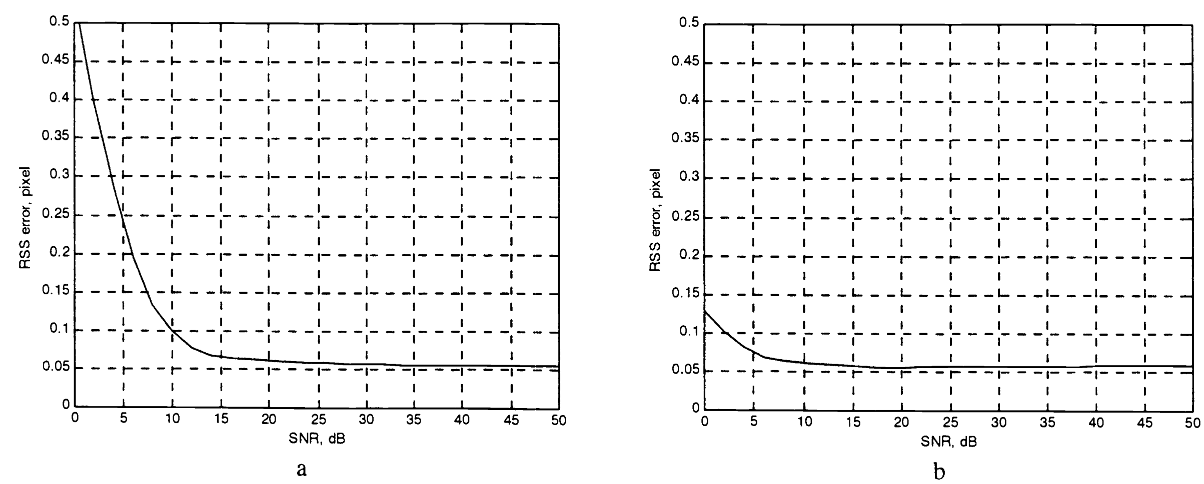


Fig. 7. Error of correlation peak position determination versus SNR in the input plane (a) and in the plane of joint power spectrum (b).

The graphics show a good correlation (errors less, than σ=0.5 pixel) even when σ of the noise is equal to maximum brightness values of the input images. High tolerance has been observed also for the joint power spectrum noise. Besides low sensitivity to the input and intermediate plane noise, these results also permit to make a conclusion about the low sensitivity of the JTC scheme to the accuracy of the grey levels representation by SLM. According to the results of simulation, if the SNR is better than 15 dB for the input plane and better than 8 dB for the joint power spectrum plane, the error of peak position estimation will be within σ=0.07 pixel.

4.5 Low percentage of reference and current images overlapping

If reference and current images are mutually shifted, only a certain part of the current image coincides to the corresponding part of the reference image (zone A on Figure 8).

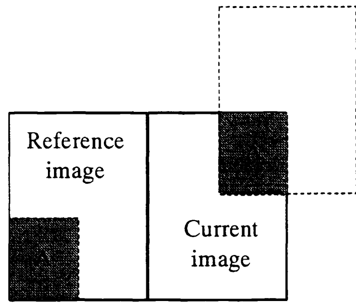
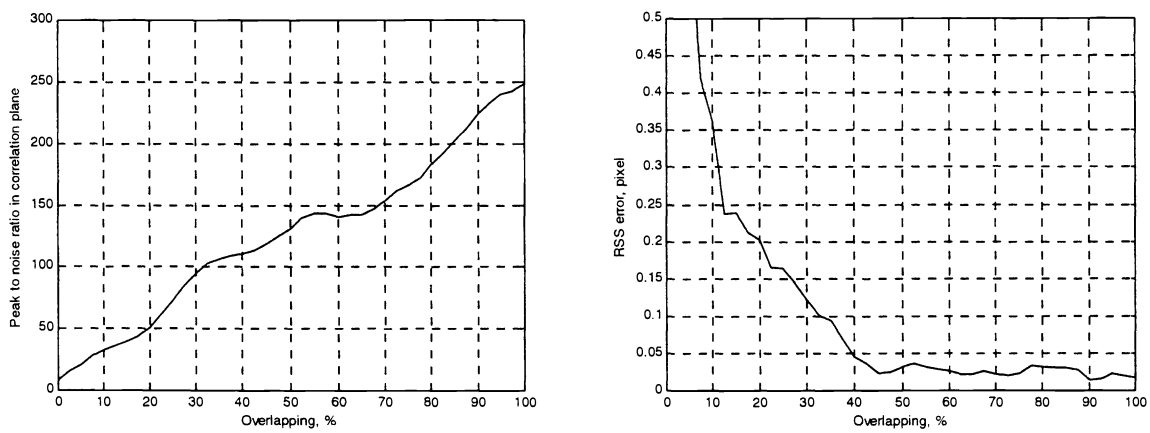


Fig. 8. Zone of images overlapping (A) for mutually shifted reference and current images, represented by input SLM

When decreasing of the overlapping zone, the correlation peaks values are degrading relative to the background noise. On the Figure 9 (plot a) the dependence of peak-to-noise ratio on the percentage of images overlapping is shown. This results in increasing of the error of correlation peak position determination. Figure 9 (plot b) represents the dependence of the peak position determination error on the percentage of current and reference images overlapping.



a b

Fig. 9. Dependence of peak to noise ratio (a) and error of peak position determination (b) on the percentage of current and reference images overlapping

Practically, the limit of the images overlapping percentage can be estimated for a given error limit. According to the results of simulation experiment the position error is expected to be within σ=0.1 pixel if the overlapping zone is more, than 35% of the reference image.

4.6 Geometrical distortions of the current and reference images

Geometrical distortions of the current image relatively to the reference image occur, if the satellite attitude changes during the time interval between the reference and current image recording. The pitch and roll angles change can cause perspective distortions, yaw angle change will cause a rotation. For given SLM and CCD parameters and 700 km orbit, the maximum time interval between reference and current images can be up to 1.37 s. If maximum angular rates are within 0.01 deg/s (typical value for communication satellites), maximum attitude change will be within 0.014 degrees. Such a small change of pitch and roll angles will not cause any noticeable perspective distortions. The rotation of the current image due to the yaw angle change is too small to cause significant degradation of the correlation peak, but can result in additional peak position error in case of large shift of current image relative to reference. For given SLM parameters, the maximum mutual shift of the images can reach 288 pixels, really no more, than 200 pixels due to correlation peak degradation. For 200 pixels current image shift and 0.014 degrees of yaw angle change, the additional error of peak position determination will be within 0.05 pixel.

4.7 Summary of errors

To estimate the expected accuracy under certain set of disturbing factors the simulated experiment has been conducted with a software model of JTC. The test images set was created according to the parameters of proposed camera (calculated in section 3) for the 700 km orbit altitude on base of available satellite imagery. The error value was estimated to be within $\sigma=0.15$ pixel for SNR=20 dB in the input plane; SNR=10 dB in the joint power spectrum plane; 40% of current and reference images overlapping and 0.01 degrees per second yaw angle rate.

5. PROCESSING RATE ESTIMATION

The OFP performs optical Fourier transform practically instantly (at a speed of light). However, the rates of the image information readout from the CCD matrix (image sensor) and loading to the SLM are limited. The frame readout time for standard CCD is 33,3 or 40 ms. The time of image loading to the SLM depends on its size. For the Kopin 320C device it can be as small, as 3 ms, so the image processing rate with this SLM and standard CCD will be determined by the CCD readout time. Others stages of the optical Fourier transform can be done in parallel during CCD readout, so with CCD readout time of 33.3 ms the image processing rate for the OFP can be up to 30 Fourier transforms per second. Digital processing of the correlation images (to determine the position of the correlation peaks) is performed only for the pixels, exceeding the certain value of brightness. For the real correlation image it means a reduction of data to be processed by 2 –3 orders of 10, so digital processing can also be done during CCD readout. For one correlation with JTC two optical Fourier transforms are required, so 15 correlations per second are possible with single OFP.

According to the proposed layout of optoelectronic unit, four OFP will be used for processing of two area sensors outputs, so the processing rate will be 30 correlations per second for a standard CCD. Such a processing rate is sufficient to follow the angular motions of the spacecraft with frequencies up to 15 Hz, including the drift of the 3-axis stabilised spacecraft within resolution thresholds of the attitude sensors, as the spectrum of this drift motion is usually limited by a few Hertz.

The processing rate of the correlator can be increased with special, multi-output CCDs used as area sensors in the focal plane and as the image sensors in the OFPs. In this case the processing rate for the whole system can reach 200 correlations per second for every area sensor. Such a processing rate is sufficient to follow spacecraft vibrations with frequency of up to 100 Hz.

For many cases it will be possible to reduce the requirements to the correlator performance by suppressing the high frequency vibrations by vibration-absorbing (flexible) mount of camera.

6. CONCLUSIONS

The concept of the secondary payload Earth observation camera with joint transform optical correlator has been proposed. The camera can be used onboard the 3-axis stabilised spacecraft with low accuracy attitude control. The long assembly of the line sensors in the focal plane and wide angle lens permit to change the view direction without moving the satellite or any camera element. To make the camera usable onboard the satellite with moderate attitude stability an optical correlator and two additional area sensors are used for real time recording of the camera pointing during recording of the Earth image by line sensor. With this record a ground computer can restore posteriori the position of every line of scanned image relatively to first line and correct the image distortions. A series of simulated experiments has been performed, their results showed the possibility of camera pointing record with sub-pixel accuracy.

7. REFERENCES

1. M. Krischke, et al., "RAPIDEYE Satellite Based Geo-Information System", Proceedings 2nd IAA Symposium on Small Satellites for Earth Observation, Berlin 1999.
2. Applications of Optical Fourier Transforms, ed. Henry Stark, Academic Press, 1982.
3. Sony Semiconductors-Product Guide. http://www.sel.sony.com/cgi-bin/semi/get_category.cgi
4. Purwadi Purwosumarto, Francis T.S. Yu. Robustness of Joint transform Correlator Versus VanderLugt Correlator. Optical Engineering. Vol. 36. No. 10. October 1997.
5. WebSite of Kopin Corporation. http://www.kopin.com
6. Janschek, K., Boge, T., Tchernykh, V., Dyblenko, S. Image Based Attitude Determination using an Optical Correlator. Accepted Paper, 4th ESA International Conference on Spacecraft Guidance, Navigation and Control Systems, 1999, Noordwijk, The Netherlands
7. Janschek, K., Kusimov, S., Sultanov, A., Tchernykh, V., Dyblenko, S. Optical Correlator for Onboard Autonomous Control of Earth Observation Camera Pointing. Digest of the 2nd International Symposium of the International Academy of Astronautics (IAA) Small Satellites for Earth Observation, Berlin, April 12 – 16, 1999.Wissenschaft und Technik Verlag, Berlin, 1999. Paper IAA-B2-0907P, pp.231-234.