

## SMARTSCAN – Smart Pushbroom Imaging System for Shaky Space Platforms

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**ABSTRACT:** The presented SMARTSCAN imaging concept offers high quality imaging for pushbroom imaging systems even with moderate satellite attitude stability on a sole opto-electronic basis without any moving parts. It uses real-time recording of the actual image motion in the focal plane of the remote sensing camera during the frame acquisition and an a posteriori correction of the obtained image distortions on base of the image motion record. Exceptional real-time performances with subpixel accuracy image motion measurement are provided by an innovative high-speed onboard optoelectronic correlation processor. SMARTSCAN allows therefore using smart pushbroom cameras for hyper-spectral imagers in particular on satellites and platforms which are not specially intended for imaging missions, e.g. micro- and nano-satellites with simplified attitude control, low orbit communication satellites, manned space stations. This expands the application area of pushbroom scanners to new domains of spacecraft with only moderate attitude stability.

The paper gives an overview on the system concept and main technologies used (advanced optical correlator for ultra high-speed image motion tracking), it discusses the conceptual design for a smart compact space camera and it reports on airborne test results of a functional breadboard model.

### INTRODUCTION

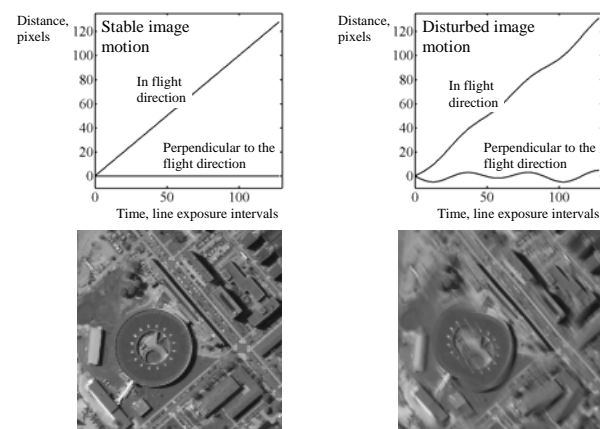
Remote sensing satellites generally use pushbroom scanners with linear image sensors. The use of such scanners allows reducing the size and cost of the imaging payload and has a number of other advantages, but requires high stability of the satellite attitude during scanning of the frame, otherwise the scanned image will be geometrically distorted. To scan the image in the flight direction, the orbital motion of the satellite is used, which results in the corresponding motion of the projected Earth image in the focal plane of the camera.

Compared with area or matrix scan cameras, pushbroom scanners have following advantages:

- they require less field of view and allow for a large image size with the same optical system;
- multi-spectral and stereo capability can be easily implemented;
- pushbroom scanners do not require any shutter and there are less costly than matrix devices.

At the same time, pushbroom scanners have one significant disadvantage: they require high attitude stability during scanning of the image. If the satellite attitude is not stable, the image motion in the focal plane will not be steady what results in geometrical distortions of the obtained images (Figure 1). For example, an image with ground resolution of 2.5 m taken from satellite on a 500 km orbit in presence of attitude change by  $5 \mu\text{rad}$  (1 arc second) will show noticeable image distortion (0.5 pixel). The spectrum of attitude disturbances spreads from 1/orbital period to few hundreds Hz. Low frequency disturbances are mainly caused by thermal deformations of the satellite

structure, atmospheric drag variations and other factors, related to orbital position. High frequency disturbances (vibrations) are caused by unbalance of reaction and momentum wheels and operations of other mechanical systems onboard the satellite. To some extent, the distortions can be corrected using the record of attitude disturbances during image scan, measured by high precision Inertial Measurement Unit (IMU) onboard the satellite. Such solution, however, will significantly increase the mission cost. Besides, it is not suitable for correction of high frequency distortions: high accuracy of IMU is usually obtained at the cost of bandwidth limitation; moreover non rigidity of satellite structure can result in significant differences of high frequency attitude records taken at non collocated mounting positions of gyros and the pushbroom camera.



**Figure 1. Pushbroom imaging with attitude disturbances**

Image distortions can be also corrected by geo-referencing of the obtained images by matching them with the previously made images of the same area. This solution does not require installation of additional devices onboard, it generally provides high correction accuracy (considering also the ground relief variations and perspective distortions), but it is suitable only for correction of low frequency distortions. Matching of the images (determination of local shifts) with high accuracy generally requires 2D correlation of sufficiently large image blocks. This determines the averaged shifts of blocks of lines without the possibility to measure the individual lines shifts. Large high frequency disturbances can also decrease the accuracy of matching or even makes the correlation of image blocks impossible.

To solve this problem the SMARTSCAN imaging concept has been developed by TU Dresden, Institute of Automation, which is based on the recording of the actual motion of the focal plane image during the frame scan with additional focal plane image sensors and subpixel image motion tracking in real-time using an onboard optical correlator<sup>1,2</sup>. The image distortions, caused by the satellite attitude instability, are then corrected on base of this image motion records by a ground computer.

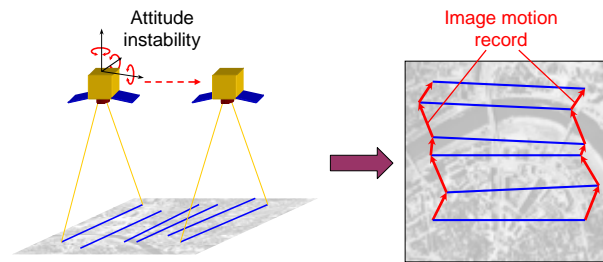
The proposed solution allows to expand the area of pushbroom scanners application to satellites with moderately attitude stability, micro satellites or to use them as secondary imaging payload for low orbit communication satellites or the Space Station.

### SMARTSCAN SYSTEM CONCEPT

The principle of SMARTSCAN operation is based on real time recording of the actual image motion in the image plane. Such record, made directly in the focal plane of the camera, automatically considers in-situ all factors, which cause the unsteadiness of image motion and corresponding image distortions. Its accuracy is linked with the resolution of the camera – the errors of such record are measured in image pixels (not in arc seconds) and will be the same for cameras with *any* ground resolution.

The image motion record is a record of the focal plane image motion with respect to the linear sensor. To simplify the explanation, it is possible to suppose, that the image is fixed and image sensors are moving with respect to it. Then the image motion record can be interpreted as the trajectory of the linear sensor in the plane of the fixed image (with respect to the first line) or as a sequence of linear sensor positions in the moments of the lines exposure (Figure 2).

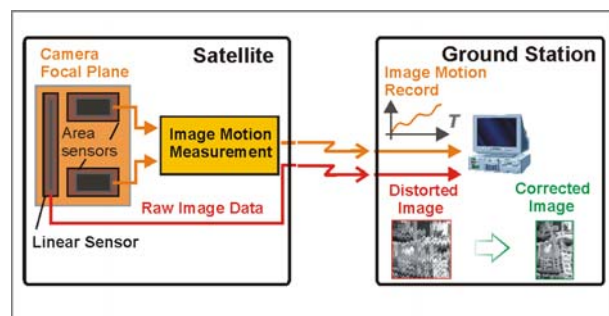
With the actual position of every line is known, the actual position of every pixel of the distorted image with respect to the first line is calculated and a correct image (corresponding to steady image motion) can easily be reconstructed by standard 2D interpolation.



**Figure 2. Disturbed pushbroom imaging and image motion record**

Such simple approach works correctly in absence of perspective distortions (non-distorting nadir oriented camera, no surface relief). In real case the “ideal” (steady) image motion at a certain point of the image depends on the local distance to imaged surface. If the camera is not nadir pointing and/or the imaged area is not flat, attitude and surface relief data should be considered for accurate image correction.

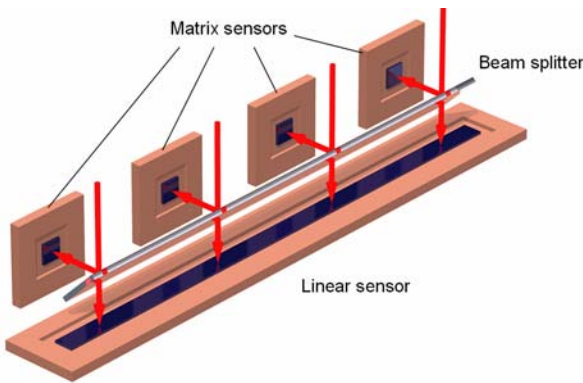
Best results can be obtained by combining the SMARTSCAN approach with matching of the obtained images with previously obtained, geo-referenced images of the same area. In this case first the SMARTSCAN image motion record can be used to correct the high frequency component of image distortions and to make the obtained image suitable for block-matching with the reference one. Low frequency distortions will be then corrected on base of matching with reference images. If no reference images of the target area are available, low frequency distortions can be corrected with high accurate attitude information from an IMU. Required high accuracy of attitude data can be obtained in this case at a cost of bandwidth limitation, by using the slow and accurate IMU or by filtering of attitude data.



**Figure 3. SMARTSCAN system concept**

The general SMARTSCAN system concept is shown in Figure 3. It consists of an onboard component (left box), which measures and records the image motion, and of a ground component (right box), which reconstructs the image on base of the image motion record. There is only a small downlink overhead necessary for transmission

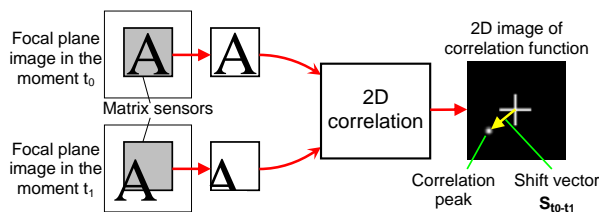
of the image motion record, which is in general negligible compared to the image data from the pushbroom line sensors. The recording of the focal plane image motion can be realized by 2D correlation of sequential images, taken by auxiliary matrix image sensors in the focal plane. A matrix sensor will be exposed at the same moments as the linear sensor, i.e. for each image line taken by linear sensor, each of matrix sensors will produce a small 2D image. To measure the (yaw) rotation of focal plane image, at least two matrix sensors should be used. The number of sensors can be further increased to provide some redundancy, e.g. four sensors configuration as sketched in Figure 4.



**Figure 4. Possible configuration of the image sensors in the focal plane**

### IMAGE MOTION MEASUREMENT

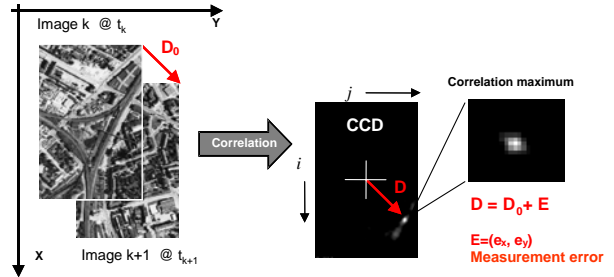
The image shift between the exposure moments  $t_k$  and  $t_{k+1}$  of neighboring lines can be determined by 2D spatial correlation of the matrix sensor images, taken in the same moments as the linear sensor exposing (Figure 5).



**Figure 5. Image shift vector determination by 2D correlation**

The second image will be shifted with respect to the first by a shift vector  $\vec{D}_0$ . This vector is defined by the size and position of overlapped parts for both images. The overlapping can be effectively determined by two dimensional (2D) correlation of the images. The 2D correlation function represents the mutual shift of the

second image w.r.t. the first image. This location is normally given by a distinctive peak in the correlation function. Detection of the correlation peak and measurement of its coordinate in the correlation plane allow determining the shift between both images with subpixel accuracy<sup>6,7</sup> (Figure 6).



**Figure 6. Image shift vector determination by 2D correlation**

For a large class of applications it is necessary to measure the motion of different parts of the camera image plane. In this case the size of the image sensor is much larger than the size of tracked image parts or blocks. This allows measuring the motion of the blocks on rather long distances and increases the operational range of the image motion tracking system.

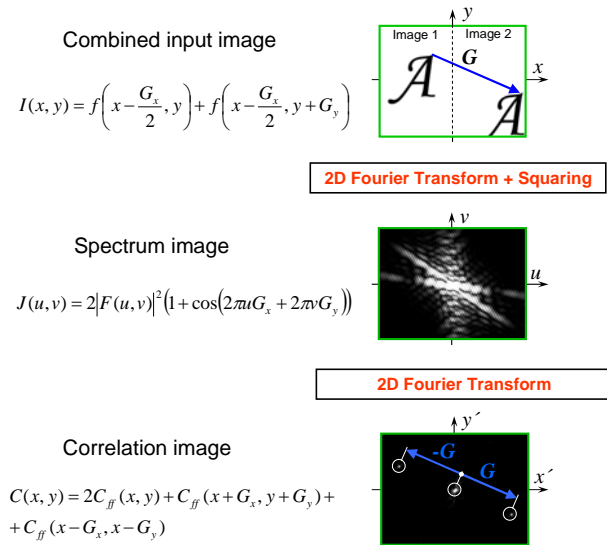
This long range tracking procedure is implemented by a prediction of motion for each tracked block and a subsequent correction of the predicted shift with the correlation data. The correlation is performed for the image from the initial position (reference image) and the image from the predicted position (current image). The prediction can use some external information about camera motion or previous results of image motion measurements.

The so-called *Joint Transform Correlation* (JTC) scheme is used to minimize the overall computational effort<sup>7</sup>. It makes use of two subsequent 2D-Fourier transforms without using phase information (this is highly beneficial for a hardware realization by optical Fourier processors, see below).

The two images  $f_1(x, y)$  and  $f_2(x, y)$  to be compared are being combined to an overall image  $I(x, y)$  as shown in Figure 7 (top). A first Fourier transform results in the joint power spectrum  $S(u, v) = \mathbf{F}\{I(x, y)\}$ . Its magnitude contains the spectrum  $F(u, v)$  of the common image contents augmented by some periodic components which are originating from the spatial shift  $\vec{G}$  of  $f_1$  and  $f_2$  in the overall image  $I$  (Figure 7 centre).

A second Fourier transform of the squared joint spectrum  $J(u, v) = S(u, v)^2$  results in four correlation functions (Figure 7 bottom). The centered correlation function  $C_{ff}(x, y)$  represents the auto-correlation function of each input image, whereas the two spatially

shifted correlation functions  $C_{ff}(x \pm G_x, y \pm G_y)$  represent the cross-correlation functions of the input images. The shift vector  $\vec{G}$  contains both the technological shift according to the construction of the overall image  $I(x, y)$  and the shift of the image contents according to the image motion. If the two input images  $f_1$  and  $f_2$  contain identical (but shifted) image contents, the cross-correlation peaks will be present and their mutual spatial shift  $\vec{\Delta} = \vec{G} - (-\vec{G})$  allows determining the original image shift in a straightforward way.



**Figure 7. Principle of joint transform correlation**

Several advantages of the correlation approach compared to feature based image motion tracking are evident. The correlation approach is much more robust against image noise. Moreover it requires no a-priori information on the image contents and it works well as long as “enough” image texture is existent. The determination of the actual image shift is reduced to the comparable simple task of determining the bright spot of the correlation peak within a certain region of the correlation image.

The main drawback of the correlation approach however is the high computational effort for the two 2D-Fourier transforms, which limits its applicability for real-time solutions. A very promising solution to this problem is given by using optical processors, as outlined in the next paragraph.

## REQUIREMENTS TO IMAGE CORRELATOR

The necessity of image shift determination for every line of the linear scanner image is setting challenging requirements to the correlation rate. A satellite on a 500 km orbit has a ground track velocity of 7059 m/s<sup>3</sup>. With ground sampling distance of 2.5 m this corresponds to a lines frequency of 2824 lines/s. With four matrix image

sensors this number should be multiplied by 4, what results in processing rate requirements of 11300 correlations/s.

Essential factors are also the correlation stability, the accuracy of the image shifts determination and the range of measurable shifts. All these characteristics are closely linked with the size of the correlated fragment.

Correlation stability here is understood as an ability to determine the shift between the correlated fragments for possibly larger range of image content (also with weak image textures and in presence of noise) and to detect reliably the cases when the correlation is not possible. Both abilities are linked with the size of correlated fragments. Generally a weak image texture results in degradation of the correlation peak which becomes finally comparable with the surrounding correlation image content and therefore difficult to detect. Increasing of the input fragments size makes the peak thinner and higher with respect to correlation image, what improves dramatically its detectability and therefore the stability of correlation.

Accuracy of the shift determination also improves with a larger size of correlated fragments as the higher peak is much less affected by correlation image noise.

Finally the measurable shifts range is directly linked with the fragment size: with large fragments proportionally large mutual shifts can be allowed with the same percentage of images overlapping.

Considering the above mentioned properties, the size of correlated fragments should be as large as possible. For practical realization reasons, however the data transmission capabilities should be also considered. For a high speed SpaceWire link the data rate is limited by 400 Mbps<sup>4</sup>. With one SpaceWire connection per matrix image sensor, the frames rate of 2824 frames/s and radiometric resolution of 8 bits/pixel a fragment size of 128x128 pixels is possible.

Taking into account these high requirements to data processing rate (11300 correlations of image fragments of 128x128 pixels per second – 4x400 Mbps input data rate) and the limitations of data processing resources it is not possible to produce this image motion record by digital data processing onboard the satellite. It is also not possible to transmit the matrix sensors images to the ground station for further processing due to very high data rate (1600 Mbps).

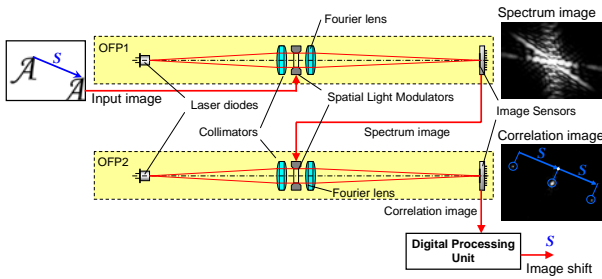
## OPTICAL CORRELATOR

To provide the required real-time onboard performance, it has been proposed to perform the image correlation with an onboard optical correlator<sup>1,2</sup>.

The principle of joint transform correlation as outlined above can be realized by a specific optoelectronic set-up forming a Joint Transform Optical Correlator. It is an optoelectronic device, capable of extremely fast image processing due to application of high parallel optical



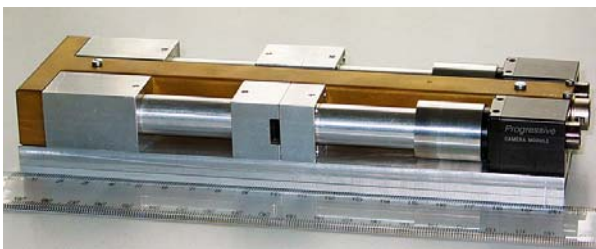
computing technology. Its operation is based on the optical Fourier transform exploiting specific diffraction phenomena to produce a 2D Fourier transform of an image. This diffraction-based phenomenon is used to perform 2D correlation of two images by two sequential optical Fourier transforms (Figure 7), according to the Joint Transform Correlation principle<sup>5</sup>.



**Figure 7. Joint Transform Optical Correlator principle**

With the 2D-Fourier transform performed optically, the time and power are consumed mainly for entering the images into the optical system and reading the results of the optical transform. This makes possible to reach a high image processing rate with limited power consumption. This advanced technology and its applications have been studied during last years at the Institute of Automation of the Technische Universität Dresden<sup>6,7</sup>. Special design solutions have been developed to make the optical correlator robust against mechanical loads and to eliminate the need for precise assembling and adjustment<sup>8,9</sup>.

To prove the feasibility of SMARTSCAN concept a hardware model of optical correlator has been manufactured (Figure 8).

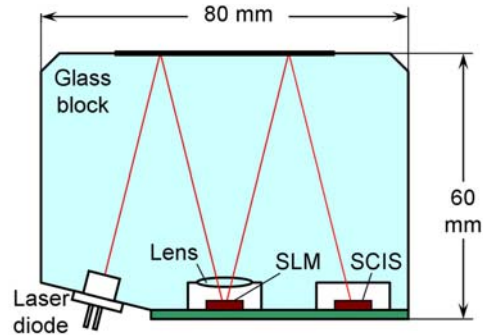


**Figure 8. Breadboard model of optical correlator**

To cope with the limited funding and to save development time, it uses standard video cameras as the image sensors. This limits the image processing rate to 60 correlations per second. The model has been successfully tested in airborne flight test campaign during summer 2002<sup>10</sup>.

Recent research has given advanced solutions for a very compact realization of such a device, suitable for onboard installation on a spacecraft. The realization concept of the optical correlator module is based on customized miniature optoelectronic components: a reflective Spatial Light Modulator (SLM) and a Spectrum/Correlation Image Sensor (SCIS). Both

optical Fourier transforms will be performed sequentially with a single optical Fourier processor. To reduce the size, a folded optical system design on the base of glass block is currently being considered (Figure 9).



**Figure 9. Advanced optical system layout**

The coherent light, emitted by a laser diode, reflects from the aluminized side of the block and illuminates the SLM surface via the embedded lens. The beam, reflected from SLM, is modulated by the input image (pair of image fragments to be correlated). It is focused by the same lens and forms (after intermediate reflection) the image of the Fourier spectrum of input image on the SCIS surface. This image is read and sent to SLM for a second optical Fourier transform, after which the correlation image is obtained. Mutual shift of correlated fragments is calculated from the correlation image peaks positions within the correlation image. This operation will be performed directly inside the SCIS chip, what makes possible to simplify the digital electronics and to reduce significantly power consumption. Using unpackaged optoelectronic components and Chip-on-Board mounting, the optical system can be realized within the volume of 80x60x30 mm. Digital image processing operations (interfaces, preparing the image fragments for correlation, control) will be realized on a single FPGA and 3 RAM modules. Expected performances of the whole optical correlator module are summarized in Table 1.

**Table 1. Expected performances of the advanced onboard optical correlator**

Correlated fragments size	128x128 pixels
Processing rate	12500 correlations/s
Shift determination error (typical image content)	$\sigma$ within 0.1 pixel
Dimensions	within 140x100x80 mm
Mass	within 1 Kg
Power consumptions	within 20 W

## SMARTSCAN AIRBORNE TESTING

Airborne flight tests have been performed with a breadboard model of SMARTSCAN system, including the camera (Figure 10, Table 2) and the optical processor model (Figure 8), a portable PC and special software for control and image processing.

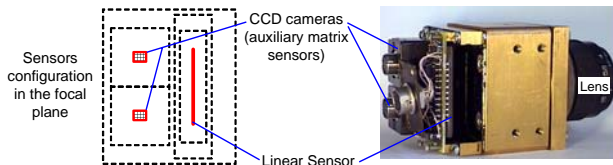


Figure 10. SMARTSCAN camera breadboard model

Table 2. Main performances of the breadboard camera model

Lens	Tessar type: $f = 75 \text{ mm}$ ; $f/4$ ; angular resolution - $187 \mu\text{rad/pixel}$
Linear sensor	Resolution: 2048 pixels in line; lines rate: 240 lines per second
Auxiliary matrix sensors	Frame size: $640 \times 480$ pixels; frames rate: 30 frames per second
Dimensions / mass	$110 \times 58 \times 50 \text{ mm}$ / 900 g

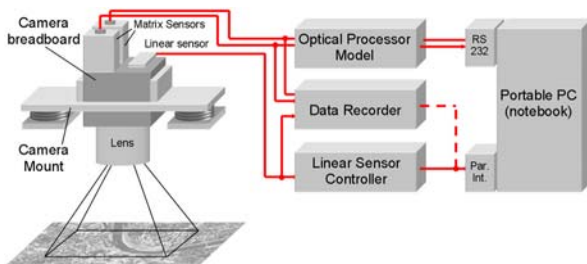


Figure 11. Test equipment configuration onboard the plane

The general configuration of the test equipment onboard the airplane is shown in Figure 11.

The tests have been performed at the DLR (Deutsches Zentrum für Luft- und Raumfahrt) facilities in Oberpfaffenhofen near Munich<sup>10</sup>. The test equipment has been mounted onboard a small, single engine turboprop aircraft (Cessna Grand Caravan – Figure 12). The camera model was mounted in one of the bottom port of aircraft, all other equipment – in a special rack in the cabin (Figure 13).

The flight altitude was approximately 2400 m with a velocity – 240 km/h (67 m/s). The ground resolution of the camera model was 0.45 m per pixel.



Figure 12. Cessna Grand Caravan

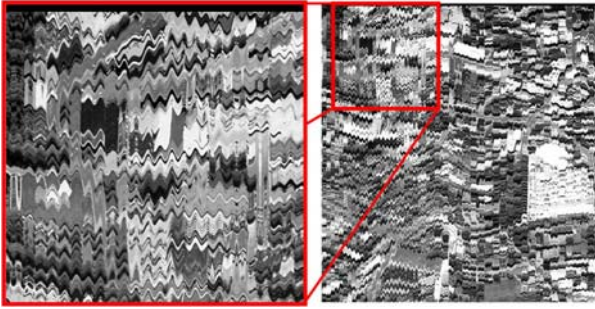


Figure 13. Test equipment mounted onboard the plane

During imaging the airplane produced considerable attitude disturbances and vibrations. The distorted image from the linear sensor has been loaded to the PC. Two streams of small images from matrix sensors have been processed in real time by the optical processor; the resulting image motion record has been loaded to PC too. After finishing of the imaging session the distorted linear sensor image has been corrected on base of the stored image motion record.

As a direct result of the tests, the complete end-to-end functionality of SMARTSCAN imaging system has been demonstrated with real remotely sensed Earth images under airborne flight conditions. Totally nine imaging sessions have been performed, each with a linear sensor image ( $2048 \times 2048$  pixels) and the corresponding image motion record produced by real time processing of the matrix sensor images by optical processor onboard the airplane. The linear sensor images, obtained during the tests, are distorted due to airplane attitude instability, vibrations and flight direction and velocity changes. An example of such a distorted raw image is shown in Figure 14.





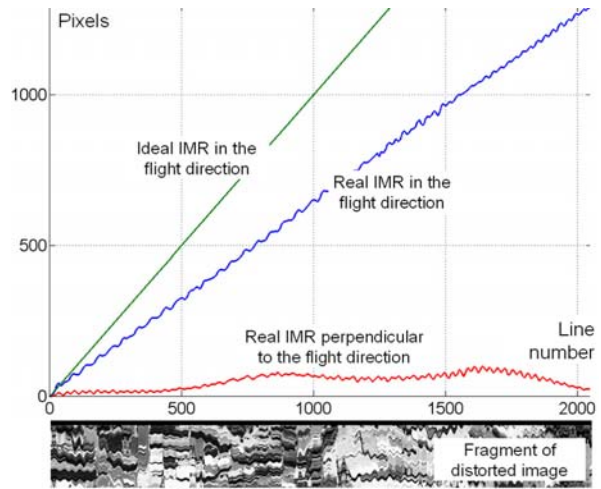
**Figure 14. Distorted raw image from linear sensor**

The image motion records for each imaging session represent the motion of both ends of the linear sensor with respect to the image. The starting points of these records coincide with the sensor position at the moment of exposure of the first image line. Figure 15 shows the dependency of the position of one end of the linear sensor from the number of obtained lines (two components – along and perpendicular to the flight direction). The motion record for the other end of the linear sensor is not presented in Figure 15 as it is practically equivalent to the first one (the rotational – yaw - component of image motion was relatively small). The record, presented in Figure 15, corresponds to the distorted image in Figure 14.

In the ideal case, the image should advance in flight direction by exactly one pixel with any obtained line, so the ideal image motion record in the flight direction should be a straight line with a 45° slope. The real record in the flight direction however has a different slope due to the airplane velocity and local variations caused by attitude instability and vibrations.

Perpendicular to the flight direction there should be no image motion in the ideal undisturbed case, so the corresponding component of image motion record

should coincide with the horizontal axis. Actually there were considerably large deviations from the ideal case due to attitude instability and vibrations also in this case.



**Figure 15. Image motion record (IMR)**

The correction of the distorted images has been made after the flight on base of the image motion records produced in-flight. Figure 16 shows the example of such an image correction result.

Some residual distortions of the corrected image are caused mainly by vibration components above the Nyquist frequency. Such distortions can be eliminated by increasing of the correlation rate. A certain degree of smoothing of the corrected image is caused by the interpolation procedure itself and (on some parts of the image) by a high local velocity of image motion due to high vibration amplitudes (which are actually *not* expected on a satellite).

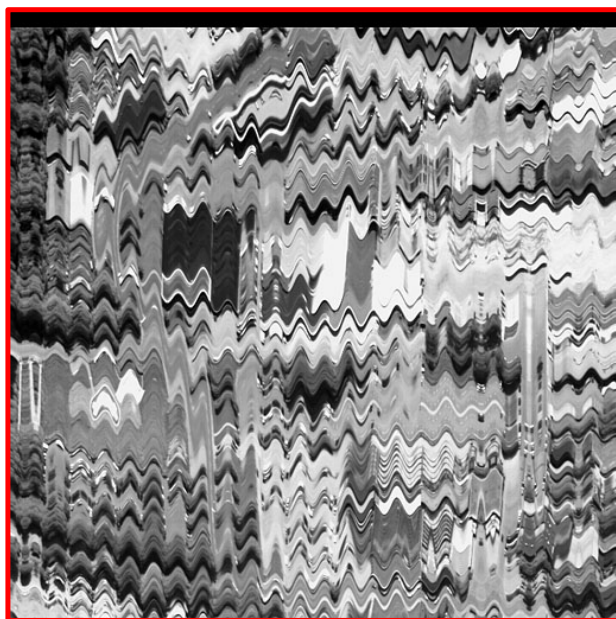


Image correction on base of image motion record



**Figure 16. Example of image correction on base of an image motion record**

## CONCLUSIONS

This paper has presented the novel SMARTSCAN concept for robust pushbroom imaging on shaky platforms. It allows getting high resolution images without any mechanical compensation mechanisms. The sole optoelectronic image motion compensation uses advanced optical correlator technology, which allows to measure image motion records with subpixel accuracy in real-time with a compact and low power device. The concept has been demonstrated successfully with airborne tests.

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