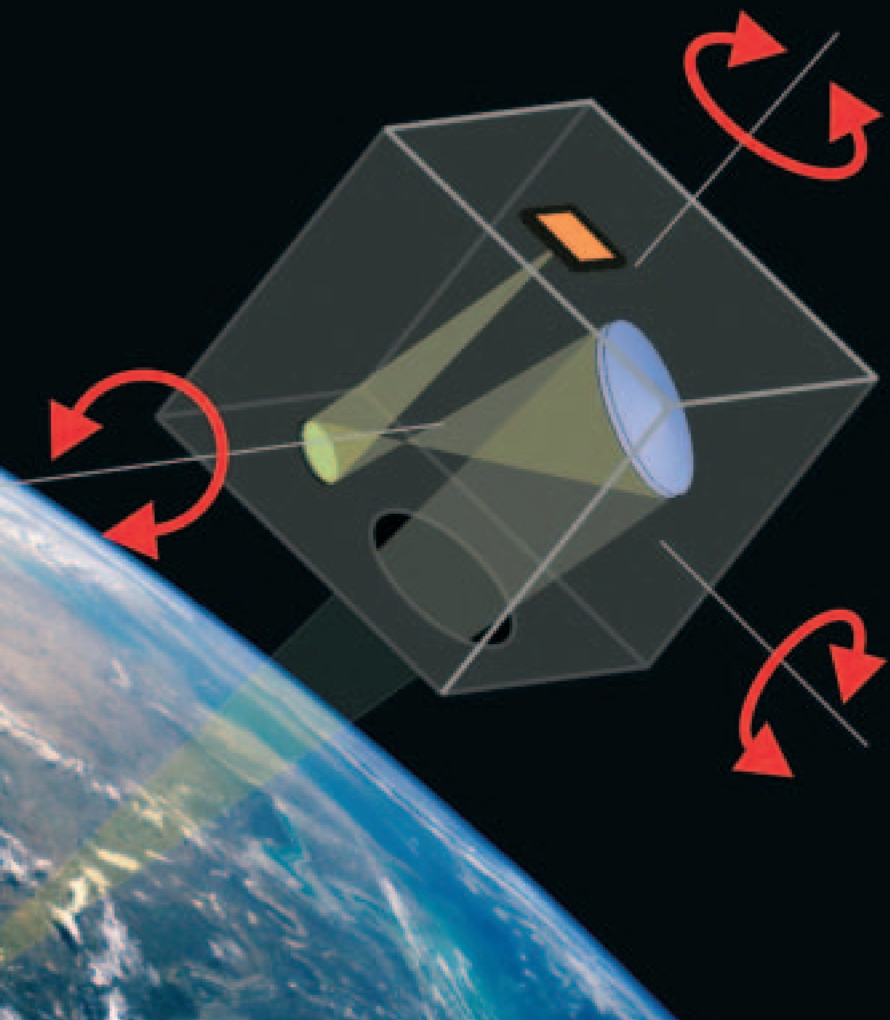
Clever Imaging with SmartScan



Distorted Raw Image

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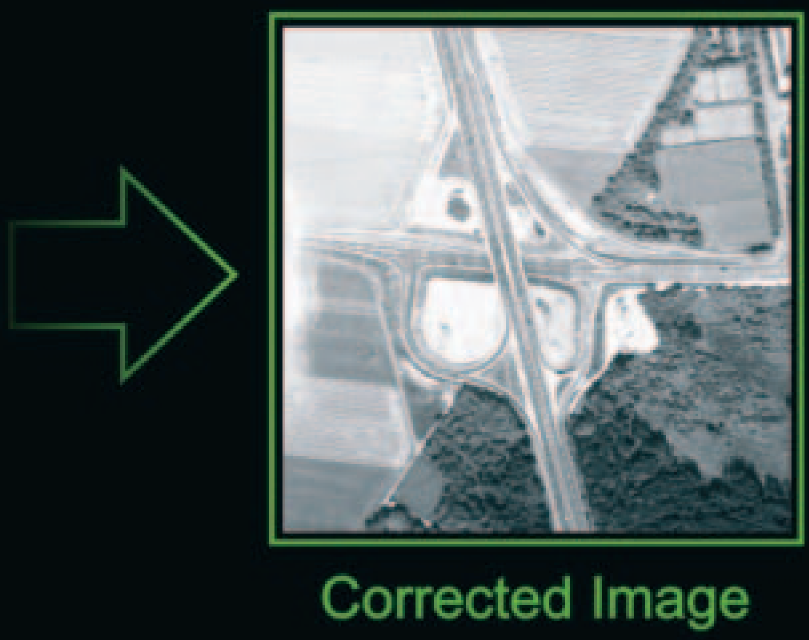
The cameras commonly used for Earth observation from satellites require high attitude stability during the image acquisition. For some types of cameras (high-resolution 'pushbroom' scanners in particular), instantaneous attitude changes of even less than one arcsecond result in significant image distortion and blurring. Especially problematic are the effects of high-frequency attitude variations originating from micro-shocks and vibrations produced by the momentum and reaction wheels, mechanically activated coolers, and steering and deployment mechanisms on board. The resulting high attitude-stability requirements for Earth-observation satellites are one of the main reasons for their complexity and high cost.

The novel SmartScan imaging concept, based on an opto-electronic system with no moving parts, offers the promise of high-quality imaging with only moderate satellite attitude stability. SmartScan uses real-time recording of the actual image motion in the focal plane of the camera during frame acquisition to correct the distortions in the image. Exceptional real-time performances with subpixel-accuracy image-motion measurement are provided by an innovative high-speed onboard opto-electronic correlation processor. SmartScan will therefore allow pushbroom scanners to be used for hyper-spectral imaging from satellites and other space platforms not primarily intended for imaging missions, such as micro- and nano-satellites with simplified attitude control, low-orbiting communications satellites, and manned space stations.



Imaging with Reduced Platform Attitude Stability

Stability of the camera's focal plane during the scanning motion of a remote-sensing imaging system is essential for good image quality. Satellite attitude perturbations disturb the imaging motion, which results in geometric distortions in the images obtained - with ground sampling every 1 metre, for example, a 0.3 arcsecond deviation corresponds to 1 pixel. Especially sensitive to this kind of disturbance are high-resolution pushbroom scanners which can, in principle, deliver a ground pixel resolution of less than 1 metre from a 700 km altitude orbit. Requirements on the satellite's attitude stability can be relaxed, however, if an appropriate correction to the distorted image can be performed on the ground.

Such a correction requires a real-time record of the image motion occurring in the camera's focal plane during the image's acquisition. With this so-called 'image-motion record', the relative position of every line and pixel can be calculated and a corrected image can easily be restored by standard 2D interpolation. To avoid degradation of the resolution after correction, the image motion needs to be recorded with subpixel accuracy.

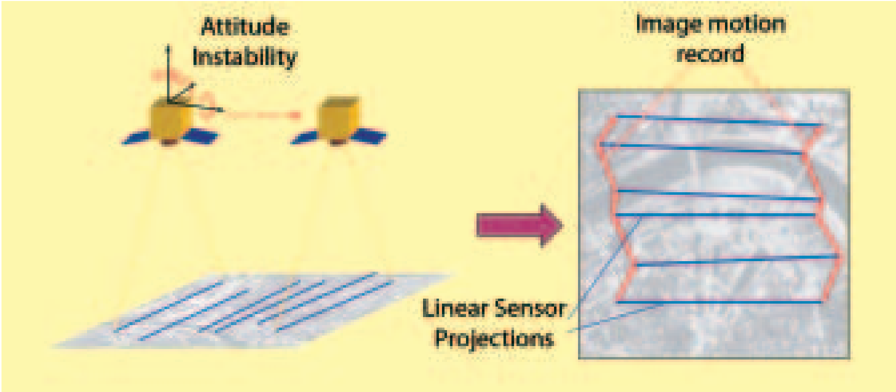
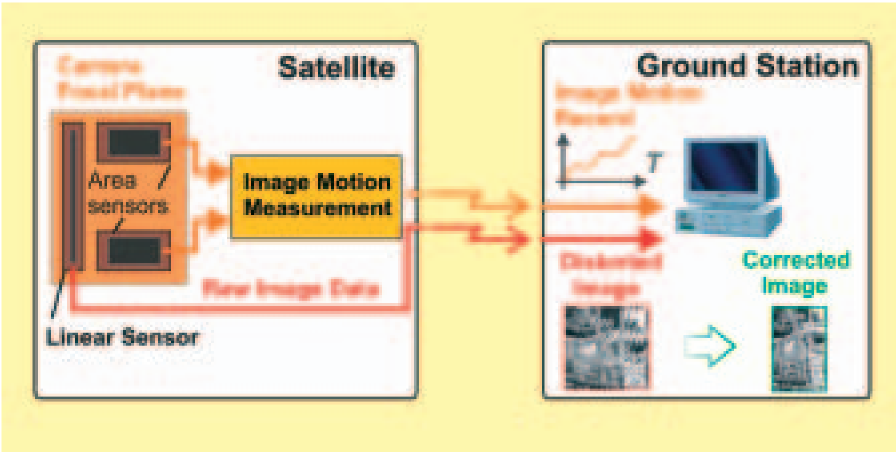


Image distortions due to satellite attitude instability while scanning with a linear image sensor



The basic elements of the SmartScan system

The Concept of Opto-Electronic Image Correction

State of the art solutions for camera image-motion measurement in aerial remote-sensing applications use high-bandwidth gyroscopes. Typically 100 times better accuracy is required, however, for satellite cameras due to their much higher operating altitude. The ideal place to measure the image motion is at the imaging instrument's focal plane, either using the image sensor itself or some auxiliary motion sensors. In the case of a pushbroom camera with one or more linear sensors (multi-spectral), at least two small auxiliary matrix image sensors installed in the focal plane of the camera are recommended. This allows in-situ measurement of all relevant image-motion distortions resulting from camera motion disturbances close to the primary image sensor. The resulting image-motion record data can be downlinked together with the primary linear sensor image data and used for posteriori image correction on the ground.

SmartScan Proof of Concept

The SmartScan concept was first proposed by the Technical University of Dresden in 1999. Between 1999 and 2002, three ESA/ESTEC-funded projects were undertaken to demonstrate the SmartScan system's feasibility and quantify the performance parameters of a spaceborne system. A follow-on system study in 2003/2004 investigated further performance improvements to SmartScan in terms of an opto-mechatronic solution, as well as further applications of the real-time image-motion tracking using optical correlators.

In the initial project (1999 – 2000), the feasibility of the system concept was proven using simulated images and a first hardware model of the optical Fourier processor. The second project (2000 – 2001) resulted in a hardware breadboard model of the SmartScan imaging system, includinges the optical processor and a smart camera, together with all necessary control and image-processing software. The model was tested with printed images on a laboratory satellite-motion simulator based on a five degree-of-freedom industrial robot. In the third project (2001 – 2002), the model was tested under flight conditions onboard a small turboprop aircraft.

The SmartScan system breadboard model includes a smart pushbroom camera and an optical processor. Standard video cameras have been used as matrix image sensors for the compact SmartScan camera due to project budget constraints, but this limits the maximum sampling frequency of the image-motion record to 30 Hz.

Image-Motion Measurement with 2D-Correlation

The spatial dynamics of imaging 'windows' can be analysed using feature- or area-based methods to derive image-motion information. Area-based methods have been proved to be much more robust, particularly for image data resulting from unstructured environment. The classical and most widely used approach is 'area correlation', which exploits the fundamental property location of the peak in the cross-correlation function of two images is gives directly the displacement vector of the image shift.

In the SmartScan configuration, each auxiliary matrix sensor acquires the sequence of 2D images in parallel with the linear-sensor exposure. The image shift between the moments of exposing neighbouring lines t_1 and t_2 is determined by 2D spatial correlation of the matrix sensor images. The image-motion record is then recalculated from the shift vectors by geometrical transformations.

Image-shift determination using the area-correlation method is extremely noise-resistant, gives sub-pixel accuracy and does not require any specific features in the image. As a drawback, the 2D computer correlation of the images requires a very large number of calculations. Taking into account the limitations of onboard data processing resources and the high sampling frequency required, it is not realistic either to produce the image-motion record by digital data processing onboard the satellite, or to transmit the matrix-sensors images to the ground station for further processing, due to the very high additional volume of data -the matrix sensors produce at least two 2D images for each line of the linear sensor image.

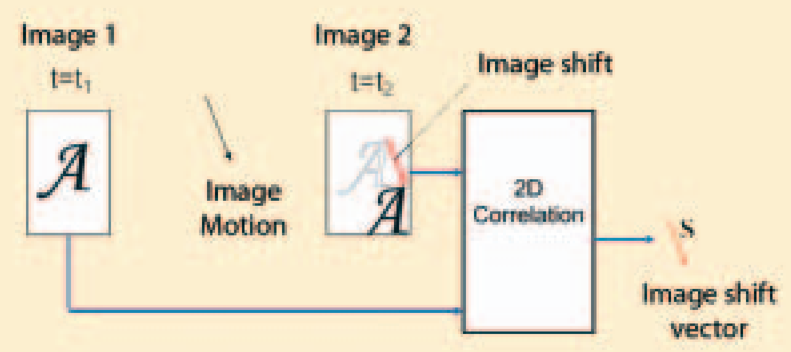


Image-shift determination with spatial 2D correlation

The optical-processor model consists of an optical unit and an electronic module. It processes two standard video signals from the camera's matrix sensors and produces the real-time image-motion record. The optical unit uses standard video cameras as image sensors for the same reason as the camera. This limits the image processing rate to 30 optical Fourier transforms per second, or 15 correlations per second per optical Fourier processor (one correlation requires two Fourier transforms). To provide the required 60 correlations per second, two identical optical Fourier processors are operated in parallel and the image-processing rate for each of them has been doubled by the simultaneous processing of two image pairs.

The in-flight tests were performed using a small, single-engined aircraft (Cessna Grand Caravan) at the DLR (Deutsches Zentrum für Luft- und Raumfahrt) facilities in Oberpfaffenhofen near Munich. In addition to the complete breadboard model of SmartScan system, a portable PC and special control and image-processing software were installed in the plane. The camera was mounted in a special pod beneath the plane, and the other equipment was mounted in a special rack inside the cabin. An additional real-time data recorder was used to store all in-flight data (raw and operational) for follow-on laboratory evaluation.

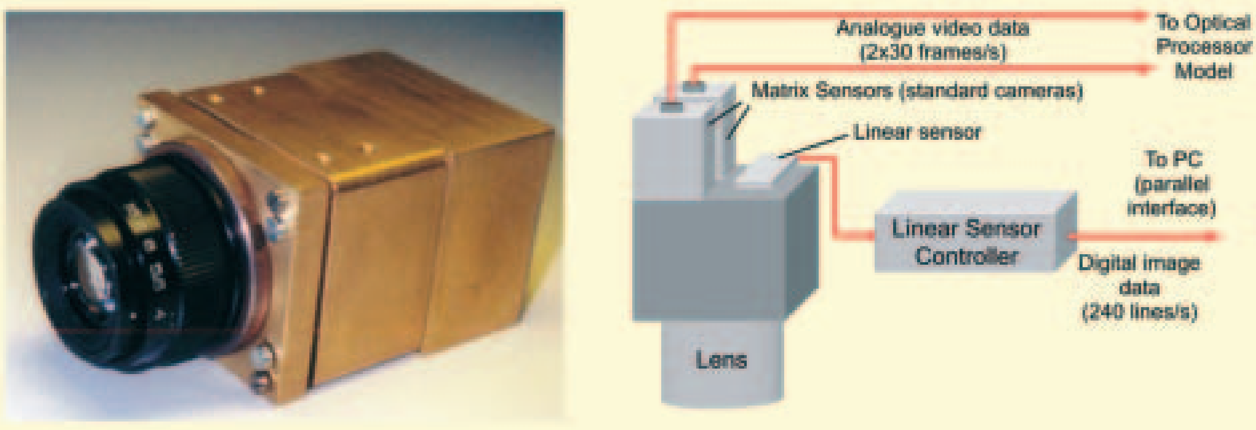
Two test flights were made, each lasting about an hour, during which a total of nine image acquisitions were performed. The altitude of the flights was approximately 2400 metres and the air speed 240 km/h (67 m/s), resulting in a ground pixel resolution of 0.45 m.

SmartScan Flight-Test Results

The linear-sensor images taken during the two test flights were considerably distorted due to variations in the aircraft's attitude, engine vibration and changes in flight direction and velocity (see accompanying figure). The images were subsequently corrected based of the in-flight image-motion record, which gives the position of every line of the distorted image with respect to the first line. With this information, the coordinates of all the pixels of the distorted image with respect to the first line were calculated and the corrected pixel positions determined using a standard two-dimensional interpolation procedure.

A direct error determination for the image-motion record was not possible for these airborne tests, because no reference aircraft attitude and position data were available with the required accuracy. Instead, an extensive cross-data analysis with the recorded image-motion sequences was performed. The mean-square deviation for all nine imaging sessions was generally within 0.25 pixels, leading to the conclusion that the error in the image-motion record was also within 0.25 pixels.

Some residual distortions in the corrected images are mainly caused by unsuppressed residual vibration components from the camera mounting. A certain degree of smoothing of the

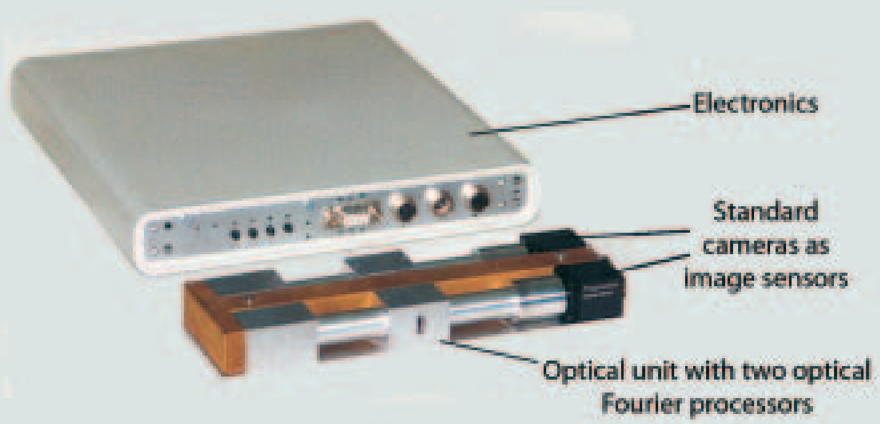


The breadboard model of the SmartScan pushbroom camera

Key performance parameters of the breadboarded SmartScan pushbroom camera

Focal length of the lens	75 mm
Linear sensor	Resolution: 2048 pixels in line
	Line rate: 240 lines per second
Auxiliary matrix sensors	Frame size: 640 x 480 pixels
	Frame rate: 30 frames per second
Angular resolution	187 µrad/pixel
Dimensions	110 x 58 x 50 mm^3
Mass	900 g

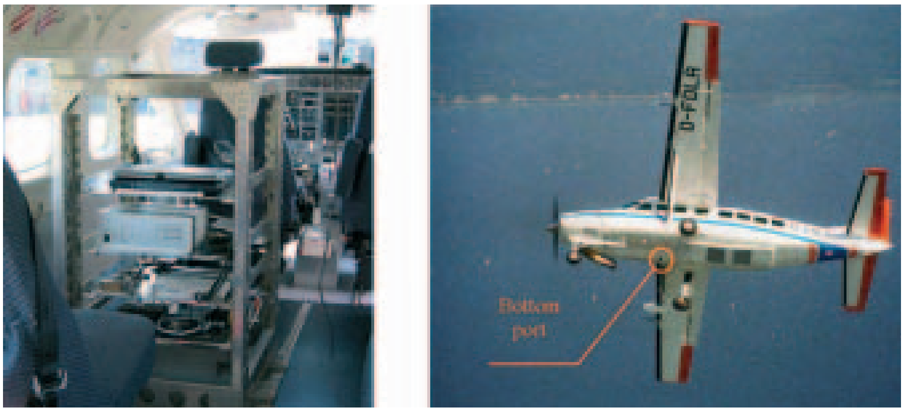
The SmartScan optical correlator breadboard model



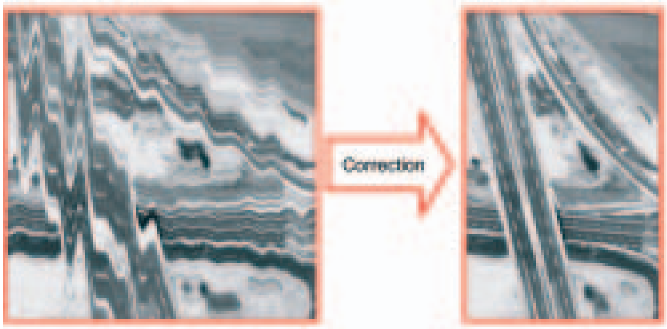
corrected image is caused by the interpolation procedure itself and (in some parts of the image) by a high local image-motion velocity due to high vibration amplitudes. These artifacts are associated with aircraft vibrations and motions, and will therefore not be present in satellite imagery.

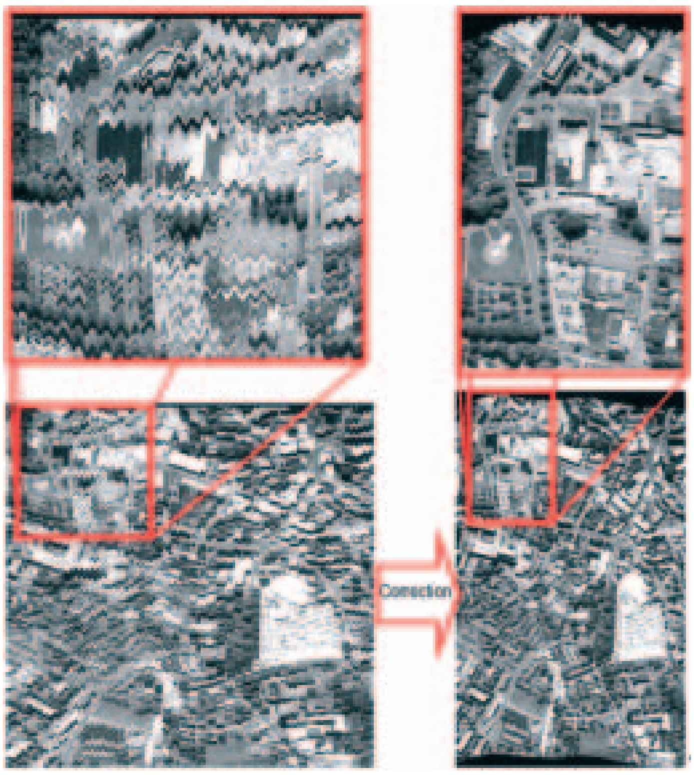
SmartScan's Performance for Spaceborne Remote Sensing

The image-processing rate of the breadboard optical processor model is currently limited to 60 correlations per second, due to the use of standard video cameras as image sensors. It is possible, however, with currently available off-the-shelf opto-electronic components to raise the performance of the optical processor to 32 000 correlations per second. This would allow the direct recording of the image position for every scan line without any interpolation. This is necessary for high-resolution imaging missions, which require extremely high line frequencies – up to 7000 lines per second for a low-Earth-orbiting satellite with 1 metre ground resolution. In principle, SmartScan will then be able to cope with any spacecraft angular velocity and acceleration during scanning, even making high-quality imaging from spinning satellites feasible without any sort of mechanical compensation device.



The SmartScan airborne flight-test configuration





Examples of SmartScan image correction on the basis of image-motion records

A high optical-processor performance also permits the image-motion record to be produced by tracking more than two image fragments, further improving its reliability and accuracy. Accuracy can be also improved by performing the correlation for a pair of images twice, once to determine the shift between the images coarsely and adjust their positions to reduce it before performing the second correlation.

The SmartScan concept using optical-correlator technology therefore offers unique opportunities for affordable spaceborne remote sensing.

Estimated performance of the full-scale SmartScan system

Sampling rate of imaging motion record	16000 samples/s for two-fragment tracking 6400 samples/s for five-fragment tracking 3200 samples/s for five-fragment tracking and double correlations (to improve accuracy)
Errors of the image motion record	σ ≤0.25 pixel with single correlation σ ≤0.1 pixel with double correlation
Dimensions and mass	Same as for optical processor + harness
Power consumption	within 12 W with full correlation rate within 5 W with 25% correlation rate