AUTOMATED DETECTION OF SPATIAL DISTORTIONS OF HYPERSPECTRAL PUSH-BROOM SENSORS - APPLICATION TO THE ENMAP MISSION

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1. ABSTRACT

The EnMAP imaging spectrometer utilises the push-broom technology and senses the surface line-by-line using two separate scan lines for each detector. Attitude variations, micro vibrations and deviations from an ideal projection of incident light such as keystone cause variations of the line of sight of each detector element. These effects need to be reduced by the ground segment geometric pre-processing chain and to be validated over time. In this work an automated image based approach will be presented as potential tool for the geometric validation of the EnMAP products. It primarily focuses on the determination of the accuracy of band-to-band and detector-to-detector registration.

For this, sub-pixel precise tie points are automatically selected based on an adaption of the Structure Invariant Feature Transform (SIFT) algorithm. These points are used to model the spatial distortions as high order polynomials for each band and detector. As a special feature of the proposed approach the results are additionally validated by an internal two-step technique of higher accuracy. First, the polynomial models are inverted and applied to reduce the spatial distortions. Second, the corrected data is then validated by inspecting detected spatial shifts using a phase correlation technique which is tie point independent.

Conducted tests with simulated EnMAP data incorporating varying noise scenarios showed that spatial distortions can be detected of an accuracy of up to 1/100 pixel on average and internally validated of up to 1/1000 pixel on average. The proposed approach is generic, fully automated and has a high potential to support the geometric validation of other push-broom sensors such as SENTINEL-2.

2. INTRODUCTION

Solar-optical remote sensing data is mainly used as a base for the extraction of geospatial information and for monitoring of the spatiotemporal alteration of objects of interest. This requires precise geometric pre-processing of bands and images. The ground segment of the EnMAP mission will achieve sub-pixel accuracy, although several sensor and trajectory specific influences degrade such a precision. However, it is necessary to avoid drawbacks in relying on a single criterion or method. Hence, ground segment independent validation tools are required e.g. a validation tool for geometric pre-processing. In this work, a first approach is presented that comprises automatic tie point selection, local sub pixel shift estimation, distortion modeling and iterative model improvement. The tie point detection is based on local extrema detection as proposed in [1] - Structure Invariant Feature Transform (SIFT). The local sub-pixel shift estimation at tie points between base and reference image that share compact support incorporates latest state-of-the-art approaches and is based on solving the phase correlation plane equation. The distortion modelling step integrates preceding circular shift estimations into higher dimensional least squares polynomial distortion modelling that is constrained by prediction error minimisation. The iterative model enhancement aims on minimising model error using the correlation maximisation and bisection principles, whereas bisection is used to reduce over- or underestimations of polynomials caused by linear discretisation of non-linearities.

To test the proposed approach, three simulated EnMAP images were specifically non-linearly distorted. Artificial distortions that are assumed to coincide with potential residual distortions after geometric pre-processing of the ground segment comprised 144 different scenarios. It has been assumed that keystone was efficiently suppressed beforehand and that the distortions are mainly related to the temporal offset between the data takes of the VNIR (visible and near infrared) and the SWIR (short wave infrared) sensor.

According to conducted tests the presented approach achieves an error rate of about 5 % on average for detecting two-dimensional non-linear distortions and, hence, fulfills the requirements to be used in the geometric validation tool.

3. MATERIALS AND METHODS

Here, the same test images were used as in [2] and simulated by the EnMAP-End-To-End-Simulator (EETES) proposed in [3] whereas the first image (fig. 1a) shows the rural area of Barrax in Spain and is based on Landsat 7 ETM+ as proposed in [4]. The second test image (fig. 1b) is based on HyMAP data takes over the mountains of Cabo de Gata in Spain. The third image (fig. 1c) shows the Makhtesh Ramon region in the Negev desert of Israel and is based on a pan-sharpened SPOT 5 acquisition.

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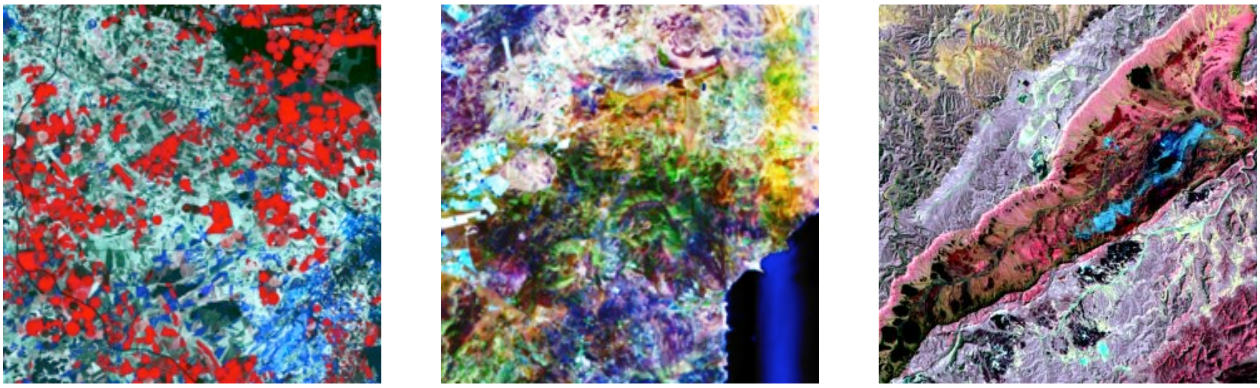
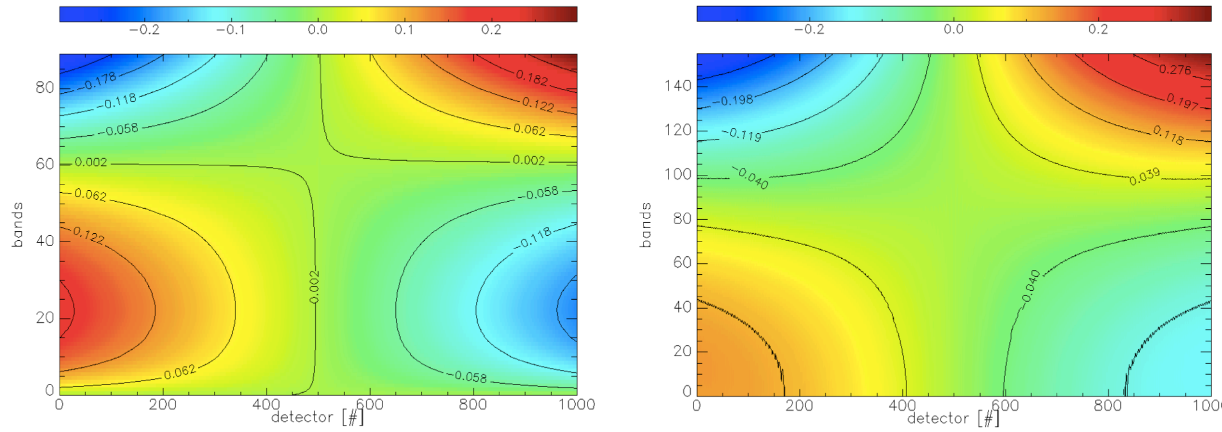


a) *b)* *c)*

Figure 1. Case study regions Barrax, Spain (a, R 864 nm, G 653 nm, B 549 nm), Cabo de Gata, Spain (b, R 2201 nm, G 801 nm, B 484 nm) and Makhtesh Ramon, Israel (c, R 2201 nm, G 801 nm, B 484 nm)

All simulations incorporated latest sensor parameters and trajectory, whereas current keystone was rescaled to enable specific simulation scenarios. Each image consists of 242 bands and incorporates a ground sampling distance (GSD) of 30 m on average - depending on local terrain and geographic latitude. These data formed the basis for succeeding distortion simulations. In this work it was assumed that pre-processing of the ground segment has reduced distortions down to 0.05 or 0.2 pixel. Preceding corrections include attitude and speed variations, micro vibrations and deviations from an ideal projection of incident light such as keystone as well as differential earth rotation between VNIR and SWIR acquisitions, whereas the differential keystone was reduced as proposed in [2]. In [2] the current keystone of EnMAP was rescaled to have an across track pixel deviation of 0.05 pixel for both the VNIR and the SWIR (compare fig. 2). Then, bicubic interpolation was applied at the new pixel positions (fig. 2).



a) *b)*

Figure 2. Simulated VNIR (a) and SWIR (b) keystone (here rescaled for better visual perception having a maximum keystone of 0.5 pixels) as pixel centre deviation

After artificial degradation the differential keystone, i.e. the keystone between spectrally adjacent bands, was estimated and reduced by 99 % on average as proposed in [2].

After keystone reduction one VNIR spectrally overlapping SWIR band of each image was artificially degraded using 144 different along and across track distortion scenarios and bicubic interpolation at new pixel positions. These scenarios included:

- Long term (~0.23 Hz) and shorter term (~0.46 Hz) harmonic across and along track non circular pixel shifts (2x2 cases) as remaining attitude variation between VNIR and SWIR and
- Linear non-circular across and along track pixel shifts (slopes -1 or 0 or 1, 1 mPixel at maximum, 3x3 cases) as remaining differential earth rotation and remaining altitude or speed variation.

Distortion scenarios were then rescaled to simulate either across or along track pixel shifts of 0.05 or 0.2 pixel (2x2 cases) as often remain after pre-processing by ground segment as exemplarily shown in fig. 3-5.

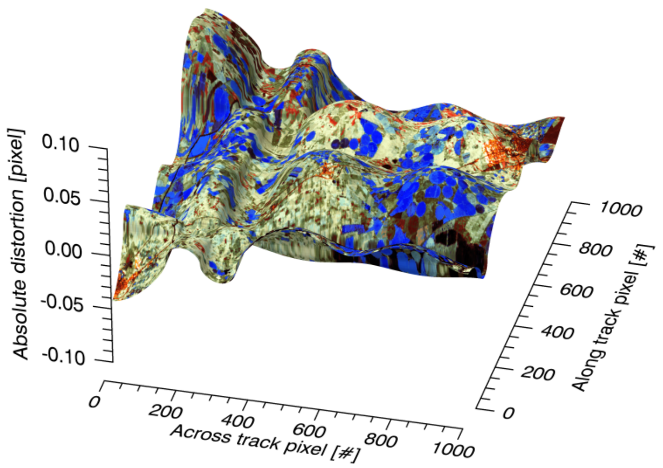


Figure 3. Simulated distortion between VNIR and SWIR for Barrax (dx ±0.2 pixel and dy ±0.05 pixel on maximum caused by 2 harmonic distortions across track and along track, negative linear distortions across track and positive linear distortion along track (Barrax scenario 102)

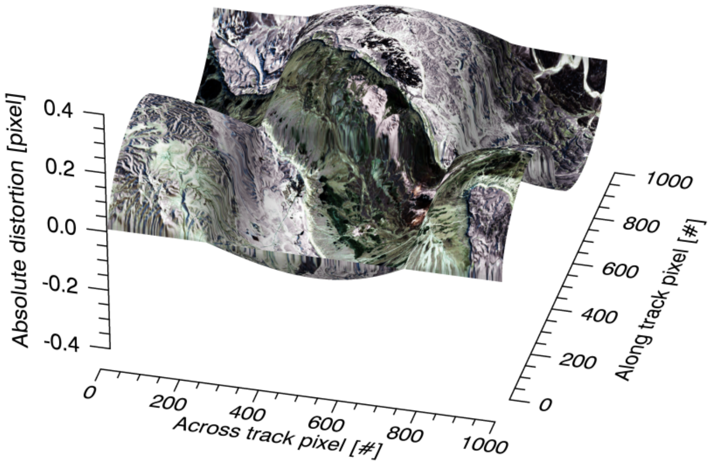


Figure 4. Simulated distortion between VNIR and SWIR for Makhtesh Ramon (dx and dy ±0.2 pixel on maximum caused by 1 harmonic distortions across track and along track (Makhtesh scenario 113)

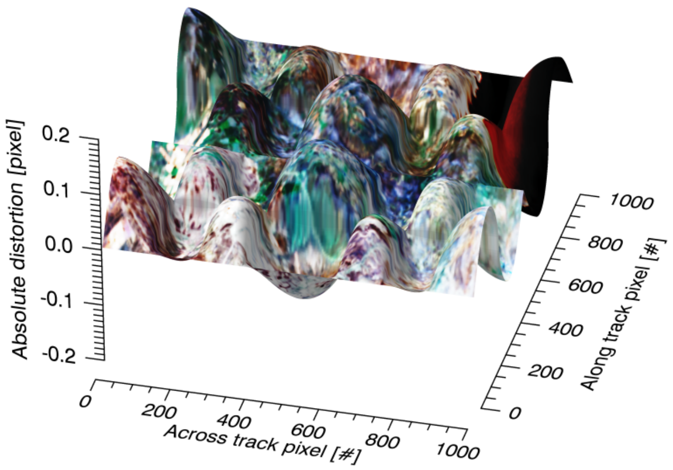


Figure 5. Simulated distortion between VNIR and SWIR for Makhtesh Ramon (dx ±0.05 pixel and dy ±0.2 pixel on maximum caused by 2 harmonic distortions across track and along track (Cabo de Gata scenario 68)

Artificially induced pixel distortions may not occur in reality, but it was assumed that preceding geometric corrections by the ground segment may cause small residual distortions that can be approximated by multiple non circular harmonic and linear shifting functions.

In the following an approach is presented that aims on estimating nonlinear distortions. It incorporates automatic tie point detection, local shift estimations, polynomial fitting and iterative global minimisation.

At first, tie points are detected as proposed in [1]. Here, potential tie points are defined as pixel positions of local extrema of an image pyramid that consists of three approximated second derivatives (Laplacian) whereas each Laplacian is approximated as Difference of Gaussians.

At second, the local sub-pixel shift is estimated for each tie point between one VNIR and its spectrally adjacent SWIR band similar to the approaches proposed in [5-6]. The enhancement of the approach given in [5-6] consists of three extensions:

- SNR and residuals related Gaussian weighting within the iterative least squares estimation of the parameters of the phase correlation plane equation to reduce aliasing and impact of noise
- Strict graduation, i.e., the results of the foregoing iteration were used to improve the unknown parameters, to enhance the accuracy of least squares estimations and to suppress outliers
- Spatial smoothing of the phase correlation matrix

According to conducted tests with 14 different images and 200’000 noise and shifting scenarios, an accuracy improvement of about 280 % in relation to the original approaches of [5-6] can be achieved that allows to model circular shifts with an accuracy significantly better than 1 µPixel (1 Pixel = 1’000 mPixel = 1’000’000 µPixel). This enhancement is also used in the approach proposed in [2] for the reduction of keystone.

At third, local shifts are used to build across and along track distortion models. This is performed by approximating low to high-order polynomials of averaged shifts and by selecting the across and along track models that provide lowest $\chi 2$-error estimates. Then, the global shifts are estimated by a polyphase decomposition as proposed in [7], because this approach provides a closed form analytical solution for sub-pixel detection that is important as described in the following.

At fourth, a minimisation approach starts. This approach follows the principles that non-circular shifts can be considered as a sum of infinitessimal spatially small circular shifts and that if, and only if, all distortions have been efficiently suppressed or removed, the correlation between both bands is maximised. It also aims to solve the problem that local circular shift estimations are based by integrated non circular shifts. According to the relation that infinitesimal spatially small circular shifts approximately correspond to non-circular shifts, local shift estimations continously over- or underestimate non-circular shifts, because local correlation windows do not consist of infintessimal small windows. If follows from this that all distortion models approximated at the third step are continously over- or underestimated.

To overcome this limitation, an iterative approach is used, that iteratively tests the influence of different model scaling factors as global shift minimiser. This is performed by bisection. If globally estimated shifts are below some thresholds (here 1 µPixel) then the best models are multiplied with estimated scaling factors. Therefore, the proposed approach consists of four processing steps (fig. 6):

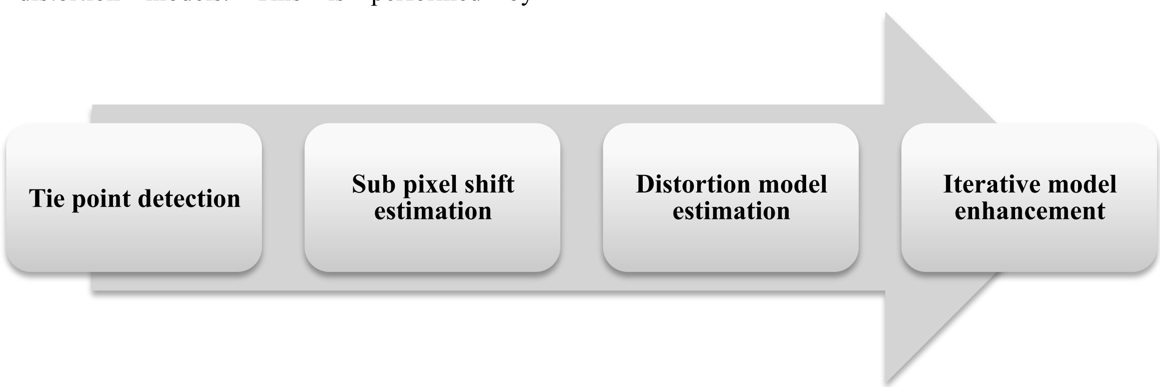


Figure 6. Work flow of proposed approach

4. RESULTS AND DISCUSSION

Estimated nonlinear distortions were subtracted from the artificially induced distortion and the absolute differences were averaged that finally gives an error estimate named as the Mean Absolute Deviation (MAD). MAD is more reliable than the simple average, because harmonic deviations fully contribute to the error estimate. The results are given in tab. 1. They show that an absolute accuracy of about 10 mPixel on average and a relative accuracy that relates to the maximum of each simulated distortion of about 8 % on average.

Criterion	Direction	Absolute [mPixel]	Relative to simulated distortion [%]
MAD	X	5.1	4.1
	Y	7.4	6.5
MAD – Half Size	X	4.1	3.1
	Y	3.8	3.0
MAD	X and Y	10.1	7.8
MAD – Half Size	X and Y	6.1	4.5

Table 1: Average performance results of proposed approach for all images and all scenarios

Additionally, MAD error estimates were computed from pixel 250 to 750 to consider potential oscillations of high order polynomials. With regard to the results of tab. 1 an absolute accuracy of about 6 mPixel and a relative accuracy of about 95 % were achieved on average for reduced image sizes. These deviations confirm the assumption that high order polynomials tend to oscillate which can cause higher error rates.
However, an absolute accuracy of about 0.01 Pixel or a relative accuracy of about 92 % has been achieved on average that is exemplarily shown in the following fig. 7.

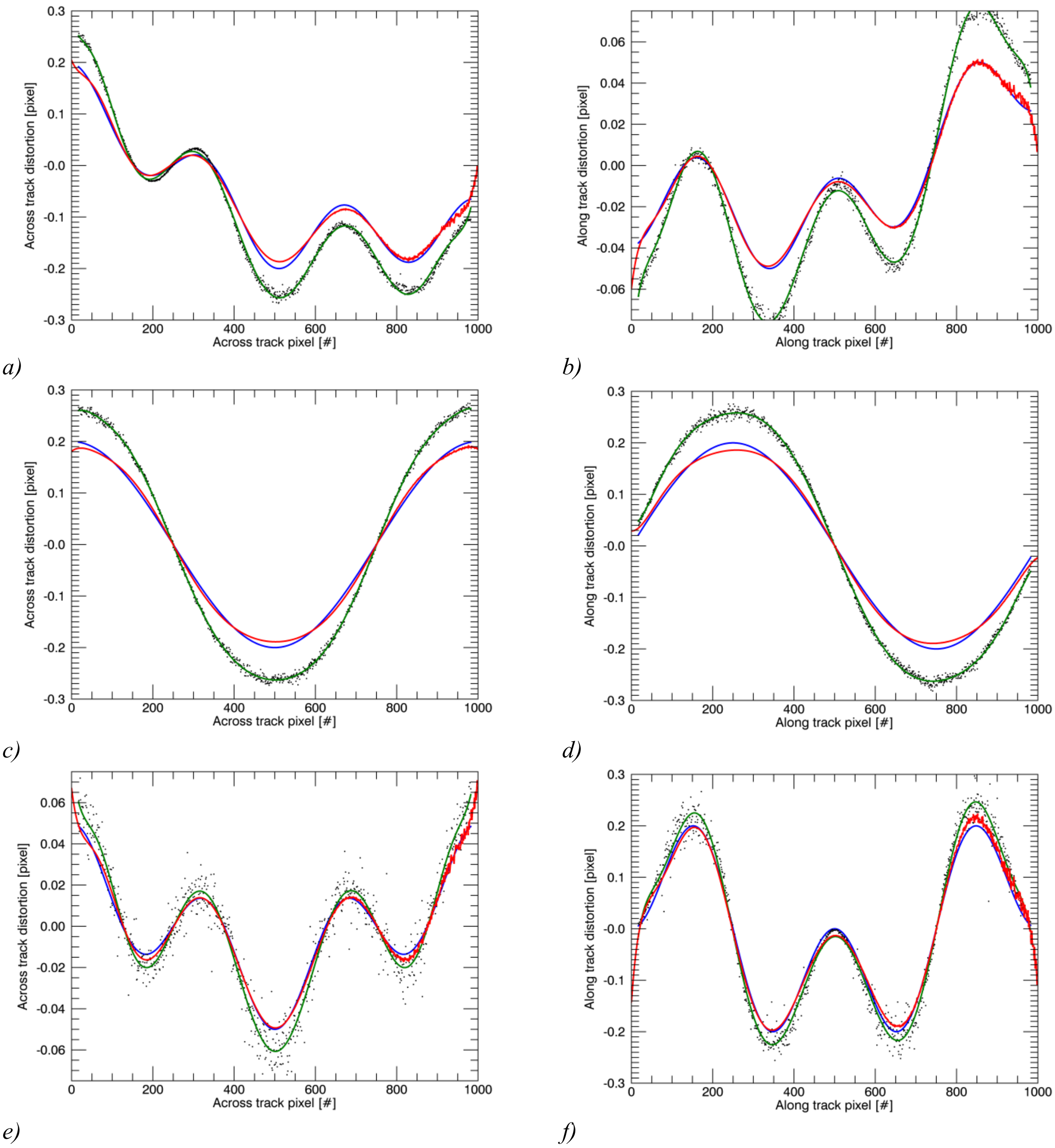


Figure 7. Simulated distortions for Barrax (scenario 102; MADabs=6 mPixel; MADrel=3.9 %) a) and b), Makhtesh (scenario 113; MADabs=9 mPixel; MADrel=4.5 %) c) and d) and Cabo de Gata (scenario 68; MADabs=9.4 mPixel; MADrel=5.5 %) e) and f) with nominal distortions (blue), polynomial fits (green), averaged pixel shifts (black) and final estimation (red)

With regard to fig. 7 averaged pixel shifts (step 2 of the proposed algorithm) clearly indicate nonlinear distortions but often over- or underestimate nominal shifts. This is also valid for succeeding polynomial fits (step 3). However, final estimations (red) are close to nominal shifts (blue). This indicates that damping factors significantly improve the assessment if those were gathered by an iterative and global correlation maximisation or sub-pixel minimisation (step 4).

5. CONCLUSION

In this work a new approach was proposed that is able to model two-dimensional nonlinear distortions at sub-pixel scale. The results show that the presented approach is well suited as potential validation tool of geometric pre-processing. However, there is still potential for further improvements, for instance, a higher degree of inclusion for detector and time variant non-linear distortions often occur during airborne acquisitions. First test with multidimensional Thin Plate Splines allowed a higher degree of modelling, but have to be studied more in-depth.

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