

Analysis of micro-vibrational effects in very high-resolution imaging using parallel pixel integration

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ABSTRACT

The [Atlantic Constellation \(AC\)](#) is a joint initiative launched by Portugal and Spain to develop an [Earth Observation \(EO\)](#) constellation providing high-revisit multispectral imagery. As a flagship programme of the Portuguese National Space Strategy, it integrates optical [Very High Resolution \(VHR\)](#) and [Synthetic Aperture Radar \(SAR\)](#) capabilities supported by a common ground and data infrastructure. [CEiiA](#) and [N3O \(CEiiA-N3O\)](#) lead the [VHR](#) space segment which is tasked with being highly agile. The necessary slew rates for the imaging scenarios require large reaction wheels that introduce vibrations in the spacecraft. [CEiiA-N3O](#) developed in-house tools to simulate the performance of the imager. Such tools include pixel integration, vibration, [Modulation Transfer Function \(MTF\)](#) convolution, a super resolution algorithm, pan-sharpening, and [MTF](#) analysis. In this work, we simulate the pixel integration disturbed by vibration motion. We consider sine vibrations for demonstration. The displacement of each pixel due to vibration motion is sampled for each integration window and the total light captured by each pixel is integrated. We perform these computations for every pixel in the detector in parallel using [Graphics Processing Units \(GPUs\)](#). After pixel integration, we assess the impact of vibrations on the [MTF](#) and the ability to use super resolution. Finally, we present results for the pixel integration processing algorithm and the analysis of scene rendering using the complete chain, with varying levels of vibration and make visual comparisons. These results complement [CEiiA-N3O](#)'s alternative micro-vibration analysis results via Monte Carlo integration.

Keywords: TDI Simulation, MTF Analysis, GPU Processing

1. INTRODUCTION

The [Atlantic Constellation \(AC\)](#) is a joint initiative launched by Portugal and Spain to develop an [Earth Observation \(EO\)](#) satellite constellation providing high-revisit multispectral imagery. Now a flagship programme of the Portuguese National Space Strategy, it integrates optical [Very High Resolution \(VHR\)](#) and [Synthetic Aperture Radar \(SAR\)](#) capabilities supported by a common ground and data infrastructure. The constellation will serve strategic sectors such as defense, maritime surveillance, agriculture, security, and disaster monitoring driven by asset diversification, global coverage, and high observation frequency.¹

[CEiiA](#) and [N3O \(CEiiA-N3O\)](#) are leaders of the [VHR](#) space segment component producing the initial generation of [VHR EO](#) satellites for the [AC](#). The [VHR](#) satellites have a mass around 300 kg and orbit in [Low Earth Orbit \(LEO\)](#) at about 500 km. The imager will operate in a push-broom configuration with multiple panchromatic bands with native [Ground Sampling Distance \(GSD\)](#) 0.6 m, several spectral ranges with native [GSD](#) 1.2 m, and a swath of 10 Km. The panchromatic bands have pixel shifts that allow for combination of bands for super resolution with 0.3 m [GSD](#). Such resolution performance was previously exclusive of larger platforms developed within long horizon programmes. Modern [VHR](#) constellations benefit from the integration of market-available subsystems, enabling the balance between performance, cost-efficiency, and reliability.²

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1.1 AC VHR Imaging Challenges

VHR imaging from space is a technical challenge that requires capturing light with small pixels at long distances. To ensure that sufficient light is captured, usually larger integration times are required. During such interval, perturbations to the satellite motion displace the sensor which results in lower quality images. Often, a compromise between both integration time and sensor stability is achieved, but VHR optical imaging pushes the spacecraft design to its limits because constraints are imposed on attitude stability and rate stability over a large frequency range beyond the bandwidth of the attitude controller.³

The AC VHR is tasked with being highly agile for various imaging scenarios including tri-stereo imaging. As such, it requires large reaction wheels to achieve the necessary slew rates. These wheels introduce vibrations into the spacecraft and consequently to the payload Line of Sight (LOS). To assess the impact of these vibrations on the performance of the imager, CEiiA-N30 developed in-house tools to simulate the performance of the imager. This includes pixel integration, vibration, Modulation Transfer Function (MTF) convolution, a super resolution algorithm, pan-sharpening, and MTF analysis. The simulation tools developed by CEiiA-N30 reproduce the impact of sensor geometry and motion perturbations, such as smear and jitter, in the image quality and inform the spacecraft design process. Moreover, non-technical stakeholders can improve their understanding of the impact of different perturbations to the image quality from the results of end-to-end image acquisition simulation.

This paper focuses on a deterministic integration method that leverages the improvements of parallel computing hardware and their associated software frameworks. It simulates the motion perturbation during imaging for any sensor geometry including Time Delay Integration (TDI) and multi-band layouts.

2. SIMULATION

The end to end imaging simulation chain developed by CEiiA-N30 and analyzed here considers the degradation from the telescope optics, the detector geometry, and image motion. In addition, it implements super resolution algorithms to simulate the images that can be obtained from the satellite. Herein, an alternative method for processing light integration of each pixel in detectors which feature TDI is assessed both in isolation and within the full simulation chain. For this purpose, modern parallel computing hardware and software is leveraged to reduce computation time while using a deterministic model of the sensor for end-to-end simulation of image acquisition.

Such integration method is complementary to stochastic integration methods developed by CEiiA-N30 which are less resource intensive and provide faster results. The deterministic model provides a cross validation method approach for the models implemented via the stochastic method.

2.1 Sensor Model

This analysis considers a Charge Coupled Device (CCD) featuring TDI in which accumulated charges from one integration interval are summed to the previous integration interval to increase the exposure time and improve the Signal-to-Noise Ratio (SNR). Here, we are concerned with the geometric performance and leave radiometric related topics for another analysis. Moreover, the results provided here are solely for tool validation.

The detector features both panchromatic and multispectral bands which allows super resolution algorithms via pixel shifts and pan-sharpening compositions resulting in data products with improved radiometric and geometric resolution. However, we leave pan-sharpening assessment as future work and consider a sensor geometry with 4 panchromatic bands with sub-pixel shift. The integration time of each detector row is about 11.6 kHz which corresponds to a nadir scan speed for a satellite orbiting around 500 km of altitude. This analysis considers artificial images and the pixel pitch is not relevant as the pixel size is defined with respect to the baseline image resolution.

2.2 Motion Perturbation Model

The perturbations were assumed to follow sinusoidal vibration model because the perturbation sources under evaluation are usually motors spinning at different velocities, in particular the reaction wheel assembly.⁴ Such vibration is defined as function of time as follows

$$J(t) = A_j \sin(\omega_j)$$

The amplitude (A_j) and frequency (ω_j) of the respective LOS disturbance.

2.3 Simulation Chain

The end to end simulation consists in the following stages as depicted in Fig. 1:

- Baseline image loading (or generation).
- Optics degradation via 2D Fast Fourier Transform (FFT).
- Parallel integration of light with motion perturbation.
- Super resolution implementation.

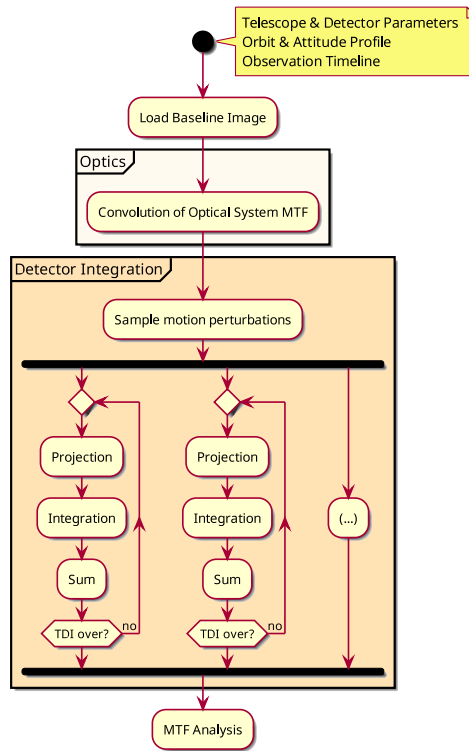


Figure 1. Parallel pixel integration within simulation chain.

The baseline image is constrained to have a resolution at least half the pixel size of the simulated detector to ensure that the lowest theoretical spatial frequency of the detector can be sampled from the imaged. The optics 2D MTF profile is obtained either from simulated optical models or empirically from experimental data. In this case, a simulated model was used with similar characteristics to those of the AC VHR.

2.3.1 Parallel Integration

The implementation of parallel integration considered that each thread performs the integration of a pixel of the final image. The integration of each **TDI** stage implements a fixed step integration model which allows precomputation of the motion perturbation before parallel execution. The parallel integration is summarized in Fig. 1 and consists of the following steps:

- **Projection:** determine pixel location on the ground.
- **Integration:** determine total charge accumulated while perturbed by motion jitter and smear.
- **Sum:** add the resulting charge to the accumulated charge from prior **TDI** stages.

Parallelization significantly reduces the time required to simulate image acquisition using a deterministic approach. The speed of the solution becomes limited by the hardware available to run it, but the modelling effort is considerably reduced. Additionally, there are optimization techniques which enable extra speed with the same hardware. For instance, we limited each computing block to a maximum of 256 threads to balance hardware load, as occupancy gains beyond 50% are often not translated into proportional speedups. Moreover, each block considered the same time interval which ensured that the same perturbations were applied to the entire block and the same memory area was read which enabled further optimization. If long acquisitions are simulated or very small integration steps are considered, the integration might need to be split for optimal resource usage. Further optimization is left as future work, but some resource savings should be possible.

3. MTF ANALYSIS

The performance of optical systems can be assessed from multiple metrics for resolution, radiometric fidelity, geometric fidelity, and aberration quality.^{5,6} One approach to evaluate resolution and sharpness is to analyze the spatial frequency response of an optical system represented by the **Optical Transfer Function (OTF)**. Often its magnitude is considered which is denoted as **MTF**. The system **MTF** is the combination of its contributors which are mostly due to the optics, the detector, and image motion.

The optical **MTF** comprises both the limitations from the optics and from the detector electronics. From the optics side the main contributions include the diffraction limit from the telescope aperture and the wavefront aberrations from the mirrors and lenses, whereas in detector electronics the pixel aperture and charge diffusion are two of the top contributors. The motion **MTF** results from the smear **MTF** and a jitter **MTF** contributions which are pointing stability error metrics respectively, from the linear component and the high frequency contribution to the motion perturbation.⁷ These can also be modelled as velocity mismatches from the relative motion between the imaging system and the object under observation or sinusoidal vibrations to the image motion from periodic perturbation sources.⁸

The resulting images obtained from the simulation chain are assessed in terms of resolution and sharpness via the **MTF**. The approach followed in this paper uses the Gaussian cumulative distribution function fitted to the **Edge Spread Function (ESF)** of slanted edges in the image as described next.

3.1 Slanted Edge Method

The spatial frequency response is measured, via the **MTF**, using the slanted edge method as follows:

- Select a region of the image which shows a slanted edge. An angle close to 10 degrees with respect to the scanning direction is targeted for better representation of the spatial frequency range of interest.
- Estimate the edge location for each row.
- Shift rows according to edge location.
- Project the intensity of each pixel into a single axis which denotes the distance from the edge.
- Fit **ESF** data with Gaussian cumulative distribution function.

- Differentiate analytically to obtain the [Line Spread Function \(LSF\)](#).
- Determine the [MTF](#) via the discrete [FFT](#).

The [ESF](#) data shows both the effect of motion and of [TDI](#) on pixel intensity at the edge. The perturbation considered here has a lower frequency than the line rate, but higher than the total integration due to [TDI](#). As such, the results for the [ESF](#) with [TDI](#) have a clearly defined edge. Moreover, it can be immediately observed the difference between the [ESF](#) width with and without jitter motion with the appropriate degradation of the [MTF](#) result.

Without [TDI](#) the edge location will clearly vary with the sinusoidal perturbation as visible in Fig. 3. In this case, the [ESF](#) fit requires extra processing the image to align the edge, because fitting the curve to the data results in an optimistic [ESF](#) as depicted in Fig. 3. Analyzing noisy [ESF](#) data from an image with motion during exposure is challenging because artifacts can be introduced that improve or degrade the metric. Despite the existence of several methods analyze edges,^{9,10} the estimation of the adequate [ESF](#) without artificially modifying the sharpness of the image is left as future work because it requires further analysis and development.

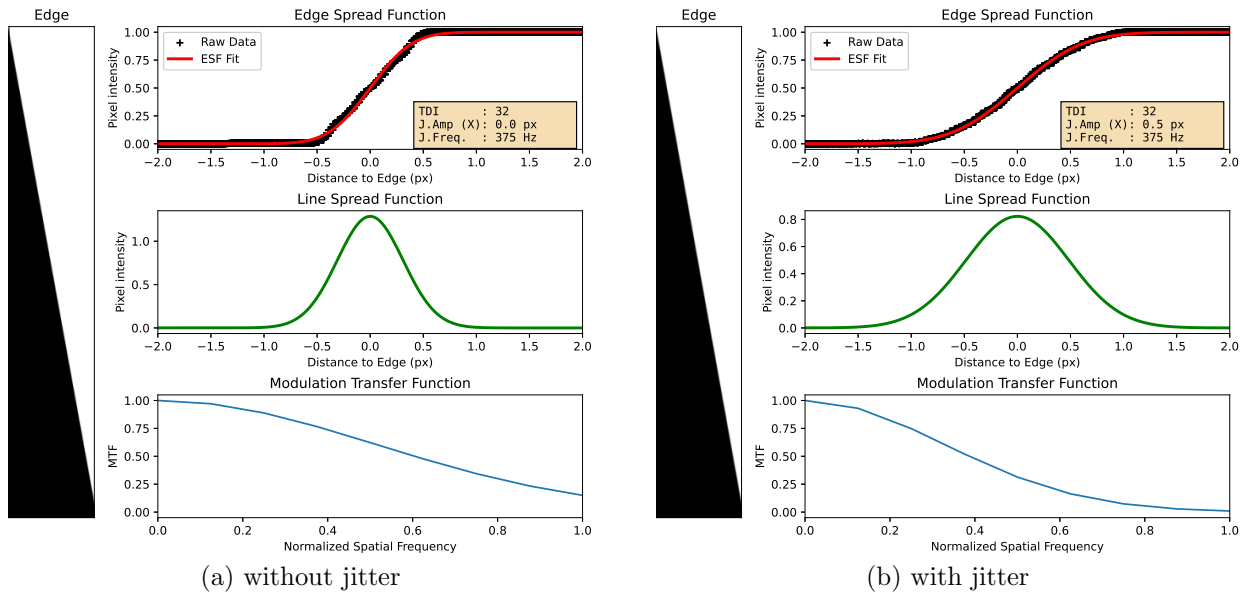


Figure 2. ESF fit for slanted edge images with TDI.

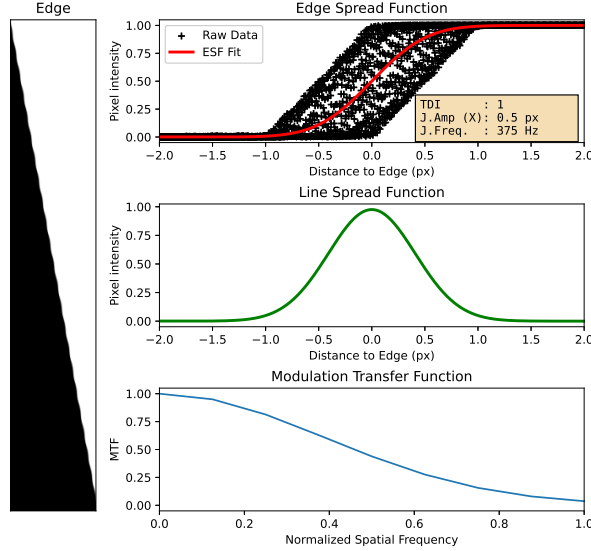


Figure 3. ESF fit for slanted edge images without TDI.

3.2 MTF Results

The integration method described in Section 2 includes the degradation from pixel aperture and image motion. Following the [ESF](#) fitting technique described in Section 3.1, the contribution of the pixel aperture and motion perturbations were assessed for several jitter amplitudes and frequencies assuming the sinusoidal disturbance model described before. The first zero of the Bessel function is plotted for comparison with the theoretical model for relatively high-frequency sinusoidal motion for vibration in which, one or more complete vibration cycles fall within the exposure period. Such function is defined as⁴

$$MTF = J_0(2\pi Nd)$$

with $N = 0.5$ denoting the spatial frequency at Nyquist and d denoting the image motion amplitude.

Fig. 4 shows the contribution from the image motion to the [MTF](#) at Nyquist against the disturbance amplitude. To obtain such value from the integration simulation the degradation from discrete pixel aperture is obtained from the zero motion result and removed from the contribution. As the amplitude of the motion perturbation increases the [MTF](#) value decreases due to the integration of light from larger areas than the pixel footprint without motion. As expected theoretically, the low frequency motion with respect to the pixel integration frequency has a reduced impact on the [MTF](#). Such perturbations are usually denoted as smear and are often defined by the linear motion component during integration.⁷ Then, as the frequency increases it approximates the first zero of the Bessel function⁴ and above the frequency of the integration of all 32 [TDI](#) stages, about 365 Hz, the contributions vary identically with the motion amplitude. For larger amplitudes the results seem to not match with the first zero of the Bessel function potentially from [ESF](#) fitting errors but should be further analyzed. These plots are useful for budgeting jitter and smear contributions and drive system design decisions.

4. SCENE SIMULATION

The complete simulation chain was also tested with high resolution baseline images from the public domain. Such simulations show the the impact of perturbations from the optics, the pixel aperture, and the image motion during integration. The results do not consider all the perturbations from system. In particular, electronics related effects are neglected. However, the impact shown can be used to illustrate the impacts of a significant set of perturbation sources.

Fig. 5 shows both the original high resolution baseline image of the scene, on the left, and, on the right, the result from the optical degradation after convolution of a simulated 2D MTF profile which was generated from

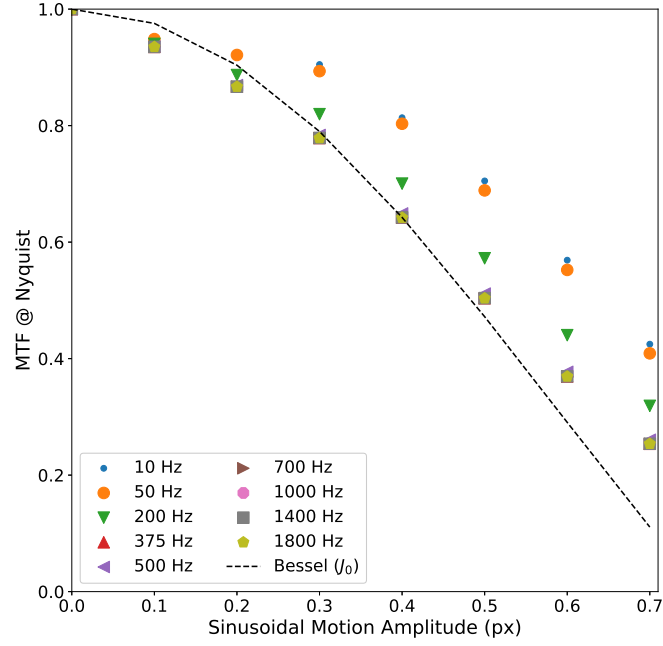


Figure 4. MTF contributor (at Nyquist) from integration.

a telescope model with similar characteristics to the [AC VHR](#) satellites. The baseline image is approximately 0.1123 m/px which is sufficient resolution for sampling with the expected native [GSD](#) of the [AC VHR](#) satellites of 0.6 m.

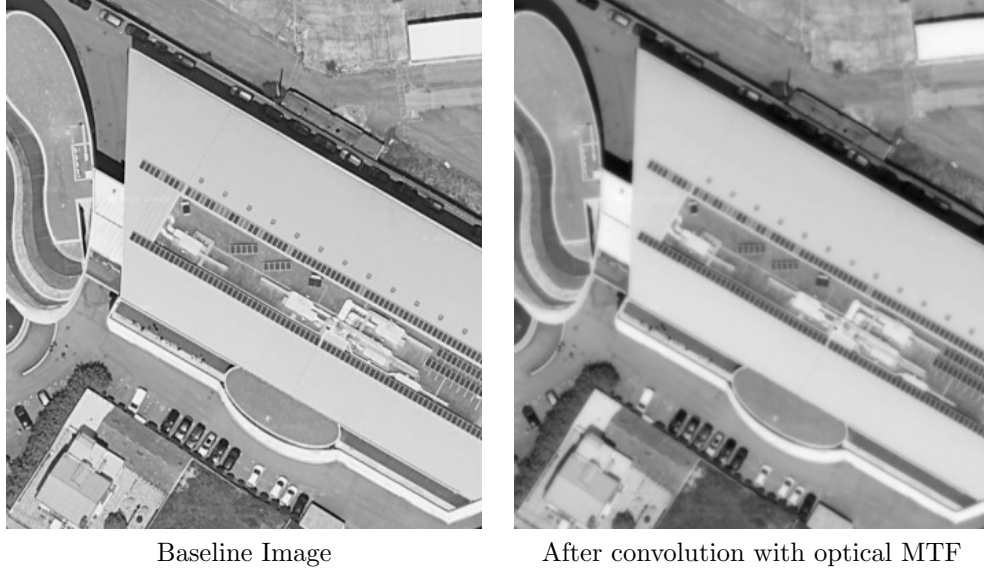


Figure 5. Input for simulation of motion perturbation scenarios.

The ensuing analysis is focused on sinusoidal perturbations whose periods are within the integration time of a single [TDI](#) stage and 32 [TDI](#) stages. Considering a push-broom imager at 500 km of altitude the integration of each stage should be approximately 11.7 kHz and the frequency for the all 32 [TDI](#) is about 365 Hz. Hence, the following scenarios consider a perturbation of 500 Hz. Four scenarios are analyzed as detailed in Table 1.

Figs. 6 and 7 show each of the resulting scenes in native resolution. From a high-level perspective, it is

Table 1. Perturbation configurations to each scene.

Case	Jitter Amplitude	Jitter Frequency	# TDI
1	0.1 px	500 Hz	32
2	0.5 px	500 Hz	32
3	0.9 px	500 Hz	32
4	1.2 px	500 Hz	32

perceptible that as the jitter motion amplitude increases the image gets blurrier with lower sharpness between some details of the scene. For instance, people on the parking lot, denoted by the red circle (A) get less distinguishable from the ground around them. Another, noticeable feature is the level of detail of the roof solar panels, in particular those in the central part of the roof, as pointed by the yellow circle (B).

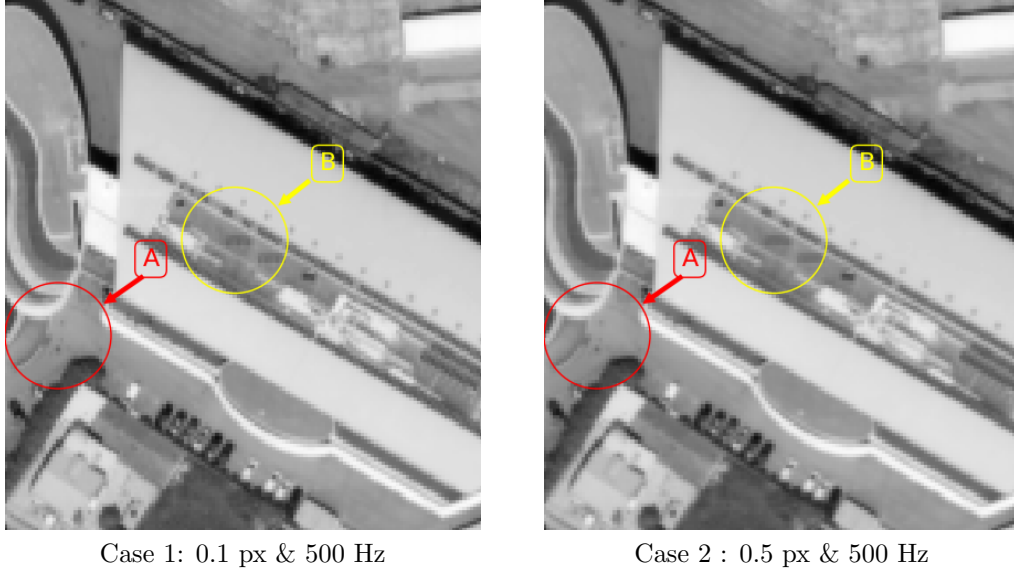


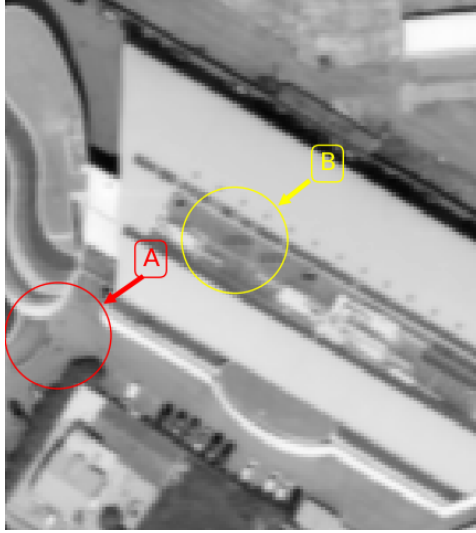
Figure 6. Native resolution images for cases 1 & 2.

Figs. 8 and 9 show each of the resulting scenes in super resolution which were obtained from four panchromatic bands with sub-pixel shifts between them. Comparing super resolution images with the native resolution ones it is clear that some information is recovered from using the sub-pixel grid. For instance, some shapes such as car and small objects become smoother which may increase the change to correctly interpret the image. As with the native resolution images, the impact of jitter is increases with the amplitude of the perturbation. However, lower levels of jitter motion seem to degrade the details in the image to a greater extent than in the native resolution, which might indicate that there is some compromise between both results. Such difference is shown in the details in the red (A) and yellow (B) circles when compared to the native resolution images. For lower amplitudes it becomes hard to distinguish people in the parking lot, but the image is smoother in some other details such as cars and building shape.

5. CONCLUSION

CEiiA-N30 simulation tools are an important development for the company's ability to design optical VHR space systems. They provide critical insights that inform engineering decisions. Specifically, the parallel geometric integration showed results which agree with the theoretical expectation of the image motion and the alternative integration methods developed by CEiiA-N30.

The simulation tools consider important contributions to sharpness and resolution degradation but should consider other contributions such as detector noise effects. Importantly, the use of vibration profiles based on

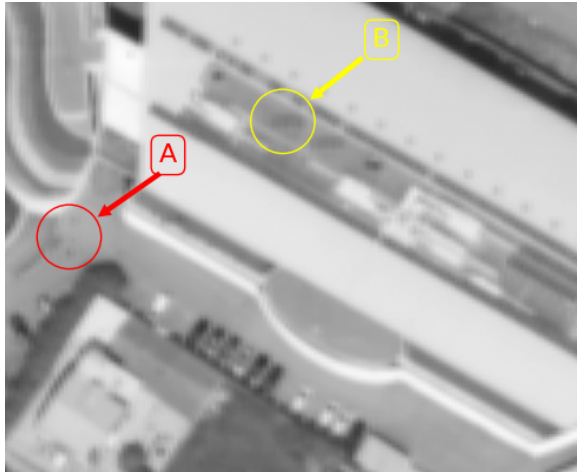


Case 3 : 0.9 px & 500 Hz

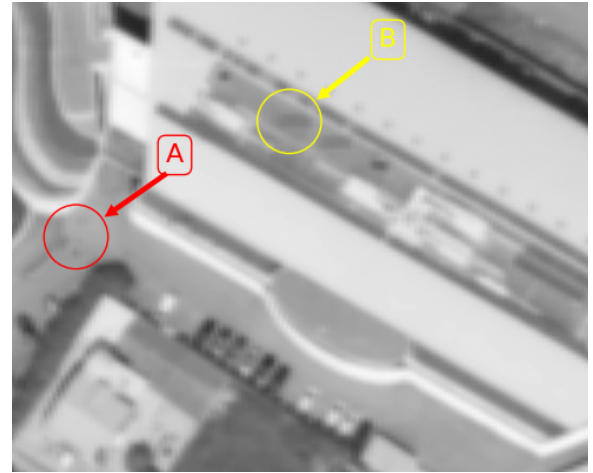


Case 4 : 1.2 px & 500 Hz

Figure 7. Native resolution images for cases 3 & 4.



Case 1: 0.1 px & 500 Hz



Case 2 : 0.5 px & 500 Hz

Figure 8. Super resolution images for cases 1 & 2.

FEM analysis is valuable for more realistic [MTF](#) results in future versions of the tool. Such features can be built on top of the current parallel integration architecture with some hardware aware optimization to enable faster results with cheaper hardware. are expected to be developed, integrated and validated soon.

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Case 3 : 0.9 px & 500 Hz



Case 4 : 1.2 px & 500 Hz

Figure 9. Super resolution images for cases 3 & 4.

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