

Analysis of micro-vibrational effects in very-high-resolution imaging with Monte Carlo integration

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ABSTRACT

The Atlantic Constellation (AC) is a joint initiative of Portugal and Spain to develop an Earth Observation (EO) satellite constellation providing high-revisit multispectral imagery. It integrates optical VHR and SAR capabilities. CEiiA and N3O (CEiiA-N3O) are leaders of the VHR space segment, producing the initial generation of VHR EO satellites with mass about 300 kg at about 500 km altitude. The AC VHR satellites are tasked with being highly agile for many imaging scenarios including tri-stereo. Thus, it requires large reaction wheels to achieve the necessary slew rates. These wheels will induce vibrations in the spacecraft. To assess the impact of these vibrations on performance, CEiiA-N3O performed literature reviews and consulted with experienced system integrators. CEiiA-N3O also developed in-house tools to simulate the performance of the imager and image processing. This includes algorithms for pixel integration, vibration, MTF convolution, super resolution, pan sharpening, and MTF analysis. The pixel integration uses a Monte Carlo process, and sinusoidal vibration is passed into the integration accounting for TDI and pixel location. The simulation of the optical MTF is based on the on-axis expected performance and applied to the base image. The super resolution and pan-sharpening algorithms were developed to assess the impact of vibrations on their performance. High frequency vibrations followed a Bessel function contribution to MTF. Results are presented of the individual processing algorithms and the analysis of scene and target rendering using those algorithms. MTF analysis as well as visual comparisons are made showing visible degradation with 0.5-pixel amplitude.

Keywords: Jitter, vibration, simulation, push-broom, Monte Carlo, super resolution, MTF, TDI

1. INTRODUCTION

CEiiA and N3O are leading the VHR space segment of the Atlantic Constellation, a joint initiative of Portugal and Spain for an EO constellation [1]. CEiiA-N3O will produce the initial generation of very high resolution EO satellites with mass about 300 kg intended for low earth orbit at about 500 km altitude [2]. The imager will operate in a push-broom configuration with multiple panchromatic (PAN) bands with native ground sample distance (GSD) 0.6 m, several spectral ranges with native GSD 1.2 m, and a swath of 10 km. The PAN bands have pixel shifts that allow for combination of bands for super resolution with 0.3 m GSD. Due the need for high moment reaction wheels and the vibrations that they will induce, it was decided to assess the impact of platform vibrations on image quality.

The major factor defining performance requirements for the project is the Modulation Transfer Function (MTF). The MTF is a measure of an optical system's ability to transmit contrast, or sharpness [3]. Its values range from 0 to 1, with 0 representing an image with no contrast and 1 perfect contrast. MTF is a function based on the spatial frequency in the resultant image. For a quality imaging system, MTF is typically monotonically decreasing from 1 to some positive value at the Nyquist frequency (above which there is no useful information in the image). The expected optical performance of the payload's imaging system is accounted for in this analysis. There are analytical models for the contribution of many other effects to the MTF of an optical system [4]. One of these is high frequency vibrations which are modelled by a Bessel function, $MTF = J_0(2\pi f_x A)$, where f_x is the spatial frequency and A is the amplitude of the vibration [5]. The MTF of the test images is determined using the edge based spatial frequency response from ISO 12233.

Many EO systems implement a push-broom time delay integration (TDI) technique [6]. TDI uses a grid of pixels and spreads the integration across one of the axes. The signal in one row is passed to the next where more signal is measured and passed on to the next. The total integration from all steps of TDI is read out on the last row. The vibration during the complete integration (across all rows) will appear in the resulting pixel values. The frequency of the stepping is determined based on the speed that the image crosses the detector. For our planned mission this will mean a frequency of

roughly 11.7 kHz in nominal mission conditions. Assuming that the chip is a rigid body at the relevant frequencies, at a given time the full chip is experiencing the same displacement due to the vibration. The detector has many bands, panchromatic (PAN) and spectral (MS), which are separated physically on the chip. The PAN bands have 0.5-pixel offsets in a grid. The physical separation of the bands means that they will read the same (or similar due to offsets) location on ground at different times and experience different vibrations during their integration. Due to the PAN bands' native GSD 0.6 m and 0.5-pixel offsets between them, when four PAN bands are combined it is possible to create a super-resolution image with 0.3 m GSD. It is also possible to use the PAN bands to increase the resolution of the MS bands. The MS bands allow colour images but have native GSD of 1.2 m.

Section 2 describes the pixel integration method as well as how vibration is introduced into the system. Section 3 describes the methods of the processing algorithms for optical MTF convolution, super-resolution, and PAN sharpening.

2. PIXEL/IMAGE INTEGRATION

The analysis presented here uses a Monte Carlo simulation to simulate the light entering the detector. A Monte Carlo simulation uses a set of sufficiently pseudo-random inputs to a system that is repeated a sufficient number of times to ensure accuracy [7]. In this paper, the input to the system is the point of origin of a photon (or group of photons) and the number of simulated photons (or groups) are chosen to have sufficient sampling. There are two methods for the photon origin that are handled differently. The first is a slanted edge target where one side of a line has light and the other does not. For this, the number of points that are placed in the light area are counted. An example of the random points falling on either side of the line can be found in Figure 1. This example does not include vibration or other effects.

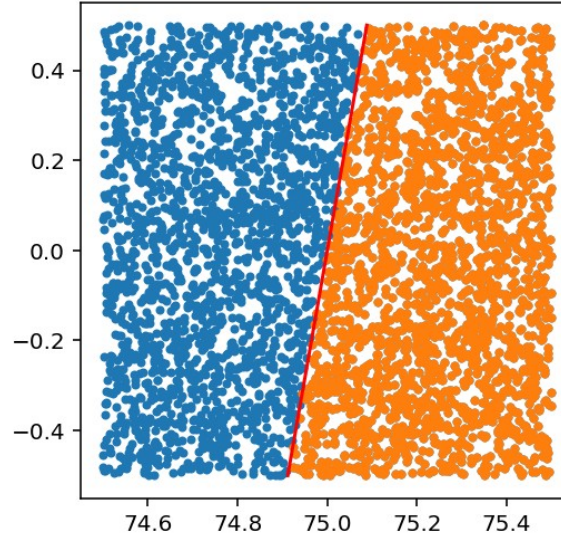


Figure 1. Image showing a set of random points generated for pixel integration with uniform distribution within the pixel area showing the knife edge and bright (orange) and dark (blue) points

The second method uses a base image with known ground sample distance to determine the colour or intensity of the incident light. The base image has a pixel density greater than twice the sample density in each axis. The intensity of each random pixel point in the base image is averaged to determine the intensity of the integrated pixel. This can be thought of as the pixel point's value is the number of photons that entered from that direction and then quantizing to a specific bit depth. Noise effects of the detector (dark current, shot noise) have not been implemented in this simulation.

The sensor being simulated is a TDI push-broom sensor, so a linear offset in the along track direction is added to the along track coordinate of the random point. The main interest of the analysis is the effect of vibration of the imager on the resulting images. In order to simulate the vibrations, an offset of the across track (opposite of the TDI direction) coordinate of the point is added based on a vibration waveform. In this paper this vibration is a simple sine wave, but any arbitrary form could be used. The vibration could also be applied to the along track direction. The vibration is subsampled with linear interpolation to determine the offset for each point in the integration as though they have equal

time difference during the integration time of the pixel. It would be possible to implement a random time during the integration for each point. It is important to have the same vibration applied to each row in the output image and, with TDI, successive rows will have some overlap of the vibration as well. To account for this, a subset of the full vibration based on the time that the pixel is integrated due to the push-broom effect is passed into the pixel integration.

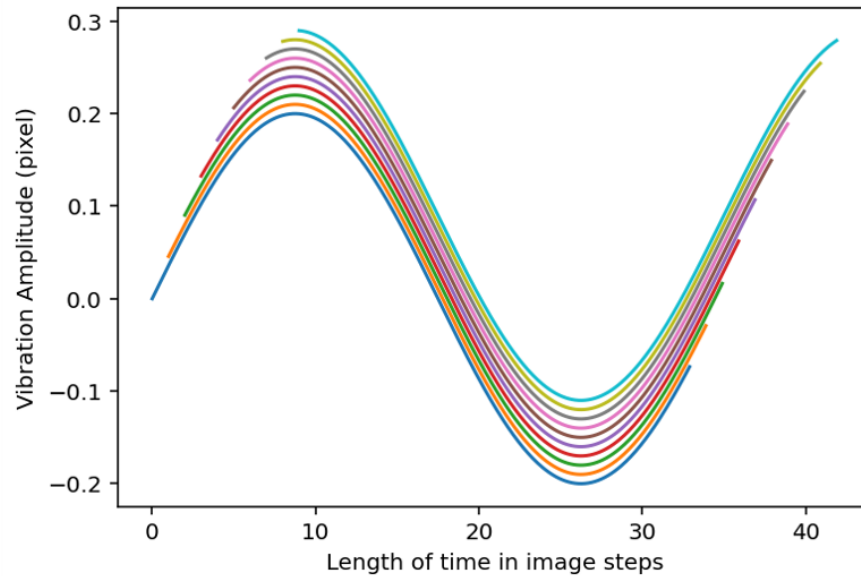


Figure 2. Plot of vibration passed into each of the first 10 pixels based on a vibration with 400 Hz, 0.2-pixel amplitude and 32 TDI. There is an added 0.1 amplitude to successive lines to see each separately. An image step is the inverse of the TDI line rate which is 11.7 kHz.

Figure 2 demonstrates the vibration that is passed into the first ten rows given a sine vibration with amplitude 0.2 pixels and a TDI of 32 steps. The successive lines are given a 0.1 pixel offset so that they can be seen separately, since successive rows overlap for 31 steps of TDI.

3. PROCESSING

Three processing algorithms were made for this analysis, one to account for the MTF of the optical system, another to test the super-resolution capability, and the final to test PAN-sharpening.

MTF blurring

The MTF represents a scaling factor of the Fourier transform of the image. Typically, it will reduce the contrast more at higher spatial frequencies. By applying the appropriate factor for the imager, the effect of the optics on the resultant images is simulated. This is applied to the base image before sampling. For MTF testing, a mathematical slanted edge was used instead of a base image. For these, if optical MTF was to be considered, the blurring was performed after integration. The base image in the example in Figure 3, Figure 4 and, Figure 5 is the high-res Google Earth image of CEiiA facilities that will be used in section 5, and the pixel size is determined using known dimensions of the building.

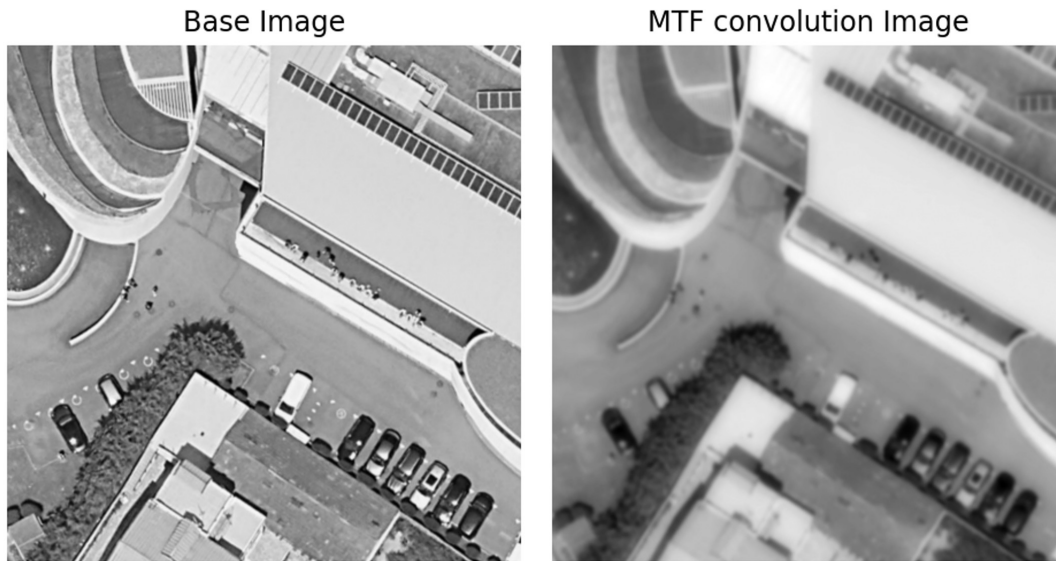


Figure 3. Comparison of the before and after applying the optical MTF from our imager to a high-resolution satellite image of CEiiA headquarters.

Super-Resolution

The sensor that will be used has an offset applied to successive PAN pixel bands. These are meant to be used to make a super resolution image by joining the four bands into one image. A specific method is not defined by the supplier. Some references essentially upscale the base images then perform transforms based on detected key parts of the images. This was deemed to be higher level than expected for this analysis, so the as designed specification from the sensor manufacturer is used for the pixel offsets. Since the offsets are half-pixel, they correspond to a full pixel in the upscaled version. Equal weights for each image were chosen to average the pixel values. In testing, the lower resolution image is downsized from the original image (in Figure 3) using OpenCV tools. One can see a marked increase in what is visible in the scene, especially in the solar panels on the roof, the group of people on the balcony, and in the car windows.

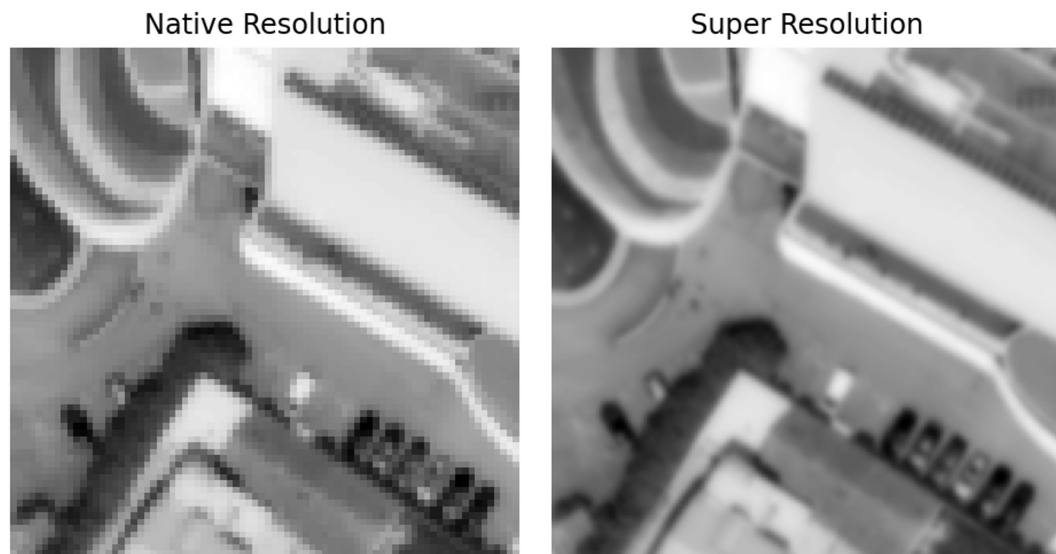


Figure 4. Comparison of native resolution and result of super resolution algorithm

PAN-sharpening

PAN-sharpening is used to increase the effective resolution of colour images using pan band images that typically have higher resolution [8]. There are several methods for performing PAN-sharpening, but a Brovey transform was chosen. The transform uses weighted summing of the colour bands to create a pseudo-PAN image that is then upscaled to the measured PAN image dimensions. The ratio of the pseudo-PAN to the measured PAN is used to rescale the intensities of the upscaled colour image. In the testing below, the original image from Figure 3 is downsampled by 25%. The original colour image is converted to grayscale for the PAN input image. These two images are used in the PAN-sharpening algorithm to create the PAN-Sharpended image.

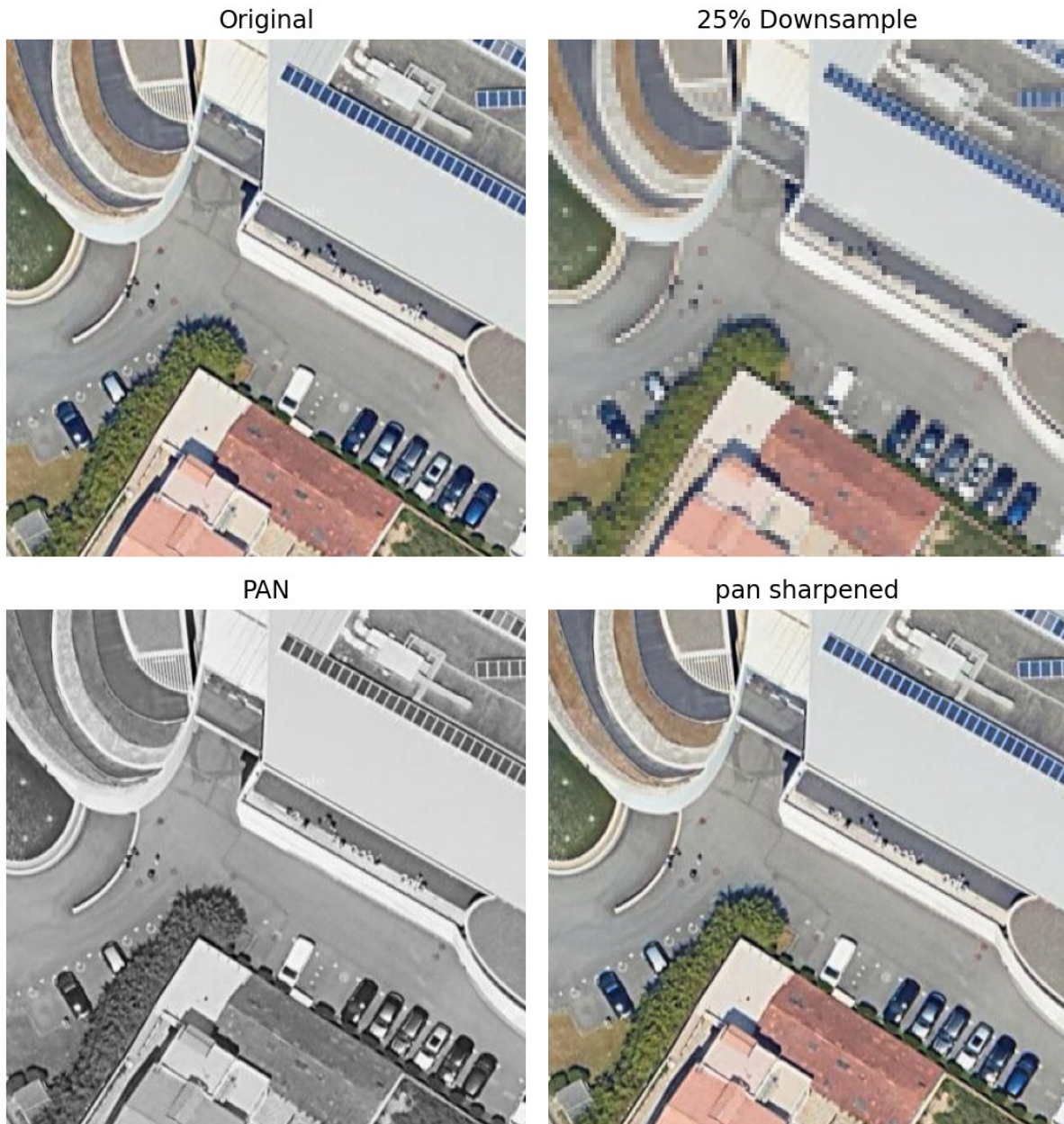


Figure 5. Images of steps of the PAN sharpening algorithm

4. MTF ANALYSIS

As the major image performance requirement of the project is the MTF, analysis of a simulated slanted edge was performed as well as the scene rendering. The slanted edge was defined mathematically by a line in the sensor's pixel space rather than with a base image. Using a slanted edge enables sub pixel measurements of the edge spread function. The edges are fit to a tanh function, and the slant of the edge is determined based on a linear fit to those edges. To account for the slant, the measured position along the edge is scaled by the sine of the angle of the slant.

The individual contributions to MTF performance and degradation are multiplied together to determine the total MTF performance [4]. To determine the contribution of just the vibration, the MTF at Nyquist with the vibration is divided by the same without to determine the MTF ratio, essentially the contribution to the MTF of the vibration.

The stability of the platform is split into fast and slow motion. The fast motion, jitter, is characterized by having a period that is shorter than the integration time of a pixel. The vibration and integration model created follows the Bessel function model closely for frequencies above the line-rate times TDI. The TDI rate used is 11.7 kHz with 32 steps of TDI for this analysis, implying that frequencies above 400 Hz should follow the Bessel function. These results are presented in Figure 6.

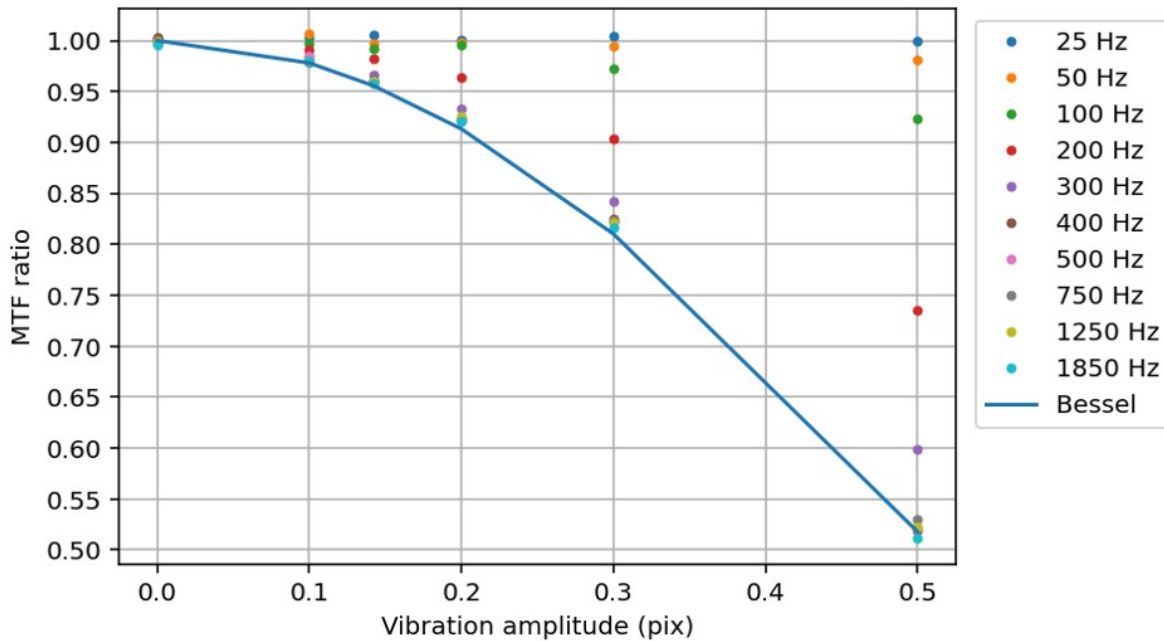


Figure 6. Plot of MTF ratio at Nyquist, with and without vibrations, for various amplitudes and frequencies where high enough frequencies follow the Bessel function analytical model

The effect of the super resolution algorithm (SRA) on the MTF with the optical MTF applied was also studied. First the MTF of an image with full sized pixels was measured (Native). Then an image was generated with half sized pixels, essentially generating an image with native resolution in the SRA final pixel dimension. Its MTF was also measured (Native Super). Next, the four native images were passed through the SRA and the MTF of the resulting image was measured (Algo Super). The Native Super image showed the best performance in MTF followed by the Native. The result of the SRA showed the weakest MTF performance. It should be noted, though, that the native resolution image does not contain relevant information at spatial frequencies above its Nyquist frequency, whereas the super resolution images double that frequency. This implies that using the SRA will generate an image with less contrast but still have more detail. The plots of the MTF for these images are presented in Figure 7. Samples from the generated images can be seen in Figure 8.

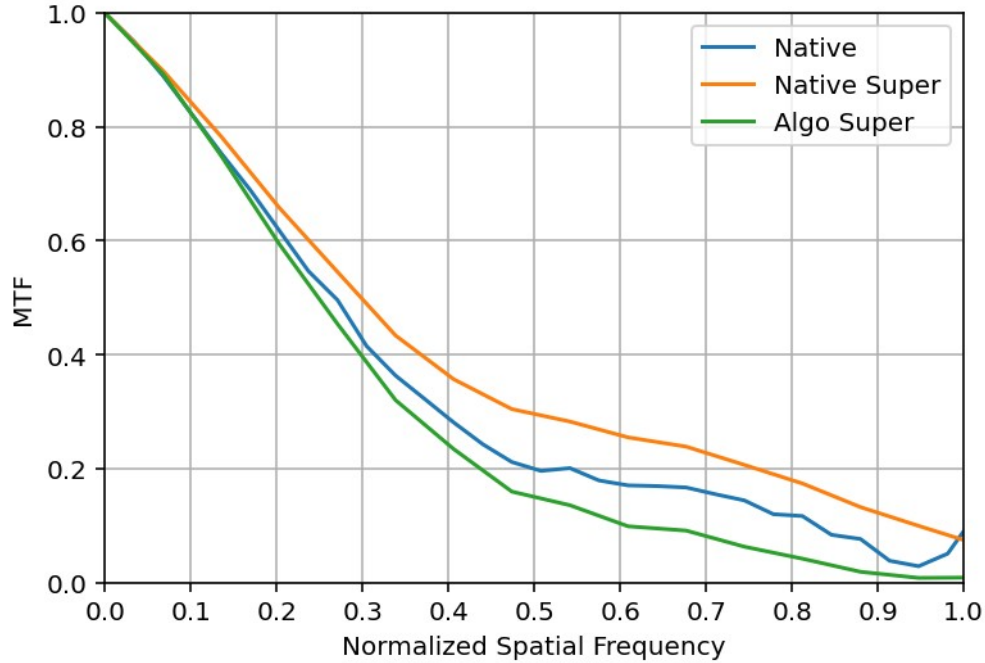


Figure 7. Plots of the MTF profile for Native resolution, an integration with half sized pixels (Native Super), and the result of the super resolution algorithm (Algo Super). The spatial frequency is normalized to the Native image.

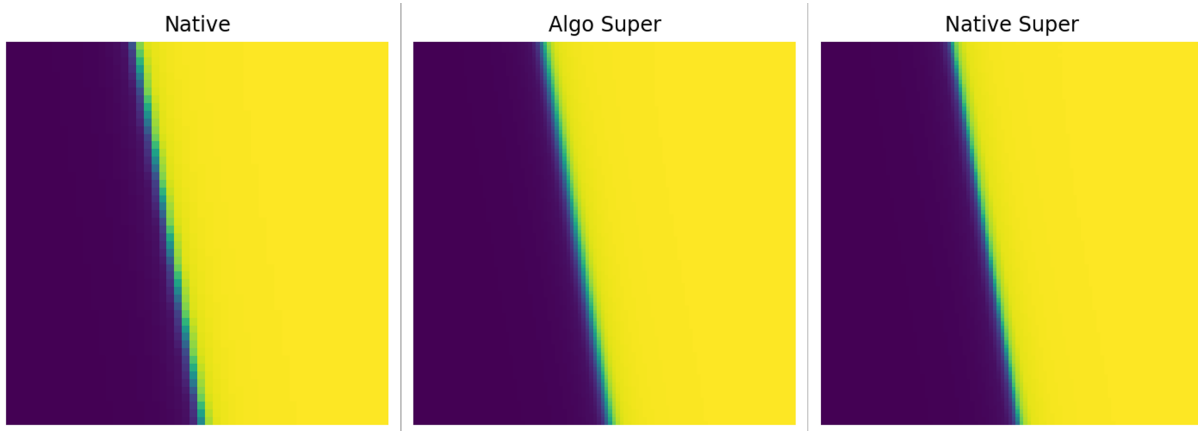


Figure 8. Images of the slanted edge that were measured for MTF presented in Figure 7.

The inclusion of vibrations with the super resolution algorithm showed different effects at lower frequencies when compared to native resolution effects. This can be seen in Figure 9. When the vibration frequency is slower than the integration time, the component of the vibration that is present during the integration for different PAN bands effectively acts as a longer integration time. The total integration of all bands can cover the peak-to-peak width of the vibration as seen in Figure 10 25hz and, thus, the MTF degradation stays relatively flat across the range. However, if the frequency is coherent with the spacing of the bands as seen in Figure 10, 100Hz, the effect of the vibration can be reduced. This is seen at 100 Hz and 200 Hz in the super resolution plot of Figure 9, 100 Hz is close to the first coherence and 200 Hz the second.

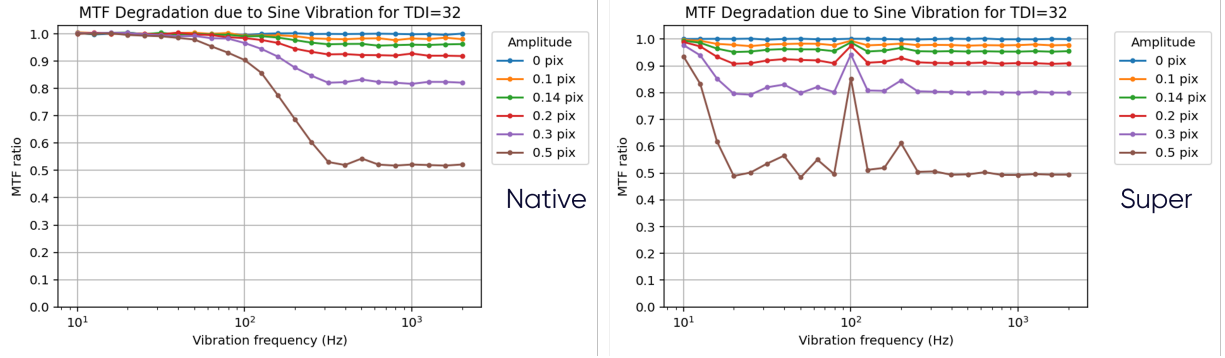


Figure 9. Comparison of MTF degradation across frequencies and amplitudes for native (left) and super resolution (right) images

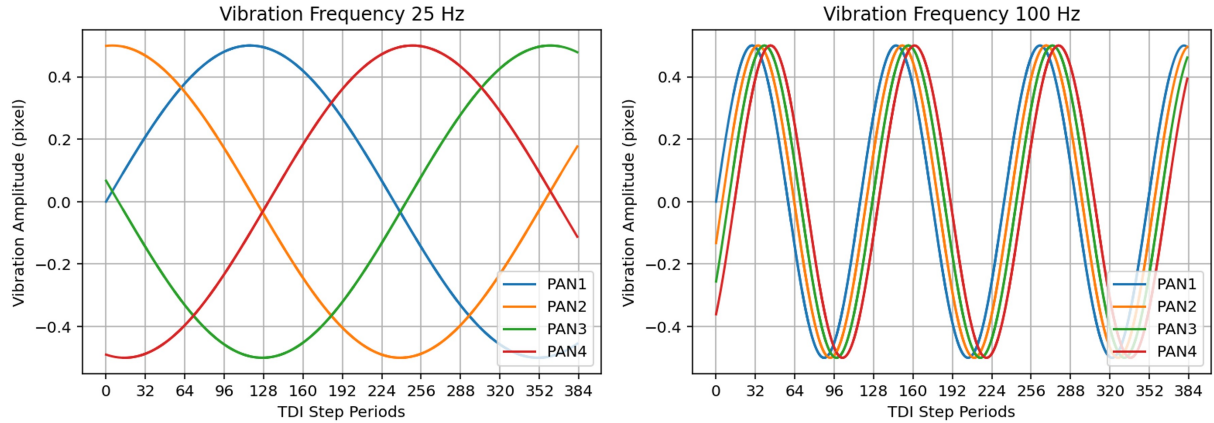


Figure 10. Plot of a 25Hz and 100Hz 0.5-pixel amplitude vibration passed into each PAN band. For many frequencies the combination of PAN bands in super resolution will fill the full peak to peak

5. SCENE RENDERING

Since many cannot correlate MTF value at Nyquist with image quality, the integrator was used to simulate an image of the N3O logo and of a satellite image scene of the CEiiA headquarters. The N3O logo was in black and white, while the satellite image was in colour (however it was generally analysed as greyscale since our project is focused on the PAN performance).

The native resolution image pixel size was chosen arbitrarily; however, the tagline of the logo is not legible in the native resolution image (Figure 11 A). After the four native resolution images are passed through the super-resolution algorithm, however, the tagline becomes legible (Figure 11 B). Vibrations were applied to the integration of the logo, and the legibility of the tagline was assessed. Once what is written is known, it is difficult to determine when it is no longer legible. A study with changing characters or words could be performed to make a better determination, however with some analysis of this image, 0.5 pixels of vibration amplitude with both 25 Hz and 200 Hz vibrations were required to become illegible (Figure 12).

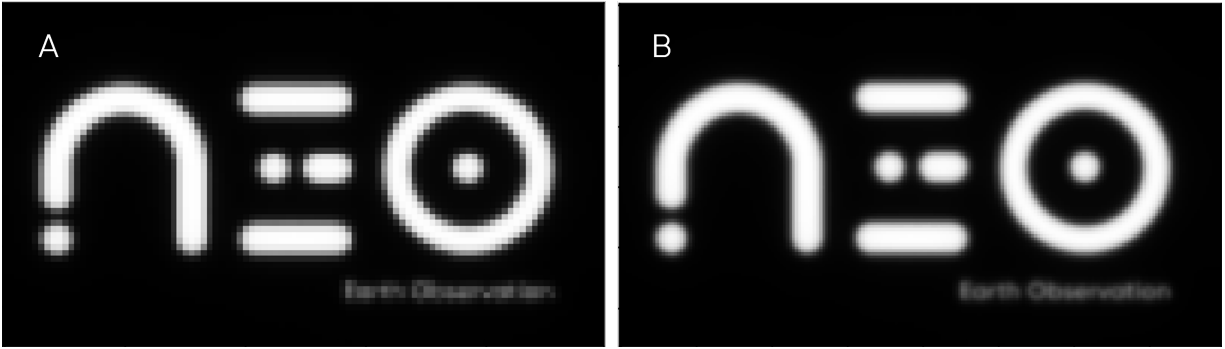


Figure 11. Image generated with the integration tool A and the post processed super-resolution image B

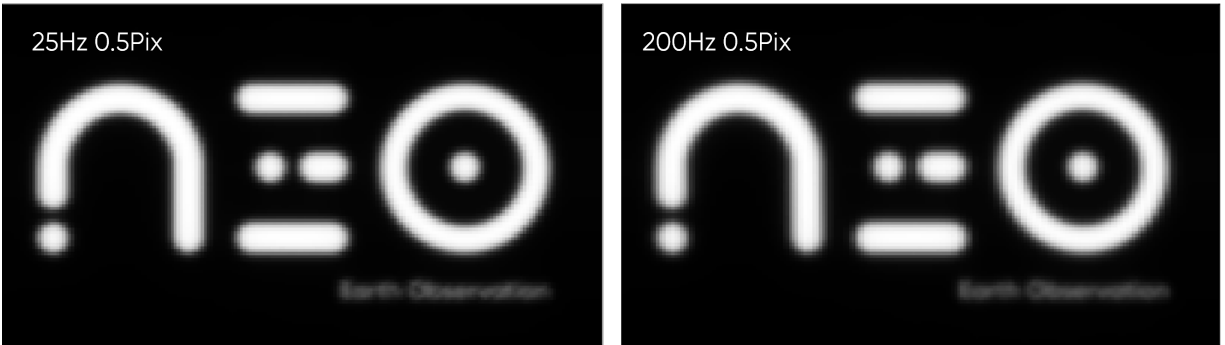


Figure 12. Comparison of 0.5-pixel amplitude vibration with 25 Hz and 200 Hz frequencies

Similar analysis was performed using an image of CEiiA headquarters from Google Earth with representative ground sample distance determined by the known dimensions of the building (Figure 13).



Figure 13. Native and super-resolution images generated using the algorithms described here and the base image with optic MTF applied that was used to generate the native image. Groups of people are circled in red.

Several effects can be seen. Of note, the solar panels on the roof of the building are indistinguishable at native resolution but can be seen individually in super-resolution. Also, groups of people on the balcony and parking area (circled in red) are observed in the super-resolution image even if it is not clear what they are (some manhole covers may be confused for humans). In the native resolution image, fewer points of interest are observed with less context in these regions. Cars are distinguishable in native resolution and in super-resolution vans or wagons can be distinguished from sedans.

When vibrations are applied, the image becomes less sharp, and the solar panels blur together by 0.5-pixel amplitude even though the people are not completely lost. With 2 pixels of amplitude, the cars start to blend together.

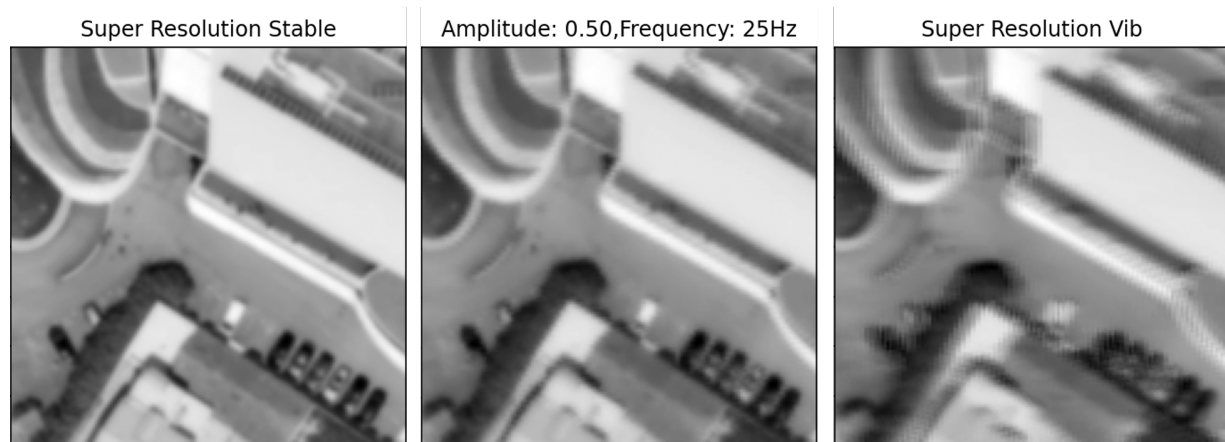


Figure 14. Images of the baseline super-resolution image without vibration, with 0.5-pixel amplitude vibration, and with 2 pixels amplitude vibration

6. CONCLUSIONS

A process for image integration accounting for platform vibrations was made to analyse the resulting images given these vibrations. Processes for optical MTF contributions, super-resolution, and PAN sharpening were also made as a part of the analysis. The resulting change to the MTF due to the vibrations followed the analytical solution of a Bessel function for vibrations higher than the integration frequency. It was determined that 0.5-pixel vibration amplitudes for slow frequencies would visibly degrade the resulting super resolution images. It was also shown that with two pixels of vibration amplitude even cars would become difficult to identify.

Many potential additions to the analysis were also suggested, namely; adding detector noise effects, the use of random time for vibration integration of Monte Carlo points, the use of representative vibration profiles based on FEM analysis, applying vibrations to both axes of the image, and changing the text to better determine the legibility cutoff of vibrations.

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REFERENCES

- [1] Andre Dias, Emir Sirage, Andre Oliveira, "The Atlantic Constellation: Addressing Global Markets of Sustainability and Security," *Proceedings of the 75th International Astronautical Congress*, pp. 23-28, 2024.
- [2] Candeias H., et al. (2024). Designing NewSpace Very-High Resolution (VHR) Constellations: optical high

performance Earth Observation (EO) small satellites opportunities, *75th International Astronautical Congress (IAC)*, Milan, Italy, 14-18 October 2024

- [3] Bardoux A., Gimenez T., Jamin N., "Dynamic MTF Measurement," *Proc. of SPIE Vol. 10565*, 2010.
- [4] Walid A. Wahballah, Taher M. Bazan, Mohamed Ibrahim, "Smear Effect on High-Resolution Remote Sensing Satellite Image Quality," *2018 IEEE Aerospace Conference*, pp. 1-14, 2018.
- [5] Haghshenas J., "Effects of satellite platform's vibrations on the image quality of a remote sensing payload: system level design and challenges," in *Optical Systems Design 2015: Optical Design and Engineering VI*, SPIE, 2015.
- [6] Wong, H.-S. and Yao, Y. L. and Schlig, E. S., "TDI charge-coupled devices: Design and applications," *IBM Journal of Research and Development*, vol. 36, pp. 83-106, 1992.
- [7] S. S. Sawilowsky, "You Think You've Got Trivials?," *Journal of Modern Applied Statistical Methods*, vol. 2, no. 1, 2003.
- [8] Environmental Systems Research Institute, "Fundamentals of pan sharpening," Environmental Systems Research Institute, [Online]. Available: <https://doc.esri.com/en/arcgis-pro/latest/help/analysis/raster-functions/fundamentals-of-pan-sharpening-pro.html#F9D>. [Accessed 2026].