JPEG2000 IMAGE COMPRESSION FOR HIGH RESOLUTION REMOTE SENSING INSTRUMENTS ON SATELLITES

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ABSTRACT: Due to the demanding interests of super high resolution satellite images, the image compression on-board is a critical issue for the improvements on the cost of transmission time and the required memory size. In this report, the performance analysis of frame-based JPEG2000 (ISO 15444-1) image compression has been studied. The sub images are sliced from their original big-swath image to satisfy the maximum resolution of the supported encoder. The JPEG2000 performance shows graceful degradation that the structural similarity index (SSIM) of which is larger than 0.92 when the compression ratio (CR) is above 12. However, it is found that there are discontinuous artifacts at the boundary of the segmented border. By extending some more pixels at the border of the segmented sub-images for compression, the recovered image is good in performance. Nevertheless, this method requires more corresponding system resources to handle the extra buffer arrangements. In this report, we proposed another feasible scheme to recover this artifact without interrupting the system arrangement. The strategy of this proposed scheme and the comparative results of different CR cases will be revealed in this report.

1. INTRODUCTION

It is the trend of the world developments on remote sensing satellites to pursue a high resolution satellite images. The most direct way to improve this index is to increase the chip size and to reduce the pixel size of the image sensor at the possible limit of the sensor process technology. Consequently, it is unavoidable that the amount of data-volume will be increased on-board. Besides that, the corresponding configurations such as memory and power consumption are also increasing respectively. Accordingly, a good image compression technique is an important key to solve the issue between the image quality and the configuration resources.

The category of image compression scheme can be divided into two types, lossy and lossless. Although lossless compression provides the possibility to reconstruct almost the same data as the original image, the possible maximum compression ratio which is around 2 typically is a serious factor for general operation of imaging satellites. On the contrary, lossy image compression technique achieves the possibility of high compression ratio yet generates certain amount of encoding noise inevitably. It is significant important to preserve the high quality image as requirement while reducing the data-volume by image compression at the mean time.

The main procedures of image compression are spatial decorrelation, quantization and entropy encoding. The process of lossy image compression is to reduce the non-necessity and redundancy of the original image. For example, the high frequency components of the image data are generally removed during the compression encoding since human eyes are more sensitive to the variation of the low frequency component. The mechanism of spatial decorrelation can be divided into DPCM (Differential Pulse Code Modulation), DCT (Discrete Cosine Transform) and DWT (Discrete Wavelet Transform) based technologies. DPCM encoding is a prediction based encoding technology that the concept of it had been delivered from 1952 [1]. It deals with the image information in space domain. DCT-based and DWT-based technologies transform the image space into frequency domain. JPEG that was delivered at 1992 and H.264 that was delivered at 2003 are the famous encoding formats based on DCT technology [2, 3]. CCSDS and JPEG2000 that was delivered just at 2000 are encoding format that based on DWT method [4, 5].

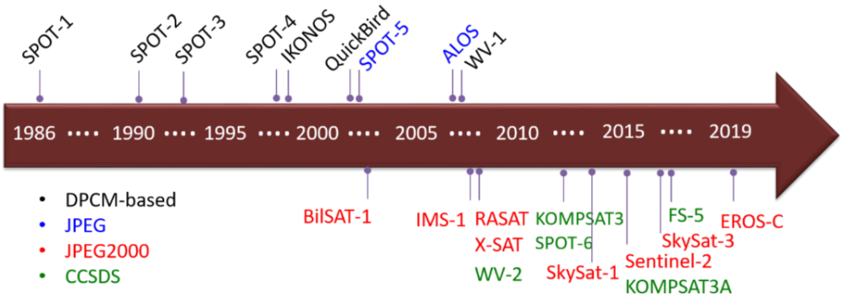


Figure 1: The developments of on-board image compression.

A comprehensive survey about the progress of image compression on-board had been organized by Guoxia Yu at 2009 [6]. Besides that, by organizing the collected data from the public platform [7, 8], the latest evolution of image compression programs until 2019 is shown as Fig. 1. Following the SPOT-1 that launches at 1986 [9], the first earth observation satellite that includes the technology of image compression on-board, those satellites launched before 2000 generally adopted the DPCM-based technology for image compression. The DWT-based encoding compression can avoid the blocking artifacts that will be happened for the DCT-based one. It is one of the important reasons that satellites launched after 2000 adopt this wavelet-based technology as the compressor scheme more generally rather than the DCT-based ones. The CCSDS is a recommended standard that was delivered for the space mission due to its similar performance to JPEG2000 but with lower requirements on hardware resources. It is adopted in many satellites such as WorldView-2、KOMPSAT-3、SPOT6、and FORMOSAT-5 (FS-5) [9-12]. Meanwhile, there are also growing numbers of satellites use JPEG2000 as their compression scheme such as SkySat-1、Sentinel-2、SkySat-3 and EROS-C that launched at 2014、2015、2016 and 2019 respectively [13-14].

JPEG2000 is the state-of-the-art compression technique based on the wavelet technology. By adopting the nearly orthogonal 5/3 and 9/7 filter, it can achieve both lossless and lossy compression by using the same encoding algorithm. Besides that, its intrinsic robustness prevents having dramatic visual impact when some packets are being missed or corrupted during data transportation. As the rapid growing speed on semiconductor technology and the better image performance by using JPEG2000 compression scheme, the adoption of JPEG2000 technology plays as the role to meet the trade-off between the required image quality and the corresponding hardware resources.

With the confidence of successful operation on the FS-5 of which the ground sampling distance (GSD) is 2 m, the first domestic earth observation satellite developed by National Space Organization (NSPO). NSPO has being developed a next ultra-high resolution satellite that is able to deliver image with GSD at the range of sub-meter. A TDI CMOS line sensor that is fabricated by NSPO and the other cooperative parties in Taiwan will be carried by this ultra-high resolution satellite. The pixel numbers of this panchromatic (PAN) line sensor is more than 24 K to satisfy the requirement of big-swath image. With the combination of interleaved PAN sensors, and four multispectral (MS) line sensors, the total data rate is estimated to be achieved ~ 8.5 Gbps. By cooperating with the X-band transmitter with data down link rate of ~ 800 Mbps, it is estimated that the compression ratio (CR) on board should be at least larger than 12 to satisfy the mission requirement of real time data response. Due to several advantages of JPEG2000 encoder, NSPO plans to adopt JPEG2000 as the encoder scheme to handle the requirement of large compression ratio for this ultra-high resolution satellite.

In order to enhance the processing time, it is a mature technology for several possible applications, such as digital cinema, broadcast, and aerial imaging, to use the hardware-based JPEG2000 encoder by adopting FPGA chip or ASIC chip. However, the possible maximum resolutions of the affordable commercial IP core for JPEG2000 encoder is limited to 4000 x 2000 pixels typically or 8000 x 4000 pixels in maximum. It means that satellite images, for example, with resolution larger than 8000 pixels had to be segmented into several sub-images before sending to the encoder. To do the preliminary test and system analysis before the configuration design of the hardware-based encoder, this paper include MATLAB® for JPEG2000 compression simulation to evaluate the image performances.

2. PERFORMANCES OF JPEG2000 IMAGE

2.1 Graceful Performance of JPEG2000 Compression

This paper will include the PAN image that was took by FS-2 as the reference image. As shown in Fig. 2, this image was took at April, 2016, and the location is at Taichung, Taiwan. The corresponding GSD is 2 m, and the 8-bit image resolution is 12000 x 2000 pixels in width and height respectively. To simulate the cases by adopting commercial FPGA encoder with limited supported pixels, the data of the original image is segmented into three sub-images with 4000 pixels in width. The sub-images are shown as Fig. 3. After compressed each sub-images by a CR of 15, the compressed sub-images are shown as Fig.4. The SSIM parameters are above ~ 0.90 for each sub-images. Figure 5 is the combination of each compressed segmented sub-images. As mentioned, the SSIM parameter of the combined image is ~ 0.90 and the room mean square error (RMSE) is ~ 6.0 when CR=15. It is not clear to see the compressed artifacts in this combined image directly. Furthermore, as shown in Fig. 6, there are only tiny differences about the envelope distribution of the intensity histogram especially at the region with higher intensity.

Figure 2: Image took by FS-2 at April, 2016 and the location is at Taichung, Taiwan.

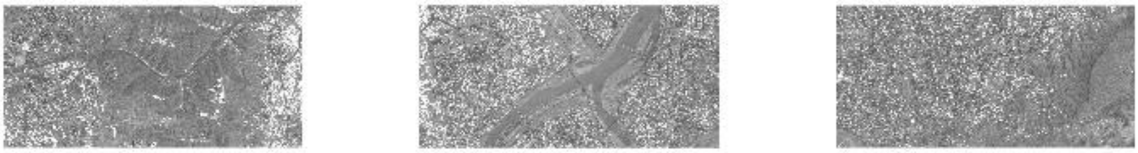


Figure 3: The segmented sub-images with width of 4000 pixels.

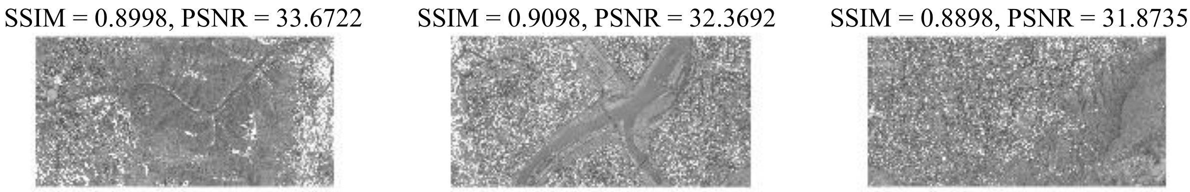


Figure 4: The compressed segmented sub-images when CR = 15.

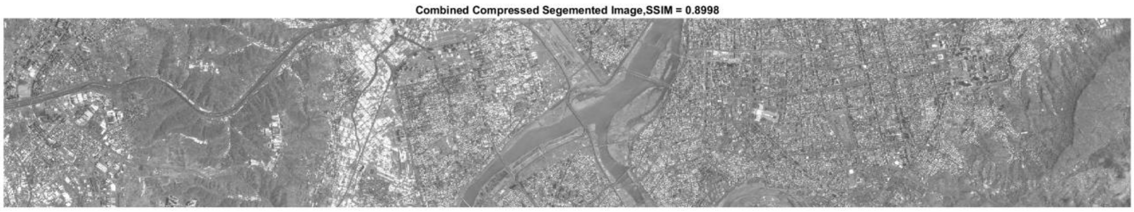


Figure 5: The combined segmented sub-images after compression.

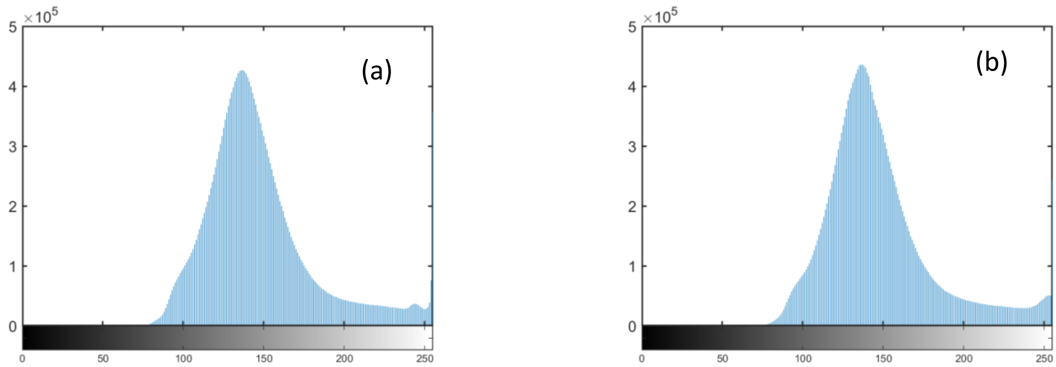


Figure 6: (a) The histogram of intensity distribution for the original image (Fig.2). (b) The histogram of intensity distribution for the compressed image (Fig.5).

2.2 Performances at the Border

The implementation of DWT includes a serial process of convolution operation by pairs of filter bank and down-sampling process. During this process, the image border will act specific padding to satisfy the structure of the original image. For JPEG2000 implementation, the method of mirror reflection is employed for the border padding. The inclusion of mirror reflection technique performs good to typical zero padding technique generally. The discontinues properties at the border can be excluded mostly and the unstable error propagation of high frequency image noise can also be mitigated. However, the data of image at the border is a relatively high frequency component compared to others. It is inevitable to prevent this border artifact when the compression ratio is high.

In order to observe the detail of the image information around the border, we have examined the statistical parameter such as the SSIM and the RMSE value. However, these statistical results do not show clear differences around the border. To face this issue in the most direct point of view, we examine the enlarged image with the range of 100 x 100 pixels around the border as shown in Fig. 7 and Fig. 8. Figure 7 is the zoom-in of the original image (Fig. 2) and Fig. 8 is the enlarged one of the combined image after compression (Fig. 5). From these enlarged images, some artifacts can be observed in straightforward. First, smoothing or blurring can be observed since high frequency components are lost during the compression process. Second, an artifact of a discontinuous line can be observed at the border and we call this as the border artifact in the later discussion.

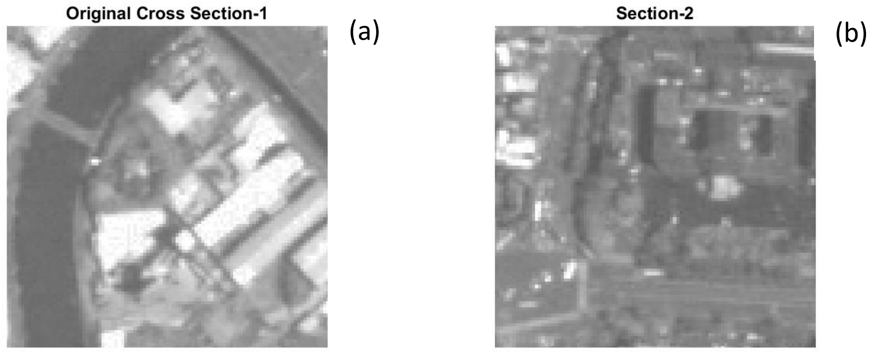


Figure 7: The enlarged original image around the border in the range of 200 x 200 m. (a) The border is located between the first and the second sub-image that the border pixel is at x = 4000 ~ 4001 in the original image. (b) The border is between the second and the third sub-image that the border pixel is at x = 8000 ~ 8001 in the original image.

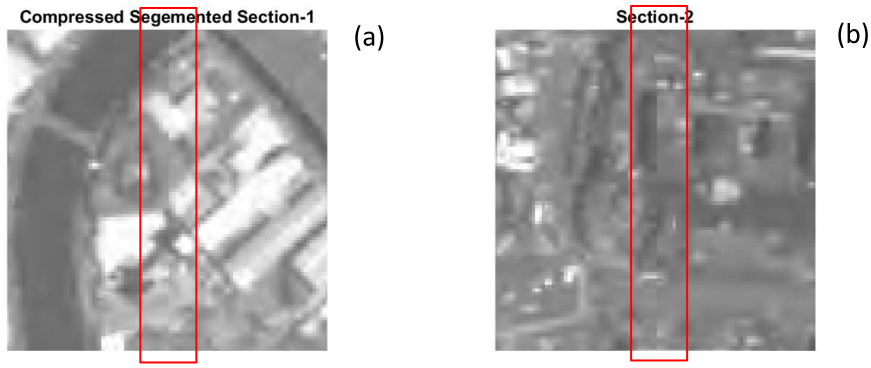


Figure 8: The enlarged compressed image around the border in the range of 200 x 200 m. (a) The border is located between the first and the second sub-image that the border pixel is at x = 4000 ~ 4001 in the combined image. (b) The border is located between the second and the third sub-image that the border pixel is at x = 8000 ~ 8001 in the combined image.

Figure 9 is the intensity distribution across the border for a certain fixed vertical position. In this figure, the border is between the pixel position of 4000 and 4001. The intensity distribution around the border has almost the same tendency except the neighbored one across the border. It shows clearly that the intensity variation for the neighbored pixels at the border indeed has a jump compared to the original case and the region of this difference occurs only for the neighbored two pixels. This is also the reason that why the statistical results of SSIM and RMSE that requires certain amount of pixels for statistical calculation can not provide significant differences for comparison. By summing the intensity difference for the neighbored two pixels along the border, it shows that this sum of difference value is ~ 55 % compared to the case of original image. We can conclude that although there is a border artifact for the compressed image at high compression ratio, yet the amount of error and the region of error occurrence are small.

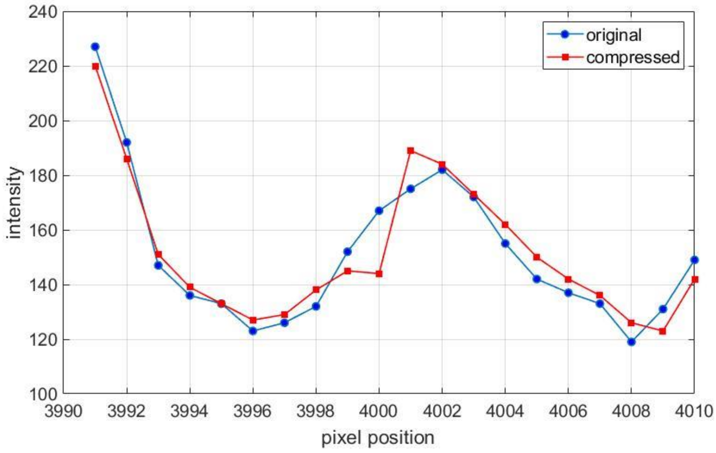


Figure 9: The intensity distribution across the 1st border (horizontal pixel at 4000 ~ 4001) for a certain vertical position in the image. The blue line is the intensity distribution of the original image and the red line is the one of the compressed image when CR=15.

2.3 Simulation Results at Different Compression Ratio

The following Fig. 10 shows the enlarged cross section around the border at different compression ratio. The performance of SSIM parameter are increasing from 0.9010 to 0.9746 when the CR is decreasing from 15 to 5. As the decreasing of compression ratio, certainly the image performance is getting closer to the original image and the discontinuous line artifact at the border can be ignored when CR is less than 5. In other words, the process to exclude the border artifacts has to be included when the operated CR is larger than 5.

Although the operation of lossless JPEG2000 compression can avoid the generation of this border artifact, the offered CR for lossless compression is too small to satisfy the mission requirements in general. Hence, a strategy to remove this artifact will be delivered in the later section.

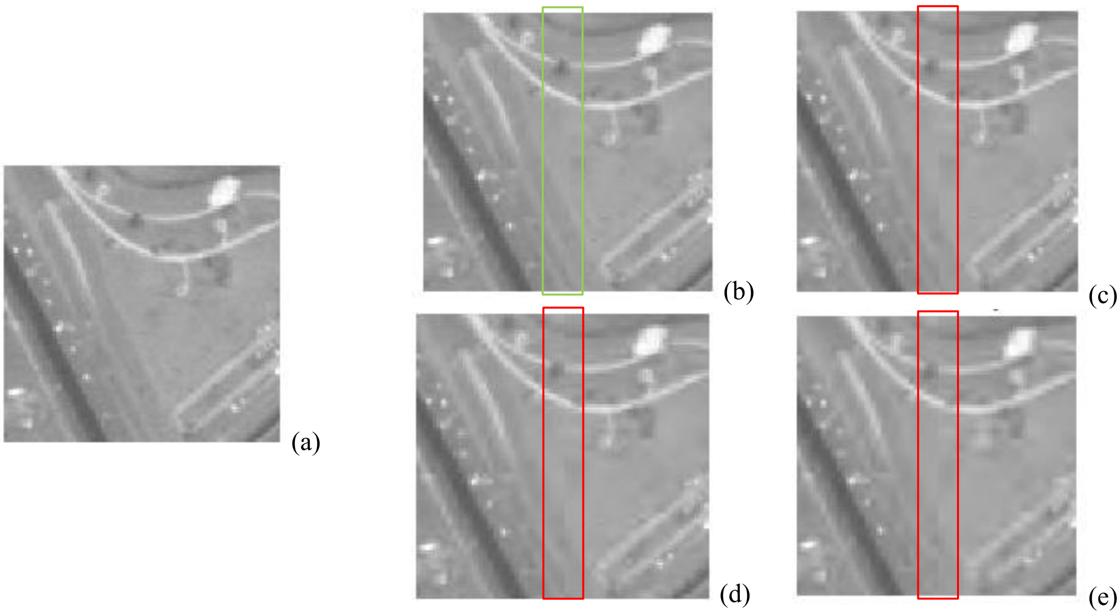


Figure 10: (a) Original image (b) CR = 5, SSIM=0.97461 (c) CR = 8, SSIM = 0.95042 (d) CR = 10, SSIM = 0.93434 (e) CR = 15, SSIM = 0.90104

3. STRATEGY TO RECOVER BORDER ARTIFACTS

3.1 Extension Scheme

According to the previous analysis result, it is suggested that the encoder should try to maximize the supported image resolution to reduce the numbers of the segmented border. In addition, to deal with this artifact, we propose a strategy by border extension to recover this artifact and the scheme concept is shown as Fig. 11. For scheme *I* that was adopted in the previous simulation, the original image is directly segmented into sub images at the border with pixel position of x_b. For scheme *II*, the right-hand side and the let-hand side of the two sub images are extended to the position of $x_b + \Delta x$ and $x_b - \Delta x$ respectively. For both cases, the two sub-images will be compressed separately on-board and the ground image processing stage will combine this two sub-images at the same border of x_b. Figure 12 shows the comparison results of the enlarged cross section at the border when CR = 15. It is clear to see from Fig.12 (b) and (c) that the discontinuous lines at the border is removed by using scheme *II*.

After several optimizations, it is found that the extension pixels must be at least larger than 64 pixels to remove this artifact when the decomposition level is set as 6. It should be noticed that although the extension scheme can recover the artifact at the border, unfortunately, the swath of the output image data will be decreased as the increasing of the required segmented sub-images. This decreasing amount depends directly on the numbers of the required sub-images. Furthermore, an extra buffer has to be organized in the hardware configuration to handle the registration and processing of the extension data. It will also lead the complication of the hardware configuration. In the next section, another recover method that can keep almost the same hardware configuration as the original one will be proposed.

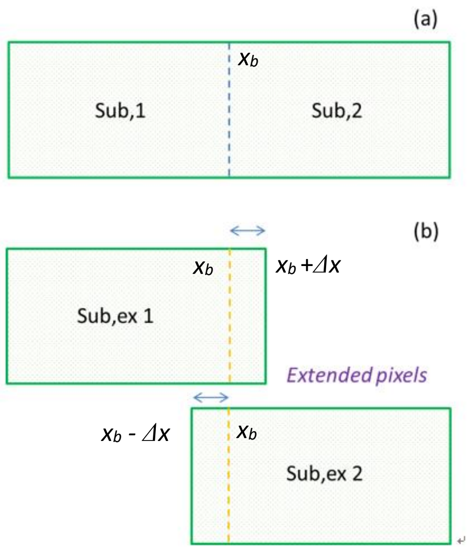
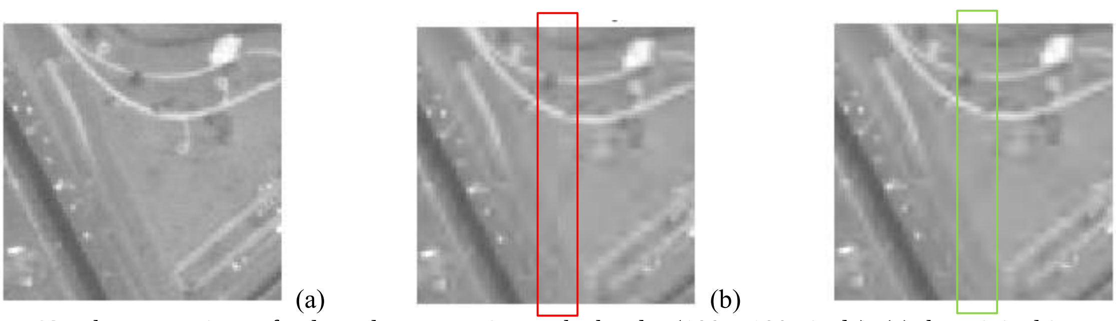


Figure 11: The scheme concept of image segmentation. (a) scheme *I*: The sub-image is directly segmented for compression. The combined image is constructed by this two sub-images. (b) scheme *II*: The sub-image is extended by some more pixels at the border in width. The combined image can be reconstructed by removing the extended pixels.



(a) (b) (c)

Figure 12: The comparison of enlarged cross section at the border (100 x 100 pixels). (a) the original image (b) the cross section of the compressed image by using scheme *I* (c) the cross section of the compressed image by using scheme *II*.

3.2 Another Method for Image Segmentation

Although the proposed scheme *II* can recover the artifacts at the border, it requires extra components to support this configuration and the corresponding system resources will be increased. Besides that, the effective swath of the output image will also be cut down. In order to simply the system configuration on board, we propose another method that the hardware configuration can be kept almost the same as scheme *I*. The concept of this proposed scheme *III* is shown as Fig. 13.

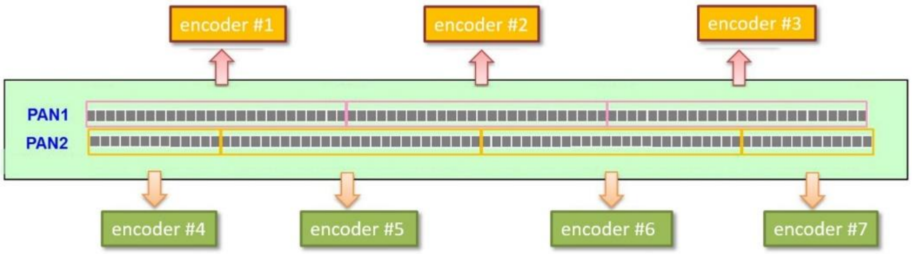


Figure 13: The proposed scheme *III* for image segmentation.

The born of this idea is coming from the interleaved sensor that will be adopted by the NSPO ultra-high resolution satellite. This interleaved sensor set are composed of two sensors and the second sensor is with a horizontal offset of 0.5 pixel in space. The main purpose of this interleaved sensor set is for the application of super resolution at the image processing stage to improve the effective image resolution. Fortunately, by using this interleaved sensor set, it is possible to replace the border artifact by using the image data from the other sensor. As shown in Fig. 13, the image data of PAN1 sensor is segmented into N sub-images and the image data of PAN2 sensor is segmented into $N+1$ sub-images. Adopting this scheme, the border position of this two sensors can be separately divided in space hence another extra buffers for space extension are not required. Since the region of border artifact is around 2 pixels in width, we consider the replacement data by the other sensor at the ground image processing stage is an efficient scheme to remove the border artifact by keeping the same system resources.

Above all, we propose schemes to deal with the border artifacts in the horizontal direction. It should be noticed that the border artifact will also occur in the vertical direction. It means that the border for each collected frame image in different time slices shall also be taken care. A circular buffer to handle the extension data is required if the concept of extension scheme is adopted to deal with the data in the time flow. Alternatively, by adopting the strategy of the proposed scheme *III* to deal with the data in different time slices, it is also considered as a nice solution to solve the artifact in the time direction. The proposed scheme *III* in this paper is suitable for any projects that the adopted sensor numbers are more than two.

4. CONCLUSION

In this report, we can have the following conclusions. First, JPEG2000 compression provides the graceful degradation images. The simulation results of FS2 image shows that the SSIM parameter is above ~ 0.90 when the CR is above 15. Second, we observe there is a border artifact for the neighboring sub-images when the CR is larger than 5. Since the statistical results could not show significant differences for comparison, we found that the encoding noise is only generated for the neighboring two pixels at the border. Third, we proposed two possible schemes to remove the border artifacts. One of this method requires extra buffer to handle the processing of extension pixels, but this method will reduce the image swath accordingly. The other method proposed to segment the sub-images with a separation in space. The image can be recovered by the image processing stage in ground and the hardware configuration is simpler.

Although image compression will give certain amount of image loss, the data-rate is also suppressed meanwhile. It is important for each project to decide clearly the mission requirement on image quality. It is the most significant issue to face for the developments of each projects.

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