Comparison of Different Image Fusion Methods Using Gaofen-6 and Sentinel-2 Imagery of Beijing City, China

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Abstract

Pan-sharpening, a technique in image fusion, is gaining attention in the image processing community. It aims to merge low-spatial and high-spectral resolution images with high-spatial and low-spectral resolution images, resulting in high-spatial and high-spectral resolution images. However, multi-sensor image fusion often leads to spectral distortion in the fused images while the performance of fusion algorithms varies based on image characteristics. This study evaluates the performance of four pan-sharpening algorithms (Gram-Schmidt (GS), Color Normalized spectral (CNS), Principal Component (PC), and Nearest Neighbor Diffusion (NND)) by fusing images from two satellites: Sentinel-2 and Gaofen-6 of the Beijing city, China. The resulting pan-sharpened images are compared both qualitatively and quantitatively in terms of spectral fidelity, while spatial enhancements are assessed through visual interpretation. The comparative analysis of quantitative and qualitative approaches reveals that the GS algorithm produces highly comparable results for exhibiting high spectral quality and spatial enhancement of both sensors. The performance variation of CNS and PC methods for both sensors is relatively insignificant. However, the NND method demonstrated excellent spatial enhancement for the Gaofen-6 sensor while retrieving highly distorted radiometry images for the Sentinel-2 sensor.

Keywords: Sentinel-2; Gaofen-6; Image Fusion; Fusion Algorithms; Pan-sharpening.

Introduction

Remote sensing data is collected by satellite sensors that record spectral information at different frequencies and wavelengths. Consequently, the spectral data resolution varies depending on the satellite dataset attributes which also differ in their spatial and temporal resolution. This spectral information is widely used for mapping and monitoring changes in the earth surface (Nencini et al., 2007). Various satellite data such as QuickBird, Landsat, IKONOS and Chines Gaofen have multispectral and panchromatic sensors. However, multispectral sensors provide high spatial and low spectral data while a panchromatic sensor offers high spatial and low spectral resolution data. (Ghassemian, 2016; Ehlers et al., 2008). According to (Pohl & Van Genderen, 1998) several

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algorithms have been created for image fusion to integrate different spectral and spatial satellite resolution images however, these algorithms employ advance image processing techniques to increase the spatial characteristics of multispectral images and known as pan-sharpening techniques (Kumar et al., 2000). Taking advantage of the both types of data, Pan-sharpening aims to fuse panchromatic and multispectral images to create synthetic images with High spectral and spatial resolution images (Wald et al., 1997). Such techniques have become widely used in remote sensing applications (Aiazzi et al. 2007; Santurri et al., 2010; Ok & Akyurek, 2011; Maurer, 2013). Due to variations in geographical location, social and economic progress, and demographics, the intensity, frequency, and duration of flash floods vary from region to region (Tariq & Giesen, 2012; Ali et al., 2017; Xiong et al., 2020). The most commonly noticed and researched reasons for floods include topography, floodplain habitation, and intense and extended rainfall (Ali et al., 2017; Xiong et al., 2020; Nasir et al., 2020; Hou et al., 2020; Dahri and Abida, 2020).

Pan-sharpening of MS images obtained by diverse satellites for example Spot and Landsat can be more challenging as compared to pan-sharpening images acquired by the same satellite. The need of high-resolution images has led to the development of image algorithms integration for enhancing spatial resolution of multispectral images (Ghassemian, 2016); Pushparaj & Hegde, 2017; Zhang & Mishra 2012). Remote sensing applications based researchers have developed several pan-sharpening algorithms such as Gram- Schmidt for remote sensing datasets (Laben & Brower 2000), Nearest Neighbor Diffusion (NND) (Sun et al., 2014), Intensity-Hue-Saturation (Choi, 2006; Choi et al., 2006; Schetselaar, 1998), Principal component (PC) analysis (Kwarteng & Chavez, 1989; Chavez et al., 1991; Shah et al., 2008; Yang & Gong, 2012), Brovey (Ltd 1990), (Hallada & Cox, 1983), Color Normalized spectral (CNS) (Vrabel et al., 2002), and Ehlers Fusion (Klonus & Ehlers, 2007). These algorithms are widely applied and easily accessible in geospatial software for example ENVI and ESRI ArcPro. Pan-sharpening algorithms vary in terms of spectral or color, as well as, statistical and visual distortion in the pan sharpened image, Which relate to the choice of suitable pan-sharpening approach depending on the degree of information preserved or enhanced in the final image (Maurer, 2013). Review of different and multi fusion algorithms and fusion of technology for green tide production in yellow sea identified using multi source satellite images. (Sing et al., 2021; Zafar et al., 2022; Ding et al., 2024).

Previous studies have focused on comparing different pan-sharpening algorithms using multi-sensor and temporal images. For instance, (Ehlers et al., 2008) compared various pan-sharpening methodologies using the SPOT-7 and FORMOSAT-2 satellites datasets and found that Ehlers outperformed all other evaluated methods in terms of color preservation for both sensors. (Ok & Akyurek, 2011) compared different methods using the QuickBird images of agriculture land, while (Jalan & Sokhi, 2012) used multi-sensor and multi-temporal data to calculate the efficiency of five pan-sharpening algorithms. Resultantly, High-Pass Filter, Gram-Schmidt (GS) and Pan-sharp methods produced high spectral quality and spatially enhanced images. However, the Color Normalized-Brovey method enhanced the spatial quality but with highly distorted radiometry. (Pande et al., 2009) analyzed three fusion methods for pan-sharpening of the Hyperion hyper spectral images, as well as, IKONOS multispectral images create that the 'Color Normalized' spectral technique preserves the spectral features of various land covers relatively better, however PCA and GS methods are suited as we differentiate to Hyperion and IKONOS. Sarp (2014) compared different methods using IKONOS and QuickBird images and finds out that PCA and Gram Schmidt preserved the spectral information and enhanced spatial information relatively enhanced than other approaches. Additionally, Du et al. (2015) evaluated the performance of fusion algorithms for water-bodies observation using the WorldView-2 images and found that GS is the ideal fusion method for their study. Lin et al. (2016) utilized Pleiades-1 images for pan-sharpening to extract the forest-land information and found that the pan-sharpened images obtained through pan-sharp and GS methods have good spatial and visual quality, as well as a strong ability to preserve spectral characteristics. The pan-sharp fused image is obtained with a classification accuracy of 86%, while the Gram Schmidt fused image have 78% accuracy at forest type, respectively.

The application of remote sensing is increasing day by day and it's vital for high spatial and spectral resolution remote sensing images. While multi sensor data archive high spectral and spatial resolution is still a challenging task in such studies. Thus, the main objective of this research is to assess the efficacy of four sharpening algorithms. Gaofen-6 has 8m four MS bands that are red, green, blue and NIR and Pan Chromatics have 2m bands, However, Sentinal-2 provides the same four MS bands at 10m spatial resolution. Based on the related previous studies, it is hypothesized for present study that GS may perform better in preserving spectral and spatial characteristics of both same-sensors and different-sensor fusion. For this purpose, both quantities and qualitative techniques are employed to evaluate the quality of the pan sharpened images generated by these different algorithms. The outcomes of this study will be useful in selecting appropriate methods for pan-sharpening of multi-sensor images.

Methodology

Study Area and Satellite Data

For present research, Beijing is selected as a project area Figure 1. Beijing lies within a zone of 50 °S of Universal Transverse Mercator (UTM) projection system at 39°26′– 41°30′ N latitudes and 115°25′–117°30′ E longitudes, covering an area of 16,000 km^2. It covers a diverse range of land cover types, hence, making. It is a suitable location for testing the efficiency of Pan-sharpening algorithms.

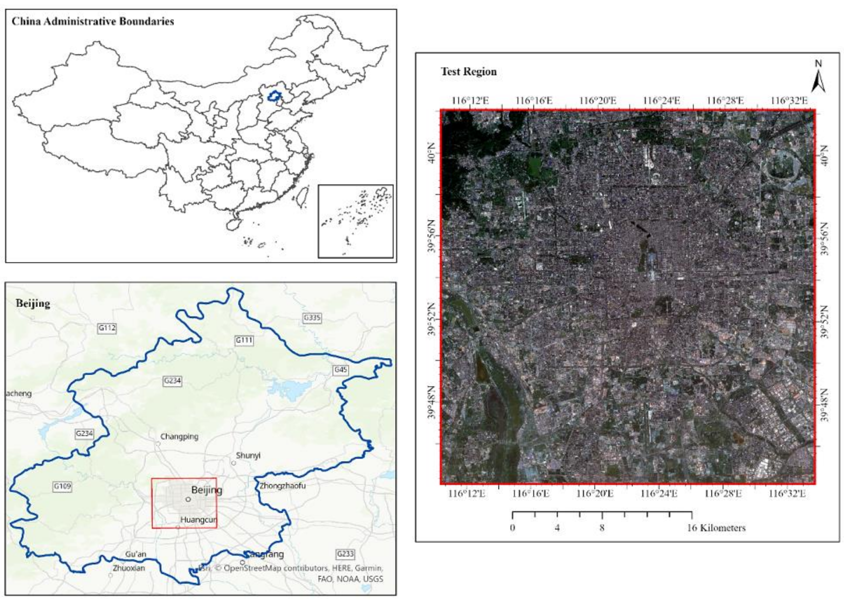

Figure: 1 Geographic site of the study area.

The experimental datasets used in the study are optical satellite images acquired in August 2020, from the Chinese Gaofen-6 and European Space Agency Sentinel-2 satellites. Gaofen-6 is a low orbit sun-synchronous optical remote sensing satellite that has both panchromatic and multispectral cameras, providing images at a 2m spatial resolution for the panchromatic band and 8m spatial resolution for the multispectral bands respectively. On the other hand, Sentinel-2 is also a sun-synchronous satellite with only a multispectral camera, but it acquires images at various spatial resolutions that as 60m three bands, 20m six bands and 10m four spectral bands. To enhance the images, the study utilized the GF-6 panchromatic (2m) band as the source data for pan-sharpening of both GF-6 multispectral (8m) image and the Sentinel-2 (10m) image. The detail of each satellite is given in Table 1.

Table 1: Details of Gaofen-6 and Sentinel-2 sensors.

Sensors	Bands	Spectral Resolution	Spatial Resolution	Acquired on
Gaofen-6 Multispectral	Blue	0.45-0.52 um	8 meters	11 Aug, 2020
	Green	0.52-0.60 um		
	Red	0.63-0.69 um		
	NIR	0.76-0.90 um		
Gaofen-6 Panchromatic	PAN	0.45-0.90 um	2 meters	
Sentinel-2 Multispectral	Blue	0.458-0.523 um	10 meters	10 Aug, 2020
	Green	0.543-0.578 um		
	Red	0.650-0.680 um		
	NIR	0.785-0.899 um		

Pre-processing

Co-registration of multi-sensor images is an essential step before pan-sharpening to ensure that the multispectral and panchromatic images are spatially aligned; otherwise, the quality of pan-sharpened images may be lowered. Co-registration involves adjusting the position and orientation of the images so that they are aligned in the same coordinate system. Using the panchromatic band as the reference image for registration is a common approach in remote sensing as it has higher spatial resolution and provides more accurate geometric information than the multispectral bands (Xie et al., 2021). Relative registration is a widely used method for co-registration which involves selecting control points in both the reference and input images and then minimizing the differences between them to achieve accurate registration. In the present approach, the relative registration method is used, and the panchromatic band of GF-6 is selected as a reference image. For this purpose, twenty-six control points are selected for geometric correction which helped to achieve absolute registration with high accuracy. The RMSE of less than 1.5 meters is achieved in the registration of the multispectral bands of Gaofen-6 and Sentinel-2 with the reference panchromatic band. It is considered to be a high level of accuracy which is suitable for evaluating the performance of pan-sharpening algorithms. Overall, co-registration is a critical step in the pan-sharpening process for which accurate registration is necessary to achieve high-quality pan-sharpened images (Wenbo et al., 2008).

Image Fusion Methods

The methods of image fusion are divided into three main categories i.e. Decision, pixel and features level. For optical remote sensing images pixel level methods are widely used as they merging of pixel level information from different sources to produce a new hybrid high resolution image. It includes spectral information merging from the

MS image spatial details from the panchromatic image at pixel level that as Gram Schmidt, intensity hue saturation transforms, PC analysis methods, and nearest NND method. Feature-level fusion methods involve extracting features from each source image and then merging them to create a new, fused image. These methods are commonly used for fusing images with different spatial resolutions and can include techniques, such as wavelet transform and contourlet transform. Decision-level fusion methods involve combining the results of different classifiers or decision-making algorithms to create a final, fused image. These methods are commonly used for fusing images with different sensor modalities, such as optical and radar images. In this study, four different pixel-level fusion algorithms including: GS, CNS, PC, and NND are employed for pan-sharpening the Gaofen-6 and Sentinel-2 datasets.

Gram-Schmidt (GS)

Laben and Brower (2000) proposed Gram Schmidt method for the first time to fused MS and Panchromatic images. The GS method involves transforming the bands of panchromatic to the MS image low resolution and then using the GS orthogonalization method to de-correlate all bands, with each band treated as one multidimensional vector. The panchromatic low resolution image is not transformed and is used as a first component. It is then replaced by panchromatic high resolution band and change is reserved to achieve fused high resolution image. The GS method can fuse any number of bands in a single process, hence, making it a versatile and efficient technique for image fusion.

Color Normalized Spectral (CNS)

This method is introduced by Vrabel et al. (2002), is a popular technique for pan-sharpening multispectral images. It is a data driven method that can increase the spatial resolution of any number of spectral bands, however retaining the dynamic change and original data type. The CNS approach can be applied to sharpen multispectral images using either a panchromatic image or a hyperspectral image. In both cases, low spectral and high spatial resolution bands are used to enhance high spectral and low spatial resolution bands. In the present approach, the input bands are collected into spectral parts based on the range of spectral sharpening bands. Each segment band is treated together by multiplying it with the sharpening of band and dividing the outcome bands in the section. This generated every pan-sharpened band. Each segment band is treated together by multiplying it with the sharpening of band and dividing the outcome bands in the section. This generated every pan sharpened band.

Principal Component (PC)

In remote sensing study PC method is widely used for Pan-sharpening of image fusion. It is created on the assumption that the main PC of the MS image is most correlated to the image of panchromatic. For this purpose, the PC transform is applied to the multispectral image, and the first PC band is then replaced with the panchromatic band to create a high-resolution multispectral image. To minimize the distortion of spectral band, the panchromatic data is scaled to compare the first PC band. Finally, contrary PC change is applied to get the fused image. According to Welch (1987), MS image is subsample to spatial resolution using resampling technique of the panchromatic image for example cubic convolution, bilinear and nearest neighbor.

Nearest Neighbor Diffusion (NND)

This method is first described in detail by Sun et al. (2014) and has been a popular technique for pan-sharpening multispectral images. However, instead of down sampling the panchromatic band with high resolution into the MS bands with low resolution, NND method first apply such as linear regression to obtain the vector T contribution. The contribution vector is then used to calculate the nearest neighbor difference of panchromatic band pixel. The contribution vector is then used to calculate the nearest neighbor pixel difference using the panchromatic band, which generates high-resolution multispectral images. After generating the high-resolution multispectral images, the NND method used the contribution T vector as the normalize weight of the high resolution MS image spectrum. This is done to confirm that the characteristics of spectral and original MS image are conserved. NDD method perform well when the MS bands cover the panchromatic band spectral range as well as when the spectral response functions of the multispectral bands have minimal overlap between them. This is because the method relies on the supposition that the spectral characteristics of the multispectral and panchromatic images are alike, which is most likely to be true when there is minimal spectral overlap between the multispectral bands.

Results and Discussion

The performance of four distinct image fusion techniques: GS, CNS, PC, and NND is assessed in the present approach utilizing the Gaofen-6 and Sentinel-2 satellites images as experimental data. For this purpose, the GF-6 Panchromatic image of 2-meter spatial resolution is merged with 8- and 10-meters multispectral bands of GF-6 and Sentienl-2 respectively, to generate high-spatial and spectral-resolution images. The primary aims of this research are to assess the fused image quality produced by applications of various pan-sharpening algorithms. Prior to the fusion, both GF-6 and Sentinel-2 multispectral images are accurately registered with the GF-6 panchromatic band, with a RSME value of less than 1.5m. To assess the efficiency of spectral and spatial fused image techniques a comparison of quantities and qualitative is employed. The qualitative evaluation is based on the comparison of band-to-band statistical parameters such as Mean, Standard Deviation, Correlation, Root Mean Square Error (RMSE) and Mean Absolute Percent Error (MAPE) values of both Gaofen-6 and Sentinel-2, multispectral and pan sharpened images, whereas the quantitative evaluation involved a comparison of Histogram evaluation and Visual interpretation.

Mean and Standard Deviation

Standard deviation and mean are important statistical indicators for the quantitative evaluation of remote sensing images. Table 2 shows the band-to-band mean and Std Dev of original multispectral bands and pan-sharpened bands of both GF-6 and Sen2 sensors, respectively. The result show that the values of mean of GS and PC fused bands in both sensors show small differences relative to their corresponding original multispectral bands. In addition, the mean values of CNS fused bands are slightly lower as matched to the original bands for both sensors, while the values of NND fused bands are significantly higher relative to the original bands for both GF-6 and Sen-2 sensors. The Std Dev of the fused bands showed that GS generates good fusion results followed by PC and CN for both the GF-6 and Sen2 sensors. However, the Std Dev of the NND fused bands is significantly higher than that of the original multispectral bands of the corresponding sensor. Additionally, the Std Dev of NND for the Sen-2 sensor is found relatively the highest.

RMSE and MAPE

The quantitative quality of fused images is assessed by estimating the RMSE and the mean absolute percent and root RMSEs between the pixel values of the original MS and fused bands generated using different fusion image algorithms. Table 3 display the band-to-band RMSE and MAPE of each fused image. The mean RMSE values show the same trend as the correlation results, with the GS method performing the best by exhibiting the lowest mean RMSE value for both GF-6 and Sen-2 fused images, followed by CNS and PC respectively. The NND method produced the highest mean RMSE for both GF-6 and Sen-2 fused images. The MAPE results are consistent with the RMSE results, with the GS method produced the lowest mean MAPE value of less than 0.2 for both GF-6 and Sen-2 fused images, followed by CNS and PC with mean MAPE of 0.15 and 0.18 for GF-6 sensor, as well as 0.2 and 0.3 for Sen-2 sensor, respectively. However, the NND method resulted in the highest mean MAPE values of0.4 for GF-6 sensor and 17.3 for Sen-2 sensor, respectively.

Table 2: Mean and standard deviation results.

	Mean of Gaofen-6					Mean of Sentinel-2				
	Original	GS	CNS	PC	NND	Original	GS	CNS	PC	NND
B1	907.28	906.65	879.15	907.55	1231.41	781.63	781.41	704.84	783.15	11818.65
B2	926.42	925.63	890.51	926.68	1254.52	959.94	959.36	875.15	960.40	14374.62
B3	879.81	878.89	837.34	880.10	1187.03	938.89	939.02	847.22	940.94	13970.88
B4	2024.09	2018.6	1948.74	2024.28	2731.90	2224.35	2222.3	2128.45	2224.46	31234.64
	Std Dev of Gaofen-6					Std Dev of Sentinel-2				
	Original	GS	CNS	PC	NND	Original	GS	CNS	PC	NND
B1	232.40	249.14	274.72	250.93	371.04	491.78	515.15	352.70	450.19	7130.04
B2	315.90	340.78	318.93	350.64	459.80	495.84	527.21	350.00	467.02	7510.90
B3	440.26	467.64	411.52	478.82	602.23	590.85	628.71	443.55	552.29	7921.33
B4	745.93	634.88	772.45	697.74	1029.30	810.51	723.72	878.74	872.01	10027.29

Table 3: RMSE and MAPE results.

	RMSE of Gaofen-6				RMSE of Sentinel-2			
	GS	CNS	PC	NND	GS	CNS	PC	NND
B1	86.33	171.24	151.14	426.73	181.18	261.31	348.29	13472.88
B2	136.30	192.11	205.13	452.62	210.56	254.60	345.11	15434.99
B3	167.50	221.62	255.43	484.44	211.30	300.86	408.50	15271.77
B4	459.72	431.32	630.70	965.22	409.86	457.13	364.79	30570.88
Mean	212.46	254.07	310.60	582.25	253.22	318.48	366.67	18687.63
	MAPE of Gaofen-6				MAPE of Sentinel-2			
	GS	CNS	PC	NND	GS	CNS	PC	NND
B1	0.06	0.13	0.09	0.39	0.20	0.23	0.44	18.79
B2	0.11	0.14	0.14	0.39	0.17	0.19	0.32	16.69
B3	0.16	0.18	0.22	0.43	0.21	0.22	0.46	18.89
B4	0.22	0.16	0.27	0.43	0.18	0.18	0.15	14.84
Mean	0.14	0.15	0.18	0.41	0.19	0.21	0.34	17.30

Correlation

Band to band correlation among the fused and original MS bands, resulting from various fusion image algorithms, can be used to evaluate the quality fused image. The correlation between the fused bands and the original multispectral bands of both GF-6 and Sen-2 sensors is illustrated in Figure 2. The GS algorithm outperforms the others with a correlation exceeding with values of 0.8 for all bands of GF-6 and 0.75 for all bands of Sen-2, respectively. The CNS and PC fused bands from the GF-6 sensor retrieved lower correlation values of 0.75 with all original multispectral bands of GF-6 in comparison to those of the CNS and PC fused bands from the Sen-2 sensor. The NND algorithm demonstrated the best performance for the GF-6 sensor with high correlation values of 0.7 for all bands. However, the lowest correlation of the NND fused bands for the Sen-2 sensor indicated a significant loss of information.

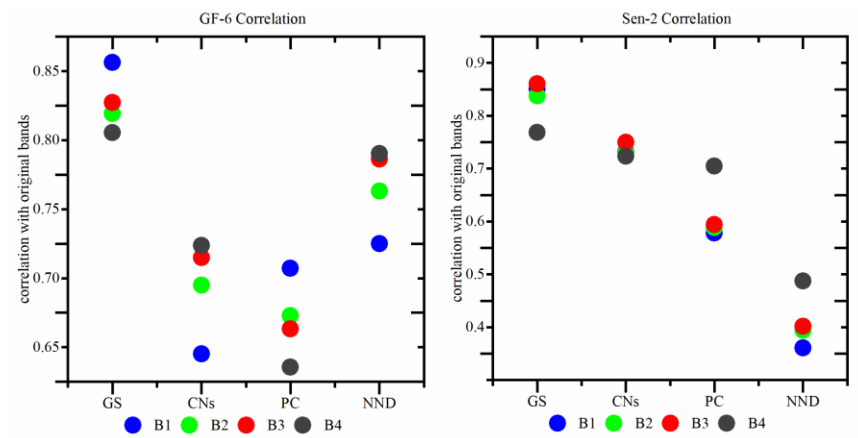

Figure: 1 Band to Band Correlation of Gaofen-6 and Sentinel-2.

Histogram Evaluation

The histogram is a visual representation of the distribution of pixel values in digital images. In this study, histograms of fusion images obtained through diverse pan-sharpening algorithms are compared to the histograms of original multispectral bands of GF-6 and Sen-2 sensors, respectively, as shown in Figure 3. The results suggest that for GF-6 data, the GS method produced fused bands with histograms that are more similar to the original MS bands. However, for Sen-2 data, all the GS fused bands showed significant changes in the shape of the histogram as compared to the original multispectral bands. CNS fused bands of the GF-6 sensor showed slightly different histograms than the original bands, while CNS-based fusion completely changed the shape of the histogram when Sen-2 data is used. The PC method based GF-6 fused bands showed significant changes in pixel values as compared to the original multispectral bands. Similarly, the PC method based Sen-2 fused bands showed significant changes in the shape of the RGB bands histogram while band-4 histogram is closer to the original band-4 of Sen-2. The NND method demonstrated good performance for GF-6 data with RGB bands histograms significantly identical to the original RGB bands of GF-6.; but a significant change is shown in the peak value of the band-4 histogram. However, for all bands of the Sen-2 data, the NND method performed poorly due to producing significant changes in both the value and shape of all the bands histograms. Overall, based on the histogram evaluation, the GS method performed relatively better for both GF-6 and Sen-2 data, followed by PC, and CNS. The NND method performed better for GF-6 data as compared to Sen-2 data. In addition, the NND method also produced the highest distortion in all bands for Sen-2 data.

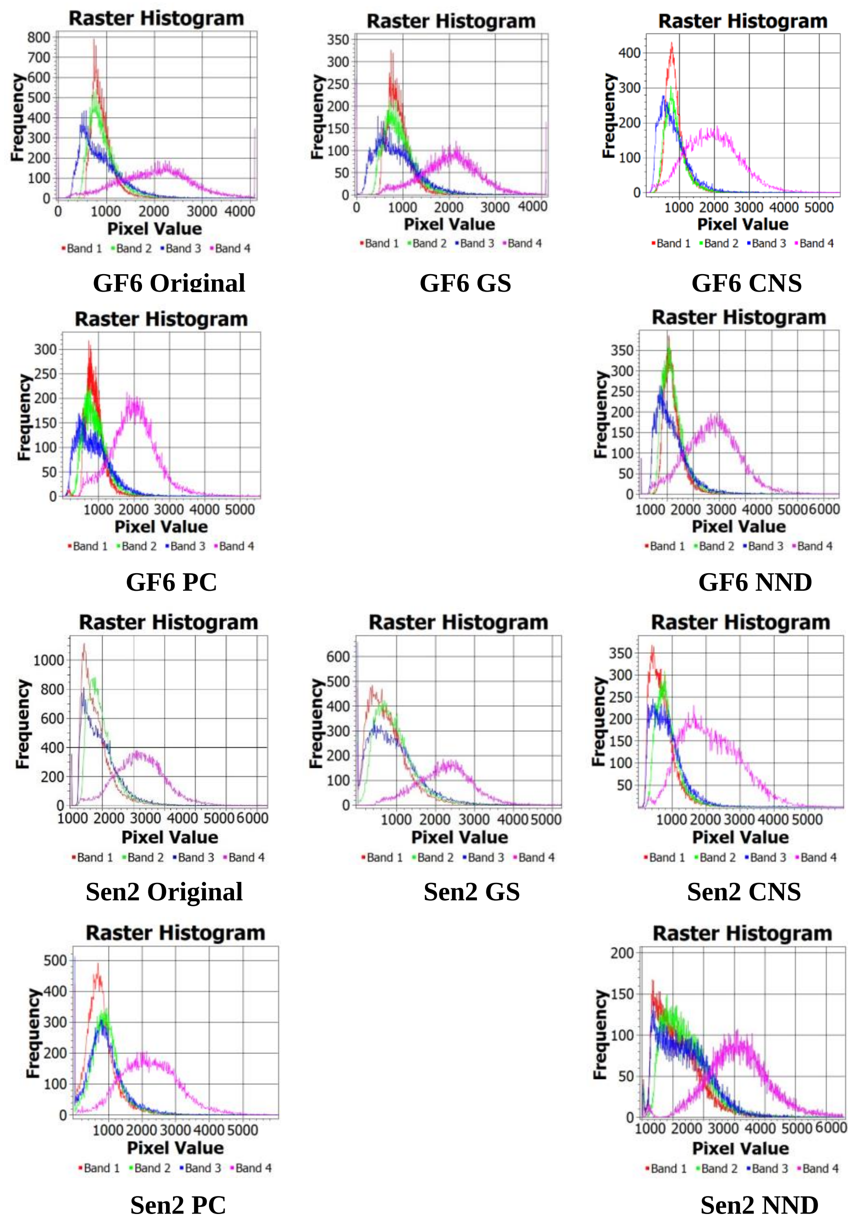

Figure: 2 Histograms of original and pan-sharpened images.

Visual Interpretation

Visual interpretation is a crucial step in remote sensing data analysis as it allows users to identify features and patterns in the image. The results of the visual comparison Figure 4 of the four fusion methods

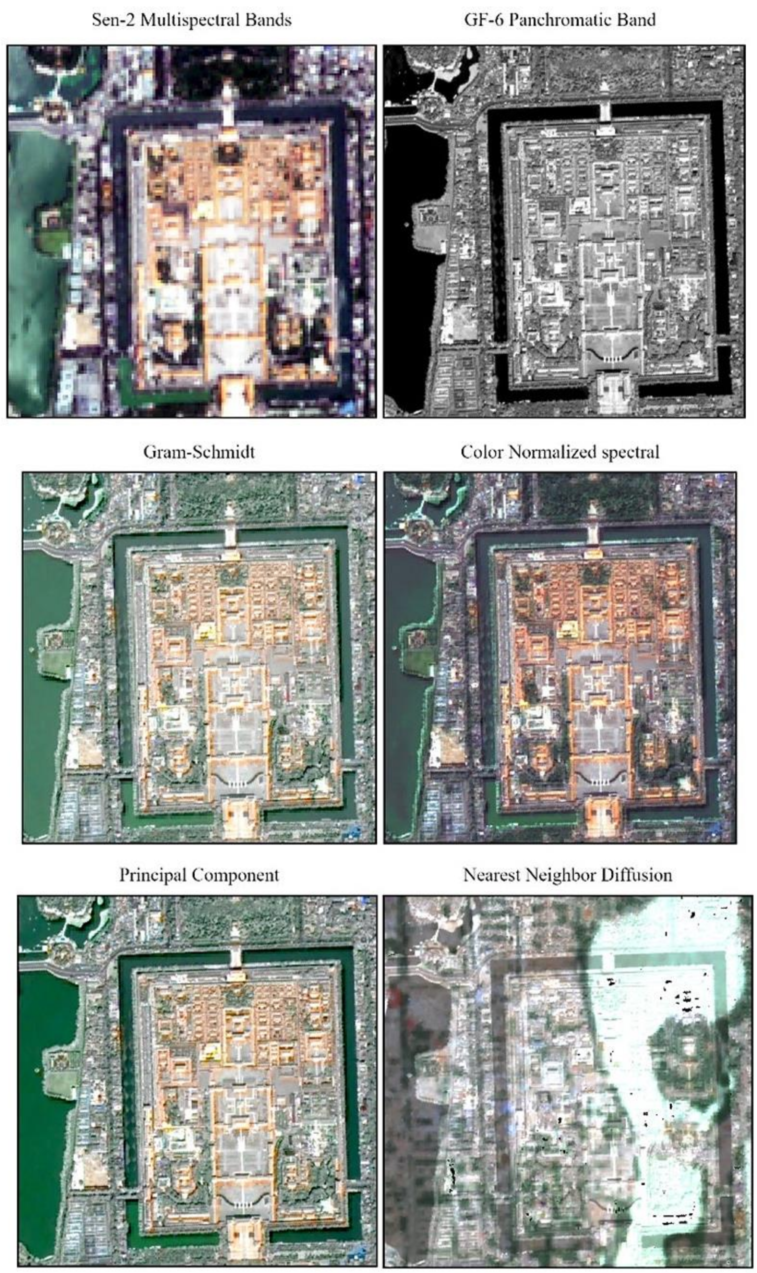

Figure: 3 False color composite with stretch type standard deviation.

using GF-6 and Sen-2 satellites-data indicate that the GS method preserved both the spectral and texture quality of input datasets and significantly enhances the quality of both GF-6 and sen-2 images. The CNS method enhanced the texture quality of both GF-6 and sen-2 images but showed slight distortion in the spectral quality of the fused images from both sensors. It is evident in the color-change of the water-bodies boundaries in both GF-6 and sen-2 data, as well as interpretation of over-sharpening. The results from the PC method for the sen-2 sensor are relatively better than the GF-6 sensor. The PC method preserved the spectral information of the GF-6 image. However, it has poor spatial quality and blurs images while the PC fused image from sen-2 has good spatial and texture quality. The NND method showed outstanding performance for the GF-6 sensor in both preserving the spectral information and enhancement of the texture details. However, its performance for sen-2 is unreliable due to complete shift in the image quality. Therefore, the NND method is more suitable for pan-sharpening of the same sensor images as compared to different sensor images. Overall, the visual interpretation suggested that GS approach is relatively better and reliable fusion approach for multi-sensor data.

Conclusion

Fusion of remote sensing images is an active method to increase image quality in term of spatial enhancement and texture. This study evaluated the performance of four image fusion methods including GS, CNS, PC, and NND methods using Gaofen-6 and Sentinel-2 images of the Beijing city (China) as a study site. The study found that the GS algorithm performed relatively best in terms of maintaining spectral information and enhancing the spatial details for both GF-6 and Sen-2 satellites datasets. The CNS algorithm resulted in over-sharpening and poor spectral quality, while the PC algorithm retrieved poor spatial quality and blurred images for GF-6; however, it performed well for Sen-2 only. The NND algorithm showed outstanding performance for GF-6 pan-sharpening by enhancing the spatial and texture quality of the fused images. However, it exhibited poor spectral consistency with the Sen-2 source image, hence, resulted in the largest spectral distortion among the four algorithms tested. Resultantly, the NND algorithm may be suitable for pan-sharpening images from the same sensor, it may not be the reliable choice for fusing images from different sensors. Based on both qualitative and quantitative evaluations, the study concluded that the GS algorithm has the best overall performance; as, it enhanced spatial and texture information for both GF-6 and Sen-2 datasets which make it a suitable choice for the multi-sensor image fusion. Conclusively, for its better for both GF-6 and Sen-2 datasets, the GS algorithm can be applied to a wider range of remote sensing data.

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Disclosure statement

The authors declare no potential conflict of interest.

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