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Quantifying the Effect of PAN/MS Resolution Ratios on Pansharpening Quality Using IDSSIM

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ABSTRACT

Pansharpening generates high-resolution multispectral (MS) imagery by combining the fine spatial detail of panchromatic (PAN) images with the spectral richness of MS data. While most prior studies emphasize algorithm development, the effect of the PAN-to-MS spatial resolution ratio on fusion quality has been largely overlooked. In this work, we systematically examine ratios ranging from 1:2 to 1:16, using Wald's protocol to simulate consistent PAN and MS inputs. A benchmark dataset of nine image pairs from GeoEye-1, WorldView-2, WorldView-3, and WorldView-4—covering diverse urban, vegetated, and agricultural scenes—was employed. Fusion was performed with the Gram–Schmidt method, and quality was evaluated using the Image Decomposition-based Structural Similarity (IDSSIM) index. Results show that moderate ratios, particularly around 1:5, consistently yield the most favorable balance between spatial sharpness and spectral preservation, although some variation occurs depending on scene characteristics. These findings demonstrate that resolution ratio selection plays a decisive role in pansharpening performance and provide practical guidance for both operational workflows and future sensor design.

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1. Introduction

Remote sensing systems frequently capture imagery at varying spatial and spectral resolutions. Combining such heterogeneous datasets has become a core objective in image fusion research, aiming to integrate complementary information from each modality to improve interpretability and analytical utility (Khateri et al., 2020). Among the available sensors, many modern platforms provide both multispectral (MS) and panchromatic (PAN) images, making pansharpening—a class of fusion techniques—particularly relevant.

Multispectral images contain valuable spectral information across discrete bands, enabling discrimination between land cover types. In contrast, panchromatic images, typically covering a broader wavelength range, offer finer spatial detail but lack spectral diversity (Dadrass Javan et al., 2021). Pansharpening addresses this trade-off by fusing the high spatial resolution of PAN imagery with the spectral fidelity of MS data to produce a synthetic image with both properties enhanced. This technique has been widely used in numerous remote sensing applications, including urban monitoring, environmental assessment, precision agriculture, and land cover classification (Vivone et al., 2021).

Multiple high-resolution satellite missions such as GeoEye-1, WorldView-2/3/4, SPOT-6/7, and Pléiades acquire co-registered PAN and MS imagery, facilitating the application of advanced pansharpening algorithms. These algorithms are typically grouped into two major categories: component substitution (CS) and multiresolution analysis (MRA)(Vivone et al., 2014). CS-based methods (e.g., Principal Component Analysis [PCA](Kumar & Muttan, 2006), Intensity–Hue–Saturation [IHS](Rahmani et al., 2010), and Gram–Schmidt [GS]) operate by transforming the MS data and injecting PAN spatial detail into selected components (Aiazzi et al., 2006). MRA approaches, including wavelet-based (Pajares & Manuel de la Cruz, 2004) and Laplacian pyramid-based techniques (Zhang et al., 2022), instead decompose input images into spatial-frequency components, which are merged in a scale-consistent manner to preserve spatial sharpness and spectral consistency (Guan et al., 2023).

While the performance of pansharpening algorithms has been extensively investigated, most prior studies focus on algorithm design and spectral/spatial trade-offs within a fixed sensor configuration. However, a less explored but equally important factor is the spatial resolution ratio between PAN and MS images—a parameter that is usually fixed by satellite hardware, but in simulation-based research, can be flexibly adjusted to understand its effect on fusion outcomes (Toosi et al., 2025). Previous works have often assumed this ratio to be a given (e.g., 1:4 in WorldView-3), without thoroughly evaluating whether it is indeed optimal across various scenes or sensors.

This study addresses this gap by systematically analyzing how the PAN-to-MS spatial resolution ratio affects pansharpening quality. We evaluate three representative fusion methods—Gram–Schmidt, Brovey, and High-Pass Filtering (HPF)—across a wide range of ratios from 1:2 to 1:16. The analysis is conducted on a benchmark dataset of nine image pairs acquired from GeoEye-1, WorldView-2, WorldView-3, and WorldView-4 satellites, representing diverse land cover types such as dense urban areas, vegetation, forests, and water bodies.

To ensure realistic and consistent evaluation of fusion quality across varying PAN/MS resolution ratios, this study employs Wald's protocol (Wald et al., 1997)—a widely adopted framework for simulating lower-resolution MS and PAN imagery from high-resolution references. The protocol ensures radiometric and geometric consistency between original and degraded images, allowing for objective benchmarking of pansharpening algorithms under controlled conditions. It involves degrading both PAN and MS images via spatial filtering and resampling, thereby generating synthetic inputs that mimic real satellite acquisitions at various spatial scales. This facilitates a fair and repeatable comparison of fusion performance across different resolution settings.

Fusion quality is quantitatively assessed using the Image Decomposition-based Structural Similarity (IDSSIM) metric, which jointly evaluates spatial structure and spectral texture similarity (Yang et al., 2016). Our analysis aims to identify the resolution ratio that yields the most effective balance between spectral preservation and spatial enhancement across different scene types and sensor configurations. The results of this work offer valuable insights for both operational image fusion and sensor design, supporting the development of adaptive pansharpening strategies.

2. Dataset

This study utilizes a subset of the PAIRMAX dataset, comprising 7 pairs of panchromatic (PAN) and multispectral (MS) images acquired by high-resolution Earth observation satellites, including GeoEye-1, WorldView-2, WorldView-3, and WorldView-4. The selected image pairs represent diverse geographic regions and land cover types, encompassing urban and natural environments such as Miami, Munich, London, Trenton, Mexico City, and Stockholm.

Each image pair consists of co-registered PAN and MS data with distinct spatial resolutions, enabling systematic simulation of various resolution ratios and evaluation of pansharpening performance. Metadata for each image, including ground sampling distance (GSD), number of spectral bands, sensor type, and land cover category, is summarized in Table 1.

To provide a visual overview of the dataset, representative examples of both PAN and MS images for all nine scenes are illustrated in Figure 1.

Table 1. The images representing the main land cover type: urban, natural, or mixed (Vivone et al., 2021).

Image NO.	Satellite	Land cover type	GSD
1 (A)	GeoEye-1	Urban with long shadows	0.46 PAN, 1.84 MS
2 (B)	GeoEye-1	Heterogeneous urban	0.46 PAN, 1.84 MS
3 (C)	WorldView-3	Urban and vegetated areas	0.31 PAN, 1.24 MS
4 (D)	WorldView-3	Agricultural fields and forested areas	0.31 PAN, 1.24 MS
5 (E) **6 (F)** **7 (G)**	WorldView-3 WorldView-4 WorldView-4	Dense urban Vegetation and water Urban	0.31 PAN, 1.24 MS
8 (H)	WorldView-2	Urban	0.46 PAN, 1.84 MS
9 (I)	WorldView-2	Urban with water	0.46 PAN, 1.84 MS

3. Methodology

This study aims to determine the optimal spatial resolution ratio between panchromatic (PAN) and multispectral (MS) imagery that maximizes pansharpening quality. The methodology consists of four main stages:
(1) simulation of PAN and MS degradation across multiple resolution ratios using Wald's protocol,
(2) image fusion via Gram–Schmidt, HPF and Brovey Methods.
(3) perceptual quality evaluation using the Image Decomposition-based Structural Similarity (IDSSIM) index (Yang et al., 2016), and
(4) analysis of results to identify the most effective ratio.
Figure 2 provides an overview of the complete processing pipeline, including the scale-space construction, fusion process, quality evaluation, and final ratio selection.

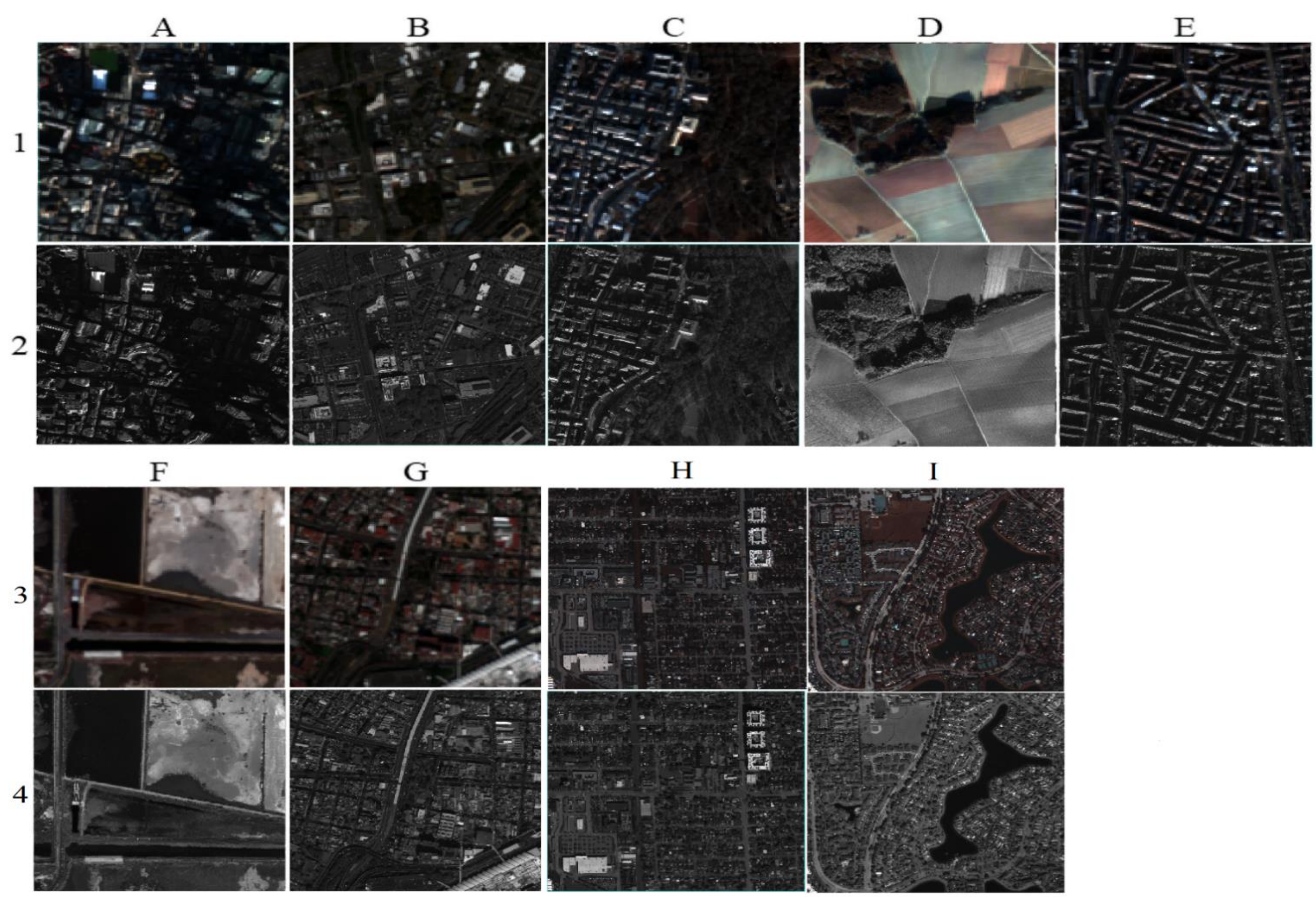


Fig. 1. Images of the 9 datasets belonging to the proposed benchmark (selected bands: red, green, and blue). First and third rows: up-sampled MS images at PAN scale; second and fourth rows: PAN images.

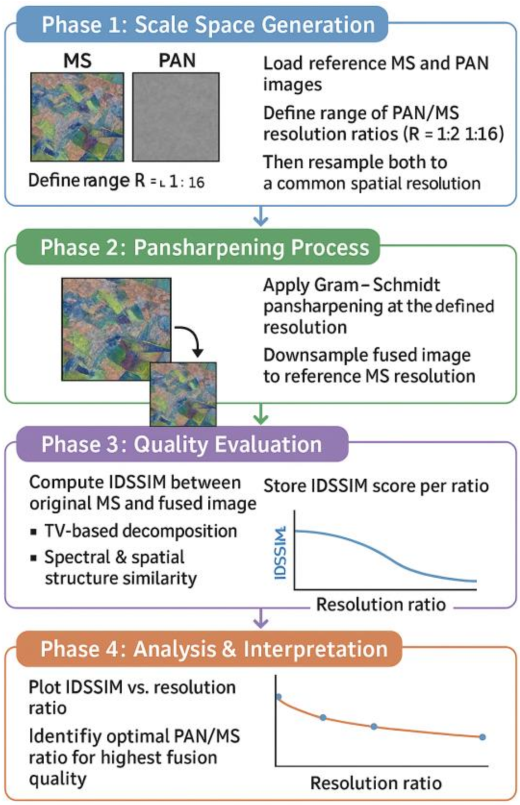


Fig 2. Overview of the proposed methodology for identifying the optimal PAN/MS resolution ratio in pansharpening.

3.1. Resolution Ratio Simulation Using Wald's Protocol

Wald's Protocol is a critical methodology used to simulate lower-resolution multispectral (MS) and panchromatic (PAN) image pairs from high-resolution imagery while maintaining geometric and radiometric consistency. This is especially important in image fusion techniques like pansharpening, where the goal is to combine the high spatial resolution of PAN images with the spectral richness of MS images. The protocol, introduced by Wald et al. (1997), involves degrading both the PAN and MS images by applying spatial filtering and resampling. These steps mimic real satellite acquisition scenarios at different spatial scales. The aim is to create synthetic, lower-resolution images that retain the essential characteristics of the original high-resolution images, ensuring that any degradation follows realistic sensor behavior. The simulated images are then used to test and benchmark pansharpening algorithms, providing a fair and controlled environment for evaluating performance across different resolution ratios (Wald et al., 1997).

The PAirMax dataset is a benchmarking collection developed by Maxar Technologies, designed to facilitate the evaluation of pansharpening algorithms. This dataset, which uses Wald's protocol for simulating various resolution ratios, consists of 14 pairs of multispectral (MS) and panchromatic (PAN) images, collected from six different satellite sensors. By applying Wald's protocol to simulate various resolution settings, the dataset provides realistic, degraded images for consistent and objective testing. It covers diverse land cover types, including urban, agricultural, and natural landscapes, providing a comprehensive testbed for pansharpening methods. Each image pair is accompanied by detailed metadata, such as sensor specifications, acquisition parameters, and scene characteristics (Vivone et al., 2021).

To evaluate the effect of spatial resolution differences on pansharpening performance, a multiscale simulation framework was developed based on Wald's protocol (Vivone et al., 2021). For each image, 15 different PAN-to-MS resolution ratios were generated, ranging from 1:2 to 1:16. This process creates a consistent and controlled set of input pairs that represent varying spatial detail levels while maintaining radiometric and geometric integrity.

Each simulated image pair was resampled to a common resolution to allow fair comparison across scales. This framework enables a robust assessment of fusion behavior over a wide range of resolution ratios using a unified reference system.

3.2. Pansharpening

The fusion process was performed using three representative methods: GS, Brovey, and HPF. These approaches cover two major categories of pansharpening techniques: component substitution (GS, Brovey) and multiresolution analysis (HPF). In GS and Brovey, spatial detail from the PAN image is injected into transformed MS components to enhance spatial resolution while preserving spectral information. In the HPF approach, high-frequency details extracted from the PAN image are combined with the MS data to sharpen edges and textures.

3.3 Image Quality Assessment Using IDSSIM

To evaluate the quality of the pansharpened images, we used the Image Decomposition-based Structural Similarity (IDSSIM) index, a full-reference metric proposed to assess perceptual image quality in fused images. IDSSIM is particularly suitable for pansharpening as it integrates both spatial structure and spectral texture in a unified evaluation framework.

The key steps in computing IDSSIM are as follows:

1. **Decomposition**: Both the fused image and the original MS image are decomposed into edge and texture components using a Total Variation (TV) flow-based

filtering scheme. This separates high-frequency details (edges) from low-frequency texture.

Given an image f, IDSSIM decomposes it into a piecewise-smooth edge/structure part f_u and a texture (fine-detail) part f_v:

$$f = f_u + f_v, f_v = f - f_u$$

The structure component f_u is obtained by a total-variation (TV) flow. Using a variational/PDE scheme, with iteration index t:

$$u^{t+1} = u^t + \mathrm{div}(g|\nabla u^t|\nabla u^t)$$

$$g(x) = \frac{1}{1+x}$$

2. **Luminance and Contrast Similarity (Texture Component)**:

Local mean and standard deviation are calculated on the texture component using a Gaussian window;

Similarity terms for luminance are computed and combined.

Let f_{v_1} and f_{v_2} denote the texture components of the reference and fused images. Using a Gaussian window, compute the local weighted mean $\mu(.)$ and standard deviation $\sigma(.)$. The luminance and contrast similarity maps are:

$$S_\mu(x) = \frac{2\mu(f_{v_1})\mu(f_{v2}) + C_1}{\mu(f_{v_1})^2 + \mu(f_{v2})^2 + C_1}$$

$$S_\sigma(x) = \frac{2\sigma(f_{v_1})\sigma(f_{v2}) + C_2}{\sigma(f_{v_1})^2 + \sigma(f_{v2})^2 + C_2}$$

The texture similarity is then:

$$TS(x) = \left[S_\mu(x)\right]^\alpha \left[S_\sigma(x)\right]^\beta$$

3. **Structural Similarity (Edge Component)**:

Gradient magnitudes are extracted from the edge maps of both images;

Structural similarity is assessed based on gradient alignment.

From the structure components f_{u_1} and f_{u_2},spatial gradients are computed with Prewitt filters:

$$G_x = \begin{pmatrix} -1 & 0 & 1 \\ -1 & 0 & 1 \\ -1 & 0 & 1 \end{pmatrix} * f, G_y = \begin{pmatrix} 1 & 1 & 1 \\ 0 & 0 & 0 \\ -1 & -1 & -1 \end{pmatrix} * f$$

and the gradient magnitude $G = \sqrt{G_x{}^2 + G_y{}^2}$ The edge similarity is:

$$ES(x) = \frac{2G_1(x)G_2(x) + C_3}{G_1(x)^2 + G_2(x)^2 + C_3}$$

4. **Fusion of Components**:

Texture-based and edge-based similarity maps are combined using weighted averaging;

The final IDSSIM score reflects overall perceptual fidelity of the fused image relative to the MS reference.

The local similarity map combines texture and edge terms:

$$S(x) = \left[TS(x)\right]^\gamma \left[ES(x)\right]^\delta$$

To reflect human visual system masking, a texture-masking map is computed as:

$$TM_m = \max(f_{v_1}(x), f_{v_2}(x))$$

The grayscale IDSSIM index is the masked average:

$$IDSSIM = \frac{\sum_{x\in\Omega} S(x)TM_m(x)}{\sum_{x\in\Omega} TM_m(x)}$$

Perceptual color consistency is incorporated by chrominance similarities on I and Q channels:

$$S_I(x) = \frac{2I_1(x)I_2(x) + C_4}{I_1(x)^2 + I_2(x)^2 + C_4}, S_Q(x) = \frac{2Q_1(x)Q_2(x) + C_5}{Q_1(x)^2 + Q_2(x)^2 + C_5}$$

The final color-aware formula is:

$$\mathrm{IDSSIM}_c = \frac{\sum_{x\in\Omega} S(x)\left[S_I(x)\right]^{\eta}\left[S_Q(x)\right]^{\varsigma} TM_m(x)}{\sum_{x\in\Omega} TM_m(x)}$$

This process is illustrated schematically in Fig. 3, which shows the flow of image decomposition, similarity computation, and score aggregation.

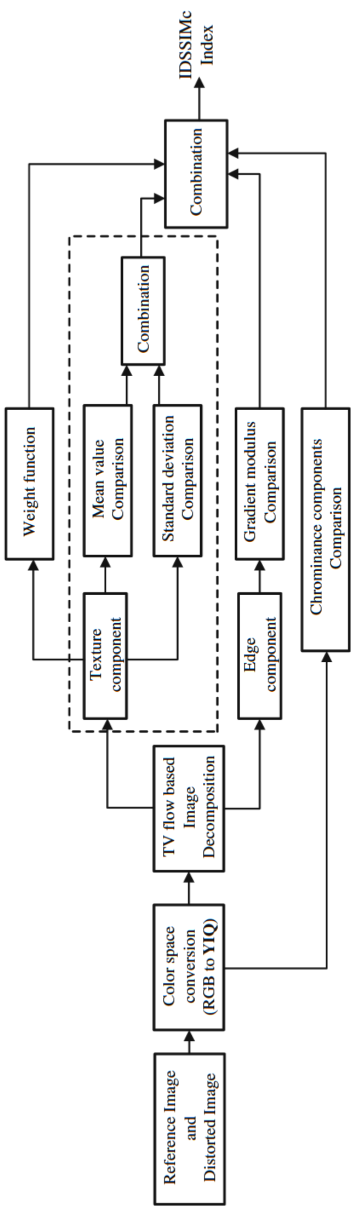


Figure 3. The framework of the proposed IDSSIM method (Yang et al., 2016).

3.4 Optimal Ratio Selection

For each of the 15 simulated PAN-to-MS resolution ratios, the corresponding IDSSIM score was computed to quantify the perceptual quality of the pansharpened image. The optimal ratio for each image pair was determined as the one yielding the highest IDSSIM value, reflecting the best trade-off between spatial enhancement and spectral fidelity. This ratio was considered the most suitable resolution configuration for that specific scene.

4. Results

The proposed fusion and evaluation framework was applied to nine high-resolution PAN–MS image pairs acquired from GeoEye-1, WorldView2, WorldView-3, and WorldView-4 satellites. These image pairs cover a broad range of land cover types, including dense urban areas, vegetated regions, agricultural fields, water bodies, and mixed environments. For each pair, fifteen different PAN/MS resolution ratios (ranging from 1:2 to 1:16) were simulated using Wald's protocol to ensure consistent and realistic degradation.

In this study, three widely used pansharpening algorithms were investigated: GS, Brovey, and HPF. Fusion quality at each ratio was evaluated using the IDSSIM index, which jointly measures spatial structure and spectral texture similarity. For each method and dataset, the IDSSIM score was recorded at all ratios, and the optimal resolution ratio was determined as the one yielding the maximum score.

Table 2 summarizes the maximum IDSSIM values and the corresponding optimal PAN/MS ratios obtained for all nine images across the three pansharpening algorithms.

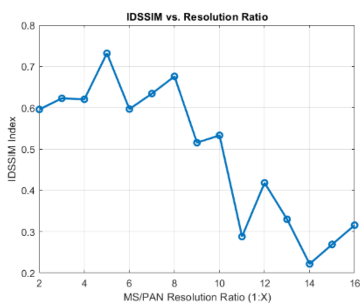
Table 2. Maximum IDSSIM Scores and Corresponding Optimal PAN/MS Resolution Ratios for All Test Images

Image NO.	Optimal Ratio (Maximum IDSSIM) Gram Schmit method	Optimal Ratio (Maximum IDSSIM) Brovey method	Optimal Ratio (Maximum IDSSIM) HPF method
1 (A)	1:5(0.79)	1:5(0.73)	1:5(0.82)
2 (B)	1:5(0.44)	1:5(0.69)	1:5(0.83)
3 (C)	1:5(0.86)	1:8(0.67)	1:4(0.83)
4 (D)	1:5(0.88)	1:5(0.63)	1:4(0.72)
5 (E)	1:5(0.89)	1:5(0.7)	1:5(0.83)
6 (F)	1:4(0.55)	1:5(0.68)	1:5(0.78)
7 (G)	1:5(0.75)	1:5(0.7)	1:4(0.72)
8(H)	1:6(0.90)	1:5(0.62)	1:5(0.79)
9(I)	1:6(0.95)	1:5(0.66)	1:4(0.78)

The results reveal several important findings. For the Gram–Schmidt method, six out of nine images reached their highest IDSSIM score at a PAN/MS ratio of 1:5, while two images peaked at 1:6 and one image at 1:4. The Brovey method showed strong consistency, with eight images achieving their maximum IDSSIM at 1:5, and one image peaking at 1:8. The HPF method exhibited a more variable behavior: five images peaked at 1:5, while the remaining four favored 1:4.

These outcomes highlight two key insights. First, despite minor variations between methods, there is a strong convergence toward moderate ratios in the range of **1:4–1:6**, indicating that this configuration provides the most effective balance between spatial enhancement and spectral fidelity across different sensors and land cover types. Second, the dominance of the 1:5 ratio—especially evident in the Brovey results and the majority of Gram–Schmidt and HPF cases—suggests that this ratio represents a robust and generalizable choice across diverse scenes, independent of algorithmic details. This reinforces the generality of the main conclusion and demonstrates that the identified trend is not specific to a single fusion technique.

To further illustrate the behavior of the IDSSIM metric across varying ratios, Figure 4 presents the results for the Brovey method as a representative case. The curves show how fusion quality evolves with changes in the PAN/MS resolution ratio from 1:2 to 1:16. Across most images, the IDSSIM score increases steadily with decreasing ratio, reaching a peak at 1:5, and then either stabilizes or slightly declines at higher ratios. In one case, however, the maximum occurred at 1:8, reflecting scene-specific sensitivity. Overall, these trends confirm that extremely low ratios (e.g., 1:2) may enhance spectral fidelity but fail to maximize spatial detail, while very high ratios (e.g., beyond 1:10) result in weak spatial injection. By contrast, a moderate ratio around 1:5 consistently offers the most favorable trade-off.



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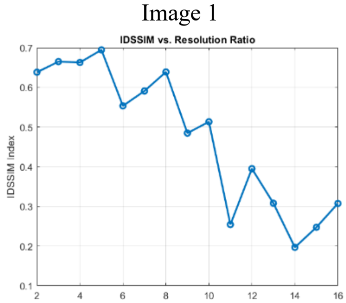

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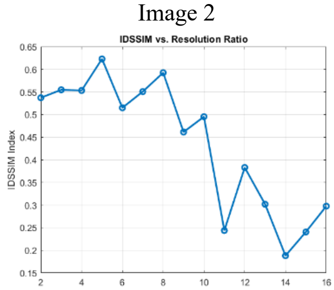

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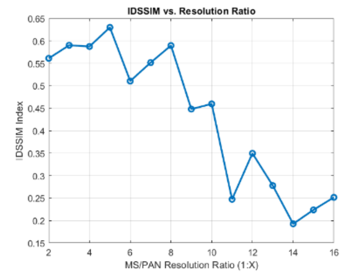

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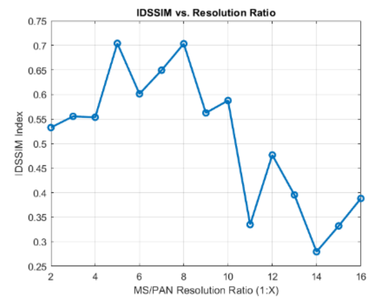

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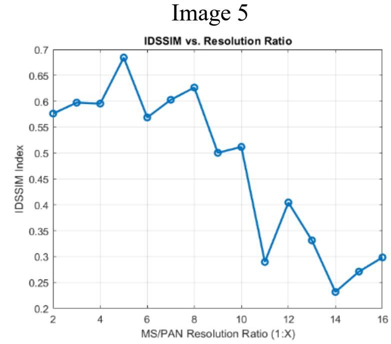

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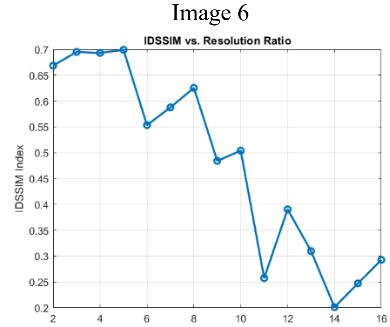

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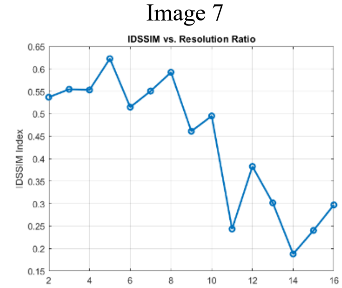

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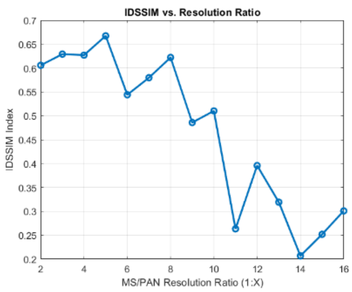


Image 9

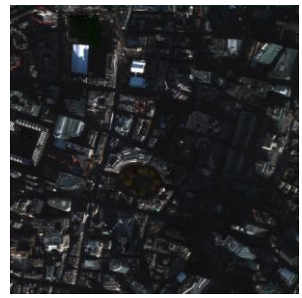
Fig 4. IDSSIM score versus PAN/MS resolution ratio for all nine image pairs. Each plot illustrates the fusion quality trend across 15 simulated ratios (1:2 to 1:16), highlighting the optimal resolution point per image.

The results exhibit consistent patterns across diverse image types and fusion algorithms:

- **Very low ratios (e.g., near 1:2)** may yield improved spectral fidelity but often result in reduced spatial enhancement, limiting the overall perceptual quality of the fused outputs.
- **Very high ratios (e.g., 1:10 and beyond)** tend to suffer from poor injection of spatial detail, leading to blurred edges and declining perceptual performance.
- **Moderate ratios in the range of 1:4 to 1:6** consistently delivered the highest IDSSIM scores across most datasets and methods, indicating an effective trade-off between preserving spatial edges and maintaining spectral integrity. In particular, the ratio of **1:5** emerged as the most frequent optimum, observed in the majority of cases for Gram–Schmidt, Brovey, and HPF.

These findings suggest that selecting a PAN/MS resolution ratio around **1:5** provides optimal perceptual quality for pansharpening tasks across a variety of land cover types, satellite sensors, and fusion algorithms. At the same time, the presence of a few cases with optimal ratios of 1:4, 1:6, or 1:8 highlights the role of scene-specific characteristics, such as texture complexity and spectral diversity, in influencing the exact optimum.

To complement the quantitative analysis, visual inspection of the pansharpened outputs was conducted. For each of the nine test scenes, the fused image generated at the optimal PAN/MS resolution ratio (as determined by the highest IDSSIM score) is displayed. These visual examples allow assessment of spatial sharpness, spectral consistency, and overall perceptual quality, providing additional insight into the performance of the proposed methodology under different land cover conditions and scene complexities.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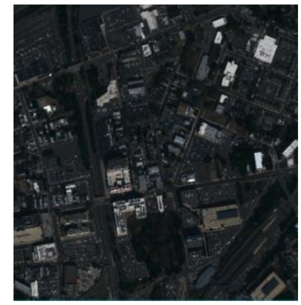
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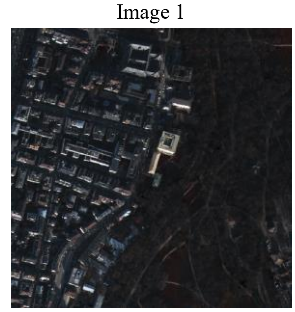
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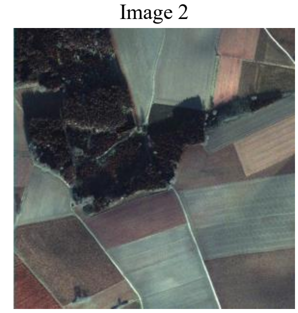
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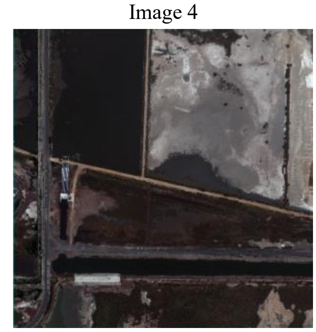
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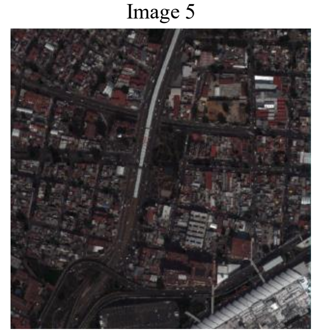
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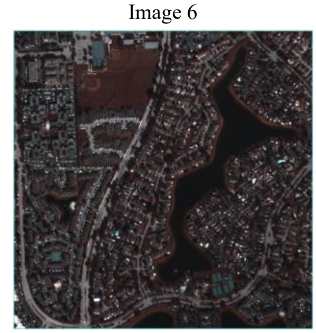
Image 8


Image 9

Fig. 5. Pansharpened outputs for the nine test images at their respective optimal PAN/MS resolution ratios using

the Gram–Schmidt method. Each subfigure shows the fusion result at the IDSSIM-maximizing ratio, visually illustrating spatial clarity and spectral fidelity across diverse land cover types.

5. Discussion

The results provide a broad perspective on how the PAN-to-MS resolution ratio influences pansharpening quality across different datasets, land cover types, and algorithms. By examining 15 ratios (from 1:2 to 1:16) on nine image pairs with three representative methods—Gram–Schmidt, Brovey, and High-Pass Filtering (HPF)—a consistent trend emerged: moderate ratios between 1:4 and 1:6 generally offered the most balanced outcomes.

For Gram–Schmidt, six images achieved their best performance at 1:5, while two peaked at 1:6 and one at 1:4. Brovey showed even stronger consistency, with eight images converging at 1:5 and one at 1:8. HPF results were more variable, with five cases favoring 1:5 and four cases 1:4. Despite these differences, the repeated appearance of 1:5 across methods indicates that it is a strong candidate for a general optimum.

The analysis also highlights the risks of extreme ratios. Very low ratios (e.g., 1:2 or 1:3) tend to preserve spectral content but often introduce artifacts or weaken spatial enhancement, particularly in complex environments such as vegetation or water. At the other end, very high ratios (beyond 1:10) inject too little spatial detail, leading to blurred edges and reduced perceptual quality. Moderate ratios consistently provided a more favorable trade-off, yielding sharper structural detail without compromising spectral integrity.

Scene characteristics influenced the exact optimum. Homogeneous textures and large-scale patterns, as in agricultural or forested areas, sometimes benefited from ratios closer to 1:6. Mixed urban or urban–water scenes were more sensitive, occasionally shifting the optimum toward 1:4 or even 1:8. This confirms that the best ratio is not universal but context-dependent.

Overall, these findings suggest that the PAN/MS ratio should not be regarded as a fixed property of a sensor. Instead, it is a tunable parameter that can be adapted to application needs or acquisition conditions. The study also underlines that data configuration is as important as the choice of fusion algorithm. While previous research has mostly emphasized algorithm design, our results demonstrate that careful adjustment of resolution ratios alone can substantially improve fusion quality. This provides valuable guidance for both operational workflows, where ratio tuning may be integrated into processing pipelines, and sensor design, where ratio selection could be optimized for future missions.

6. Conclusion

This study examined the effect of PAN-to-MS resolution ratios on pansharpening quality using three widely applied methods: Gram–Schmidt, Brovey, and High-Pass Filtering (HPF). Nine high-resolution image pairs from GeoEye-1, WorldView-3, and WorldView-4 were analyzed under 15 simulated ratios (1:2 to 1:16) generated with Wald’s protocol. Fusion quality was consistently measured with the IDSSIM index.

Across algorithms and datasets, moderate ratios between 1:4 and 1:6 provided the most favorable trade-off between spatial enhancement and spectral preservation. Among these, the ratio of 1:5 appeared most often as the optimum, although exceptions occurred in specific cases (e.g., 1:6 for some Gram–Schmidt results, or 1:8 for one Brovey case). This variability reflects the role of scene characteristics, including textural complexity and spectral diversity.

These findings emphasize that pansharpening performance depends not only on algorithm choice but also on the spatial configuration of input data. Treating the PAN/MS ratio as a flexible parameter, rather than a fixed sensor property, opens opportunities for both improved operational fusion workflows and future sensor design.

In summary, a ratio close to 1:5 consistently delivered strong results across methods, sensors, and land cover types. Beyond confirming this trend, the study contributes practical recommendations for fusion practice and highlights the importance of resolution ratio as a design parameter. Future research may extend this framework by incorporating additional fusion techniques, expanding the range of geographic test sites, and exploring adaptive strategies such as machine learning for context-aware ratio selection.

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