NEW CONCEPTS AND ADVANCED STUDIES IN AGRICULTURE, FOREST AND WATER ISSUES

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Editor

Prof. Dr. NİGAR YARPUZ BOZDOĞAN

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Pansharpening Techniques in Remote Sensing: A Comprehensive Review of Methods, Applications and Advances

Selçuk ALBUT [1]

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INTRODUCTION

Pansharpening resolves the enduring trade-off in remote sensing between spatial resolution and spectral fidelity. Contemporary satellites like Landsat-8, Sentinel-2, and WorldView-3 deliver high-quality data, however frequently lack both features concurrently. Over the past two decades, researchers have suggested numerous fusion strategies. Recent advancements indicate substantial enhancements through the utilisation of AI-based models (Ciotola et al., 2022:60; Xu et al., 2023:31; Li et al., 2025:185).

The accessibility of high-resolution imaging facilitates applications in agricultural, urban surveillance, hydrology, forestry, and disaster response. Nonetheless, obstacles persist in refining techniques that enhance performance while maintaining computational economy.

The swift advancement of satellite sensors has led to the extensive utilisation of remote sensing images. Nevertheless, owing to the technical constraints of the sensors and other variables, current remote sensing instruments must engage in a basic trade-off between spatial and spectral resolutions (Fletcher, 2023:1206, Restaino, 2025:16). There are two primary constraints. The radiation energy received by the sensor. The high spatial resolution (HR) panchromatic (PAN) image possesses a greater bandwidth, whereas the low spatial resolution (LR) multispectral (MS) image exhibits a smaller bandwidth. To enhance photon collection and optimise the signal-to-noise ratio (SNR), the dimensions of the MS detector must be increased, resulting in a bigger instantaneous field of view (IFOV) and consequently a reduced spatial resolution. The volume of data gathered by the sensor. The data capacity of the HR MS image is considerably more than that of the combined LR MS and HR PAN images. Consequently, this can surmount the challenge of restricted on-board storage capacity and the data transmission from the platform to the ground. PAN/MS image fusion, commonly known as "pansharpening," integrates the geometric detail of the high-resolution PAN image with the spectral information of the low-resolution MS image to produce a high-resolution MS image, effectively addressing the tradeoff between spatial and spectral resolutions of satellite sensors (Kaur et al., 2021:4961; Shen et al., 2016:7135; Aiazzi et al., 2012:533; Ghassemian, 2016:32; Zhang et al., 2024:943).

In the domains of GIS (Geographic Information Systems) and Remote Sensing, pan-sharpening is a crucial technique employed to enhance the resolution of images captured from satellite or aerial platforms. This technique often involves the integration of multispectral images with low spatial resolution with panchromatic images with high spatial resolution. This amalgamation produces a novel image that encompasses both elevated spatial and spectrum information (Kaur, et al., 2024:980).

The significance of panoramic sharpening, or pan-sharpening, can be summarised as follows.

- Comprehensive Examination: Pan-sharpening enhances the spatial resolution of photographs, facilitating better and more detailed study of terrestrial objects. This is particularly vital in domains such as urban planning, agriculture, and environmental monitoring.
- Conservation of Spectral Data: The pan-sharpening procedure maintains the colour and spectral attributes of multispectral data, yielding spatially enhanced images. This mitigates misinterpretations in applications such as environmental assessments and vegetation surveys.
- Enhanced Efficiency and Precision: Images produced through pan-sharpening facilitate more accurate classification and object detection. This presents a significant advantage, particularly in search and rescue missions as well as military operations.
- Reduced Data Storage and Processing Burden: Images with great spatial resolution are typically huge in size. Pan-sharpening integrates lower-resolution multispectral data with high-resolution panchromatic data to produce detailed information while minimising storage requirements and processing power.
- Enhancing Image Interpretation Skills: It enables the disaggregation of various land types, particularly metropolitan regions, agricultural land, or forest ecosystems. For instance, edifices, thoroughfares, or arable land become more conspicuous.

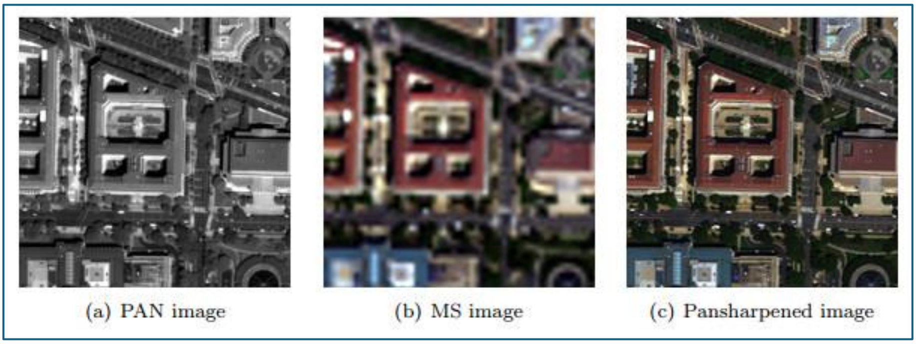

Figure 1: An example of pansharpening (Zhang et al., 2024:943)

Applications of Pansharpening

The pansharpening procedure enhances spectral and spatial detail by integrating high-resolution panchromatic (PAN) images with low-resolution multispectral (MS) images. This procedure is utilised in various domains. Pansharpening enhances both spectral and spatial information by merging high-resolution panchromatic (PAN) images with low-resolution multispectral (MS) images. This procedure is utilised across various domains (Yang et al., 2023:16857; Bandara and Patel, 2022:1767; Wang, 2023:2311; Zhang et al., 2024:943). The primary applications of the pansharpening technique are as follows:

Assessment of Agricultural Zones and Product Monitoring:

- Land Use/Land Cover Mapping (LULC) is employed to identify many categories of land use, including agriculture, forestry, aquatic surfaces, and urban regions.
- Identification of Agricultural Zones and Product Monitoring: Thrace is a significant agricultural region in Turkey. Multispectral pictures are utilised to identify regions of agricultural crops including wheat, sunflower, maize and grapes. Nevertheless, due to the frequently low resolution of these multispectral images, product classification can be enhanced by augmenting the detail using Pan-sharpening.
- The Normalised Difference Vegetation Index (NDVI) can be estimated with greater accuracy using pan-sharpened pictures.
- Agriculture and Vegetation Analysis: This methodology is employed to identify crop varieties in agricultural terrains, monitor crop health, and facilitate precision agriculture initiatives.

Urban Planning and Land Management: High-precision maps can be generated through their application in urbanisation, infrastructure initiatives, and construction assessments. Satellite imagery enables the monitoring of urbanization's progression over time, as well as alterations in agricultural land and forested regions. Pan-sharpening enhances the clarity of features such as new constructions, roadways, and industrial zones.

Natural Resource Management and Environmental Monitoring: It is utilised for the surveillance of forest regions, the analysis of watersheds, and the prolonged observation of environmental alterations. Pan-sharpened satellite imagery enables more precise monitoring of characteristics such as water levels, vegetation alterations, and coastline shifts in critical wetlands. High-resolution photos acquired using pan-sharpening offer significant benefits for monitoring deforestation, assessing post-fire recovery, and identifying illicit logging activities.

Disaster Management and Risk Assessment: Pan-sharpening yields clear images for the analysis of natural disaster impacts, including earthquakes, floods, and fires, facilitating the creation of risk maps.

Examination of Industrial and Environmental Impacts: Industrial facilities are proliferating swiftly in numerous agricultural regions. Comprehensive analysis of images is required to assess aspects such as the proliferation of industrial zones, its effects on agricultural regions, and environmental contamination. Pan-sharpening enhances the detection of items such as industries, waste sites, and sources of smoke or water pollution.

Pansharping Data

Pansharpening is the technique of augmenting the spatial resolution of multispectral images through the integration with a higher-resolution panchromatic image. Table 1 summarises prominent global satellite systems that feature "panchromatic" (PAN) and "multispectral" (MS) bands, facilitating both imaging modalities. (Aiazzi, et al., 2012:533, Fasbender, et al., 2008:1847, Alparone, et al., 2007:3012, Zhou, et.al., 2022:274, Guan, et.al., 2023:6860, NİK System, 2025).

Table 1. Example Satellite Sensors Used in Pansharpening

Satellite	PAN Resolution	MS Resolution	Number of MS Bands	Countries & Organizations Name
DEIMOS-2	1 m	4 m	4	European technology group
GÖKTÜRK-2	2.5 m	5 m	4	Turkiye
CARTOSAT-3	0.25	1.14	4	Indian Space Research Organisation (ISRO)
Landsat-8 OLI	15 m	30 m	11	NASA & USGS (U.S. Geological Survey)
WorldView-2	0.46 m	1.84 m	8	DigitalGlobe / Maxar
WorldView-3/4	0.31 m	1.24 m	8	Maxar
GeoEye-1	~0.41 m	1.65–1.84 m	4	Maxar
Pléiades 1A/1B	0.5 m	2 m	4	Airbus
Pléiades Neo	0.3 m	1.2 m	4	Airbus
SPOT 6/7	~1.5 m	6 m	4	Airbus
Ikonos	~0.8 m	~3.28 m	4	
SkySat, SuperView-1	0.5 m	2 m	4	Beijing Space View
Kompsat-3A	0.55 m	2.2 m	4	KARI, South Korea

TripleSat	0.8 m	3.2 m	4	SSTL
Jilin-1	0.72 m	2.88 m	4	Chang Guang, China
Alsat-1B	12 m	24 m	4	Algeria
KhalifaSat	0.7 m	2.98 m	4	UAE
Kanopus-V-IK	2.7 m	12 m	4	Russia

Pansharpening seeks to integrate spatial features from PAN images with the spectral richness of MS images. Panchromatic (PAN): High-resolution, monochromatic greyscale imaging. Multispectral (MS): Several lower-resolution bands that capture distinct wavelength ranges. The data utilised in the pansharpening procedure often comprises:

Panchromatic Image (PAN)

A panchromatic image is a monochromatic greyscale image obtained by a sensor that detects a broad spectrum of wavelengths, usually encompassing the entire visible spectrum and occasionally reaching into the near-infrared range. The term "panchromatic" derives from the Greek words "pan" (meaning "all") and "chromatic" (meaning "colour"), signifying that the sensor captures light over the whole visible spectrum.

Panchromatic images provide superior spatial resolution due to the sensor's ability to capture light across a wide wavelength spectrum, facilitating greater detail than multispectral images. Satellites such as WorldView-3 and Landsat offer panchromatic images with resolutions ranging from 30 cm to 15 meters, contingent upon the sensor employed.

Panchromatic images, in contrast to multispectral images that capture various bands (e.g., red, green, blue, near-infrared), are single-band and depict the intensity of light across their whole sensitive wavelength range.

Panchromatic sensors often encompass a wide spectrum of wavelengths, typically ranging from approximately 450 nm (blue) to 800 nm (near-infrared), but this may differ based on the specific sensor. Panchromatic photographs, being single-band, are rendered in greyscale, with pixel values indicating the strength of light reflected from the surface. Panchromatic photos are frequently combined with lower-resolution multispectral images to produce high-resolution colour images. The elevated spatial resolution renders panchromatic images optimal for discerning intricate elements, including edifices, thoroughfares, and other infrastructure. Panchromatic photographs are valuable for tracking temporal changes, such as urban expansion or deforestation, owing to their great resolution. They are employed in disaster response to evaluate damage with great accuracy.

A panchromatic image is a high-resolution, single-band image that encompasses a broad spectrum of wavelengths, rendering it essential for intricate spatial analysis and as a constituent in pansharpening techniques.

Multispectral Image (MS)

Multispectral imaging is a method that enables the capture of images of an item or surface at many wavelengths, typically including visible light, near-infrared, and mid-infrared. This technique is employed to disclose information that is imperceptible to the unaided eye.

A multispectral image comprises a series of images obtained at various wavelengths of the electromagnetic spectrum, typically encompassing both visible and non-visible light, including infrared and ultraviolet. In contrast to conventional RGB images that solely capture red, green, and blue light, multispectral imaging encompasses a broader range of wavelengths, offering enhanced information regarding the scene or item being scanned.

The resolutions of multispectral images from various satellites differ based on the capabilities of their sensors and their designated applications (Alcaras, 2023:93).

The multispectral resolutions of some significant remote sensing satellites are as follows:

Resolution, band quantity, and observation frequency are essential criteria in satellite selection. Satellite data must be picked based on the intended application.

- Landsat and Sentinel-2 are utilised for the surveillance of extensive regions at medium resolution.
- WorldView-3 and GeoEye-1 are proficient in high-resolution urban and environmental assessment.
- The SPOT-6/7 and PlanetScope are appropriate for commercial and agricultural monitoring.
- MODIS is employed to observe extensive alterations in the atmosphere, ocean, and terrestrial surface.

Panchromatic images are excellent for comprehensive structural investigation owing to their high resolution, although they lack spectrum information. Multispectral images offer significant spectral information for material separation, but at reduced spatial resolution.

To achieve optimal results, both images are frequently amalgamated (pan-sharpening) to produce high-resolution multispectral images.

Table 2: Comparison of Panchromatic and Multispectral Images

Feature	Panchromatic Image	Multispectral Image |
Definition	Acquires an image in a singular, extensive spectral band, typically in greyscale (monochrome).	Acquires images over various designated spectral bands (e.g., Red, Green, Blue, Near-Infrared, etc.).
Spectral Range	Encompasses a wide array of wavelengths, typically within the visible spectrum.	Encompasses various distinct wavelength bands, including visible and infrared spectra.
Resolution	Elevated spatial resolution resulting from extensive bandwidth, yielding intricate visuals.	Inferior spatial resolution relative to panchromatic images, although possessing more extensive spectral information.
Color Information	Devoid of colour and spectral distinction.	Offers colour and spectral information, essential for material differentiation.
Applications	Optimal for high-resolution mapping, edge detection, and terrain analysis.	Utilised in vegetation analysis, water quality evaluation, land cover categorisation, and remote sensing.

In certain conditions, supplementary data may be utilised alongside panchromatic and multispectral satellite imagery in pansharpening applications. These;

Hyperspectral Data (Optional): Hyperspectral data, when accessible, can offer enhanced spectral information for sophisticated pansharpening methods.

Digital Elevation Model (DEM): Occasionally employed to enhance geometric rectification and spatial alignment during the fusion process.

Radiometric Calibration Data: Metadata pertaining to the sensor, atmospheric corrections, and radiometric calibration to guarantee precise fusion.

Ground Truth or Reference Data: High-resolution reference images or field data for validation and accuracy evaluation.

PANSHARPENING TECHNIQUES

A substantial variety of pan-sharpening techniques have been documented in the literature to far. Upon examination of these approaches, it is observed that they typically preserve either the spectral structure or the spatial detail content. Consequently, it is infeasible to discuss 'the optimal pansharpening method.

An examination of the current literature reveals the absence of a standardised classification for pan-sharpening methods. Due to the varying criteria employed for classification, it is typical for the identical pan-sharpening method to be categorised differently across various studies. Traditional pan-sharpening techniques in the literature were analysed under four categories: component substitution-based, multi-resolution analysis-based, color-based, and hybrid methods. Modern methods encompass morphology-based, sparse representation-based, deep learning-based, and metaheuristic optimization-based approaches (Şerifoğlu Yilmaz, Ç., et al., 2021:1340).

Pansharpening is a conventional method for amalgamating the spatial elements of a high-resolution panchromatic image with the spectrum information of a low-resolution multispectral image to generate a high-resolution multispectral image. A multitude of pan-sharpening techniques has been established (Du, 2007:518; Zhang, 2024:657; Garzelli et al., 2008:81; Pohl and Van Genderen, 1998:823). Pansharpening techniques are primarily classified into four categories: Component Substitution (CS), Multi-Resolution Analysis (MRA), Model-Based/Hybrid Approaches, and Deep Learning-driven methods (Kamala et al., 2024:1; Meng et al., 2019:102; Deng et al., 2021:6995; Ozcelik et al., 2021:3486).

The CS and MRA methodologies are crucial in the field of pansharpening. They have demonstrated commendable performance with an equitable computational load. The CS-based techniques depend on the principle of projecting the MS image into an alternative domain, wherein the spatial information may be readily distinguished into a component, typically referred to as the intensity component. The (potentially equalised) PAN image may be replaced with the intensity component. The enhanced form of the MS image is achieved using inverse projection, restoring the data to its original MS domain. CS-based approaches can produce results with excellent spatial fidelity, often at the expense of increased spectrum distortion. Notable examples of methods in this category include band-dependent spatial-detail (BDSD) with local parameter estimation, the robust BDSD-PC method, partial replacement adaptive component substitution (PRACS), and Gram–Schmidt (GS) spectral sharpening (Garzelli et al., 2008: 228; Vivone, 2019: 6421; Choi et al., 2011: 295; Laben and Brower, 2000; Adelwhab and Cherifa, 2025: 517).

MRA-based methodologies incorporate spatial features derived from the PAN image using an MRA framework into the MS image to achieve a high spatial resolution MS image. MRA-based devices retain spectral information but may experience spatial distortion. Examples of methods in this category include the smoothing filter-based intensity modulation (SFIM) and the additive wavelet luminance proportional (AWLP). The "à-trous" wavelet transform, the Laplacian pyramid (LP), the generalised Laplacian pyramid (GLP), the GLP with robust regression, and the GLP with full-scale regression (GLP-Reg) (Deng et al., 2021:6995; Ozcelik et al., 2021:3486; Liu, 2000:3461; Otazu et al., 2005:2376; Shensa, 1992:2464; Burt and Adelson, 1983:532).

Recently, VO methodologies have demonstrated competitive efficacy in resolving the pansharpening challenge. This class encompasses Bayesian methods, variational approaches, and compressed sensing techniques. Notwithstanding their formal mathematical sophistication, VO methodologies yield only marginal enhancements relative to the state-of-the-art CS and MRA techniques; such enhancements entail significant computational demands and necessitate extensive parameter tuning, elucidating the prevalent endorsement of CS and MRA for both benchmarking and practical applications (Jiang, et al., 2015:540, Duran, et al., 2014:761, Fang, et al., 2013:2822, Wang, et al., 2019:227, He, et al., 2014:4160).

The CNN-based approaches rely on extensive dataset training to acquire a nonlinear functional mapping between low spatial resolution multispectral (MS) pictures and high spatial resolution MS images (Deng et al., 2021:6995; Yang et al., 2017:5449; Huang et al., 2015:1037; Xie et al., 2020).

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