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Research on Optimizing the Orthorectification Workflow for Large-Scale Remote Sensing Datasets using the Pixel Factory System

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***Abstract*— This research aims to assess and optimize the processing workflow for massive SPOT6 remote sensing data blocks utilizing the Pixel Factory (PF) high-performance system, a dedicated platform designed for automated, parallel processing at scale. The procedure entails data standardization, block bundle adjustment, orthorectification, image mosaicking, and ortho-map generation. Experimental datasets comprised 10 SPOT6 strips (1.5m PAN and 6m MS), 123 Ground Control Points (GCPs) stratified into various test configurations, and Digital Elevation Models (DEMs) at three distinct resolutions (20m, 30m, and 40m). Findings indicate that the PF system substantially minimizes the requisite number of GCPs to merely 4–6 points per scene, without compromising adherence to technical accuracy regulations. Specifically, the 20m DEM provided optimal accuracy suitable for 1:10,000 scale mapping, while the 30–40m DEMs proved adequate for smaller-scale cartography. Furthermore, the pansharpening process employing the Color Normalization algorithm demonstrated superior spectral fidelity, thereby facilitating AI-driven applications and thematic analysis. Conclusively, the study validates the PF system as a robust solution for handling large-scale remote sensing data, effectively curtailing production time while augmenting product consistency.**

Keywords: Pixel Factory, Large-scale Remote Sensing, Orthorectification, SPOT 6, Workflow Optimization, High-Performance Computing (HPC).

I. INTRODUCTION

In recent years, the rapid advancement of optical remote sensing technology has led to continuous improvements in the spatial resolution of satellite data, accompanied by a substantial increase in daily acquisition volumes. This surge in data imposes an urgent demand for enhanced data processing capabilities, particularly for large-scale projects such as orthophoto generation over extensive areas [7]. The SPOT 6 remote sensing satellite, featuring high spatial resolution (1.5m) and agile data acquisition capabilities, provides high-quality imagery serving various domains, including natural resource monitoring, agriculture, environmental management, and urban planning [8]. However, the massive data volume associated with SPOT 6 imagery presents significant challenges to traditional processing workflows, which are typically time-intensive and prone to error due to manual intervention [9].

To address this necessity, numerous automated and semi-automated image processing solutions have been developed. Among these, High-Performance Computing (HPC) systems represent a specialized platform for large-scale remote sensing image processing. By supporting parallel processing across multiple servers, HPC systems significantly reduce processing time while ensuring the consistency and accuracy of output products [2]. The application of HPC systems in processing high-resolution remote sensing imagery differs fundamentally from traditional software solutions, which typically rely on standalone workstations.

The objective of this paper is to research, analyze, and evaluate the optimization of both the processing workflow and input parameters—specifically the number of Ground Control Points (GCPs) and Digital Elevation Model (DEM) resolution—to enhance economic efficiency in the application of HPC systems.

II. STUDY AREA

A. Selecting a Template (Heading 2)

The research focuses on a specific geographic region in Northern Vietnam, delineated by the solid black polygonal boundary in Figure 1. This Area of Interest (AOI) represents a substantial block of the Northeastern region (Dong Bac) and the Red River Delta, selected to evaluate the processing capabilities of the Pixel Factory system over a spatially heterogeneous landscape.

Geographically, the study block encompasses a diverse range of administrative jurisdictions. It extends from the major urban and economic centers in the south—specifically the capital city of Hanoi, the port city of Hai Phong, and Bac Ninh province—moving eastward to the coastal province of Quang Ninh, and stretching northward through Thai Nguyen and Lang Son, reaching up to the high-latitude border province of Cao Bang adjacent to China.

Topographically, the area exhibits significant relief variation, which is critical for assessing orthorectification accuracy and Digital Elevation Model (DEM) quality. As

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illustrated by the elevation color scale (where green indicates lowlands and yellow/orange indicates highlands), the terrain transitions from the flat, low-lying alluvial plains of the Red River Delta and the coastal zones of the East Sea (Biển Đông) in the southeast, to the rugged, complex mountainous terrain in the north and northwest.

This topographic heterogeneity—ranging from near-sea-level deltaic zones to high-altitude mountainous areas—presents a comprehensive test environment. The inclusion of both dense urban infrastructure (in Hanoi and Hai Phong) and complex natural topography (in Lang Son and Cao Bang) allows the study to rigorously validate the optimization of Ground Control Points (GCPs) and processing parameters across different terrain types and land cover classes.

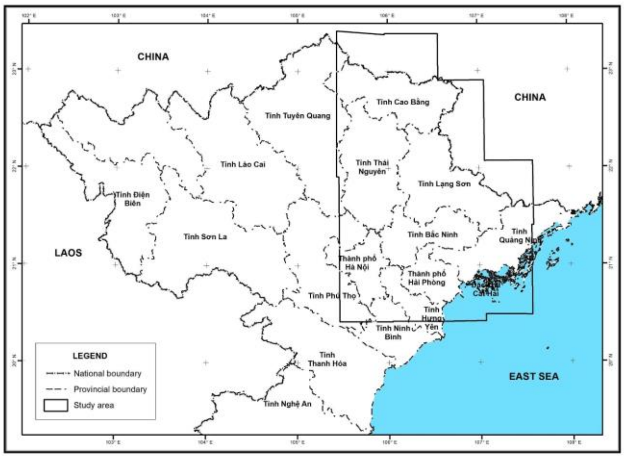

Fig. 1. Study area

III. METHODOLOGY AND DATA ACQUISITION

A. *Workflow and Remote Sensing Data Processing Methods*

The workflow for processing remote sensing data using the Pixel Factory (PF) system in this study is designed as a fully automated pipeline, spanning from the initial data preparation phase to the generation of complete digital orthophotos (Figure 2).

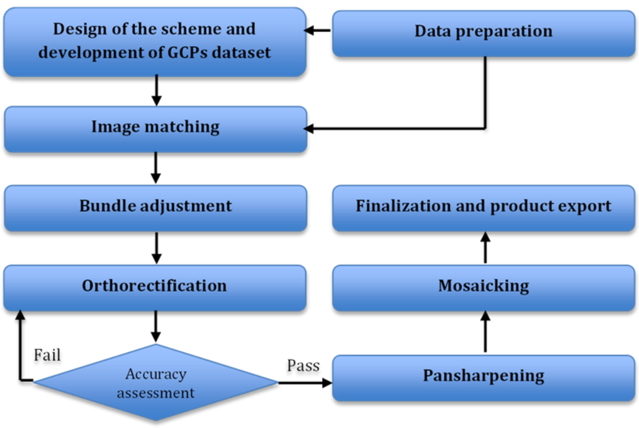

Fig. 2. Workflow

The primary stages include:

1) *Data Preparation:*

Remote sensing data is ingested in its raw format accompanied by metadata, which includes orbital parameters, sensor models, and essential geometric processing information. All data is imported into the PF input data manager for integrity verification and classification by scene or image strip. In addition to the SPOT 6 imagery, the data preparation phase involves the organization of three distinct Digital Elevation Model (DEM) datasets at varying resolutions and three Ground Control Point (GCP) datasets with differing point densities for experimental testing.

2) *GCP Network Design and Acquisition*

Ground Control Points (GCPs) were sourced from existing geodetic databases, large-scale topographic maps, or direct field surveys, ensuring a rational and uniform distribution across the entire processing area. GCPs play a critical role in enhancing the geometric accuracy of the final orthophotos. The density (quantity) of GCPs is directly correlated with the resulting geometric rectification accuracy.

3) *Block Adjustment*

Utilizing the satellite physical sensor model and the input GCPs, the system performs Block Adjustment to minimize geometric deviations between individual scenes or strips and to optimize the exterior orientation parameters. This process ensures precise alignment during the subsequent mosaicking phase.

- Accuracy Standards: The results of the block triangulation are evaluated in compliance with Article 21, Clause 3 of Circular No. 10/2015/TT-BTNMT [1]. This regulation stipulates that the planimetric residual of control points after adjustment, relative to the nearest GPS control points, must not exceed 0.5 pixels. For areas with occlusions or shadows, the error tolerance is extended to 1.0 pixel.

4) *Orthorectification*

Following block adjustment, the image data is combined with the Digital Elevation Models (DEMs) and subjected to orthorectification. This process removes terrain-induced distortions and corrects pixel positions to their true ground coordinates. During this stage, experiments were conducted using the varying DEM resolutions and GCP configurations prepared in step (1).

- Quality Assessment: The quality of the orthorectified product is assessed based on Article 22, Point 4 of Circular No. 10/2015/TT-BTNMT [1]. The standards mandate that the mean positional displacement of identifiable features on the orthophoto, compared to the base map, must not exceed 0.4 mm for distinct features and 0.6 mm for indistinct features (calculated at map scale). Furthermore, edge matching errors between adjacent rectified scenes must not exceed 0.7 mm for flat terrain and 1.0 mm for mountainous terrain (at map scale).

5) *Pansharpening (Image Fusion)*

The Pixel Factory system executes pansharpening by fusing high-resolution panchromatic (PAN) imagery with lower-resolution multispectral (MS) bands. This process generates high-resolution multispectral imagery that retains original spectral information while significantly enhancing spatial detail. The system offers three primary methods for this fusion:

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Color Normalize Method: This technique minimizes spectral and brightness discrepancies between the PAN and MS bands prior to fusion, thereby effectively preserving color balance [3].

Standard Mode: Serving as the default setting, this method provides an optimal trade-off between spatial sharpness and spectral fidelity [4].

Auto Method: This mode automatically selects the most suitable algorithm and processing parameters based on intrinsic image characteristics (e.g., spectrum, Signal-to-Noise Ratio (SNR), texture, and Modulation Transfer Function (MTF)), eliminating the need for manual calibration by the user [5][6].

6) Image Mosaicking

The orthorectified image strips are stitched together to form a seamless image block covering the entire study area. To ensure radiometric uniformity and visual continuity, the PF system employs advanced algorithms for color balancing, automatic seamline detection, and feathering (blending). These processes effectively mitigate brightness variations and visible edges between adjacent strips.

7) Product Export

The final mosaic is tiled and formatted into digital orthophoto maps. These products are exported in standard raster formats (e.g., GeoTIFF), accompanied by comprehensive metadata, rendering them immediately compatible with Geographic Information Systems (GIS) and ready for subsequent thematic analysis.

B. *Experimental Data*

To conduct the experiments, the study utilized the following datasets:

- Remote Sensing Imagery: The dataset comprises 10 strips of SPOT 6 satellite imagery acquired during the 2024–2025 period. Each strip consists of a Panchromatic (PAN) band with a spatial resolution of 1.5m and four Multispectral (MS) bands (Blue, Green, Red, and Near-Infrared) with a spatial resolution of 6m (Table 1).

TABLE I. SPECIFICATIONS OF SPOT 6 IMAGERY AND GROUND CONTROL POINTS (GCPS) USED IN THE STUDY

No.	Scene/Strip ID	Acquisition Date	GCPs (Control/ Check)
1	SPOT6_202412220319370	22/12/2024	08/02
2	SPOT6_202501120308590	12/01/2025	08/02
3	SPOT6_202404270306114	27/04/2024	10/02
4	SPOT6_202501120308324	12/01/2025	07/02
5	SPOT6_202501120309222	12/01/2025	12/03
6	SPOT6_202410070305450	07/10/2024	12/03
7	SPOT6_202410070305214	07/10/2024	12/02
8	SPOT6_202410260309134	09/11/2024	07/02
9	SPOT6_202410070303504	07/10/2024	07/02
10	SPOT6_202411090301502	09/11/2024	08/02

- Ground Control Points (GCPs): A total of 123 GCPs were employed within the study area. Of these, 91 points served as Ground Control Points (for orthorectification) and 22 points served as Independent Check Points (ICPs) for accuracy validation (Table 1). The GCPs were uniformly distributed across the experimental area and were categorized into three distinct subsets for testing: configurations of 4, 6, and 9 GCPs per scene.

- Digital Elevation Models (DEMs): To evaluate the impact of elevation data quality, DEMs with varying spatial resolutions were utilized, specifically: 20m, 30m, and 40m (Figure 3).

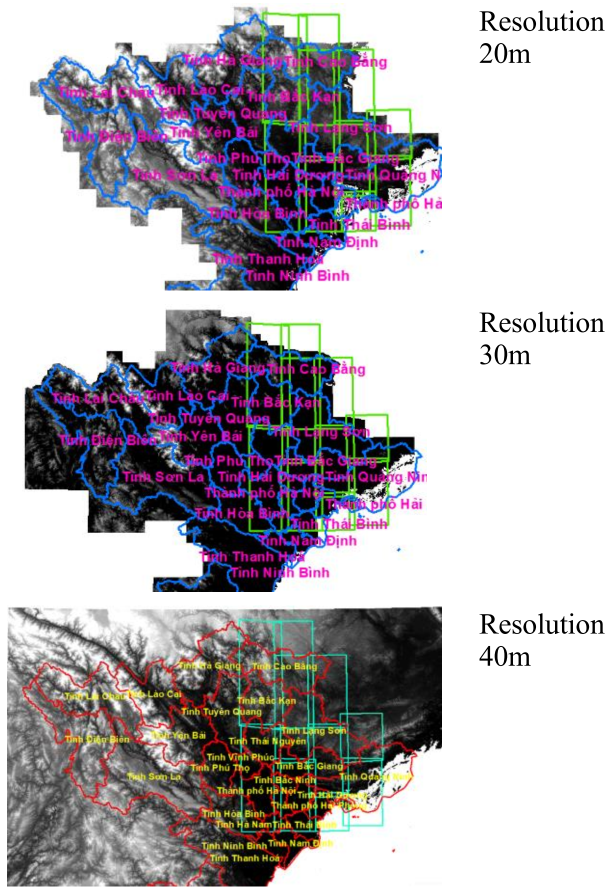

Fig. 3. DEM with different resolutions

C. *Equipment and Technology*

This study employs the Pixel Factory (PF) system, a high-performance remote sensing processing platform developed by Airbus Defence and Space. This infrastructure was procured for the National Remote Sensing Department within the framework of Sub-project 3, "Establishment of a Monitoring System for Riverbank and Coastal Dynamics in the Mekong Delta," under the "Mekong Delta Integrated Climate Resilience and Sustainable Livelihoods Project."

Designed as a centralized, industrial-scale solution for remote sensing data production, the system features advanced capabilities such as massively parallel processing, rapid data generation, and a high degree of automation across production

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workflows. It boasts an annual orthorectification capacity of 1 million for very high-resolution imagery (0.5m) and 6 million for high-resolution imagery (1.5m).

Furthermore, the PF system is built upon a modular architecture, offering users the flexibility to configure specific modules based on operational requirements. This architecture also supports scalability, allowing for the addition of processing nodes to expand capacity and meet future demands [2].

IV. EXPERIMENTAL RESULTS AND DISCUSSION

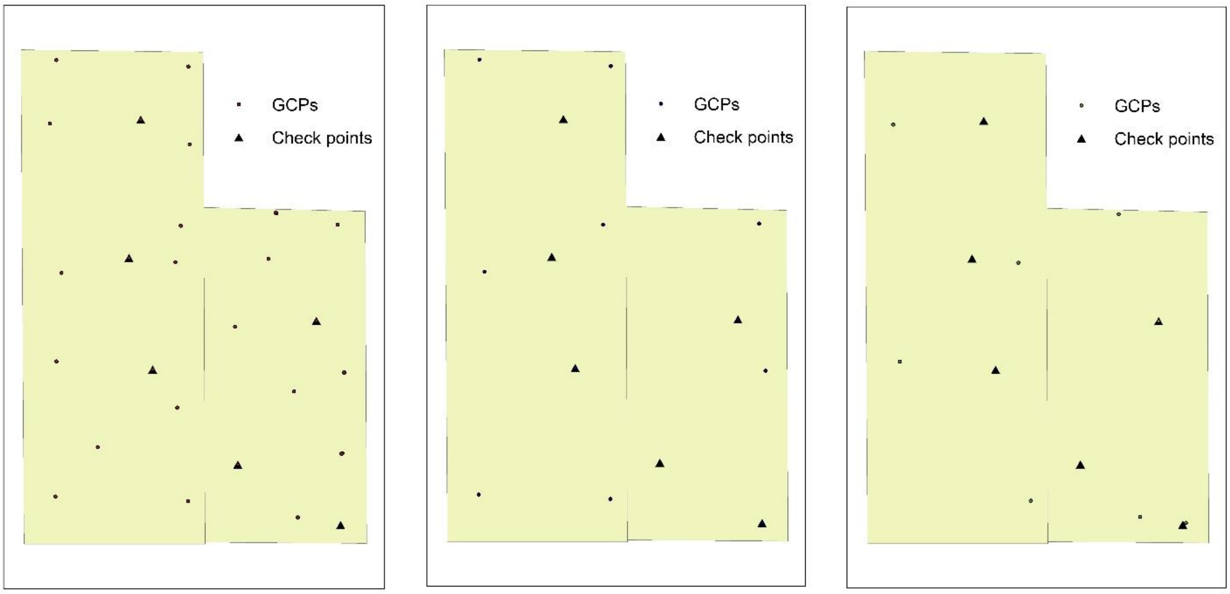
A. Evaluation and Determination of Optimal GCP Quantity

To determine the optimal number of Ground Control Points (GCPs) for the geometric rectification of large-scale remote sensing data blocks using High-Performance Computing (HPC), this study employed the Pixel Factory system for orthorectification. Initial experiments were conducted using the Panchromatic (PAN) band of the SPOT 6 dataset.

The PF system incorporates the satellite's physical sensor model (rigorous model), which significantly enhances geometric rectification accuracy. Consequently, this capability allows for a substantial reduction in the number of required GCPs during the rectification process while strictly adhering to accuracy regulations.

To empirically evaluate and identify the optimal GCP density for the image block within the PF environment, the orthorectification phase was tested under varying GCP configurations (Figure 4), specifically:

- 09 points (Figure 4a)
- 06 points (Figure 4b)
- 04 points (Figure 5c)



(a) (b) (c)

Fig. 4. The GCPs distribution

The evaluation results of the geometric rectification accuracy for the image block under different GCP configurations are presented in **Table 2**.

TABLE II. ORTHORECTIFICATION RESIDUALS (ERRORS) FOR DIFFERENT GCP CONFIGURATIONS (M)

Name	9 GCPs			6 GCPs			4 GCPs		
	dx	*dy*	*SSTP*	*dx*	*dy*	*SSTP*	*dx*	*dy*	*SSTP*
KT10	1,84	1,35	2,28	1.79	-2.90	3.41	-2,98	3,44	4,55
KT11	-1,91	0,64	2,01	-3.82	-0.10	3.83	-2.53	-2.55	3.59
KT12	-3,14	-1,77	3,61	-3,62	-0,26	3,63	-4.71	-4.15	6.28
KT13	-3,00	-1,88	3,54	0,87	0,08	0,87	-2,75	-3,19	4,21
KT14	-2,25	0,75	2,37	-2.13	-3.56	4.15	-3.12	5.45	6.28
KT15	-1,50	3,00	3,35	-2,47	3,00	3,88	2.86	3.24	4.33

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Given the 1.5m spatial resolution of SPOT 6 imagery, the data is suitable for generating orthophoto maps at a scale of 1:10,000. Consequently, to meet accuracy standards at this scale, the positional displacement of points on the rectified image relative to check points must not exceed 4m for well-defined features and 6m for indistinct features or mountainous terrain. Furthermore, edge matching errors between adjacent rectified strips/scenes must remain within 7m for flat terrain and 10m for mountainous regions.

As observed in Table 2, the planimetric errors for the SPOT 6 orthophotos across all three experimental configurations ranged from 2.01m to 3.54m. These values fall strictly within the permissible limits stipulated by the technical regulations [1].

The results indicate that the optimal quantity of Ground Control Points (GCPs) ranges from 4 to 6 points per scene or image strip. Based on these findings, to proceed with the orthorectification of the large-scale remote sensing data block covering the entire study area (10 strips), this research adopted the configuration of 6 GCPs for control and 2 Independent Check Points (ICPs) per scene/strip.

B. Evaluation and Selection of Optimal DEM Resolution

To assess the impact of Digital Elevation Models (DEMs) on the accuracy of remote sensing orthorectification and to identify the optimal DEM resolution for generating orthophoto maps at specific scales, experiments were conducted using DEMs of varying resolutions. The study applied DEMs with resolutions of 20m, 30m, and 40m (refer to Figure 3) to the large-scale remote sensing dataset comprising 10 SPOT 6 image strips (1.5m resolution).

The accuracy results for the experimental DEM configurations are summarized in Table 3 and Figure 5. Table 3 indicates that the 20m resolution DEM yielded the highest accuracy, with positional Root Mean Square Error (RMSE) ranging from 1.81m to 3.77m. Conversely, for the 40m resolution DEM, the positional RMSE was significantly higher, ranging from 4.46m to 7.37m.

These findings demonstrate that to generate orthophoto maps meeting the accuracy standards for 1:10,000 scale using SPOT 6 data, a 20m resolution DEM is requisite. Meanwhile, DEMs with resolutions of 30m or 40m are suitable only for orthophoto mapping at a scale of 1:25,000 or smaller.

TABLE III. ORTHORECTIFICATION ACCURACY ASSESSMENT RESULTS USING DEMS OF VARYING RESOLUTIONS

Tên điểm	**DEM 20m**			**DEM 30m**			**DEM 40m**		
	dx	***dy***	***SSTP***	***dx***	***dy***	***SSTP***	***dx***	***dy***	***SSTP***
KT01	0,25	-3,75	3,76	-4.29	3.32	5.42	-5.63	-1.13	5.74
KT03	-0,38	3,75	3,77	-3.96	3.49	5.28	-5.56	3.13	6.38
KT06	2,06	-1,37	2,48	-2.71	-4.49	5.24	2.61	0.83	7.37
KT04	0,00	0,94	0,94	-4.09	-0.45	4.12	-4.53	4.21	6.18
KT07	0,51	-0,36	0,63	-3.96	-0.62	4.01	-4.96	1.36	5.14
KT09	0,98	2,47	2,66	2.41	-2.72	3.64	0.35	8.30	8.31
KT10	1,84	1,35	2,28	1.79	-2.90	3.41	3.84	-0.15	3.84
KT11	-1,91	0,64	2,01	-3.82	-0.10	3.83	-2.53	-2.55	3.59
KT12	-3,14	-1,77	3,61	-2.52	-2.77	3.74	-4.71	-5.15	6.98
KT14	-2,25	0,75	2,37	-2.13	-3.56	4.15	-3.12	5.45	6.28
KT13	-3,00	-1,88	3,54	-3.46	-3.18	4.71	-4.09	-3.06	5.11
KT15	-1,50	3,00	3,35	2.86	3.24	4.33	-4.09	3.24	5.22
KT16	-0,34	3,79	3,81	-3.41	4.37	5.54	-4.12	3.70	5.53
KT18	0,31	1,78	1,81	1.74	3.64	4.03	4.77	-2.14	5.22
KT20	2,50	2,00	3,20	-0.74	4.89	4.95	-1.74	4.89	5.19
KT21	1,50	1,50	2,12	-2.93	-3.05	4.23	2.46	-3.72	4.46

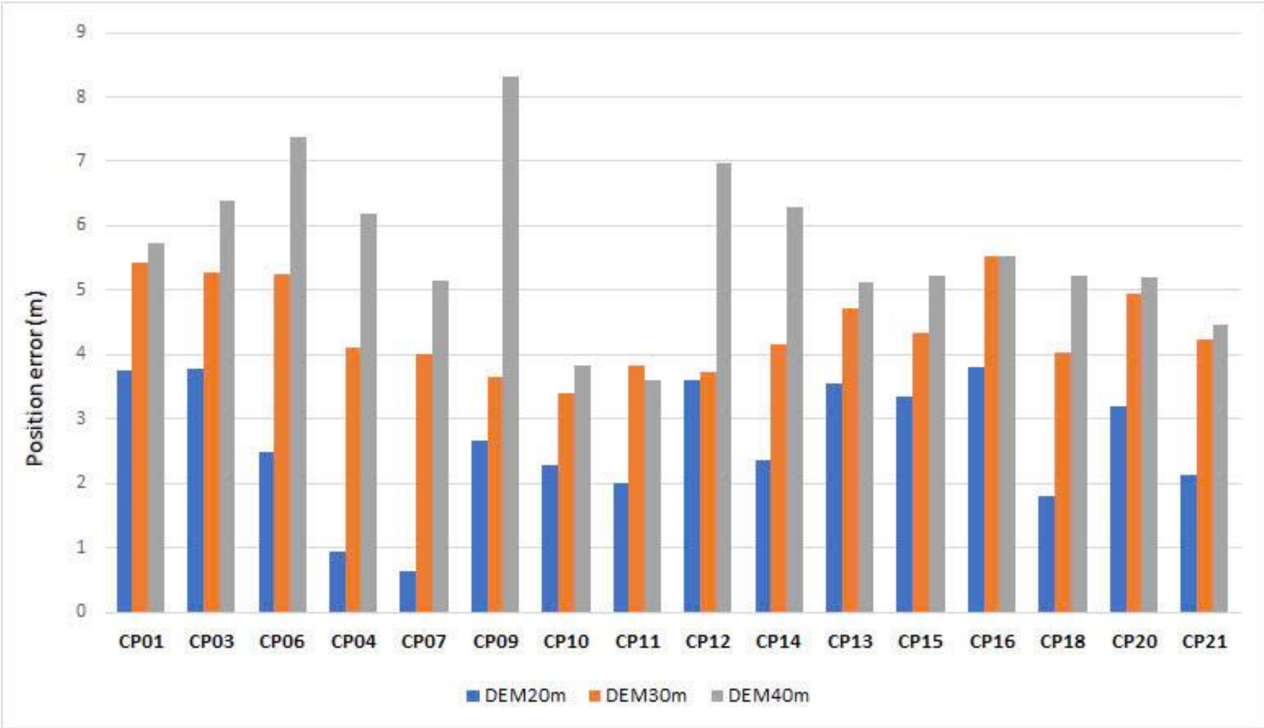

Fig. 5. Orthorectification error chart using DEMs with resolutions of 20m, 30m, and 40m.

To verify the edge matching errors between image strips/scenes within the rectified block, an assessment was conducted by comparing the displacement of linear features—such as rivers and transportation networks—across adjacent strips.

The results indicate that within the entire rectified block, the minimum edge matching error was 0.73 m, observed at the vertical overlap between strip SPOT6_202412220319370 (left) and strip SPOT6_202501120308590 (right). Conversely, the maximum error was 5.528 m, observed at the horizontal overlap between strip SPOT6_202412220319370 (top) and strip SPOT6_202501120309222 (bottom).

These findings confirm that the geometric rectification of the Panchromatic (PAN) band for the entire image block adheres to the required accuracy standards. Consequently, this validation permits the subsequent geometric rectification of the Multispectral (MS) bands for the extensive SPOT 6 dataset.

In this phase, selecting GCPs specifically for the MS imagery is unnecessary, as the Pixel Factory system automatically performs band-to-band co-registration, aligning the MS bands to the rectified PAN band. However, regarding the overall block, in certain areas characterized by complex topography or a scarcity of high-quality GCPs, the adjustment and orthorectification processes may still require manual intervention to ensure compliance with accuracy requirements.

C. Assessment of Spectral Distortion in Pansharpening

Pansharpening is the process of fusing Panchromatic (PAN) and Multispectral (MS) imagery to generate high-resolution multispectral data. This technique aims to retain the spatial details of the PAN band while preserving the spectral characteristics of the original MS bands. The Pixel Factory (PF) system offers several technical solutions for this process, including: (1) Color Normalize, (2) Standard, and (3) Auto.

Inherently, images subjected to orthorectification and pansharpening often exhibit alterations in spectral values compared to the original raw imagery. Such spectral distortion significantly impacts the accuracy of thematic analysis and interpretation, particularly when employing Artificial Intelligence (AI) workflows such as Deep Learning and Machine Learning.

To evaluate the spectral preservation capability (spectral fidelity) of these methods, following rigorous surveying and experimentation, this study determined that Method 1 (Color Normalize) within the PF system yields the most superior spectral preservation. Table 4 presents a comparative analysis of the spectral values between the four MS bands of the original SPOT 6 Level 1A imagery (6m resolution) and the corresponding bands after orthorectification and pansharpening (upscaled to 1.5m resolution).

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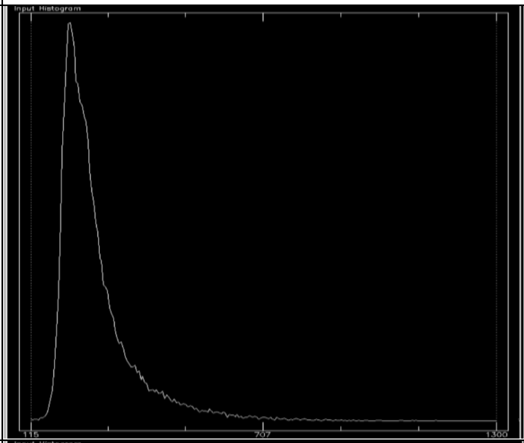
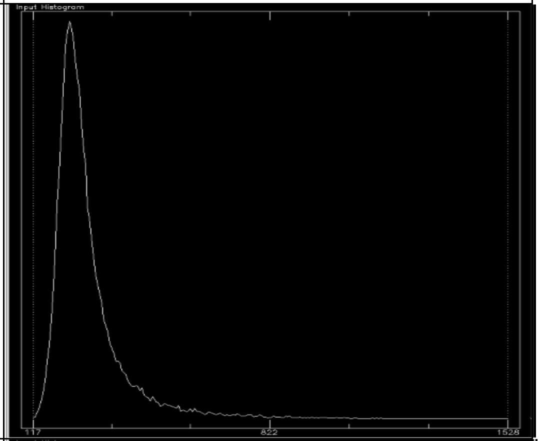
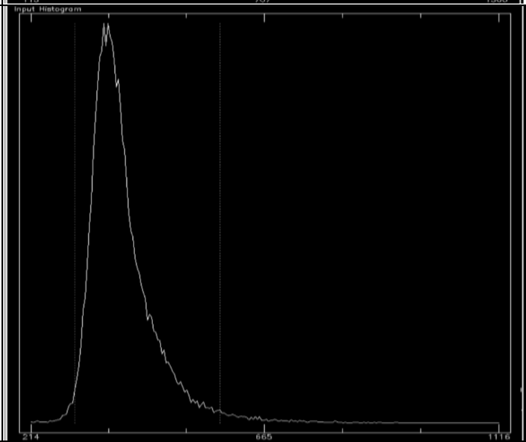
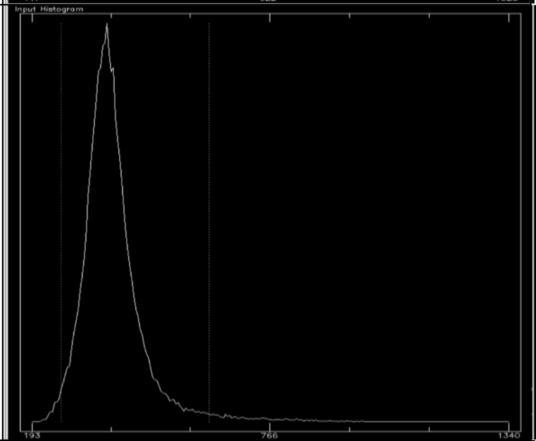
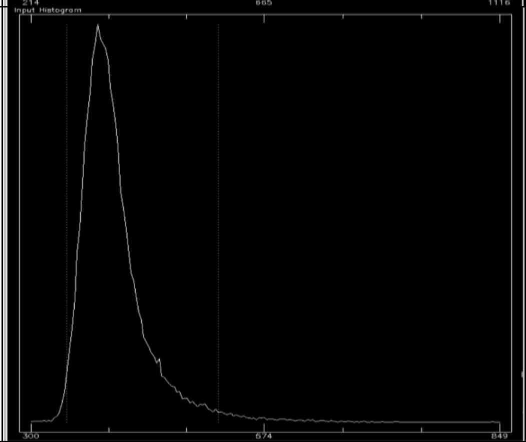
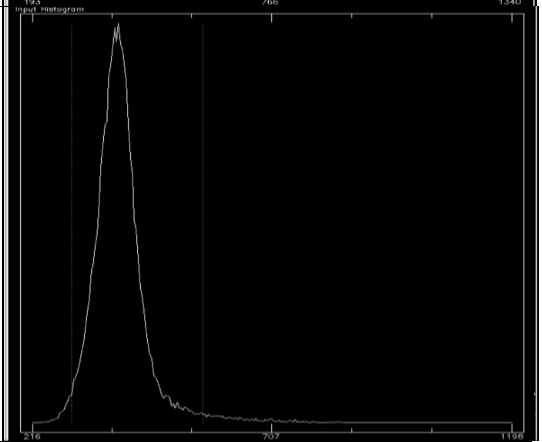
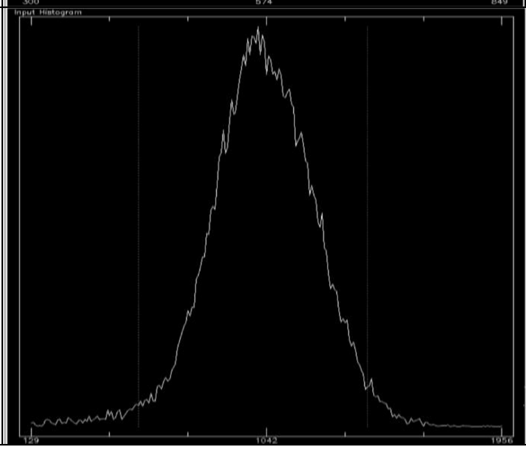
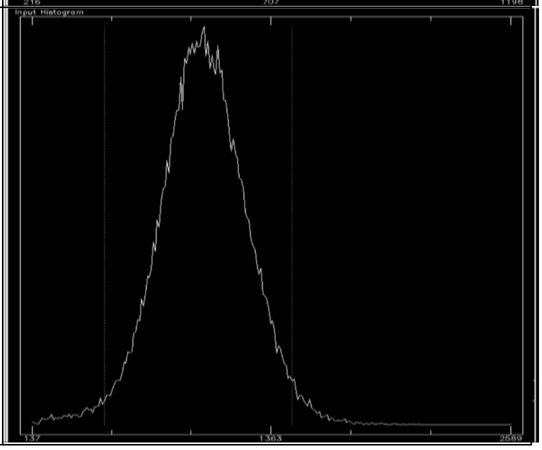
TABLE IV. COMPARISON OF SPECTRAL VALUES BETWEEN ORIGINAL MS IMAGERY AND PANSHARPENED ORTHOPHOTOS

Band	Original Image (6m Resolution)	Pansharpened Image (1.5m Resolution)
B1 Red(R)		
B2 Green (G)		
B3 Blue (B)		
B4 Near Infrared (NIR)		

V. CONCLUSION

This study has demonstrated the significant efficacy of the Pixel Factory (PF) high-performance system in optimizing the workflow for processing large-scale remote sensing data blocks, particularly concerning high-resolution SPOT 6 imagery. The PF system enables the automation of the majority of the processing pipeline—ranging from block bundle adjustment, orthorectification, and multispectral band co-registration to pansharpening and mosaicking—thereby substantially minimizing manual interventions and mitigating the risk of human error.

Experimental results indicate that the PF system allows for a reduction in the required number of Ground Control Points (GCPs) to merely 4–6 points per scene while strictly maintaining accuracy in compliance with technical standards. This contributes to the optimization of both surveying costs and time. Regarding elevation data, comparative analysis reveals that the 20m resolution DEM yields the highest accuracy, making it suitable for orthophoto production at a 1:10,000 scale, whereas the 30m and 40m DEMs meet requirements only for smaller scales. Furthermore, the Color Normalize pansharpening method within the PF system effectively preserves the spectral characteristics (spectral fidelity) of the original imagery, facilitating subsequent AI applications, Deep Learning models, and thematic analyses.

In conclusion, Pixel Factory represents a robust technological solution that effectively meets the demands of large-scale remote sensing data processing, enabling reduced production cycles and enhancing product consistency and accuracy. However, the system remains heavily reliant on the quality of input data and metadata; areas characterized by complex topography or a scarcity of high-quality GCPs still require supplementary manual validation. Nevertheless, given its high efficiency and scalability, PF serves as a suitable platform for deployment in national mandates regarding natural resource monitoring, environmental management, and the development of foundational remote sensing databases.

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