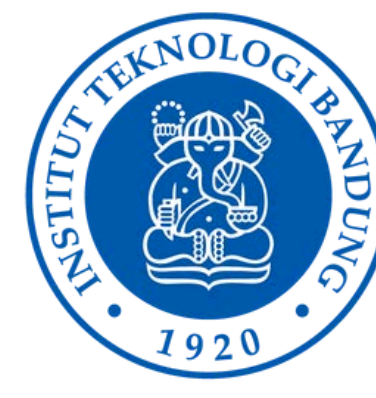


# Wave Direction Estimation Based on Local Gradient Techniques from Satellite Imagery for Coastal Dynamics Monitoring



## Introduction

Coastal regions are highly dynamic environments where wave action plays a critical role in shoreline changes, sediment transport, and coastal erosion. These processes are strongly influenced by the movement and direction of waves, making accurate estimation of wave direction essential for coastal monitoring and management.

Traditional wave observation methods, such as in-situ buoys and numerical models, provide valuable data but are often limited by sparse spatial coverage, high deployment costs, and computational complexity. With the increasing availability of high-resolution satellite imagery, image-based approaches offer a promising alternative for capturing spatially continuous wave information.

This study proposes an image-processing framework for estimating wave direction directly from satellite images. By detecting wave crests and analyzing their orientation relative to the shoreline, the method provides an efficient tool for understanding coastal dynamics.

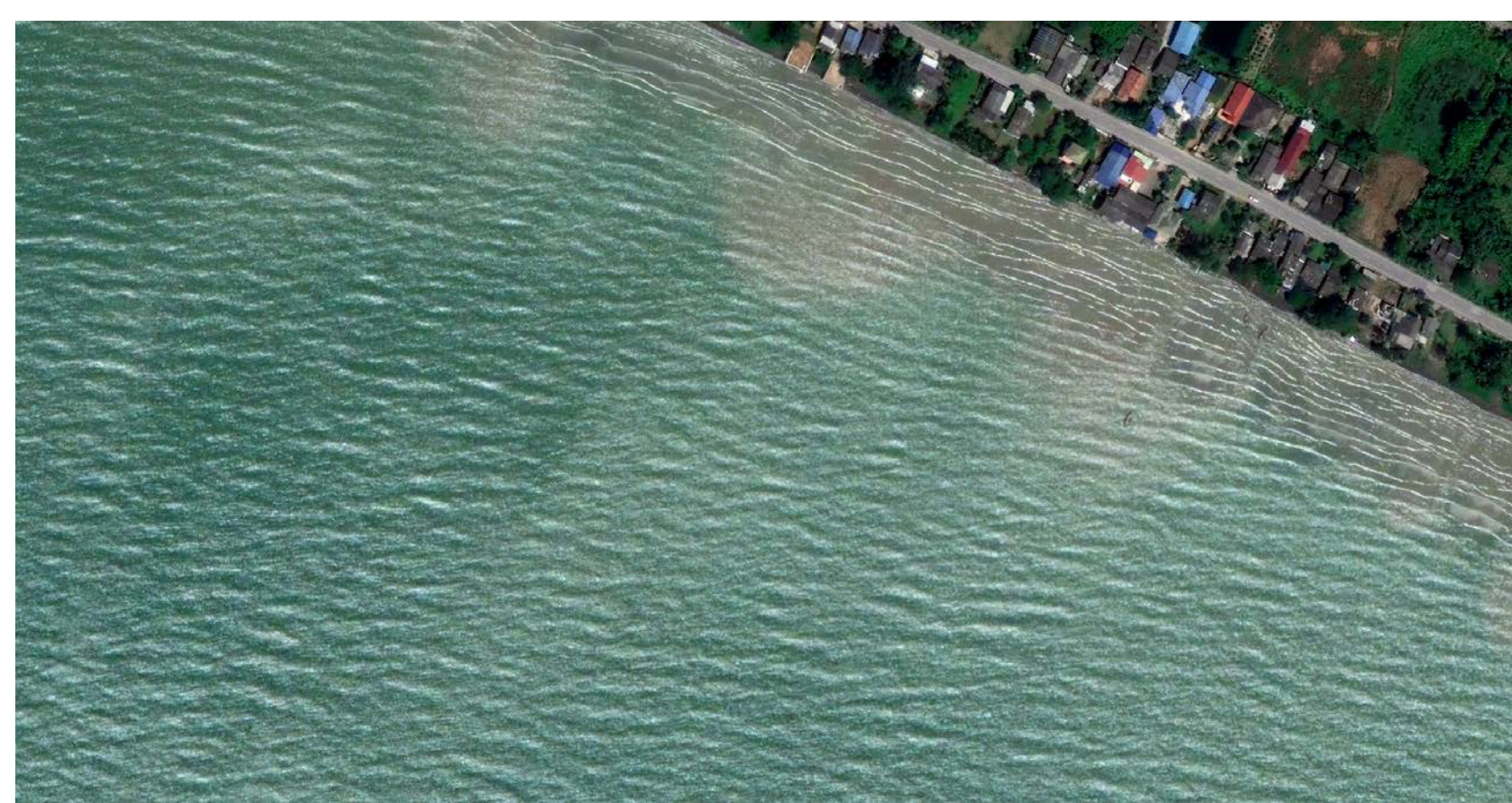


Fig. 1. Original image before with 244x244 grid overlay

## Proposed Method

Image Loading and Preprocessing

The input images are first converted to grayscale to highlight intensity variations. Then, histogram equalization enhances contrast, and Gaussian smoothing ( $5 \times 5$  kernel,  $\sigma^2 = 1.21$ ) reduces noise while preserving edges.

Image Enhancement and Filtering

Gradients are computed using the Sobel operator in both directions, followed by deriving magnitude and direction. A 90th percentile threshold keeps key edges, and a  $5 \times 5$  median filter removes remaining noise without blurring wave patterns.

Edge Detection and Analysis

The  $180^\circ$  ambiguity of wave crests is resolved using a double-angle averaging technique. Once the ambiguity is corrected, the final wave direction is determined as being orthogonal to the crest orientation.

Output Visualization

Finally, directional arrows are overlaid on the processed satellite images to visually illustrate the estimated wave direction, using north as the reference point.

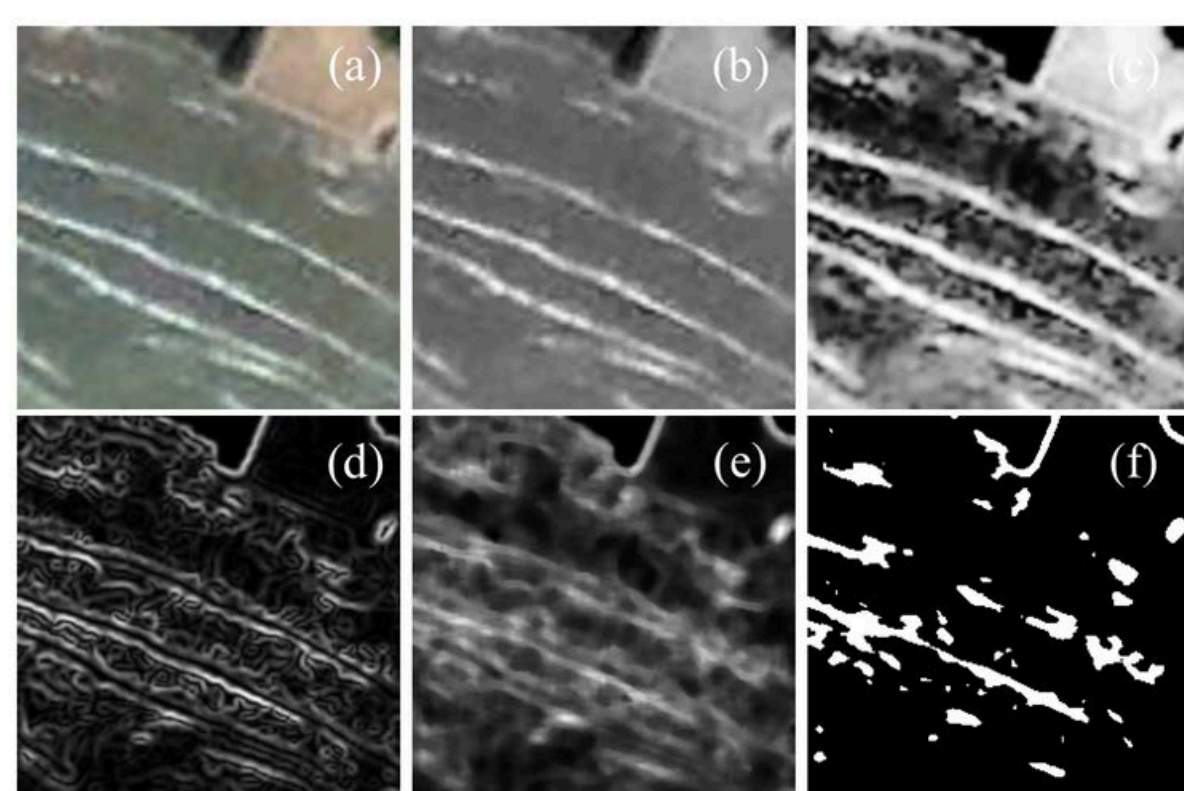


Fig. 2. Sequential visualization of the proposed wave direction estimation process: (a) original image patch, (b) grayscale conversion, (c) histogram equalization, (d) sobel edge detection, (e) median filtering, and (f) thresholding.

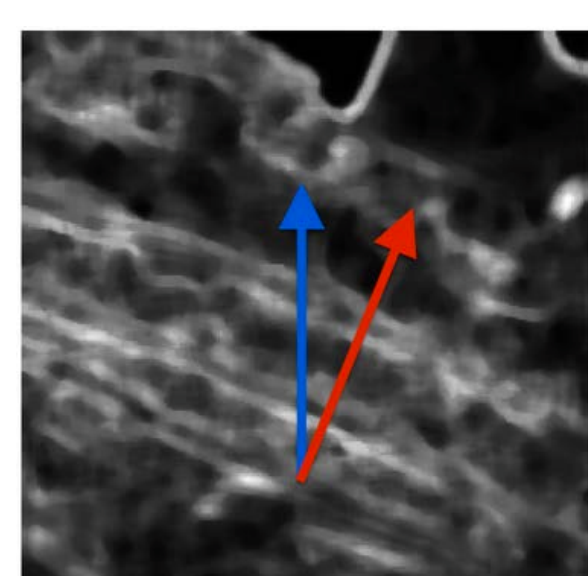


Fig. 3. Visualization of the final wave direction estimation, with directional arrows overlaid on the processed image patch.

## Experiment and Evaluation

- Sites: Chaloe Burapha Chonlathit Road (403 samples) and Sattahip Beach (281 samples)
- Metrics: MAE (Mean Absolute Error), RMSE (Root Mean Square Error), Directional Accuracy  $\pm 15^\circ$ , and Small flips (minor reversals due to  $180^\circ$  ambiguity)

Wave direction prediction metrics for the chaloe burapha chonlathit road site

Model	MAE ( $^\circ$ )	RMSE ( $^\circ$ )	Accuracy within $\pm 15^\circ$ (%)	Small Flips
No median filter	22.07	28.15	40.40	30
<b>Median filter with k = 5</b>	<b>9.54</b>	<b>11.02</b>	<b>80.90</b>	<b>52</b>
Median filter with k = 7	9.57	11.04	79.70	55
Median filter with k = 9	9.71	11.19	77.40	53

Wave direction prediction metrics for the sattahip beach site

Model	MAE ( $^\circ$ )	RMSE ( $^\circ$ )	Accuracy within $\pm 15^\circ$ (%)	Small Flips
No median filter	9.98	12.29	40.40	0
Median filter with k = 5	4.28	5.56	80.90	0
<b>Median filter with k = 7</b>	<b>4.23</b>	<b>5.47</b>	<b>98.90</b>	<b>0</b>
Median filter with k = 9	4.25	5.44	77.40	0

### Key Findings:

- Median filtering significantly reduced noise.
- Kernel size  $7 \times 7$  provided the best trade-off between smoothing and preserving directional details.
- Average performance: MAE  $\approx 6.9^\circ$ , RMSE  $\approx 8.3^\circ$ , Accuracy  $\pm 15^\circ \approx 89.5\%$ .

## Conclusion

This study proposed a wave direction estimation method based on local gradients, Gaussian smoothing, and double-angle orientation averaging. Incorporating a median filter significantly improved directional accuracy, particularly with a kernel size of  $k=7$ , which consistently delivered low error and high accuracy.

Experiments on two coastal sites in Thailand demonstrated the method's effectiveness, achieving over 98% directional accuracy in favorable conditions. The method is lightweight, interpretable, and suitable for operational wave monitoring applications.

## Future Work

Future enhancements may include integration of deep learning-based segmentation, probabilistic ambiguity resolution models, and hybrid systems combining physical and data-driven approaches.

## Acknowledgments

The ASEAN IVO project (<http://www.nict.go.jp/en/aseanivo/index.html>), titled "Coastal Erosion Monitoring Platform Based on Wireless Sensor Networks and 3D Point Clouds from Airborne LiDAR," was involved in the production of the contents of this work and financially supported by NICT (<http://www.nict.go.jp/en/index.html>).

