

# SPUD: Simultaneous Phase Unwrapping and Denoising Algorithm for Phase Imaging

JESUS PINEDA<sup>1</sup>, JORGE BACCA<sup>2</sup>, JHACSON MEZA<sup>1</sup>, LENNY A. ROMERO<sup>3</sup>, HENRY ARGUELLO<sup>2</sup>, AND ANDRES G. MARRUGO<sup>\*1</sup>

<sup>1</sup>Facultad de Ingeniería, Universidad Tecnológica de Bolívar, Cartagena, Colombia

<sup>2</sup>Department of Computer Science, Universidad Industrial de Santander, Bucaramanga, Colombia

<sup>3</sup>Facultad de Ciencias Básicas, Universidad Tecnológica de Bolívar, Cartagena, Colombia

\*Corresponding author: agmarrugo@utb.edu.co

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Recent methods for phase unwrapping in the presence of noise include denoising algorithms to filter out noise as a pre-processing stage. However, including a denoising stage increases the overall computational complexity resulting in long execution times. In this paper, we present a non-iterative Simultaneous Phase Unwrapping and Denoising algorithm for phase imaging, referred to as SPUD. The proposed method relies on the least-squares Discrete Cosine Transform (DCT) solution for phase unwrapping with an additional sparsity constraint on the DCT coefficients of the unwrapped solution. Simulation results with different levels of noise and wrapped phase fringe density reveal the suitability of the proposed method for accurate phase unwrapping and restoration. When compared to the 2D windowed Fourier transform filter, SPUD performs better in terms of phase error and execution times. The processing of experimental data from synthetic aperture radar showed the capability for processing real images, including removing phase dislocations. An implementation of the proposed algorithm can be accessed and executed through a Code Ocean compute capsule.

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## 1. INTRODUCTION

Two-dimensional (2D) phase unwrapping is a necessary process in many applications such as synthetic radar aperture, fringe projection profilometry, interferometry, magnetic resonance imaging, among others [1–3]. The unwrapping process consists in retrieving the continuous phase  $\varphi$  from its wrapped version  $\psi$ , which lies in the interval  $(-\pi, \pi]$  [4]. In the noiseless scenario, phase unwrapping is trivial and straightforward. However, in practice,  $\varphi$  is affected by noise, which makes phase unwrapping difficult and decreases the measurement accuracy [5, 6].

Phase unwrapping has been traditionally approached from two perspectives [7]. In the classical approach, the goal is to obtain a continuous phase regardless of the presence of noise. Conventional phase unwrapping algorithms such as path-following approaches [8], quality-guided path-following methods [9, 10], mask-cut phase unwrapping [11], Flynn's minimum discontinuity [12], and minimum  $L^p$ -norm algorithms [1, 13], follow this perspective [1, 14]. Quality-guided and  $L^p$ -norm phase unwrapping algorithms have shown the best performance in the

presence of low-level noise [1], although the computation of quality maps increases the complexity [15]. Recently, an iterative least-squares-based phase unwrapping method referred to as CPULSI [16] has proven to be highly suitable even on extremely noisy phases [5]. However, despite obtaining an accurate continuous phase map, a further denoising stage must be applied to estimate a phase map suitable for quantitative measurements [5, 17].

The second perspective includes denoising preprocessing stages to produce a restored wrapped phase map, followed by phase unwrapping. For instance, Montresor and Picart [18] evaluated the performance of state-of-the-art algorithms for phase data denoising including Wiener filtering [19, 20], Wavelet thresholding approaches [21, 22], non-local means [23–25], transform-based block-matching 3D (BM3D) filter [26, 27], 2D windowed Fourier transform filter (WFF) [10, 28, 29], and the SPADEDH algorithm [30, 31]. They quantitatively assessed these algorithms and ranked them according to their performance to isolate the genuine phase gradients from the noisy wrapped

# Denoising Phase Unwrapping Algorithm For Precise Phase

**Xiang Xie**



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