

# Phase unwrapping algorithms for radar interferometry: residue-cut, least-squares, and synthesis algorithms

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The advent of interferometric synthetic aperture radar for geophysical studies has resulted in the need for accurate, efficient methods of two-dimensional phase unwrapping. Inference of the lost integral number of cycles in phase measurements is critical for three-pass surface deformation studies as well as topographic mapping and can result in an order of magnitude increase in sensitivity for two-pass deformation analysis. While phase unwrapping algorithms have proliferated over the past ten years, two main approaches are currently in use. Each is most useful only for certain restricted applications. All these algorithms begin with the measured gradient of the phase field, which is subsequently integrated to recover the unwrapped phases. The earliest approaches in interferometric applications incorporated residue identification and cuts to limit the possible integration paths, while a second class using least-squares techniques was developed in the early 1990's. We compare the approaches and find that the residue-cut algorithms are quite accurate but do not produce estimates in regions of moderate phase noise. The least-squares methods yield complete coverage but at the cost of distortion in the recovered phase field. A new synthesis approach, combining the cuts from the first class with a least-squares solution, offers greater spatial coverage with less distortion in many instances. © 1998 Optical Society of America 1507-40-3230/98/030586-03

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## 1. INTRODUCTION

Algorithms that relate individual phase measurements on a two-dimensional field, motivated largely by interest in interferometric synthetic aperture radar (SAR) techniques, have proliferated over the past ten years.<sup>1-4</sup> These algorithms seek to infer the integral number of cycles lost when a phase measurement is made from a two-dimensional complex signal amplitude observation, which uniquely identifies only the phase value modulo  $2\pi$ . We refer to such algorithms here as phase unwrapping, as distinguished from the use of that term for reconstruction of signal amplitudes from frequency-domain phase data, a common problem associated with one-dimensional signal processing.

We report here a comparison of several of the phase unwrapping algorithms in more common use today and identify and contrast the strengths and weaknesses of each. We also present a synthesis approach that combines some of the more effective features of the existing algorithms and can extend the range of phase unwrapping situations amenable to automated solution. Rather than revolutionize present capabilities, these new algorithms represent another approach for phase unwrapping procedures that aid in some situations where the existing algorithms fare poorly. Because we (1) do not review each existing algorithm comprehensively, (2) do propose new variations of the algorithms suited to particular styles of input data, and (3) do not believe that the existing set of approaches is the final word on phase unwrapping procedures, this article serves more as a progress re-

port rather than as a review of phase unwrapping procedures.

The advent of interferometric SAR for geophysical studies, in particular, has resulted in the need for accurate, efficient methods of two-dimensional phase unwrapping. Radar methods for fast and precise measurement of topographic data,<sup>5,6</sup> determination of centimeter-level surface deformation fields,<sup>7-9</sup> and surface velocity fields<sup>10,11</sup> all require that the relative phases over large areas be known. Strictly speaking, each of these techniques requires, in addition, knowledge of the absolute phase values;<sup>12</sup> however, in practice contextual clues or known fiducial values (tie points) often permit geophysical inference with only the relative phases, given that the phase field is unwrapped.

Although many insights into underlying surface processes may be obtained by visual inspection of the initial, wrapped radar interferogram,<sup>13,14</sup> this unwrapping by eye may be applied only to simple phase fields without significant and complicated structure. Moreover, automated topographic mapping approaches and the application of three-pass deformation algorithms are precluded by the necessity of human interaction on a pixel-by-pixel level with the interferometric data. For instance, even a small-area topographic map may contain millions of meter-spaced posts. Accuracy also drives the requirement. In regions of finely spaced fringes, it may be difficult to estimate the phase manually to better than a large fraction of a cycle accuracy, whereas performance of the radar system itself allows accuracies corresponding to

# Phase Unwrapping Algorithms For Radar Interferometry

**Arturo Cuomo**



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## **Table of Contents Phase Unwrapping Algorithms For Radar Interferometry**

1. Understanding the eBook Phase Unwrapping Algorithms For Radar Interferometry
  - The Rise of Digital Reading Phase Unwrapping Algorithms For Radar Interferometry
  - Advantages of eBooks Over Traditional Books
2. Identifying Phase Unwrapping Algorithms For Radar Interferometry
  - Exploring Different Genres
  - Considering Fiction vs. Non-Fiction
  - Determining Your Reading Goals
3. Choosing the Right eBook Platform
  - Popular eBook Platforms
  - Features to Look for in an Phase Unwrapping Algorithms For Radar Interferometry
  - User-Friendly Interface
4. Exploring eBook Recommendations from Phase Unwrapping Algorithms For Radar Interferometry
  - Personalized Recommendations
  - Phase Unwrapping Algorithms For Radar Interferometry User Reviews and Ratings

- Phase Unwrapping Algorithms For Radar Interferometry and Bestseller Lists
- 5. Accessing Phase Unwrapping Algorithms For Radar Interferometry Free and Paid eBooks
  - Phase Unwrapping Algorithms For Radar Interferometry Public Domain eBooks
  - Phase Unwrapping Algorithms For Radar Interferometry eBook Subscription Services
  - Phase Unwrapping Algorithms For Radar Interferometry Budget-Friendly Options
- 6. Navigating Phase Unwrapping Algorithms For Radar Interferometry eBook Formats
  - ePub, PDF, MOBI, and More
  - Phase Unwrapping Algorithms For Radar Interferometry Compatibility with Devices
  - Phase Unwrapping Algorithms For Radar Interferometry Enhanced eBook Features
- 7. Enhancing Your Reading Experience
  - Adjustable Fonts and Text Sizes of Phase Unwrapping Algorithms For Radar Interferometry
  - Highlighting and Note-Taking Phase Unwrapping Algorithms For Radar Interferometry
  - Interactive Elements Phase Unwrapping Algorithms For Radar Interferometry
- 8. Staying Engaged with Phase Unwrapping Algorithms For Radar Interferometry
  - Joining Online Reading Communities
  - Participating in Virtual Book Clubs
  - Following Authors and Publishers Phase Unwrapping Algorithms For Radar Interferometry
- 9. Balancing eBooks and Physical Books Phase Unwrapping Algorithms For Radar Interferometry
  - Benefits of a Digital Library
  - Creating a Diverse Reading Collection Phase Unwrapping Algorithms For Radar Interferometry
- 10. Overcoming Reading Challenges
  - Dealing with Digital Eye Strain
  - Minimizing Distractions
  - Managing Screen Time
- 11. Cultivating a Reading Routine Phase Unwrapping Algorithms For Radar Interferometry
  - Setting Reading Goals Phase Unwrapping Algorithms For Radar Interferometry
  - Carving Out Dedicated Reading Time
- 12. Sourcing Reliable Information of Phase Unwrapping Algorithms For Radar Interferometry
  - Fact-Checking eBook Content of Phase Unwrapping Algorithms For Radar Interferometry
  - Distinguishing Credible Sources

13. Promoting Lifelong Learning
  - Utilizing eBooks for Skill Development
  - Exploring Educational eBooks
14. Embracing eBook Trends
  - Integration of Multimedia Elements
  - Interactive and Gamified eBooks

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