COMPARISON OF GLOBAL AND LOCAL APPROACH TO PHASE UNWRAPPING FOR RUGGED TERRAIN

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ABSTRACT/RESUME

Phase unwrapping is the most informal step of the interferometric SAR processing for calculation of digital elevation model. Present algorithms use two ways for resolving this problem: local and global approach. In this paper we analyze efficacy of three phase unwrapping methods (and their modifications) using standard ERS SAR scene for the Baikal Lake region (the Barguzin valley with mountainous surrounding). We estimate advantages and disadvantages of both approaches.

1 INTRODUCTION

Nowadays phase unwrapping problem has great number of resolving methods. Investigator has to choose the most appropriate one in order to get the best result for particular data. There is primary classification of phase unwrapping algorithms into two groups: first group uses global approach and second one uses local approach. In this paper we consider both approaches: two methods from local group and one from the global group.

Well-known branch cut method [1] and frequency estimation method [2] use the local approach. Classical branch cut algorithm consists of the following steps: one should find the residues, draw the cuts, and integrate along regular paths. Frequency estimation method examines a surrounding of each pixel using FFT and produces a mask of bad pixels (integration paths should not cross the areas that consist of bad pixels). Least-squares method [3] is global, and it gives the solution of discrete Poisson equation on the rectangular grid.

2 DATA SET

For our experiment we took ERS Tandem interferogram over the Baikal Lake region acquired on October 10-11, 1997. The interferogram was resampled in azimuth direction in order to equalize pixel sizes. In the following we call the result of this resampling “non-averaged interferogram”.

The whole scene includes some flat regions (like the Barguzin valley), water surfaces (the Baikal Lake and numerous little lakes), and mountains with different (moderate and very steep) slopes. Thus there are many areas of low coherence in the interferogram for this scene because of shadowing, undersampling, and temporal decorrelation effects. All these causes make the phase unwrapping problem rather complicated. In order to get the better result and to adjust the methods to the data we had to modify the algorithms under consideration.

3 MODIFICATIONS OF METHODS

3.1 Branch Cut Algorithm

Branch cut method works perfectly on the valley, where the topography is smooth and coherence is high. But the presence of low-coherence areas makes the computing procedure more complicated. For example, mountain ridges often produce under-sampled belt-looking areas of low coherence, and cut lines of the algorithm usually cannot cover the whole “bad” area to avoid integration across it. And just one pass crossing such a belt is sufficient to make the integration inconsistent. Another problem, that faces the investigator, is the choice of averaging: to smooth or not to smooth. In fact, smoothing of the original interferogram decreases the noise and reduces the number of residues. Nevertheless, the less residues, the less cuts, and hence the less cuts, the more passes through bad areas. So a masking procedure is needed. The second reason for masking is the presence of lakes: interferometric phase on water surface is decorrelated for the two-pass scheme. Even in the case of smoothing there is a big number of residues in the lakes, which increases computational complexity in vain, because areas of decorrelated phase differences do not need to be unwrapped. Interferometric coherence is an indicator of interferogram quality, and it masks water surfaces and foreshortenings of mountain ridges very well, therefore coherence is a good candidate for initial masking.

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The steps of modified branch cut algorithm are:
- compute residues over the whole scene,
- compute initial mask by thresholding of the coherence,
- add to the mask all residues and cuts computed for non-masked areas,
- compute residues balance for every masked area and add to the mask new cuts between areas of opposite “charge”,
- integrate phase differences along paths which do not cross the mask.

Here the “charge” of connected set of masked pixels means the arithmetic sum of individual charges of all residues occurring in the set. Individual charge is equal to +1 for positive residues and –1 for negative residues. We can find an example of such a cut between masked areas on the Fig. 1b).

3.2 Frequency Estimation Algorithm

This algorithm uses both amplitude and phase information for estimation of two-dimensional spatial frequencies at each pixel on the complex interferogram. It constructs a mask of bad pixels like the branch cut algorithm, and their similarity extends further: masked areas often correspond to the residue-rich areas, so the chains of masked pixels produced by the frequency estimation algorithm follow the cut lines produced by the previous one. As mentioned above, sometimes branch cut algorithm works better after adding to residues and cuts (that are points and lines) some two-dimensional sets of pixels (masked areas). Here we have the reverse situation: our masked pixels form two-dimensional areas, but in some places (like passes through the mountain ridge) we should add lines to the mask in order to avoid inconsistencies. Appearance of such inconsistencies is unpredictable for the cases of rugged relief; hence the simplest way to improve the mask is drawing the necessary lines manually. To make this task easier, we used homemade software, which creates a map of 2π levels (number of 2π which we should add to interferogram to unwrap the phase) and marks the areas of inconsistency. The same software allows the estimation of masking quality for modified branch cut method.

3.3 Least-squares Algorithm

This well-known phase unwrapping algorithm belongs to the group of the global approach. The main idea of the approach is to approximate given phase differences (which are somewhere inconsistent) in sense of least-squares. Mathematically, the problem is equal to discrete Poisson equation [3]. The solution of this partial differential equation depends on boundary conditions. If one has some initial guess about these conditions (e.g., zero), one can take it. But in the absence of a priori information on boundary conditions, one can use the mirror-reflection technique described in [4]. Mirror boundary conditions guarantee the uniqueness of the solution.

Computational procedure of unweighted least-squares method includes calculation of a Laplacian, Fourier (or cosine) transform, weighing in the frequency domain, and inverse transform. Reference [3] proposes weighted iteration algorithm for data, which include discontinuities, areas of low coherence or noisy areas. To apply this technique one should have two-dimensional weighting array. The simplest weighting array is the mask: “bad” pixels have zero weight. And we took the mask of “bad” pixels introduced in frequency estimation algorithm.

3.4 Data Smoothing

Although we used non-averaged interferogram to produce the mask in local methods, the smoothed one is preferable for last step of unwrapping for all three algorithms. It allows to reduce computational complexity for branch cut algorithm, the number of manual corrections for frequency estimation algorithm, and the number of iterations in the least-squares algorithm.

4 COMPARISON

4.1 Statistical Comparison

Before analyzing the phase unwrapping solutions for the mountainous area we verified three modified algorithms on the appropriate test site. The Barguzin valley is the flat non forested surface covered by meadows and marshlands. But the interferogram is not trivial on the valley: there is permanent phase drift in azimuth direction across the valley because of imprecise orbital parameters, and some fringes appear in it.

Thus this test site is very suitable for the modified algorithms test. First of all we tested our methods, using a square fragment of the interferogram located in the central part of the valley. The result that we got was not unexpected: all three images of unwrapped phase were in perfect agreement with each other. Differences of unwrapped phase have a mean less than 0.01 radians with standard deviation of 0.05 for difference between two local methods and 0.2 for difference between the local (branch cut) and the global (least-squares) method.

Wooded mountains surround the Barguzin valley. To the west of it there is a long mountain ridge, which is very steep (Peredovoy Hrebet). Unfortunately, its front slope defies unwrapping because of strong foreshortening effect. But its back slope was unwrapped satisfactorily. The area to the east of the valley with mountains and ravines is representative in the sense of phase unwrapping difficulties. On Fig. 1 there are the corresponding interferogram (a) and two differences of unwrapped phase (b, c).

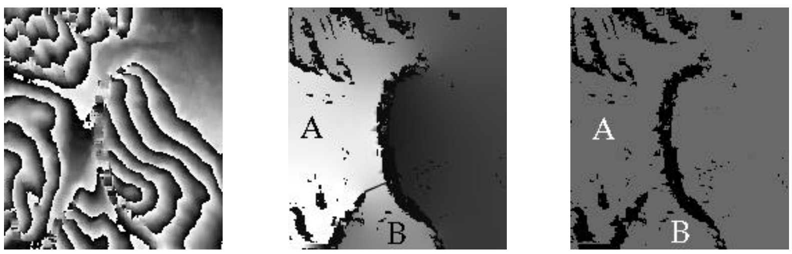
We studied differences between phase unwrapping solutions for two pairs of three studied algorithms: pair of local algorithms (frequency estimation and branch cut) and between local and global algorithms (least-squares and branch cut). Statistical results are given in table 1.

Table 1
Mean and standard deviation of differences between phase unwrapping solutions produced by three algorithms

Difference	Mean (radians)	St. dev. (radians)	Area on Fig.1
Least-squares – Branch cut (Fig. 1b)	0.86	3.49	Whole area
	8.11	0.25	Sub-area A
	2.69	0.34	Sub-area B
Freq. estimation– Branch cut (Fig. 1c)	-0.09	1.41	Whole are
	-0.01	0.04	Sub-area A
	0.01	0.03	Sub-area B

One can see on the Fig. 1b) that the difference between global and local algorithms consists of parts with different levels of mean. The borders between the parts can be sharp (e.g., between A and B sub-areas) or fuzzy (e.g., between sub-area A and upper part of the fragment). Inside each part the values of standard deviation are moderate. For example, the sub-area A on the Fig. 1 has a mean of 8.11 radians; it's the maximal value of difference for the area. But the standard deviation is rather low: it means that in this sub-area we have the systematic shift in the values of unwrapped phase. Right half of the image on the Fig. 1b) corresponds to negative values of mean between 0 radians in upper right corner and -3.07 radians in the dark area near the masked slope.

Fig. 1c) shows the difference in the work of two local methods. On account of different ways of masking in the algorithms we see also rather high standard deviation value computed for the whole area. But for sub-areas, which are almost free of masked pixels (like A and B), a mean and a standard deviation are approaching the zero value. Consequently, this pair of algorithms gives almost identical solutions for phase unwrapping problem even in the case of rugged topography.



a) b) c)

Fig. 1. Fragments of phase images
a) smoothed interferogram;
b,c) difference between phase unwrapping solutions:
b) least-squares and branch cut , c) frequency estimation and branch cut.
Black features on b),c) corresponds the masked pixels.

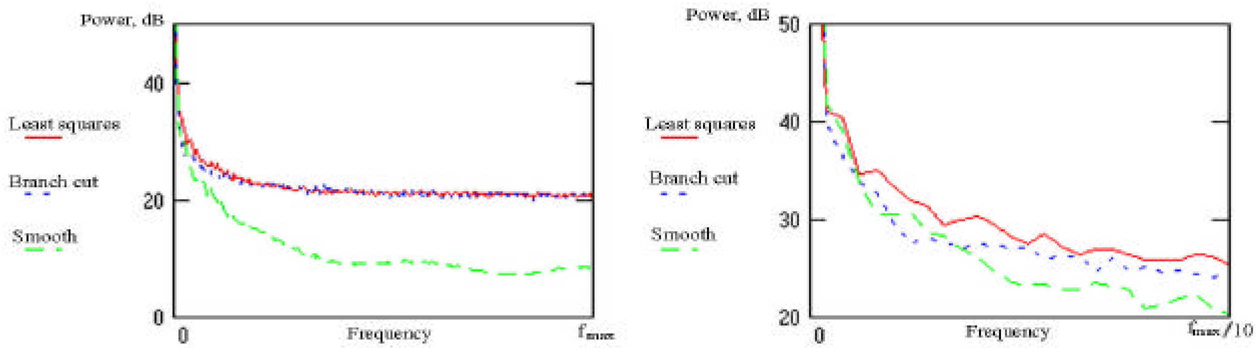
4.2 Comparison of Distortions

Least-squares algorithm smoothes the unwrapped phase in the areas of low weight. In the case of lakes it is useful because the water surface is flat. But in the case of converged interferometric fringes of high density (or foreshortenings) it results in the error of several periods, which means dozens of meters in digital elevation model. And the investigator should remember that this method makes slight distortions even in the regular areas all over the image in order to ensure continuity of the solution.

Distortions produced by local methods have other characteristics. Firstly, in the case of rugged topography it is difficult to avoid inconsistencies in the resulting unwrapped phase. Just one irregular non-masked pixel can generate discontinuity line. Such distortions follow the integration paths. Secondly, in the case of numerous residues the location of cut lines is ambiguous; hence the solution is also ambiguous.

4.3 Spectra Comparison

The comparison of algorithms according to spectral properties of unwrapped phase is presented on Fig. 2. On Fig. 2 f_{max} denotes maximal spatial frequency. A green dashed line corresponds to frequency estimation method applied to the interferogram smoothed by 5x5 window. Other methods were applied to non-averaged interferogram. The noise suppression in the case of smoothing is about 6–12 decibels on the frequencies over $f_{max}/10$. The noise levels for least-squares and branch cut algorithms are very close to each other at higher frequencies. It means that the least-squares algorithm does not possess properties of low-pass filter in a form of sliding window. But at lower frequencies one can see increase of spectral power up to 3 decibels. It may be explained by presence of large-scale deviations of the phase unwrapped by least-squares algorithm.



a) b)

Fig. 2.

Spectra of spatial frequencies for unwrapped phases computed by three algorithms in the case of plain topography.
a) full spectral band, b) low frequencies band
Red and blue: least-squares and branch cut algorithms, non-averaged interferogram;
green: frequency estimation algorithm, smoothed interferogram.

5 RESUME

Summarizing the results of comparison for phase unwrapping algorithms, we formulate the following statements.

For areas of moderate topography without numerous discontinuities in the interferogram, the choice of algorithm has an influence not on the result of the unwrapping, but on the computational details (e.g., in least-squares algorithm the sizes of the image should be increase to the nearest power of 2 before processing).

For areas of moderate noise with medium coherence the least-squares global approach gives the result more readily than branch cut or frequency estimation local methods.

For the case of numerous discontinuities (shadowings, layovers, and converging interferometric fringes) the least-squares algorithm gives just a qualitative assessment of unwrapped phase. Such interferograms can be unwrapped using local methods. The choice between frequency estimation method and branch cut method depends on data. The balance between number of isolated areas and number of objectionable passes (resulting in discontinuities) gives a key for the preference. Global approach can be applied in this case for getting an overview on the phase function behavior in the surroundings of is olated areas.

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