COMPARISON OF PHASE UNWRAPPING PERFORMANCE USING A NOISY INTERFEROGRAM

Ian Cumming, and Wei Xu — Radar Remote Sensing Group (RRSG), Dept. of Electrical & Computer Engineering, University of British Columbia, 2356 Main Mall, Vancouver, BC, Canada V6T 1Z4

ianc ee.ubc.ca , weix ee.ubc.ca
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Abstract

In this paper, we present a comparison of the phase unwrapping of the noisy Sardegna interferogram between the new region-growing algorithm and two of the most widely-used phase unwrapping algorithms: the cut-line algorithm and the weighted least squares algorithm, by verifying the unwrapped phase with topographic map data.

The verification and comparison show that the region-growing algorithm unwraps more of the low-coherence areas successfully, and makes fewer ambiguity errors than the other two algorithms.

Keywords: Phase unwrapping, Region-growing, Cut-line, Weighted least squares, DEM

Introduction

Phase unwrapping has been a difficult step in interferometric SAR processing. A number of phase unwrapping algorithms for SAR interferograms have been proposed. However, none of the existing phase unwrapping algorithms give satisfactory results when noisy and/or dense fringes occur. We have developed a new region-growing phase unwrapping algorithm, which can cope with very noisy interferograms [1,2]. The verification of the unwrapped phase of the noisy Sardegna interferogram will help to compare the performance of the algorithms.

The Region Growing Algorithm

The success of phase unwrapping algorithms often depends upon the path selected to perform the unwrapping, or the lack of a path. In the region growing algorithm, better performance is sought by dynamically adjusting the unwrapping path according to local noise and phase continuity conditions. The algorithm is also able to correct unwrapping errors to a certain extent, and to stop their propagation. The algorithm achieves these goals in the following way:

- Unwrapping is carried out concurrently in a number of regions. A region is started from a seed where the phase is locally smooth and is allowed to grow outwards along controlled data-dependent paths during the unwrapping procedure.
- Each pixel is unwrapped based on predictions made from its unwrapped neighbours. Unlike other algorithms, the predictions allow phase changes between two adjacent pixels larger than *pi*.
- Information from as many directions as possible is used to unwrap each pixel. This mitigates the effect of errors in the individual prediction directions.
- A reliability check based on the consistency of phase predictions is applied to each unwrapping attempt to validate (or disallow) the proposed unwrapping value.
- The reliability tolerance is gradually relaxed to allow as many pixels as possible to be unwrapped while keeping the unwrapping consistency above a specified level.
- When regions grow together, an attempt is made to merge them. Consistency checks are applied to the ambiguity numbers of the common pixels. If merging is allowed, the ambiguity numbers of the merged regions are adjusted accordingly.

Unwrapping the Sardegna ERS-1 Interferogram

The Sardegna Interferogram

The ERS-1 data of Sardegna, Italy, collected on August 2, 1991 (orbit 241) and August 8, 1991 (orbit 327) with 126 m perpendicular baseline was used to test the unwrapping algorithms. A 16 km square portion of frame 801 was used, centered at 40 degrees 8 minutes North and 9 degrees 32 minutes East, and situated towards the far range of the full scene. The interferogram was formed, smoothed to square pixels, and roughly flattened. The phase and local coherence of the 512 x 512 pixel interferogram are shown in Fig. 1.

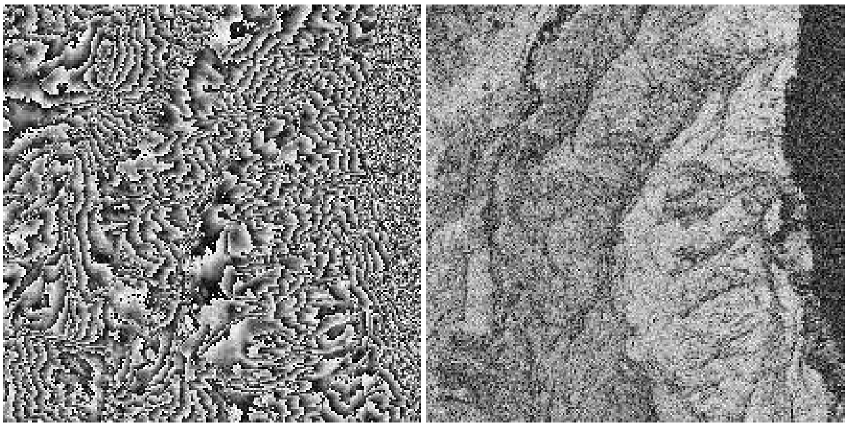

Fig 1: Phase (a) and coherence (b) of the Sardegna interferogram

This SAR interferogram is considered to be difficult to unwrap because of its large areas of low coherence, which are mainly caused by layover due to the extreme local topography. These areas of low coherence segment the interferogram into many pieces, which creates structural difficulties for the unwrapping algorithms [2].

Unwrapping Using Three Algorithms

The Sardegna interferogram was unwrapped using the region-growing (RG) algorithm with typical quality control parameters . The phase of the largest unwrapped region is shown in Fig. 2. The algorithm automatically recognizes that the low-coherence sea area on the right side should not be unwrapped. The low-coherence regions caused by layover in the land area are prominent in the figure as they are left wrapped, although small isolated unwrapped areas may be present in some of the black areas.

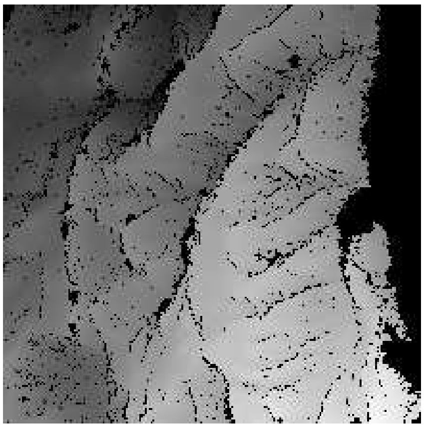

Fig 2: Unwrapped phase using the RG algorithm (click here for the positions of the verified lines)

Unwrapping using the "cut-line" (CL) algorithm was implemented by Dr. Ian Joughin of JPL [3], using a modified version of the original CL algorithm [4]. The phase of the largest unwrapped region is shown in Fig. 3a. Again the sea area is not unwrapped. However, the CL algorithm has not been able to merge a large area in the bottom left of the interferogram (shown black in Fig. 3a) into the main unwrapped area.

The unwrapping using the "weighted least squares" (WLS) algorithm was implemented at DLR [5], and the resulting unwrapped phase is shown in Fig. 3b. The WLS algorithm gives a result which is pleasing in appearance because of its completeness and smoothness, but it is clear that misleading results are obtained in the sea area and in places of sharp topography.

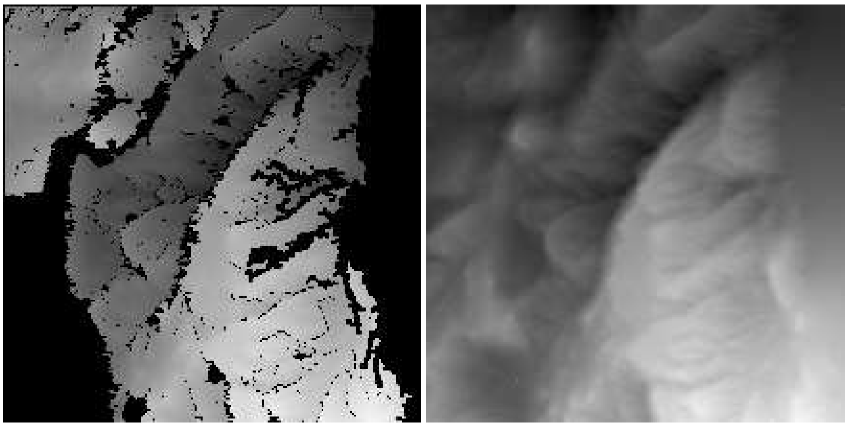

Fig 3: Unwrapped phase using CL (a: left) and WLS (b: right) algorithm

Verification of the Unwrapping with Map Elevations

Although the three algorithms agree well in some regions, there are many parts of the interferogram where the unwrapping results disagree substantially. In these cases, ground truth can be used to understand and resolve the differences, thereby helping to evaluate the unwrapping quality of the three algorithms. As accurate digital elevation model (DEM) data for the whole interferogram was not available to us, elevation data from a 1:25,000 topographic map for 5 range lines are used to compare the algorithms.

A Representative Range Line

Range line 127 (see Fig. 2) is chosen as a representative range line because all three algorithms unwrapped most of the pixels on this line, and challenging topographic features are present. As the interferogram is not accurately flattened, it is useful to begin by comparing the unwrapped phase of the three algorithms. This is a fair comparison because the imperfect flattening affects the results of each algorithm equally. The comparison of phases is shown in Fig. 4a. Gaps in the RG and CL curves indicate where the phase values are not unwrapped (or are unwrapped into unjoined regions).

The following observations can be made for each group of range cells (RC) in Fig. 4a:

RC 196-310: The best agreement occurs in this area because it is here that a datum was chosen to align the ambiguity levels of the three algorithms. The WLS exhibits smoothing in the lower-coherence area around RC 275.
RC 1-105 and RC 131-165: The largest differences are evident in this area: differences of 11 ambiguities between the CL algorithm and the RG algorithm, and 5.5 or 6.5 ambiguities between the WLS algorithm and the RG algorithm.
RC 106-130 and RC 166-195: The RG algorithm worked through or around the low-coherence areas. The WLS algorithm smoothed over these areas, while the CL algorithm left it not unwrapped.
RC 326-440: The three algorithms are roughly one ambiguity apart in this area, with the CL algorithm losing 2 ambiguities relative to the other two algorithms at the break near RC 365.
RC 440-512: Only the WLS algorithm mistakenly attempts to unwrap the area of the sea.

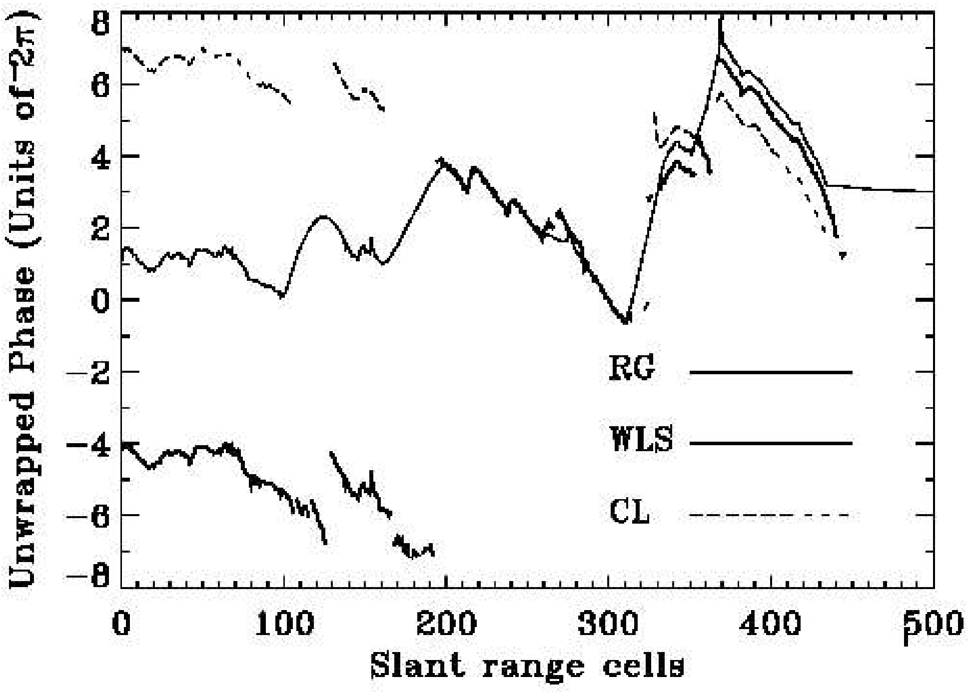

Fig 4a: Comparison of unwrapped phase for line 127

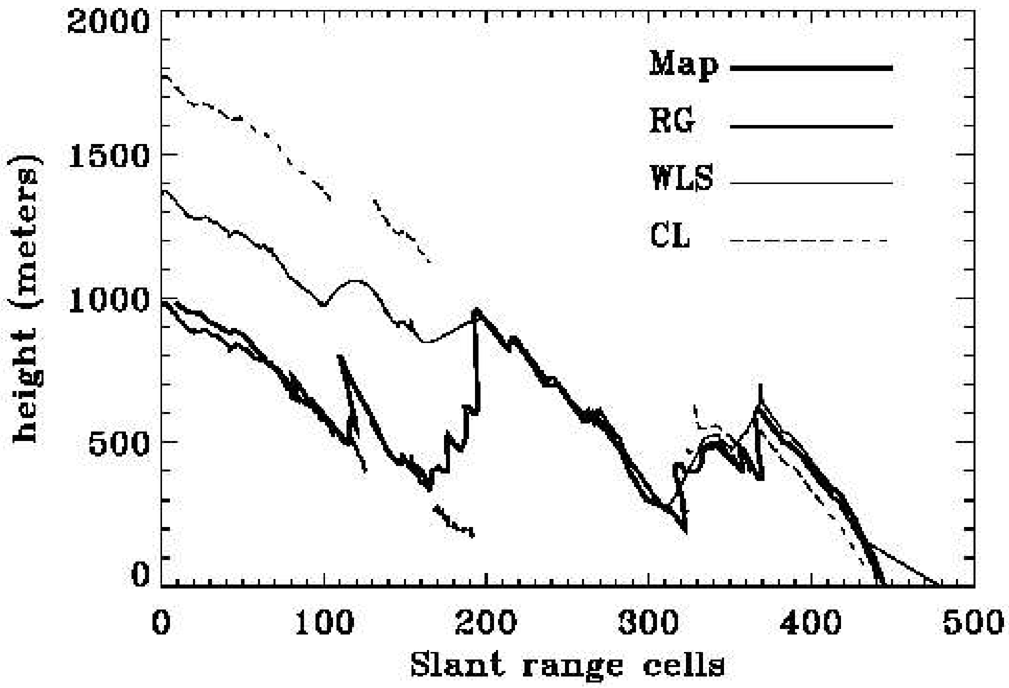

Fig 4b: Comparison of elevation for line 127

In Fig. 4a, the fine structure of the phase of the three results agree reasonably well, but major differences exist in the ambiguity levels. The map elevations will be used to identify which of these solutions is best.

To verify the unwrapped phase values, they were converted to elevation values and then compared to the elevation data from the maps. The elevation data was read from the 1:25,000 topographic maps in the ground range domain and then converted to the slant range domain.

After using map data to refine the interferogram flattening, the phase-derived elevations are compared with the map elevations in Fig. 4b. One ambiguity of 2 corresponds to about 70 m of elevation change with this 126 m baseline.

From the comparison in Fig. 4b, the following observations can be made:

> RC 196-310: All algorithms agree closely with the map in the left half of this high-coherence region. In the right half, small differences with the map are observed, which could be due to errors in reading the map or due to the radar scattering properties.
> RC 1-105 and RC 130-165: The RG algorithm agrees closely with the map in these regions, because it has been most successful in propagating the absolute phase from the central region. The more limited abilities of the WLS and CL algorithms to follow absolute phase over difficult regions have resulted in offsets of about 5.5/6.5 and 11 ambiguities (about 400 and 800 m) respectively.
> RC 106-130 and RC 166-195: The RG algorithm is the only one to effectively unwrap into the gaps. It agrees closely with the map in RC 106-115, but it makes local mistakes of up to 5 ambiguities (about 350 m) in the other areas in doing so. However, these errors are restricted in small areas as a result of the intelligent unwrapping path. Moreover, with a proper adjustment to the region merging quality check thresholds, these errors may be avoided.
> RC 326-440: The RG algorithm and WLS algorithms both work well in this region, with WLS giving a slightly better result. The CL algorithm is more bothered by the steep topography near RC 365, losing 2 ambiguities (about 150 m).

Other Range Lines

The other range lines chosen for verification are line 63, line 191, line 255, and line 383 as shown in Fig. 2. Fewer lines are chosen near the bottom because DEM values are only available on the near range side there.

The comparison of phase-derived elevations with the map elevations for these lines are shown in Fig. 5.

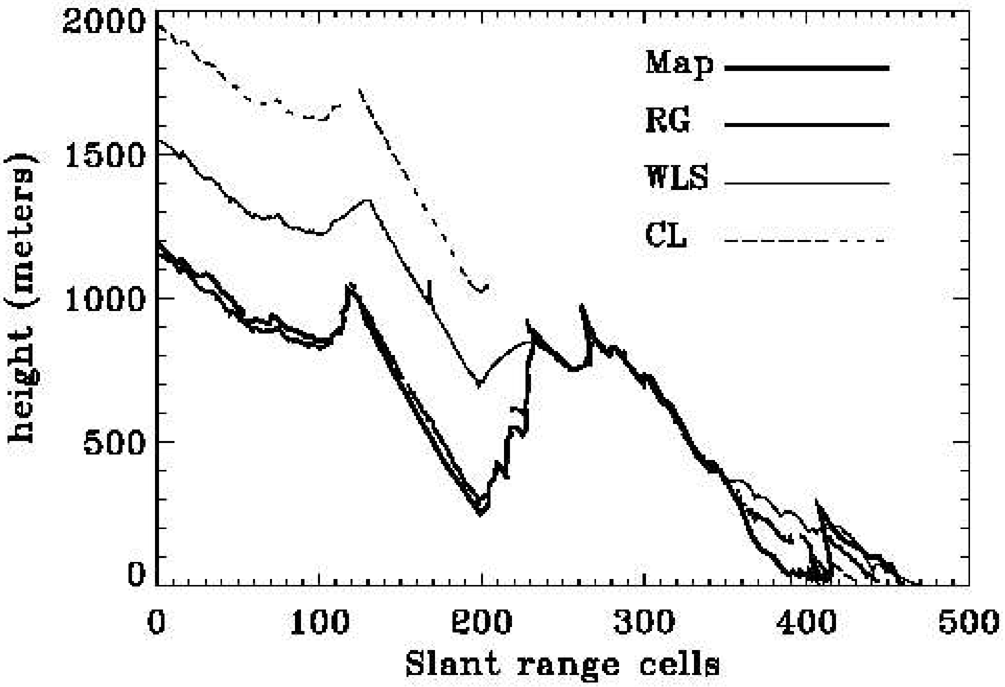

Fig 5a: Comparison of elevation for line 63

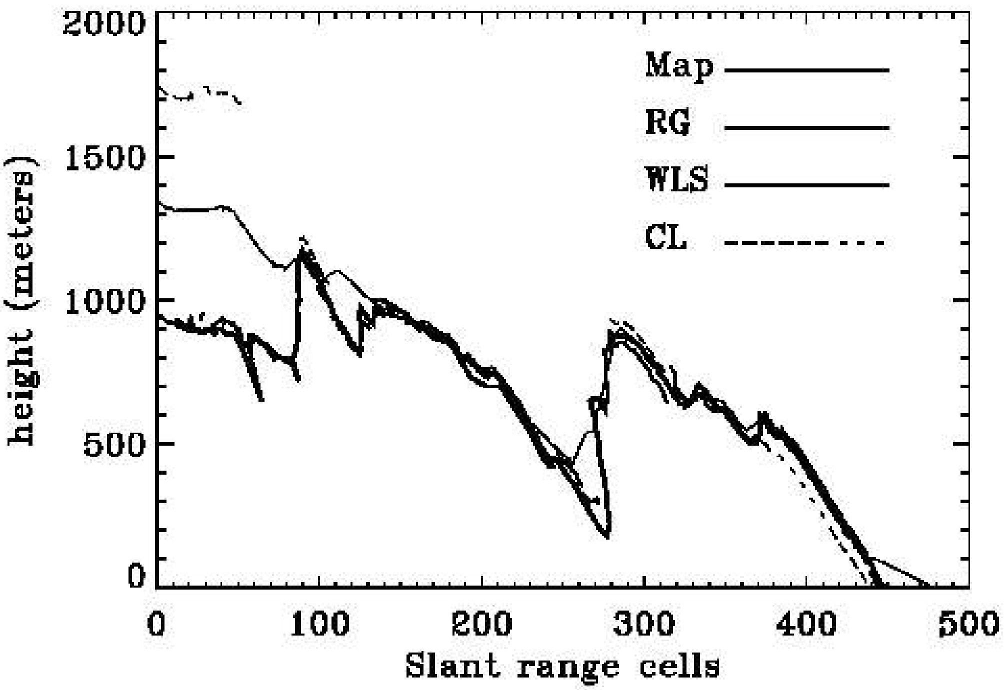

Fig 5b: Comparison of elevation for line 191

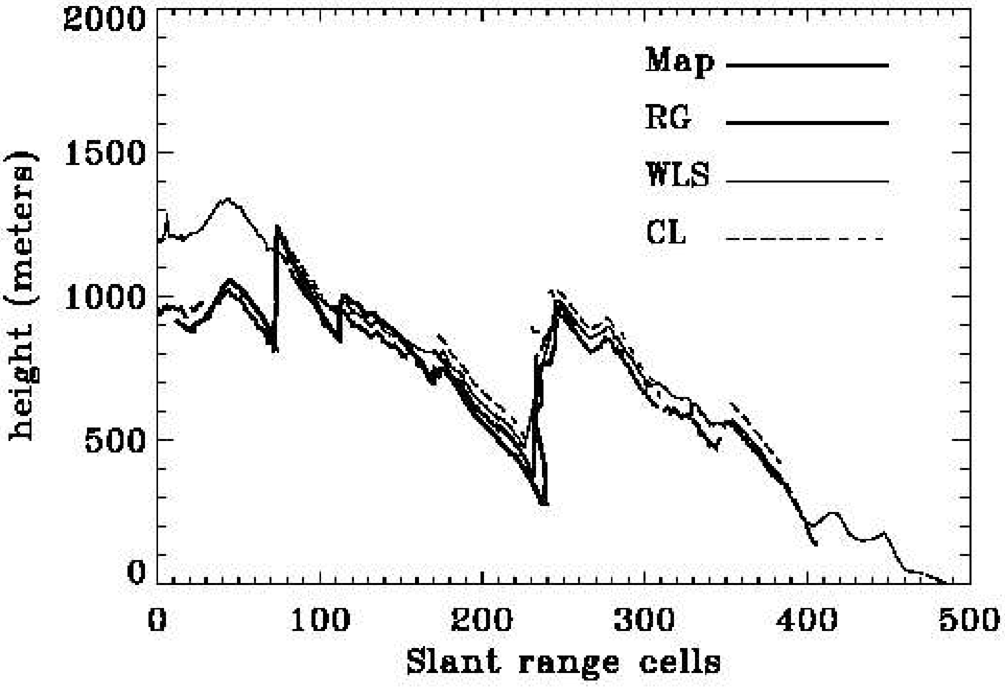

Fig 5c: Comparison of elevation for line 255

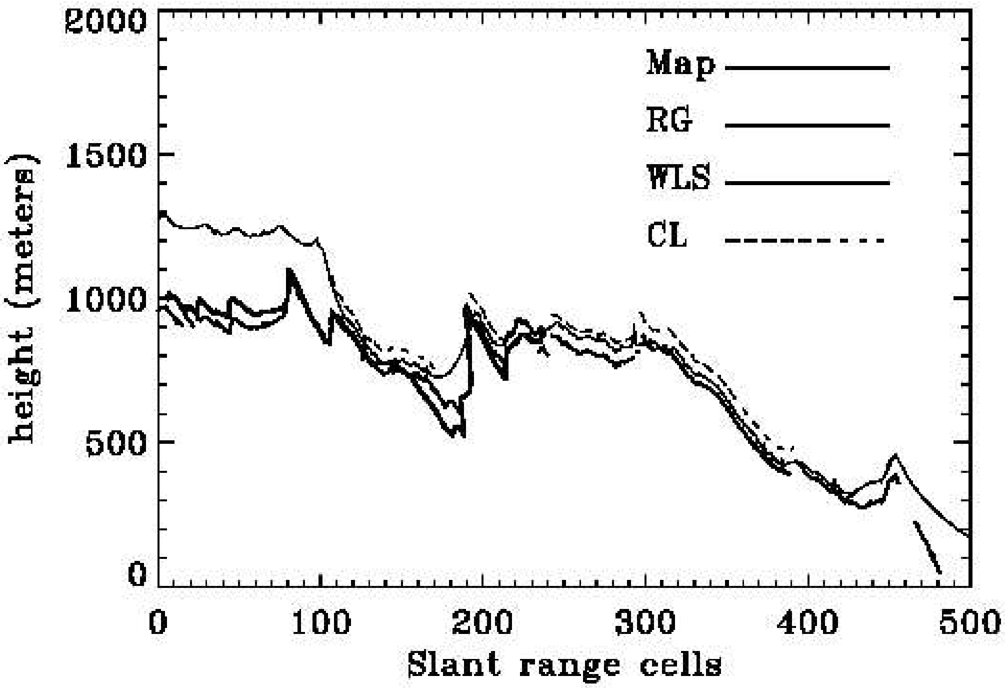

Fig 5d: Comparison of elevation for line 383

Although errors in the map elevations within one ambiguity exist, as the purpose of the verification is to show the correct ambiguity rather than to measure the exact error of the InSAR derived heights, the accuracy of the map derived heights is sufficient. The RMS differences to the map elevations are shown below in Tab. 1.

Range Line Number	63	127	191	255	383
RG vs. Map	54	96*	52	51	45
WLS vs. Map	281	256	169	159	182
CL vs. Map	542	473	271	105**	87**

Tab. 1: RMS differences (meters) between the InSAR-derived and map elevations

** The large error is mainly caused by the layover at RC 190-192.*
*** The CL algorithm does not provide unwrapped phase in the difficult area.*

From Fig. 5 and the table values, the following observations can be made.

On the left side of the image where large differences exists among the three algorithms, the RG algorithm provides the correct ambiguity in most areas with errors of only one ambiguity in other areas. In contrast, the WLS algorithm shows large errors of about 5 ambiguity levels, and the CL algorithm shows the largest errors of about 10 ambiguity levels in the top lines where unwrapped phase is available or is not able to provide the unwrapped phase. In the remainder of the area where the difference between the algorithms is generally within one ambiguity.

The error from the RG algorithm is generally with one ambiguity RMS, which is partly caused by the inaccuracy of the map elevations, except in the line 127 where unwrapping around RC 190-192 proceeds from the facing slope while the regular spaced map elevations take the value from the back slope and cause about 400 m additional error. The WLS algorithm is with 2-4 ambiguities RMS. The CL algorithm is generally with 4-8 ambiguities RMS, except in the line 255 and 383 where unwrapping in the difficult area are not provided and the error looked smaller.

The observations from the additional range lines are in general agreement with the observations from the representative range line.

Discussion

In the comparison with map data, the RG algorithm has proven to be less susceptible to large errors that can occur in noisy areas of the interferogram. This is largely because of the ability of the RG algorithm to venture deeper into noisy regions, attempting to work its way through from many different directions and stop unwrapping from unreliable directions. Therefore, the comparison illustrates the effectiveness of the region growing algorithm in unwrapping difficult areas.

In the authors opinion, the CL algorithm results in unwrapping errors because it cannot avoid linking the wrong pairs of residues when the residue density is high. Also, the WLS algorithm results in unwrapping errors because it tries to fit the unwrapped phases to a smooth model in low-coherence areas, which is not valid in areas of significant topographic changes.

As the 5 lines examined spans the interferogram from the top to bottom, our observations above will likely apply to other areas of the interferogram.

Conclusions

With the help of 1:25,000 topographic maps, the unwrapped phase of the Sardegna interferogram has been verified along a representative set of range lines. In the verification, the region-growing phase unwrapping algorithm was compared with two of the most popular algorithms available. The Sardegna interferogram was used for the comparison, because it has extreme topography, which has caused problems for many other phase unwrapping algorithms. It has been shown that the region-growing algorithm can successfully unwrap further into the low-coherence regions than the other two algorithms, and makes fewer ambiguity-level errors. This is because of its ability to work across and around low-coherence regions, which results in more accurate connecting of the high-coherence regions. This results in a higher proportion of the interferogram being unwrapped, and more regions being joined into one contiguous region.

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