Phase unwrapping using coherence measurements.

Dominique Derauw

Centre Spatial de Liège, University of Liège
Avenue du Pré Aily, B4031 Angleur, Belgium.
Phone : ++ 32 41 67 66 68 Fax.: ++ 32 41 67 56 13 e-mail: CSLULG@VM1.ULG.AC.BE

1. ABSTRACT

We propose a method of phase unwrapping based on residue connection[1], using coherence measurement as a complementary information source. Coherence measurement are shown to be improved when an approximated phase due to topographic fringes is removed. The coherence map so obtained is used as a mask to guide connection process.

2. INTRODUCTION

The phase in a SAR interferogram is given modulo-2π and must be unwrapped to recover the absolute phase values which yield the correct optical path differences (OPD's). To do so, the phase must be integrated adding or subtracting 2π when a phase jump is detected. There are, however, phase errors due to time decorrelation, baseline decorrelation or layover and shadowing effects. The integration path must then be carefully chosen to avoid error propagation . We use the residue method[1][2] , which identifies the residues (points generating a phase error of ±2π when integrating on a path surrounding them) and connect them to obtain a global connection having a null charge (e.g., containing as many residues generating a positive error as residues generating a negative error). The residue connection is based on coherence measurements.

A study of the coherence measurements in SAR interferometry lead us to build a new processor for phase unwrapping. It is well known that coherence measurements are improved when the phase due to the relief of the observed scene is not taken into account in the calculation. Accordingly, we propose to measure coherence after removing an approximated phase due the local heights. This procedure allows us to obtain a coherence map, corresponding more closely to the scene decorrelation, in which the location of the phase discontinuities are clearly visible. After residue detection in the filtered interferogram, this map is used as a mask to guide the connection of residues belonging to the same discontinuity.

3. COHERENCE

Coherence is a measure of the correlation between two signals. Two radar echoes will be coherent if each represents nearly the same interaction with a set of scatterers. For imaging radars, coherence implies that the speckle patterns are similar[3][4][5]. Eq. 1 expresses the returned signal corresponding to one pixel in the i^{th} image:

$$\mathrm{Im}_i(x,z) = \left|\mathrm{Im}_i(x,z)\right| e^{-jk_{z0}z}\, e^{j\varphi(x,z)} \qquad (1)$$

where (x,z) are the azimuth-range coordinates of the considered pixel. The first phase term, $k_{z0}z$, corresponds to the optical path. The second phase term, φ(x,z), is the phase resulting from the superposition of all the signals emitted by the independent scatterers within the pixel. This reconstruction phase yields speckle. When generating the interferogram, this reconstruction phase must be preserved to cancel correctly, giving rise to an interferogram in which the phase depends only on OPD's (eq. 2):

$$\mathrm{Im}_1\, \mathrm{Im}_2^* = \left|\mathrm{Im}_1\right|\left|\mathrm{Im}_2\right| e^{jk_{z0}(z_2-z_1)}\, e^{-j(\varphi_2-\varphi_1)} \qquad (2)$$

There are two main sources of decorrelation, i.e.,time decorrelation and baseline decorrelation. If the scene changes between the two takes, more precisely, if the independant scatterers within a pixel move or change, the reconstruction phase will vary and a loss of coherence will occur. This corresponds to time decorrelation. Baseline decorrelation stems

0-8194-1948-6/95/$6.00

from the fact that each terrain element corresponding to a pixel is observed with a different view angle in each image of the interferometric pair. The relative position of the independant scatterers within the pixel will vary from one observation to the other inducing a different reconstruction phase, in other words, another speckle figure. This geometric phenomenon is highly dependent on the local slope of the observed pixel. Baseline decorrelation is then clearly visible in case of foreshortening and layover. In fact, each time aphase error, or a phase discontinuity is present, whatever is its origin, it will induces a local loss of coherence. It is thus assumed that coherence is a reliable information source to connect residues belonging to the same phase discontinuity.

4. COHERENCE MEASUREMENTS

Since the scene decorrelation is only related to reconstruction phase decorrelation, it is clear from eq. 2 that the topographic fringes (fringes from OPD's) must be removed to perform a correct coherence measurement.

As we, a priori, do not know the relief, since it is the information we are looking for, we have to approximate the phase it induces. As a first approximation, one can use the flat Earth phase. Figure 1 shows the coherence map obtained without any phase correction on a small sample of an interferometric pair. Figure 2 shows the coherence map evaluated on the same sample but after flat Earth phase removal. It is interesting to see that some regions that seem to have high coherence in the first calculation show lower coherence in the second and conversely, which shows that phase due to the relief perturbe the measurement. In the two measurements, we get the same histogram but not the same information. The completely black zone on the right corresponds to the sea.

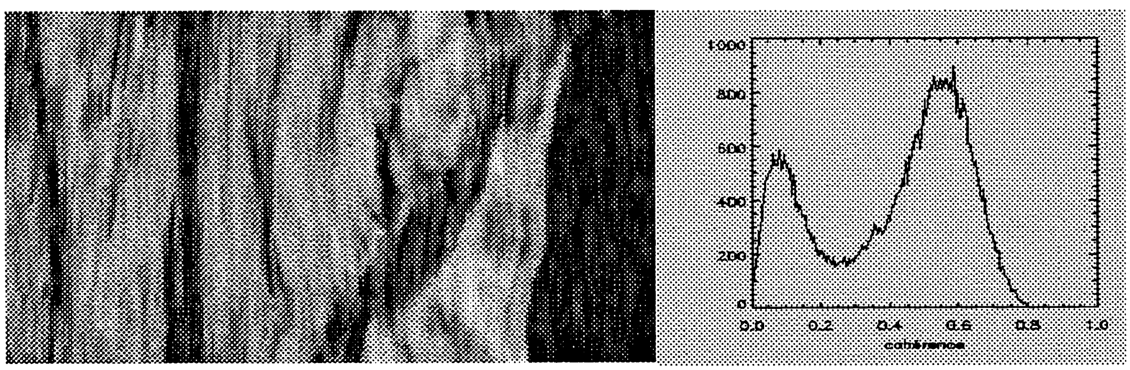

Figure 1. Coherence measurement without any phase correction.

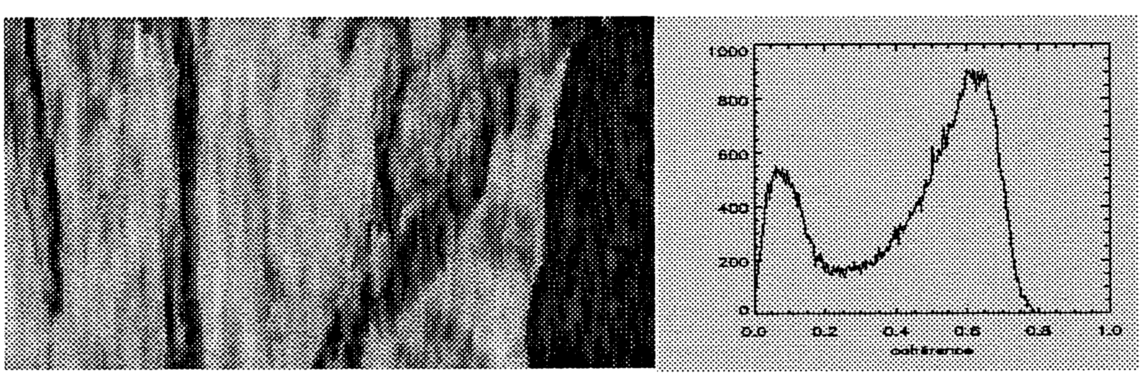

Figure 2. Coherence measurement after flat Earth phase removal.

As a first conclusion, removing the flat Earth phase may not be suitable particularly in hilly regions as it is the case here. We thus have to find another way to evaluate the phase due to the relief.

4.1. Approximate calculation of the phase due to local heights.

The phase due to local heights may be evaluated using the filtered interferogram. Figure 3 shows the original and the filtered interferogram used.

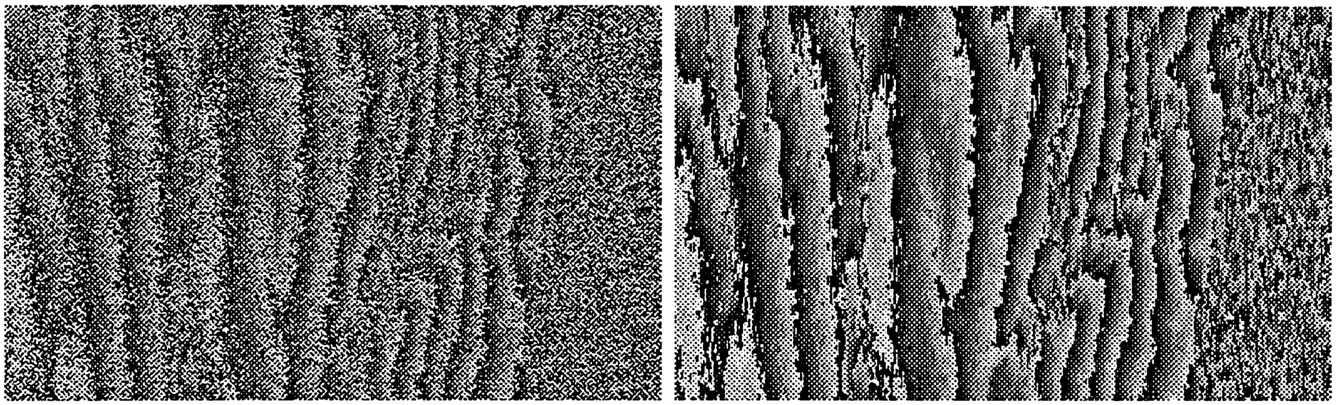

Figure 3. Original and filtered interferogram

For each point, we use the filtered interferogram to find the best local plane of phase. Its slope depends on the local OPD variation. This plane corresponds, thus, to the phase due to local altitudes, and the noise around comes from the reconstruction phase difference (eq. 2). To evaluate the best local plane of phase, we unwrap the phase spirally around the considered point (Fig. 4), and the best plane is found by mean square calculation. Next, this best local plane of phase is retrieved from the original (or from the filtered) interferogram, and so on for each point, before classical coherence measurement. Even if this method seems heavy and complicated, this phase retrieval corresponds to simply deducing the mean phase obtained by spiral phase unwrapping.

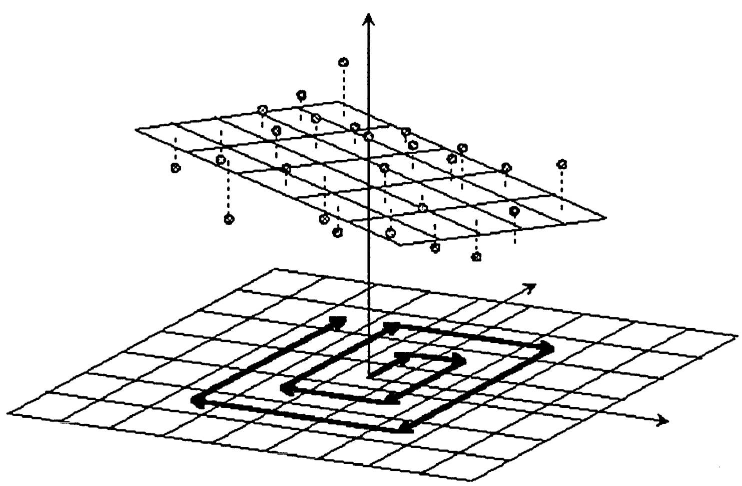

Figure 4. Evaluation of the local plane of phase.

When correcting the original interferogram, we obtain a coherence map that corresponds more closely to scene decorrelation (Fig. 5). We can see that we obtain now a relatively uniform coherence in regions where the fringes shows a good signal to noise ratio (SNR) even if the fringe spacing is different. Conversely, losses of coherence are more contrasted. Since we have now a more appropriate scene decorrelation measurement, it is expected that some information about soil structure or vegetation cover might be obtained (study in progress).

Since it is the filtered interferogram that will be unwrapped, we may also correct this one, following the above procedure, and use it to measure the coherence associated to it. If the filter used is an interferometric multilooking process, the coherence map so obtained corresponds to the true scene decorrelation, with reduced resolution. If another kind of filter is used, the result obtained is not strictly speaking the coherence, but an information that is closely related to it (Fig. 6). In any cases, low coherence regions enclose residues and actual phases discontinuities. Thus, this kind of information may be used to guide the connection process.

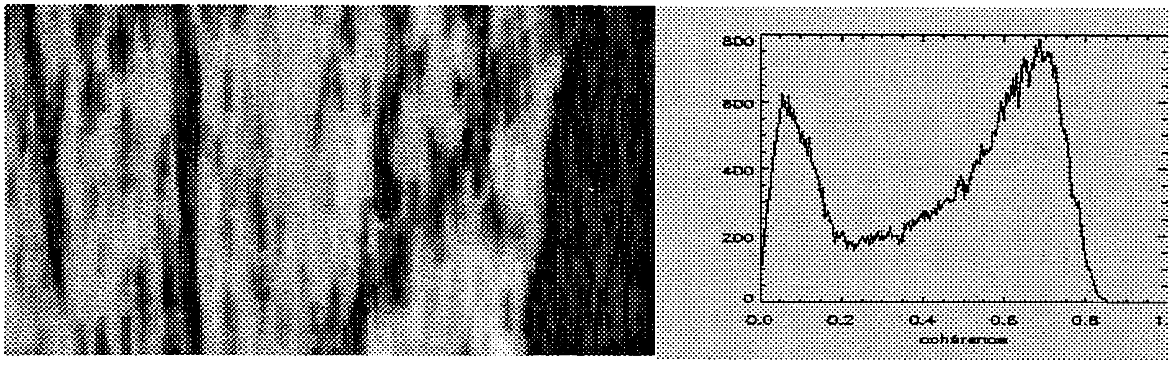

Figure 5. Coherence measured from the corrected original interferogram.

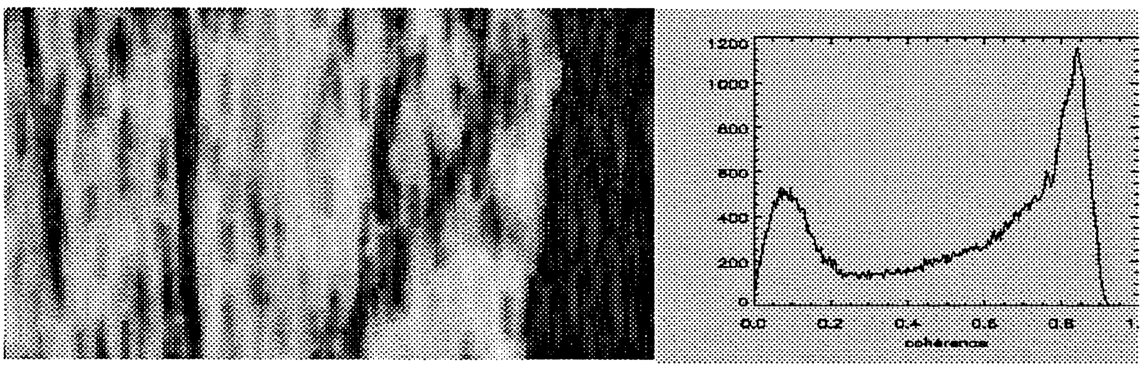

Figure 6. Coherence measured from the corrected filtered interferogram.

The patched aspect of these results comes from the fact that the local plane of phase is approximated on a square that is shifted pixel by pixel. Moreover, when a residue is met during spiral unwrapping, it induces a false result giving rise to low coherence as expected. But, the more the square is enlarged, the more the low coherence zones spreads out giving as result an underevaluated coherence.

5. RESIDUE CONNECTION AND PHASE UNWRAPPING

Residue connection is based on two criteria. The first one is the minimal distance between residues as in the method proposed by Goldstein & al.[1]. The second criterion is derived from the hereabove results: Two residues may be connected if and only if they belong to the same phase discontinuity. To satisfy this second criterion, the map of coherence is used as a mask to guide the connection process. The main possible source of errors is the presence of borders. When a connection encounters a border, it has to be considered as good even if its charge is different from zero, leaving some orphan residues. Generally, this case is very well handled, since the connection starting from these orphan residues will follow the same low coherence guide till it meets the already formed connection. A problem appears when a phase discontinuity crosses right through the image. As early as a border is met, the connection is stopped. When starting from an orphan residue, a connection with the other border might be created, giving rise to two, or more, connections in place of one. To overcome this problem, the easiest way to proceed, is to use the coherence image as a binary mask superimposed to the residue connections to forbid phase unwrapping in regions having coherence under a preset threshold

Figure 7 shows the image of the connections obtained as described hereabove. Figure 8 shows the residue connections with a coherence mask corresponding to a threshold of 0.2 (see histograms). Both are superimposed to the coherence map used for residue connection.

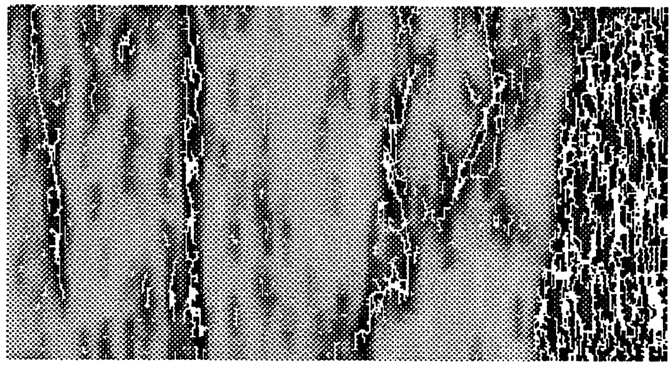

Figure 7. Residue connections superimposed on the coherence map.

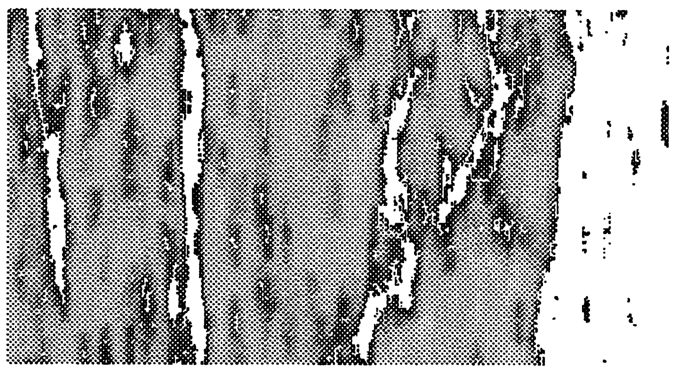

Figure 8. Residue connections and coherence mask superimposed to the coherence map.

The filtered interferogram is then unwrapped using the connections presented figure 8. The altitudes deduced from the unwrapped phase are presented in gray levels on figure 9.

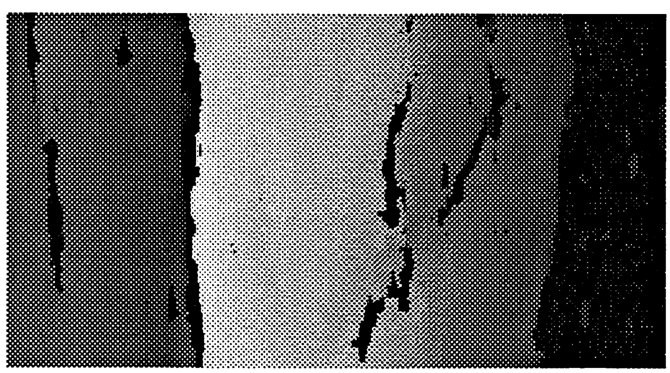

Figure 9. Altitudes, in grey levels, calculated from the unwrapped phase.

We can see two seperated regions who were unwrapped independently. These one corresponds to those who are clearly visible in the coherence map. In each of the regions, the unwrapped phase is continuous on both sides of small connections showing that they were correctly located. The coherence threshold was chosen in order to avoid phase unwrapping in the region corresponding to the sea. Considering regions under a preset coherence threshold as forbidden, will ensure us to unwrap only regions where the phase make sense.

6. CONCLUSIONS

It is shown that the coherence measurement is strongly improved when removing, from the calculation, the phase component due to topography, even approximated.The CSL phase unwrapping processor is based on these improved coherence measurements. The resulting coherence image, which depends on phase confidence, is used as a mask to guide residue connections. Since it use an information closely related to the actual phase discontinuities, it allows to perform a completely automated phase unwrapping ensuring a minimal error rate.

7. ACKNOWLEDGEMENTS

This work was supported by the Belgian Services Fédéraux des Affaires Scientifiques, Techniques et Culturelles (SSTC), under Contract Nr. T3/12/012 of the TELSAT-III National Remote Sensing Program.

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