Multi-Baseline Interferometric SAR for Iterative Height Estimation

Douglas G. Thompson, Adam E. Robertson, David V. Arnold, David G. Long
Brigham Young University
459 CB, Provo, UT 84602
voice: 801-378-4884, FAX: 801-378-6586, e-mail: thompsod@ee.byu.edu

Abstract— The tradeoff in choosing baseline length in interferometric SAR is that short baselines allow higher error while long baselines cause greater phase unwrapping problems. Combining information from baselines of different lengths can take advantage of the greater accuracy of long baselines while determining the phase wrapping from shorter baselines. This paper describes an iterative method which starts at the shortest baseline and proceeds to longer and longer baselines. The height is estimated for each baseline, using the previous estimate only to determine the phase wraps. If the signal-to-noise ratio of the interferometer is known and a value for the probability of error in the phase wraps is chosen, an optimal sequence of baseline lengths can be calculated. Simulations show that errors tend to propogate and become worse, so mean or median filters are used between each iteration. This paper will describe the technique and show examples from a simulated scene.

INTRODUCTION

The applications of interferometry are limited by the restrictions imposed by the wrapped nature of the phase data. Phase unwrapping algorithms typically fail to determine the phase for regions of data isolated by phase discontinuities. In this paper, we propose a method to use multiple baseline lengths to reduce or eliminate the need for phase unwrapping. The height of a scene can be unambiguously resolved, even for regions of the image isolated by phase discontinuities.

Several other methods for reducing or eliminating phase unwrapping have been proposed, e.g. [1, 2, 3, 4, 5, 6]. Most of the proposed methods use an initial estimate of the height from a DEM or from a short baseline interferogram to resolve the ambiguity in determining ϕ from ψ. As stated in [5], "The main unresolved problem of this processing is still the error propagation of the noise effects." The use of multiple interferograms to determine the height may result in an increased amount of noise in the height estimate. Any linear combination of interferograms will result in an increase in the noise measurement and an unreliable estimate of the height of the scene. This work addresses the error propagation issue and presents an application similar to the projection method suggested by Xu et al. [1] to more than three antennas while minimizing the propagation of noise induced errors.

This paper briefly describes our iterative method of combining multiple baselines to improve the height estimate and gives the results of simulations.

ITERATIVE MULTI-BASELINE TECHNIQUE

Our multi-baseline technique [7] is iterative in that we first estimate the height map using a small baseline. We then proceed to larger baselines, each time using the previous estimate only to determine phase wraps. The final product combines the accuracy of the large baseline with the continuity of the small baseline.

This technique is applied in a very straightforward manner. An initial baseline length is chosen based on the known radar characteristics and the expected terrain such that no phase wraps are expected. A height map is generated from this baseline. The choice of the next baseline length is based on the error in the first height map. A new height map is generated from the longer baseline, using the previous height map to determine integer phase wraps. Errors in the first height map which correspond to phase changes greater than 2π in the second baseline will cause errors in the final height; errors smaller than this will disappear. Thus the second baseline length is chosen so that most of the error will disappear. The third baseline is similarly chosen so that most of the error from the second baseline will disappear. This process is repeated iteratively with longer baselines until the maximum number of baselines is reached or the baseline becomes so long that spatial decorrelation occurs. The probabilities of these errors depend on the signal-to-noise ratio (SNR) of the SAR data. In practice, these lengths will be chosen before the data is collected, so the lengths will be optimized for the instrument and a typical scene and may not optimize the probability of error for any particular scene.

Phase wrap errors may enter the estimate from large errors in initial height estimates at each step. These errors tend to propogate through the iterations and become worse, so it is important to minimize them. First, the probability of error used in determining the baseline lengths in each step must be chosen carefully. Second, either a median or a mean filter is used between iterations to further reduce the noise.

The baseline lengths for each step must be chosen carefully. If the next baseline is too short compared to the current one, the height errors will add, which increases the total error in the height estimate. If the next baseline is too long, the probability of integer phase wrap error will be too great. The total height error between two iterations can be written as $\sigma_{ht} = \sqrt{\sigma_{hs}^2 + \sigma_{hl}^2}$ where σ_{hs} is the height error with the short baseline alone and σ_{hl} is the error with the long baseline alone. The optimal value for λ^*, the height change causing a 2π phase

0-7803-5207-6/99/$10.00 © 1999 IEEE.

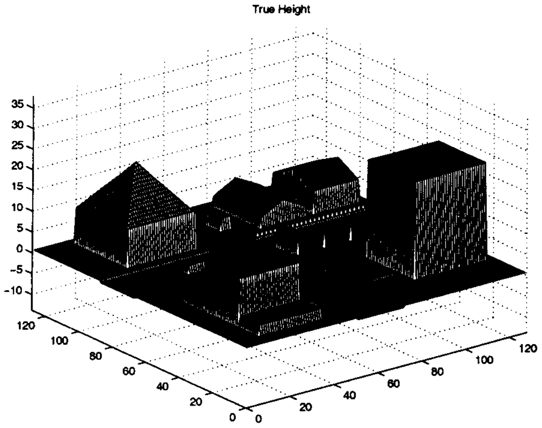

Figure 1: True Height of the Simulated Urban Scene

change, is

$$\lambda^* = 2\sigma_{ht}\mathrm{erf}^{-1}\left(\frac{1-P_{error}}{2}\right) \tag{1}$$

where P_{error} is the allowed probability of integer phase wrap errors. Since σ_{ht} is a function of σ_{hl} which in turn is a function of λ^*, this equation must be solved numerically. The optimum baseline length can then be determined from λ^* and the radar geometry.

SIMULATION

A synthetic urban scene is illustrated in Fig. 1. Georectification and the removal of the nominal flat earth induced phase difference are assumed. It is also assumed that data with an SNR of 10 dB is available at all points in the image. The examples shown here assume the imaging geometry given in Table 1.

Table 1: Interferometric Imaging Geometry

Parameter	Symbol	Value
Nominal Platform Height	H	300 m
Radar Wavelength	λ	0.03 m
Pixel Size	R_y	0.6 m
Baseline Length	B	1 m
Baseline Tilt	α	45°
Incidence Angle at Beam Center	θ	45°

Figure 1 gives the true height of the simulated scene. Each ground pixel represents 0.6 × 0.6 meters. The tallest building in the image is eight stories tall, assuming 3 m per story. The building with a pyramid shaped roof reaches a total height of 21 meters, and the smaller building in the foreground is four stories tall with 1 story side wings and steps leading up to the building (steps are not clearly visible from the perspective shown). In the upper corner of the image, one story and two story houses are simulated with 2 m high fence posts placed along the road. The road is 0.3 meters below the level of the buildings, the size of a large curb. A 3 m high truck and a 2 m high car are visible in the streets as well as a 6 m high 1 pixel wide bar representing a stop light support. 6 m street lights are represented between the tallest building and the houses.

For a comparison of standard phase unwrapping with multibaseline techniques, consider Fig. 2, the simulated height estimate from a single baseline using Flynn's minimum discontinuity phase unwrapping method [8]. Phase unwrapping algorithms can not determine the height of regions of the image isolated by phase discontinuities and consequently assume the step size is less than λ^*. When the phase is continuous, such as for the slanted roofs and the steps leading up to the building with side wings, the phase is properly unwrapped.

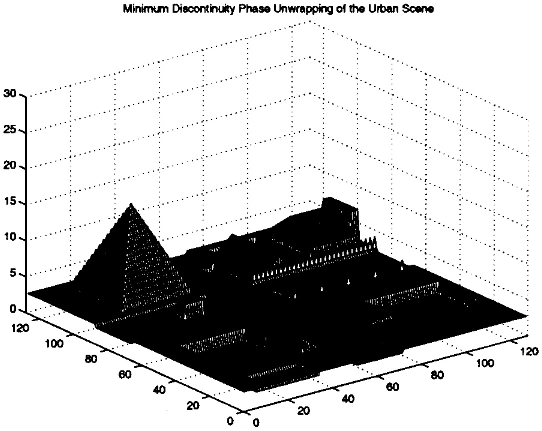

Figure 2: Height estimate of an urban scene using a single interferometric baseline and Flynn's minimum discontinuity phase unwrapping method. For simplicity, noiseless phase measurements were used. Phase unwrapping assumes any step discontinuity to have a magnitude of less than λ^*.

For our first example we use the mean filter with P_{error}, the probability of a phase wrap error at each iteration, set to 0.05. The rounding effects of the iterative spatial average are a noticeable undesirable side effect of the mean filter. Table 2 shows the baseline lengths for each iteration, the height λ^* which causes a 2π phase change for that baseline, $\sigma_{measured}$, the measured height accuracy for the simulation, and σ_h, the theoretical height accuracy for that baseline alone. The values for $\sigma_{measured}$ in the table are from a flat area in the scene and do not account for the rounding effect of the mean filter at each step discontinuity in the image. These values are lower than the theoretical primarily because of the filtering step. The results in the table are intuitively pleasing. For each iteration, the new value for λ^* is roughly half of the previous value. As the baseline length increases, the spatial decorrelation increases, and the percent change in λ^* correspondingly decreases. Figure 3

Table 2: Baseline length selection for $P_{error} = 0.05$. The measured standard deviations represent the result of a using a 3×3 mean filter to eliminate errors in the height estimate.

B	λ^*	$\sigma_{measured}$	σ_h
0.3	30.3	3.4	3.4
0.593	15.3	0.967	1.8
1.11	8.19	0.437	1.03
1.86	4.89	0.295	0.671
2.71	3.35	0.239	0.497

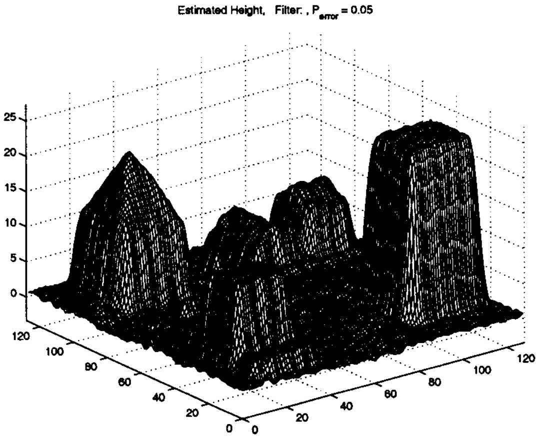

Figure 3: Final height estimate of the scene using a 3×3 mean filter. The resulting standard deviation is listed in Table 2.

illustrates the result of the iterations performed using the baselines in Table 2. As expected, the light poles and fence which were only one pixel wide are completely removed by the 3×3 pixel mean filter. The stop light support pole is undetectable for the same reason. The sides of the buildings all have a distinct slope due to this filter.

The median filter produces similar results without the undesirable rounding of the edges of buildings. Table 3 shows the baseline lengths used for $P_{error} = 0.05$ and the resulting height standard deviations, measured from each height estimate, $\sigma_{measured}$, and theoretical for a given baseline, σ_h.

SUMMARY

Phase unwrapping is an important problem in interferometry. In this paper we have presented an iterative method of combining multiple interferometric baselines to reduce or eliminate the need for phase unwrapping. This method has shown good results in simulations.

Table 3: Baseline length selection for $P_{error} = 0.05$. The measured standard deviations represent the result of a using a 3×3 median filter to eliminate errors in the height estimate.

B	λ^*	$\sigma_{measured}$	σ_h
0.3	30.3	3.4	3.4
0.593	15.3	0.773	1.8
1.11	8.19	0.45	1.03
1.86	4.89	0.297	0.671
2.71	3.35	0.225	0.497

ACKNOWLEDGEMENTS

This work was supported in part by a National Science Foundation Graduate Research Fellowship to DGT and by a NASA grant to DVA and DGL.

References

[1] Wei Xu, Ee Chien Chang, Leong Keong Kwoh, Hock Lim, and Wang Cheng Alice Heng. Phase-unwraping of SAR interferograms with multi-frequency or multi-baseline. *International Geoscience and Remote Sensing Symposium*, pages 730–732, 1994.

[2] J. Homer, I. D. Longstaff, and G. Callaghan. High resolution 3-d SAR via multi-baseline interferometry. *International Geoscience and Remote Sensing Symposium*, pages 796–798, 1996.

[3] Didier Massonnet, Helene Vadon, and Marc Rossi. Reduction of the need for phase unwrapping in radar interferometry. *IEEE Transactions on Geoscience and Remote Sensing*, 34(2):489–497, March 1996.

[4] Charles V. Jakowatz Jr., Daniel E. Wahl, and Paul A Thompson. Ambiguity resolution in SAR interferometry by use of three phase centers. *Proceedings of the — SPIE - The International Society for Optical Engineering,*, 2757:82–91, 1996.

[5] G. Corsini, M. Diani, F. Lombardini, and G. Pinelli. Reduction of the phase-unwrapping drawbacks by the three-antenna interferometric SAR system. *International Geoscience and Remote Sensing Symposium*, pages 1536–1538, 1997.

[6] Klaus Schmitt and Werner Wiesbeck. An interferometric SAR processor avoiding phase ambiguities. *International Geoscience and Remote Sensing Symposium*, pages 1713–1715, 1997.

[7] Adam E. Robertson. Multi-baseline interferometric SAR for iterative height estimation. Master's thesis, Brigham Young University, Provo, UT, December 1998.

[8] Dennis C. Ghiglia and Mark D. Pritt. *Two-Dimensional Phase Unwrapping, Theory, Algorithms, and Software*. John Wiley and Sons Inc., 1998.