Detecting Building Layovers in a SAR Interferometric Processor Without External References

Cristian Rossi, Michael Eineder and Thomas Fritz
German Aerospace Center, Remote Sensing Technology Institute, Wessling, Germany. Email: cristian.rossi@dlr.de

Abstract

A novel technique for the derivation of building layovers is presented. It makes use of the behaviour of the geocoding processing stage embedded in an interferometric SAR processor for this particular case. It is shown how layover pixels create a regular pattern in the range mapping matrices, with a multiple mapping of a single SAR pixel for different DEM cells. The exploitation of these patterns yields a generation of a layover map without the use of external supports. The integration in an interferometric processor with a limited additional computational load and the capability to isolate building signatures are additional benefits. The algorithm is tested on a TanDEM-X spotlight acquisition over Berlin (Germany).

1 Introduction

The simplest building shape is a rectangular cuboid, with the ground represented by the lower horizontal segment, the roof by the higher one and the wall by the vertical segment (Fig. 1). In the layover area the signal return is a superposition of three contribution: ground, wall and roof. In the interferometric framework, for the master satellite, the slant range distance R_0 between the satellite and the three layover scatterers is not varying. On the contrary, three different distances are measured between slave satellite and ground (R_1), wall (R_2) and roof (R_3). The master focused signal at the range and azimuth times $\bar{t}_{rg}, \bar{t}_{az}$ in the layover area can be modelled as [1]:

$$s_0^M\left(\bar{t}_{rg}, \bar{t}_{az}\right) = A_1\left(\bar{t}_{rg}, \bar{t}_{az}\right)\exp\left(-j\frac{4\pi}{\lambda}R_0\right) + A_2\left(\bar{t}_{rg}, \bar{t}_{az}\right)\exp\left(-j\frac{4\pi}{\lambda}R_0\right) + A_3\left(\bar{t}_{rg}, \bar{t}_{az}\right)\exp\left(-j\frac{4\pi}{\lambda}R_0\right), \tag{1}$$

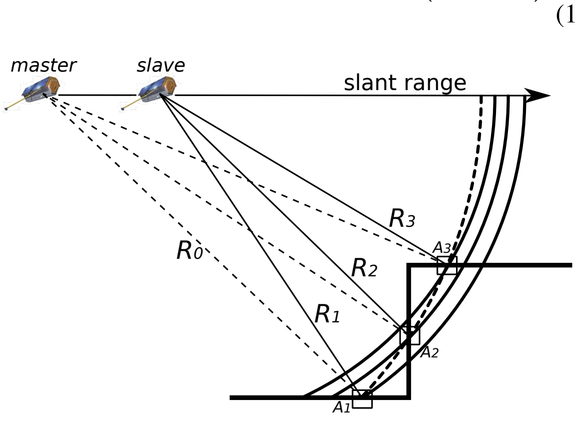

Figure 1: Interferometric signal model for a building layover pixel.

where

$$A_i\left(\bar{t}_{rg}, \bar{t}_{az}\right) = \sqrt{\sigma_i}\exp\left(j\varphi_i\right)w_r\left(\bar{t}_{rg} - \frac{2R_0}{c}\right)\cdot w_{az}\left(\bar{t}_{az}\right)\exp\left(j2\pi f_{DC}\bar{t}_{az}\right) \tag{2}$$

and $\sqrt{\sigma_i}\exp\left(j\varphi_i\right)$ is the complex radar cross section, w_{rg} and w_{az} are the range and azimuth envelopes (rect and sinc functions respectively) and f_{DC} is the Doppler centroid frequency.
With the approximation of equal scattering and weighting between master and slave geometries (i.e. (2) is valid for both geometries), the slave focused signal is modelled as:

$$s_0^S\left(\bar{t}_{rg}, \bar{t}_{az}\right) = A_1\left(\bar{t}_{rg}, \bar{t}_{az}\right)\exp\left(-j\frac{4\pi}{\lambda}R_1\right) + A_2\left(\bar{t}_{rg}, \bar{t}_{az}\right)\exp\left(-j\frac{4\pi}{\lambda}R_2\right) + A_3\left(\bar{t}_{rg}, \bar{t}_{az}\right)\exp\left(-j\frac{4\pi}{\lambda}R_3\right), \tag{3}$$

Finally, the interferogram pixel is built as:

$$I\left(\bar{t}_{rg}, \bar{t}_{az}\right) = s_0^M\left(\bar{t}_{rg}, \bar{t}_{az}\right)s_0^S\left(\bar{t}_{rg}, \bar{t}_{az}\right)^*. \tag{4}$$

Considering the layover modelling in (1) and (3) and removing the time dependency for simplicity, the complex interferogram results:

$$I = \left(|A_1|^2 + A_2A_1^* + A_3A_1^*\right)\exp\left(j\frac{4\pi}{\lambda}\left(R_1 - R_0\right)\right) + \left(|A_2|^2 + A_1A_2^* + A_3A_2^*\right)\exp\left(j\frac{4\pi}{\lambda}\left(R_2 - R_0\right)\right) + \left(|A_3|^2 + A_1A_3^* + A_2A_3^*\right)\exp\left(j\frac{4\pi}{\lambda}\left(R_3 - R_0\right)\right). \tag{5}$$

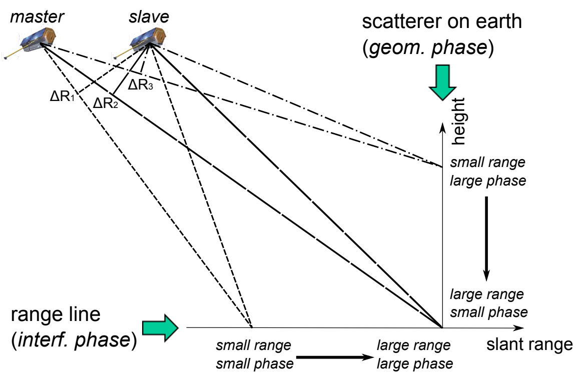

Figure 2: Basic concept of the geocoding algorithm developed in ITP. In the slat range domain, the interferometric and geometric phases intersect as they have opposite monotonicity. The phases are proportional to the range difference ΔR: for the sketched satellite configuration $\Delta R_1 < \Delta R_2 < \Delta R_3$.

The argument of I in (5) defines the layover interferometric phase $\phi(r)$, being r the slant range. The analytical derivation without further approximations is not bringing to a compact expression, instead simulations and test on real data have been conducted [2]. The interferometric phase trend in layover areas has been found to be a decreasing function for increasing slant ranges in case of positive height of ambiguities. In the beginning of the area, a phase discontinuity is also noticeable [3].

2 Algorithm

This peculiar trend has a strong impact in the geocoding processing step of an interferometric processor. In the Interferometric TanDEM-X Processor (ITP), the geocoding algorithm proposed by Schwaebisch [4] is employed. The basic idea of the algorithm is to find the intersection between two curves:

- the interferometric phase $\phi(r)$, which has a monotonous (decreasing or increasing) behavior as a function of range time. This is the output of the multi-baseline phase unwrapper, corrected with a phase offset in order that its value is proportional to the range delay [5].
- The geometric phase $\varphi(r)$, linking the interferometric phase to the height of one scatterer on the earth. This phase can be related to range time, as a vertical straight line of increasing terrain height crosses the circles of constant range delays, and it is monotonous as well, with a trend opposite to $\phi(r)$, intersecting thus the first one. It is computed through an *inverse geocoding* stage relating different terrain height to the satellite positions.

In Fig. 2 a visual explanation of the opposite phase trends is depicted. For the sketched satellite configuration, the interferometric phase has a monotonous increasing trend, while for the geometric phase it is decreasing, due to the proportionality with the range difference ΔR. These trends have opposite sign when changing the height of ambiguity sign, i.e. when switching the satellite positions. This concept allows in a single step to obtain a digital elevation model from the unwrapped phase, since it links all the parameters involved for geocoding: azimuth and range times, interferometric phase and terrain height. The derivation of the layover portion from the interferometric phase, i.e. searching for a phase discontinuity and subsequent slope, may result difficult due to the phase noise superimposed to the signal. The proposed algorithm exploits instead the geocoding algorithm and in particular an output sub-product named *mapping counter*. The mapping counter is a map, in slant range coordinates, whose pixels describe the occurrences of a SAR pixel in the final DEM. For flat terrain, the SAR mapping on the DEM raster depends on the heading angle, the DEM posting and the subsampling used in the interferometric processing. In particular, the number of SAR pixel contributing to a DEM cell is:

$$n_{SAR} = \frac{1}{2}\left(\frac{\Delta_{DEM}^{LON}}{\Delta_{InSAR}^{gr_{rg}}} + \frac{\Delta_{DEM}^{LAT}}{\Delta_{InSAR}^{az}}\right), \tag{6}$$

where Δ_{DEM}^{LON} and Δ_{DEM}^{LAT} represent the DEM posting, respectively for the northing and easting direction, $\Delta_{InSAR}^{gr_{rg}}$ and Δ_{InSAR}^{az} represent the interferogram sampling respectively in ground range and azimuth dimensions, and θ_{head} is the SAR heading angle. ITP is designed to have $n_{SAR} \approx 1$, triggering the interferometric subsampling and number of looks. In this scenario, for an ideally flat terrain and noiseless interferogram, every SAR pixel would be used once and the mapping counter would be a unit matrix. A divergence with this condition is an indicator of problematic areas.

The layover portion of a building creates, in a slant range line, a multiple mapping region ($n_{SAR} > 1$) followed by a non-mapping ($n_{SAR} = 0$). For an isolate building, this area is enclosed in a normal mapping ($n_{SAR} = 1$) region. The multiple mapping area is associated to the phase discontinuity inherent to the first layover pixel. In here, the geometric phase intersects the connection between two interferometric phase samples for $m > 1$ DEM cells, converging then to the same slant range pixel (or to two consecutive depending on the first convergence point). As a consequence, the following m slant range pixels result unmapped. For large buildings, having portion of the roof with a normal mapping, the layover ending point can be defined as the last unmapped pixel (considering $n_{SAR} = 1$). However, when a building is totally under the layover effect, also its shadow area can result unmapped. For this reason, the interferometric coherence is exploited to define the layover ending point through a threshold. The threshold is an approximation of the coherence estimation bias value when the true coherence is zero [6]

$$t_0 = \frac{1}{2}\sqrt{\frac{\pi}{N_c}}, \tag{7}$$

where N_c is the number of sample used to estimate the coherence. Unmapped pixels having a coherence lower

than t_0 are considered as shadow pixels.
The following considerations must be also addressed.

- First, the algorithm assumes the existence of an absolute phase discontinuity to detect the multiple mapping zone. Even if the discontinuity is predicted considering the difference between the model in (5) and the single scatterer (non-layover) model $I = |A_1|^2 \exp(j4\pi/\lambda (R_1 - R_0))$, its presence is ensured only when a correct phase unwrapping stage has been performed for the building under study. This brings a geometrical constraint on the building height, which must be smaller than half height of ambiguity [3].

- Second, non-detection rate is strongly depending on the weighting terms of the three exponential in(5). For instance, when the ground weight strongly dominates over the wall and the roof ones ($A_1 \gg A_2+A_3$) the discontinuity may be too weak to be detected, moreover when masked with noise.

- Third, the intersection between the interferometric and the geometric phase may intersect in more than one point. The algorithm, to properly work, must consider as solution the intersection corresponding to the smallest slant range.

- Fourth, in the previous analysis, n_{SAR} is assumed as one. If this is not the case, the *multiple mapping* and *non-mapping* areas delimiting the layover region must be redefined according to n_{SAR}.

- Last, phase noise plays an active role in the algorithm. In the interferogram, there may be noisy areas generating phase discrepancies and consequent wrong detections in the mapping counter. An efficient phase reduction algorithm (i.e. an adaptive multi-looking technique) should be used to attenuate these detection artefacts. Moreover, an inetrferometric bistatic configuration, as for the TanDEM-X mission, is suggested to remove possible atmospheric artefacts. Nevertheless, small artefacts can be always discarded considering the minimum spatial support of the building in the SAR interferogram. A median filter on the mapping counter may be also applied to reduce the artefacts.

The algorithm can be resumed in the following steps:

1. *Generation and optional cleaning.* Derive the mapping counter from the geocoding processing stage. Depending on the phase quality (i.e. adaptive vs boxcar multilooking) optionally apply a filter (i.e. median).

2. *Detection.* For every slant range line, detect the multiple mapping zones and non-mapping zones. Select as valid building those having the multiple mapping and the non-mapping zones mutually linked.

3. *Segmentation.* Apply a morphological filter (opening and closing, basic element a 2 by 2 square) to the detected map to isolate single buildings.

4. *Refinement.* Discard the detected portion of a building having interferometric coherence less than t_0. Discard also small detected areas.

The proposed algorithm is not considering any assumption about the layover building shapes (i.e. rectangular patches). Moreover, it comes almost *for free*, with a very limited computational cost, out of the interferometric processor.

3 Results

The layover detection algorithm is tested in a interferometric TanDEM-X scenario. A bistatic spotlight acquisition acquired on the 4th of January, 2012 over the city of Berlin (Germany) is chosen. The satellites had a normal baseline of about 110 meters yielding a height of ambiguity of 65 meters, the incidence angle at the center of the scene is 41.8 degrees. The same dataset was used in [3] to test the TanDEM-X DEM generation capabilities over urban areas. As the paper purpose is to investigate over single buildings, a spotlight acquisition is of fundamental importance due to the high resolution capable to isolate building signatures. The bistatic configuration is as well an advantage to avoid false detection resulting from temporal decorrelations. The detection of layover zones starts with the generation of the mapping counter. For a correct analysis of the map, the number of SAR pixels contributing to a DEM cell must be computed. The ground range and azimuth interferogram sampling are respectively $\Delta_{InSAR}^{gr_{rg}} =$ 2.03 m and $\Delta_{InSAR}^{az} =$ 2.60 m. The TanDEM-X processing is set to generate a DEM with longitude and latitude postings of $\Delta_{DEM}^{LON} =$ 2.26 m and $\Delta_{DEM}^{LAT} =$ 2.47 m. n_{SAR} (6) results 1.03. Thus, building layover is defined for mapping counter range segments having pixels larger than one (multiple mapping) followed by null pixels (non mapping). In Fig. 3 the result of the algorithm described in Sec. II is shown. The result yields a detection of single building layovers. The additional processing time required for the generation of the layover map in the interferometric chain (from the focused data to the DEM) is just about 1% of the total time.

4 Conclusions

A technique to detect building layovers during the interferometric processing has been proposed as an alternative to post-processing algorithms. No high-resolution DSMs are needed in input. The limited cost and the absence of a-priori hypothesis make the method suitable to be included in operational processors commanded to map urban areas.

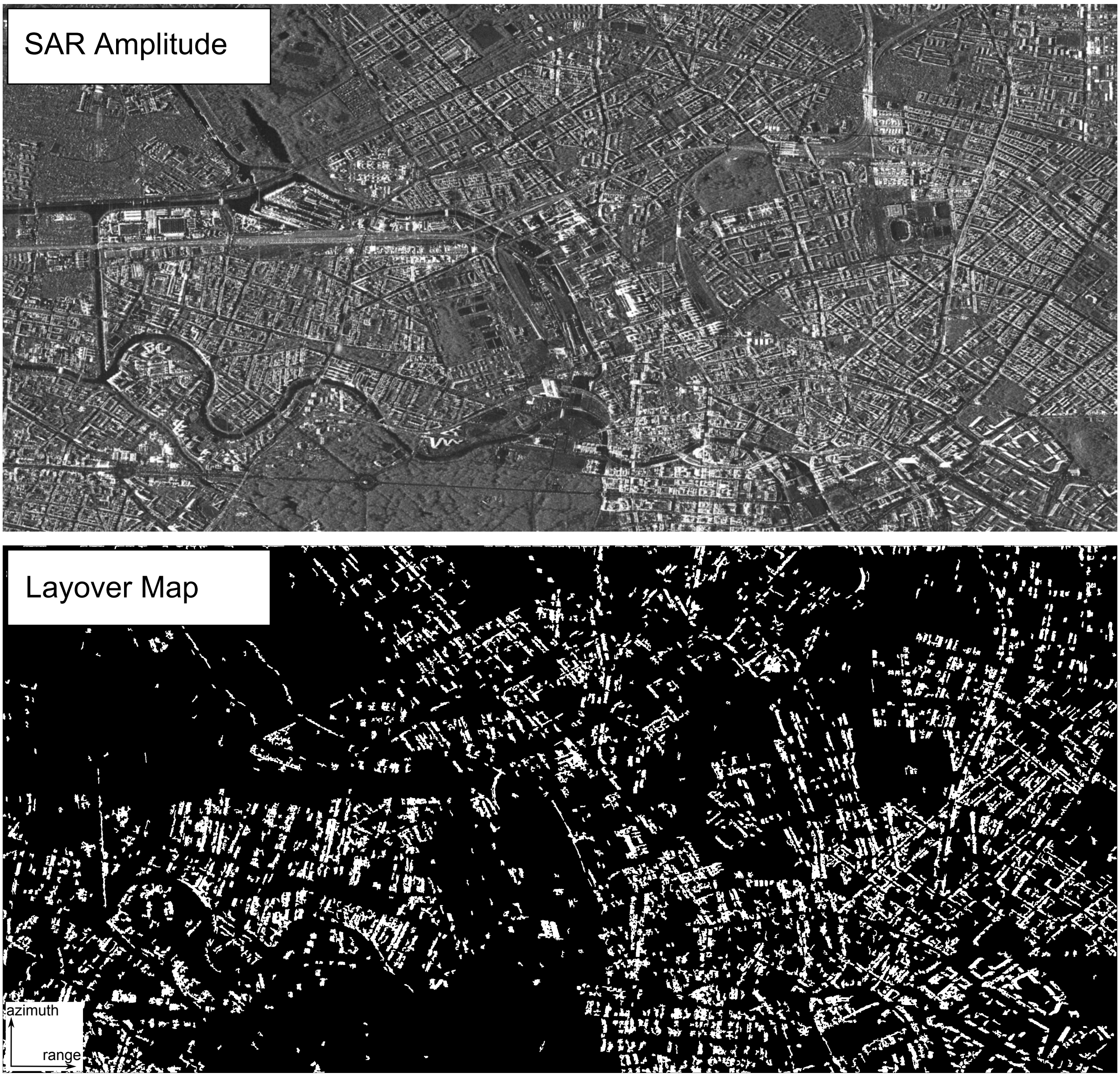

Figure 3: SAR amplitude of the master channel of the TanDEM-X spotlight acquisition over Berlin (top) and building layover estimation (bottom, white).

References

[1] I. G. Cumming and F. H. Wong, Digital Processing of Synthetic Aperture Radar Data: Algorithms and Implementation. Norwood, MA: Artech House, 2005.

[2] A. Thiele, J. D. Wegner and U. Soergel, "Building reconstruction from multi-aspect InSAR data." In *Radar Remote Sensing of Urban Areas*, Springer Netherlands, pp. 187-214, 2010.

[3] C. Rossi and S. Gernhardt, "Urban DEM generation, analysis and enhancements using TanDEM-X," *ISPRS J. Photogramm. Remote Sens.*, vol. 85, pp. 120-131, Nov. 2013.

[4] M. Schwaebisch, "A Fast and Efficient Technique for SAR Interferogram geocoding", Proceedings of IGARSS98, 1998.

[5] C. Rossi, F. Rodriguez Gonzalez, T. Fritz, N. Yague-Martinez and M. Eineder, "TanDEM-X calibrated Raw DEM generation," *ISPRS J. Photogramm. Remote Sens.*, vol. 73, pp. 12-20, Sep. 2012.

[6] C. Oliver and S. Quegan, *Understanding Synthetic Aperture Radar Images*. Norwood, MA: Artech House, 1998.