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A CubeSat Add-on to Improve Robustness and Accuracy of Radar-Derived Digital Elevation Models

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Abstract: Highly accurate digital elevation models (DEMs) can be obtained with spaceborne synthetic aperture radar (SAR) interferometry. Unwrapping the interferometric phase is a key step in the DEM generation, but, even with high-quality interferograms, such as those produced by TanDEM-X, unwrapping errors occur. These errors can be resolved if additional interferograms with different baselines are available, which, however, requires additional satellites, increasing the system cost and complexity, or additional passes of the satellites, making the system less suitable for monitoring fast-changing phenomena. This work proposes to augment a bistatic SAR interferometer with a low-cost CubeSat add-on whose data, despite their low quality due to the small antenna size, make the final DEM robust to unwrapping errors and improve its accuracy by enabling the use of larger baselines. A processing scheme is presented along with a model that can be used to impose requirements on the CubeSat antenna size. Finally, a design example of augmenting a TanDEM-X-like interferometer is presented along with simulations based on TanDEM-X data. This concept represents a cost-effective solution for the generation of highly accurate, robust DEMs in a single pass of the satellites and paves the way to distributed SAR interferometric concepts based on CubeSats.

1. INTRODUCTION

Synthetic aperture radar (SAR) is a class of active coherent radars particularly suitable for satellite remote sensing [1], [2]. Across-track SAR interferometry is a technique where two SAR images taken over the same area from different tracks, whose separation in the across-track direction is called the baseline, are combined into an interferogram, whose phase is proportional to the terrain height. By exploiting this relation, SAR interferometry enables the generation of accurate high-resolution digital elevation models (DEMs). Spaceborne single-pass SAR interferometry was demonstrated by the Shuttle Radar Topography Mission (SRTM), and later by the TanDEM-X mission, where two satellites fly in close formation. Both these missions achieved the goal of producing global-scale digital elevation models with unprecedented accuracy [3].

The two-dimensional unwrapping of the interferometric phase is a critical step in the DEM generation, and, even with high-quality interferograms, such as with TanDEM-X, phase unwrapping errors may occur [4], resulting in large regions of the DEM being displaced in height. The information from an additional interferogram acquired over the same area but with a different baseline can be used to resolve phase unwrapping errors. TanDEM-X uses this approach, with the additional interferogram being obtained in a second pass of the satellites [4], which requires adapting the formation to the new baseline, impacts the acquisition plan of the mission, and limits the system's capability of monitoring fast-changing dynamic phenomena.

2. A CUBESAT ADD-ON FOR RESOLVING PHASE UNWRAPPING ERRORS

We propose an interferometric SAR system concept where a bistatic SAR interferometer is augmented with one or two CubeSat SAR receivers that provide information for detecting and resolving phase unwrapping errors [5]-[6]. Two configurations are considered. In the first, shown in Figure 1 (a), a single CubeSat is added with a small baseline to one of the main satellites, possibly with some along-track separation to accommodate formation flight safety requirements. A second configuration, shown in Figure 1 (b), is proposed where two CubeSats are added with a small baseline between themselves and a significant separation from the main satellites, avoiding the challenge of maintaining a CubeSat in close formation with the larger main satellites. One of the main satellites or both in alternation are responsible for transmitting the pulses that illuminate the scene, and all satellites record the echoes.

Three interferograms are formed from the received images: the large-baseline interferogram is formed from the images of the main satellites; the small-baseline interferogram is formed, in the first configuration (cf. Figure 1 (a)), from the images of the CubeSat and the closest main satellite, and, in the second configuration (cf. Figure 1 (b)), from the images of the two CubeSats; the medium-baseline interferogram is formed, in the first configuration (cf. Figure 1 (a)), from the images of the CubeSat and the furthest main satellite, and, in the second configuration (cf. Figure 1 (b)), by combining the large- and small-baseline interferograms as described in [4].

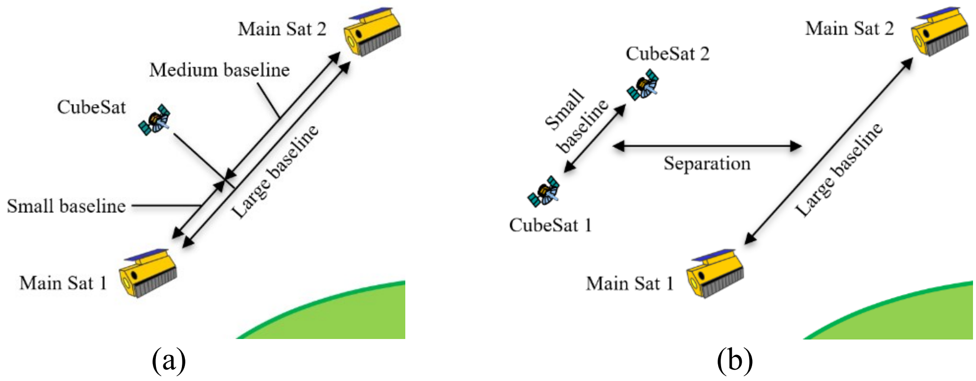


Figure 1 Diagram showing the two proposed configurations for the CubeSat add-on to a bistatic SAR interferometer. In the first (a), a CubeSat is added in formation with a small baseline to one of the main satellites, possibly with some along-track separation. In the second (b), two CubeSats are added with a small baseline between themselves, but with a significant separation from the main satellites.

To leverage the additional information provided by the CubeSat add-on, a multi-baseline phase unwrapping algorithm can be used. In this work, we propose a processing concept based on the dual-baseline phase unwrapping framework for TanDEM-X [4]. The three interferograms are unwrapped independently and converted to heights, forming three DEMs. The large-baseline DEM has a high accuracy, but is susceptible to phase unwrapping errors. The small-baseline DEM is robust to unwrapping errors, but has poor height accuracy, both due to the low phase-to-height sensitivity and due to the lower quality of the CubeSat images used to form it. This DEM is used as reference to correct the phase unwrapping errors of the large-baseline DEM, i.e., the large-baseline DEM height is translated by a multiple of its height of ambiguity — the height corresponding to a 2π phase variation — to approach the height of small-baseline DEM. The final DEM therefore retains the resolution and accuracy of the large-baseline DEM and incorporates the robustness to unwrapping errors of the small-baseline one.

The probability of residual unwrapping error, i.e., the pixelwise probability that an unwrapping error is present in the final DEM after the correction using the data provided by the CubeSat add-on, can be evaluated from the probability distribution of the interferometric phase in the large- and small-baseline interferograms. The usual model for this probability distribution is described in [1] and has as one of its parameters the signal-to-noise ratio (SNR) of the images used to form the interferogram. The SNR of the CubeSat images is in turn related to its antenna area, so this model can be used to translate requirements of minimum probability of residual unwrapping errors into requirements of minimum CubeSat antenna area.

3. DESIGN EXAMPLE

A design example based on a TanDEM-X-like bistatic interferometer with a CubeSat add-on in the first configuration, shown in Figure 1 (a), is presented to demonstrate and analyze the phase unwrapping correction capability brought by the proposed concept. The analysis uses as input the coregistered pair of images from a TanDEM-X acquisition over an area southwest of Rosenheim, Germany. From them, estimates of the backscatter, interferometric coherence and terrain height across the scene are computed and used to simulate the focused SAR images of the three satellites. The baseline between the two main satellites is 573 m. It is much larger than the usual for TanDEM-X [3], which improves the accuracy of the final DEM, and is possible because the drawback of increased likelihood of phase unwrapping errors is resolved by the CubeSat add-on. The small baseline between the CubeSat and one of the main satellites is 164 m.

Figure 2 shows the probability of residual unwrapping error for the system as a function of the CubeSat antenna area and the SNR of the SAR images acquired by the main satellites. The figure shows that a CubeSat with a 50 cm square antenna added to a TanDEM-X-like system leads to a probability of residual unwrapping error smaller than 0.1% for any soil and rock backscatter in the 90% occurrence interval. The probability increases when other disturbances are included in the model, such as decorrelation due to volume scattering, but remains below 1%. Similar results are of course achieved with a reflector antenna of equivalent size.

The resulting large-baseline DEMs is shown in Figure 3 (a), and contains many unwrapping errors in the mountainous region as evidenced by the various discontinuities indicated by the yellow arrows. The final DEM, resulting from using the small-baseline DEM to correct the unwrapping errors in the large-baseline one, is shown in Figure 3 (b). The residual unwrapping errors present in it are shown in Figure 3 (c). They generally occur on areas with very low coherence, such as the edge of forests or the foreshortening areas on the mountainous region. 96% of the residual unwrapping errors occur in pixels where the coherence is smaller than 0.4 in the large-baseline interferogram. Conversely, the rate of residual unwrapping errors is 0.1% or less for areas where the coherence is larger than 0.6 in the large-baseline interferogram. The overall percentage of residual unwrapping errors is 0.27%, 0.07%, and 0.02% in the areas with coherences larger than 0.4, 0.5, and 0.6 in the large-baseline interferogram, respectively.

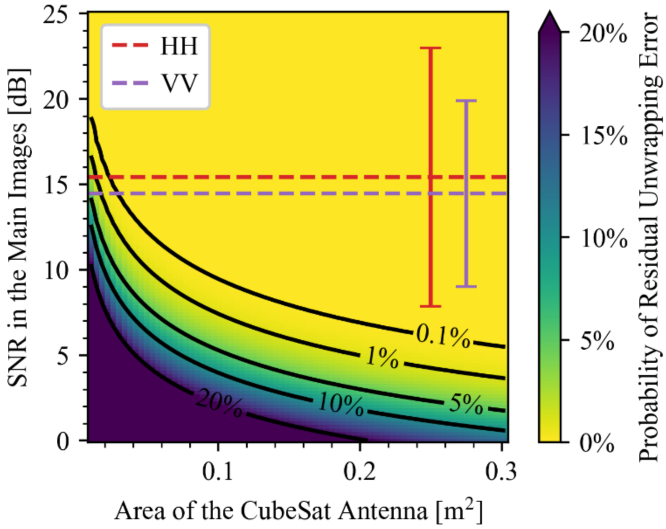
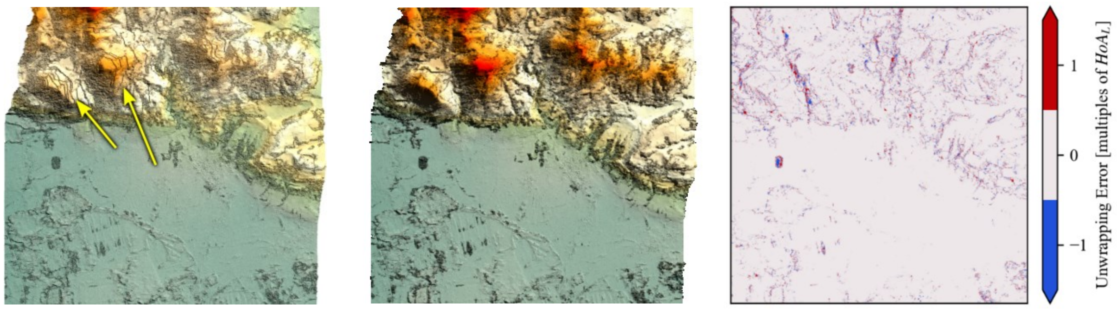


Figure 2 Probability of residual unwrapping error as a function of the area of a square CubeSat antenna and the SNR in the images of the main satellites. The horizontal dashed lines and associated error bars mark the SNR corresponding to the mean and 90% occurrence interval of the backscatter from soil and rock at X band for the (red) HH and (purple) VV polarizations.



(a) (b) (c)

Figure 3 (a) DEM obtained by unwrapping the large-baseline interferogram with yellow arrows pointing to some of the height discontinuities characteristic of unwrapping errors. (b) Final DEM obtained by using the small-baseline DEM as a reference to correct the unwrapping errors in the large-baseline one. (c) Residual unwrapping errors in the final DEM.

4. CONCLUSION

A CubeSat add-on to bistatic SAR interferometry for detecting and correcting phase unwrapping errors in a single pass of the formation is proposed and analyzed. The concept enables the capability of monitoring fast-changing dynamic phenomena, which is limited in the dual-pass approach employed by TanDEM-X. A design example shows that, even having a lower quality (due to the much smaller aperture), the additional interferograms, which use the CubeSat add-on data, are effective to correct phase unwrapping errors in the bistatic interferometer through the use of a phase unwrapping algorithm based on the one used in TanDEM X for combining two passes [4] with key modifications that improve its performance. With the proposed concept, residual unwrapping errors are mostly only present in areas with very low coherence. The CubeSat add-on therefore allows obtaining accurate digital elevation models, free of phase unwrapping errors, in a single pass of the satellites and paves the way to distributed interferometric systems using clusters of CubeSats.

5. REFERENCES

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