Deployment and design of bi-directional corner reflectors for optimal ground motion monitoring using InSAR

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Abstract

SAR interferometry (InSAR) requires coherent radar reflections to measure ground displacements. However, natural coherent reflectors are not always available due to changes in the scattering properties of the ground, e.g., growing vegetation. Furthermore, the opportunistic nature of InSAR measurements can limit its use for infrastructure monitoring. The scattering properties of infrastructure may not be optimal to monitor it, because some parts may appear invisible to radar for a particular observing direction. This is especially problematic for satellite InSAR. To overcome these problems, corner reflectors are usually employed. They are installed in areas where the radar does not detect coherent reflections with their orientation pointing at the required observing angle. However, corner reflectors also have some limitations. To provide with high signal-to-clutter ratio (SCR) and avoid decorrelation noise, their size is required to be large, which can complicate their deployment and maintenance. In addition to that, traditional corner reflectors are unidirectional and cannot provide with reflections at orthogonal directions as required for a vector decomposition of the displacement. We demonstrate that with a predefined deployment formation the size of reflectors can be reduced while maintaining the overall SCR. We also provided a new design of a small, bidirectional reflector tile, which can reflect at required multiple angles for ascending and descending satellite passes.

1 Introduction

Trihedral Corner Reflectors (CRs) are traditionally used as calibration targets for synthetic aperture radar imaging due to their large radar cross section (RCS) and wide RCS pattern [1]. CRs can also be exploited to measure deformation where coherent reflections are not available [2]. However, CRs deployment has *contradicting* requirements [3]. For example, an ideal CR holds: 1) large RCS, 2) wide RCS pattern, 3) small physical size, 4) stable RCS, 5) dominant and insensitive RCS compared to the surrounding environment, and 6) low incoherent interaction with the terrain.

In this contribution, we show how we can meet the above mentioned requirements by deploying many small sized reflectors with a predefined deployment pattern to measure the deformation of the surface or specific object of interest. The use of small reflectors is of relevance for infrastructure monitoring, for the ease of their installation. Although particularly developed for dike monitoring (e.g. grass and vegetation covered dikes), the reflectors can be very well suited for other types of infrastructure, such as large bridges and dams whose orientation is not optimal to be observed by satellite radar.

Furthermore, the reflectors that we propose are bidirectional especially created for optimal vector decomposition of displacements. Ascending and descending satellite passes are used in this case. The efficiency of these small-and-bidirectional reflectors and its formation schemes for measuring deformation is demonstrated using TerraSAR-X data acquired over a test site in the Netherlands. It is also worth noting that other solutions, namely small active transponders have been proposed [4]. However, being active they have the disadvantage of needing power supply and transmission license.

2 Corner reflectors for infrastructure monitoring

Small bidirectional reflectors offer a clear advantage for infrastructure monitoring. In the following sections, we explore a method to improve the accuracy of interferometric phases despite the above mentioned constraints. Furthermore, we also propose a new design for bidirectional reflectors.

2.1 Corner reflectors deployment

Small reflectors have the advantage of easy deployment; however, since their SCR is low the interferometric phase noise tends to be high. To reduce noise in InSAR observations, we propose to deploy the reflectors in a predesigned and therefore recognizable pattern.

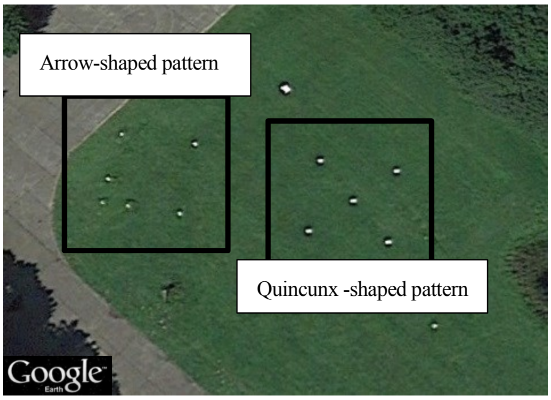

Figure 1. Reflectors deployed following a predefined pattern, (Google Earth).

The chosen pattern helps to both, to identify the reflectors within the SAR image and to yield an efficient method for spatial filtering. For example, a matched filter can be used for fast and accurate localization of the reflectors within a SAR image. Figure 1 shows two examples of deployment patterns that can be easily recognized in a radar image.

The increase in SCR is achieved by a coherent summation of the complex signal of the selected pixels, the pixels that have reflectors. The complex summation, although simple operation, appears to be very effective, because we include only pixels with very similar scattering properties. Therefore, the common signal adds up; and noise due to clutter reduces due to its random nature. In the following sections we prove experimentally that, despite the low power returned by individual reflectors, our method greatly reduces phase noise.

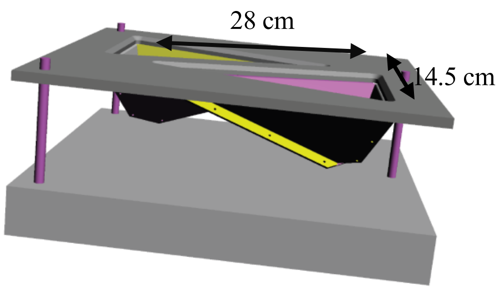

Figure 2: Bidirectional reflector tile.

2.2 Bidirectional reflector tiles

The reflector that we propose consists of two small corner reflectors installed in a tile, see Figure 2. The pointing direction of each reflector is such that one is oriented to the ascending pass direction, and the other to the descending. They provide some orientation versatility because their 3-dB elevation beamwidth (for the X-Band) is around 45 degree. The largest size of each reflector is 28 cm, the small rib is 14.5 cm. The total dimensions of the tile are around 35 cm x 20 cm; they are of similar size to frequently used paving tiles. As shown in Figure 2, ascending and descending reflectors are built in the same structure and they lie within the same resolution cell. Therefore they should represent the same signal related to ground displacements. To make them weather proof, a hole is drilled at the bottom of each reflector to drain rain water. Other solutions, such as a radome, are also possible.

3 Experimental results

We tested the proposed deployment method and reflector tile in a controlled experiment using SAR images acquired by TerraSAR-X over the Netherlands, with both ascending (incidence angle ~39^{o}) and descending (incidence angle ~24^{o}) passes. Reflectors were installed in a grass field as our first goal was monitoring dikes which has similar vegetated surface.

3.1 Set-up

In order to place many small CR in a predefined deployment formation, the spatial distances among each CR has to be carefully chosen to make them all visible in the radar image. Distances should not be too short, to avoid interference between reflectors, but also not too long to confine the reflectors in a reduced area.

In principle, the minimum spatial separation is dictated by the resolution in azimuth and ground range of a specific satellite and its image acquisition mode. However we tested the minimum distance between reflectors (see figure 1 arrow shaped pattern; distances vary between 1 and 5 resolution cells). If separated by only one resolution cell there is some interference between their radar returns (they appear to be mixed). From the experiments, we found that the distance between reflectors should be at least two resolution cells to avoid mutual reflector interference.

3.2 SCR

We estimated the SCR of the reflector tiles individually. The SCR is estimated using eq. (1),

$$\mathrm{SCR} = P/P_c \qquad \text{eq. (1)}$$

Where P is the power (amplitude squared) of the pixel of interest and P clutter power. We estimate P_c by taking the mean radar power of the small area (with grass) where the reflector is later installed. After the reflector is placed we estimate the ratio of the two powers.

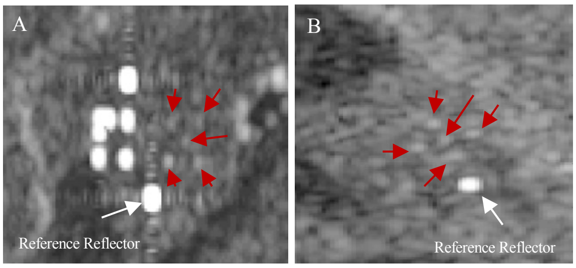

Figure 3. Time-averaged SAR images for A) descending and B) ascending passes. Reflector tiles are indicated with red arrows. White arrows indicate reference reflectors, which are larger corner reflectors.

Figure 3 shows the time-averaged amplitude returned by the reflector tiles, A) for descending pass and B) for ascending. The quincunx shape can be distinguished with the help of the red arrows that indicate the tile locations. The images display the average amplitude over a time series of ~10 images. In one single image reflector tiles appear to be undistinguishable. Figure 4 displays the received power for the images acquired by the descending pass. The results for the ascending pass (not included in the figure) show similar behavior.

After the tiles were installed, the received power at the corresponding pixel positions increased ~7 dB. As explained above, this power difference can be assumed to be the SCR. From radar detection theory is known that reliable detection of a target requires an SCR about 13 dB or more; hence tiles are 6 dB below detection threshold. In principle, this make the reflector tiles suitable for covert operations.

3.3 Interferometric measurements

After the interferograms are formed with respect to a common *master* image and the contribution of the reference body, WGS84, is removed [5], we calculate the interferometric phase differences of all reflector tiles with respect to the reference reflector. To ease phase unwrapping, we also remove the time-average value of all interferograms; which centers the phases around zero.

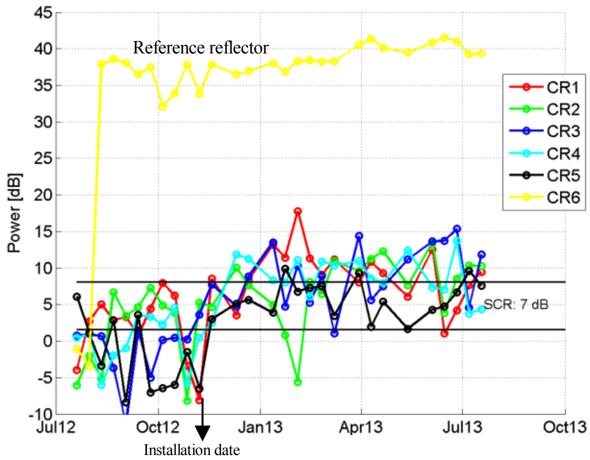

Figure 4. Estimated SCR for tile reflectors observed in the descending pass (red arrows in Figure 3). The reference reflector is a traditional trihedral reflector (white arrows in Figure 3).

Figure 5 shows the displacements for descending (A) and ascending (B) passes after the installation of the reflector tiles, on 5th of December 2012, marked with an arrow. Before this date, the phases behaved randomly due to temporal decorrelation, which was expected and not shown in the figure. After the installation of the tiles, the phases of individual reflectors appear relatively stable, with the exception of the period around mid-January, when the reflectors were covered with snow. Interesting enough, despite the low SCR of individual reflectors (~7 dB on average), which makes them invisible in the amplitude images, the phase signal appears reasonably coherent, see Figure 5. Phase noise is then reduced by taking the (complex) mean value of the interferometric phases of the reflectors, shown in Figure 5 as black triangles. Effectively, the variability of the signal of the mean is considerably less than those of individual reflectors.

For noise variance estimation, we approximate the displacements with a second degree polynomial model. After removal of the estimated polynomial, we determined a noise standard deviation of 3 mm for individual reflectors, the sensor wavelength is 31 mm. After complex mean operation, we estimated 1.5 mm standard deviation. This is in agreement with the expected theoretical improvement of $\sqrt{N}$, being N the number of reflectors, equal to five in our case. The variance estimated in this manner includes unmodeled deformation, and other signals that are not truly noise. For example, the sharp subsidence observed at the beginning of January seems to correlate to a snow fall and it may not indicate an increase of the noise. In any case, this method helps to measure the improvement obtained with the complex mean compared to individual reflectors.

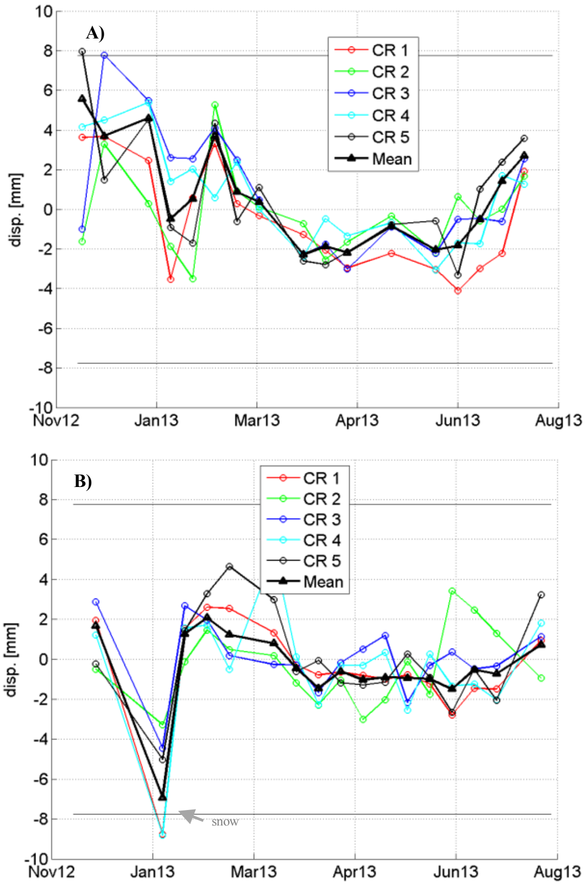

Figure 5. Displacements estimated from interferometric phases for A) descending and B) ascending. Values represent motion w.r.t. the reference reflector. Mean value is shown with black triangles). Only observations after the installation of reflectors are included.

In principle, the observed displacements are expected to be mostly in the vertical direction. Therefore, discrepancies between the signal observed at ascending and descending passes are caused by a difference in the incidence angle between passes (~39° and ~24°, respectively).

In addition to that, we should take into account that we employ different reference reflectors for ascending and descending passes. Different sampling times can also produce large variations between these two time series. For example, the snow fall in the beginning of January 2013 was closer in time to the ascending acquisition than to the descending one, as can be seen by comparing Figure 5 A) and B).

4 Conclusions

We have introduced a small and bidirectional reflector tile concept along with a predefined deployment pattern to tackle limitations of InSAR for infrastructure monitoring. We have proved the utility of these bidirectional tiles, each as small as 28cm x 14.5cm, in a control experiment with TerraSAR-X ascending and descending pass acquisitions. These tiles can provide InSAR observation at any location of interest, irrespective of decorrelation constraints. Furthermore, we have provided a simple method to improve the INSAR measurement accuracy of small reflectors. We deployed them in a recognizable pattern, to aid their detection. The separation between reflectors should be at least 2 resolution cells to avoid interference.

From real experiments, we conclude that, despite the low SCR of the reflectors, the complex mean of the interferometric signals improves the phase accuracy by, approximately, $\sqrt{N}$, being N the number of reflectors in the ensemble. We estimated for each reflector tile 3 mm standard deviation of the interferometric phase noise, compared to 1.5 mm, for the average of 5 CRs.

References

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