Infrastructure stability surveillance with high resolution InSAR

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Abstract. The construction of new infrastructure in largely unknown and difficult environments, as it is necessary for the construction of the New Silk Road, can lead to a decreased stability along the construction site, leading to an increase in landslide risk and deformation caused by surface motion. This generally requires a thorough pre-analysis and consecutive surveillance of the deformation patterns to ensure the stability and safety of the infrastructure projects. Interferometric SAR (InSAR) and the derived techniques of multi-baseline InSAR are very powerful tools for a large area observation of surface deformation patterns. With InSAR and derived techniques, the topographic height and the surface motion can be estimated for large areas, making it an ideal tool for supporting the planning, construction, and safety surveillance of new infrastructure elements in remote areas.

1. Introduction

The construction of new infrastructure can lead to a decreased stability along the construction site. The extent and the safety risk of the decreased stability depend on the geological and geomorphological situation, but it can lead to an increase in landslide risk and deformation caused by surface motion. Interferometric SAR (InSAR) and the derived techniques, like differential InSAR and multi-baseline InSAR, are very powerful tools for a large area observation of such deformation patterns.

With TerraSAR-X, COSMO SkyMed, and Kompsat-5, high-resolution SAR satellites are available that are capable of providing detailed information that can be used for mapping. Thanks to their interferometric capability, precise digital elevation models (DEM) can be created that can e.g. be used during the planning and construction phase of new infrastructure projects. Even more so, with differential interferometry and derived techniques, surface motions can be estimated in a very high precision [1]. These techniques therefore allow for high-precision deformation measurements along e.g. roads and railways. This offers the possibility to detect deformations not only along a road or railway, but also deformation patterns nearby the corresponding infrastructure project that could cause problems in the near future. This is true for the risk to the traffic infrastructure itself, as well as for the surrounding infrastructure like urban settlements or energy infrastructure.
However, for the observation of long linear structures, like roads and railways, the current limitations of data acquisitions of spaceborne systems makes this task very difficult. Roads and railways do not follow the orbit directions of the SAR systems. Consequently, a large number of data acquisitions to track and trace these structures are required. However, as the acquisition capability of existing systems is limited, conflicts in the acquisition plan can (and will) occur, which typically leads to interruptions in the acquisition process, which may cause time gaps in the acquisition of adequate time series. This makes the InSAR processing difficult or, in case of large deformation with high amplitudes or temporal decorrelation, even impossible.

Next Generation X-Band SAR systems, like the follow-on mission of TerraSAR-X, will be able to use 1200 MHz spectrum range, as approved recently at the World Radio Conference in November 2015. This will constitute a game changer in terms of imaging capacity, image resolution and image quality. Specifically, larger areas can be mapped more frequently as much larger swath width can be achieved for stripmap imaging modes. Additionally, very high image resolution, which can achieve 0.25 m x 0.25 m with a very high radiometric performance, will significantly increase the density and accuracy of measurements. Thus, precise deformation measurements along long linear structures will be possible in an unprecedented way.

In the following section, we will describe the status of high-resolution SAR data today. In section 3, we demonstrate persistent scatterer interferometry (PS-InSAR) with very high resolution data. Then, in section 4, we will discuss and give an outlook to future SAR systems. Finally, conclusions are drawn.

2. Very high-resolution SAR data
With the introduction of the new SAR imaging modes for TerraSAR-X in 2014 [2], a new very high resolution SAR mode, the staring spotlight mode, was made available allowing for an increased resolution in azimuth direction up to around 25 cm. This is achieved by increasing the synthetic aperture length with an increased illumination time.

In the opposite way, Sentinel-1, achieves wide coverage using TOPS [3]. TOPS is basically the opposite of the spotlight mode. When in spotlight mode the synthetic aperture is enlarged by changing from forward squinting to backward squinting along azimuth, in TOPS the synthetic aperture is shortened by shifting from backward squinting to forward squinting during acquisition. This allows an improvement to the normal ScanSAR mode by avoiding scalloping effects.

As we can see in Figure 1, mid-resolution SAR systems, like Sentinel-1, are useful for regional surveillance, but details in urban areas are hardly recognizable. With 3m spatial resolution stripmap data, as shown in Figure 2 with an example from Kompsat-5, details in urban areas are clearly recognizable on a building block level. However, when we move to very high-resolution staring spotlight data, as shown in Figure 3, details on single buildings, are clearly identifiable, making it ideal for the surveillance of dense urban areas. Staring spotlight does, due to the nature of spotlight mode data acquisition, not allow continuous coverage in azimuth and is therefore only suitable for hot-spot surveillance, but not for large or regional scale surface motion estimation.

Using SAR for interferometric applications, like height measurement or surface motion estimation e.g. with PS-InSAR, the application can benefit from a higher resolution. Although in principle the achievable precision in height and motion measurement depends on the wavelength and not on the spatial resolution, an improved spatial resolution can be used for a better characterization of objects, DEM generation with finer resolution, or e.g. noise reduction by averaging over larger areas. So, although in theory the precision of interferometric measurements does not depend on the spatial resolution, a very high resolution can in practice tremendously improve the product quality, as we will demonstrate below in section 3.
Figure 1. Subset of the Sentinel-1 IW image of Wuhan acquired on 2016-01-24 (Copernicus Sentinel data 2016)
Figure 2. Subset of the Kompsat-5 stripmap image of Wuhan acquired on 2016-01-03 (© KARI, 2016)
Figure 3. TerraSAR-X staring spotlight mode image of Wuhan acquired on 2016-01-12 (© DLR 2016)
3. Very high-resolution PS-InSAR

Persistent scatterer interferometry (PS-InSAR) uses point-scatterers that are interferometrically stable over time to estimate long-time deformation at these stable scatterers that are called persistent scatterers (PS) [4]. PS-InSAR can be used to estimated surface motions for urban areas and infrastructure. Below in Figure 5, we can see the estimated surface motions of the Beijing International Airport derived from a stack of 30 TerraSAR-X stripmap images with approximately 3 m spatial resolution shown in Figure 4. This demonstrates the high resolution and high precision deformation estimation with TerraSAR-X stripmap data.

![Figure 4. Mean amplitude of 30 TerraSAR-X stripmap images](image-url)
An even higher spatial resolution can lead to a higher PS point density and a better estimation of the atmospheric phase screen. As shown below in Figure 6, a very high PS point density can be achieved with the TerraSAR-X staring spotlight data. In the example below, we see a PS density of around 25,000 PS / km². With such a high PS density, several independent deformation measurements on a single building are possible, allowing for the detection of motion differences in single buildings; such motion differences are especially dangerous and it is therefore important to have a high PS point density, to be able to detect such dangerous motion patterns.
4. Discussion and outlook to future systems
As demonstrated above in section 3, a high PS point density is beneficial for urban subsidence estimation and is crucial for infrastructure stability analysis. However, in spotlight mode, and even more so in staring spotlight mode, the coverage is limited. As we can see above in Figure 3 and Figure 6, only a small subset of Wuchang can be acquired in staring spotlight mode and this is just a fraction of the urban area of Wuhan. Staring spotlight is therefore valuable for the surveillance of small areas or single objects of interest, but not suitable for city-wide or regional motion estimation. However, in stripmap, ScanSAR, or TOPS mode, the spatial resolution is reduced and the achievable PS point density is significantly lower.

Therefore, we would like to achieve a high spatial resolution with a better coverage. This is even more true, if we move from city-wide surveillance to regional applications as it will be necessary for the New Silk Road. However, there are several restrictions in sensor design limiting the available resolution and swath width. One is the limited bandwidth that limits the possible spatial resolution in range direction. Before the World Radio Conference in November 2015, the bandwidth for X-band SAR systems was limited to 300 MHz, limiting the range resolution of X-band SAR systems to around 80 cm. Now, since November 2015, up to 1200 MHz spectrum range are now possible, which will allow an increased resolution in range for new SAR systems, like the follow-on mission of TerraSAR-X.

This will allow stripmap mode data acquisition in approximately 0.25 x 0.25 m resolution. With such a system, a wide area coverage with very high resolution and good radiometric quality would be possible. This is ideal for very high resolution interferometry, especially regarding the stability analysis of buildings and infrastructure.

5. Conclusions
With the launch of TerraSAR-X, high-resolution SAR data become widely available. This lead to a paradigm shift in SAR and interferometric SAR processing. Nowadays, persistent scatterer interferometry with high-resolution SAR data can be used to detect several PS points on a single building and estimate motion differences on a single building.

However, the highest resolution is achieved in spotlight mode, hindering the acquisition for large areas. We would prefer to achieve this resolution in stripmap mode, so that large areas can be acquired with high resolution. This will be possible in future SAR systems and such a high resolution sensor would provide the perfect data basis for high resolution and high precision surface motion estimation for ensuring the stability and safety of infrastructure projects, e.g. along the New Silk Road.

References

[1] Ferretti A, Savio G, Barzaghi R, Borghi A, Musazzi S, Novali F, Prati C, Rocca F 2007 Submillimeter Accuracy of InSAR Time Series: Experimental Validation IEEE Transactions on Geoscience and Remote Sensing 45(5) pp. 1142–1153.

[2] Mittermayer J, Wollstadt S, Prats-Iraolo P, Schreiber R 2014 The TerraSAR-X staring spotlight mode concept IEEE Transactions on Geoscience and Remote Sensing 52 pp. 3695-3706.

[3] Yague-Martinez N, Prats-Iraola P, Rodriguez Gonzalez F, Brcic R, Shau R, Geudtner D, Bamler R 2016 Interferometric Processing of Sentinel-1 TOPS Data IEEE Transactions on Geoscience and Remote Sensing 54(4) pp. 2220–2234.

[4] Ferretti A, Prati C, Rocca F 2001 Permanent scatterers in SAR interferometry IEEE Transactions on Geoscience and Remote Sensing 39(1) pp. 8–20.

[5] Perissin D, Wang Z, Wang T 2011 The SARPROZ InSAR Tool for Urban Subsidence/manmade Structure Stability Monitoring in China Proc. of ISRSE 2011, Sidney, Australia.