Persistent Scatterers (PS) interferometry results in the deformation history of time-coherent scatterers. Although several applications focus on smooth, spatially correlated signals, we aim for the detection, identification and analysis of single anomalies. These targets can be indicative of, e.g., strain in structures, potentially leading to the failure of such structures. For the identification and analysis it is of the greatest importance to know the exact position of the effective scattering center, to avoid an improper interpretation of the driving mechanism. Here we present an approach to optimize the geolocation of important scatterers, when necessary aided by an a priori Lidar-derived DSM (AHN-1 data) with 15cm and 5m resolution in vertical and horizontal directions, respectively. The DSM is also used to validate the geocoding. We implement our approach on a near-collapse event of a shopping mall in Heerlen, the Netherlands, to unravel its driving mechanism.

Key words: geolocation of persistent scatterers; Lidar.

1. INTRODUCTION

Persistent Scatterers (PS) interferometry is a powerful tool to investigate ground deformation evolution with millimetric accuracy [4, 6]. Although the output such as PS deformation velocity maps aids people to reconstruct/exploit historical surface movements due to the natural hazards and anthropogenic activities, we concentrate on the detection, identification and analysis of single anomalies which could easily escape the notice in conventional PSI processing. However these targets can be indicative of, e.g. strain in structures, potentially leading to the failure of such structures. Aiming at the identification and analysis, it is of the greatest importance to know the exact position of the effective scattering center, to avoid an improper interpretation of the driving mechanism.

Lately, the topic of precise PS geolocalization in three dimensions arise people’s attention [10]. Theoretically, the uncertainty of the target positioning in PS techniques is around 1m [4, 1] which is much higher than the ground resolution of radar sensors (e.g. ERS-1/2 and Envisat with 20m in range and 4m in azimuth). But inaccuracies in the satellite orbits, instruments, atmospheric delay or improper interpolation, the precision of absolute 3D geolocalization can be in the order of several meters. Proper interpretation often requires sub-meter precision. Scharroo, Visser and Doornbos [11, 2] reported that the accuracy of along-track and radial components of ERS orbit are 4cm, 15cm respectively, based on different gravity models. For Envisat, the DORIS system (Doppler Orbitography and Radiopositioning Integrated by Satellite) provides the accuracy of the best orbit products is estimated to be 3cm in the radial component and 10cm in 3D [8]. For the GPS orbits of ALOS, the deviations are between 2cm to 15cm in 3D [9]. Regarding to TerraSAR-X, the orbit accuracy has reached the 2cm level [12]. Moreover, the inaccuracy of sub-pixel position estimations and the error propagation in coordinate system conversion are increasing the height uncertainty as well. In this paper, we first briefly review the geocoding theory, then discuss the height error sources and elaborate our proposed method to optimize the geolocation of targets by using the Lidar-derived DSM (Digital Surface Model), then implement our approach on Heerlen, the Netherlands by using ERS-1/2, Envisat and Radarsat-2 data. The results can be used to interpret the driving mechanism for a near-collapse shopping mall in this region. Finally the conclusions are drawn.

2. REVIEW OF GEOCODING

Geocoding is applied to convert the radar coordinates to geocoded coordinates in a unified geodetic reference system, for instance WGS84(\(\varphi, \lambda, H\)), where \(\varphi, \lambda\) denote the geodetic latitude and longitude, respectively, and \(H\) is the height above the reference ellipsoid. Presently WGS84 uses the EGM96 (Earth Gravitational Model 1996) geoid, revised in 2004. This geoid defines the nominal sea level surface by means of a spherical harmonics series of degree 360 (which provides about 100 km horizontal resolution), giving an irregular equipotential surface which is considerably smoother than the earth’s physical surface.
After the final PS detection in the radar image coordinates and the parameter estimation, the three dimensional position: azimuth, range, and height $\Delta H$ of PS points need to be reconstructed to the WGS84 reference system, which can be solved by means of a set of Doppler, Range and ellipsoid equations [5]. All the PS heights are intrinsically relative heights w.r.t a reference PS point, need to be converted to corresponding absolute heights in the WGS84 reference system. Three surfaces are required to be considered during the processing, one contains buildings and other objects, with elevations relative to the physical terrain, another is 'topography', one is 'geoid' (the equipotential surface, also a physical reality), the other is 'ellipsoid' (the mathematical idealized surface for computations). In practice, the topographic phase can be substracted from the interferogram based on a Digital Elevation Model (DEM) e.g. derived from the Shuttle Radar Topography Mission (SRTM), or GTOPO30 data.

In Figure 1, it shows the relationships between reference surfaces, including the geoid undulation $N$ which is the height in meters of the geoid above the WGS84 ellipsoid reference, the orthometric height $h$, and the object elevation $\Delta H$ which refers to the surface including e.g. buildings. The absolute ellipsoidal height $H_i$ is expressed as a function of orthometric height of the reference point scatterer, geoid height at that location, and height difference between point $i$ and reference PS point $0$

$$H_i = h_0 + N_0 + \Delta H_{0i} \quad (1)$$

where $h_0$ and $N_0$ is orthometric height and geoid undulation of reference point $P_0$, and $\Delta H_{0i} = \Delta H_i - \Delta H_0$ (here $\Delta H_0$ is $H_0$ height residual due to the height difference between the actual topography and DEM. When $\Delta H_0 = 0$, $\Delta H_i = \Delta H_{0i}$), are the height difference between $P_i$ and $P_0$. It is noted that since the radar images are arranged in range and azimuth direction, the observation values record the relative height of the ground objects w.r.t. a certain reference object other than from geoid or reference ellipsoid, the error $\sigma_{H0}$ of reference point propagate to the final solution when performing the coordinate transformation and height estimation. And the error sources for height estimation can be estimated by equations presented in the following Section. 3.

### 3. HEIGHT ERROR SOURCES

The improper height estimation is mainly caused by the orbital error, instrument inaccuracies (e.g. the time error of atomic clock), the atmospheric inhomogeneities and the uncertainty of sub-pixel position. Here we stress the last one since it is of greatest influence than the others.

When removing the flat earth reference phase for the interferogram, the reference phase is no computed at the exact location of the scatterers’ center but at the leading edge of certain pixel, namely, the upper-left corner, which results in a reference phase errors remaining in both azimuth and range direction. Thereby a so-called sub-pixel phase term is introduced into the interferometric phase observation. Kampes [7] presented that the sub-pixel phase is expressed as

$$\phi_{i,\eta} = \frac{4\pi}{\lambda} \frac{B_\perp}{R} \cos \theta_m \cdot \eta_i \quad (2)$$

where $\eta_i$ is the range sub-pixel position, $\lambda$ denotes the radar wavelength and $R$ is the slant range with local incidence angle $\theta_m$ between satellite (master) and ground target, $B_\perp$ represents the perpendicular baseline. Since the height residual/error $\sigma_{\Delta H}$ is proportional to $B_\perp$ as well, the height residual is calculated together with its range sub-pixel position. Consequently, a range sub-pixel position shift/error will cause the height estimation error. The height residual $\sigma_{\Delta H}$ can be derived by

$$\sigma_{\Delta H_i} = - \sin \theta_m \cos \theta_m \eta_i \quad (3)$$

then this height residual causes a horizontal deviation $\sigma_{r,\text{hor}}[m]$ (or the geolocation uncertainty in ground direction) of approximately calculated as

$$\sigma_{r,\text{hor}} = \frac{\sigma_{\Delta H_i}}{\tan(\theta_m)} \quad (4)$$

Apparently, the horizontal deviation is inversely proportional to the local incidence angle, see an example of Figure 2 for a height error of 1m. Suppose the height estimation dispersion is around 0.5m $\sim$ 1m for C band batch processing [3] in ERS conditions whose look angle is $23^\circ$, its horizontal deviation scales up to $2.4 \times \sigma_{\Delta H_i}$ which is about 1.2m $\sim$ 2.4m. The sub-pixel position can be done by the sub-location searching of maximum amplitude in every pixel based on the oversampling method.

![Figure 1: Relationships between reference surfaces: topography, geoid and ellipsoid with two points $P_0, P_i$ as an example. There are the geoid undulation $N$ which is the height in meters of the geoid above the WGS84 ellipsoid, and the orthometric height $H_i$, and the object height $\Delta H$ which refer to the surface.](image-url)
In the PSI processing, a stack of interferograms can be used to well-estimate the parameters including the height differences w.r.t a reference point. Operationally, Eq.(3) is used to compute height residual for every interferogram, and to evaluate the global quality of height estimations in this stack of interferograms. In literature, the uncertainties of the height estimation in sub-pixel position for most radar satellites are less than 1 m [1, 10].

4. GEOCODING AIDED A LIDAR DSM MEASUREMENT

It is evident that the precision of geocoding results is dependent on the quality of the observation and of the optimal mathematical model, but the PS geolocation mismatch between actual location and the corresponding estimation happen in many studies area. Aiming to match the actual PS geolocation for PSI processing results and bypass the adjustment for the orbital error and instrument inaccuracies, the Lidar DSM data are employed to correct every PS height components, then to re-calculate PS horizontal locations. In the Netherlands, accurate detailed height measurements by using laser altimetry were carried out between 1997 and 2007, resulting in the Actual Height data of the Netherlands (AHN-1). The vertical resolution are up to 15cm, and the horizontal resolution is 5m. An intermediate product retained the heights of buildings. We used this to correct the estimated PS geolocalization by computing the offset between both height distribution histograms

$$E \{H^p_i - H^A_{HN}\} = h^\text{shift}_i$$  \hspace{1cm} (5)

where $H^p_i$ indicates the height estimation from PSI processing for a PS $i$ and its approximately corresponding height $H^A_{HN}$ which is extracted from AHN elevation data. The height shift $h^\text{shift}_i$ is unique value for all points. In the sense of iteration, $h^\text{shift}_i$ would approach to zero since the difference between AHN and PS gradually become smaller.

5. HEERLEN CASE STUDY

In this section, we elaborate a case study over Heerlen, the Netherlands jointly using 69 ERS-1/2, 71 Envisat, 20 Radarsat-2 images (descending) acquired between April 1992 and October 2011, with emphasis on the dynamic interpretation of a near-collapsed shopping mall ‘t Loon based on our proposed approach. We generated a set of interferograms by the single master PSI method to exploit the deformation time series over this region, and estimated the geolocation of all PS points associating with the validation by a Lidar DSM. Figure 3 illustrates the available SAR image in the area of study with two data time gaps in 1994 and 2001 to 2002, and one data overlap time in 2010.

In December 2011, the parking garage under shopping mall ‘t Loon nearly collapsed due to the failure of some pillars. Cavity upward migration underground is considered as the most probable driving mechanism based on the knowledge of local geological condition, the mining history and cavity upward migration. Here we do not concentrate on the driving mechanism study but focus on the analysis of the anomalous temporal behavior PS points associated with their precise geolocation. Because the location of such anomalies play an important role on the exploration of the shear distribution before the collapse happened.

Based on the Lidar-derived (AHN-1) height data, we showed the three dimensional shopping mall ‘t Loon (pointed out by a black arrow in Figure 4) in WGS84 coordinate system. Note that the high-rise apartment of ‘t Loon is smoothed by the interpolation. In addition, we also built ‘t Loon 3D model by pro/ENGINEER Wildfire software which is also shown in Figure 4 and used as backdrop for the final results in 3D visualization.
Figure 4: Lidar-derived (AHN-1) height map over ’t Loon area. ’t Loon is pointed out by a black arrow and shown as in proENGINEER-plot 3D model as well. The color from blue to red denotes increasing height. Note that the high-rise apartment of ’t Loon is smoothed by the interpolation.

The oversampling method by factors \([32, 32 \times 5]\) were applied to obtain the sub-pixel position (w.r.t its upper-left corner) in azimuth and range directions in order to correct latitude \(\varphi\) and longitude \(\lambda\) estimations. Figure 5 illustrate a sub-pixel position correction for PS1 (see Fig.7) with the offset az [m] in azimuth and rg [m] in range w.r.t its upper-left corner.

Considering the uneven terrain in our area of interest (AoI), the SRTM DEM data is employed to subtract the reference DEM from each interferogram. Then the absolute height of all PS point are estimated by Eq.(1). However, due to e.g. the poor resolution of SRTM DEM (90 m) and imperfect data processing, the error will propagate to the final PS height estimation. By using Lidar DSM (AHN) data assistant approach in Section. 4, the geolocation of PS points are re-estimated and validated by Lidar DSM data. Figure 6 show the histograms of the Lidar DSM height data, PS height estimation histogram before adaptation and the offset between AHN-1 and PS heights for Envisat (in 10km by 10km area). A.) the distribution of Lidar-derived (AHN) height close to PS points in our AoI. B.) the original distribution of PS height. C.) the height offset distribution between AHN-1 data and PS height, and the first offset value \(h_{\text{shift}} = -4.824\) m. D.) the final height offset distribution, and the final offset by the iterative offset estimation. The iteration will continue until the offset value is below AHN vertical resolution (15cm).

In the first near 18 years, its average vertical deformation rate was \(-3\) mm/yr, but there were suddenly five-times accelerating in the last period. It is evident that the shear-stress distribution pattern was changing because of the underground motion.

6. CONCLUSIONS

In this study, we considered the error sources and propagation in the Geocoding/PS geolocation. Using a Lidar 15cm precision DSM, we improved vertical absolute positioning to about \(\sim 14\) cm precision, yielding a horizontal absolute precision of \(\sim 0.32\) m. The influence of the sub-pixel position adds an uncertainty of \(\sim 6\) m and \(\sim 1\) m horizontally, east and north respectively, and \(\sim 2\) m vertically. Combined, this yields \(\sim 2\) m vertical precision, \(\sim 6\) m horizontal precision (east) and \(\sim 1\) m horizontal precision (north). To pinpoint PS to infrastructure, we conclude that both sub-pixel positioning as well as DSM improvement are absolutely required, but may still be insufficient for medium resolution SAR systems.
Figure 5: Sub-pixel position correction for PS1 (see Fig.7) with the offset az [m] in azimuth and rg [m] in range w.r.t its upper-left corner.

(a) az=0.6875, rg=4.7500  
(b) az=1.0000, rg=4.4375  
(c) az=0.6875, rg=3.5000

Figure 7: PS location and vertical velocity map after adaptation by using Lidar DSM data. The subfigures A, B and C individually show the results derived from ERS-1/2, Envisat and Radarsat2 satellite data processing. The color represents the vertical deformation rates (mm/yr) of PS points in ’t Loon above the ground, note that the color range of Radarsat2 is larger than ERS-1/2 and Envisat. Subfigure D shows the orientation of the building with the near-collapsed part indicated in red. This proves that we observe structural deformation of the building (in stead of the subsidence of the ground), many years before the near collapse.
REFERENCES


