Multi-track PS-InSAR datum connection

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Abstract—**InSAR data acquired from independent overlapping tracks can be exploited for a reliability assessment of the Persistent Scatterer InSAR (PS-InSAR) technique. This is obtained by means of the datum connection of multiple tracks, simultaneously evaluating the misclosures between multi-track PS-InSAR estimates.**

Due to a different viewing geometry, many of the detected PS will physically not be the same. However, their estimates may still refer to the same deformation signal. The existence of independent observations of the same deformation signal provides a powerful tool to increase the redundancy and evaluate the reliability. The datum connection can be subdivided in two steps. The first step consists of the conversion of PS locations to a common datum. Secondly, the PS-InSAR parameter estimates (velocities, displacements, heights) are connected. In stead of the conventional approach of separately geocoding each track, we propose the use of a common radar datum defined by the acquisition geometry of the 'master track'.

Multi-track datum connection has been applied in the Groningen region, the Netherlands, which is affected by subsidence due to gas extraction with displacement rates up to 7 mm/year. The main reservoir is (partly) visible in 6 independent overlapping ERS tracks from 1992 (ascending and descending). Datum connection resulted in a consistent set of PS-InSAR deformation estimates. Additionally, the deformation signal was decomposed in horizontal and vertical movements, utilizing the different viewing geometries of the tracks.

I. INTRODUCTION

The application of the PS-InSAR methodology over a large spatial extent requires large PS networks both in space and time. Numerous PS phase difference observations and large systems of equations, combined with the presence of residual errors that propagate over a large extent (orbits, atmosphere, unwrapping), complicate the quality assessment of the PS-InSAR deformation estimates. At the same time, the availability of PS-InSAR estimates from multiple overlapping independent tracks provides a powerful tool for a reliability assessment of the technique itself, prior to the integration with other geodetic measurement techniques.

The integration of PS-InSAR estimates from multiple tracks is considered as a datum connection problem. The PS-InSAR estimates of independent tracks are located in their own local radar datum and refer to their own reference PS. As a consequence, a datum connection between all tracks needs to be established. This datum connection consists of two steps:

1) the definition of a common datum,
2) connection of the PS-InSAR parameter estimates (velocities, displacements, heights).

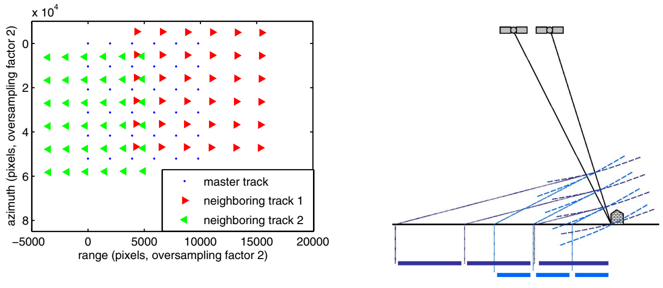
II. A COMMON DATUM

A. Radar versus geographic datum

For the datum connection of PS-InSAR estimates, the likelihood that PS from different tracks refer to the same physical target or deformation regime should be optimized. Therefore, the multi-track PS localization should be unambiguous. Geocoding each track independently does not resolve for the range and azimuth timing error per track and the uncertainty in the reference PS height. Here we propose to define a common radar datum: the acquisition geometry of one of the tracks that is appointed as '**master track**'. The remaining tracks are denoted as 'slave tracks'. Based on the PS point fields and image contents in the multi-image reflectivity map, the relative azimuth and range timing errors between the tracks can be estimated to sub-pixel accuracy. Furthermore, the uncertainty in the reference PS heights decreases in the intercomparison of multiple tracks, prior to geocoding. The conversion of multiple overlapping tracks to a common radar datum leads to a consistent PS localization. Furthermore, it reduces the degrees of freedom in the geocoding to one range and azimuth timing error.

B. Orbit based radar datum transformation

Based on the precise orbits of the master scenes for each track, an approximate transformation between the tracks can be estimated. For P tracks, $P-1$ independent transformations can be defined. The maximum ground level height difference in the Groningen area is approximately 30 meters. Even for a baseline of 50 kilometers between adjacent tracks, this leads to relative pixel location errors in the order of 0.1 pixel, which falls within the coregistration precision. Hence, uniformly spaced subsets of radar coordinates are transformed to geographical WGS84 coordinates on the ellipsoid, that are subsequently projected to the internal radar datum of an overlapping track (Fig. 1). The offsets between the radar coordinates in the master and slave track are the observations in the system of equations for the estimation of the radar datum transformation parameters between the tracks. The radar datum



(a) (b)

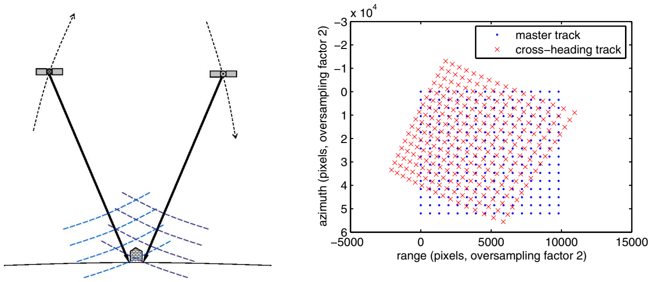
Fig. 1. The effect of a different viewing geometry of adjacent tracks.

transformation is parameterized as a p^{th} degree polynomial:

$$\begin{aligned}\Delta\xi(\xi,\eta) &= \sum_{i=0}^{p}\sum_{j=0}^{i}\alpha_{i-j,j}\xi^{i-j}\eta^{j},\\ \Delta\eta(\xi,\eta) &= \sum_{i=0}^{p}\sum_{j=0}^{i}\beta_{i-j,j}\xi^{i-j}\eta^{j},\end{aligned} \tag{1}$$

where $\Delta\xi$ and $\Delta\eta$ are the offsets in azimuth and range direction respectively . The transformation parameters α and β describe the relative distortion of the slave tracks with respect to the master track (Fig. 2).

The estimation procedure of the radar datum transformation parameters is followed by a testing procedure that evaluates the residuals over the full overlap between two tracks. Depending on the precise orbits and the relative distortion of the radar datum, the degree of the polynomial has to be increased to ensure that the transformation is geometrically at sub-pixel level. Tab. I shows that in the Groningen area a polynomial degree of 5 was required to ensure a geometrical radar datum transformation at sub-pixel level both for adjacent and cross-heading tracks.



(a) (b)

Fig. 2. Radar coordinate distortion of a cross-heading track projected on the master track.

Note that when the area of interest contains significant height differences, modeling the radar datum transformation as a polynomial may not be accurate enough. Additional geometrical corrections can be determined based on the estimated PS heights, analogue to DEM-assisted coregistration.

C. *PS point fields*

The orbit based datum transformation parameters (see II-B) do not account for relative timing errors in range and azimuth direction. These have to be estimated based on the image contents. Under the null hypothesis, timing errors are parameterized as an additional offset in range and azimuth direction. Since the PS point fields are available for each track, the optimal shift between their location fields can be determined. From the convergence regions in Fig. 4 it can be deduced that the additional range and azimuth shift cannot unambiguously be obtained from PS location fields for cross-heading tracks. This can be explained by the opposite viewing geometry and a difference in incidence angle of approximately 45 degrees. The amount of identical PS or PS that refer to the same object will be very limited.

TABLE I
MAXIMUM RANGE COORDINATE RESIDUALS FOR THE GRONINGEN AREA (PIXELS, OVERSAMPLING FACTOR 2).

polynomial degree	adjacent	cross-heading
2	3	40
3	0.3	6
4	0.15	1.5
5	0.1	0.25

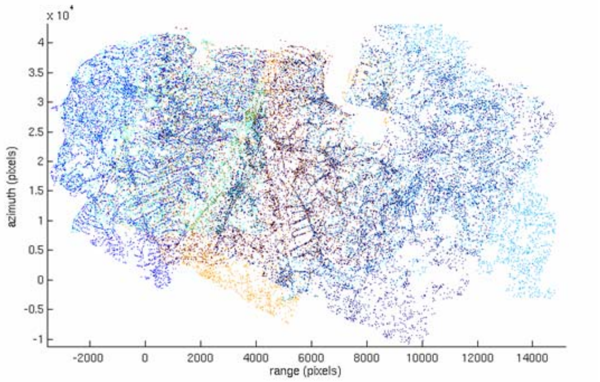


Fig. 3. PS point fields of multiple overlapping tracks.

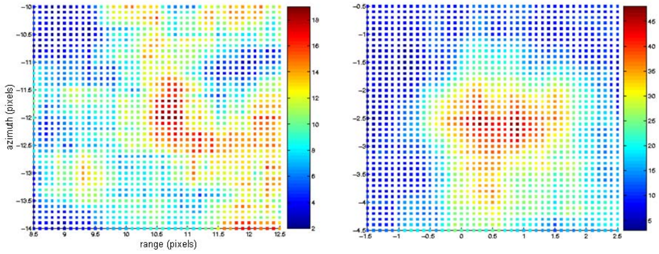


Fig. 4. Estimation of refined datum transformation based on PS point fields: search space additional range and azimuth shift for (left) two cross-heading tracks and (right) two adjacent tracks.

D. *Multi-image reflectivity maps*

Besides the PS locations, the multi-image reflectivity maps per track can be utilized to estimate a refined radar datum transformation between tracks. As the viewing geometry from different tracks is not the same, the ground resolution and orientation of the overlapping multi-image reflectivity patches vary. Hence, the following procedure is applied:

1) selection of randomly distributed multi-image reflectivity windows around PS targets,
2) resampling of the selected windows to the master track radar datum using the initial orbit based transformation,
3) estimation of range and azimuth shift using correlation optimization.

In stead of oversampling the multi-image reflectivity windows, the sub-pixel shift in range and azimuth direction has been determined by an image matching technique based on amplitude gradients [1]. The precision of these shifts is 0.25 pixel for adjacent tracks, and 0.5 pixel for cross-heading tracks. This is sufficient to identify multi-track PS within resolution cell distance. In future research, the maximum achievable precision of multi-image reflectivity window matching can be further exploited, as well as the effect of alternative hypotheses for the transformation parameterization.

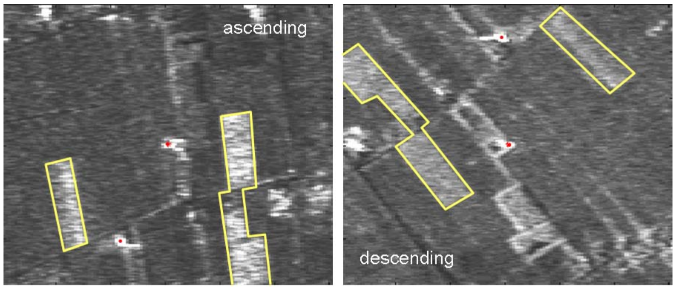


Fig. 5. Cross-heading neighboring PS targets.

III. Multi-track PS-InSAR parameter estimates

The transformation of PS coordinates to the datum of the master track enables the unambiguous identification of physically identical and clusters of neighboring scatterers in adjacent and even cross-heading tracks. This is an important step before the datum connection of PS-InSAR deformation estimates: the likelihood that closeby PS refer to the deformation regime has been optimized. To avoid any assumptions on the functional model of the (unknown) deformation regimes, the PS-InSAR estimate misclosures are the observations in the datum connection.

The incidence angle of adjacent tracks is only a few degrees different, implying that trihedral targets pointing in the satellite look direction are likely to be observed in multiple tracks. Cross-heading tracks however have an almost opposite viewing direction. Cylindrical poles are observed in ascending and descending mode [2], but such natural scatterers do not necessarily exist in the area of the interest.

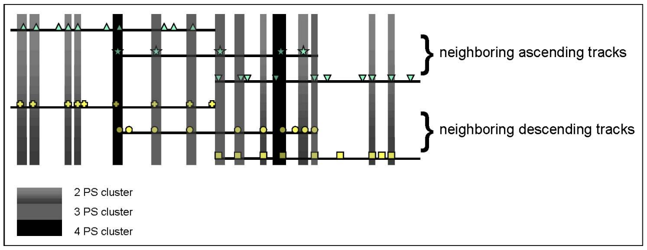


Fig. 6. Schematic overview of PS clusters.

Physically identical targets represent the same deformation regime, provided that the reflection type is the same (mirror, dihedral). This does not imply that neighboring PS targets cannot be used for the datum connection (Fig. 6). The detected PS in overlapping tracks clearly follow man-made structures in the terrain (Fig. 7). Although it is possible that neighboring targets are moving due to different deformation regimes (e.g. due to foundation instabilities of a building), the shorter the distance between the PS, the higher the likelihood that they represent the same deformation regime.

In the datum connection of multi-track PS-InSAR deformation estimates (velocities, displacements), we therefore start with the null hypothesis that clusters of neighboring targets belong to the same deformation regime. Utilizing the high redundancy in the estimation of the transformation parameters of the overlapping tracks, a datasnooping procedure is applied that removes PS clusters that do not refer to the same deformation regime.

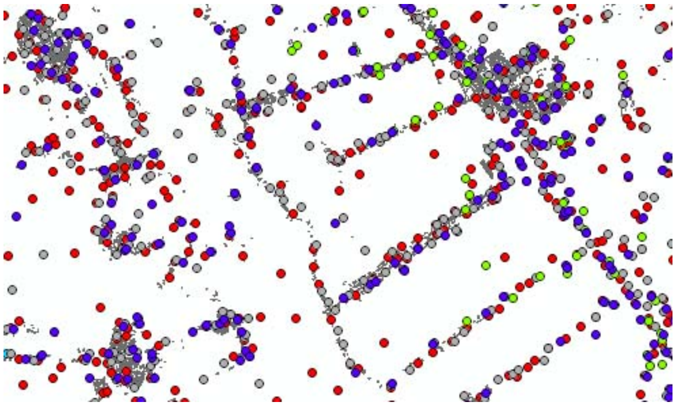


Fig. 7. Detected PS in overlapping tracks following man-made structures in the terrain; different colors represent different tracks.

The difference between PS-InSAR parameter estimates (velocities, displacements, heights) should theoretically only be an offset per track because of a different reference PS. However, due to residual orbital and atmospheric effects and unwrapping errors, the set of transformation parameters is extended with trend parameters in range and azimuth direction.

IV. Groningen multi-track PS-InSAR

The subsurface of the Northern part of the Netherlands contains several gas fields that are located at a depth of approximately 3 kilometers. The Groningen gas field is the largest, with a diameter of 30 kilometers. Since it has been taken into production in the 1960s, the reservoir pore pressure decreased which resulted in a compacting layer. Subsidence at ground level has the spatial pattern of a smooth ellipsoidal bowl, with maximum displacement rates of approximately 7 mm/year that are (nearly) linear in time. The Groningen subsidence bowl is (partly) covered by 6 independent overlapping ERS tracks. Fig. 8 shows the PS displacement rates after datum connection in the entire Northern part of the Netherlands, including a part of Germany. All subsiding areas due to gas extraction clearly show up in the results, and are spatially consistent. The temporal sampling increases as well: a PS is viewed by up to 4 tracks, that are distributed over the repeat interval of 35 days (Fig. 9).

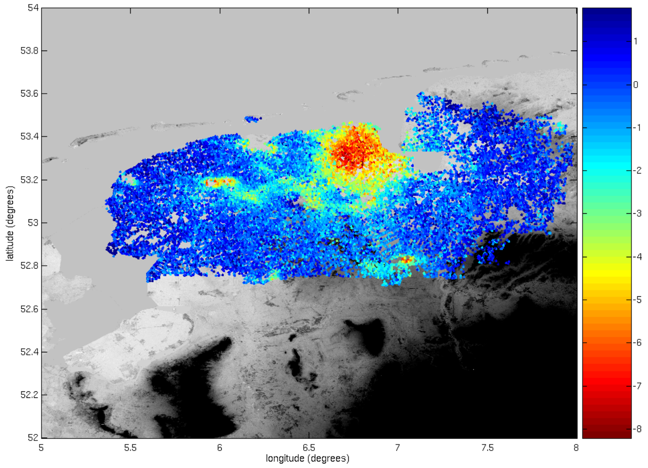


Fig. 8. PS velocities (mm/year) after data connection for the entire Northern part of the Netherlands, including Germany. Period: 1992-2005.

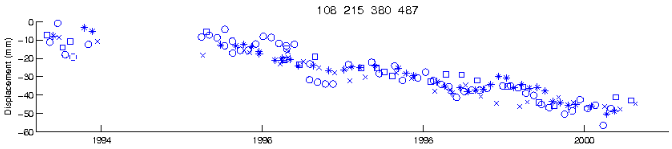


Fig. 9. Displacement timeseries of neighboring PS (mutual distance < 500 meters) that are viewed from 4 tracks.

After datum connection, the PS-InSAR results are mutually consistent in the reference system of the master track. However, the reference system of the master track can still contain small systematic components due to unmodeled residual effects. These are estimated in the order of several mm/year over 100 kilometers. This trend cannot be unambiguously addressed to either real deformation signal or unmodeled residual components in the PS-InSAR estimation. It can be corrected for, as long as the error bounds are clearly defined. Utilizing the different viewing geometries, the PS deformation estimates have been further decomposed into a vertical and a horizontal component along ascending look direction [3]. To increase redundancy, this procedure was applied after quadtree decomposition of the subsidence signal. Fig. 10 shows local horizontal movements towards the center of the main subsidence bowls of 2–3 mm/yr. This approximately corresponds in direction and magnitude with a theoretical prediction of 2–4 centimeters in 10 years, based on a simplified representation of the Groningen gas field [4].

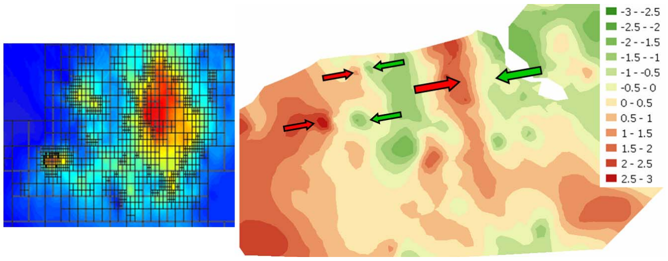


Fig. 10. Quadtree decomposition and interpolated horizontal PS velocities (mm/year) along ascending look direction.

V. CONCLUSION

A mathematical framework for the datum connection of multiple independent overlapping tracks has been introduced. Based on orbits, PS point fields and the multi-image reflectivity maps per track, it has been demonstrated that multi-track PS locations can be converted into a common radar datum defined by the master track. Subsequently, clusters of identical or neighboring PS from different tracks could be detected, that form the basis for the datum connection of PS-InSAR estimates (displacements, velocities, heights). The datum connection was successfully applied in the Groningen subsidence area and resulted in spatially coherent velocity estimates over a large spatial extent and with an increased temporal observation density.

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