ON THE USE OF POINT TARGET CHARACTERISTICS IN THE
ESTIMATION OF LOW SUBSIDENCE RATES DUE TO GAS EXTRACTION
IN GRONINGEN, THE NETHERLANDS

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ABSTRACT

The subsurface of the north-eastern part of the Netherlands contains large gas reservoirs that have been taken into production since the early 1960s. The resulting subsidence has been precisely and reliably estimated using measurements from repeated leveling campaigns and is now for the first time unambiguously observed using PS-InSAR. The subsidence rates are small (<1 cm/year) and the PS density is relatively low due to the rural character of the area. Particularly it is difficult to distinguish the PS deformation components due to gas extraction from other possibly superposed deformation regimes. Besides a strict quality description of the estimated parameters, the characterization of physical PS properties is therefore of major importance.

In this paper we focus on the interpretation of PS-InSAR deformation estimates in Groningen by investigating the scattering properties of the detected PS. Through combining the shape of their complex spectrum and estimated heights from PS-InSAR processing, the nature of the PS is investigated. Important issues for performing the scatterer characteristics analysis, such as coregistration and SAR amplitude calibration, are addressed. After analyzing the effect of temporal and perpendicular baseline and Doppler frequency variations, the PS-InSAR deformation estimates from different reflection types are evaluated on their performance for estimating subsidence due to gas extraction.

1 THE GRONINGEN GAS FIELD

The north-eastern part of the Netherlands contains large gas reservoirs at a depth of approximately 3 kilometers below ground level. The largest is the Groningen gas field with a diameter of roughly 30 kilometers. The reservoir itself consists of a 100-200 m thick porous sandstone layer. Since the early 1960s it has been taken into production by the Nederlandse Aardolie Maatschappij B.V. (NAM). During the production, the reservoir pore pressure is decreasing resulting in a compacting layer. As the layers on top of the compacting reservoirs are subsiding as well, the ground level is subsiding. Surface deformation due to gas extraction has the shape of a spatially smooth ellipsoidal subsidence bowl [1], depending on the depth and shape of the reservoir. The subsidence rate is approximately linear, with a decreasing velocity further away from the center of the bowl. The NAM is legally obliged to monitor the subsidence due to gas extraction, to be able to assess the influence of gas extraction on water management and environmental issues. Hence leveling campaigns have been performed since the start of production. Geodetic adjustment and testing techniques have been applied to estimate subsidence due to gas extraction from height difference observations. Besides tracing measurement errors and point misidentifications also tests on autonomous benchmark behavior are evaluated. The total estimated subsidence in the center of the bowl is 24.5 cm for the period up to 2003, which implies an average subsidence rate of 7.5 mm/year.

Currently, the application of PS-InSAR for estimating subsidence due to gas extraction is evaluated. Complicating factors are the low subsidence rates (<1 cm/year), the rural character of the area and atmospheric disturbances. Besides these issues, a major challenge lies in the interpretation of the estimated PS velocities. Contrary to traditional geodetic techniques using well-defined benchmarks, the PS measurement point – the effective reflectivity center – is less well known. As a result it may be difficult to discriminate which PS displacements are caused by a certain deformation regime (gas extraction, shallow compaction, structural instabilities). A way to gain more insight on PS properties, is to investigate if they can be classified in specular and dihedral reflections. With the objective to be able to discriminate subsidence due to gas extraction from other deformation regimes, the PS reflectivity patterns are analyzed. Methods as described in [2] are evaluated for the Groningen gas field.
2 GRONINGEN PS-INSAR RESULTS

2.1 Processing methodology

A PS-InSAR analysis has been performed both for ascending and descending mode. The coregistration residuals have been checked and appeared to be lower than 0.1 pixel for the majority of the acquisitions within the stacks. Ambiguities have been resolved using the ambiguity function, followed by a geodetic spatial network testing which should assure a success rate close to 1 for correctly resolving the ambiguities. The PS displacements are parameterized with a minimum number of parameters, which means linear velocity. This is the strongest model in terms of redundancy. It needs to be followed by a residual analysis to trace possible model deviations which influence the parameter estimates. Acquisitions with a Doppler difference (relative to master) higher than 500 Hz are excluded from the PS velocity and height estimation, as the noise level of most PS observations is significantly higher. Only few PS have such ideal point target properties, that they are visible over a wide range of squint angles. In the reflectivity analysis they are again included, as its strength depends on the variety of viewing angles in range and azimuth direction. The temporal acquisition frequency of the descending mode is twice the temporal frequency of the ascending mode. The number of interferograms used for the PS velocity estimation is 72 and 32 for descending and ascending mode, respectively.

2.2 PS-InSAR results

The results in Fig. 1 show that PS-InSAR is able to estimate wide scale surface deformation coinciding with the gas extraction areas. The main Groningen subsidence bowl is clearly visible, as well as some other subsiding areas which are not necessarily caused by gas extraction. Subsidence rates vary generally from -8 mm/year up to 2 mm/year uplift relative to the reference point. They correspond with the subsidence rates estimated from the leveling campaigns, although this comparison has to be further refined.

The density in the rural areas is remarkably high. Although the Groningen area contains numerous agricultural fields, the majority of the buildings in this area serves as a PS, especially when combining different tracks. The PS density is not comparable to that of an urban area (> 100 PS/km²), but it is sufficient to cover the spatial extent of the subsidence bowl.

The PS results of both ascending and descending mode detect the spatial subsidence pattern located at the Groningen gas field. After converting the PS velocities to the vertical, differences in average PS velocity per km² remain with a standard deviation of 1.8 mm/year. First of all this may be due to different physical PS properties representing different deformation regimes. Especially in areas with a low PS density this may lead to local differences between ascending and descending velocities. Secondly, the lower observational redundancy in ascending mode (less images) may lead to less precise estimates.

Figure 1: (a) PS-InSAR velocities descending mode, track 380, frame 2533, (b) PS-InSAR velocities ascending mode, track 487, frame 1063.
2.3 Model imperfections

As the stochastic model of InSAR observations is not very well known a-priori, a Variance Component Estimation (VCE) is carried out per arc [3]. In this study, the variance-covariance matrix of the observations is considered to be a superposition of measurement noise, atmospheric noise, and temporally correlated residual non-linear deformation. As estimations are performed per arc, atmospheric noise can not be distinguished from measurement noise. The estimated variance factor therefore accounts for both measurement and atmospheric noise, acting as a scaling factor for different atmospheric disturbances [4]. When performing VCE, we check the validity of model assumptions to avoid that model imperfections are incorrectly addressed as measurement noise or atmospheric noise. Fig. 2 shows the estimated velocities and their estimated precision for a small study area. Fig. 2(b) contains an area with a significantly lower precision than the surroundings. The main question is whether this can be contributed to a higher PS measurement noise, PS instability, or that the hypothesis of linear velocity is not valid. To trace model deviations, a residual analysis is performed based on the least-squares residuals of the PS height and velocity estimation after correctly resolving the ambiguities. The area is divided in blocks of 3 by 3 km$^2$, assuming a spatially smooth behavior of the signal of interest. From the residuals of all PS within a block (with reference to the reference point), a variance-covariance matrix is created:

$$C_\varepsilon = \hat{\varepsilon} \hat{\varepsilon}^T$$  \hspace{1cm} (1)

where $\hat{\varepsilon}$ is the matrix of least-squares residuals (number of interferograms by number of PS) and $C_\varepsilon$ represents the variance-covariance matrix of the residuals. This variance-covariance matrix is decomposed into eigenvectors and eigenvalues. For each block the eigenvector corresponding to the largest eigenvalue, accounting for the largest variability within the block, is analyzed. From Fig. 2(c) it is easy to see that the blocks with a lower precision show a systematic residual behavior deviating from the linear velocity model. When looking into the PS time series, there is indeed a breakpoint in the displacement rate, see Fig. 2(d). Using the residual eigenvector analysis areas can be traced where model assumptions have to revised and alternative hypotheses have to be evaluated. In this case the delayed onset of the subsidence is confirmed by the start time of gas production in the area.

3 TARGET CHARACTERIZATION

3.1 Separation of deformation regimes

Besides model imperfections, uncertainties regarding PS characterization can complicate a precise and reliable estimation of the signal of interest: subsidence due to gas extraction. Contrary to traditional geodetic techniques, the physical properties of the measurement point are less well defined for PS-InSAR. If the PS is located in an area where several deformation regimes are superposed, it is of major importance to know the PS reflection type: is it a direct specular reflection or is it a dihedral reflection where the surroundings are involved? Due
to the soft soils in the Netherlands the potential presence of several deformation regimes cannot be neglected. As buildings in the Groningen area are generally founded on a deeper subsurface layer, direct reflections from settled buildings are more suitable to estimate deep subsurface displacements like gas extraction as they do not contain the shallow subsurface displacement component. To gain more insight in PS properties, the PS reflectivity pattern and the estimated PS-InSAR heights are utilized. Envisat HH/VV Alternating Polarization images could also be beneficial for PS interpretation [5], but unfortunately such an image has not yet been acquired for the Groningen area.

3.2 Reflectivity pattern parameterization

Target characterization focuses on the PS reflectivity pattern as a function of the local incidence angle, dependent of the perpendicular baseline, the squint angle (Doppler centroid), and the local terrain slope [2]. This technique exploits the variations in viewing and squint angle to identify the PS reflectivity behavior. Contrary to dihedral and trihedral reflections, specular reflections are assumed to exhibit a high directivity in both range and azimuth direction. The power of distinguishing specular from dihedral reflections depends on the range of viewing and squint angles within a stack and the number of observations (acquisitions). For the Groningen descending stack there are in total 106 acquisitions available with a Doppler range of 9050 Hz, which corresponds with a squint angle variation of 5.3 degrees. The range in perpendicular baseline is 2215 m, causing a viewing angle range of 0.13 degrees.

In [2] the PS amplitude observations are modeled as a sinc function of perpendicular baseline and Doppler difference. The unknown parameters are the target extension and the position of maximum reflection (shift) in range and azimuth direction. The target extension is the target size across track and along track in meters, and is inversely proportional to the sinc width. For estimation purposes, we use normalized intensities ($\sigma_0$) as observations. As the reflection patterns in range and azimuth direction are considered to be uncorrelated, a joint estimation of the parameters that characterize the reflectivity pattern is modeled as the multiplication of two sinc$^2$ functions, preceded by a multiplication factor describing the maximum signal strength. Furthermore, Doppler and perpendicular baseline variations have been converted to viewing and squint angles, to show the angular sensitivity of PS reflections.

To reduce the effect of backscatter variations due to sensor characteristics, the PS intensities have to be calibrated. By performing an empirical calibration – the estimation of multiplication factors per image based on the amplitudes of potential PS –, intensity variations due to a different viewing geometry may be partially adapted to a mean level. Especially for the relatively few acquisitions with a high Doppler difference there is a potential risk of increasing the amplitude level to the majority of the acquisitions. Therefore, the ESA ERS SAR calibration [6] based on physical sensor parameters has been applied, restricted to calibration constant, replica pulse power and elevation antenna pattern gain. All corrections for different viewing geometry have been omitted. In a first approach, integer least-squares methods were applied to estimate the five unknown reflectivity parameters from the backscatter observations. However, convergence of the linearized systems of equations appeared to be problematic, probably because of non-idealistic point target properties of the PS and the sparse distribution of observations in the higher Doppler deviations. Therefore the best fit of the reflectivity pattern is detected in a pre-defined search space of the unknown parameters. Although this method is not optimal in the sense that it is guaranteed that the estimator is unbiased and has minimum variance, it is applied to obtain an initial assessment of the detectability of specular reflections.

3.3 Reflectivity analysis in a stable area

The main objective in the Groningen area is to estimate subsidence due to gas extraction from PS-InSAR displacements. Therefore, PS displacements representing structural instabilities and shallow compaction need to be excluded from the subsidence estimation procedure. Specular reflections from settled buildings founded on a deeper subsurface layer are the most suitable targets for the estimation of subsidence due to deep subsurface displacements. In the following, we focus on the classification of targets by means of reflectivity pattern analysis (Point Target Analysis, PTA) for a stable area, to avoid interference of additional ongoing processes. First, all point targets in the PS-InSAR results are detected, using complex multiplication of oversampled PS patches for the entire
stack. This way, speckle is suppressed, and point targets can easily be detected by a convolution with a sinc² kernel. Second, the parameters corresponding to the best fit to the normalized intensity observations are determined. This yields five parameters per point target: maximum reflection, target extension in range and azimuth direction and perpendicular baseline and Doppler difference of maximum reflection. It can be argued that specular reflections require a strict pointing towards the master observation geometry (and therefore have their maximum reflection at zero baseline and zero Doppler difference), to be detected as a PS. However, because of their narrow reflectivity pattern, there is a certain degree of freedom for the maximum to appear in another part of the Doppler and baseline range that is sufficiently sampled by observations. Therefore we restrict to the target extension for a first classification of point targets.

![Image](image.png)

Figure 3: (a) Reflectivity pattern fit: normalized intensity observations as a function of viewing and squint angle, reflectivity pattern fit and its profiles in range and azimuth direction, (b) PS velocity distribution before and after selection on range target extension, (c) PS velocity distribution before and after selection on PS height. Solid bars represent the PS velocity distribution of the selected area. Open bars represent the velocity distribution after selection on target extension or PS height.

A reflectivity pattern example as a function of viewing and squint angle is shown in Fig. 3(a). Due to the high Doppler deviations of ERS-2 after 2000, the range of squint angles is much higher than the range of viewing angles. For this example the sensitivity for changes in viewing angle is low, which indicates that the PS is a possible double-bounce reflection. In case of specular reflections, the reflection pattern exhibits higher localized intensity changes.

The question is whether specular reflections can be distinguished from dihedral reflections based on their smaller reflectivity signature, corresponding with a larger target extension. This case study does not attempt to define the target extension boundary for specular and dihedral reflections. Because of the diversity of PS targets, this may be complicated without additional data.

Hence, the point target extension is evaluated against the distribution of PS velocities, based on the assumption that specular reflections stem from buildings mounted on a stable subsurface layer, exhibiting lower PS velocities. The dark grey histogram in 3(b) shows the PS velocity distribution in the selected area of 30 by 30 km that is not affected by deep subsurface displacements. This skew-symmetric PS velocity distribution has a tail of negative PS velocities, which may be caused by relative shallow compaction or autonomous movements. The light grey histogram shows the velocity distribution when only the 30% PS with the smallest reflectivity width (hence, more specular types of reflection) in range direction are selected. Indeed this PS velocity distribution is more concentrated in the stable domain. A similar shift of PS velocities is observed when selecting PS based on their estimated heights. By calculating height histograms for moving windows over the area of interest, PS heights above ground level have been estimated, based on the assumption that the histogram peaks correspond with ground level, which needs to be verified by AP data [2] in further research. The selected PS with a relatively higher height above ground level are relatively more concentrated in the stable domain of PS velocities.

The PS velocity histogram results based on the reflectivity pattern analysis correspond with what one would physically expect. Reflectivity pattern analysis can aid a first selection of PS suitable for the estimation of subsidence due to gas extraction. The procedure should be refined to subsequently compose a set of derived PS displacements measurements including their variance-covariance matrix as input for the geodetic adjustment and
testing procedure. In this procedure, alternative hypothesis will be tested to remove autonomous movements that are not spatially correlated.

4 CONCLUSIONS

It has been shown that wide scale surface deformation smaller than 1 cm/year corresponding with gas extraction areas in the northern part of the Netherlands can be measured using PS-InSAR. Despite the rural character of the area, the majority of the buildings in the area serve as PS which causes the PS density to be promising for the estimation of the signal of interest. PS-InSAR model imperfections can be traced by performing a residual eigenvector-eigenvalue analysis. The width of the PS reflectivity pattern can be used as a first distinction between specular and dihedral reflections.

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