SURFACE DEFORMATION OF THE WHOLE NETHERLANDS AFTER PSI ANALYSIS

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ABSTRACT

Being a coastal country with low topography, the Netherlands is seriously threatened by the risk of being flooded. Improving our knowledge of the deformation signals affecting the country is therefore a need. Dutch authorities carry out periodic leveling measurements to monitor surface heights. A major country wide campaign happens every 20 years, but if we take into account not only first order network campaigns but also higher order ones, heights are measured every 5 to 10 years, area dependent. However, the knowledge we obtain from these observations is very limited because the reduce density of benchmarks, around 1 every 10 km, (area dependent) and the low temporal sampling. A more thorough analysis can be performed with other geodetical techniques, in particular, time-series InSAR. These methods are able to provide with a density of reliable measurements of about 100 per km², although this is case dependent. Furthermore, the archive of the European space Agency (ESA) provide us with an observation every 35 days for the Netherlands, with one year data gap in 1994 and 3 years gap from 2001-2004.

To estimate land deformation over the whole of the Netherlands we need to combine InSAR estimates obtained for different tracks (satellite foot-prints), but this operation is not trivial. First, to capture large scale deformation we need to take into account that radar images are usually affected by orbital errors and atmosphere. Second, since InSAR produce deformation maps relative to an area (or pixel) that is part of the observed track, data combination requires to change these relative measurements to a common area or reference point.

In this contribution we explore a method for data combination to produce a velocity map of the whole Netherlands that reflect the average rates of the period 1992-2010. We combine all InSAR tracks available over the country for this period, plus leveling and GPS. These last two techniques help to better constrain the long-wavelength deformation signal and remove ramps produced by atmosphere or orbital errors that affects InSAR measurements.

Key words: Persistent scatterer ; time series; ERS-Envisat; large scale map.

Figure 1. Flood prone areas in the Netherlands, after Rijkswaterstaat (2007).

1. INTRODUCTION

The Netherlands is a coastal country with very low topography, 40% of the territory is below mean sea level. Flooding risks are therefore a major concern. Figure 1 show the areas in the Netherlands that are prone to be flooded, which occupy most of the western and northern part of the country. Hence, monitoring surface deformation in the Netherlands is crucial to plan and reduce flooding risks. Surface displacements are measured by Dutch authorities mainly through leveling, with the intrinsic limitation of being spatially sparse and having a low temporal resolution.

Other techniques, in particular, Persistent Scatterer Interferometric SAR (PSI) (see, e.g., Ferretti et al. (2001), Hooper (2006), Kampes and Adam (2006)) have also
proved to be very valuable to measure land deformation. These techniques provide with an unmatched density of observations for large coverage (100 x 100 km²) and high measurement frequency (usually 1 observation every 35 days with some data gaps).

PSI employs a stack of radar images to detect scatterers that remain coherent over time and, therefore, are almost not affected by noise. The noiseless nature of these scatterers facilitates phase unwrapping (unfolding of the phase outside its nature range of [-π, π]) and the estimation of the atmosphere and other spatially correlated noise.

PSI has been successfully applied in the Netherlands to measure land deformation caused by, e.g., gas production (Ketelaar, 2008), water extraction (van Leijen and Hanssen, 2007) and water rebound in abandoned coal mines (Caro Cuenca and Hanssen, 2010). However, until now PSI coverage, although large, has been limited to the nominal image size (100 x 100 km²). Better comprehension of the deformation phenomena can be achieved by studying a wider area.

In this contribution, we employ PSI to produce a velocity map over the whole Netherlands, covering a total area of 200 x 350 km². Furthermore, for areas where PSI may fail to produce reliable results, e.g. due to low number of images we apply the method known as multitemporal InSAR (MTI) which combines PSI with small baseline (SB) techniques (Hooper, 2008). The goal of SB methods is to minimize decorrelation noise by selecting those images pair with short temporal and geometric distances (Berardino et al., 2002; Mora et al., 2002). Once the network of interferograms is built, reliable pixels are detected based on the dispersion of amplitude differences (Hooper, 2008).

The radar images used in this study were acquired by the European Satellites ERS1/2 and Envisat. The radar data covers the time range from April 1992 to January 2001, and from November 2003 to September 2010, for ERS1/2 and Envisat, respectively.

The final deformation map combines all available information on surface displacements. We include not only rates estimated from time series InSAR methods but also leveling and GPS estimates. To integrate multi-track InSAR rate maps with GPS and leveling velocities, we propose a least squares approach with the focus on mitigating orbital errors and other large scale nuisance signals that usually affect InSAR data.

2. RATES ESTIMATION

2.1. GPS

We select nine continuous GPS stations located in the Netherlands and vicinity. GPS locations are shown in fig. 3. They belong to the EUREF network (EUREF, 2011). They provide with the rates of each station and the time series (A. Kenyeres pers.comm 2011).

![Figure 2. Leveling network of selected benchmarks. Spatial coordinates are given in RD (Rijksdriehoeks) coordinate system, which is usually used in the Netherlands.](image)

2.2. Leveling

Leveling time series are provided by the Dutch Ministry of Transport (Rijkswaterstaat, 2011). Different leveling campaigns are periodically carried out by the Dutch authorities. Leveling heights are then adjusted and given with respect to the Dutch vertical datum known as Normal Amsterdam Peil (NAP). In 2005, the Dutch ministry of transport changed the height of the NAP after estimating that this reference point was moving. We take into account this correction and remove it from the time series.

We only select those benchmarks that were measured at least three times during the period covered by InSAR (1992-2011) to be able to estimate a linear function (2 unknowns) and to test the reliability of the estimates. The time series that do not pass overall model tests (Teunissen, 2000) are rejected.

We observe that the measuring frequency is area dependent. Although, first order network leveling are performed once every 20 years, lower order networks are measured more often. On average we find the each selected benchmark (17,000 in total) has been measured once every five years. Figure 2 shows the location of these benchmarks.
3. INSAR PROCESSING

We process all available ERS1/2 and Envisat images that were acquired over the Netherlands. We do not employ the nominal image length of 100 km but change it accordingly to cover the whole country. The data with non nominal length is delivered by ESA in RAW format. Therefore, these unprocessed images are required to be focused. We focus the RAW images using the JPL/CalTech Repeat Orbit Interferometry Package (ROI PAC) (Rosen et al., 2004). In total, we processed about 600 images with a width of 100 km and length that changes from 100 to 300 km. The whole data set includes 8 descending tracks (3 Envisat and 5 ERS1/2), and 11 ascending tracks (6 ERS1/2 and 5 Envisat), see fig. 3.

To produce interferograms, each track is processed independently. The images belonging to a given track are coregistered and resampled to a master (or reference) image geometry. The master image is selected to maximize coherence (correlation between SAR images) for the whole stack. Interferograms are created with the software DORIS (Kampes and Hanssen, 2000).

3.1. InSAR time series processing

Although for most of the tracks we use PSI processing, (Hooper et al., 2007), in the cases where the number of images is judged to be low (less than 20) or the PS density could compromise phase unwrapping, e.g. due to large water bodies, we employ MTI. This technique merges coherent pixels found by PSI and SB before phase unwrapping, (Hooper, 2008). Once the time series are unwrapped we estimate orbit ramps by fitting a 2-D first order polynomial to the each interferogram. The estimated ramps are then removed from the observations. Atmosphere is also modeled and removed using the classical approach, (Ferretti et al., 2001), where atmospheric artifacts are obtained by high pass filtering in time and smooth interpolation in space. As mentioned earlier, these operations are performed per interferogram. After removing orbital errors and atmospheric artifacts we estimate velocity maps per track.

4. DATA COMBINATION

At this stage we have estimated velocity maps for different InSAR tracks, leveling benchmarks and (few) GPS stations. Before merging results, we need to solve for the fact that each map has its own reference point. Furthermore, the observations are at different spatial locations, for example, leveling benchmarks do not correspond to selected PS and vice versa. Thus, we first interpolate the rate maps to a common grid using ordinary kriging (Wackernagel, 1995). We do not extrapolate, which means that InSAR estimates are interpolated to those grid cells that are within the track limits. From ordinary kriging, we also estimate the variance of each observations that depends on the distance from the original observations to the grid cell and the variability of the observations (Wackernagel, 1995).

After spatial interpolation, we correct for the relative motion between reference points. To do so, we assume that all techniques observe the same signal despite measuring at (slightly) different periods, i.e. we assume the rates are stationary. For the areas where this assumption does not hold, the final results will represent the average deformation over the time 1992-2010, which still very valuable information.

We select as global reference the Dutch vertical datum (NAP) employed in leveling adjustments. To explain the process let us take the example of any given track e.g. ERS1/2 in descending mode. This can be generalize to any other case. The average difference between leveling and this track is caused by the relative motion between references. We estimate this offset using Best Linear Unbiased Estimator or BLUE (Teunissen, 2000). The system of equations for this example can be written as a Gauss-Markov model, where the functional model is given by:

$$E\left\{ \begin{bmatrix} v_{ers,desc}^1 - v_{lev,LOS}^1 \\ \vdots \\ v_{ers,desc}^n - v_{lev,LOS}^n \end{bmatrix} \right\} = \begin{bmatrix} 1 \\ \vdots \\ 1 \end{bmatrix} \begin{bmatrix} x_{offset} \end{bmatrix}, \quad (1)$$

and the stochastic model by:
Where \(v_{\text{ers,desc}}\) and \(v_{\text{lev,LOS}}\) represent the deformation rates at grid cell \(i\) estimated for a descending ERS1/2 track and leveling transformed to the satellite line of sight (LOS), respectively; with \(i = 1, \ldots, n\) being \(n\) the number of grid cells where we have both leveling and InSAR for the track in question. In this case, transformation to LOS is done assuming the observed deformation is vertical. A more appropriate decomposition is performed when estimating the final vertical rates, see eq. (4).

The parameter \(x_{\text{offset}}\) represents the unknown, (offsets between maps), that we aim estimating. In the stochastic model of eq. (2) the variance-covariance matrix is assumed to be diagonal. The diagonal elements include the total variances of the observations. These are the variances of the current track \(v_{\text{ers,desc}}^{2,i}\) plus the variance of leveling \(v_{\text{lev,LOS}}^{2,i}\) for grid cell \(i\). As explained earlier, both are obtained from ordinary kriging.

The estimated offset \(x_{\text{offset}}\) is obtained from BLUE:

\[
\hat{x}_{\text{offset}} = \frac{A_{\text{ers,desc}}^{T}Q_{y}^{-1}y}{A_{\text{ers,desc}}^{T}Q_{y}^{-1}A_{\text{ers,desc}}}, \tag{3}
\]

where \(y\) is the vector of observations \(v_{\text{ers,desc}} - v_{\text{lev,LOS}}\), \(A_{\text{ers,desc}}\) the design matrix defined in the functional model eq. (1), the superscript \(\{\cdot\}^{T}\) indicates transposition and \(Q_{y}\) the variance-covariance (v-c) matrix of the observations given by eq. (2).

After the reference point correction, we obtain different estimates of the same stationary rate per grid cell. We use these estimates as observations to obtain the final deformation rate per grid cell. We employ again BLUE. Let us take a generic example again where a grid cell is observed by ascending and descending ERS1/2 and Envisat tracks and leveling, which actually is the most common situation in the Netherlands. GPS can also be included, but it is left out for simplification. The functional and stochastic model for this grid cell can be written as:

\[
E\{\begin{bmatrix} v_{\text{ers,asc}} \\ v_{\text{as},\text{asc}} \\ v_{\text{ers,desc}} \\ v_{\text{as},\text{desc}} \\ v_{\text{lev}} \end{bmatrix} \} = \begin{bmatrix} \cos \theta & -\sin \theta \cos \alpha_{\text{asc}} \\ \cos \theta & -\sin \theta \cos \alpha_{\text{asc}} \\ \cos \theta & \sin \theta \cos \alpha_{\text{desc}} \\ \cos \theta & \sin \theta \cos \alpha_{\text{desc}} \\ 1 & 0 \end{bmatrix} \begin{bmatrix} V \\ H_{\text{East}} \end{bmatrix}, \tag{4}
\]

and

\[
\begin{bmatrix} v_{\text{ers,desc}} - v_{\text{lev,LOS}}^{1} \\ \vdots \\ v_{\text{ers,desc}} - v_{\text{lev,LOS}}^{n} \\ \sigma_{\text{ers,desc}}^{2,1} + \sigma_{\text{lev,LOS}}^{2,1} \\ \vdots \\ 0 \\ \sigma_{\text{ers,desc}}^{2,n} + \sigma_{\text{lev,LOS}}^{2,n} \end{bmatrix} = \begin{bmatrix} \sigma_{\text{ers,asc}}^{2} & 0 & 0 & 0 & 0 \\ 0 & \sigma_{\text{as},\text{asc}}^{2} & 0 & 0 & 0 \\ 0 & 0 & \sigma_{\text{ers,desc}}^{2} & 0 & 0 \\ 0 & 0 & 0 & \sigma_{\text{as},\text{desc}}^{2} & 0 \\ 0 & 0 & 0 & 0 & \sigma_{\text{lev}}^{2} \end{bmatrix}, \tag{5}
\]

The subscripts \(\{\cdot\}_{\text{asc}}\) and \(\{\cdot\}_{\text{desc}}\) are used to indicate ascending and descending pass, respectively; \(\{\cdot\}_{\text{ers}}\) for ERS1/2 and Envisat, respectively; and \(\{\cdot\}_{\text{lev}}\) for leveling.

With the functional model of eq. (4) we estimate two unknowns per grid cell, its vertical \(V\) and horizontal (in the east direction) \(H_{\text{East}}\) rates. The design matrix transforms InSAR LOS deformation rates to these two directions. For simplification, we write all tracks having the same look angle \((\theta)\). The heading angle is written as \(\alpha_{\text{asc}}\) and \(\alpha_{\text{desc}}\), for ascending and descending tracks. The variances of the stochastic model were previously estimated during the kriging interpolation. Observations are assumed to be uncorrelated.

The estimation of \(V\) and \(H_{\text{East}}\) is performed for all grid cells independently by changing accordingly eq. (4) and eq. (5), depending on the number and type of available observations. Furthermore, we also obtain with BLUE the v-c matrix of our estimates \(V\) and \(H_{\text{East}}\), written as \(Q_{\delta}\):

\[
Q_{\delta} = (A_{\text{rates}}^{T}Q_{y}^{-1}A_{\text{rates}})^{-1}, \tag{6}
\]

where \(A_{\text{rates}}\) is the design matrix of eq. (4) and \(Q_{y}\) the v-c matrix of the observations given in the stochastic model of eq. (5).

In the text stage, we focus on reducing the effect of unmodeled atmosphere and orbital errors. To do so, we smooth spatially the residuals (observed minus modeled rates e.g. \(\hat{v}_{\text{ers,asc}} - \hat{v}_{\text{ers,asc}}\)) of InSAR velocity maps. We perform this operation per track and satellite. The window of the low spatial filter (20 km) is selected to be much larger than the decorrelation distance of the deformation rates. The (low-pass) filtered residuals are assumed to be the unmodeled atmosphere and orbital errors we are searching for. We remove them from the corresponding velocity map and repeat the estimations with the models of eq. (4) and eq. (5).
Figure 4. A) Estimated average vertical rates for the period 1992-2010. B) Estimated standard deviations for vertical rates of (A). Some areas are further described in the text.

Figure 5. A) Estimated average horizontal rates in East direction (East is positive) for the period 1992-2010. B) Estimated standard deviations for rates of (A). Some areas are further described in the text.
5. RESULTS

Figures 4A and 5A display the estimated vertical rates and horizontal (in the east direction) rates over the period 1992-2010. The corresponding estimated standard deviation, obtained from the diagonal of matrix $Q$, of eq. (6), are shown in figs. 4B and 5B.

In the map of vertical velocities (fig. 4A), we mark five different areas that we find to be of interest. From north to south, we first observe the subsidence of the gas field areas due to gas production. This effect is well known and has already been studied with PSI (Ketelaar, 2008). The already reported values (Ketelaar, 2008) match our findings.

To the south-west of this area, we observe the subsidence of one of the dikes. This phenomenon was already known by the Dutch authorities and measures are taken to stabilize the dike.

The deformation found in the center west of the Netherlands (referred to as peat areas) is caused by peat oxidation. The soil of this area has a very high peat content. Due to the water pumping that is required to keep the surface dry (the topography in this area is below mean sea level), the peat gets in contact with the air and oxides. The oxidation reduces peat volume producing the consequent subsidence. We analyzed this signal in our previous work (Caro Cuenca and Hanssen, 2008).

The vertical rates map show also two strong uplifting signals. The deformation we find in the city of Enschede has not been reported earlier, at least to our knowledge. After an initial analysis of the results we found different sources, the source of the deformation seems to be related to a decrease of water pumping. Effectively, several industries in the area have recently changed water extraction or decrease their pumping rates. In depth analysis of this signal is outside the scope of this paper however efforts are planned to continue in this direction. In the southern Netherlands (referred to as abandoned mines), the cause of uplifting is the cease of water pumping in the abandoned coal mines. Coal production ceased in the Netherlands at the end of the seventies but water pumping continued until 1994 to avoid flooding of the German mines that were still active. After pumping completely ceased (1994), the rapid increase of mine water level induced surface uplift, (Pöttgens, 1985; Bekendam and Pöttgens, 1995; Caro Cuenca and Hanssen, 2010).

We also observe a long-wavelength deformation signal. The Netherlands seems to be tilting. The east part of the country is uplifting with respect to the west part. Previous studies (Lorenz et al., 1991; Kooi et al., 1998) explained this signal to be produced by glacial isostatic adjustment caused by the melting of the scandinavian ice sheet after the last ice age (see, e.g., Milne et al. (2001); Schotman and Vermeersen (2005) as well). We are able to capture this signal from leveling and GPS estimates because in the process of removing orbital ramps from the velocity maps obtained with InSAR we remove as well any other possible large scale signals.

In addition to that, the map of the horizontal rates 5A shows that the horizontal signal concentrates in the area of gas fields and the abandoned mines. The rest of the country shows not significant horizontal deformation. The displacements appear to be in the same order of the estimated standard deviation 5B. These are probably produced by interpolating errors and atmosphere.

It is also interesting to notice that the estimated standard deviation of vertical and horizontal rates, (4B and 5B, respectively) mostly depends on the number of available InSAR data. We see that the places with overlapping tracks the standard deviation drops.

6. PREVIOUS STUDIES

In 1997, the Dutch Ministry of transport and its department of Rijkswaterstaat, estimated the total deformation in the Netherlands for the year 2050 (Rijkswaterstaat, 1997). Figure 6 shows the results of this study. The prediction was mainly based on borehole (geological) analysis, but it also modeled the deformation caused by isostatic adjustment and human intervention, mainly through the gas production, see Kooi et al. (1998) as well.

If we compare visually the vertical rates estimated with our method 4A with those showed in fig. 6, despite the units, we observe some clear differences. There are two strong uplifting signals, in the city of Enschede and the abandoned mines, there were not modeled in Rijkswaterstaat (1997). These effects were probably not known or underestimated at the time the map was created. Furthermore, we estimate stronger subsidence in the the deformation in the western gas fields. On the other hand, with our method we do not observe deformation in the western part of the island of Flevoland as shown in fig. 6. This is probably caused by a shallow mechanism, i.e., sediment compaction. Although we can only speculate at this stage, we think that our method does not capture this shallow deformation because most of the leveling benchmarks and PS in this area are located in well founded objects e.g., buildings. Further analysis will be performed in this direction.

7. SUMMARY AND CONCLUSIONS

We developed a method to combine velocity maps obtained from leveling, GPS and multitrack InSAR. The method was applied to the Netherlands to produce a velocity map of the whole country. The method used as observations the rates estimated by different available techniques. Although in some areas the deformation may not be truly linear over the full time span (1992-2010), using average rates helps us to simplify data combination. Our approach also focused on minimizing the effect of orbital errors and other large scale signal that could hamper the estimation of longwavelenght deformation. After an initial analysis of the results we found different deformation signals affecting the Netherlands. They were mainly related to gas production, peat oxidation
and water rebound. Evenmore, our map seems to capture as well the effect of glacial isostatic adjustment on the Netherlands with a tilt of about $\sim 1.5$ mm/yr over 200 km, with the eastern part uplifting with respect to the western side of the country. The tilt is in the same order of magnitude as the one estimated in previous studies (Kooi et al., 1998).

8. FUTURE WORK

Further efforts will focus on a more precise quality description of the different data applied in this study. We, therefore, expect that this will contribute to a more reliable variance of the estimated rates. We will also distinguish deep and shallow deformation sources, because based on previous works, our method seems to underestimate shallow compaction rates, in particular in the island of Flevoland.

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