SUBSIDENCE DUE TO PEAT DECOMPOSITION IN THE NETHERLANDS, KINEMATIC OBSERVATIONS FROM RADAR INTERFEROMETRY

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ABSTRACT

The western part of the Netherlands has a typical Dutch landscape with drained peat meadows in polders below sea level. The area is used in concert for agriculture, recreation, residence, and nature conservation. Water levels are being artificially controlled in the area. Large areas of this region are fen-meadows that consist of wet pasture lands with drained peat soils alternated by natural and artificial lakes, ditches, reed swamps and quaking fens. The current fen-meadows have originated from the drainage of a large peat system dating back from 1800 B.C. To keep the land suitable for agricultural use, the peat area has been drained deeper in recent decades. This drainage has resulted in a subsidence of the soil and as a result the polders with fen-meadows are now 1–2 m below sea level. In between the fen-meadows, deep polders with a clay soil are found. These deep polders used to be large lakes, which have been reclaimed in the 17th century for agricultural use. Presently, these polders are 2-6 m below sea level. The observation of subsidence of wetlands is notoriously difficult using conventional geodetic techniques, due to the absence of fixed benchmarks. Here we show that analyses from persistent scatterer interferometry (PSI) can be used to infer subsidence rates of several millimeters per year, using coherent targets identified in the area. These results are obtained over the Green Heart, an open area surrounded by a horseshoe-shaped ring of cities, Randstad Holland. The derived subsidence rates will be interpreted and related to processes in the shallow subsurface. This paper presents preliminary results of the investigation.

Key words: PS InSAR, subsidence, peat compaction.

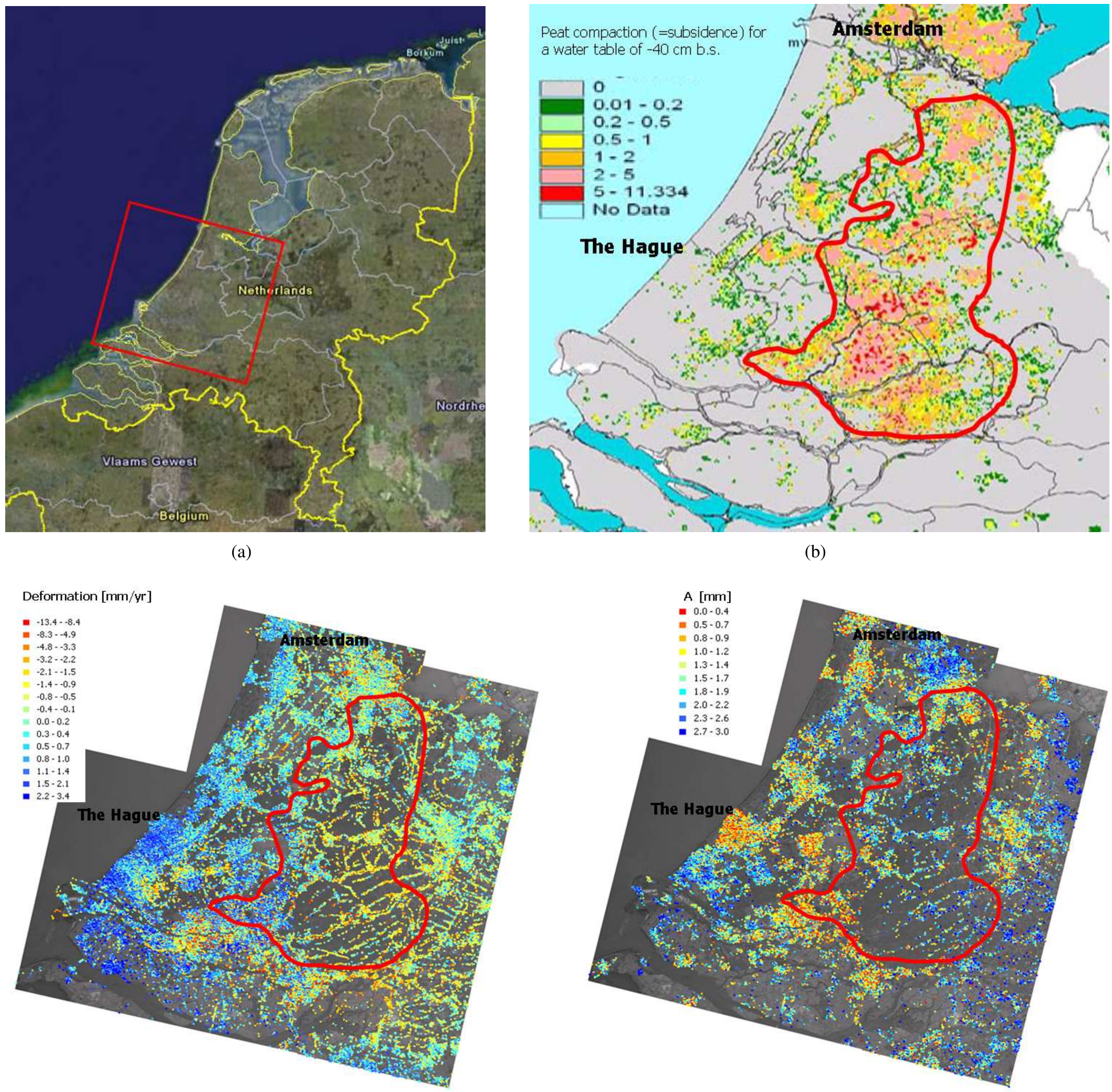
1. INTRODUCTION

The position of the Dutch shoreline has varied over time with the rate of sea-level rise and the rate of sedimentation. During the glacial era the coastline of the North Sea was approximately 200 km further north-west than its present position. In the warmer Holocene era, the sea level rose and the North Sea flooded the western and southern part of the Netherlands. Sand ridges (called old dunes) were formed parallel to the present coastline. In about 1000 AD 'young dunes' developed on the west side. Although the latter eventually dominated the old dunes, the sea occasionally invaded the land, cut streams and formed lakes in the eroding peat area that had developed behind the dunes (Huisman, 2004).

The first settlers in these 'low lands', some 5,000 years ago, found themselves in a poorly drained flat delta or flood plain intersected by creeks, tidal inlets, and small and large rivers. Their dwelling places were on the high ridges or artificially raised hills along these water courses. People lived by hunting and fishing. Around Roman times, small dikes and flumes were built to create conditions appropriate for agricultural activities on a very local scale.

A marked increase in the population of Western Europe took place about 1000 AD. To increase rye and wheat production the land was systematically cultivated. In the marshy land consisting of peat and clay, at that time lying 2 or 3 m above m.s.l., field drains and ditches were dug to lower the groundwater table and make agriculture possible. The drop in the groundwater level subsided the peat and clay layers. Moreover the peat oxidized. The subsidence forced the people to deepen the drains and ditches further and to dig canals to lower the groundwater table in order to keep the land suitable for agriculture. This of course led to further subsidence of the surface. The permanent need to lower the groundwater table provoked an irreversible subsidence process, that is still ongoing today.

By about 1100 AD the subsidence had increased to such an extent that large areas bordering the sea were flooded during high tide. Besides the man-made subsidence, the natural sea-level rise also affected the drainage problem. Their combined impact resulted in an increase in the scale of mitigating intervention over the course of time. Measures included digging ditches, construction of dikes and dams, creating polders with artificial drainage, reclamation of former water areas, large-scale drainage by inter-



(a) (b)

(c) (d)

Figure 1. a) The Netherlands, the red square shows the 100×100 km area covered in this study (GoogleEarth). b) Expected deformation due to peat oxidation estimated from boreholes for a water table of −40 cm below surface, (after van der Linden et al. (2002) slightly modified). The cities of Amsterdam and The Hague and the 'Green Heart' area with highest peat deformation rates have been outlined. c) Linear deformation estimated from PSI in mm/y. d) Amplitude values of the seasonal movements in mm.

mediate storage and closure of estuaries and the inland sea (Huisman, 2004).

Subsidence and the sea-level rise increased up to a level where the area behind the dikes and dams dropped below mean sea level. Gravity discharge of the superfluous water from the embanked regions became impossible. Behind the dikes and closure dams the embankment of small areas was started. From these small inner areas, called *polders*, the excess water was artificially removed and brought to the former natural water courses. It was released from these water courses by sluices into closure dams at low water. The former inlets and creeks were and are still being used as intermediate storage areas (called *'boezem'*) during high water levels. This stepwise drainage system is very typical in the Netherlands. Windmills became available for artificial drainage on the low regions in the 13th century. The invention of turning the sails of the mills into the varying wind directions has been vital for the survival and development of the Netherlands.

In the 16th century the drainage techniques reached such a high standard that it became possible to reclaim shallow lakes. The practice was to dig a canal around the lake or pond, constructing the enclosing dikes on both sides along the canal with the removed ground. Windmills drained the polder. In the course of time large areas have been reclaimed, in total 600.000 ha.

The continuing subsidence of the surface in the polders and the rise in sea level have resulted in about 25% of the Netherlands now being situated below mean sea level (up to 6.7 m). Without dikes and dunes 65% of the land would be flooded daily. This situation makes the Netherlands vulnerable to storm surges and river floods.

The 'Green Heart, (Groene Hart) is a rural area part of the Dutch Randstad, surrounded by the biggest cities in the Netherlands: Amsterdam, The Hague, Rotterdam and Utrecht, see figure 1a. The soil of the Green Heart contains mainly sand, peat and clay, see fig. 2. The ground water level is controlled in order to avoid fast subsidence due to peat oxidation and at the same time to maintain a dry surface. Peat is composed of organic material which oxides when it is in contact with air, reducing in volume and producing the consequent subsidence. As a results the surface gets closer to the ground water. Then, the land is periodically drained to keep it suitable for agriculture, construction and recreation.

Observing precise subsidence rates of peat and marsh lands using geodetic techniques is notoriously difficult, due to the fact that no fixed benchmarks can be installed in the soil. Moreover, due to the soft soils, modern buildings have pile foundations, with pilings up to 25 m lang, reaching to stable pleistocene sand layers. Consequently, while subsidence due to shallow surface compaction continues, most new buildings remain relatively stable.

Measuring such a shallow process is a challenge for persistent scatterer interferometry, (PSI), see, e.g., Ferretti et al. (2001). Although PSI does not suffer the problems of traditional geodetic techniques, we cannot be certain about the object we observed, nor the kind of surface deformation it quantifies. Moreover, to distinguish simply from even and odd bounces new techniques shall be used such a dual polarisation, which is not usually available since the acquisitions are in single polarised mode. Studying shallow processes could certainly help in our understanding of the scatterers. In theory, doing so we could distinguish between objects located on the surface from others with deep foundations. However we have to bear in mind than the PS are not single objects but the sum of the reflection of the scatterrers of an area given by the resolution of the radar with a dominant reflector, (van Leijen et al., 2005). The results presented here after are preliminary and subject to further work.

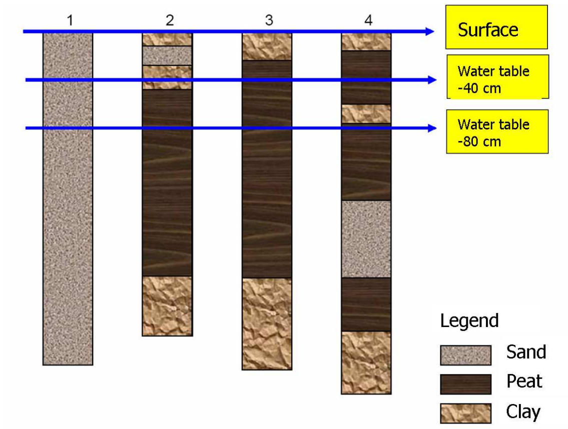


Figure 2. Various shallow cores retrieved in the west of the Netherlands. Peat layers above the ground water table will be subject to oxidation and cause subsidence.

2. PROCESSING METHODOLOGY

In this study 73 images were processed, dating from 1992 to 2005. All of them were acquired by ERS-1 and ERS-2. The entire single look image (SLC) was processed, representing an area of 100×100 km corresponding to the area shown in figure 1. To do so and in order to reduce computational burden, each image was divided into 4 parts, i.e. crops, representing approximately one quarter of the scene, with an overlap of about 5 km. Each crop was then processed independently. The crops were named following a clockwise order starting from the one located upper left. This convention will be used here after.

A first order network, (in the geodetic sense, i.e. the most reliable points), of PS was created based in amplitude dispersion to estimate the atmosphere phase screen, (APS). Once the APS was removed, a second order network, denser than the previous one using also amplitude dispersion, was then employed to estimate the deformation and topographic height. The integer ambiguities were solved by bootstrapping (Teunissen, 2001). This method was used because of its computing time performance, which was cruicial for such a large area.

The line-of-sight displacement of a point x can be described using a set of base functions, (Kampes and Hanssen, 2004)

$$d(t,x) = \sum_{d=1}^{D} \alpha_d(x) \cdot p_d(t), \quad (1)$$

where t is the time respect to master image, $p_d(t)$ are the base functions with amplitudes $\alpha_d(x)$ and D the number of parameters describing the displacement as a function of time.

In first instance a simple linear model was assumed, i.e., $D = 1$ and $p_d(t) = t$. Then $\alpha_1(x)$ gives the deformation rate. The results, after connecting all crops, are shown in figure 1c.

Based in the assumptions that the peat areas would be more sensitive to seasonal movements due to the high water tables, a second deformation model was also processed which included linear and periodical deformation. The total deformation is then given by,

$$d(t) = vt + A\sin(\frac{2\pi(t-t_0)}{T}) + A\sin(\frac{2\pi t_0}{T}), \quad (2)$$

where v is the linear velocity, A is the amplitude of the seasonal signal, and t_0 the time offset respect to the master. The term $A\sin(\frac{2\pi t_0}{T})$ has been added to reference the deformation respect to the master image, the variable x has been dropped for the sake of simplicity.

In this case the base functions are (Kampes, 2005),

$$\begin{aligned} p_1(t) &= t \\ p_2(t) &= \sin(\frac{2\pi t}{T}) \\ p_3(t) &= \cos(\frac{2\pi t}{T}) - 1, \end{aligned} \quad (3)$$

where T is the period of the seasonal signal, assumed to be 1 year. The estimated amplitude A of the seasonal signal is shown in figure 1d, presenting the four crops already merged.

Employing the scatterers located in the overlapping areas the crops were connected. The results were referenced to a common point. The average of the differences in the estimation of the overlapping areas respect to a fixed crop were minimal. They are summarised in tables 1 and 2. This provides confirmation that the estimation was performed correctly. In any case, these were accounted for and removed from the estimations.

3. ANALYSIS OF THE RESULTS

As explained in the previous section, two deformation models were used for processing the data. The first one was a simple linear model. The results of the deformation are shown in figure 1c. Figure 1b shows the expected deformation due to peat oxidation estimated from 300.000 core drillings considering a water table of -40cm below the surface (b.s.), (van der Linden et al., 2002). The area of the Green Heart at which the strongest subsidence was expected is outlined in red for the sake of discussion. Comparing figs. 1c and 1b one may find a good agreement, however not exact. The PS show no deformation in the South-Western part of the Green Hart, as it was estimated by van der Linden et al. (2002). These area may be the most urbanised on of the Green Heart, and this could explain the differences. In addition to that, the PS results reveal a deformation rate of the peat areas of about 2 mm/y respect to The Hague. This city was chosen as reference because its soil is mainly composed of sand, therefore considered as stable. These values of the deformation are significantly lower compared to those reported by van der Linden et al. (2002).

The major difficulty when analyzing PS data is that we cannot be certain of the scattering object. In fact, PSI measurements are the sum of the reflections of an area equivalent to the radar resolution cell in which there is a dominant scatter. This dominant reflector might well be a roof of a building, a double bounce (curb-to-wall) or even a street lamp post (Perissin and Rocca, 2006). In those three examples the foundations are different, and this would reflect different deformation regimes. If we consider that most of the reflections are due to curb-to-wall double bounce, a possible hypothesis to explain the underestimations is that the road will not deform fast because it is close to the buildings which have deep foundations, see figure 3. It seems clear that most scatterers are man-made objects and in its building process the soil may have been disturbed (compacted or even changed) when compared with the soil found in a open country side.

Apart from that one may argue about a possible orbital trend in the results given in figure 1c. Trends have been removed using the fact that several areas, in the corners of the image, have a stable sand underground. These areas have been used to correct for a wide scale trend.

In any case, in the lower left corner of figure 1c subsidence in Delft, (see also van Leijen and Hanssen (2008)), and in the industrial area of Rotterdam are visible, giving us certain confidence about the results.

Table 1. Average of the differences respect to crop1, considering only linear deformation.

	crop 1	crop 2	crop 3	crop 4
α_1 [mm]	0.000	0.083	0.504	0.056

It has been reported that the fluctuations in the water level from winter to summer ranges from 25 to 40 cm, in the Green Heart, (Hoving, 2006), being low in summer and high in winter. In addition, the ground water in this area is generally kept high in order to avoid fast subsidence due to the decomposition of the peat. Based on that, a new model including the seasonal variations, see equation 2,

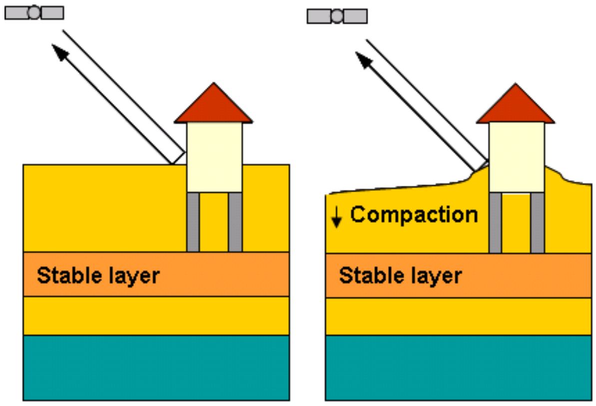


Figure 3. Curb-to-walls reflection as a possible answer for PS underestimations

Table 2. Average of the differences respect to crop1, considering linear plus periodic deformation.

	crop 1	crop 2	crop 3	crop 4
α_1 [mm]	0.000	-0.025	0.133	0.012
α_2 [mm]	0.000	0.147	0.294	0.320
α_3 [mm]	0.000	-0.304	0.243	-0.253

was tested. The results of the amplitude of the periodic signal are shown in figure 1d. As expected, the peat areas, encircled by a red line, present higher amplitude than the reference, at The Hague. This value is around 3 mm. Figure 4 showed the deformation time series of a point at the center of the Green Heart. The estimated deformation is plotted in red. The graph shows that at master time, $t = 0$, which was on the 23rd of August, the periodic signal is starting to increase after reaching its minimum value. The results coincide with the assumptions that the periodic signal is water level related (low in summer and high in winter). However, we expected this time shift, (time from when the periodic signal is minimum to $t = 0$), to be smaller than what we estimated, about 2 months. We have also obtained some results we cannot explain so far, such as the high amplitudes os the seasonal signal in Amsterdam and the area at the east of the Green Hart, and the decrease of the number of selected PS.

4. CONCLUSION

The results of PSI processing show a correlation with the peat areas of the Green Hart. Therefore we think the deformation we observed is peat related, probably due to its oxidation. However, the values of the deformation, around 2mm/y seem underestimated. In fact, the expected deformation due to peat oxidation is around 1cm/y. So far, we cannot explain it completely. A possible hypothesis is that the differences are due to the type of scatterers, i.e. most of the reflections are due to curb-to-wall double bounces, which is a hybrid system between stable foundation objects, e.g. a building, and supercial scatterers, e.g. the road. On the other hand, the big majority of scatterers are man-made objects and in its building process the soil, therefore the peat thickness, may have been disturbed (compacted or even changed) when compared with the soil found in a open country side, which would also explain the underestimation.

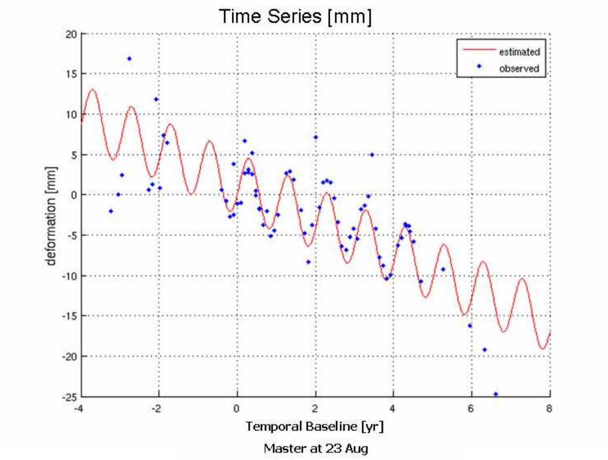


Figure 4. Time series of a point in center in the Green Heart with respect to The Hague.

When studying the seasonal signal, the results show that the peat areas have higher than other stable zones, such as The Hague. The time series of the PS in the peat areas also showed a periodic signal. Based in the time when the master image was acquired, end of August, we concluded there is a good agreement, although not complete, with the assumption the peridodic signal is related to the changes in water level, i.e. low is summer and high in winter.

Therefore, at this stage, we can conclude that the PS observations in the area of the Green Hart seem to be related to shallow surface deformation. However, it will be subjected to further confirmation, for example through water level measurements and PS identification.

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