

# GROUND WATER MANAGEMENT AND ITS CONSEQUENCES IN DELFT, THE NETHERLANDS AS OBSERVED BY PERSISTENT SCATTERER INTERFEROMETRY

Freek J. van Leijen and Ramon F. Hanssen

*Delft University of Technology, Delft Institute of Earth Observation and Space Systems (DEOS),  
Kluyverweg 1, 2629 HS Delft, The Netherlands, Email: F.J.vanLeijen@tudelft.nl*

## ABSTRACT

The city of Delft, The Netherlands, is very vulnerable for ground water. A better understanding of the relation between ground water level (fluctuations) and surface displacement would assist future water management. The displacement field in Delft is analyzed by Persistent Scatterer Interferometry (PSI) using a periodic displacement model. Both ERS-1/2 and Envisat SAR data are observed, covering a period between 1992 and 2007. Comparison with ground water level measurements show high correlation with the PSI time series. The displacement signals have a delay of about 1 month with respect to the ground water fluctuations.

Key words: Persistent Scatterer interferometry; Ground water.

## 1. INTRODUCTION

Infrastructure in Delft, the Netherlands, is threatened by ground water. As large parts of the country, Delft is situated below mean sea level and maintenance of ground water levels is therefore of high importance. Subsidence in combination with ground water level rise has resulted in severe problems, especially in the last 20 years. Currently, the difference between ground level and mean ground water level is at certain locations only 50-60 cm, with even lower margins during periods of heavy rain, see Fig. 1. Especially buildings in the historical city center are vulnerable for these relative high ground water levels.

Apart from natural causes, artificially induced ground water level fluctuations and subsidence deteriorate the situation. An industrial complex in Delft has been withdrawing ground water since 1916. The amount of extraction has changed over time and has a seasonal cycle. The withdrawal effects the relative ground water level and causes subsidence. However, due to changes in the production process in 2004 the use of ground water has become unnecessary. As instant termination of the extraction process would have a severe impact on the already sensitive ground water situation, a gradual decrease of

the extraction volume is proposed. However, because of the unique soil decomposition in the Dutch coastal area (sand, clay, peat), even the effects of a gradual decrease cannot be predicted very well. A more profound understanding of the relation between ground water extraction, subsidence (or uplift) and ground water level is therefore necessary.

In this contribution Persistent Scatterer Interferometry (PSI) results of the city of Delft are used to deduct the relation between ground water fluctuations and subsidence. Since 2000 ground water levels at 155 locations in Delft are measured automatically on an hourly basis, providing a unique opportunity to relate subsidence with the actual ground water level. Using ERS-1/2 as well as Envisat SAR data, the full period between 1992 to 2007 is analyzed.



Figure 1. Examples of high level of (ground) water in Delft, The Netherlands. The lower right image shows the historical city center of Delft, which contains a lot of canals.

## 2. PSI USING PERIODIC FUNCTIONS

The ERS-1/2 and Envisat data sets of Delft are analyzed accounting for a periodic signal in the data. This addi-

tional signal with respect to the standard linear deformation rate can easily be added to the estimation process using the TU Delft implementation of PSI. This implementation is based on the Integer Least-Squares (ILS) technique [1, 2]. The ILS technique has the advantage that extra parameters can be added without an increase in the computational burden. The deformation model using a linear and a periodic signal becomes

$$\varphi = -\frac{4\pi}{\lambda}(D_1 \cdot t + A \sin(2\pi(t-t_0)) + A \sin(2\pi t_0)), \quad (1)$$

where  $\varphi$  is the deformation phase,  $\lambda$  is the wavelength of the radar signal,  $D_1$  is the linear deformation velocity,  $t$  describes the temporal baselines with respect to the master image,  $A$  is the periodic amplitude and  $t_0$  is the periodic offset. The last term assures that the total deformation is zero at  $t = 0$  (which is an obvious constraint). Unfortunately the periodic part of the model Eq. (1) is not linear. However, it can be re-written to the linear model

$$\varphi_{\text{per}} = -\frac{4\pi}{\lambda}(\sin(2\pi t) \cdot A \cos(2\pi t_0) + (\cos(2\pi t) - 1) \cdot -A \sin(2\pi t_0)). \quad (2)$$

Here  $\varphi_{\text{per}}$  denotes the periodic phase. Note that a one-year period of the seasonal signal is assumed. Model Eq. (2) is used in the estimation process and results in estimates for the terms

$$D_2 = A \cos(2\pi t_0) \quad (3)$$

and

$$D_3 = -A \sin(2\pi t_0). \quad (4)$$

From these estimates, the desired amplitude and offset can be obtained by

$$A = \sqrt{D_2^2 + D_3^2} \quad (5)$$

and

$$t_0 = -\text{sgn}(D_3) \cdot \arccos(D_2/A)/(2\pi). \quad (6)$$

Note that in this way the amplitude is always positive and that the offset differentiates between signals of opposite behavior (with possibly the same amplitude).

### 3. PSI RESULTS OF DELFT

Both ERS-1/2 and Envisat data sets are used to analyze the deformation behavior in an area around Delft, resulting in a coverage between 1992 and 2007. The ERS-1/2 set consists of 83 images from 26 April 1992 to 8 March 2006. Note that after January 2001 only 8 images could be used because of high Doppler values. The Envisat data set has 44 images, starting 12 February 2003 and ending 24 October 2007. The estimated linear deformation rates for both sets are shown in Fig. 2.

The figure indicates deformation in Rotterdam (Envisat especially) and in the region around De Lier. For a closer

look on the situation in Delft, a zoom is visualized in Fig. 3.

The ERS-1/2 result shows linear deformation in the northern part of the city, which corresponds to the location of water extraction (where the maximum effect is expected). The signal has largely disappeared in the Envisat result. This can be explained by the reduction of the water extraction in the last couple of years.

The periodic displacement is referenced to the coastal area in The Hague which is assumed to be stable. The estimated amplitudes are shown in Fig. 4. The north-western part of the crop is relatively stable, whereas the (northern part of the) city of Delft shows a periodic signal with an amplitude of about 3 mm. In the Envisat result a strong amplitude in the eastern part is visible. This is possibly related with a change in water management in the region in the last couple of years.

As a means of validation, Fig. 5 shows the estimated periodic amplitude of three corner reflectors which are deployed by TU Delft for validation purposes (within the blue ellipse), together with the direct surroundings. The estimated amplitudes match well with the results of a dedicated radar time series analysis and leveling [3].

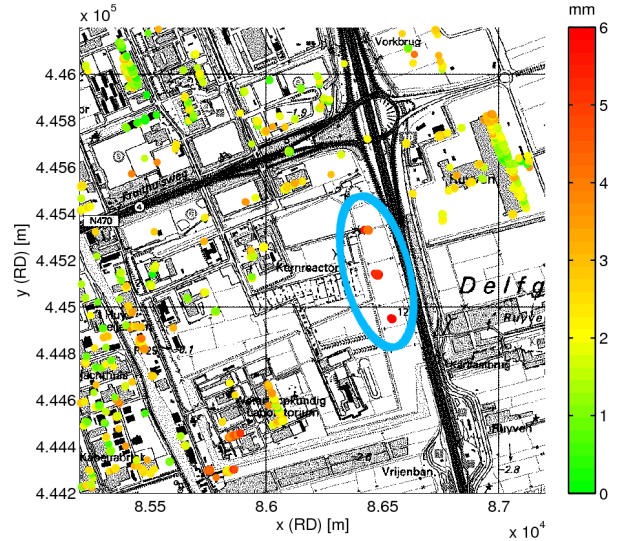


Figure 5. Periodic amplitudes of three corner reflectors which are deployed in an open field by TU Delft (within the blue ellipse), together with the direct surroundings.

Together with the amplitude, the offset of the periodic signal is estimated. This offset is the start of the estimated sinusoid with respect to the time of the year of the master image. Histograms of the offsets are visualized in Fig. 6. Because the master images for the ERS-1/2 and Envisat sets are different, the estimated offsets are shifted with respect to each other (but could be adjusted in a deterministic way). The physical start of the periodic signal in both data sets is estimated by assuming that the mode of the histogram (red line) represents the main signal in the area. This mode corresponds to 9 November for ERS-

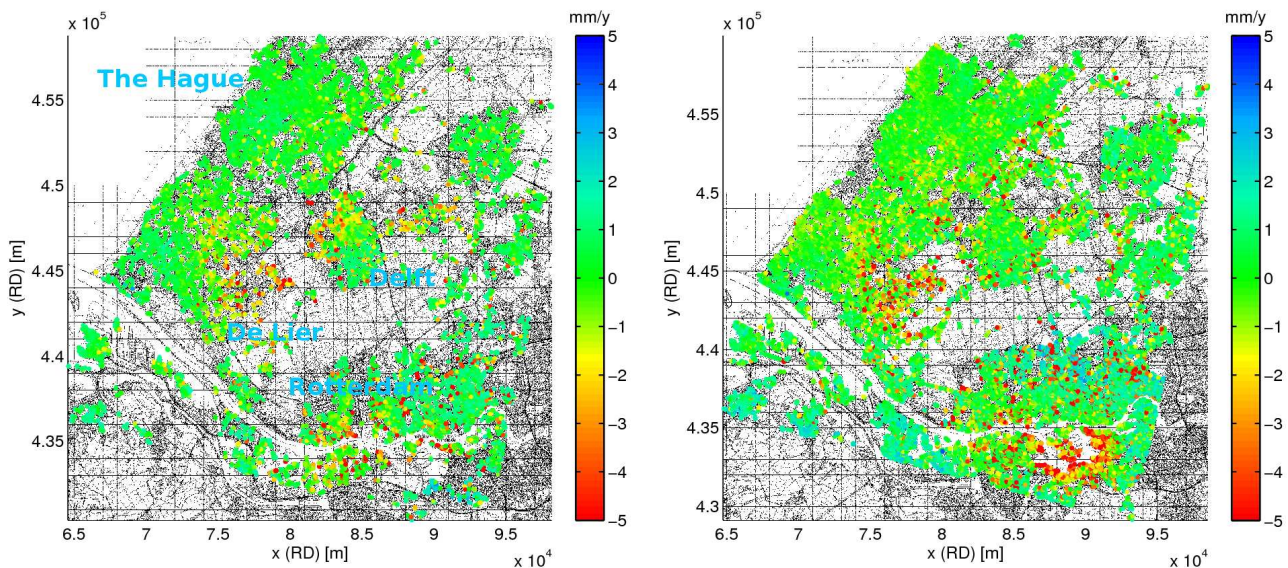


Figure 2. Linear deformation rates in an area around Delft. Left) ERS-1/2 data set, 26 April 1992 to 8 March 2006 (only 8 images after January 2001 because of high Doppler values). Right) Envisat data set, 2 February 2003 to 24 October 2007.

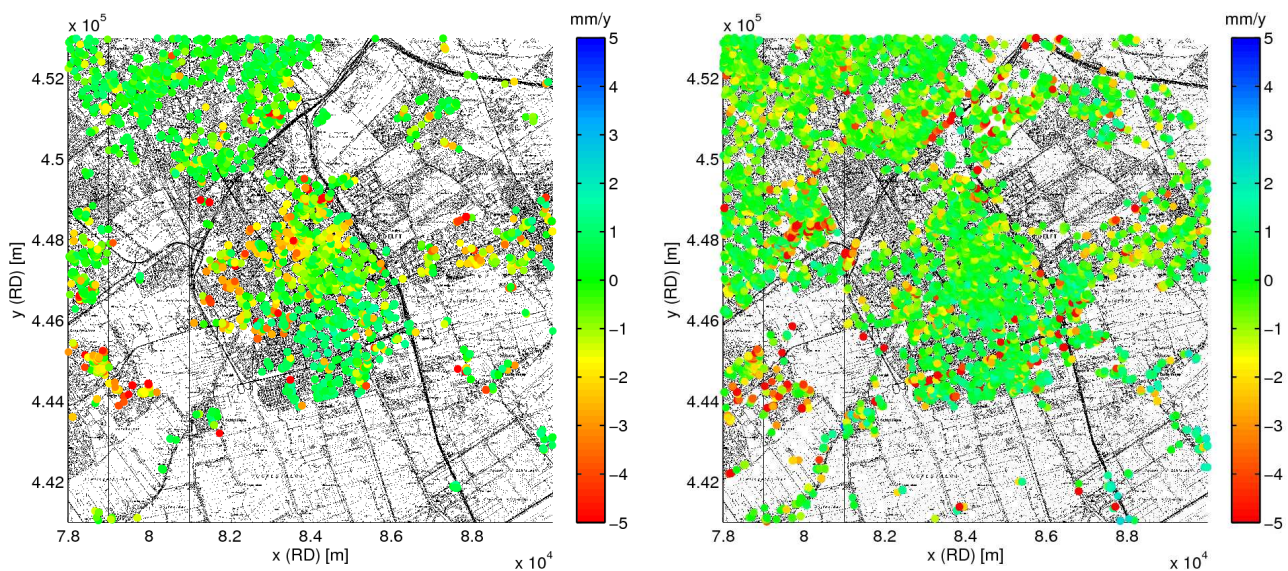


Figure 3. Linear deformation rates in Delft (zoom of Fig 2. Left) ERS-1/2 data set, 26 April 1992 to 8 March 2006 (only 8 images after January 2001 because of high Doppler values). Right) Envisat data set, 2 February 2003 to 24 October 2007.

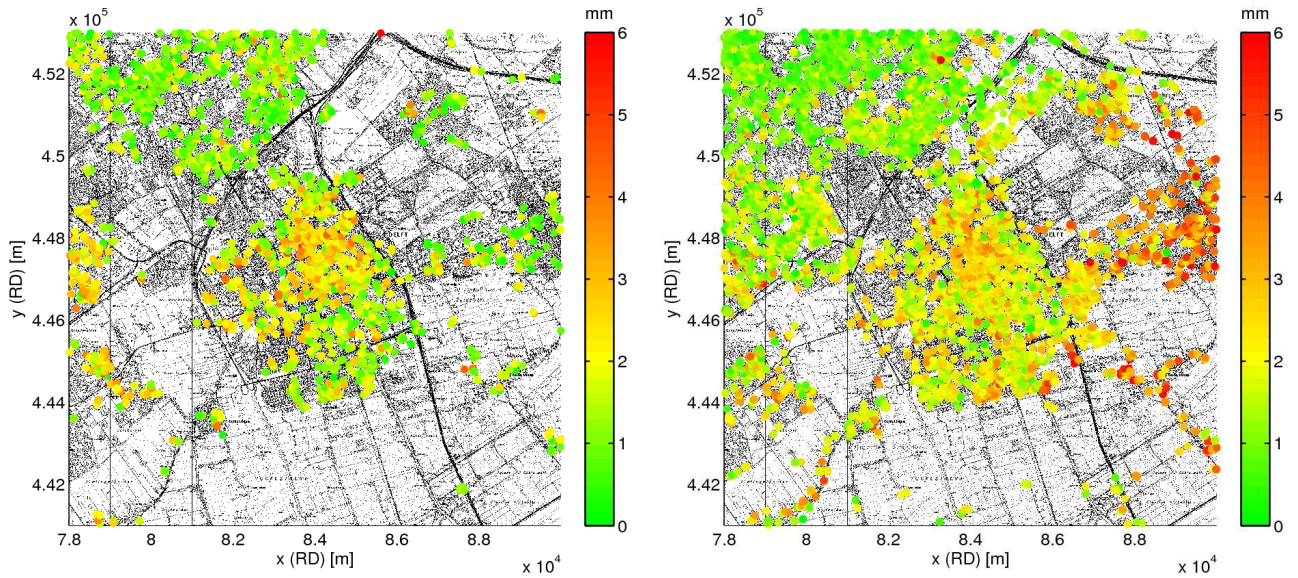


Figure 4. Periodic amplitude in Delft. Left) ERS-1/2 data set, 26 April 1992 to 8 March 2006 (only 8 images after January 2001 because of high Doppler values). Right) Envisat data set, 2 February 2003 to 24 October 2007.

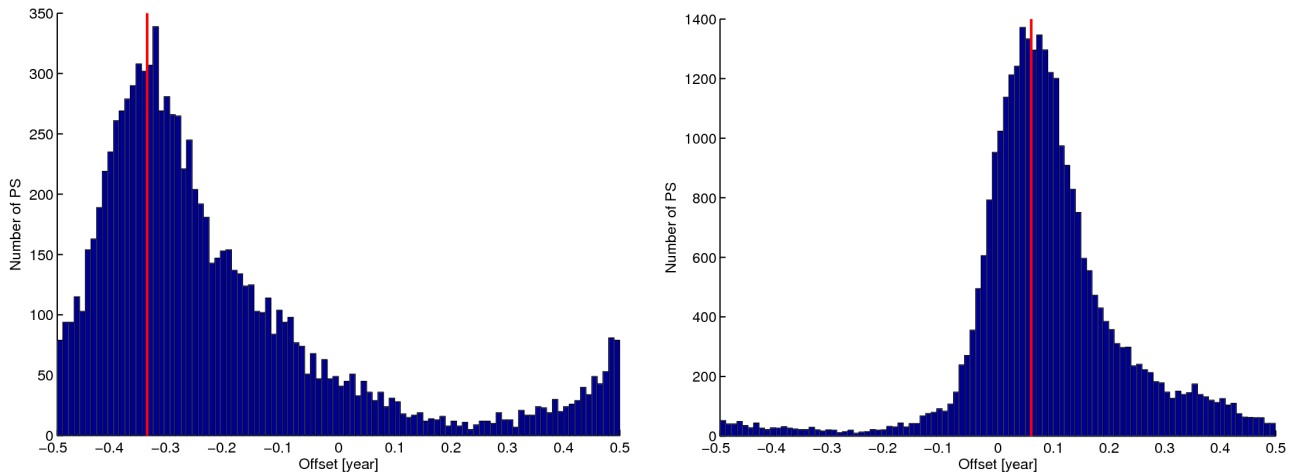


Figure 6. Histograms of the periodic offsets. Left) ERS-1/2 data set, 26 April 1992 to 8 March 2006. Right) Envisat data set, 2 February 2003 to 24 October 2007. The red lines show the mode of the histogram, which is assumed to represent the main signal in the area. For the ERS-1/2 data set this mode corresponds to 9 November, whereas for Envisat this is 20 November.

1/2 and 20 November for Envisat, hence a difference of 11 days. Considering the spread of the histograms, this is rather consistent. The offsets result in a maximum rise of the PS in February and consequently in a minimum in August. Because of this observation, the inference is made that the signal is related to ground water fluctuations and not (primarily) to thermal expansion. For thermal expansion a rise of the PS in the summer is to be expected. Fig. 7 shows the relation between amplitude and offset in a scatter plot. Indeed there are some high amplitude signals visible with a peak in the summer period (red circle) which is assumed to be thermal expansion, but the majority of the signal has a different periodicity. The relation of the signal to ground water level fluctuations is further studied in Section 4.

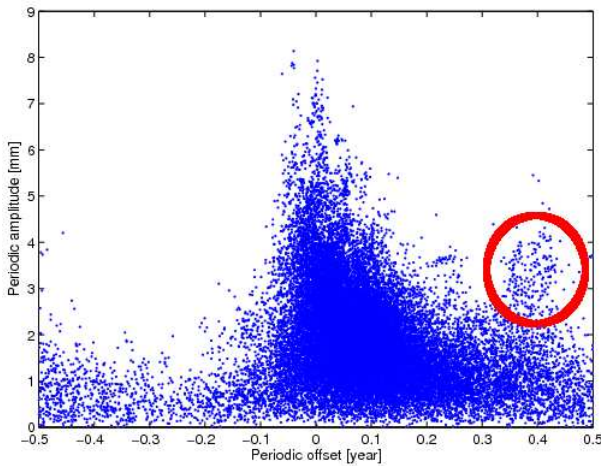


Figure 7. Scatter plot of the periodic offset with respect to the amplitude. The red circle indicates PS which behavior can be explained by thermal expansion. The majority of PS are assumed to have a relation with ground water fluctuations.

#### 4. PSI VS. GROUND WATER

The periodic signal estimated by PSI for the city of Delft suggests a relation with annual ground water level fluctuations. To verify this, the PSI results are compared with ground water levels automatically registered by the municipality of Delft at 155 locations. Fig. 8 shows the distribution of these ground water benchmarks. The colorbar represents the number of days at which a measurement is available. These daily measurements are derived from the original hourly data acquisitions by averaging. To verify the relation between the displacement measured by PSI and the ground water level, for each ground water benchmark the PS within a radius of 100 meters are selected. Because the measurements of ground water level started in 2000, only the Envisat results are considered. An example of a time series of ground water level and the time series of nearby PS is shown in Fig. 9. Observe that the extent of the time series unfortunately only overlap partially. The estimated periodic models for ground water

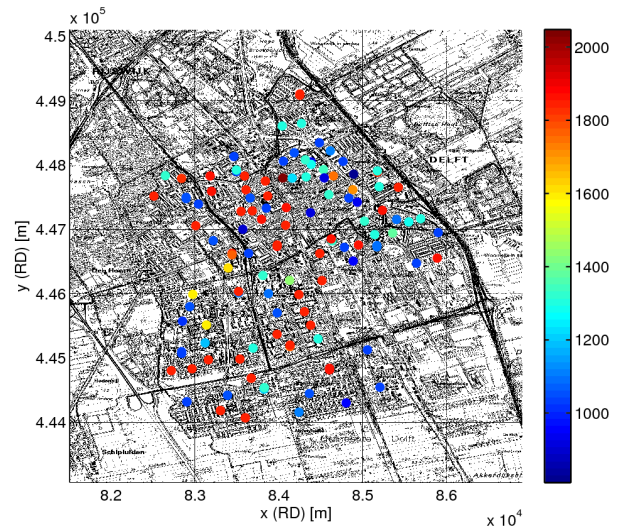


Figure 8. Distribution of automatically registered ground water benchmarks. The colorbar shows the number of days at which a measurement is available in the period 2000-2005.

and PSI are shown in red. As a reference, the red vertical line represents 1 January 2004. Comparison of the estimated periodic offsets of the ground water signals and the mean offsets of the PS within the 100 meter radius results in the scatter plot shown in Fig. 10. The mean value of the deformation offset (0.09 year) and the mean ground water offset (-0.01 year) differ 0.10 year, which represents a delay of the deformation of about 1 month with respect to the ground water signal. Hence, the surface acts on a change in ground water level, as can be expected. Further study will focus on the relation between the amplitudes of the deformation signal and the ground water fluctuations.

#### 5. CONCLUSIONS

The PSI technique is able to estimate periodic displacement behavior on a wide scale and with a high spatial sampling. The difference between the periodic offsets estimated from the ERS-1/2 and Envisat data set for the Delft area is only 11 days (9 and 20 November) and the signals are therefore regarded as being consistent. The majority of the periodic signal in the PS results can be assigned to ground water fluctuations. The number of PS showing thermal expansion is minimal. The deformation signal has a delay of about one month with respect to the ground water fluctuations. Further study will focus on the relation between the amplitudes of the deformation and the ground water signal.

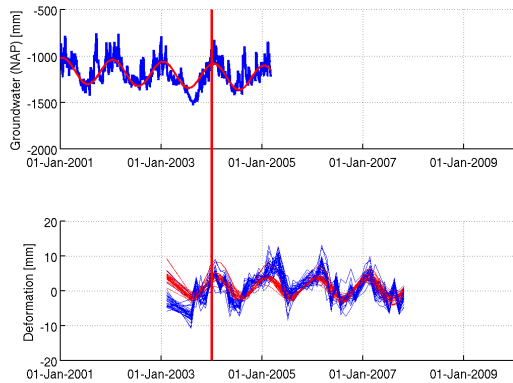


Figure 9. Example of a ground water level time series (top) in combination with the time series of PS within a 100 meter radius from the ground water benchmark. The estimated periodic signals are shown in red. The vertical red line represents 1 January 2004. Unfortunately, the ground water levels are not available after February 2005 yet.

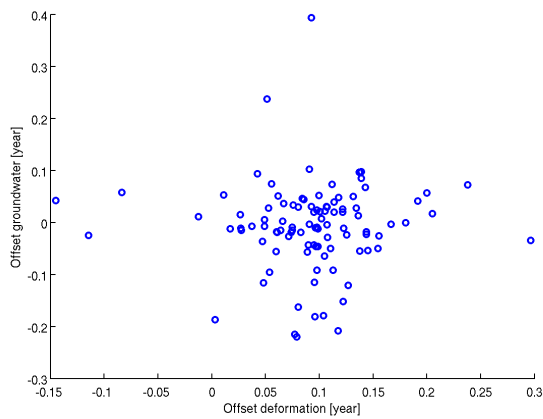


Figure 10. Scatter plot of the estimated mean periodic offsets of the PS and the ground water levels. The mean value of this scatter plot indicates a delay of about 1 month of the deformation with respect to the ground water signal.

## ACKNOWLEDGEMENTS

We would like to acknowledge the municipality of Delft for the availability of the ground water level measurements. Furthermore, we thank the European Space Agency (ESA) for their support via the Cat1-1212 project.

## REFERENCES

- [1] P J G Teunissen. Least-squares estimation of the integer GPS ambiguities. In *Invited Lecture, Section IV Theory and Methodology, IAG General Meeting, Beijing, China, august 1993*, 1993. Also in: Delft Geodetic Computing Centre, LGR Series, No. 6, 1994.
- [2] B M Kampes and R F Hanssen. Ambiguity resolution for permanent scatterer interferometry. *IEEE Transactions on Geoscience and Remote Sensing*, 42(11):2446–2453, November 2004.
- [3] P Marinkovic, G Ketelaar, F van Leijen and R Hanssen. InSAR quality control: analysis of five years of corner reflector time series. In *Fifth International Workshop on ERS/Envisat SAR Interferometry, 'FRINGE07', Frascati, Italy, 26-30 Nov 2007*, 2007.