A first quantitative evaluation of atmospheric effects on SAR interferometry

Ramon Hanssen, Arnout Feijt

Abstract— **Considerable interest has been generated recently in the use of SAR interferometry for monitoring slow deformation processes. Previous studies have shown that atmospheric inhomogeneities can form a major error source in these measurements. Since these inhomogeneities are distributed with a significant temporal and spatial variance, the corresponding phase delay can be observed within a single interferometric SAR pair. Especially in sea-bordering countries as the Netherlands, interferometric pairs are influenced considerably by the rapidly changing tropospheric conditions. In this study it will be tried to give a first quantitative evaluation of observed effects in SAR interferograms of the Netherlands. Using additional measurements and standard meteorological information, the plausibility of the effects to be atmospheric of origin is examined.**

Keywords— **insar, atmosphere, deformation**

I. Introduction

SINCE the state-of-the-art in SAR interferometry is strongly progressing towards a more quantitative and localized approach, the influence of error budgets is becoming more important. The influence of atmospheric inhomogeneities on SAR interferometry has been studied by several authors (see e.g. [1],[2],[3], and [4]). In this study, special attention is paid to the influence of tropospheric inhomogeneities for small baseline tandem interferograms of an area with no significant variation in elevation. The purpose of these interferograms is to estimate the feasibility of the detection of very slow subsidence rates over a long time span. Although the main problem for this type of measurements seems to be the temporal decorrelation, atmospheric effects can be easily misinterpreted as subsidence. Therefore, it is tried to estimate what the magnitude of the phase shifts due to atmospheric effects can be, and to suggest some possibilities to tackle these problems. The area of interest, Groningen, is situated in the North-East of the Netherlands and is slowly subsiding due to the extraction of natural gas.

This work is confined by emphasizing on tropospheric effects, especially the partial water vapor density, and the restriction to two-pass interferometry. Furthermore small baselines were used on a very flat area, so no Digital Elevation Model was necessary, and ERS1/2 tandem data with their one day time interval to avoid strong temporal decorrelation.

The two main topics we address in this paper are the following. In first instance we want to get some feeling for the relationship between tropospheric parameters as temperature, relative humidity and pressure with respect to relative interferometric phase changes. Secondary, it is tried to give a meteorological interpretation of these relationship in terms of feasibility.

After a short introduction on the subject, some aspects of the nature of the atmospheric effects are mentioned with emphasis on their behavior in SAR imagery. The following paragraph focusses more on the quantitative aspect, in which we will evaluate the sensibility of the interferometric phase against some important parameters. A small case study is performed next, where different data sources are combined to evaluate a SAR interferogram of the Groningen area. Some ideas on the way to approach the atmospheric problem for slow subsidence studies are discussed, after which we will make some concluding remarks.

Ramon Hanssen, Delft Institute for Earth Oriented Space Research (DEOS), Delft University of Technology, P.O. Box 5030, 2600 GA, Delft, the Netherlands. E-mail: hanssen@geo.tudelft.nl

Arnout Feijt, Royal Netherlands Meteorological Institute (KNMI), PO Box 201, 3730 AE, De Bilt, The Netherlands E-mail: feijt@knmi.nl

II. Characteristics of atmospheric disturbances on INSAR

For two-pass, short baseline interferometry, the influence of elevation on the interferometric phase is small due to the large height ambiguity. Therefore,assuming sufficiently correlated imagery, an interferometric phase change can only be due to surface deformations and inhomogeneities in the propagating medium. Whereas SAR interferometry for the estimation of Digital Elevation Models (DEMs) is strongly dependent on the length of the baseline, its use for deformation studies is not. The phase shift due to atmospheric inhomogeneities is equal for both DEM applications and deformation studies. However, the magnitude of these errors in the final products, DEMs and deformation maps, is different. For DEMs, the magnitude of the error is directly proportional to the height ambiguity, and therefore inversely proportional to the baseline. For deformation maps, the magnitude of the error is not related to the baseline.

Important properties of SAR interferograms are the relatively high resolution in an image of approximately 100 by 100 kilometers, and the fact that we use two semi-instantaneous observations. Translated to the atmosphere, this is related to the high spatial variability in the atmosphere's parameters, and the fact that there is no correlation between the state of the atmosphere at the two observation times.

Ionospheric disturbances have been reported by Tarayre and Massonnet([2]) and Massonnet et al ([5]). Traveling Ionospheric Disturbances (TID) are defined as areas in which the total electron content is significantly different from its surroundings. The influence of the electron content on the propagation of electro magnetic waves is dependent of the frequency of the signal and have been observed up to 2.8 cm for C-band radar ([6]). The spatial extension of TID's are mostly larger than 30 km, which is an important characteristic for recognizing and identifying the effects. Due to this relatively long extension, we expect the effect of ionospheric disturbances to be almost linear for ERS quarter scenes.

Tropospheric disturbances are more common to occur, even on sub kilometer scale. The often turbulent behavior of masses of air causes a constant mixture of temperature, pressure and relative humidity. Cloud forming processes are an example for the temporal and spatial scale of the inhomogeneity of this part of the atmosphere. A more quantitative evaluation of tropospheric disturbances will be given in the following paragraph.

III. Magnitude of the tropospheric inhomogeneities

A. Theory

The phase shift of a radio signal that propagates two-way in a medium with a refractive index equal to 1 (free space) can be expressed as:

$$\varphi = \frac{4\pi}{\lambda}\rho \qquad (1)$$

where rho is the one-way propagation path length. For a signal propagating in a medium with a refractive index unequal to 1, an incremental path length will be observed due to the signal delay in the medium, hence

$$\varphi = \frac{4\pi}{\lambda}(\rho + \Delta\rho) \qquad (2)$$

If we compare the phases of two SAR images, to calculate the interferometric phase, we obtain

$$\varphi_{12} = \varphi_1 - \varphi_2 = \frac{4\pi}{\lambda}(\rho_1 - \rho_2 + \Delta\rho_1 - \Delta\rho_2) \qquad (3)$$

Assuming that we are dealing with a very short baseline (< 50 m) and a flat, horizontal area with no deformations, the only coherent phase fluctuations will be caused by the difference in incremental path length:

$$\varphi_{12} = \frac{4\pi}{\lambda}\Delta\rho_{12}. \qquad (4)$$

From the latter equation we see that we cannot differ between the tropospheric states of the two acquisitions.

Experimental measurements of the influence of atmospheric pressure, temperature and the partial pressure of water vapor (Smith and Weintraub, 1953)(Zebker and Rosen,1996), have shown that the incremental path length can be approximated by integrating these parameters over the total path length in the troposphere:

$$\Delta\rho = 7.76 \cdot 10^{-5}\int_0^{top}\frac{P}{T}dx + 3.73 \cdot 10^{-1}\int_0^{top}\frac{e}{T^2}dx \qquad (5)$$

In practice, however, the vertical profiles of the three parameters, needed for the calculation of the delay, cannot be calculated for every pixel. Fortunately, the incremental path length caused by the tropospheric delay can be estimated using, e.g., a Saastamoinen tropospheric model. This model expresses the incremental path length as a function of *pressure*, *relative humidity*, *temperature* and *inclination.*

B. The Saastamoinen model

The height integral over the refractive index $\int(n-1)dr$of the atmospheric refractivity for electromagnetic waves, taken from the earth's surface up to the top of the atmosphere, is directly proportional to the ground pressure. This follows from the law of Gladstone and Dale, and the fact that the barometer measures the weight of the overlying atmosphere.

Therefore the refraction formulas can be simplified and improved by determining the refractivity integral without a detailed knowledge of the height distribution of the refractive index (Saastamoinen,1972).

For the latitude of the Netherlands, a simplified form of the Saastamoinen model is

$$\Delta\rho = 2.277 \cdot 10^{-3}\frac{P + (\frac{1225}{t+273.15} + 0.05)e - 1.156\tan^2\theta}{\cos\theta} \qquad (6)$$

in which P is the total atmospheric pressure in HPa, t is the temperature in degrees Celsius, theta is the inclination angle and e is the partial water vapor pressure. The latter can be derived from the relative humidity rh[%] using:

$$e = \frac{rh}{100}e^{(-372465+0.213166(t+273.15)-0.000256908(t+273.15)^2)} \qquad (7)$$

The important consequence of this model is that an estimation of the phase delay can be determined without having to know all the parameters a priori.

C. A quantitative evaluation of the parameters

The Saastamoinen model can be used to perform a first quantitative evaluation of the sensibility of phase changes due to the three major parameters; *relative humidity* ,*temperature* and *pressure.* What we assume here, is that the atmosphere is divided spatially into columns with a certain average value of the three variables. In the horizontal direction, differences can occur between the columns, resulting in a relative phase shift in the interferogram.

Figure 1 shows the influence of pressure changes (HPa) on the interferometric phase. We can see that, e.g., a difference of 5 HPa represents a corresponding phase shift of 0.4 phase cycle. Note that the pressure is not correlated with temperature or relative humidity. Pressure changes of 5 HPa over 50 kilometers are possible to occur in a meteorological front zone, and will be visible as a linear trend in the interferogram. In figure 2 the connection between temperature and relative phase change is shown for three values of the relative humidity and a fixed pressure of 1010

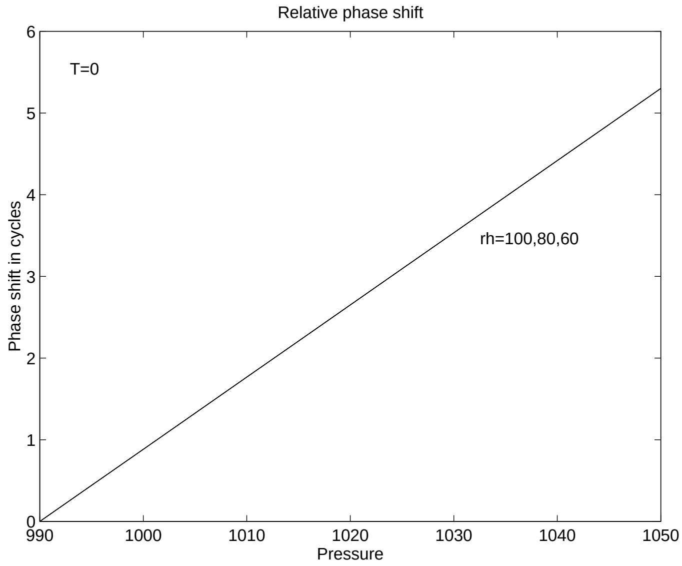

Fig. 1. Relative phase shift as a function of pressure in the Saastamoinen model. Pressure is expressed in HPa.

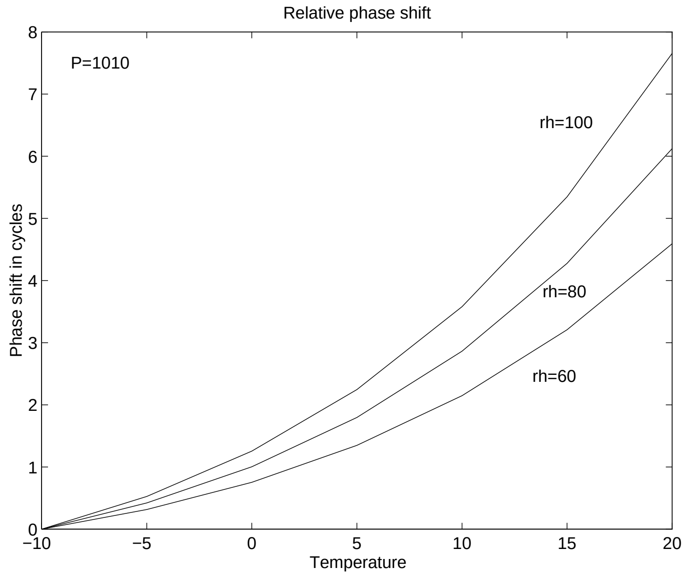

Fig. 2. Relative phase shift as a function of temperature in the Saastamoinen model. Temperature is expressed in degrees Celsius.

HPa. Here we see that a (horizontal) temperature gradient of 5 degrees can have considerable influence on the corresponding phase shift, depending on the absolute temperature and the relative humidity. If we keep in mind that in a standard atmosphere the temperature drops with 6.5 degrees every kilometer, the influence of the lower layers will be significantly more important than higher layers.

In the horizontal direction the first 40 meters above ground level can have strong variations in temperature, depending on the nature of the surface. Above this layer, at fixed altitudes, the horizontal differences in temperature will be limited to large scale trends. Due to the limited extend of this lower layer, it can be doubted if it will have enough influence to alter the interferometric phase. Finally, figure 3 shows the influence of the relative humidity on the relative phase change, for three different temperatures. These temperatures can be coupled directly to altitude, and due to the decrease in temperature with height, the influence of a humidity change at low temperatures becomes significantly more important than at higher temperatures. For a temperature of 0 degrees Celsius, a 20% change in relative humidity horizontally would count for a half cycle phase difference in the interferogram.

Strong variations in relative humidity are to be expected, e.g., near cumulus clouds, where dry and warm air is moving upwards, cools down, and condensates (increase in relative humidity). The consequence of this movement is a downward movement at some distance from the upward one. In this downward movement, cold and humid air is warmed up, hereby decreasing in humidity. As a consequence we might expect changes in relative humidity of tens of percents, even on a kilometer scale.

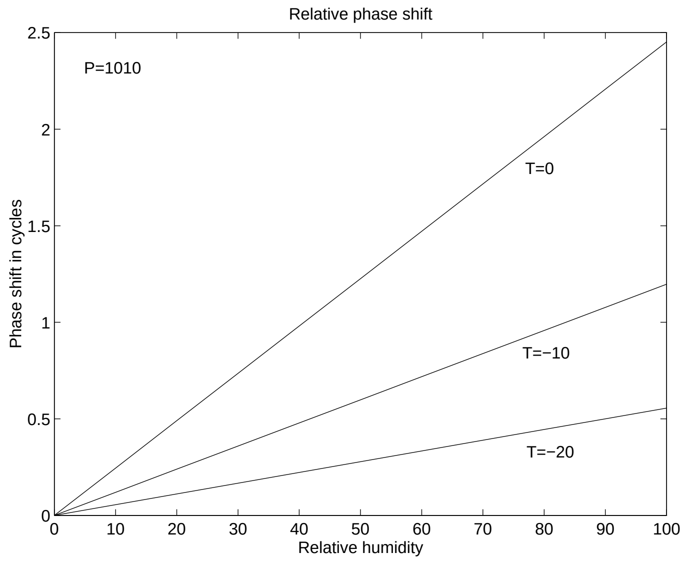

Fig. 3. Relative phase shift as a function of the relative humidity in the Saastamoinen model.

IV. Case study: Groningen Interferometric SAR experiment

A. Interferometric observations

In the Groningen Interferometric SAR Experiment (GISARE), an interferogram was obtained using the ERS images of 26 and 27 February, 1996 at 10:29 UTC (see figure 4). The elevation differences in this area do not exceed 5 meters, which corresponds to a phase cycle of 0.02 for this baseline. Therefore, topography can be neglected as a source of phase changes in the interferogram.

The remaining phase differences are not influenced by the baseline, so only phase delay or surface deformation will be visible in the interferogram. However, large scale deformations are unlikely within a time period of one day. Over the land areas we see changes in interferometric phase of about 0.4 phase cycle, corresponding with approximately 1 cm excess path length in the direction of the satellite. Furthermore, there appear to be patterns in these disturbances in North-East South-West direction. The inclination of the image for this descending orbit is approximately 13 degrees.

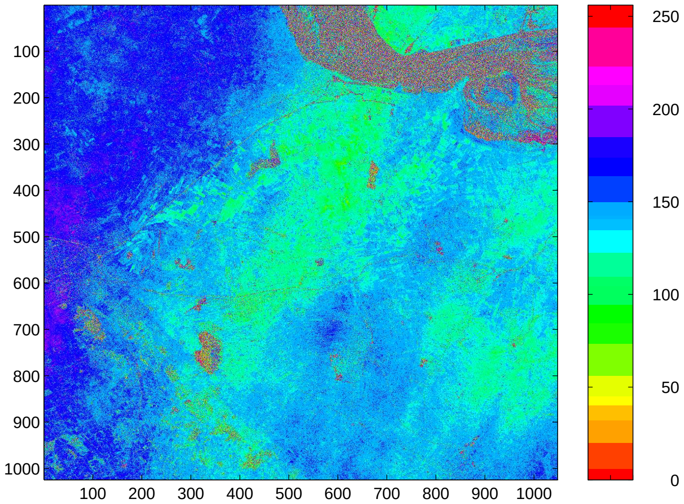

Fig. 4. Interferogram of the Groningen area

B. Meteosat an NOAA-AVHRR observations

Three minutes before the ERS image acquisitions, Meteosat observations of the area were made. At that time, the visual channel (VIS) was operating in a double resolution mode of 2.5 by 5 kilometers for this latitude. NOAA-AVHRR (Advanced Very High Resolution Radiometer) images were acquired 115 minutes later. All four images show approximately the same area. In the NOAA images, the contours of the Netherlands overlay the data. The Groningen area, shown in the interferogram, is located in the North-Eastern part of the area. We can see patterns in these images, especially on 27 February, which correlate in direction with the interferometric patterns.

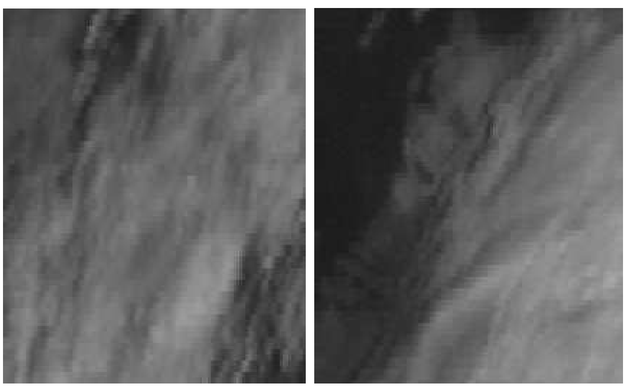

Fig. 5. Meteosat Double VIS, 26 and 27 February 1996, 10:26

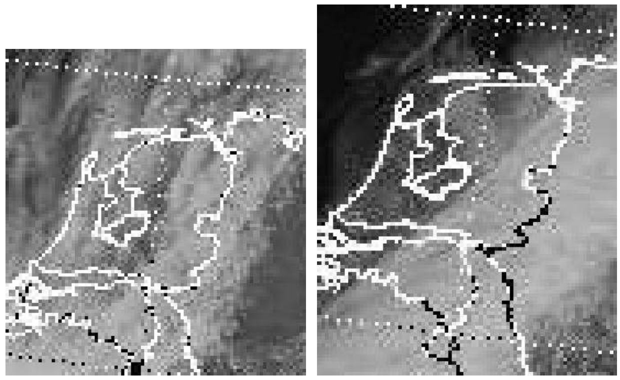

Fig. 6. NOAA-AVHRR, channel 2, 26/2/96, 12:14, and 27/2/1996, 12:02

C. Radio probe observations

From the Meteosat and NOAA-AVHRR imagery it can be clearly seen that a frontal zone passed the Groningen area during the SAR acquisitions. In the frontal zone relative humidity is high from the ground up till several kilometers. Behind the frontal zone the atmosphere dries out. This can be clearly seen from the radiosonde profiles of relative humidity. Such a frontal zone could due to the high spatial variability of the relative humidity perpendicular to the frontal zone,and influence the results from the SAR interferometer. To test this hypothesis, vertical radio probe profiles of temperature, pressure and relative humidity were analyzed from ground level to a height of 12 kilometers. The total path delay was calculated using formula 5. It resulted in a constant increase in path delay of 1.5 cm during the 24 hours in which the frontal zone passed. These calculated path delays from actual atmospheric profiles clearly support our hypothesis.

D. Meteo observations Groningen airport

Meteorological ground observations at Groningen airport were acquired at the moment of the SAR data acquisitions. The airport is located in the imaged area. The data are presented in table 1 and 2. Evaluation of the results show that they can be used to get a first estimation for the parameters in the Saastamoinen model.

E. Analysis

A smoothed version of the interferogram is shown in figure 7. We applied a bicubic low pass filtering to obtain an image with a pixel size of 200 by 200 m. The colors represent the phase changes in the interferogram, using a colorbar from 0 to 255, which corresponds with one phase cycle (2.8 cm). Note that by this procedure water surfaces will get an average value which we should not falsely interpret as an area with constant phase!

In this smoothed image, a profile was taken from one corner to the other, perpendicular to the main disturbances.

Parameter	26/2/96	27/2/96
Temp (C)	1	1
Pres (hPa)	1007	1020
RelHum (%)	100	100
Wind speed (m/s)	11	1
Wind dir (deg)	180	*various*
Precip	*Very light drizzle*	*No*
Cloud layer 1	Sc, 2/8, 700-900 m	-, 8/8, 1.2 km
Cloud layer 2	Ac, 8/8, 3.7-4 km	-,-,-

TABLE I

Meteorological data Groningen airport, 26 and 27 February 1996

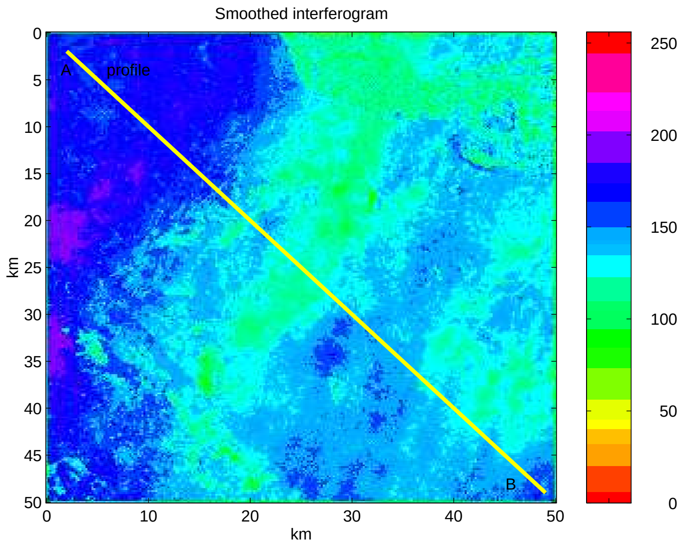

Fig. 7. Smoothed Interferogram of the Groningen area

This profile is plotted in figure 8. We see differences in interferometric phase in the order of 0.2 phase cycle. Using the Saastamoinen model, assuming a mean temperature of -10 degrees Celsius and a ground pressure of 1010 HPa, we can calculate how large relative humidity changes have to be in order to explain the phase variation. For a phase variation of 0.2 phase cycles, the corresponding change in relative humidity is 20%.

V. Alternative approaches

For detecting subsidence rates over more than a year time span in areas with much agricultural use, the biggest problem is formed by the temporal decorrelation, which will obscure most of the data for further interpretation. The only regions that were found to be coherent are e.g., urban areas, roads and public works. However, for these parts of the area, atmospheric disturbances will play an important role, since we cannot actually see the spatial structures in the mostly decorrelated interferogram. Here we will give some preliminary ideas for suppressing the influence of the disturbances.

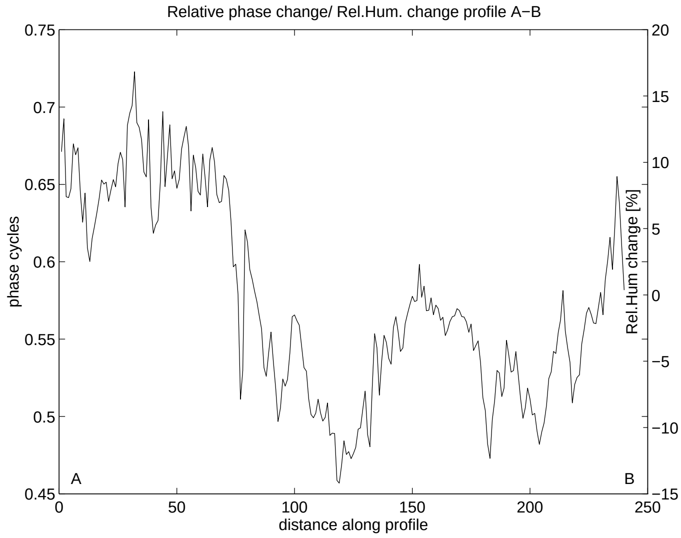

Fig. 8. Profile A-B: left axis is interferometric phase change, right axis is the corresponding change in relative humidity, assuming the Saastamoinen model. The distance along the profile is expressed in the number of pixels.

A. *Time series filtering*

Time series seem to be a possible approach for eliminating or suppressing atmospheric artifacts. If a significantly long time series of coregistered interferograms is analyzed, it can be expected that atmospheric phase shifts will behave like noise with a wavelength of less than 30 km. Therefore, by low-pass filtering of the images, using appropriate statistical assumptions, the effects might be suppressed.

B. *Pair wise combinations*

Another possibility, which is only possible for a time series of correlated interferograms, is to estimate the atmosphere's influence on one particular image. This can be based on the comparison of three SAR images in two interferograms. Since the effects of the atmosphere will be unique for every image, the two interferograms must convey the identical features of the image which is used twice. In flat areas, as which we are discussing here, we only have to distinguish between deformations and atmospheric effects, were it should be noted that the time scale of the subsidence deformations is likely to be much larger than that of the atmosphere.

C. *Additional measurements*

Different types of other techniques can give useful information on the possible disturbance of the atmosphere. GPS is able to estimate accurate zenith delays which can be mapped to the incidence angle of the SAR sensor. Although these measurements yield point wise information, information on the variability of the atmosphere can be extracted from time series of measurements. Satellite systems as Meteosat or NOAA-AVHRR deliver images which could be used, e.g., if water vapor content is measured. Unfortunately the resolution of these instruments for the latitude of the Netherlands is in the order of kilometers, and they seem more appropriate for a qualitative than a quantitative analysis. An important restriction to all these additional measurements is that they should be made simultaneously with the two SAR images, due to the high temporal variation of the atmospheric conditions.

D. Data selection

A last, and very straightforward, possibility is the selection of those interferograms which are not contaminated by atmospheric effects. As long as sufficient SAR images have been observed, it is possible to use only those which are likely not to be too much disturbed by weather conditions. Unfortunately, for a lot of regions in the world undisturbed images are quite unlikely.

The influence of the atmosphere on interferometric SAR images is strongly determined by its high temporal and spatial variability. Atmospheric models are mostly too generalized to explain the artifacts that can occur within one interferogram. With respect to the spatial variability, SAR images are influenced by artifacts of the size of single clouds.

The phase value of every SAR image is always influenced by the atmosphere. Problems arise when the spatial variability of e.g., the three main tropospheric parameters pressure, temperature and relative humidity is such that the horizontal path delay differences are significant with respect to the wavelength of the radar signal. Using the Saastamoinen model, these differences can be related to changes in the average integrated value of these three parameters over a column of air. It seems that especially relative humidity is an important parameter causing local path delays.

For a qualitative evaluation of observed effects, meteorological satellites can be used. A more quantitative analysis is always strongly influenced by the models that were used. However, when atmospheric effects can be detected and positively identified, possibilities arise for their elimination. Further studies need to be performed on how this detection and elimination can be improved.

VI. Acknowledgment

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