SAR interferometry: a new tool for deformation measurements? *

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Compared to optical sensors the use of radar for earth observation has only just begun. The first use of radar for this purpose was reported in the sixties. The most important reason to use radar in stead of optical sensors is of course its capability to penetrate through clouds and its day and night imaging capabilities. However, radar interferometry might add yet another reason to use radar. Recently it has been shown, that with spaceborne Synthetic Aperture Radars, deformations of the surface of the Earth can be measured with sub-centimeter accuracy's. This information becomes available by using interferometric processing techniques of multiple satellite images from the satellite. In this article we will outline the basics of the technique and its potential as well as the limitations.

Since the launch of the sRS–1 satellite by the European Space Agency ESA in 1991, the topic of interferometric processing of the signals from the Synthetic Aperture Radar has gained a lot of attention in the radar Remote Ssensing community. The reason for all this attention is the fact, that with this very sensitive measurement technique it becomes possible to measure deformation effects of the Earth's surface over large area's and with a sub–centimeter accuracy. A demonstration of the power of the technique was given by Massonnet et al and published in Nature in 1993. It showed that this satellite technique was capable of measuring the horizontal and vertical displacements after an earthquake. Comparison of the satellite measurements with numerical models showed remarkable resemblance with the satellite measurements. Besides deformation measurements, the technique also allows the creation of digital elevation maps of the Earth, even in cloudy areas.

A Synthetic Aperture Radar (SAR) is an imaging radar device which images the radar backscatter of the surface of the earth over large areas (100×100 km for a satellite system) with a moderate resolution (10–20 m.). In the satellite not only the power of the backscattered electro–magnetic radiation is recorded, but also its phase. In radar interferometry the interference is taking place between the backscatter of two different SAR images from the same terrain, taken from slightly different positions or taken at different times. Very small changes of the path length can thus be measured and related to either surface deformation or topography. Because the radar is an imaging device the information on deformation can in principle be obtained for every image pixel within the scene, leading to a high resolution image of the deformation. This is a unique feature of this technique. This article will explain the basics of this new technique, which is called radar interferometry, a comparison with other techniques for deformation measurements and give an outlook to the future.

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1 Principles of the technique

The SAR instrument emits microwave pulses to the Earth under a specific look–angle (23 degrees in the case of ERS–1). These pulses are reflected at the Earth's surface, and a small part of this reflection can be detected again by the SAR antenna. Due to this look–angle one can record the time history of the reflected pulses. Pulses which reach the Earth first are also detected first by the antenna, hereby discriminating in the ranging direction, perpendicular to the flight direction. If only the time–delay of the transmitted pulse would be measured, the achieved height resolution would be in the order of 10–20 meter. The signal that is received by the SAR antenna contains an *amplitude*, which is depending on the intensity of the reflection on Earth, and a *phase*. With the known wavelength of the emitted radiation, the recorded phase expresses a fraction of this wavelength and can therefore be considered as a distance measure. The phase that is received by the SAR antenna is actually a summation of the phases of all the scattering elements that are located within a resolution element. Therefore, the absolute phases of pixels in a SAR image are actually quite random, and a phase plot of only one SAR image would not contain any useful information. If, however, the summation of all these scattering elements is the same for the second image—hence the signals are *correlated*—the differences between the phases in the first and second image will vary only due to path length differences.

Contemporary spaceborne SAR's have not been designed for interferometric applications. A specially designed interferometric SAR would typically have two antenna's: one for *receiving* the reflected radiation and one for *sending and receiving*. Due to the fact that the spaceborne SAR has only one antenna, use is being made of the repeatability of the satellite's orbit. This way, the required constellation of the two antenna's (figure 1) can only be achieved after a specific period of time: the repeat orbit. This technique is referred to as 'repeat-pass interferometry'. The methods that use two fixed antenna's can be used in several applications. When the antenna's are placed in the flight direction the constellation is particularly sensitive to horizontal movements, e.g. to determine the velocity of a moving object ('along track interferometry'). 'Across-track interferometry' uses an antenna positioning perpendicular to the flight direction and is more sensitive to height differences. If the constellation of sensors and earth is considered as depicted in figure 1, the measurement of heights or height differences reduces more or less to a geometric problem. When the distance between the radar and a resolution element on the ground is obtained by means of time measurement, and the height of the satellite is known, it is possible to reconstruct the height of this resolution element above a certain reference level. The important parameter that enables this geometric reconstruction is the local look–angle to the resolution element. This angle can indirectly be determined by the phase measurement in the images. The phase difference for every pixel is proportional to the difference in path length from the two satellite positions to the resolution element. An important aspect in this approach is the availability of a precisely determined baseline, in distance as well as in spatial orientation. The baseline requirements are also dependent on the type of observations one is aiming at. For the creation of DEM's, the baseline should have a certain minimal length, between 10 meters and at most a few kilometers. This length is necessary to ensure sufficient geometry to solve for the goniometry. However, for precise deformation measurements a zero–baseline would have the best characteristics. A zero-baseline ensures minimal phase variations due to topography, and therefore the only fringes phase differences would occur for the pixels that moved in the interval between the two data takes. Naturally, from a practical point of view a zero-baseline is an ideal situation so that in practice only very small baselines can be used.

2 Deformation measurements

When part of the surface imaged by the radar deforms, this will result in a slight change in the path length between that particular part of the surface and its surroundings. This leads to a contrast in the interferogram phase image as calculated with the interferometric SAR processor. This is the principle of the technique as explained above. However, there are other causes of changes of the path length such as: different atmospheric conditions during the first and second pass and the topography of the terrain itself. In order to use interferometric SAR processing for the purpose of deformation measurements, the path length differences caused by these effects will have to be distinguished from the path length difference caused by the deformation. This is straightforward for the effects of the topography. Using a digital elevation map will allow for correction of the path length differences. If such an elevation map is not available, one can make use of a third SAR image to estimate the topography and after that measure the deformation. The atmospheric effects, however, can limit the accuracy of the technique. Research is conducted in the Netherlands toward quantifying these effects and relating it to meteorological conditions. It has been shown, that under bad conditions the atmosphere can introduce uncertainties in the order of 1 cm. Under favourable conditions these effects are less than 2 mm.

An example of the measurement of very small local vertical movements is shown in figure 2. It shows an interferogram of a part of the province Zeeland in the Netherlands. The path length differences are color coded with a color bar as indicated from 0 to 2.5 cm height change. Clearly visible are local variations which seem to be related to land use: they correlate with the agricultural field boundaries. Comparison with a soil map indicates that there is also a correlation between soil type and height change. During the data take of the first SAR image the temperature was below zero and the ground was frozen. During the second data take the temperature was above zero. It seems very likely that these path length differences are caused by swelling of the ground caused by frost and thaw. Since the water contained in the clay ground was frozen, the ground may well have swollen during the first pass. The amount of swelling depends on the amount of water contained in the ground and thereby on the amount of clay in the ground. The sandy grounds did not show any path length differences. The magnitude of the effect ranges from several mm's up to 1 cm. It shows that the technique is indeed capable of measuring very small deformations with a high accuracy.

However, measuring slow deformation processes is more difficult than the fast processes as described above. This is caused by the inherent assumption in the technique, that the small scale structure of the surface of the Earth does not change in between the data takes. This is a valid assumption for data takes taken shortly after each other or for rocky areas. However, it is not valid for water surfaces or even agricultural areas. This leads to a time dependent loss of information which is called *temporal decorrelation*. In practice it means, that the information of the deformation is limited to those areas in the image which do not change in structure over time. This can be illustrated with figure 2, which shows an interferogram of the province Groningen in the Netherlands. The center parts of this province slowly subside due to the extraction of natural gas. The rate of the subsidence is less than 6 mm per year. The interferogram was created from images taken one year apart. Areas which contain only noise are masked. It is clear that only urban areas remain stable enough over the period of one year to provide information on the subsidence. For Groningen the information contained in the urban areas still suffices to perform subsidence measurements. As mentioned above the temporal decorrelation will depend on the surface. At the moment its magnitude and thereby its influence on the measurement accuracy is not well known and is the topic of ongoing research.

3 Topography

Figure 4 shows an interferogram of the island of Sardinia (Italy) as processed using two ERS–1 images taken six days apart. The colours in this figure correspond to small path length differences between the antenna during both data takes and the surface of the Earth. These differences are directly related to the terrain height and therefore the coloured lines can be interpreted as contour height lines. What can also be observed is that the colours bands repeat, meaning that there is an ambiguity between the measured path length difference and the height. This ambiguity is inherent to the interferometric technique: the path length difference is measured in units of the wave length. When the path length difference becomes larger than the wave length, it is *wrapped* within a band of one wave length. At many places on the world methods are being developed at the moment to *unwrap* these interferograms in order to create high accuracy digital elevation maps. The accuracy's which are reported are in the order of 10 meter for the use with the ERS–1 satellite. This technique of measuring digital elevation maps with radar can also be performed with airborne radars. Airborne radars have a much better horizontal resolution—from a few meters down to 50 cm for some experimental systems. The digital elevation maps created with airborne systems are more accurate than those created with satellite systems. Accuracies of 50 cm vertical accuracy have been reported for some dedicated laboratory systems.

4 Comparison with photogrammetric and terrestrial measurements

As mentioned above there are two main application areas for the INSAR technique. One is the mapping of deformations, the other are relative height measurements. At first glance, the INSAR technique might show strong similarities with e.g. stereo–photogrammetry: there are *two sensors* with a certain intermediate *distance* which is called the*baseline* and it is possible to retrieve *height information*. However, there are some very different aspects in both approaches. In stereo–photogrammetry, the baseline should be in the order of 0.6 proportional to the height of the sensor. The height information is retrieved from the parallax between both images. For INSAR this baseline should be much smaller, for spaceborne DEM generation between 10 meters and a few kilometers. These restrictions to the baseline length are caused by the change in backscatter which would occur if the baseline would be to long. In other words, if the position of the second antenna is too far from the first, the scattering elements within a resolution cell behave in such a different way, that corresponding pixels cannot be compared anymore. A practical limitation for spaceborne SAR is that the instrument is only aimed at one particular direction. Stereo–SAR[1] is an existing technique, but it is necessary to look at the same area from two positions far apart. With a fixed SAR antenna this is not possible. Another difference between stereoscopic techniques and interferometry is the vertical resolution. The 'stereo' information of interferometric SAR is obtained by a radio phase measurement and hence, the resolution is a function of the wavelength. For the C-band instruments, fractions of the wavelength can be measured as precise as some millimeters. This is the feature that makes interferometry such an accurate technique if especially deformation measurements are concerned. When compared to terrestrial height measurement techniques for deformation measurements such as levelling, it can be said that, with the different error sources of the deformation measurement with of interferometric SAR, the levelling accuracies can currently only be reached in ideal circumstances. However, the feature that makes INSAR so promising is the possibility to get accurate height change

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[1] A technique that uses two SAR amplitude (!) images to form a stereo–pair

information at every pixel from only two observations. This nearly continuous coverage of an area located anywhere on Earth makes it a very attractive technique when compared to point–positioning geodetic techniques as levelling or differential GPS. Furthermore, since the height information obtained by INSAR is a relative measurement, it could play a complementary role if combined with e.g. the absolute GPS measurements. The practical choice for a certain height determination technique is depending on a number of considerations. The size and type of the area of interest, the desired coverage and accuracy of this area, the costs and the availability of data are the main aspects that need to be determined before a profound decision can be made.

5 Application areas

Many future application areas are foreseen for the INSAR technique amongst which:

- deformation measurement
- earthquake monitoring
- monitoring of vulcano's
- plate tectonics
- creation of digital elevation maps.

In a number of universities and government laboratories the technique of SAR interferometry is being developed at the moment for as well deformation measurement as for the generation of digital elevation maps. The research focuses on many aspects of the technique such as algorithms to convert interferograms into digital elevation maps by 'unwrapping' the phase, studies on elimination of topography and atmospheric effects from the deformation measurements and integration of these techniques with the more conventional levelling measurements and GPS. Internationally the research is being coordinated through an ESA working group, 'Fringe', which supplies researchers with high quality data and provides a platform for the exchange of results. Recently an IAG Special Study Group on radar interferometry was erected to develop the use of this technique in the geodetic community.

6 Conclusion

Radar interferometry is a young technique which has just left its 'embryonic' stage and is developing rapidly. It is to be expected that within a few years the first products based on this technique will appear on the market. Considering the amount of information which is obtained, the price of the basic product, the SAR images, which is at approximately 1 US dollar per square km, must be considered low. However, the main part of the total product price will probably not be the imagery, but the additional processing which is necessary for a specific application. This will highly depend on the user's accuracy requirements. It is too early to comment on that. Still, radar interferometry is a very promising new technique with a bright future. It will allow new, accurate, area extended measurements of deformations of the Earth's surface of the Earth which can be very helpful in many areas of the geology and geodesy.

7 Biography of the Authors

Erik van Halsema studied Physics at the Leiden University in the Netherlands. He joined the Physics and Electronics Laboratory of TNO in 1983 as a research scientist. He worked on topics concerning the radar remote sensing of water surfaces. In 1986 he received a fellowship from the Canadian government to work for one year at the Canada Center for Remote Sensing in Ottawa. He is now responsible for the land applications of remote sensing. This includes the development of new processing technologies such as radar interferometry.

Ramon Hanssen graduated from the Delft University of Technology in 1993 with a degree in Geodetic Engineering. He has worked in the field of geophysics (gravity and aero-magnetics) and is currently involved as an assistant researcher in the SAR interferometry group of the section Physical, Geometrical and Space Geodesy at the Faculty of Geodetic Engineering of the Delft University of Technology. The main interest of his work is to study the feasibility of Interferometric SAR for the monitoring of deformations. This research is carried out in close collaboration with the above mentioned Physics and Electronics Laboratory of TNO and the Survey Department of Rijkswaterstaat in the Netherlands.