APPLICATIONS OF SAR INTERFEROMETRY IN TERRESTRIAL AND ATMOSPHERIC MAPPING[1]

Ramon F. Hanssen and Roland Klees

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, klees@geo.tudelft.nl

Abstract

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 instead 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 height maps can be created with accuracies of 10–20 meters, whereas deformations of the Earth's surface can be measured with sub-centimeter accuracy. Apart from these terrestrial applications, also the high resolution mapping of atmospheric signal delay has been demonstrated. This information becomes available by using interferometric processing techniques of multiple satellite images. Here we will outline the basics of the technique and its potential as well as the limitations.

INTRODUCTION

Since the launch of the ERS–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 sensing 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. (1993) and published in Nature. 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. Besides deformation measurements, the technique also allows the creation of digital elevation maps, even in areas dominated by cloud cover.

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 electromagnetic radiation is recorded, but also its phase. In radar interferometry the interference is taking place between the backscatter in 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, topography, or atmospheric delay. Because the radar is an imaging device the information on deformation, height or delay can in principle be obtained for every image pixel within the scene. This is a unique feature of this technique. This paper will explain the basics of SAR interferometry and Differential SAR interferometry, make a comparison with other geodetic techniques like photogrammetry, VLBI and GPS and give an outlook to the future.

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-1/2). 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 the oblique look-angle the time history of the reflected pulses can be recorded. Pulses which reach the Earth first are also detected first by the antenna, hereby discriminating in the range direction, perpendicular to the flight direction. If only the time-delay of the transmitted pulse would be measured, it would be impossible to discriminate between points within the same range R_1 but with different heights, see figure 2.

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

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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—the signals are *coherent*—the differences between the phases in the first and second image will vary only due to path length differences.

Interferometry

Contemporary spaceborne SAR's have not been designed for interferometric applications. A specially designed interferometric SAR[2] would typically have two antenna's: one for *receiving* the reflected radiation and one for *sending and receiving*. Due to the fact that the current spaceborne SAR's have 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 h or height differences ∂H reduces more or less to a geometric problem. When the distance R between the radar and a resolution element on the ground is obtained by means of time measurement, and the height of the satellite, H, 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, θ 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, δ, from the two satellite positions to the resolution element. An important aspect in this approach is the availability of a precisely determined baseline B, 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 about a kilometer. This length is necessary to ensure sufficient geometry to solve for the trigonometry. 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 acquisitions.

Differential interferometry

Naturally, from a practical point of view a zero-baseline is an ideal and therefore uncommon situation. Therefore, the technique of *differential* interferometry is applied for measuring deformations. The problem in repeat pass interferometry with a non-zero baseline is that phase differences can be caused either by spatial or by temporal path length differences. The former is determined by the length of the effective baseline, the latter by lateral deformations of the topography or by signal delay. The corresponding accuracies are also dependent on the baseline for relative height differences (yielding an accuracy of some meters), whereas the topographic changes in between the two image acquisitions can be measured as a fraction of the effective wavelength (sub-centimeter accuracy). In differential interferometry, it is tried to use a priori information on the height distribution, translate these heights to a phase differences, and to subtract these phase differences from the interferogram. This way, no height information is apparent in the interferogram, and the only phase differences are caused by deformations of the surface. Two possibilities for a priori height information are an existing DEM obtained with other techniques, or a DEM obtained from a previous interferometric SAR pair, of which it is known that no deformation took place. Both techniques have been extensively demonstrated on seismic deformation, volcano deflation, glacier movement, and ground swell.
In the following section we will try to give a short overview of the most important interferometric concepts to get from a measured phase to a height, deformation, or differential delay value.

Phase conversion

The interferometric configuration is given in figure 1. Combining the physical and the geometrical relationships between the two observations yields height information. This procedure is sketched in the following five steps.

1. **Physical relation**

[2]The Shuttle Radar Topographic Mission (SRTM), to be launched in 1999, is such a specially designed interferometric SAR

The received phase (propagation part) for the satellites is

$$\phi_{1p} = \frac{2\pi \cdot 2R_1}{\lambda}; \quad \phi_{2p} = \frac{2\pi \cdot 2R_2}{\lambda}. \tag{1}$$

The interferometric phase is

$$\phi_p = \phi_{1p} - \phi_{2p} = \frac{4\pi(R_1 - R_2)}{\lambda} = \frac{4\pi\delta}{\lambda}. \tag{2}$$

The derivative of the interferometric phase is now

$$\partial\phi_p = \frac{4\pi}{\lambda}\partial\delta. \tag{3}$$

2. **Geometrical relation**

   The path length difference δ can be expressed as

$$\delta = B\sin\psi, \quad \text{with} \quad \psi = \theta - \alpha, \tag{4}$$

   which yields

$$\delta = B\sin(\theta - \alpha) \tag{5}$$

   The derivative of the path length difference is

$$\partial\delta = B\cos(\theta - \alpha)\partial\theta. \tag{6}$$

3. **Combination of physics and geometry**

   From the combination of steps 1 and 2 follows the relationship between an interferometric phase change and a small change in the incidence angle θ.

$$\partial\phi_p = \frac{4\pi}{\lambda}B\cos(\theta - \alpha)\partial\theta, \quad \text{or} \tag{7}$$

$$\partial\theta = \frac{\lambda}{4\pi B\cos(\theta - \alpha)}\partial\phi_p. \tag{8}$$

4. **Differential height**

   The height of the satellite above the *zero-plane* can be expressed as

$$H = R_1\cos\theta, \tag{9}$$

   and the derivative with R_1 considered constant gives the relationship of a change in incidence angle θ due to a differential height ∂H:

$$\partial H = (-)R_1\sin\theta\partial\theta \quad (= h). \tag{10}$$

5. **Height as a function of interferometric phase**

   Using step 3 and 4 we derive the relationship between a differential height ∂H, which is actually the height h above the *zero-plane* or *reference-plane*, and the observed phase difference $\partial\phi_p$:

$$\partial H = \frac{\lambda R_1\sin\theta}{4\pi B\cos(\theta - \alpha)}\partial\phi_p \quad \text{or} \tag{11}$$

$$h = \frac{\lambda R_1\sin\theta}{4\pi B^{\perp}}\partial\phi_p. \tag{12}$$

   This relationship gives the *height ambiguity*—the height difference corresponding with a 2π phase shift—when $\partial\phi_p = 2\pi$ is inserted.

To conclude this evaluation, let us combine the influence of topography and surface displacement on the interferometric phase. Using equation (3) and (11), we find

$$\partial\phi_p = \frac{4\pi}{\lambda}\partial\delta + \frac{4\pi B^{\perp}}{\lambda R_1\sin\theta}\partial H. \tag{13}$$

This implies for the case of ERS with an effective baseline $B^{\perp}$ of 100 meters that a height difference ∂H of 1 meter yields an interferometric phase difference of approximately 4.5 degrees, well below the noise level of some 40 degrees, and therefore practically undetectable. However, in the differential case, a change $\partial\delta$ of 1 cm in the range direction, yields a phase difference of 127 degrees, which is easily detectable.

SAR INTERFEROMETRY AS GEODETIC TECHNIQUE

To give SAR interferometry a complementary position in the range of contemporary geodetic techniques, a short comparison with the following techniques is made: photogrammetry, VLBI, GPS, levelling, and optical remote sensing.

Photogrammetry

In table 1, some important differences and similarities between photogrammetry and INSAR are given. The most important difference between both techniques is that the former is based on the concept of *parallax*, whereas the latter actually depends on *coherency* and interferometric phase differences. This is translated into the need for a relatively large baseline for photogrammetry and a very small baseline for SAR interferometry. For photogrammetric applications, a major restriction is being formed by cloud cover. Since SAR is an active sensor, it creates its own illumination, at a wavelength that penetrates through clouds. A significant difference in the imagery is the layover effect. This is *angle dependent* in photogrammetry, and *distance dependent* in interferometric SAR. Therefore, layover is away from the sensor in photogrammetry, and towards the sensor for INSAR.

VLBI

A limited comparison between INSAR and VLBI is given in table 2. Naturally, the major differences between both techniques are their applications, although some interesting similarities might give reason for a fruitful exchange of the research issues. VLBI uses one source, the quasar, and two receivers. With SAR interferometry there are two possibilities. Either one source (antenna) illuminates the terrain, and two antenna's record the backscattered reflections, or two sources (antenna's) illuminate the terrain after some time epoch and both only record their own reflections. This configuration is based on coherent scattering. An interesting field of common research questions is formed by the influence of tropospheric and ionospheric signal delay. Although the longer observation epochs with VLBI may enable a different approach, these common problems deserve closer study.

GPS

Although GPS is an ideal system for point positioning, especially in its differential mode, one would need some 37.5 million GPS receivers to reach the same coverage as a SAR quarter scene. Furthermore, due to the incidence angle, a SAR is especially sensitive for height information, whereas the height for GPS is usually the weakest component. However, GPS permits long time series of surveys, whereas SAR can be seen as an instantaneous measurement. Another important difference between the techniques is that GPS yields absolute coordinates, whereas SAR interferometry only performs relative difference measurements. Some selected characteristics are given in table 3. GPS and INSAR can be regarded as complementary techniques: spatial versus temporal continuity.

Levelling

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 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 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.

Optical remote sensing

For optical remote sensing applications, similar comments can be made as for photogrammetry. A major restriction is being formed by cloud cover. For example, in Europe only 10% of all acquired data is useful for DEM purposes. SAR is an active sensor, it creates its own illumination. Another problem is formed by those

areas that do not exhibit good optical recognition characteristics, like the white snow coverage in polar regions. In these areas, stereoscopic parallax is hard to find. In SAR interferometry, similar problems exist when the scattering characteristics of the topography change, resulting in a loss of coherence.

ERROR SOURCES

Since SAR interferometry only works under coherent conditions, in which the received reflections of the pulse are correlated in the two SAR images, this is evidently the most important limitation and error source. The loss of coherence, denoted here as decorrelation, can be due to a number of causes. Decorrelation due to the *registration* of the two images can be distinguished into two parts. The *spatial coregistration* and the necessary resampling introduce noise in one of the images, resulting in a reduced coherence in the interferogram. The *spectral registration* error (also referred to as baseline decorrelation) is caused by the different mapping of harmonic features of the scene to the two different look directions of the satellites. For repeat pass interferometry, *temporal decorrelation* is a key problem in large parts of the world—major area's within a SAR scene change due to weather or antropogeneous activity. A decorrelation effect can be directly coupled to the variance of the interferometric phase, and hence propagated to the parameters which are inferred from this phase.
Apart from error sources causing direct decorrelation, which is often easily observable, there can be a problem in distinguishing between the different geophysical or technical sources of coherent phase variation. As stated previously, the observed interferometric phase is a coherent superposition of effects from topographic height, surface deformation between the acquisitions, the state of the atmosphere during both acquisitions, and possible errors in the orbit of the sensor. The interpretation of a SAR interferogram, aimed at only one of these applications, is therefore dependent on prior knowledge about the other contributions. In differential interferometry, e.g., an error in the applied a priori elevation model yields artifacts in the deformation maps which are produced using these DEM's.
Other error sources can occur in the interferometric processing sequence. Especially the process of *phase unwrapping*, in which the phase ambiguities are solved, can be quite cumbersome in accidented terrain, leading to local or global errors in the inferred height.
It can be noted that possibilities exist to overcome or suppress some error sources. The *multi-looking* procedure e.g. is a trade-off in a spatial averaging (hence, a loss in image resolution) is performed to obtain better phase statistics. Elevation models can be used to discern topography from surface deformation, and a priori meteorological information can be used to assess the amount and signature of atmospheric signal in the interferogram.

APPLICATION AREAS

Several application areas can be identified for SAR interferometry, amongst which:

- the creation of digital elevation maps (geocoded products which have—for airborne interferometry—a sub-meter resolution and a height accuracy of 1–2 meters),
- deformation measurements with accuracies of a fraction of the radar wavelength, such as
  - earthquake monitoring,
  - monitoring of volcanic activity,
  - land subsidence, and
  - monitoring of ice movement,
- monitoring of agricultural activity (by means of interferometric coherence evaluation), and
- High resolution mapping of atmospheric signal delay, directly connected to water vapor distribution.

In a number of universities, laboratories, and in some private enterprises the technique of SAR interferometry is currently being developed for deformation measurement as well as for the generation of digital elevation maps or signal delay 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 the ESA working group, *FRINGE*, which supplied researchers with high quality data and provides a platform for the exchange of results. Recently an Special Study Group on radar interferometry of the International Association for Geodesy was erected to develop the use of this technique in the geodetic community.

CONCLUDING REMARKS

In the reference list, a number of key papers on SAR interferometry and differential SAR interferometry are recommended.

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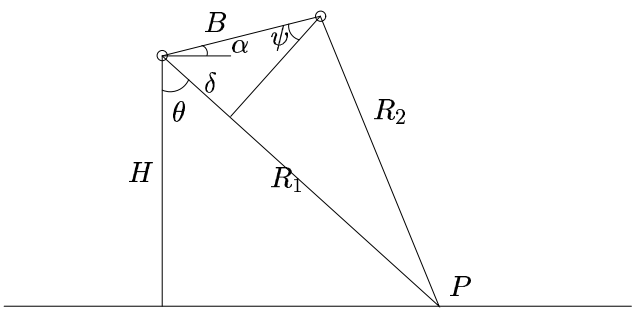

Figure 1: Interferometric configuration: two SAR sensors mounted on a platform are separated by a baseline B, and observe the complex response of a resolution element P. The *look-angle* θ is determined, using the slant range R and the height H of the platform

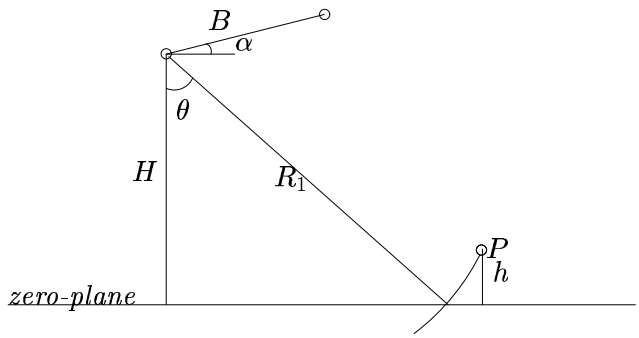

Figure 2: The configuration for a height h. The difference between point P and a point on the zero-plane is determined by the difference in θ.

Table 1: Some selected features of photogrammetry and their counterparts in SAR interferometry

	photogrammetry	INSAR
source	sunlight	radar
sensor	camera	radar
operation	passive	active
geometry	baseline	baseline very small
	$0.6 \times height$	compared to height
information	height	height and/or
		height change
position	spatial	spatial
principle	parallax	phase differences
wavelength	nm range	cm–m range

Table 2: Some selected features of VLBI and their counterparts in SAR interferometry

	VLBI	INSAR
source	quasar	"resolution element"[3]
sensor	e.m. antenna	e.m. antenna
operation	passive	active
geometry	"very long" baseline	"very short" baseline
		(10–1000 m)
	far field approx.	far field approx.
information	Earth orientation	height and/or
	parameters	height change
position	point	spatial
principle	phase differences	phase differences
	$(\Delta\phi(time))$	$(\Delta\phi(distance))$
wavelength	?	cm–m range

Table 3: Some selected features of GPS and their counterparts in SAR interferometry

	GPS	INSAR
source	GPS satellite	radar
sensor	e.m. antenna	e.m. antenna
operation	active	active
geometry	multi-satellite	two-antenna's (airborne–spaceborne)
information	absolute position	relative heights/ relative height-changes
position	point	spatial
principle	phase or carrier	phase
wavelength	dual frequency	one frequency

Table 4: Some selected features of levelling and their counterparts in SAR interferometry

	Levelling	INSAR
source	optical	radar
sensor	human	e.m. antenna
operation	passive	active
geometry	instrument and 2 rods	two-antenna's (airborne–spaceborne)
information	relative height	relative heights/ relative height-changes
position	point/line	spatial
principle	equipotential	phase
wavelength	optical	one frequency

Table 5: Some selected features of optical remote sensing and their counterparts in SAR interferometry

	optical R.S.	INSAR
source	optical	radar
sensor	camera	e.m. antenna
operation	passive	active
geometry	baseline (large)	baseline(short)
information	relative height	relative heights/ relative height-changes
position	spatial	spatial
principle	parallax	phase
wavelength	nm	cm–m range