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PSInSAR and DInSAR methodology comparison and their applicability in the field of surface deformations – A case of NW Slovenia

Primerjava uporabe metodologije PSInSAR in DInSAR za opazovanje premikov površja – primer SZ dela Slovenije

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Ključne besede: permanentni sipalci, deformacije površja, diferencialna interferometrija, InSAR, Posočje, Slovenija

Abstract

In the recent years radar interferometry (InSAR) has become an important tool in various studies. It can be used to produce accurate digital elevation models and observe small surface displacements. Differential interferometry (DInSAR) can detect movements in the radar look direction that are in the order of wavelength used, i.e. less than one centimetre with ERS data. In the presented study DInSAR has been used to observe surface movements in western Slovenia. Three ERS radar images have been supplemented with an external digital elevation model to produce three differential interferograms that temporally covered the Posočje earthquake, which happened on April 12, 1998. For the area around Bovec a land subsidence of approximately 0.5 cm has been observed; the largest movements detected exceeded 2 cm. DInSAR has been compared to the permanent scatterers interferometry (PSInSAR). Both methods are complementary and both have individual advantages and disadvantages.

Izvleček

Radarska interferometrija (InSAR) je razmeroma nova tehnika, ki se je v zadnjih nekaj letih uveljavila v najrazličnejših študijah. Najpomembnejše področje njene uporabe je izdelava digitalnih modelov višin in opazovanje majhnih premikov. Zelo uporabna je tudi diferencialna interferometrija (DInSAR), s katero lahko opazujemo premike tal velikostnega reda valovne dolžine uporabljenega radarskega valovanja, kar znaša pri satelitih ERS približno pol centimetra. V predstavljeni študiji so bili s tremi podobami območja Posočja in uporabo zunanjega modela višin ustvarjeni trije diferencialni interferogrami. Z upoštevanjem dejstva, da so modeli, dobljeni iz različnih interferogramov, odvisni, so bili določeni premiki, nastali ob potresu v zgornjem Posočju, 12. aprila 1998. Interferometrija je pokazala, da se je okolica Bovca v povprečju posedla za 0,5 cm, največji opaženi premiki pa znašajo več kot 2 cm. Opravljena je bila tudi podrobna analiza potenciala metode DInSAR in primerjava z metodo permanenthih sipalcev (PSInSAR). Metodi sta komplementarni, vsaka pa ima svoje prednosti in pomanjkljivosti. DInSAR namreč daje ploskovne rezultate, PSInSAR pa točkovne, vendar omogoča daljše časovno opazovanje, kar je še posebej pomembno v območjih pokritih z vegetacijo, kjer dekorelacija onemogoča uporabo tehnike DInSAR. PSInSAR predstavlja odlično alternativo tudi klasičnim geodetskih tehnikam, saj jih v mnogočem prekaša. Glavna prednost pred slednjimi je velika gostota merskih točk, dolgo časovno opazovanje ter možnost opazovanja brez predhodne namestitve instrumentov. V študiji zahodnega dela Slovenije je bilo mogoče opazovati več kot 20 točk na kvadratni kilometer v obdobju skoraj deset let z natančnostjo desetinke milimetra. Pokazalo se je, da so premiki, določeni z metodama DInSAR in PSInSAR, enakega velikostnega reda, a PSInSAR omogoča njihovo opazovanje skozi daljše časovno obdobje. Raziskava, predstavljena v tem prispevku, je pokazala, da je interferometrija permanentnih sipalcev zelo uporabna metoda, saj predstavlja nadgradnjo “klasične” DInSAR metode in se obnese bolje od nje povsod, razen na gosto naseljenih območjih, kjer je stopnja korelacije visoka tudi skozi daljše obdobje. Največje omejitve PSInSAR tehnike so zapletena interpretacija, nezveznost podatkov (DInSAR lahko služi kot dodatna informacija), neuporabnost metode za opazovanje poraščenih območij, omejeno obdobje ponovitve vzorčevanja, ki je vezano na povratno dobo satelitskega snemanja in neuporabnost metode za opazovanje hitrih premikov oziroma deformacij.

Introduction

Radar interferometry (InSAR) is a relatively new technique based on stereo pairs of aerial or satellite imagery high resolution images of the Earth's surface. Its primary fields of application are the production of digital elevation models and detection of minor displacements or deformations in vertical direction. The latter is especially useful in areas where the deformations are hard to measure with classic methods (i.e. geodetic measurements). The accuracy of the digital elevation models is about 10 meters in the horizontal (location) and several meters in the vertical (elevation) direction. A special InSAR method, the differential interferometry, is a very useful method that can be applied in ground deformation detection and measurements in the range of the radar wavelength. For ERS satellites the radar wavelength is 5.6 cm resulting in displacement accuracy of approximately half a centimetre (Oštir, 2000, 2006).

The radar interferometry approach uses complex satellite radar images that are composed of the amplitude and of the phase of the backscattered signal. The phase is dependent upon the surface's characteristics and the travelling distance of the radar signal (between the emitting antenna, the surface, and the receiving antenna). The advantage of having two images of the same area, taken from slightly different orbits, can be, considering the viewing geometry, exploited for creating the link between the interferogram (the phase difference of the two images) and the surface elevations. This principle can only be used if both images meet the requirements of interferometric analyses, which are 1) they both have to be acquired from orbits that are close to each other, which means that they have similar image acquisition geometry, and 2) the phase reflectance or geophysical properties of the surface must not change substantially between the acquisitions, which means that the time between acquisitions of the image pairs must be short enough to guarantee minimal distortion of the image (Oštir, 2000).

Similarly, this principle can be used in differential interferometry (DInSAR) for the detection of small relative displacements or deformations from the set of three images of the ground area with similar image acquisition geometry. With this method, two interferograms can be calculated and with their comparison the differential interferogram is produced. One interferogram is created from the first two images and the second interferogram from the last two images. If no changes occurred, the differential interferogram is equal to zero. If the phase reflectance has changed or if the surface has undergone deformations the differential interferogram will not be equal to zero. The phase reflectance represents noise and its elimination from further analyses is necessary, while the second factor enables accurate displacement detections (Oštir, 2000; Hanssen, 2005).

Permanent (also persistent) Scatterers InSAR (PSInSAR) technique is an upgrade of DInSAR. For analytical purposes this method uses coherent radar targets that can be clearly distinguished in all images and do not vary in their properties (Ferretti et al., 2001). Based on their permanent properties they are called permanent scatterers. By using permanent scaterers the atmospheric effects can be filtered out and the temporal and geometrical decorrelation can be eliminated. The drawback of this method is a loss of data continuity. The data are a set of points with a density depending on the form and coverage of the surface. These coherent radar targets are abundant in urban areas, but are very scarce in the vegetated and mountainous areas.

The theoretical background of interferometry has been known for more than two decades and over fifteen years ago the first successful interferometric analysis was conducted (Zebker in Goldstein, 1986). The real breakthrough in the field of interferometry came in 1991 with the launch of the first European satellite for Earth observation, the ERS-1. Since then this technique has been applied in many fields of terrestrial research, from hydrology (Borgeaud & Wegmüller, 1997; Goldstein et al., 1989; Rodriguez et al., 1996), seismology (Massonnet et al., 1993; Massonnet et al., 1994; Dixon, 1995; Peltzer et al., 1996; Massonnet et al., 1996; Peltzer et al., 1999; Carnec & Delacourt, 2000), glaciology (Mohr & Madsen, 1997), ecology (Dixon, 1995; Ludwig et al., 2000), volcanology (Massonnet et al., 1995, Salvi et al., 2004), subsidence (Ferretti et al., 2000), and slow-landslide detection (Ferretti et al., 2001; Hilley et al., 2004). Despite the wide range of applications, the interferometry still hasn't reached its full operational stage, either due to the lack of data processing standards, due to the complex software or because of the difficulties in combining interferograms. Since the PSInSAR technique is a relatively young method, which is only gaining its recognition among a wider user domain, its application is still very limited.

This paper will in short present the theoretical background of interferometry, the differential interferogram analyses and the permanent scatterer technique. The results of the DInSAR and PSInSAR analyses in the upper Soča valley in north-western Slovenia will be compared and evaluated.

Study area and data used

The study area was defined as an intersection of DInSAR and PSInSAR data acquisition range (Fig. 1). The north-western part of Slovenia was chosen as the study area due to its neotectonic activity (Poljak et al., 2000; Zupančič et al., 2001; Grenerczy et al., 2005) and due to a number of landslide, rockfall and debris flow occurrences (Komac et al., 2005). Prior to the PSInSAR data acquisition in the NW part of Slovenia, the DInSAR analyses were conducted in the Bovec basin in order to analyse the influence of radar interferogram combination on digital elevation and movement accuracy (Oštir, 2000).

For the DInSAR analyses of surface deformations, related to the earthquake of 12th April 1998 in the Soča valley area, three ERS-2 satellite images were used. Images were acquired before and after the earthquake. The digital elevation model of the area was calculated from two images, taken before the event in the so-called tandem acquisition where satellites ERS-1 and ERS-2 acquired images with a 24-h delay. One day difference in image acquisition enables good coherence between images. The description of images used for the DInSAR analyses is shown in Table 1.

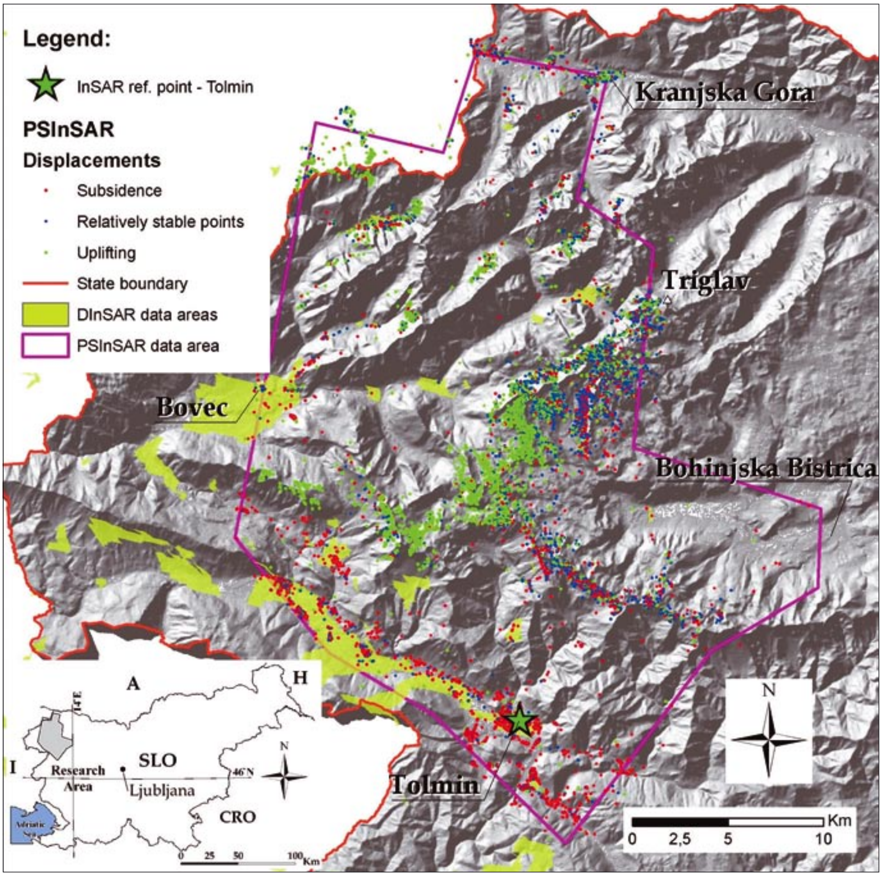

Fig. 1.
The study area is located in the NW part of Slovenia.

Slika 1.
Obravnavano območje se nahaja v SZ delu Slovenije.

Table 1. Description of images used for the DInSAR analyses of the study area

Satellite	*Orbit*	*Path*	*Frame*	*Date*	*Time*	*Use*
ERS-2	15235	351	2673	20.3.1998	9:56	deformations
ERS-2	15736	351	2673	24.4.1998	9:56	deformations
ERS-2	16237	351	2673	29.5.1998	9:56	deformations
ERS-1	24888	351	2673	18.4.1996	9:56	elevations
ERS-2	5215	351	2673	19.4.1996	9:56	elevations

As a part of Interreg III B project Climate Change, Impacts and Adaptation Strategies in the Alpine Space (ClimChAlp) permanent scatterers in the north-western part of Slovenia, between Tolmin in the south and Kranjska Gora in the north, were analysed. The area extends over 700 km^2. The primary goal of the research was to determine the slope mass movements using PSInSAR technique and at the same time to determine the use of this method for other geologically based applications. For this purpose 57 images from the descending orbits of ERS-1 and ERS-2 satellites were used. Images were acquired in the period between April 21st 1992 and December 29th 2000. As the reference image, the image taken on September 26th 1997 was selected. Based on the preliminary data analyses and geological prospection for the reference point (stable or a "zero" displacement point), the location near the town of Tolmin was chosen. The location of the reference point is 46°11´3.44´´N, 13°44´45.12´´E, the velocity of the point – 0.13 mm/year and the overall coherence 0.84. The average density of permanent scatterers is 23 per square kilometre, and the minimum density required for analysis is 15 per square kilometre. Average displacements in the line of sight were determined for the whole population of targets with a coherence higher than 0.5. Altogether 16304 permanent scatterers were used. For approximately ten most reliable percent of the population (1646 PS with a coherence higher than 0.74) the displacement data of all 57 acquisitions were calculated. For these targets, time series of displacements from 1992 to 1994 and again from 1995 to 2000 was derived.

Methodology

Radar interferometry

Radar interferometry is a technique that has been successfully applied in different fields. The Earth's topography can be observed with interferometry by using two approaches, with either one or two passes (overflights). In the first approach emission and reception antennas are placed on the same platform (airplane or satellite), while in the second approach, which is usually used in satellite acquisition, the same or identical platform overflies the same area with a time lag from slightly shifted orbits (Oštir, 2000, 2006). All equations are taken from Oštir (2000).

In Fig. 2 the two radar antennas, located in points O_1 and O_2, simultaneously observe the surface. Vector $\vec{B}$ is called baseline has a distance B, which represents the distance between the radar antennas, is inclined at angle ξ in respect to the horizontal plane. The first antenna (O_1) is located at elevation H above the selected reference plane (h = 0). The distance between the antenna O_1 and the observed surface is defined by r, while the distance between the antenna O_2 and the same point on the observed surface is defined by $r + d$. The phase of the backscattered wave is:

$$\phi_i = \frac{2\pi}{\lambda}(r_{ti} + r_{ri}) = \phi_{ti} + \phi_{ri}, \qquad \text{Eq. 1}$$

where φ represents phase, indexes t and r represent emission and reception. The interferogram of the images with a common emitter represents only the reception part of the phase since the distance from the emitting antenna to the target is the same for both receptors. This is due to the same location of emitting source and hence the difference is equal to zero. In the described case one antenna emits and receives the radar signal and the other only receives the signal. Both antennas are placed on the same platform, plane, space shuttle or satellite. A different situation occurs when there are two emitters located on the same platform or when the same antenna system images the same area twice. In this case the interferogram represents the difference of two distances between the antenna and the target.

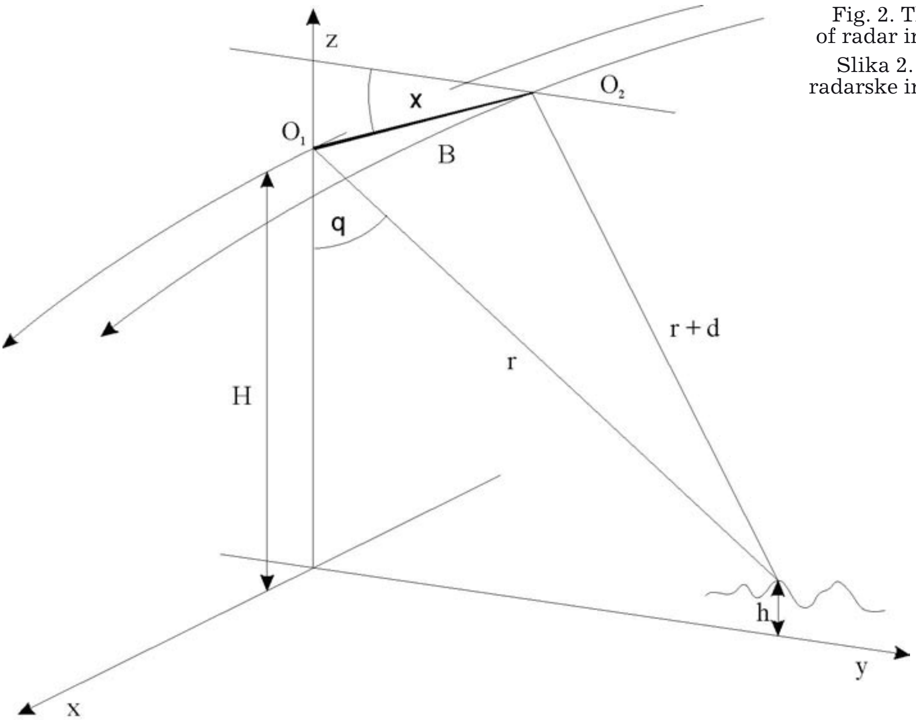

Fig. 2. The geometry of radar interferometry.

Slika 2. Geometrija radarske interferometije.

The interferogram is derived through an exact coregistration of images and through a complex multiplication of pixel values from the first image with the conjugated pixel values of the second image. The phase difference is defined as:

$$\phi = \phi_1 - \phi_2 = \frac{2\pi p}{\lambda}\delta, \qquad \text{Eq. 2}$$

$$\delta = \frac{\lambda \phi}{2\pi p}, \qquad \text{Eq. 3}$$

where p stands for the number of emitting antennas ($p = 1$ for one source and $p = 2$ for two sources/antennas). The phase that is shown on the interferogram is a modulus of absolute phase. The procedure of defining the absolute phase φ from the measured phase φ_M is called phase unwrapping.

The phase difference between both signals depends upon the geometry of observation and upon the height (h) of the target above the reference plane ($h = 0$). Considering the fact that observation geometry can be influenced or defined with adequate accuracy, the elevation of targets $h(x,y)$ can be determined. The achieved accuracy can be in the range of several metres, with the precondition of phase uncertainty elimination.

From Fig. 2 the following two rules can be concluded:

$$h = H - r\cos\theta, \text{ and} \qquad \text{Eq. 4}$$

$$y = r\sin\theta, \qquad \text{Eq. 5}$$

where θ represents the incidence angle of the radar signal to the Earth's surface and hence the angle of observation. From Eq. 2, 3 and 4 the desired elevation of the target or the surface can be derived:

$$h(y,\phi) = H - y \times ctg\left(\xi - \arcsin\left(\frac{\lambda\phi}{2\pi pB}\right)\right). \qquad \text{Eq. 6}$$

Elevations derived from radar interferometry represent the average elevation of the pixel (or the basic resolution element) in the image. Usually the size of the pixel is ten or several tens of metres. With the ERS satellite data the resolution achieved can reach between 20 and 25 metres.

Displacement observation using DInSAR

What happens with interferograms if deformations of the surface occur between two acquisitions? Is it still possible to define the topography of the surface? The answer to these questions depends upon the dimension of the difference or deformation. If the relative position of scatterers within a pixel changes for more than the wavelength of used radar signal, the measurements can't be conducted. In that case the phase correlation is lost and the comparison of images or production of topography is impossible. The only information available is that differences are greater than the wavelength, not even knowing in which direction they occurred.

The differences of two elevation models which were calculated one from the image-pair acquired before and the other from the image-pair after the event (i.e. earthquake, subsidence…) can be used to determine surface deformation. The accuracy of such surface deformation model is identical to the accuracy of primary elevation models. In case of ERS satellites the accuracy would be several metres (Oštir, 2000; Hanssen & Ferretti, 2002; Hanssen, 2005).

Deformations can also be observed when the displacements on the surface are coherent and spread over several neighbouring pixels. In this situation the user assumes that the scatterers' locations within a pixel haven't changed, while the whole area of pixel and its neighbours has shifted upwards, downwards or to the side. In this case the phase comparison of images can be conducted. The so-called differential phase contains the information on the change in the direction of the observation or in the line-of-sight (LOS).

The displacement measurement accuracy that can be achieved with differential interferometry is in the range of less than the radar signal wavelength. Usually the dimensions vary from several millimetres to several centimetres. With systems ERS-1 and ERS-2 that have the wavelength of λ = 5.6 cm measurement accuracy of half a centimetre can be achieved (Oštir, 2000). The high accuracy is the consequence of observing the difference of interferograms and not the actual elevation models or their changes. This enables the highly accurate target motion detection. To achieve such high accuracy of motion detection, a good knowledge about topography and the position and direction of the antennas is necessary.

Phase difference measurements based on two successive radar images enable the definition of only one component of the movement vector in space, in the sensor-target direction (LOS). Only one-dimension measurements are a substantial drawback of this technique, while the big advantage is the possibility of spatial coverage of the observed area. Combining the radar data from ascending and descending orbits in analyses would enable the definition of two components of movement, which is usually sufficient for analyses.

Motion measurements with radar interferometry depend upon the nature of the motion. There are two basic conditions for satisfactory results (Oštir, 2000):

- Changes during the acquisition of images must not be too big. This applies especially to their gradient, which should not be too big within a pixel.
- Radar scattering within a pixel at the time of acquisition must be as equal as possible. More precisely, the position of emitters within the observed resolution cell should not change more than 20% of the wavelength of the used microwave radiation.

The first condition is generally not a major problem. If large changes occurred during image acquisition – e.g. due to a volcano outburst or a destructive earthquake – the elevation model before and after the event is simply subtracted. In this way changes within the range of several metres can be detected. Of course the production of a precise elevation model before and after the observed event may present a limitation of the described method.

The second condition is considerably more problematic. When it is not fulfilled, we speak about *time decorrelation*. Time decorrelation is one of major problems in the use of radar interferometry, because it renders difficult or even impossible comparison of two phases of radar images. Decorrelation – partial or complete – can be observed in images obtained at a few hours' intervals on areas covered with vegetation and exposed to wind. On the other hand a good phase correlation can be achieved even among images taken several months or even years apart. The condition for a high correlation between images is the observation of the surface which is not covered with vegetation, e.g. desert or urban areas. In general bare areas are more adequate than vegetated, dry areas are better than wet and radars with a larger wavelength are more appropriate than those with smaller. The difficulties with decorrelation can be solved by permanent scatterers technique, which takes into account only those areas (points) which are coherent (i.e. phase stable).

In order to understand differential interferometry we can imagine two radar antennas observing the Earth's surface at different time intervals (Oštir, 2000; Hanssen, 2005; Hanssen & Ferretti, 2002). This is the so called *repeat pass interferometry.* The phase of an individual pixel in the radar image is equal to the sum of the *travelling part* (contribution due to the double path between the satellite and the observed area) and the *radiation part* (due to the interaction between the radar wavemotion and the ground). In case that the surface properties have not changed between image acquisitions, the radiation part may be removed by subtracting the phases of two images. Only the part remains that is directly related to the geometry of observation.

If the approximation of parallel signals is again taken into account, the following equation is obtained

$$\delta = B\sin(\xi-\theta) = B_{\|}. \qquad \text{Eq. 7}$$

Here $B_{\|}$ is a component of the baseline in the radar signal movement direction. If it is assumed that there is another interferometric pair where one of the images is equal to the image in the first interferogram. In this case r and θ remain unchanged, thus enabling the comparison of phases of individual pixels. The other interferogram has a different baseline B' and its orientation ξ'. If the equations are combined, the result for an interferogram pair is

$$\phi = \frac{4\pi}{\lambda}B_{\|}, \qquad \phi' = \frac{4\pi}{\lambda}B'_{\|}. \qquad \text{Eq. 8}$$

The relation between phases of the first and the second interferogram depends only on the relation of the parallel components of the baseline and is completely independent of topography, because the wavelength is the same in all image acquisitions.

Let us change observation conditions by including the Earth's surface movements due to an earthquake or volcanic activity and assume that there are three images, two of which were created prior to "the event" and one after it. The movements should be of the type where several resolution elements moved in correlation, meaning that radar reflections are of the same type. In this case, due to the surface topography, in the observed phase also an additional phase change because of the movement Δ in the direction of radar signal movement has to be taken into account (Fig. 3). In this case the phase of the second interferogram is

$$\phi' = \phi_1' - \phi_2' = \frac{4\pi}{\lambda}(\delta' + \Delta) = \frac{4\pi}{\lambda}\left(B\sin(\xi-\theta)+\Delta\right) = \frac{4\pi}{\lambda}\left(B_{\|}'+\Delta\right). \qquad \text{Eq. 9}$$

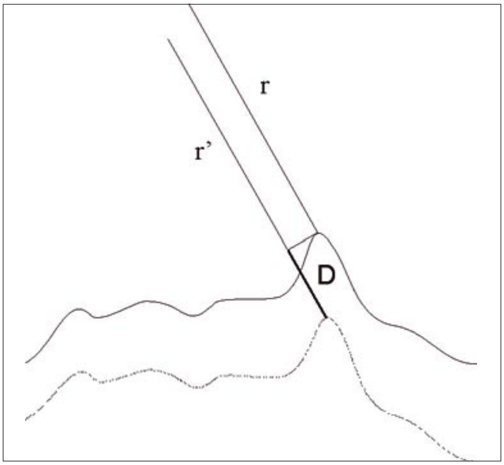

Fig. 3. Geometry in differential radar interferometry

Slika 3. Geometrija diferencialne radarske interferometrije.

According to the equation the surface movement has to be added to the topography part, resulting in an additional element in analyses. Fortunately the contribution of topography can be removed by subtracting the correctly weighted first interferogram, so that only the part depending on the movements of surface Δ remains. This can be expressed as

$$\Delta = \frac{\lambda}{4\pi}\left(\phi' - \frac{B_{\|}'}{B_{\|}}\phi\right). \qquad \text{Eq. 10}$$

The movements are determined only by phases φ and φ' of individual interferograms. Differential interferometry thus enables the measuring of small movements in the direction of radar look angle for each point of the differential interferogram.

The relation of baselines is a function of the look angle θ, which is dependent as well from the geometry of the radar system as also from the topography of the observed surface in each point of radar image. In order to determine the movements, a model of elevations has to be either constructed from one interferometric pair or it has to be obtained from another source.

Precision of interferometry

A radar interferogram phase is, as has been illustrated, dependent to topography and to the movements which occurred during image acquisition. The sensitivity of phase measurements to topography and movements is calculated by differentiation of the equation for the phase by h elevation and Δ (movements). The relation $h = H - r\cos\theta$ is taken into account and derived first by elevations and then by movements.

$$\frac{\partial\phi'}{\partial h} = \frac{\partial\phi'}{\partial\theta}\frac{\partial\theta}{\partial h} = \frac{4\pi\cos(\xi'-\theta)}{\lambda\sin\theta}\frac{B'}{r}, \qquad \text{Eq. 11}$$
$$\frac{\partial\phi'}{\partial\Delta} = \frac{4\pi}{\lambda}.$$

Since the baseline B is much smaller than the slanting distance r, phase difference is much more sensitive to surface movements than to changes in elevation. Radar interferometry enables the measuring of absolute elevation within some metres' accuracy, while movements can be determined with the precision of one centimetre or even millimetre. Satellite ERS, orbiting at the elevation H = 770 km and facing the Earth's surface at an average angle θ = 23° with the wavelength λ = 5.6 cm, has at a baseline B' = 300 m and the signal-noise relation SNR = 10 dB and phase error σ_φ = 0.6, an elevation error σ_h = 3.3 m. Under the same circumstances the inaccuracy of movement measurements σ_Δ is 2.8 mm, which is more than a thousand times more precise (Oštir, 2000).

A higher precision in the detection of vertical movements is achieved by repeated observations and averaging of pixels, and also by decreasing the baseline, thus decreasing the system noise. The size of movements which can be detected by differential interferometry is strongly influenced also by the wavelength of the sensor. One colour circle on the interferogram corresponds to the change of one half of the wavelength. Due to the relatively short wavelength (λ = 5.6 cm) satellites ERS are almost ideal for movement observation.

Differential interferometry has two very important limitations (Oštir, 2000; Hanssen & Ferretti, 2002). The reflected radar radiation of all three images must be in correlation – there must be no time decorrelation. The second, more important limitation is that interferogram phases have to be developed prior to their comparison. Only then can the second interferogram be used to detect small changes in the surface. This problem may well be solved by having a digital elevation model and by having sufficient knowledge of recording geometry. However, in this case a differential interferogram is obtained, for which later a phase must be unwrapped in order to be able to determine absolute movements. Therefore the movements of at least a few points on the Earth's surface have to be known.

Processing procedure

The procedure of interferometric processing is in spite of the more or less explicit theoretical basis relatively complex. It can roughly be divided into some basic steps, which are schematically illustrated on the next page (Fig. 4; Oštir, 2000):

- selection of image pairs,
- co-registration of images,
- preparation of the external digital elevation model[1],
- interferogram generation,
- interferogram enhancement,
- phase unwrapping,
- production of a digital elevation and movement model, and
- geocoding.

Interferometry is very sensitive to input parameters and used algorithms. The fact is that the quality of results is influenced by each individual step. While today's hardware equipment is efficient enough for processing, software still presents a major problem, since it is limited in algorithm capacity, in speed optimization, and in memory demands.

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[1] The extrenal digital elevation model is used in two ways in interferrometric processing. The first one is the increased precision of the produced height models, because the knowledge of the rough form of the surface reduces the interferogram's complexity and facilitates phase development. In differential interferometry the extrenal elevation model makes redundant the need for three images and enables the detection of differences already from two images.

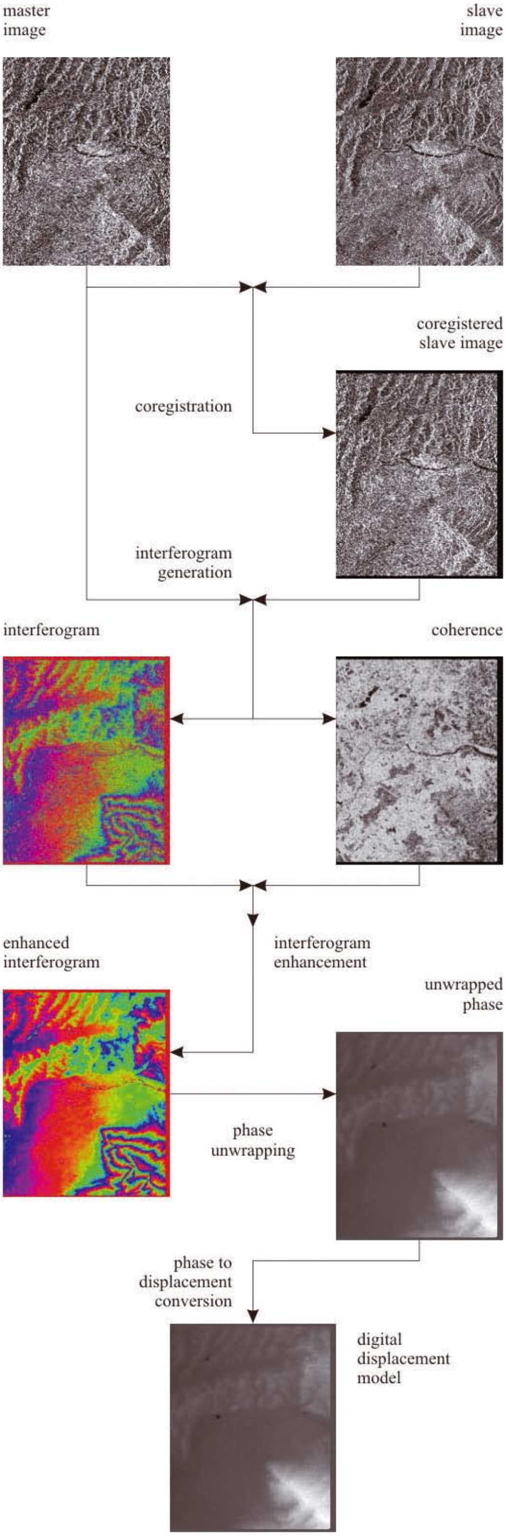

Fig. 4. The procedure of interferometric processing (Oštir, 2000).

Slika 4. Potek interferometrične obdelave podob (Oštir, 2000).

Displacement observation using PSInSAR

Also the differential InSAR method has its limitations such as changes in the reflection of objects or areas, atmospheric influences, and signal disturbances. A statistical minimization of these disturbances can be achieved by using radar data over a longer period and by determining coherent radar targets – permanent scatterers. This method is named Permanent Scatter Interferometric Synthetic Aperture Radar or PSInSAR. Fig. 5 shows the basic principles of InSAR permanent scatterer functioning.

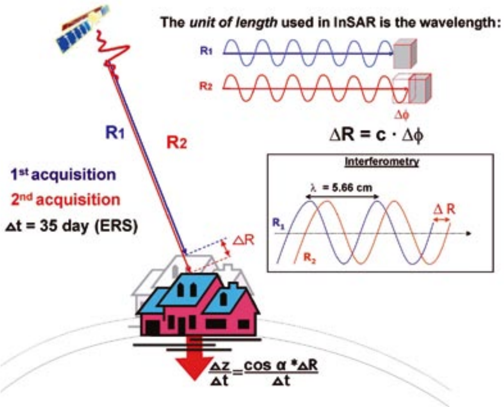

Fig. 5. Basic principle of PSInSAR (Premanent Scatterer Interferometric Side Aperture Radar) functioning (after Ferretti & Crespa, 2006).

Slika 5. Osnovni principi delovanja PSInSAR metode (po Ferretti & Crespa, 2006).

Satellites (ERS-1 in ERS-2) providing images that are the main source for PSInSAR (Permanent Scatter InSAR) have an orbit cycle of 35 days. Movements (Δ) in the line of sight which are during this time smaller than half of the wavelength used (5.6 cm), can be registered on the basis of wave difference ($\Delta\varphi$) of the backscattered signal.

The methodology can be used to register surface changes, i.e. subsidence or elevation of the surface, with the emphasis on movements in the direction of emitted signals (Δ). The registration of relative changes in surface elevations is interesting for numerous areas. Land subsidences can be an indicator of a subsiding area due to mining or surface exploitation, groundwater pumping, landsliding, subsidence due to ground consolidation after construction and similar. The results are most applicable also in the analysis of tectonic movements of the Earth's crust. The method is still in the phase of application development, therefore the span of its applications is actually undefined.

Similarly as differential GPS measurements, all PS measurements are based on the measuring of changes in relation to the reference radar target. This property or condition has impact on the precision of InSAR measurements. Precision is determined by several factors such as: the number of images used, the density of permanent scatterers, atmospheric conditions in the time of recordings, the distance of the measured location from the reference point etc. By averaging the InSAR data over a longer period and by the definition of coherent radar targets – permanent scatterers – the above mentioned disturbances can be reduced to a minimum. The measurements of changes of surface (or observed objects) with the PSInSAR method are very precise, since the measurements of movements in the direction of signal travelling can reach a yearly accuracy of under one millimetre. Table 2 gives descriptions of usual measurement quality values for a location at less than 2 km distance from the reference point.

Table 2. Usual measurement quality values for a location at less than 2 km distance from the reference point (according to Ferretti & Crespa, 2006)

Location	E–W	N–S	Vertical
Precision (1s)	**6 m**	**3 m**	**2 m**

LOS* error	Average error	Single measurement
Precision (1s)	**0.5 mm/year**	**3 mm**

*LOS – Line Of Sight

Advantages and limitations of the PSInSAR technology

Like any other measuring technology, also the PSInSAR technology has its advantages and limitations (Table 3). The PSInSAR technology can be due to its precision of measurements in the vertical direction very useful as a supplementary method to classic approaches such as GPS, which is very precise in the horizontal direction. In addition to its precision in the vertical direction, the advantages of the PSInSAR methodology are also a high spatial density of data or measurements and periodic (monthly) repetition of measurements for the entire observed area. Due to the quality of data this technology can serve also as an aid in the optimization of GPS station locations. The advantages of GPS methodologies are precise measurement in the horizontal direction and very dense time measurements, while their limitation is a very low spatial density of measurements. The two methods thus supplement each other like two items in the complex of observations of the Earth's surface. Together they enable the elimination of systematic errors in PS measurements and the observation of three-dimensional movements.

Table 3. Advantages and limitations of the PSInSAR technology (Ferretti & Crespa, 2006)

Advantages	Limitations
Regular and financially acceptable measurements of larger areas	Vegetated areas disable the use of PSInSAR
High density of PS (up to 1.000 PS/km^2)	Inapplicability on continous surfaces
Fast data processing / little need for inclusion of end user	Time measurements are limited with the satellites' orbiting intervals
High accuracy	Detection of slow deformations (< 10 cm/year in the LOS direction)
Simple export into GIS	

As it has been mentioned, the application areas of PSInSAR technology are still in the development phase. In geology and related sciences this technology can be applied in the observation of surface subsidence due to excavations or surface mining or due to resource exploitation (oil, gas and water), for the detection and monitoring of landslides. It can be used to detect tectonic activities of the observed area, and also to monitor the movement of individual objects (buildings, bridges, dams, long-distance mains...).

Comparison of DInSAR and PSInSAR

The biggest limitation of the "classic" differential radar interferometry (DInSAR) in the observation of surface movements is the loss of coherence that is of phase relation between recordings (Ferretti et al., 2001; Ferretti & Crespa, 2006). This presents a problem especially in areas covered with vegetation and where surface diversity causes the appearance of shadows. In the observed area of western Slovenia observation is practically impossible due to temporal and geometric decorrelation. Poor coherence completely disables the observation already during successive recordings. Fig. 6 illustrates that it is possible to obtain observations in several temporal spans only for smaller parts of unconnected surface.

The problem can be sucessful overcome by a special processing technology, where only Permanent Scatterers InSAR or PSInSAR are observed. The PSInSAR technology functions with the same procedure as "classic" InSAR, only it does not observe the entire surface, but only individual objects called *permanent scatterers* (Ferretti et al., 2001, 2005). Permanent scatterers are objects which can be recognized on satellite radar recordings and are coherent over a longer period of time. In other words this means that their properties practically do not change. The technology of permanent scatterer detection was developed at Politecnica in Milan, and it is applied by their "spin-off" company Tele-Rilevamento Europa. The process was protected by the European patent »Process for Radar Mea-

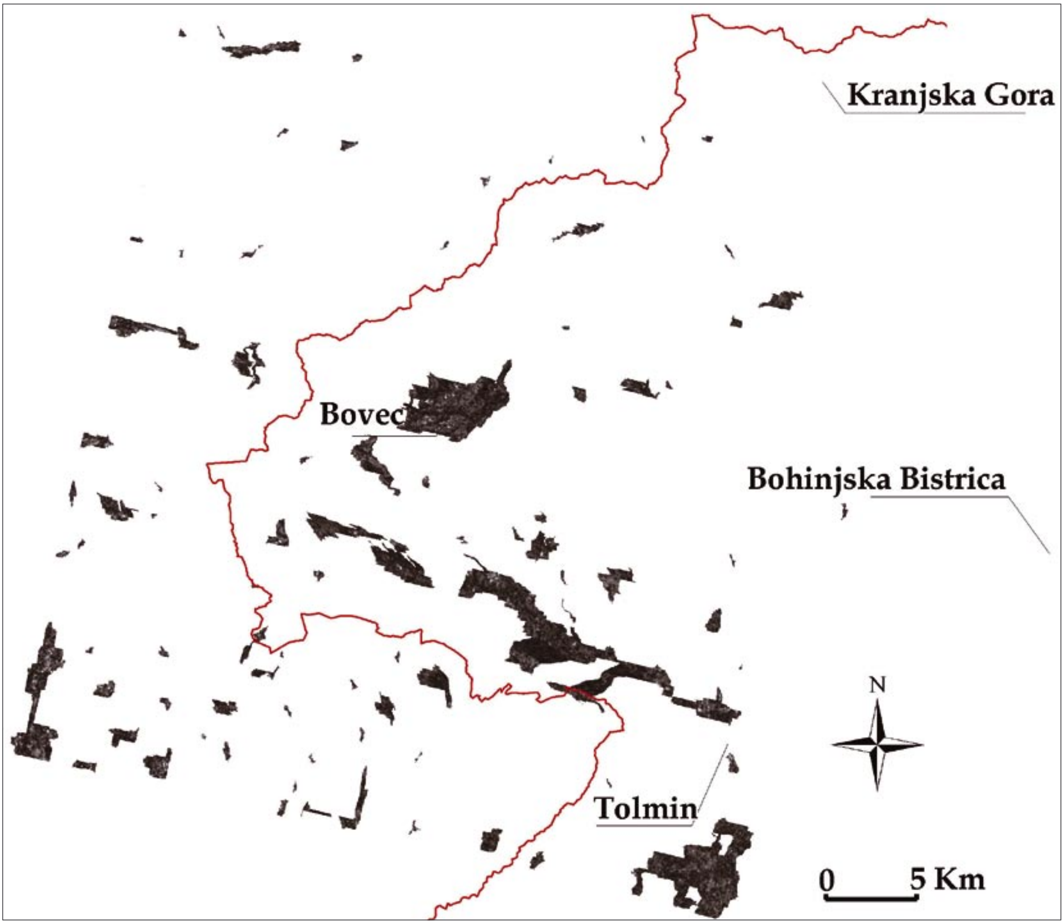

Fig. 6. Areas with the degree of coherence that enables phase development. Different shades of grey denote areas which are "interferometrically stable", meaning that they can be observed differentially.

Slika 6. Območja z različno stopnjo koherence, ki omogoča razvoj faze. "Interferometrično stabilna" območja so prikazana z različnimi odtenki sive in določajo površine, ki jih je možno opazovati z metodo diferencialne interferometrije.

surement of the Movement of City Area and Landsliding Zones« (Nr. 1,183,551 granted in 2004).

The PSInSAR technology gives the best results in urban areas and in areas with bare rocks, and overall where it is possible to identify objects the reflection of which does not change with time (Ferretti et al., 2001; Dixon et al., 2006; Bürgmann et al., 2006). Due to the wavelength of the emitted signal this methodology is useful for movements that are smaller than the wavelength of emission in the period between two acquisitions in the signal travelling direction. With ERS satellites, the images of which are most frequently used, this value is approximately 5 cm in the period of 35 days. The movements are actually determined relatively with regard to the reference point within the observed area. As a rule, this is a well measured geodetic point which is estimated not to be subject to major movements.

Permanent scatterers can be natural, e.g. rock outcrops, or artificial, such as buildings, bridges, dams, antennas, and similar objects (Ferretti et al., 2001). Also intentionally constructed scatterers may be used, like simple metallic plates or rectangular reflectors constructed from three rectangular plates (Fig. 8). The PSInSAR technology analyses an area of several thousand square kilometres and by the searching of scatterers creates a sort of "natural geodetic network", by which surface deformations and stability of certain objects can be determined. The technology enables the determination of the scatterers' geographical coordinates, usually the geographical latitude and longitude in the WGS 84 reference system, and the degree of movements within the precision

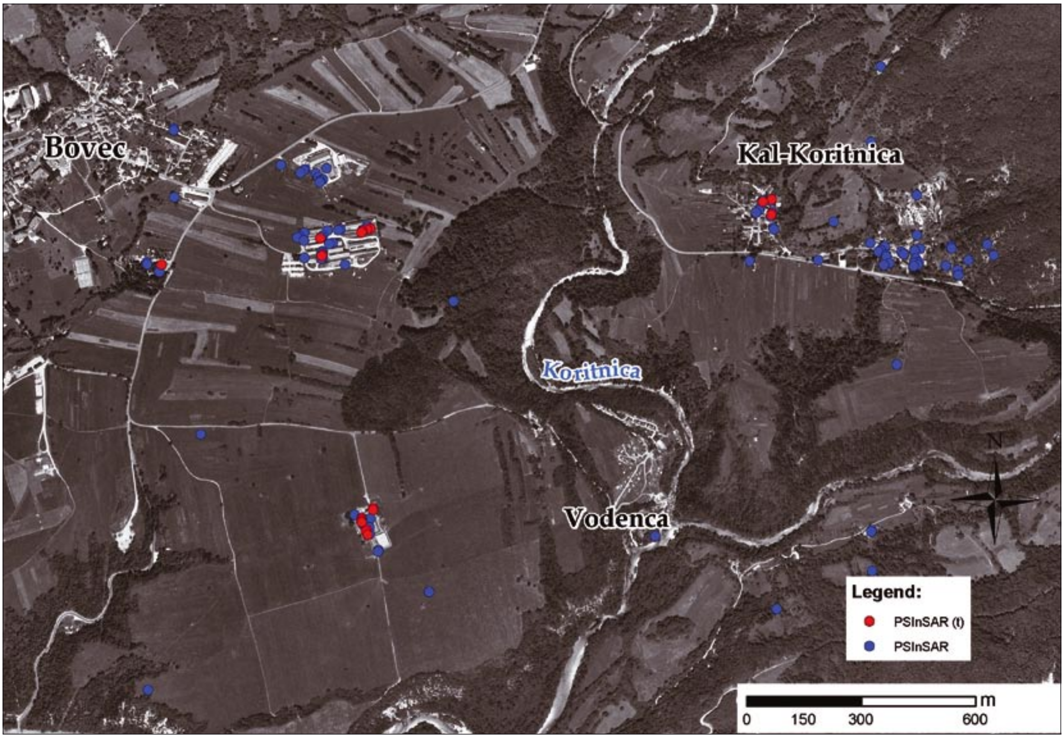

Fig. 7. Permanent scatterers are mostly found on artificial objects, rarely also on rocks or on bare ground. Red points represent PS where temporal displacements are available (PSInSAR(t)), and blue points represent all PS in the area (PSInSAR). Example is from the Bovec basin. The background of the image is a digital orthophoto in the scale 1 : 5.000 (source: DOF 5, 1999–2004, © Geodetska uprava Republike Slovenije).

Slika 7. Najpogosteje se kot permanentni sipalci pojavljajo umetni objekti, redkeje pa tudi izdanki kamnin ali gola tla. Z rdečo barvo so označeni PS s časovnim nizom premikov (PSInSAR(t)), z modro pa so označeni vsi PS na predstavljenem območju (PSInSAR). Predstavljeno območje se nahaja v Bovški kotlini. Podoba v podlagi je digitalni ortofoto v merilu 1 : 5.000 (vir: DOF 5, 1999–2004, © Geodetska uprava Republike Slovenije).

Fig. 8.
Artificial rectangular permanent scatterer (TRE, 2006).

Slika 8.
Umetna permanentna sipalca (TRE, 2006).

of 0.1 mm/year, depending on the quantity of acquisitions used and the density of permanent scatterers. It is possible to observe the "history" of movements of an individual scatterer with the precision of about 1mm for each movement (Ferretti et al., 2001, 2005).

The measurements acquire an added value if they are included in the geographical information system (GIS) and correlated with other data. The major disadvantage of PSInSAR compared to DInSAR is measurement discontinuity, since points are dealt with in the first case and planes in the second. On the other hand, measurements with usual differential interferometry over a longer period of time are mostly not possible due to decorrelation. Moreover, PSInSAR technology is considerably more precise; it eliminates undesired atmospheric influences and is less sensitive to the geometry of image acquisition. PSInSAR needs between 15 and 20 acquisitions for a successful result, while DInSAR requires only 2 (Ferretti et al., 2001).

Results and discussion

Analysis of observation of western Slovenia with DInSAR technology

In the study, the DInSAR technology was used in the area of western Slovenia to observe coseismic movements at the Posočje earthquake event. The area was on 12th April 1988 at 12:55 local time struck with one of the strongest earthquakes with the epicentre in Slovenia in the 20th century. The earthquake occurred in the Krn mountain range, at coordinates 45.309° N and 13.632° E at a depth of 7.6 km. Its local magnitude calculated from four records of the national monitoring network was MLV = 5.6. The earthquake's intensity in the wider epicentre area was VII–VIII according to the European macroseismic scale EMS-98 (Gosar et al., 1999).

The focus mechanism of the earthquake shows that the earthquake was the consequence of either a pure right displacement along the vertical fault in the NW–SE direction (Dinaric direction) or a left displacement along the fault in the NE–SW direction (transverse-Dinaric direction). On the basis of the prevailing direction of the after-earthquakes, which usually occur on the plane of the main earthquake, it was concluded that the earthquake occurred along the Dinaric fault. Morphologically the most typical fault in this direction in the Posočje area is the Ravne fault, extending from the confluence of the Soča and the Koritnica, over Lemež, by the Krn lake into the Tolminka valley and towards the Bača valley. The earthquake of 1998 in the Posočje area caused several rockfalls, but there has so far been no proof of a co-seismic movement on the surface. Due to the earthquake's magnitude and great depth of the focus it is quite possible that there was no rupture on the surface (Gosar et al., 1999).

The aim of interferometric observation of the Posočje area was to discover possible coseismic movements and surface subsidence. The selection of adequate ERS satellite images presented a significant limitation in the observation of movements, since it was very difficult to obtain useful interferograms (Oštir, 2000). The best results were obtained by using an external elevation model and combining the images acquired on 20. 3. 1998 (first image), 24. 4. 1998 (second) in 29. 5. 1998 (third) – that is before and after the earthquake.

The three elevation models enabled controled merging, yet there were substantial difficulties with interferogram processing due to the "non-ideal" season. The third image was taken at the end of May when vegetation is already well developed, while the first two were made before the period of intensive growth. Coherence of the first interferogram (I_{12}) is in spite of terrain diversity rather high, while it is very low in the other two (I_{13} in I_{23}) (Fig. 9; Oštir, 2000).

The final movement model was constructed by means of controled combination technology, where the first interferogram brought a major contribution in the weighted average (Fig.10). The result of merging shows small vertical ground movements for the Posočje earthquake, registered in the Bovec basin. Radar interferometry allows the conclusion that the surface on the southern side of the Soča is relatively stable, since approximately 1-cm movements can only be observed in the vicinity of Čezsoča. Quite more dynamic is the area to the north of the river, where beside some "stable" areas, especially around the sports aerodrome, also areas with substantial movements can be observed. The largest movements recorded have the size of over 2 cm and they can be observed in parts of Bovec, in the vicinity of Kaninska vas, in Rakovnica and south-west of the aerodrome (in Brezje). The largest movement where probably also landslides and subsidence oc-

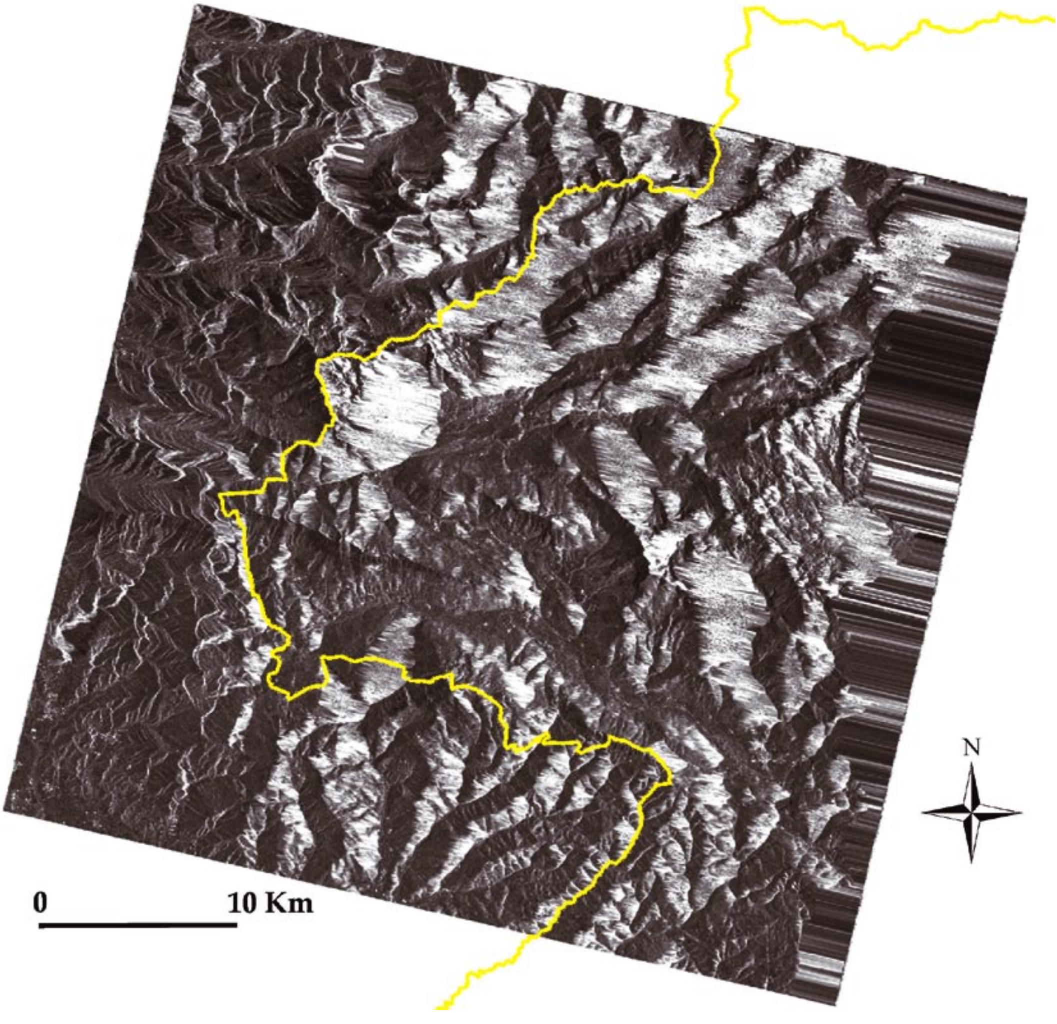

Fig. 9. Radar satellite recording of western Slovenia. Geometric anomalies may be observed, which hinder interferometric processing.

Slika 9. Satelitski radarski posnetek zahodne Slovenije. Opazne geometrične anomalije otežujejo interferometrično obdelavo podob.

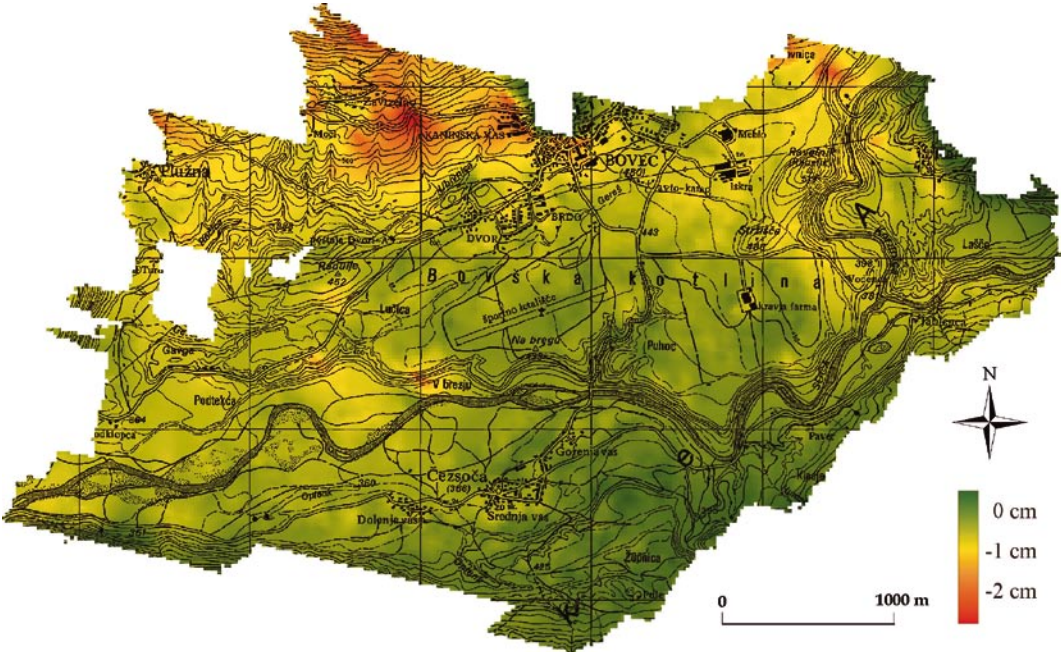

Fig. 10. Vertical movements recorded at the Bovec basin, an area struck by an earthquake on 12th April 1998. The model was produced with controlled merging of image interferograms acquired on 20. 3., 24. 4., and 29. 5. 1998. Movements obtained from the first pair contribute the most to the model, because the coherence of the other two is relatively low because of vegetation growth.

Slika 10. Vertikalni premiki, nastali ob potresu v Posočju, dne 12. 4. 1998. Model je bil izdelan po postopku nadzirane združitve interferogramov, pridobljenih 20. 3., 24. 4. in 29. 5. 1998. K podatkom modela največ prispevajo premiki, pridobljeni iz prvega interferogramskega para podob, saj je koherenca pri drugih dveh parih zaradi rasti vegetacije relativno nizka.

curred can be observed in the relatively steep part west of Kaninska vas (Zavrzelino). A better insight into the geodynamics of the earthquake area could be obtained with the analysis of a larger area, but the application of radar interferometry was not possible on the larger area of Posočje due to its rugged topography (Oštir, 2000).

Comparison to PSInSAR measurements

A direct comparison of interferometric results to "classic" geodetic measurements is not possible, because the above mentioned area was not observed in detail prior to the earthquake. However, a comprehensive analysis with the PSInSAR technology was conducted by the Geological Survey of Slovenia in cooperation with the company TRE from Milan within the project Climate Change, Impacts and Adaptation Strategies in the Alpine Space (A Programme initiative of the Community INTERREG III B – Alpine area) (Komac, 2006).

As it has been noted, the PSInSAR technology provides point measurements and enables comparison over a longer time period. For analytical requirements in western Slovenia 57 images, acquired by ERS-1 and ERS-2 satellites between 1992 and 2000, were used. The average density of permanent scatterers in the observed area is 23 scaterers/km^2, and the minimum required density for analysis is 15 scaterers/km^2. Average yearly movements were calculated for all of 16304 scatterers, i.e. points with a coherence higher than 0.5. The PSInSAR technology can be used to observe the rising of the Julian Alps region with the precision of up to 0.1 mm/year. The method is very useful in the observation of slower movements of slope masses, especially of deep landslides and of larger-scale landslide areas, of road and bridge subsidence and potentially also of smaller linear infrastructural objects. Although analyses are still going on, the first results are very promising (Komac, 2006).

A sample of temporal displacements for nine permanent scatterers with coherence higher than 0.85 that were located in the vicinity of Bovec (Fig. 11) is shown in the Fig. 12. The time frame of displacement data (Fig. 12) is spanning from pre- to post- Krn earthquake event on April 12th 1998. Average displacement values for nine selected permanent scatterers indicate constant trend of subsidence in comparison to reference point, set in Tolmin for the period from 1992 to 2000 (Fig. 13). The most obvious deviations from the trend are related to the Krn earthquake; however the displacements do not occur immediately after the earthquake, but later, in the period between April 24th and May 29th 1998, where the average subsidence for the nine permanent scatterers is – 10.46 mm. Following this subsidence, even more obvious uplift (to an average 6.85 mm) and another subsidence (to an average – 0.52 mm) occurred (Fig. 13). All displacement values are expressed relatively to the reference point. These oscillations of surface obviously indicate that the observed area subsided, uplifted and subsided again due to tectonic activity. Whether the displacement lag is a consequence of post-earthquake surface equilibration or a consequence of some other factor (i.e. data processing lag) remains unanswered. Considering the nature of displacements the most probable explanation is the post-earthquake surface equilibration.

Due to the low coherence of images used in the DInSAR analyses, the comparison of both technologies is, as already indicated in the text above, possible only in the area of Bovec and its surroundings (Fig.14), where 123 permanent scatterers occur with an average coherence of 0.62 and the highest 0.92 (minimum was 0.50). The analysis showed that 43 scatterers are rising and 80 descending, their movements ranging from approxi-

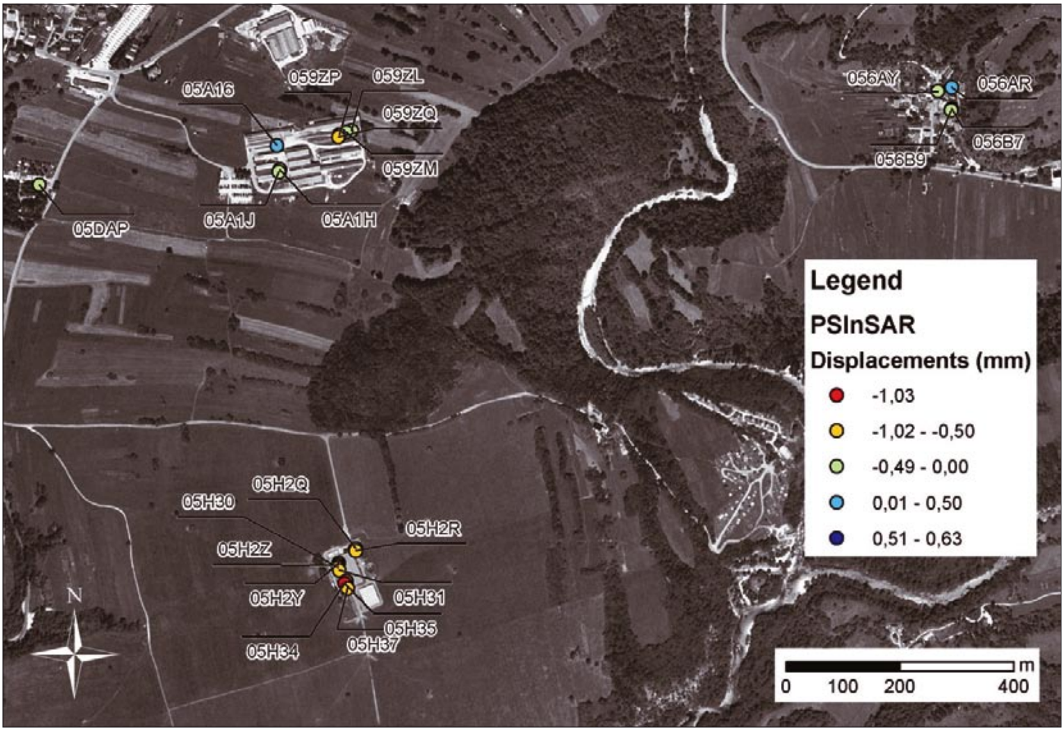

Fig. 11. Permanent scatterers in the surroundings of Bovec where temporal displacements are available. In the figure average displacememnts of permanent scatterers are shown according to their magnitude. The background of the image is a digital orthophoto in the scale 1 : 5.000 (source: DOF 5, 1999–2004, © Geodetska uprava Republike Slovenije).

Slika 11. Lokacije premanentnih sipalcev v okolici Bovca, pri katerih so dodtopni podatki o premikih skozi čas. Legenda prikazuje trende povprečnih premikov permanentnih sipalcev glede na magnitude. Podoba v podlagi je digitalni ortofoto v merilu 1 : 5.000 (vir: DOF 5, 1999–2004, © Geodetska uprava Republike Slovenije).

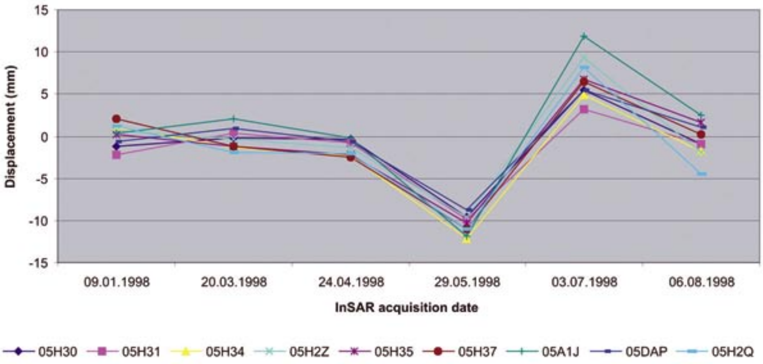

Fig. 12. Sample of temporal displacements for nine permanent scatterers with coherence higher than 0.85. PS are located east of Bovec. Note the obvious subsidence of PS only some time after the Krn earthquake that occured on April 12th 1998 (in the period between April 24th and May 29th 1998), followed by the extreme uplift and again subsidence.

Slika 12. Izsek premikov na devetih lokacijah vzhodno od Bovca s koherenco, večjo od 0,85, skozi čas. Zelo opazni so premiki (posedki) opazovanih lokacij, ki pa so se zgodili s časovnim zamikom glede na potres, ki se je zgodil 12. 4. 1998 (v obdobju med 24. 4. in 29. 5. 1998). Posedkom sledi močan dvig in nato zopet posedanje.

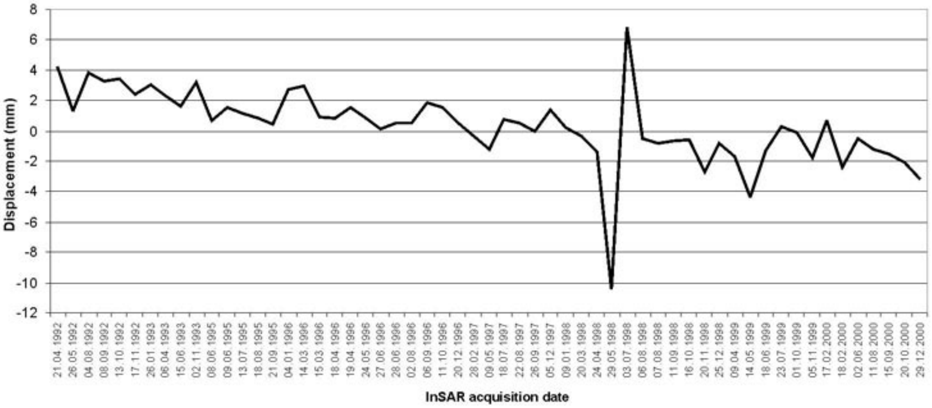

Fig. 13. Average displacements in millimetres for nine permanent scatterers from Fig. 12 relatively to the reference point. The post-earthquake surface equilibration is obvious.

Slika 13. Relativni povprečni premiki (v mm) za devet permanentnih sipalcev s slike 12 glede na referenčno točko v Tolminu. Očitno je popotresno “valovanje” površja.

mately – 9 mm to approximately 6 mm per year. It can be concluded that the Bovec basin is subsiding with an average of – 0.41 mm/year.

The DInSAR measurements cover a shorter time period, during which considerable instantenous movements occurred. The coherence of recordings is very low, averaging at only 0.25 even for the selected area, and only in rare points surpassing 0.5, which is the condition for permanent scatterer analysis. Similar to PSInSAR, also DInSAR measurements are relative, meaning that the movements have to be compared to the reference point. A more detailed analysis was performed by observing 23 permanent scatterers, mostly located in urban areas (Fig. 7, 12 and 14). The comparison of coherence shows that it is high as well in DInSAR (average 0.56) as also in PSInSAR (0.81). Both technologies provide almost exactly the same average movement amounting to – 0.50 mm in DInSAR and – 0.56 mm in PSInSAR, while the dispersion is slightly bigger in PSInSAR (standard deviation is 1.34 mm compared to 0.66 mm in DInSAR, Fig. 15). It can be concluded that both technologies provide good measurements, while for a single event, such as an earthquake, DInSAR gives a clearer picture because of

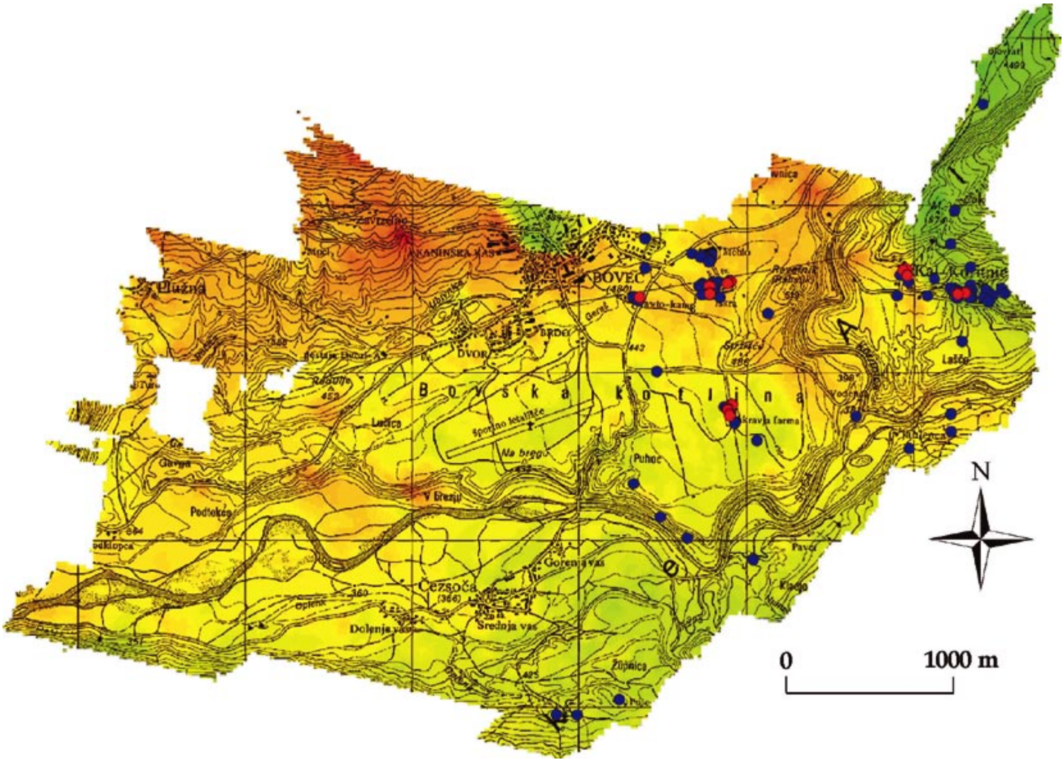

Fig. 14. The position of permanent scatterers in the DInSAR analysis. A more detailed comparison of DInSAR and PSInSAR was performed for scatterers with a known history of movements, which are shown in red.

Slika 14. Lokacije premanentnih sipalcev na kontinuiranem modelu premikov, dobljenem z DInSAR metodo. Za 23 točk z znanimi premiki skozi čas (označene z rdečo barvo) je bila izdelana primerjava med DInSAR in PSInSAR rezultati

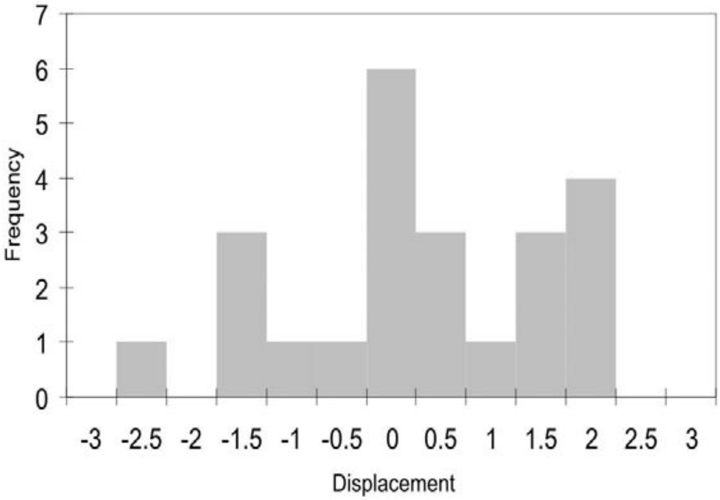

Fig. 15. Difference between displacements (in mm) defined by DInSAR and PSInSAR for 23 permanent scatterers.

Slika 15. Razlike v premikih (v mm) med DInSAR in PSInSAR metodama za 23 permanentnih sipalcev.

continuity. This is the case in spite of the fact that coherence is relatively low in the larger part.

Concluding remarks

Radar interferometry has recently become an indispensable tool in numerous studies. It can be used to construct precise elevation models and to observe very small movements of the Earth's surface. The differential method may be used to observe surface movements of the size of a part of the wavelength, which is about half a centimetre with ERS satellites. Due to the large amount of radar – satellite and airplane – systems, interferometry enables good temporal and spatial coverage, and provides precise results because of favourable microwave properties.

In the presented study, three images of the Posočje area and an external elevation model were used to create three differential interferograms. Taking into account the fact that models obtained from various interferograms are related, movements which occurred in the upper Posočje area earthquake on 12th April 1988 were determined. Interferometry showed that the vicinity of Bovec subsided by 0.5 cm on the average, while the largest movements observed exceed 2 cm.

A detailed analysis of the DInSAR technology potential was made and compared to PSInSAR. It was found out that the movements are in the same size range, but the technologies are nevertheless difficult to compare. The fact is that DInSAR gives continous results and PSInSAR gives point results, but enables observation over a longer time span. This is of importance especially in vegetated areas, where decorelation disables the use of DInSAR. PSInSAR presents an excellent alternative also to classic geodetic technologies, surpassing them in several aspects. The main advantages over the latter are a large density of measurement points, long-term observation and the possibility of observation without preliminary installation of instruments. In the study of the western part of Slovenia more than 20 points per square kilometre could be observed during a period of almost ten years and with the accuracy of a tenth of a millimetre.

The PSInSAR technology has proved extremely effective and it can be stated that it is (except for the observation of urban environment) more adequate than the classic DInSAR. Its biggest limitations are a more complicated analysis or interpretation, the need for additional spatial modelling in case a continuous model is required (where a combination with DInSAR may be of significance), and a patent protection of the processing procedure.

Data about temporal permanent scaterers elevation changes are very useful in further analyses of the impact of earthquake activity on surface movements in the research area and of the influence of seismic activity and precipitation on slope mass movements, which are the primary research objectives within the ClimChAlp project.

Acknowledgments

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