Suitability evaluation of the differential radar interferometry method for detection and deformation monitoring of landslides

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Abstract
Differential radar interferometry (D-InSAR) is a powerful remote sensing technique for detection and deformation monitoring of landslides. However, as a consequence of the radar specific imaging geometry spatial distortions, such as the layover and shadowing effect, occur in the radar image, which have a negative impact on the suitability of the radar images for D-InSAR applications. Therefore we present a GIS-routine to accurately predict the areas which will be affected by layover and shadowing, before recording the area of interest by radar. Furthermore, the measurable percentage of movement of a potential landslide can be determined. The main types of land cover are classified in regard to the applicability of the D-InSAR-technique, depending on the characteristics of the sensor used. These analyses allow stakeholders without expert knowledge of the D-InSAR-method to objectively evaluate the applicability of the D-InSAR-technique for landslides on a detailed, site specific or regional scale.

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1. Introduction

Using the active remote sensing technique differential radar interferometry (D-InSAR) it is possible to detect and measure deformation of the Earth’s crust, such as landslides, with an accuracy of a few millimeters.

But due to the obliquely downward illumination of the Earth’s surface by the air- or satellite-borne radar sensor, spatial distortions occur in the radar image. The main distortions are the so-called layover effect (an overlapping of different radar signals) and shadowing (e.g. areas behind steep mountains, which are not sampled by the radar beam). These distortions typically appear in areas with a high topographic relief (where landslides usually occur) and have a negative impact or even prohibit the use of the radar images for differential interferometric applications (Barbieri & Lichtenegger 2005, Lillesand & Kiefer 2007).

Beside these geometric distortions, the land cover has great influence on the applicability of differential radar interferometry. For D-InSAR applications areas with a high constancy of their backscattering properties are necessary. Variances on ground in the time between the two radar recordings (e.g. caused by plant growth and movements of trees due to wind) lead to changes of these backscattering properties.

As yet prior to an investigation using D-InSAR these limiting effects usually are only roughly estimated, sometimes leading to disappointing results when the actual radar images are analyzed, causing low acceptance of the D-InSAR method in practice.

This paper presents a GIS-routine which provides an objective pre-survey estimation of the potential applicability of the D-InSAR technique prior to the costly investment of a radar survey.

The GIS procedure is able to predict the areas in which layover and shadowing will occur. Furthermore, another algorithm calculates the percentage of movement of a potential landslide measurable by the D-InSAR-technique. Additionally, depending on the sensor characteristics, the main types of land cover within the footprint area are classified in terms of the applicability of the D-InSAR-technique.

2. Layover-shadow-simulation

D-InSAR-applications cannot be used in areas affected by layover and shadowing (Barbieri & Lichtenegger 2005, Lillesand & Kiefer 2007). Therefore it is important to know whether the area of interest will be affected by these disturbances or not before ordering the expensive actual radar records. The layover-shadow-simulation presented in this pa-
per precisely predicts the areas which will be affected by layover or shadow before the
area of interest is recorded by the radar sensor. Figure 1 schematically shows the program
sequence of the layover-shadow-simulation. The main part of the program comprises se-
veral GIS-models built with the model builder in ArcGIS. Additionally several Python-
Scripts and VBA-Scripts are used (e.g. for calculating the attributes of the observer points).
These observer points simulate the radar satellite. The program uses two observer points
for each pixel of the digital elevation model (DEM) of the footprint area (one observer for
layover- and one for shadow-simulation). The required input parameters – also needed for
the calculation of the measurable percentage of movement – are (1) the incidence angle:
the angle the satellite illuminates the Earth’s surface, (2) the corner coordinates of the foot-
print: ground area which is recorded by radar, (3) information about the orbit of the satel-
lite: ascending or descending pass, (4) a DEM of the footprint area and its surroundings.
In step 1 of the layover-shadow-simulation (Fig. 1) the area of the footprint is determined
by using the coordinates of its four corners. Step 2 involves defining a test area for which
the DEM is required. The size of this area depends on the topographic relief of the
footprint area and its surroundings, and the incidence angle. To reduce computing times
the optimal size of the test area is automatically calculated. Then the DEM of the test area
is rotated so its pixels are oriented parallel and its columns orthogonal to the satellite
viewing direction. The rotation is necessary for GIS-technical reasons. After that for each
pixel of the DEM (within the area of the footprint) two so-called observer points are created
(one observer for layover- and one for shadow-simulation). Then the shadow observer
points are moved towards the satellite and the layover observer points are moved in the
opposite direction by a certain distance. The moving distance depends on the same
factors as the size of the test area. Step 5 is the calculation of the attributes of the
observer points. To guarantee that each observer only monitors the pixel dedicated to it,
the visual field of the observer points has to be constricted. This is done by calculation of
the horizontal and the vertical visual field of each observer in a Python-Script. Additionally
the height of each observer is calculated. The next step of the simulation is the so-called
visibility testing: the program tests for each observer point whether it is able to ‘see’ the
pixel dedicated to it or not. A pixel is in the area of shadowing, if it cannot be seen by its
shadow observer. On the other hand, a pixel is affected by layover, if it cannot be seen by
its layover observer. The result of the simulation is presented as a map of the footprint
area which precisely predicts the areas of layover and shadowing. The last step of the
simulation is the backwards rotation of that map to the original orientation of the footprint. So each pixel again has its original geodetic coordinates.

3. Layover-shadow-simulation

3.1. Simulation with SRTM DEM

Figure 2 shows the result of the layover-shadow-simulation (based on an 80 m Shuttle Radar Topography Mission-DEM - SRTM) of the footprint “Sudelfeld” located near Bayrischzell in the southern Bavarian Alps and compares it with a real radar image. Due to the very steep view of the satellite down onto the test region (incidence angle ca. 25.8°) very strong layover, but no shadowing occurs. The orbit of the footprint “Sudelfeld” is an ascending pass (flight pass of the satellite from south to north). Therefore the illumination of the test area is from west to east. Thus layover occurs only on steep west facing slopes, which lean towards the radar sensor. Altogether the result of the simulation is 8 % layover coverage of the footprint’s area. Therefore the D-InSAR-technique is not suitable for monitoring landslides in 8 % of the area of footprint “Sudelfeld”.

Beside the geocoded High-Resolution SpotLight Mode radar image of TerraSAR-X (Fig. 2), also the so-called “Geocoded Incidence Angle Mask” (GIM) of the area of footprint “Sudelfeld” was provided by DLR. The GIM shows the layover calculated by DLR (“real” lay-
over). It is calculated by the use of a DEM and several imaging parameters (e.g. incidence angle).

The simulated layover and the “real” layover show a generally good match (Fig. 2). But a detailed look reveals that the shape of the simulated layover is much rougher than the shape of the “real” layover. Furthermore, some areas of the “real” layover had not been recognized by the simulated layover. These effects are caused by the rougher resolution of the DEM (80 m) used for the layover simulation in comparison to the DEM (21 m respectively 62 m) used for the GIM (“real” layover) calculation by DLR.

In spite of this rough resolution, the layover-shadow-simulation provides useable results for analysis on a regional scale. One gets an overview of the anticipated layover-shadow-coverage of a radar image. The big advantage of the simulation is that it can be executed at minimal cost before a radar image is taken as the underlying SRTM data is freely available (e.g. at the CGIAR Consortium for Spatial Information: http://srtm.csi.cgiar.org). In contrast the GIM (“real”) layover provided by DLR is only available after ordering a radar image.

Figure 2: Layover simulation of footprint “Sudelfeld” based on a SRTM DEM. The comparison of the simulated layover (magenta) and the real layover (yellow) shows a generally good match.
3.2. Simulation with laserscan DEM

Figure 3 shows the result of the layover-shadow-simulation of a part of the footprint “Sudelfeld” using a laserscan DEM with a resolution of 10 m. Additionally the figure again includes the GIM-Layover. In the lower middle part of the image a very good conformity of the simulated layover and the “real” layover (GIM) can be recognized. However in the right section of the picture small dispersed areas of the simulated layover occur, which do not exist in the “real” layover. This effect is caused by the considerably higher resolution of the DEM used for the simulation (10 m laserscan) in comparison to the DEM used for the calculation of the GIM by DLR. Due to the higher resolution of the laserscan DEM, the simulated layover is more detailed and more close to reality than the GIM-Layover.

Figure 3: Layover simulation of part of the footprint “Sudelfeld” (area of laserscan) based on a 10 m DEM. The comparison of the simulated layover (blue) and the “real” layover (yellow) shows a very good match. On the left site one can see a mismatch of the “real” and the simulated layover caused by the differences between the laserscan DEM and the DEM used for the “real” layover calculation by DLR.

At the west edge of the laserscan (left side) is a large area of “real” layover (GIM) that is only partially covered by the simulated layover. This effect is caused by differences between the laserscan DEM and the DEM used for the GIM calculation by DLR. By comparing the geocoded radar image and the laserscan DEM it was ascertained that the mountain ridge at the west side of figure 3 is at different positions in both DEMs. In the radar image this mountain ridge is further to the east than in the laserscan DEM. Therefore the GIM-layover reaches farther to the east than the simulated layover (based on the more ac-
curate laserscan). As the positioning accuracy of the laserscan is considerably higher than the accuracy of the GIM DEM, the simulated layover should be more close to reality than the GIM-layover. As laserscan data is only available in some regions and mostly quite costly, the use of this high quality data is best used in single case studies.

4. **Measurable percentage of movement**

The measurable percentage of movement is the percentage of total movement of a landslide that can be captured and recorded from the satellite when using D-InSAR. The satellite is only able to detect movements occurring in the satellite’s viewing direction. The measurable percentage of movement is almost 100 % of the real movement on ground, if the orientation of the landslide’s motion is parallel to the satellite line-of sight (perpendicular to satellite orbit), or 0 %, where the motion direction of the landslide is parallel to the flight pass of the satellite (azimuth).

The basic assumption of this model is that a landslide mostly moves down slope along the steepest gradient of the slope. The model, presented in this paper, calculates the percentage of a possible movement that can be detected by the D-InSAR-technique for given imaging parameters. The measurable percentage of movement depends on the incidence angle and the orbit of the satellite. If the measurable percentage of a possible movement in a certain area is known, one can calculate the part of the real movement, which can be detected by the use of the D-InSAR-technique, before the radar image is taken. Therefore it is possible to choose the optimal orbit and incidence angle for monitoring a certain landslide. Furthermore, by using the described model, it is also possible to determine the best positions of corner reflectors to detect as much as possible from a landslide’s movement (a corner reflector sends the entire energy irradiated by the radar sensor back to the satellite).

The following steps are calculated for each pixel of the DEM within the area of the footprint by a fully automated GIS-procedure (ArcGIS-model). It separately calculates the horizontal and the vertical components of the measurable percentage of movement and then multiplies the two results.

The horizontal component of the measurable percentage of movement $x$ depends on the orbit (ascending pass or descending pass) of the satellite; more precisely on the cosine of the angle $\delta$ (angle between the viewing direction of the satellite (range) and the dip direc-
tion $\gamma$ of the slope (Fig. 4)). The angle $\delta$ depends on the slope’s dip direction $\gamma$ and the angle $\tau$ (angle between range and the E-W-axis):

Ascending Pass:

$$x_{\text{Asc}} = |\cos(\delta)| = |\cos(90^\circ - \gamma - \tau)|$$

Descending Pass:

$$x_{\text{Desc}} = |\cos(\delta)| = |\cos(90^\circ - \gamma + \tau)|$$

From the equations (1) and (2) it follows that the satellite is able to detect 100% of the real movement on the ground, if the dip direction of the slope is equal to the viewing direction of the radar sensor (range). The larger the angle $\delta$ between range and the slope’s dip direction becomes the smaller the measurable percentage of movement $x$ becomes. Where dip direction of the slope $\gamma$ is parallel to the flight pass of the satellite (azimuth), $\delta$ is equal to $90^\circ$ and the measurable percentage of movement is reduced to 0%. That means, a movement on the Earth’s surface occurring in that direction cannot be detected by the D-InSAR-technique.

Figure 4: The satellite is only able to measure movements in its viewing direction (range). The horizontal component of the measurable percentage of movement $x$ depends on $\gamma$ (the dip direction of the slope) and $\tau$ (the angle between range and the E-W-axis).

The second component – the vertical part of the measurable percentage of movement – depends on the incidence angle $\theta$ and the reduced dip of the slope $\alpha$ (based on the view-
ing direction of the satellite). Here one has to distinguish between slopes leaning towards the radar sensor and slopes that are averse to the satellite.

The reduced dip of the slope $\alpha$ (based on the viewing direction of the satellite) depends on the angle $\delta$ between the viewing direction of the satellite (range) and the dip direction $\gamma$ of the slope (Fig. 4); more precisely on the cosine of the angle $\delta$ (cf. horizontal part of the measurable percentage of movement). The reduced dip of slope $\alpha$ also depends on the real dip of slope $\rho$ (Eqn. (3)).

\[(3) \quad \alpha = \arctan[\cos(\delta) \cdot \tan(\rho)]\]

Figure 5 (left) shows the imaging geometry for slopes that are averse to the radar sensor. Thereby $x_1$ is the vertical measurable percentage of movement, B the real occurring movement and $\sigma_1$ the difference of the angle $\varphi (= 90^\circ - \theta)$ and the reduced dip of the slope $\alpha$ (based on the viewing direction of the satellite):

\[(4) \quad x_1 = \cos(\sigma_1) = \cos(\varphi - \alpha) = \cos(90^\circ - \theta - \alpha)\]

From equation (4) it can be concluded that the maximum value of the vertical measurable percentage of movement $x_1$ is achieved if $90^\circ$ minus the incidence angle $\theta$ almost match with the reduced dip of the slope $\alpha$. It is not possible to detect 100 % of the movement of a landslide, because if $\varphi$ is equal to $\alpha$ shadowing already occurs. The larger the value of $\sigma_1$ (= $\varphi - \alpha$), the smaller is the value of the vertical measurable percentage of movement.

Figure 5 (right) shows the imaging geometry for slopes leaning towards the radar sensor. Here B also represents the real occurring movement. $\sigma_2$ is the sum of the reduced dip of the slope $\alpha$ (based on the viewing direction of the satellite) and the angle $\varphi (= 90^\circ - \theta)$. The vertical measurable percentage of movement $x_2$ is calculated by equation (5).

\[(5) \quad x_2 = \cos(\sigma_2) = \cos(\varphi + \alpha) = \cos(\alpha + 90^\circ - \theta)\]

For slopes leaning towards the radar sensor, the vertical measurable percentage of movement is reduced to 0 %, if the illumination by the satellite is directly perpendicular to the slope surface ($\sigma_2 = 90^\circ$). In this case the movement cannot be detected by the satellite.
10

The vertical component of the measurable percentage of movement $x_1 / x_2$ depends on the reduced dip of slope $\alpha$ (based on the viewing direction of the satellite) and the incidence angle $\theta$. B is the real occurring movement.

The 3-dimensional measurable percentage of movement $x_{3D}$ is achieved by equation (6).

$$(6) \quad x_{3D} = x_{\text{horizontal}} \cdot x_{\text{vertical}}$$

With: $x_{\text{horizontal}} = x_{\text{Ascending}}$ resp. $x_{\text{horizontal}} = x_{\text{Descending}}$ and $x_{\text{vertical}} = x_1$ resp. $x_{\text{vertical}} = x_2$

Both parts of movement can achieve values from 0 to 1. The method described above, ensures that if one part of movement is zero, automatically the complete measurable percentage of movement (3D) becomes zero.

As the basic idea of the model is that a landslide mostly moves down slope along the steepest path of the slope, flat areas are treated in the simulation separately (here: the measurable percentage of movement is not calculated).

5. The influence of land cover for D-InSAR applications

For D-InSAR applications radar interferograms with high coherence are very important. The coherence is reduced by changes on ground between the dates of the two radar recordings. For example vegetation-free areas such as buildings, roads and rocks show a high coherence (high stability of their backscattering properties) (Lu 2007, Daito et al. 2004), whereas areas covered by vegetation, especially forests (Bamler & Hartl 1998), have varying backscattering properties at different times (due to wind). Therefore the land cover of the footprint area strongly influences the coherence. This influence also depends on the properties of the radar sensor (especially the wavelength). Therefore a classification of the main types of land cover affecting the D-InSAR-method was developed (Table 1). The classification accounts for the operational wavelength of the radar sensor and ranges in value from 1 (very suitable) to 6 (not at all suitable for D-InSAR). This
classification can be applied to all land cover data that is available for the area of the footprint. In this paper the CORINE Land Cover 2000 data was used.

Table 1: The classified main types of land cover with reference to the D-InSAR technique.

<table>
<thead>
<tr>
<th>Category</th>
<th>X-band (3.1 cm)</th>
<th>C-band (5.6 cm)</th>
<th>L-band (23 cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Continuous urban fabric</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Discontinuous urban fabric</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Roads</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Rocks</td>
<td>2</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Alluvium (debris, gravel, sand)</td>
<td>3</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Grassland</td>
<td>4</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>Forest</td>
<td>6</td>
<td>5</td>
<td>3</td>
</tr>
<tr>
<td>Farmland</td>
<td>6</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>Water surfaces</td>
<td>6</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>Glacier and perpetual snow</td>
<td>6</td>
<td>6</td>
<td>6</td>
</tr>
</tbody>
</table>

6. Conclusion

By combining the results of the layover-shadow-simulation (section 3) and the calculation of the measurable percentage of movement (section 4) with the classification of the land cover for the different bands (section 5), one can evaluate the applicability of the D-InSAR technique for each single landslide within the area of a footprint prior to commissioning a radar survey (Fig. 6). Table 2 summarizes the results of the analysis for selected landslides in the area of the footprint “Sudelfeld” and gives objective rating (from “1” = very well to, “6” = unsuitable) of the anticipated applicability of the D-InSAR method for landslide monitoring purposes. The measurable percentage of movement is not stated for fast movements (e.g. rockfall) as these cannot be monitored using D-InSAR. With this information stakeholders can easily evaluate if it is possible to use the D-InSAR method in a certain area of interest or if different conventional ground based monitoring methods are more
promising. In addition, other factors such as ground resolution, data availability (repeat orbit), atmospheric disturbances, need to be considered when deciding whether to use D-InSAR or not. By undertaking a pre-survey assessment of the expected data coverage and quality using the method presented in this paper a first pass evaluation can be performed, delineating the areas in which the D-InSAR method is appropriate. In future it is planned to include additional parameters into the analysis for more comprehensive results. Using the freely available SRTM DEMs reasonable results are archived only on a regional scale (e.g. a whole footprint). For more detailed analysis (e.g. for positioning corner reflectors on a landslide) higher quality DEMs or digital surface models DSM (including trees and buildings) should be used.

While the GIS based analysis now is semi-automated (certain processing steps still need user interaction of a GIS expert), it is planned to develop a fully automated web processing service in future, thereby providing easy access to the analysis results for widespread application.

Figure 6: Using this map one can assess whether a landslide falls within an area of layover and/or shadowing and which percentage of the real movement can be detected by the satellite, before radar recording.
Table 2: Applicability of the D-InSAR-method for a selection of the georisk objects of foot- 
print “Sudelfeld”.

<table>
<thead>
<tr>
<th>Georisk Object</th>
<th>Type of movement</th>
<th>Layover (L), Shadow (S)</th>
<th>Measurable percentage of movement [%]</th>
<th>Land cover class</th>
<th>Applicability of the D-InSAR technique*</th>
</tr>
</thead>
<tbody>
<tr>
<td>...00002</td>
<td>Slide</td>
<td>-</td>
<td>91.49</td>
<td>6</td>
<td>5</td>
</tr>
<tr>
<td>...00012</td>
<td>Slide</td>
<td>-</td>
<td>93.85</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>...00022</td>
<td>Slide L (100 %)</td>
<td>L (100 %)</td>
<td>45.25</td>
<td>6</td>
<td>5</td>
</tr>
<tr>
<td>...00032</td>
<td>Rockfall</td>
<td>-</td>
<td></td>
<td>6</td>
<td>5</td>
</tr>
<tr>
<td>...15005</td>
<td>Slide L (70 %)</td>
<td>L (70 %)</td>
<td>56.44</td>
<td>4</td>
<td>3</td>
</tr>
</tbody>
</table>

* Applicability rating: 1: all three sensors can be used (X-, C- and L-band); 2: suitable using C- and L-band sensors; 3: suitable only when using L-band and longer wavelength sensors; 4: partly layover and/or shadow coverage (only partly suitable at the chosen imaging parameters); 5: completely layover respectively shadow coverage (not suitable at the chosen imaging parameters) and/or too low measurable percentage of movement (at the chosen imaging parameters) and/or too small size of the landslide (not suitable); 6: Due to the type (velocity) of movement not suitable (e.g. rockfall) and/or covered by water or ice.

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