DIFFERENTIAL SAR INTERFEROMETRY USING AN AIRBORNE PLATFORM

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ABSTRACT

Up to now, only space-borne sensors have been used for differential interferometry. This implies several problems: Space-borne SAR data is affected by atmospheric effects, often causing great unreliability of differential interferograms. Also the loss of coherence over the long data acquisition intervals of space-borne sensors is critical. In the last time, the availability of suitable space-borne data has become a problem, too. Finally, for the very important field of catastrophe management, space-borne sensors are not flexible enough to be really helpful.

Airborne sensors overcome the problems mentioned above, but require new approaches for data processing and error correction. Based on data acquired by DLR’s experimental SAR system (E-SAR) in the interferometric repeat-pass mode, we address in this paper the realisation of airborne differential SAR interferometry. This includes particularly the correction of residual motion errors in heavily decorrelated interferograms as well as an overall experimental analysis of decorrelation behaviour in longer wavelength like L-band.

1 INTRODUCTION

Differential interferometry using space-borne sensors has become an established tool for the analysis of very small surface deformations. Its idea is to analyse the phase errors in SAR interferograms caused by surface displacements between the data takes. Generally, the interferometric phase difference between two SAR images can be expressed as:

\[
\Phi = \Phi_{\text{topo}} + \Phi_{fe} + \Phi_{\text{noise}} + \Phi_{\Delta r}
\]

with \(\Phi_{\text{topo}}\) denoting the phase contribution caused by terrain topography, \(\Phi_{fe}\) the flat earth component caused by the imaging geometry, \(\Phi_{\text{noise}}\) a noise contribution due to decorrelation effects and \(\Phi_{\Delta r}\) the differential phase caused by displacement of the scatterers between the two data takes. Differential interferometry tries to estimate \(\Phi_{\Delta r}\) by subtracting \(\Phi_{\text{topo}}\) and \(\Phi_{fe}\), either by using an external DEM or a second interferogram without differential effects. Thereby, surface displacements of fractions of the radar wavelengths [1] can be detected. A displacement of \(\lambda\) in line-of-sight direction is causing a differential phase of \(4\pi\):

\[
\Phi_{\Delta r} = \frac{4\pi}{\lambda} \Delta r
\]

This makes SAR sensors unique for many of applications like large scale detection and monitoring of ecological stress-change processes including sudden co-seismic displacements and long-term tectonic movements. Also volcanic bulging before eruptions, land subsidence in mining areas, land sliding in mountainous areas as well as ice deformations and glacier dynamics can be detected with this method.

However, there are several limitations of differential SAR interferometry. Most current space-borne sensors are operated in C-band, a relatively high frequency, in which decorrelation effects, particularly over vegetated areas, are strong. Additionally, the repeat cycles of satellites, after which the same region is imaged again, is often rather long. This usually causes a loss in coherence and precision, and can even prevent the generation of proper differential SAR interferograms. Further on, atmospheric effects are also causing differential phase contributions which cannot be easily distinguished from surface displacements.

Another problem is the incapability of space-borne sensors to react to spontaneous user needs. For example, it is possible with differential SAR interferometry to measure the displacement field generated by an earthquake [2] by using data sets before and after the incident. But often preceding short-term effects cannot be analysed because of lack of data. In this respect space-borne sensors are not the optimum for many possible applications of differential SAR interferometry.

The usage of airborne SAR sensors for differential interferometry is therefore of great interest. On one hand the usage of longer wavelengths with better coherence behaviour, like L- or P-band, offers the possibility of an analysis of long-term processes even in case of vegetated areas. On the other hand, also the capabilities for monitoring of short-term processes is improved by the greater flexibility of airborne sensors. Particularly, the combination of operationally generated space-borne interferometric SAR data with flexibly acquired airborne data seems to be very promising. The big problem of airborne sensors is that the aircraft movement is a differential effect and has to be corrected very carefully. An uncompensated motion of only half the wavelength (i.e. 12cm in L-band) is already causing a phase error of 360°, rendering the differential interferogram almost unusable.

As a first step to airborne differential SAR interferometry, this paper should illustrate the possibilities of airborne sensors for the analysis of surface deformations. This includes first an analysis of the coherence of L-band SAR images of vegetated areas with very long temporal base-
lines. Second, preliminary results of differential interferometry using L-band data acquired by the E-SAR sensor of DLR are also shown.

2 LONG-TERM COHERENCE ANALYSIS

An important parameter for differential interferometry is the coherence of the interferogram containing the differential effects. It is well known that coherence decreases with time, because of change processes of the scatterers in between data acquisitions. In longer wavelengths the situation is generally better, as the coherence is sensitive to changes on the scale of the radar wavelength.

In order to get an impression of the degree of coherence which can be expected from L-band data, we have investigated the baselines of all flights performed in L-band over the test-site of Oberpfaffenhofen during the last two years. As far as the horizontal baseline is concerned there was no problem to find baselines below 10 m, since the navigation of the E-SAR carrier, a Do-228, is controlled by differential GPS. Nevertheless, vertical baselines of up to 300 m have been encountered due to the flight level dependence on barometric altitude. This has restricted the useful number of scenes to a total number of 6. Four of them have been acquired during summer month and two during winter and early spring. The vertical baselines between the summer and winter acquisitions is in the order of 170 m. For the investigations presented in this paper we have selected only the acquisitions performed during the summer month. The acquisition dates are 15. June 2000 (track 1), 15. September 2000 (track 2) and two times 27. August 2001 (track 3 and 4), with perpendicular baselines between the tracks always below 10m. The resulting coherence maps in HH and VV polarisation are shown in Fig. 1.
The analysis of these coherence maps offers interesting insights: Big parts of the Oberpfaffenhofen airport remains correlated even after one year. For the runway itself this is not astonishing, but also the meadows around show a quite high coherence. The L-band response seems not to be influenced too much by the reflection of the vegetation and shows a stable contribution which comes from the bare soil echo. This assumption is supported by the observation that the coherence does not decrease significantly between three months and one year time difference. The coherence of the meadow is higher in VV than in HH, which is supposedly due to the stronger echo of the soil in VV, while the response of the grass appears more in HH.

The agricultural fields behave differently. Some of them stay correlated, while others loose their coherence. This behaviour is to be expected as fields which are worked between data acquisitions should show no coherence at all. Again a higher coherence can be observed in VV polarisation than in HH polarisation. Untouched fields seem to have a certain coherence which can even increase after three months. This is probably due to the different season for the three months temporal baseline, while the season is almost the same for track 2 and 3.

Most astonishing is that even after almost one year the forest, present in the upper right side of the image, does not appear completely decorrelated, both in HH and VV polarisation. It can be assumed that the double-bounce echo, i.e. the ground-stem interaction generates a quite stable contribution to the measured signals. A strong indication for this is that the long-term coherence of forest is better in HH than in VV polarisation, as the a double bounce contribution appears stronger in the HH channel than in the VV channel [4]. Also observable is a significant further decrease of the coherence after three months. Why this happens can only be presumed and is topic for further investigations. Generally a loss of coherence in time is the expected effect and forest ground and stems should be no exception.

3 GENERATION OF DIFFERENTIAL INTERFEROGRAMS

The generation of interferograms using airborne sensors requires an accurate compensation of the deviations of the aircraft from the ideal straight flight track. It has been proven that motion errors of up to some tens of metres can be easily compensated by advanced processing algorithms if they are precisely known. However, current navigation systems provide only a position accuracy of about 5-10 cm. The residual uncompensated motion error causes strong phase errors in the interferogram, as it is a differential effect. For example in L-band a phase error of up to one fringe can be expected.

Therefore, in order to correct the residual phase errors, the interferogram phase correction proposed in [5] has been applied to the interferograms between track 2 and 3 and to the interferograms between track 3 and 4. This method estimates the phase errors due to erroneous motion compensation out of the image offsets measured during the coregistration step. It requires an integration of the coregistration parameters along azimuth. Low coherence usually limits the precision of any coregistration method and with it the precision of this compensation of residual motion errors.

In the first interferogram the coherence was generally quite low because of the temporal baseline of 1 year, and the correction in its pure form failed here. It was necessary to select only the coregistration offsets from areas and single stable scatterers with sufficiently high coherence. The offsets for the rest of the image were then interpolated using thin plate splines. The integration step leading to the final phase correction was then performed on the mixed set of true and interpolated offsets. As the interferogram is coherent enough in most parts and even over forested areas, this correction task is still quite straightforward. But for very low quality interferograms, with only few coherent permanent scatterers, a better solution has to be found.

Because the residual motion error correction is based on integration it cannot be used to solve for a constant baseline offset. This remaining error an error like this is causing a wrong flat earth component in the interferograms, as well as an error in the calculation of the differential interferogram due to the usage of wrong baselines. The error can be estimated using the interferometric phase of two corner reflectors with different range distance. Assuming that no differential effect (i.e. displacement) happened on them between the data takes, the phase difference between both allows to estimate the baseline error. In the following, updated baseline values are used.

For the generation of a differential interferogram, the interferogram between tracks 3 and 4 is used for estimating the topography. Additional to its high coherence, it also has a significant baseline of about 10 m. For the long term interferogram, track 2 and 3 are chosen, because after one year some differential effects can be expected. The baseline between these two tracks was very small, between 1 and 5 metres. The actual differential interferogram is calculated using a simple approach: By using the factor between the two baseline values, the unwrapped interferometric phase between track 3 and 4 \( \Phi_{34} \) can be scaled to the geometry of track 2 and 3. In this way, the topographic effects in the long-term interferogram are eliminated:

\[
\Phi_{dinsar} = \Phi_{23} - \frac{B_{23}}{B_{34}} \Phi_{34},
\]

with \( B_{23} \) and \( B_{34} \) denoting the baseline between track 2 and 3, resp. track 3 and 4, and \( \Phi \) the two unwrapped interferometric phases after flat earth removal. It has to be noted, that in the airborne case \( B \) is varying strongly with both range distance and azimuth position. A residual flat earth component could be observed in the final differential interferogram, whose origin is unclear. In order to obtain a representation, which reflects only surface displacements, it has been removed.

The final differential interferogram is shown in Fig. 2. The Oberpfaffenhofen test site is an area where generally no surface displacements can be expected. Therefore, the final differential interferogram reflects mainly the quality of the data processing. Any uncompensated motion error
should be visible as phase modulations along azimuth. It can be observed that this does not happen.

Despite of these remaining problems, the generated displacement map already shows several interesting effects which seem not to be related to data processing. In the big coherent area of the airfield a significant displacement does not take place. But on some of the agricultural fields, present above the airport, displacements can be observed. Depending on the respective field, both positive and negative movement directions are occurring. The edges in the displacement map correlate well with edges of fields in the SAR amplitude image. This is astonishing, because it is unlikely that the observed displacements are related to changes in vegetation height. The backscattering component of vegetation, particularly after one year and with different heights, should not be coherent. Possible explanations are local changes in the soil moisture, causing different penetration depths or even small changes in the height of the soil surface.

The same question arises for the forested areas in the upper right and the lower middle of the image. In both areas, the dark colouring in Fig. 2 indicates a slight rise of the location of backscattering. Whether these are processing artifacts or have some physical explanation has to be clarified with further investigations.

4 CONCLUSIONS

It has been demonstrated in this paper, that the SAR backscattering in L-band is stable enough to provide acceptable coherence over vegetated areas even after one year. Except of some worked fields the coherence was sufficiently high to guarantee a precise coregistration and with this an accurate compensation of residual motion errors. The preliminary results of differential interferometry already show interesting effects happening on vegetated areas.

The whole data processing is not yet completely stable and more work is necessary in this area. Up to now, good differential interferograms cannot be generated from every data set. The quality of the acquired motion data still seems to have a crucial influence on the final image phase, although residual errors should, in principle, get compensated automatically. Also, for the moment, residual flat-earth components in both range and azimuth are unavoidable. For further airborne acquisitions, with the scope of performing differential SAR interferometry, it is indispensable to adjust the flight altitude to differential GPS measurements, rather then to the barometric height, which is usually the case in air traffic control. Otherwise, vertical baselines cannot be kept within few meters.

Further work will also include the investigation of additional data sets acquired during the winter months within the same one year period (shifted by approx. 4 month). Additionally, it is planned to have a look at possible polarimetric effects. Last but not least, in future it will be necessary to validate the measured displacement maps by static ground measurements. Once the approach is validated, the application of airborne differential SAR interferometry may become feasible for a great variety of test-sites.

5 REFERENCES


