ABSTRACT

Within the Exupéry Project of the German Early Warning Systems program in the Geotechnologien framework, a Volcano Fast Response System (VFRS) is being developed by a consortium of German Universities (see http://www.exupery-vfrs.de). One component of the VFRS is a ground based hybrid deformation monitoring system which combines areal measurements of the ground based SAR IBIS-L with GPS measurements at discrete points. IBIS-L operates at a frequency of 17.2 GHz (Ku-band) with a synthetic aperture of 2 m. The achievable spatial resolution is 0.75 m in range and 4.5 mrad in cross-range. From April to August 2009 a prototype of the VFRS was installed at the Fogo volcano on Sao Miguel, Acores.

The image sampling rate of ground based SAR is in the order of several minutes and the number of images can easily reach several thousands. The conventional Persistent Scatterer Interferometry (PSI) technique developed for spaceborne SAR would therefore result in an unacceptable computational effort. Here a sequential PSI analysis is described that allows the near real-time computation of displacements. First results from the processing and analysis from data gathered during the field test on the Acores and others are presented.

Key words: Ground-based SAR; IBIS-L; Persistent Scatterer Interferometry.

1. INTRODUCTION

Within the Exupéry Project of the German Early Warning Systems program in the Geotechnologien framework, a Volcano Fast Response System (VFRS) is being developed by a consortium of German Universities (see Zaksek et al. [4] and http://www.exupery-vfrs.de). One component of the VFRS is a ground based hybrid deformation monitoring system which combines areal measurements of the ground based SAR (GB-SAR) IBIS-L with GPS measurements at discrete points.

The requirements such a system has to fulfil are in general:

- high mobility for quick deployment;
- high temporal and spatial resolution;
- continuous automated monitoring;
- real-time evaluation.

IBIS-L is a GB-SAR developed by IDS, Italy (see http://www.idscompany.it). It operates at a frequency of 17.2 GHz (Ku-band) with a bandwidth of 200 MHz. The synthetic aperture is realized by moving the radar head on a linear rail of 2 m length (see Figure 1). The achievable spatial resolution is 0.75 m in range and 4.5 mrad in cross-range with a maximum range of 4 km. The highest possible sampling rate is between 5 to 10 min depending on the maximum range.

![IBIS-L instrument](image)

Figure 1. IBIS-L instrument.

The major problem in real-time evaluation of SAR data is the phase unwrapping and atmospheric correction. Due to a high sampling rate this is less critical in GB-SAR but it must nevertheless be dealt with. Especially at large distances and difficult atmospheric conditions the phase unwrapping can become a challenge.

To overcome these difficulties the Persistent Scatterer Interferometry (PSI) as e.g. presented in Kampes [1] is a
good tool. However, the conventional PSI is not real-time-capable and to add new observations reprocessing would be necessary. In contrast to spaceborne SAR, with GB-SAR the number of images can easily reach several thousands and each reprocessing would result in an unacceptable computational effort.

Here a sequential PSI analysis is described that allows the near real-time computation of displacements. First results of the processing and analysis of data gathered during two test campaigns are presented.

2. SOFTWARE CONCEPT

Figure 2 shows the concept of the automatic processing. The algorithms are based on the PSI technique STUN by Kampes [1] and a sequential processing strategy using Multi-Modal Adaptive Estimation (MMAE) as described by Marinkovic et al. [2].

![Figure 2. Concept of automatic processing.](image)

A triangulated network of selected persistent scatterers is formed consisting of arcs connecting the scatterers. For each arc a number of parallel Kalman filters exist containing different ambiguity solutions. At each time step new observations are added to each filter. The optimal solution is found by computing the probability of each possible ambiguity. The network consistency must always be assured: for every time step the objective is to maximize the probability under the condition that the triangle sum is zero.

To keep the number of filters under control, the ambiguities of past time steps are fixed when either the maximum number of filters is reached or the probability of one solution approaches 1.

The characteristics of this sequential form of the PSI technique are:

- real-time capability with low computational effort;
- spatio-temporal unwrapping;
- not restricted to deterministic displacement functions.

3. DISPLACEMENT MONITORING

Table 1 shows the specifications of two IBIS-L measurement campaigns presented here.

<table>
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<th>Table 1. Specifications of analyzed data sets.</th>
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<td><strong>Period</strong></td>
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<tr>
<td><strong>Object</strong></td>
</tr>
<tr>
<td><strong>Distance</strong></td>
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<td><strong>Sampling rate</strong></td>
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<td><strong>Conditions</strong></td>
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In July 2008 a test campaign was carried out in an active quarry owned by the Odenwlder Hartstein Industrie in Dieburg, Germany. A photo and the amplitude dispersion index are shown in Figure 3 and 4, respectively. The amplitude dispersion was used to select persistent scatterers for analysis. The red circles indicate selected pixels for which the unwrapped displacements are shown in Figure 5.

In this campaign, the maximum distance was 300 m and the weather conditions were mainly sunny and dry except for some hours of rain. For atmospheric correction a second order model was applied that assumes linear variations of atmospheric conditions with range. During the measurements digging was carried out in the quarry and resulted in high noise at part of the scatterers due to the digging equipment driving around.

The upper graph of Figure 5 shows the unwrapped displacements of three selected scatterers. The lower graph is the Kalman filtered displacement. The phase was modelled as a first order Gauss-Markov process. Scatterers 20 and 30 are situated in the stable area, scatterer 10 is situated on a hill of gravel and showed a displacement in line of sight of -5 mm in four days.

In spring 2009 a prototype of the VFRS was installed at the Fogo volcano on Sao Miguel, Acores. Due to a period of unrest between 2002 and 2006 [3], this volcano was chosen as test object for the VFRS. IBIS-L monitored part of the Fogo caldera from April to August 2009. A photo and the amplitude dispersion of the monitored area are given in Figure 6 and 7, respectively.
With high humidity, fog and a lot of rain, the Acores are a challenging terrain for GB-SAR. Due to power limitations (solar power supply only) a sampling rate of 11 min had to be chosen. This and the fact that the atmospheric conditions can change very quickly make the unwrapping a difficult task.

As absolute reference for the displacement measurements, four corner reflectors, partly equipped with GPS, were established in the monitored area. Exemplary, the unwrapping results of four days for the corner reflectors are given in Figure 8. The displacement of reflector 300 and 400 might be caused by residual atmospheric disturbances or ground movements due to heavy rain. No significant long-term displacements could be detected. This conclusion is in agreement with the GPS results at the reflectors.
4. CONCLUSION AND OUTLOOK

The developed software proved to fulfil all requirements necessary (e.g. real-time, low computational effort). The success rate of unwrapping and the computation time highly depends on the variance of the observed phase. When the variance is high the unwrapping results are very sensitive to the choice of filter model parameters.

The observations with IBIS-L and GPS revealed no significant long-term displacements in the monitored area at Fogo volcano, Sao Miguel, Acores.

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REFERENCES