UTILIZING THE CR-NETWORK IN ICELAND FOR AN AUTOMATED INTERFEROMETRIC PROCESSING CHAIN - CASE STUDY WITH ERS-TANDEM DATA

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ABSTRACT

The monitoring of geodynamic processes related to geothermal, seismic, and volcanic activity and of climate change in the highly active Neovolcanic Zone of Southern Iceland is in the focus of several ESA-projects since 1995. Within the project AO.2 D 116 a total amount of 30 corner reflectors (CR) were installed in the years 1995 and 1998 around three test sites in South Iceland: the central volcano Hekla, the plateau glacier Mýrdalsjökull with the subglacial Katla Caldera and the Vatnajökull ice cap covering several fissure swarms and central volcanoes.

The experiences of the ENVISAT-ASAR monitoring (ENVISAT project ID 142) during the recent Grímsvötn eruption (01.11.2004 – 06.11.2004) at the Vatnajökull glacier revealed the basic necessity of an automated SAR processing chain, on the way of pushing the monitoring to a real time service.

In the paper we analyse the main processing steps of an interferometric phase processing with respect to automation and present results of a case study with ERS-Tandem data.

1. INTRODUCTION

Due to climatic and physical conditions Iceland presents an ideal test site for monitoring subglacial volcanism with radar remote sensing techniques. Today approx 11 % of the 103.000 km² volcanic island is glaciated, consisting mainly of the four large plateau glaciers Vatnajökull (8.100 km²), Langjökull (953 km²), Hofsjökull (925 km²) and Mýrdalsjökull (596 km²) [1]. The huge ice masses of these glaciers cover several volcanic systems with central volcanoes, crater chains and fissures. The rift zone of the Mid-Atlantic ridge is responsible for the high seismic and volcanic activity.

In the southern part the Neovolcanic Zone crosses the island with an eastern (EVZ = Eastern volcanic Zone) and a western (WVZ = Western Volcanic Zone) branch. The active rifting continues from the center of Iceland as a single zone (NVZ = Northern Volcanic Zone) to the north coast. At total the Neovolcanic Zone covers roughly 35.000 km², approximately one third of the island (Fig. 1) [8].

Since the end of the last ice age, about 200 volcanoes have been active with a magma flow between 400 – 500 km³ [8]. All Icelandic subglacial events are characterized by phreatic eruptions which melt huge volumes of ice. Besides the usual volcanic hazards, the ice-volcano interaction leads to enormous meltwater torrents [Icelandic: jökulhlaup], devastating large areas in the surroundings of the affected glacier.

The priority objective of the ongoing
ENVISAT project „Hazard Assessment and Prediction – Long-term Observation of Icelandic Volcanoes and Glaciers Using ENVISAT-ASAR and Other Radar Data“ (ID 142) is the establishment of an largely operational SAR monitoring service to be employed for risk assessment, early prediction and damage mitigation. To consider as much precursors (e.g. seismic activity) of an imminent subglacial eruption as possible a multi-source GIS was specially developed to meet the conditions of the southern regions of Iceland [6]. The recent subglacial eruption at the Vatnajökull test site served a test case for the SAR-based hazard observation:

On November, 1st 2004 (ca. 22.00 GMT) an eruption at Grímsvötn caldera - a subglacial volcanic system beneath the western part of Vatnajökull glacier - started, after a dormant phase of only 6 years since its last outbreak in December 1998. In spite of the usual eruption characteristics a glacial torrent (Icelandic: jökulhlaup) occurred (30.10.2004) before the eruptive phase and triggered the eruption due to the release of the overburden water pressure [9].

Due to the breaking development ESA arranged a fast access to ASAR processed data, allowing to have SLC products over the Grímsvötn area up to 5 hours following data acquisition. An NRT observation of a subglacial outbreak over the whole eruption period was possible. The experiences led to two main conclusions:

- It is fundamental to know the exact location of the eruption site, which enables the matching of the corresponding glacio-hydrological catchment's and therefore the prediction of the periglacial regions threatened by the melt water discharge.
- The most critical parameter is time. The whole archiving, processing, and interpretation procedure must be faster than the propagation of melt water under the glacier. During the last major jökulhlaup (05.11. - 07.11.1996) triggered by the Gjálp eruption (30.09. – 13.10.1996) the propagation of melt water which was stored in the subglacial Grímsvötn Caldera to the 50 km southerly terminus of the Skeidararjökull took approx. 10.5 hours.

2. AUTOMATED PROCESSING

An automated SAR or interferometric SAR (InSAR) processing is a prerequisite on the way of pushing the monitoring towards a real time service. Due to the SAR inherent recording characteristics and the influence of topography a DTM based geocoding is necessary before any analysis of the time series of images or prediction can be made. The quality of this pre-processing step depends on the quality of the reference DTM and the accuracy of the SAR imaging parameters. Differential interferometric SAR approaches are described e.g. in [13], [5] or [8]. Neglecting the crucial phase unwrapping step the interferometric phase processing up to the differential phase again depends on the quality of the two reference information sources (DTM and SAR meta information). For the latter optimization methods based on reference target information (ground control points: GCPs) and least squares adjustment techniques have been used for many years. An overview of different approaches can be found in [4].

2.1. Sensor modelling

A key objective for the SAR/InSAR parameter adjustment is its applicability to any type of SAR data. This requires a suitable and flexible mathematical formulation of an SAR/InSAR model as can be found in [3]. For the definition of the SAR/InSAR mapping equations a geocentric 3D Cartesian XYZ co-ordinate system is considered. The relationship between these Cartesian XYZ co-ordinates and the SAR image entities like time and range pixel co-ordinates is determined by two basic equations addressed as the radar Doppler or azimuth (1), and range equation (2):

\[
\text{Doppler: } F_D : \sin \tau - \frac{(\hat{p} - \hat{s})(\hat{p} - \hat{s})}{r} = 0
\]

\[
\text{Range: } F_R : r = |\hat{p} - \hat{s}|
\]

In case of an InSAR parameter adjustment these two equations hold for the master and the slave image. In addition the interferometric phase equation (3) can be formulated:

\[
\text{Phase: } F_p : \delta r = \frac{\lambda}{4\pi} (\phi + \phi_c) = |\tilde{p} - \tilde{s}_d| - |\tilde{p} - \tilde{s}_s|
\]

Here, \(\hat{s}\) denotes the sensor position vector, \(\hat{\tilde{s}}\) the sensor velocity, \(\tilde{p}\) the target position vector, \(\tilde{\rho}\) the target velocity, \(r\) the slant range distance, \(\lambda\) the wavelength, \(\tau\) the processed squint angle, \(\phi\) the interferometric unwrapped phase and \(\phi_c\) a phase constant to be determined.
2.2. Reference information

Generally the only interactive task in any SAR processing chain is the time-consuming and time-critical manual measurement of ground control points. To avoid this interactive step, several techniques for the automated retrieval of reference points were introduced.

In [9] subsets of a reference scene showing prominent image features are matched with the current scene to be geocoded. Though this method generates registered stacks of multiple remote sensing data very satisfactory it depends on a first (manual) measurement of reference points.

In [12] a SAR backscatter using an available DTM and the meta information accompanying the actual SAR image is simulated first. In a second step a grid of points is identified in the acquired and the simulated SAR backscatter image automatically. Again this method has a dependency on the quality of the available DTM and of the roughness of the imaged terrain.

Thus for time critical monitoring purposes we propose the usage corner reflectors which can be identified in SAR scenes in an automated way without any pre-requisite.

2.3. Automated CR detection

Generally the only interactive task in the SAR/InSAR processing chain is the time-consuming and time-critical manual measurement of ground control points. This is avoided by an automated detection of the installed CRs:

First the ground coordinates of the CRs are transformed into the slant range geometry using the meta information of the corresponding SAR scene. This leads to a coarse location of the corner reflector in the image because of the inaccurate orbit information and SAR imaging parameters.

In a second step the coarse point location is used as the centre of a search window. Then a search for the local intensity maximum is performed leading to the final slant coordinates of the CRs in the corresponding scene.

The automated CR-detection was applied to 10 ERS scenes and about 30 ENVISAT-ASAR scenes. So far this method could detect all corner reflectors within the scene independent of seasonal or atmospheric conditions. In Fig. 2 image subsets of two CRs and the corresponding manual and automatically retrieved image coordinates are summarized.

3. CASE STUDY

Deformation is known to be one of the main precursors of volcanic unrest, whereas InSAR is a proven technique for mapping ground deformation using radar images from Earth-orbiting satellites. As well as in the geocoding processing line the only interactive task during the interferometric phase processing is the time-consuming and time-critical manual measurement of ground control points (GCPs).

The quality of (differential) interferometric results depends again on the quality of the above mentioned information. Thus the benefits of automatic CR-detection for the interferometric processing chain are of dual nature: On one hand the time-consuming manual GCP measurement drops out, on the other hand better results are achieved because of the adjusted InSAR geometry.

3.1. Test site

Myrdalsjökull is the fourth largest Icelandic plateau glacier with an expanse of app. 596 km². It is sited on the southern end of the highly active Eastern Volcanic Zone (EVZ), covering the 100 km² large caldera of the Katla central volcano.
The central part of the glacier reaches an altitude of about 1480 m a.s.l., the steep outlet glaciers descend down to 130 m a.s.l. The caldera of the Katla central volcano contains app. 45 km³ of ice. Besides the normal volcanic hazards, the ice-volcano interaction leads to enormous melt water torrents, devastating large areas in the surroundings of the glacier. Considering the eruption cycle of this subglacial volcano (dormant phase max. 80 years, min. 13 years) [5] and the significant increase in seismic activity over the recent years, a fresh outbreak releasing huge glacial torrents is expected in the near future. At the peak of the last major event in 1918 the glacier’s discharge reached a volume of 300,000 m³/s.

Fig. 3: Shaded relief of the Mýrdalsjökull test site with the locations of the corner reflectors. Reflectors M3 and M4 are highlighted.

Fig. 4: Left: Assembling of a corner reflector at the Hekla test site in 1995. The reflectors had to be fixed properly, due to the Icelandic weather conditions. Right: Location of the reflectors M4 at Mýrdalsjökull test site. The CR related to the descending orbit is in the foreground, the ascending CR in the middle ground (red arrow).
3.2. CR network

In view of the upcoming ERS-Tandem mission corner reflectors were set up around the test sites Mýrdalsjökull (Fig 3.) and Hekla in 1995 (5 ascending, 5 descending at each site). The third test site Vatnajökull was equipped in 1997. They are all located in areas with low surface roughness. The spatial separation between the reflectors for the ascending and descending satellite passes is 150 m at minimum to avoid interferences of the backscattered signal (Fig 4.). Due to the same orbit constellation of the ERS-1/2 and ENVISAT satellites the CRs can be fully used as ground reference for both missions.

3.3. ERS-Tandem scenes

In the (differential) interferometric processing chain the automated CR-detection was tested with ERS tandem data sets, because the 35-day repeat cycle of ENVISAT leads to an insufficient coherency of the corresponding scenes under the Icelandic weather conditions. The scenes were acquired on 31.07.1997 (ERS-1) and 01.08.1997 (ERS-2) with an orthogonal baseline of 116 m.

Tab. 1 summarized statistical values of image residuals achieved for 5 detected CRs with initial and adjusted ERS geometries. The initial and adjusted geometries were used to calculate differential interferograms by simulating the topographic phase contribution using an accurate reference DTM. The results are summarized in Fig. 5. The histograms of the differential phase show that systematic phase errors were eliminated using the adjusted InSAR geometries.

<table>
<thead>
<tr>
<th>5 CRs</th>
<th>Initial</th>
<th>Adjusted</th>
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<tbody>
<tr>
<td></td>
<td>Azimuth</td>
<td>Range</td>
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<tr>
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</tr>
<tr>
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</tr>
<tr>
<td>Min</td>
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<tr>
<td>Max</td>
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<td>-3.83</td>
</tr>
</tbody>
</table>

Tab. 1: Image residual statistics of the initial and adjusted geometries.

4. SUMMARY

An automated SAR and interferometric SAR processing was discussed. Although the differential interferometric analysis fails for the central part of the Mýrdalsjökull glacier test site due to strong temporal decorrelation, the applicability for future missions especially with shorter revisiting intervals could be demonstrated. Generally the automated CR detection has the potential for allowing real time SAR observation of the highly periled Neovolcanic Zone in Iceland, as well as in other affected regions worldwide.

5. REFERENCES

Fig. 5: Results of the interferometric phase processing of the ERS tandem scenes. Upper line: Amplitude (left) and modulus of coherency of interferogram (right). Lower line: Differential phase calculated with initial InSAR parameters (left) and adjusted parameters (right). © ESA, 1997