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Detection of Structural Changes in River Dynamics by Radar-Based Earth Observation Methods

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Abstract: Today, river dynamics is strongly influenced by human activities in the catchment affecting the hydrological behaviour, but also by activities in the floodplain. The knowledge in recent and historical river dynamics and the related morphological and structural changes in the Earth's surface (e.g. sedimentation, accumulation, river bed movement) is one essential point regarding the flood risk estimation and the vulnerability of resources and structures. Operational Earth Observation (EO) systems provide data to monitor and to analyse both, the river dynamics and the small surface changes. Especially the radar-based systems and the interferometric data analysis approach are of high interest because of its potential in 3D information gathering. With selected sites at the river Odra area, we analysed the potential of radar-based EO-applications due to the detection of structural changes, validated by fieldwork. With the multitemporal approach we analysed the recent surface changes in the regions of interest, especially with view to the exceptional flood event in 1997. With the interferometric approach we were able to derive 3D information showing historical and recent river dynamics. Historical flood patterns but also retention areas were detected, important to modelling the behaviour of the river system. On the other hand, the integration of EO derived historical information in existing geo-databases is resulting in vulnerability maps showing high risk areas in the floodplain.

Keywords: Earth Observation; SAR Interferometry; River Dynamics, Flood, Disaster Management

1. INTRODUCTION

Today, river dynamics is strongly influenced by human activities in the catchment affecting the hydrological behaviour, but also by activities in the floodplain (e.g. embankments) affecting directly the flood risk. Floods cannot be prevented, but flood damages can be limited. The more intensively river basins are used and the less user functions are adapted to natural river dynamics, the bigger damages will occur if a flood crisis happens. To take successful measures will demand studies of the spatial and temporal flood distribution.

The main aim of the research described in this paper is the investigation of morphological processes in floodplains of large rivers during high-water phases.

In July/August 1997, a flood disaster occurred in the river Odra region. All littoral states of the river Odra were affected. The flood was particularly strong in Poland and the Czech Republic. Partially, the flood was influenced by human impact. Above all, the importance of natural retention areas (floodplains) was shown dramatically: Bursting of embankments in Poland brought huge flooded areas but also a noticeable reduction of the flood peak at the German-Polish section of the Odra.

For a better understanding of morphological dynamics of large rivers the spatial and temporal distribution is studied with satellite radar images. Structural changes in the floodplain's surface as well as erosion and accumulation to indicate morphological dynamics are discovered and analysed.

2. RADAR-BASED EO-SYSTEMS

2. 1 Potential Value of Radar-Instruments

The potential value of the ERS-SAR instrument must be viewed based on the two major benefits of the Synthetic Aperture Radar (SAR) instrument:

- the Image Acquisition possibility by night and under cloud coverage (<==> optical sensors)
- the availability of 2-D and 3-D information by receiving and analysing Amplitude and Phase Information.

The phase information of the radar signal is able to deliver important additional data from the earth's surface that cannot be detected by optical instruments or even backscatter analysis. Another objective of the project was therefore to find out the benefits of ERS-SAR data analysis for the flood disaster application domain. The evaluation focuses on three main application-themes InSAR technology has a high potential for (STABEL & FISCHER 2001):

Change detection analysis (e.g. flood evolution monitoring): Changes can either be detected by optical sensors looking for geometric patterns, or by SAR systems classifying textures. Here, the benefit of the SAR instrument is the potential of image acquisition under cloud coverage, a typical situation during the flood crisis phase (e.g. monitoring the flood evolution).

Detection of small surface movement: The detection of small surface movements is one of the most challenging applications of the SAR instrument. It has a special relevance for detecting hazardous phenomena like subsidence, dunes, crustal motion, etc. But also in the flood-disaster monitoring (e.g. damage estimation) it provides useful information. The detection is based on differential InSAR processing.

Generation of Digital Elevation Models (DEMs): DEM's are important base information for civil engineering activities and environmental planning (e.g. retention areas). For differential processing there is a need of DEM's that remove the terrain height influence. The generation of DEM's from remote sensing is of high importance because of the very limited availability of products for most of the regions on earth.

2.2 Multitemporal Approach

The multitemporal image is a system of producing colour imagery that is based upon the additive properties of primary colours. The multitemporal technique uses black and white radar images taken on different dates and adds them to the red, green and blue colour channels. The resulting multitemporal image (RGB) reveals change in the Earth's surface by the presence of colour in the image. The hue of the colour indicates the date of the change and the intensity of the colour the degree of change. The reason for change may be the growth of crops, a change in soil moisture, a change in soil structure, or the presence of floodwater in one image where there was none before.
RGB images are created with SAR images of the PRI product level. In this study, two images from different time intervals can be used in order to distinguish flooded areas from permanent surface water. A multitemporal colour composite with three images taken before, during and after flood, is able to show the flood progress but also morphological changes as accumulation or erosion.

2.3 Radar Interferometry (InSAR) Approach

In this study, we used also the repeat-pass radar interferometry (InSAR). Repeat-pass radar interferometry is a technique to extract information about the Earth's surface using the phase difference between the signals arriving at the antenna during repeated observations of the same platform (PRATTI et al 1994, SOLAAS et al 1996). The distance information from antenna to Earth is encoded in the phase. The satellite orbits have a small degree of drift such that they are not returning to the exact location on subsequent orbit repeats. These repeats are generally parallel and separated by a distance, called baseline, on the order of a few hundred meters. This baseline between passes provides the different viewing angles necessary for interferometry to work.

Repeat-pass interferometric SAR uses two antenna positions to acquire two SAR images. The phase difference is directly related to the difference in path lengths between the point on the Earth´s surface and the two positions of the antenna. The phase difference in the SAR images acquired in two passes at corresponding locations, allow a measurement of the incident angle of the incoming radiation. The combination of distance with incident angle and with the location of the SAR platform gives a three-dimensional localization of points on the Earth's surface.

In repeat-pass SAR interferometry, the interferograms are formed from repeated observations of the same platform. With respect to the Earth, the ERS-1 and ERS-2 satellites go through 35-days cycles of orbits which means that the satellite returns to the same position every 35 days. After this period of time, one or more orbit repeat cycles, the same area may be imaged again to acquire additional SAR images.

The basic requirements to apply repeat-pass SAR interferometry can be described as (SOLAAS et al 1996):

- Terrain of sufficient and stable backscatter, without or only with very slow changes, in the order of C-band wavelength between 2 passes
- Similar atmospheric conditions during the acquisitions
- Stable viewing geometry
- Preservation of inherent phase information within the SAR processor

The whole chain of InSAR processing includes the selection of appropriate input data (SLC/I products fitting the baseline and weather conditions requirements), the image co-registration and the generation of the interferogram. Coherence generation, altitude of ambiguity, phase unwrapping, DEM construction, computing of map projection are other processing steps to name but a few. Details related to the technique of InSAR processing can be found in GENS & VAN GENDEREN (1996).

There are three different interferometric products relevant for the flood application domain:

- Coherence maps
- Digital Elevation Models (DEM's)
- Differential Radar Interferometry Products.

2.4 SAR Instrument at ERS Spacecraft's

The Active Microwave Instrument (AMI) combines the functions of a Synthetic Aperture Radar (SAR) and a Wind Scatterometer (WNS). It is operating at a frequency of 5.3 GHz (C-band). With the SAR antenna the Earth's surface is illuminated and the backscattered energy is received to prepare high-resolution images.

The SAR operates in image mode for the acquisition of wide-swath and all-weather images and provides high-resolution two-dimensional images with a spatial resolution of 26 m in range (across track) and between 6 and 30 m in azimuth (along track). Image data is acquired for a maximum duration of approximately ten minutes per orbit. As the data rate is too high for on-board storage it is only acquired within the reception zone of a suitably equipped ground receiving station.

The rectangular antenna of the SAR is aligned along the satellite's line of flight to direct a narrow beam sideways and downwards onto the Earth's surface to obtain strips of high-resolution imagery of about 100 km in width. Imagery is built up from the time delay and strength of the return signals, which depend primarily on the roughness and dielectric properties of the surface and its range from the satellite.

The SAR's high resolution in the range direction is achieved by phase coding the transmit pulse with a linear chirp and compressing the echo by matched filtering; range resolution being determined by means of the pulse travel time; and the azimuth resolution is achieved by recording the phase as well as the amplitude of the echoes along the flight path. (ESA 1992)

3. REGION OF INTEREST (ROI)

The Odra River has a length of 850 km with its source in the Czech Republic. The river catchment area of about 124 000 km^2 has an important role for the water economy of the western part of Poland and the north-eastern part of Germany.

Due to regulation works -which started at the end of the 18th century and continued up to the early decades of the 20th century- the course of the river Odra was shortened by 154 km (NIENHUIS et al. 2000). The construction of regulation infrastructure in the upper, middle and lower Odra has caused large-scale degradation of the river bed (e.g. erosion and deepening of the river bed up to 3m) and in some areas a lowering of the ground water table.

On the other hand, recent hydraulic measures were not taken in the Odra basin. Therefore, large areas of the Odra still have the characteristics of a natural river and it's not surprising that some authors name the river Odra the most natural large river in Europe (NIENHUIS et al. 2000.

The greatest flood in the last century caused by the river Odra occurred in summer 1997. After strong rainfall in the middle and upper catchment area Odra floods appear in summer typically with short and steep flood waves. Exceptionally strong-rain falls, which occurred in three flood places of origin from 4.-8. July 1997 and from 17.-21. July 1997, brought a huge flood disaster to the Odra and most of its tributaries with extensive inundations. The running time of flood waves from upper course to the German-Polish border takes in general about seven to ten days. Breaches in the embankment of the Polish Odra with an overall length of 40 km and an inundation area of 55 000 km^2 deformed the two flood waves and slowed down the running time. This caused an extended flood wave at the German-Polish Odra section with extremely high water level for a period of 3-4 weeks which resulted in an extremely large stress to the embankment. Water gage Eisenhüttenstadt measured the highest flood peak on 24. July 1997. As a result of the persistent high water level two breaches in the embankment of the German-polish Odra section occurred. That's how 6 000 ha of "Ziltendorfer Niederung" were flooded. The decline of water from the inundated area took some weeks.

The map of the flood pattern shows huge flooded areas in Poland (about 55 000 km^2). Therefore, the flood damages were much bigger in Poland than in Germany.

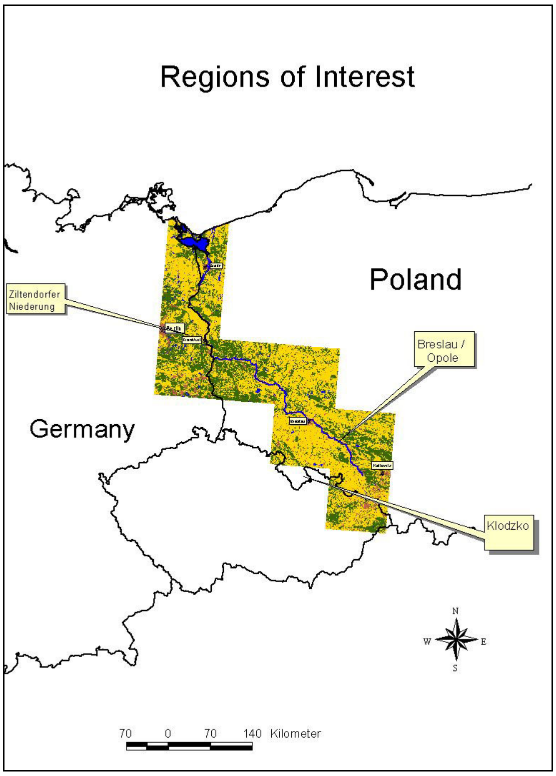

Figure 1. Location of selected research sites.

Because of their special dynamics with view to the flood evolution but also with view to the dimension and size of the related morphological processes, the following regions were selected as test sites (see map 1):

- Ziltendorfer Niederung situated at the German-Polish border south of Frankfurt/O. (breaches in the embankments and flood evolution)
- Floodplain between Opole and Wroclaw (large-scale flood extension with accumulation processes)
- Glatzer Neiße area (deep linear erosion phenomena)

The selection is also done with view to the ground resolution of the EO instruments. This means that the phenomena analysed must have a minimum spatial dimension making sense to use satellite remote sensing methods.

4. RESULTS

4.1 Flood Line Detection

Discussing vulnerability with view to flood hazards, the first step is determining the maximum extent of the flood in the affected areas. Therefore, the flood lines were extracted from the images at different acquisitions during the flood.

Radar intensity images can be viewed as single channel greyscale images with a characteristic "salt and pepper" appearance. The pixel values represent the strength of the returned radar signal from the earth's surface. For each surface feature, there is a statistical distribution of the probable strength of that returned signal. Each pixel representing that surface is assigned a value randomly selected from the statistical distribution. Therefore, a seemingly homogeneous surface has an irregular distribution of dark and light pixels, producing a granular effect. This effect is termed "speckle" and is an inherent property of radar images. Special filters have to be used to reduce the speckle noise.

Water surfaces without waves act as a smooth surface. When the radar sensor transmits a beam of radar energy towards this smooth surface, the result is no backscatter return to the radar sensor but rather the scattering of the radar energy away from the sensor.

Using the supervised classification approach, the processing of the intensity images was resulting in three different classes:

- Class 1: water bodies (incl. flooded areas)
- Class 2: land (not covered with water)
- Class 3: regions of uncertainness

The following images show an example of a SAR intensity image (ROI Ziltendorfer Niederung) and the derived water bodies' lines (class 1) which were vectorized for a later Geodata integration.

Figure 2. Example of ERS-SAR imagery

At the image above, within the flooded areas we can recognise streets and settlements with a strong radar return (white pixels) despite the fact that they were flooded at the time of image acquisition. This phenomena is related to important principles of radar backscatter: the corner reflection and the double-bounce scattering.

Two or three dimensional corner reflection is caused by the existence of buildings. Scattering from a forest canopy (or even from trees beside the streets) can present a complex case of volume scattering. Double-bounce scattering between trunks and the ground is one important effect in volume scattering. This can give a strong return if the ground is covered with water. Buildings and trees are able to redirect a radar beam which was backscattered from a smooth water surface back to the radar sensor. This is why some flooded settlements and streets (with trees) can look even brighter than not flooded areas.

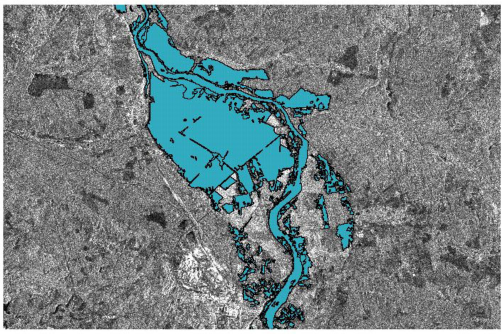

Figure 3. Classified and vectorized water bodies

This is just one example of how any automated unsupervised classification performed without an additional visual interpretation can result in false information.

4.2 River Dynamics

The digital elevation model, derived by interferometric data processing, provides us with some ideas about the historical river dynamics, the geographical distribution of the recent flood patterns and the need of retention areas to reduce the flood peak.

Figure 4 visualise the classified DEM of the ROI Ziltendorfer Niederung (see also Figure 2, 3).

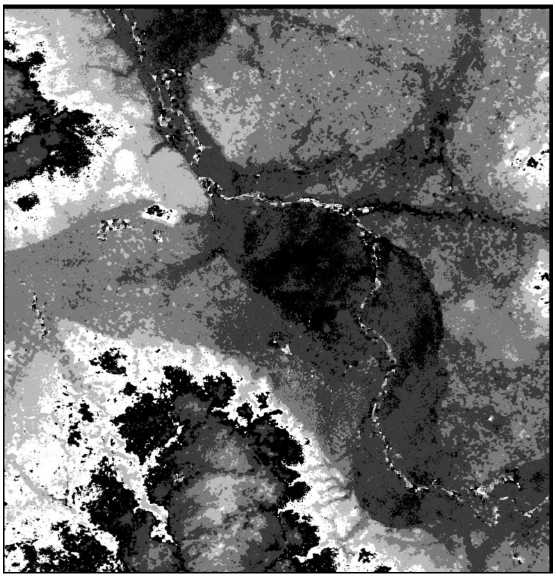

Figure 4. Classified DEM Ziltendorfer Niederung

The white line shows the river Odra that is embedded in the floodplain (classes with black and dark grey colour).

The time before the regulation works, the river - not pushed between embankments- was able to choose a new riverbed if there was a need. In addition, flooding the floodplain was a regularly process in historical river dynamics. Geomorphologic surveys within the floodplain indicate a frequent sedimentation process resulting from former flood periods.

Today, there is a reduction of the area available for water extension in the floodplain by more than 90% (ROI Ziltendorfer Niederung) caused by embankments. It is a logical consequence that this is linked with a higher flood peak, a fast ongoing flood wave and –as it happened with the exceptional flood event in 1997- a rise in the risk to the man built infrastructure behind the embankments. Under such conditions, river dynamics is only able to induce structural changes in the floodplain during flood phases. At that time they can be catastrophic.

4.3 Surface Changes

Single images display only surface water bodies existing at the time of image acquisition. It is not possible to distinguish permanent water bodies from flooded areas. In contrast, image pairs from the crisis phase and the post crisis or pre-crisis phase enable the discrimination of permanent water bodies and flooded areas. Creating colour composites can easily perform this task. Permanent surface waters shown as black versus flooded areas at different time intervals can be displayed in different colours on the multitemporal colour composite (RGB).

In addition, this technique is also able to point at surface changes related to the flood event (e.g. accumulation, erosion). At one site, the same area on the post crisis image shows brighter features coinciding with previously flooded areas. Brighter features were related either to terrain with higher surface roughness (due to ploughing or accumulation) or to a higher soil moisture. In this case, sedimentation of course materials did not occur nor was ploughing the reason for higher backscatter values. Therefore, it was concluded that excessive soil moisture was the reason for that bright backscatter values.

Other changes pointed out by the multitemporal approach were sand bank accumulations. We were not able to detect the deep linear erosion phenomena at the Glatzer Neiße area. Mainly the lack in a very high ground resolution of the sensor used but also some problems with the image data quality were the reasons for this problem.

4.4 Vulnerability Mapping

Within the next steps in the data analysis chain, there will be the integration of the different sources of Geodata. The combination of the DEM with flood lines and information about land use and infrastructure will result in vulnerability maps.

With this kind of thematic product, the option exists to estimate the flood related risk for the sensitive areas. In addition, vulnerability maps will provide an option to support floodplain-planning activities, especially with view to the installation of retention areas and the reduction of unadapted forms of land use.

5. CONCLUSIONS

Floods are natural. They become catastrophic by an uncontrolled use and settlement in the potentially targeted areas. Changes in the land-use of the floodplain induced mainly by the embankment of the river are resulting also in hydrological effects. It is not only the rise in the run-off speed combined with a deepening of the riverbed which is resulting finally in a drop of the groundwater. The significant reduction of the floodplain available for flood extension is affecting the dynamic behaviour of the river linked with a rise in the risk of breaks in the embankment.

The flood risk can be minimized by a wise use of the landscape, which includes the historical information into the river basin management. Especially the EO-derived DEM's and their indication of the spatial dimension of former areas available for flooding should be taken into account into the planning process. It is not sufficient only to come from a regional, sectional approach towards an international, integrated approach. We also have to include historical information, partially derivable by radar Earth Observation.

6. ACKNOWLEDGEMENTS

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