Concepts for Monitoring and Surveillance using Space Borne SAR Systems

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ABSTRACT

In this paper we introduce a concept for monitoring and surveillance based on SAR imagery. A workflow for detection and characterization of changes is presented and discussed. SAR imagery is quite efficient for detection of changes, but less adequate for characterization of the changes. For this purpose context information can be used or detailed geographical information, derived from optical satellite imagery. We discuss two case studies on basis of the workflow, one with present-day satellite SAR data and one with high-resolution air borne SAR data resembling data from future high-resolution radar satellites.

1. INTRODUCTION

One of the main objectives of surveillance from space is monitoring of changes on Earth's surface. Changes can be caused by various kinds of processes such as natural or man-induced and on various timescales. A natural process on longer time scales is vegetation growth, and on shorter time scales destruction due to a tsunami, for example. Man-induced processes or human activity on longer timescales are for example deforestation or changes in infrastructure due to construction works, and on shorter timescales for example displacement of vehicles.

In order to detect these changes regular monitoring is required with time intervals which critically depend on the phenomenon that has to be seen. The possible time intervals depend on the number of satellites and the revisit time of the satellites. For a single satellite revisit times are in the order of weeks to several days, while daily monitoring requires several satellites. If short monitoring intervals are required without any observation gaps SAR imaging is indispensable due to its unparalleled all-time and all-weather capability.

Detection of a change is not enough since also the changes need to be characterized. For this purpose higher resolution is beneficial, but even with high-resolution SAR imaging recognition and identification of objects in the image is a difficult task. In this paper we present a concept for satellite SAR surveillance in combination with high resolution optical satellite imagery and detailed geographical information. These concepts will be illustrated with two case studies: one of monitoring Baghdad during Operation Iraqi Freedom in 2003 using multi-temporal Radarsat fine beam imagery, and one of monitoring third party interference of high-pressure gas pipelines with multi-temporal high-resolution SAR data, representing SAR data from future space based systems.

van den Broek, A.; Dekker, R.; Steeghs, P. (2005) Concepts for Monitoring and Surveillance using Space Borne SAR Systems. In *Integration of Space-Based Assets within Full Spectrum Operations* (pp. 16-1 – 16-14). Meeting Proceedings RTO-MP-SCI-150, Paper 16. Neuilly-sur-Seine, France: RTO. Available from: http://www.rto.nato.int/abstracts.asp.

2. SAR MONITORING AND SURVEILLANCE CONCEPT

The most appealing feature of SAR sensors for monitoring is the potential to gather imagery during adverse weather circumstances and also during night. This makes SAR a very suitable sensor for surveillance for which imagery at regular time intervals is required. Almost identical space borne imagery can be obtained at successive times when the satellite is in the same orbit, since SAR imagery is obtained by an active sensor with it own illumination source. Because of this changes can be detected efficiently and automatically, so that SAR imagery collected at a high temporal rate can be used to track changes. This is in contrast with optical imagery where differences in shadowing, cloud cover, and atmospheric transmissivity hinder automatic detection of changes.

A drawback of SAR imagery is the poor ability to recognize the detected changes in the scene. This is due to the backscatter mechanisms for microwaves, which give rise to peculiar phenomena in the image, such as speckle noise and specular reflections. Classification of the detected objects therefore has to be performed using other information sources such as geographical and context information, which can be derived from maps, geographical information systems or from earlier optical imagery. Optical imagery is suitable to provide up-to-date and refined geographical information, since this information is generally less time critical. Therefore optical imagery can be obtained at a lower temporal rate for this purpose so that problems due to possible cloud cover can be overcome. On basis of the above argumentation we present a workflow for surveillance mainly based on satellite SAR imagery and to a lesser extent on optical satellite imagery in combination with other information sources.

The workflow is schematically depicted in the following figure and summarized here. As main source of monitoring and surveillance we use SAR imagery obtained at regular time intervals. These data are used to detect changes. The SAR data are complemented by so-called base data for the area consisting of maps and data from geographical information systems if available. High resolution optical imagery is used to update the geographical information and needs to be acquired at a less regular and with a lower temporal frequency compared to the SAR imagery. The classification of the detected changes is done using the geographical, context, and other auxiliary information acquired independently or/and derived from the optical imagery.

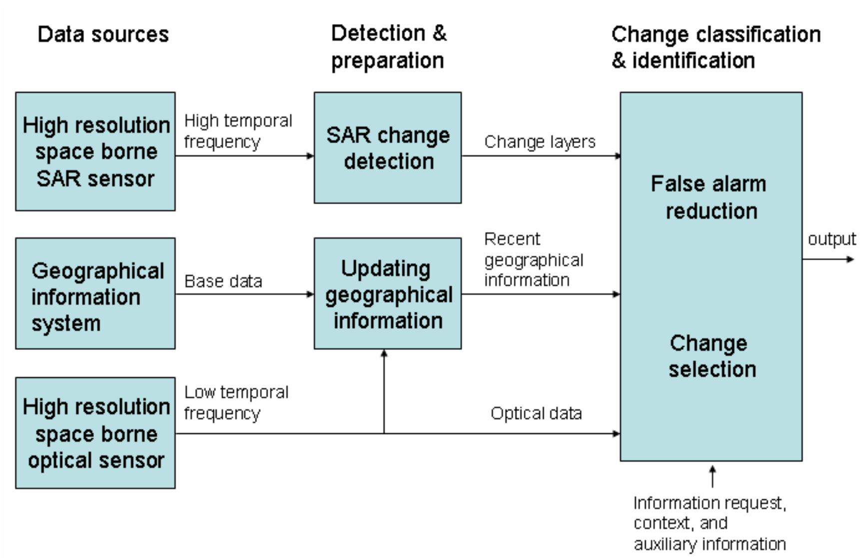

Figure 1. Workflow for detection and characterization of changes in space borne SAR imagery

In the following sections we describe the various processing steps.

2.1 Data sources

Current high-resolution radar satellites such as Radarsat I offer data with a resolution down to 10 meters. In the near future several systems will be available, such as TerraSAR-X, Radarsat II, Cosmo-Skymed, and Sarlupe with resolutions varying from 3 meters down to less than 1 meter.

Geographical data from a geographical information system (GIS) can simply be a scanned topographical map, but also topographical data suitable for use in a GIS like the global VMAP data or detailed national foundation data provided by the NMA (national mapping agencies). Geographical data can be updated using high-resolution optical satellites like Spot5, Ikonos, Orbview, or Quickbird with resolutions of 5 meter down to 1 meter or less. In the near future more such satellites (Pleiades, Rapideye) will become available. The high resolution optical data can also be used directly as source of context information.

2.2 Detection & preparation

2.2.1 SAR change detection

Speckle noise in SAR imagery hinders the interpretation. Also, for change detection this phenomenon is a problem since the speckle varies independently for images of different dates. Due to the speckle pixel values change over time giving rise to unreal and irrelevant changes. The amount of speckle is depending on the number of looks so that irrelevant changes due to the speckle are decreasing with increasing number of looks. There are several techniques for change detection [3], which handle the speckle problem. We discuss here three techniques: threshold on filtered image ratio, eigenvector decomposition, and object-based techniques.

Threshold on filtered image ratio

For this technique the ratio is taken of the powers values in two successive images. Filtering of the ratio is performed using appropriate templates which preserve points, lines and edges [5]. A next step is to apply a threshold to the image ratio to select the pixels, which can be attributed to changes. As a following step adjacent pixels can be grouped and isolated pixels can be rejected, so that as a final result clusters of pixels are obtained which represent changes. For these clusters features can be derived such as dimension, mean intensity, texture etc, which can be used in the classification of the changes (see next section). For this technique it is essential that the images are perfectly aligned, i.e. co-registered accurately enough, since otherwise false changes will be introduced. Correlation techniques can be applied in order to detect and to remove small local displacements between the images.

In figure 2 we show an example of changes detected in two Radarsat fine beam images for the main airport of Baghdad (Iraq). The two images from different dates are shown in complementary colour channels (cyan and red), so that changes are coloured and no change will show up as grayish (see figure). The result of this technique, changes consisting of pixels and grouped together into clusters, is also shown in figure 2.

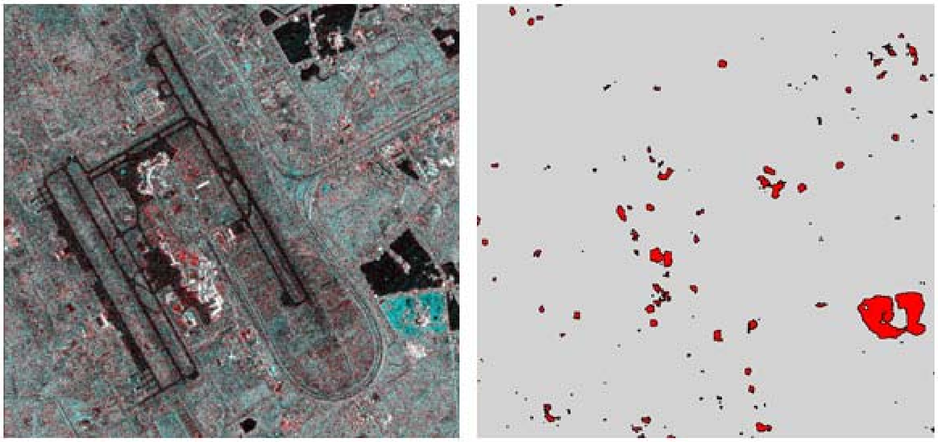

Figure 2. Left: Radarsat colour composite of the main Baghdad airport. Right: detected changes

Eigenvector decomposition

In this technique a moving window is used to select a sample of pixels from a stack of images of various dates. We can construct a multi-dimensional space where the axes correspond to the pixel values of an image of a single date. For the pixel sample a covariance matrix can be calculated, followed by the calculation of eigenvectors and eigenvalues of the covariance matrix. Changes can be expected when the eigenvector with the largest eigenvalue deviates from the 'no-change' line along which most of the pixels in the image stack cluster. This method works only well when most of the pixels do not change so that the no-change line is well defined. The speckle is a smaller problem here, since a sample of pixels is analyzed so that the speckle noise is averaged. Another advantage of the method is that changes are obtained for a multi-temporal data-set consisting of imagery from several dates and not only between two successive images. Since a moving window is used small misalignments do not introduce false detections so that the co-registration needs to be less precise. Just like in the previous method the detected pixels can be clustered and features can be derived for these clusters.

Object based techniques

In this case an image is not considered to consist of pixels but as a collection of objects. An object possesses certain characteristics like the same intensity, the same texture etc, in a similar way the human eye interprets an image. Objects are obtained by segmenting the image. By using appropriate segmentation parameters the influence of speckle is reduced and by stacking images of different dates a multi-temporal analysis can be made. Features, such as mean intensity, can be derived for the objects. For a multi-temporal data-set features are vectors which elements correspond to a specific date. An object is considered as a change when differences between the elements exceed a certain threshold. No clustering needs to be considered here, since the object covers the complete change. Before segmentation the images need to be co-registered accurately just like for the first method.

2.2.2 Updating geographical information

A first step for analyzing detected changes is to use so-called base data, i.e. existing geographical data, which are preferably globally available. A suitable data-set for this purpose is VMAP and DTED level I data corresponding to a scale of 1:250,000. Within the near future also VMAP and DTED level II data (scale 1:50,000) will be available for many places of interest. In developed countries more detailed topographical data suitable for use in a geographical information system are often available. For other countries maps are available which may be outdated. In these cases optical satellite imagery can be used to update and to refine the geographical information.

Multi-spectral optical imagery is quite suitable for land use classification in order to obtain up-to-date geographical information that can be compared with detected changes from radar imagery. The required resolution of the optical imagery depends on the scale of the geographical data that has to be updated. Scale and resolution in meters are roughly related by a factor of 5000, so that for a scale of 1:250,000 a resolution of about 50 meters is required. Multi-spectral Landsat imagery with 30 meters resolution is quite adequate in this case. For a scale of 1:50,000 multispectral imagery from SPOT5 (10 meter resolution) can be used and for small scale data appropriate for urban areas high resolution imagery (e.g. Ikonos or Quickbird) is needed.

We discuss here updating of VMAP level I data using Landsat imagery. The six multi-spectral bands in the Landsat data are segmented to obtain objects. This is done with the eCognition software package [1], in which segmentation and the object method are conveniently implemented. The objects are classified using multi-spectral and textural features for the objects. The original VMAP level I data are used for training of the classification procedure. In figure 3 we show VMAP level I data for an area in the Netherlands with classes urban area (red), soil/grass (yellow), forest (dark green) and water (blue). A corresponding Landsat image (0.56, 1.65 and 2.2 micron bands are shown in blue, green and red colour channels, respectively) is also shown. The classification result shows the following classes: urban area (red), industrial area (orange), soil/heather (yellow), grass (light green), forest (dark green) and water (blue) and is clearly much more refined compared to the original VMAP level 1 data.

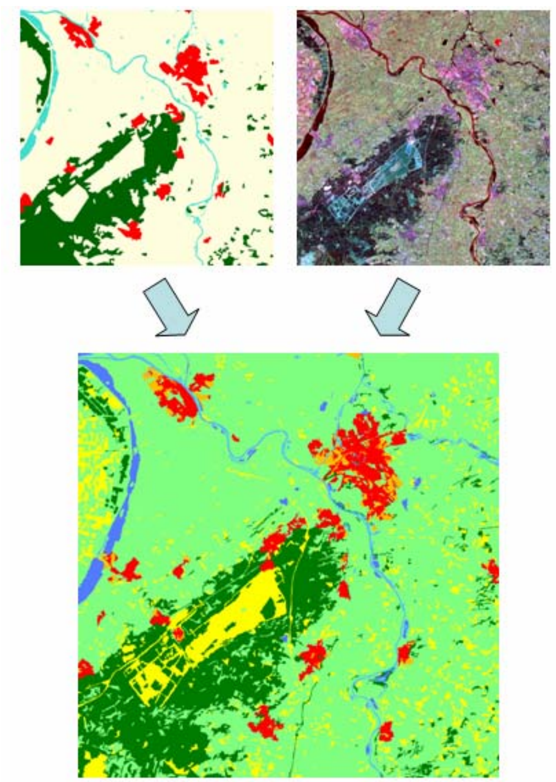

Figure 3. Top-left: VMAP level I data. Top-right: Multi-spectral Landsat data. Bottom: updated and refined VMAP data.

High-resolution optical multi-spectral imagery, like those obtained with Ikonos or Quickbird clearly provides more information compared to Landsat imagery. With increasing resolution the number of classes, which have to be classified also increases. This may not always lead to a workable product for interpretation of the detected changes by the SAR sensor. In such cases an interpreter can use high-resolution optical image data directly as a source of context information.

2.3 Change classification & identification

We present here a workflow for classification of the changes. The first step is to only select significant changes by removing irrelevant changes and so-called false alarms. This step reduces the number of changes to be considered and involves knowledge (features) about *objects* that are to be monitored, knowledge about the *sensor*, and combination with geographical information of the *scene*.

In the second step changes are positively selected and identified from the reduced set of changes, where *context* information (maps and optical images), information from earlier monitoring (*time series*) and preferences of the *user* are used. In the following figure we give an overview of the workflow.

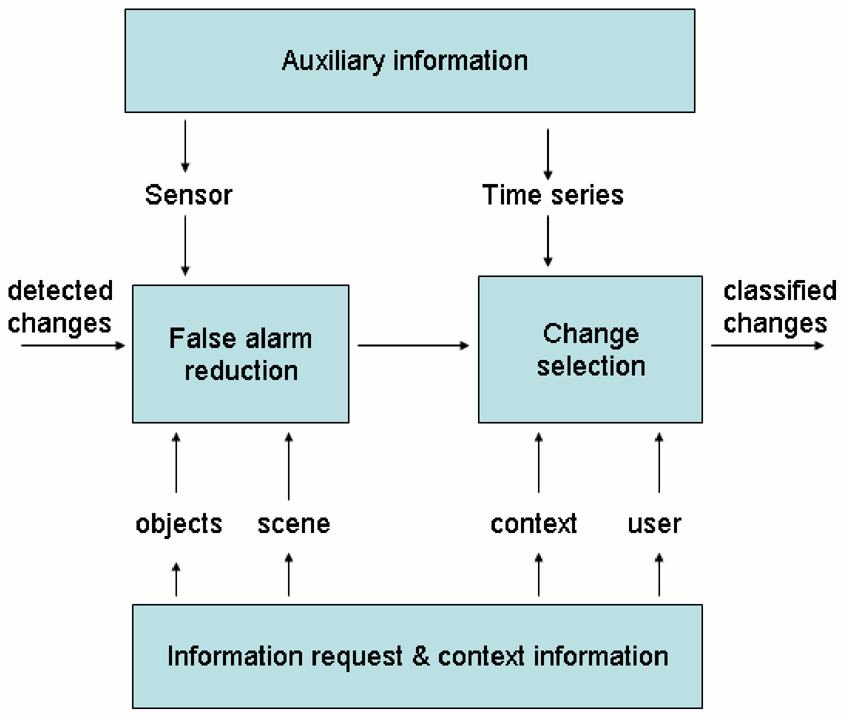

Figure 4. Workflow for change classification

2.3.1 False alarm reduction

Changes in imagery can be due to various causes other than a real change on the surface. For example a change in specular reflection, or change in shadow due to little differences in aspect and incidence angles, can cause change detection. These kind of detected changes are typically related to the *sensor* and the *sensor* geometry and can clearly be discarded. If we know what we are looking for, e.g. an *object* with specific dimensions and specific radar signatures we can discriminate such a change from changes with other dimensions and signatures. Another way to reduce the number of changes is knowledge about the *scene*, when it contains areas where changes are not important. For example, in case of maritime surveillance only changes on water surfaces need to be considered. This kind of reduction, which uses information from the *sensor*, *object*, and *scene*, can be performed mostly automatically. It involves feature extraction and criteria for these features, radar characteristics of objects, and geographical analysis of the scene. The criteria are quite objective and are not very susceptible to change once an optimal working procedure is obtained.

2.3.2 Change selection

A second less automatic step for classification is selection by an interpreter. Selection of changes can be performed by using *context* information. Such information can be areas of interest, such as pipeline corridors or certain areas with a specific ethnic population. Context information may also be derived from interpretation of a high resolution optical image. In case of regular monitoring of a certain area, which is often the case for surveillance, a comparison can be made with detections from earlier monitoring cycles, so that analysis of *time series* is possible. This also helps to select changes. An example is given by repetitive changes due to regular parking of vehicles, which may not be interesting for the goal of the monitoring. Another reduction is the choice of the interpreter not to consider certain changes, since he assesses that these changes will not be of interest for the *user*. For example the user only wants to know about military activity and is not interested in changes due to civil activities.

In the next section we will present two case studies in which we discuss the analysis in the light of the workflow described above.

3. CASE STUDY: CURRENT RADAR SATELLITES

We present here results from an analysis of Radarsat I fine beam data, collected for the Baghdad area before, during and after Operation Iraqi Freedom. Using data from maps and data from optical satellites, detected changes can be identified to belong to categories such as infrastructural, damage, economical, military, environmental, agricultural, etc. Radarsat 1F1 fine beam data with a resolution of about 10 meters were collected on 17 January, 30 March and 23 April 2003 and on 17 July 2005. In the following we present several cases of change detection where one of the items (*scene, sensor, object, time series, user, and context*) described in the workflow of the previous section plays an important role.

3.1 Detection of damage

During the war end of March/ beginning of April several barracks, probably used as storages for military equipment, were blown-up when coalition forces arrived. These changes can easily be detected by Radarsat. Before the destruction the buildings reflect microwaves mainly by double bounce scattering between walls and the ground, which implies that only part of the outline of the buildings are seen in the image. After destruction the debris scatters the microwaves in all directions so that the whole site of the destructed barracks is seen in the image. In figure 5 we show two Radarsat images before the war (17 January 2003) and immediately after the war (23 April 2003) in two complementary colour channels (cyan and red, respectively). In figure 5 large red spots are visible due the backscatter from the debris in the colour composite. For comparison we show detected changes in overlay on a map and for validation we also show Quickbird imagery before and after destruction of the complex that is present in the right-lower corner of the Radarsat composite. Change detection of such destructed objects can easily be performed automatically using information about the *object* and appropriate criteria for size and backscatter intensity.

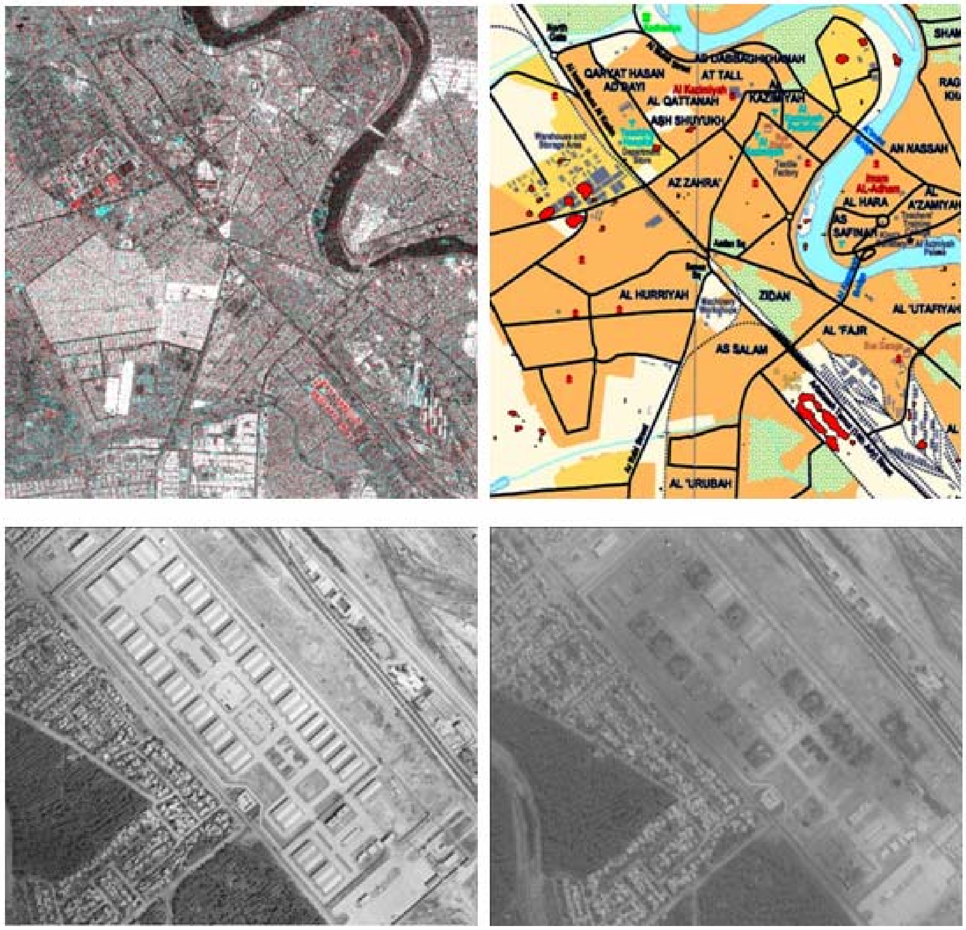

Figure 5. Top-left: Radarsat colour composite. Top-right: corresponding map with changes (red) in overlay. Bottom-right: Quickbird before destruction. Bottom-left: Quickbird after destruction.

3.2 Detection of military activity

After the airport was captured by the coalition forces, large quantities of military equipment have been shipped in. Detection of changes in the airport area are thus of interest for every intelligence officer who wants to follow the military activity. It is here the *user* (intelligence officer) who determines which changes are to be selected. Of course also interpretation is needed using other (*context)* information (e.g. derived from a map) to achieve a final characterization of the changes at the airport. Analogous to figure 5 we show the same Radarsat colour composite as in figure 6, but now showing the airport area. For example, the clear red spots in the centre of the airport are not associated with the platform and are probably military vehicles which are parked near buildings.

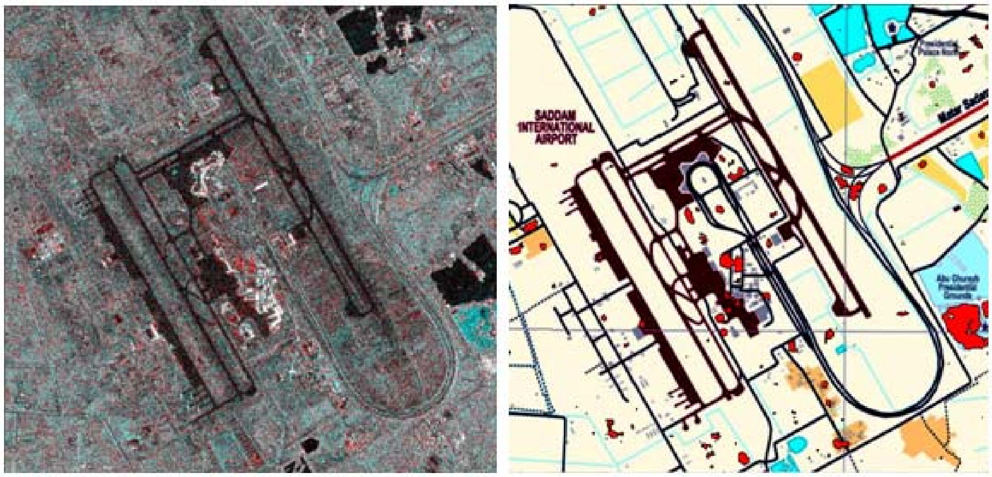

Figure 6. Left: Radarsat colour composite. Right: corresponding map with changes (red) in overlay.

3.3 Detection of new infrastructure

During the war one of the bridges across the rivers near Baghdad was damaged so that a new bridge had to be constructed. Such changes are easily detected and characterized using information of the *scene* (location of rivers with respect to changes combined with appropriate criteria for a bridge). Analogous to figure 5 we show the same Radarsat colour composite as in figure 7, but now showing a river crossing. The red spot connecting both sides of the river obviously is the new bridge.

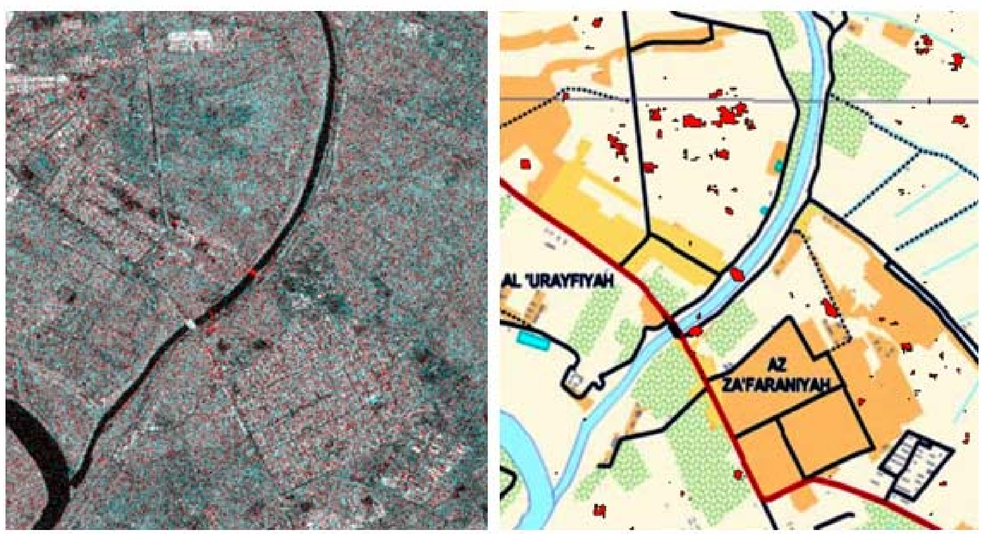

***Figure* 7. Left: Radarsat colour composite. Right: corresponding map with changes (red) in overlay.**

3.4 Detection of economical activity

Many trucks are needed in areas with a large population such as a city of Baghdad for the transport and supply of food and goods. These trucks are often stored at certain assembly points in and around the city, often near crossings of main roads. In order to avoid damage during the war trucks were removed from the assembly points and probably hided elsewhere. After the war trucks are again stored at the assembly points. Because of this, we can analyze a *time series* of Radarsat images in order to find places, such as assembly points. In figure 8 we show three Radarsat images in a colour composite, where images of different dates (17 January 2003, 30 March 2003 and 17 July 2005) are displayed in the green, blue and red colour channels, respectively. When the assembly points are only used before the war they show up as green and when they are again used after the war they show up as yellow in the colour composite. In figure 8 two assembly points are present that show up both in green and yellow which implies that before the war more trucks were stored than after the war. For comparison we also show these assembly points in an earlier Ikonos image of 2000. Appropriate features for the *objects* (backscatter and dimension for the assembly points with trucks) together with information from the *time series* and the *context* (near main roads and crossings) enable us to find these places almost automatically and to make an assessment of the economical activity.

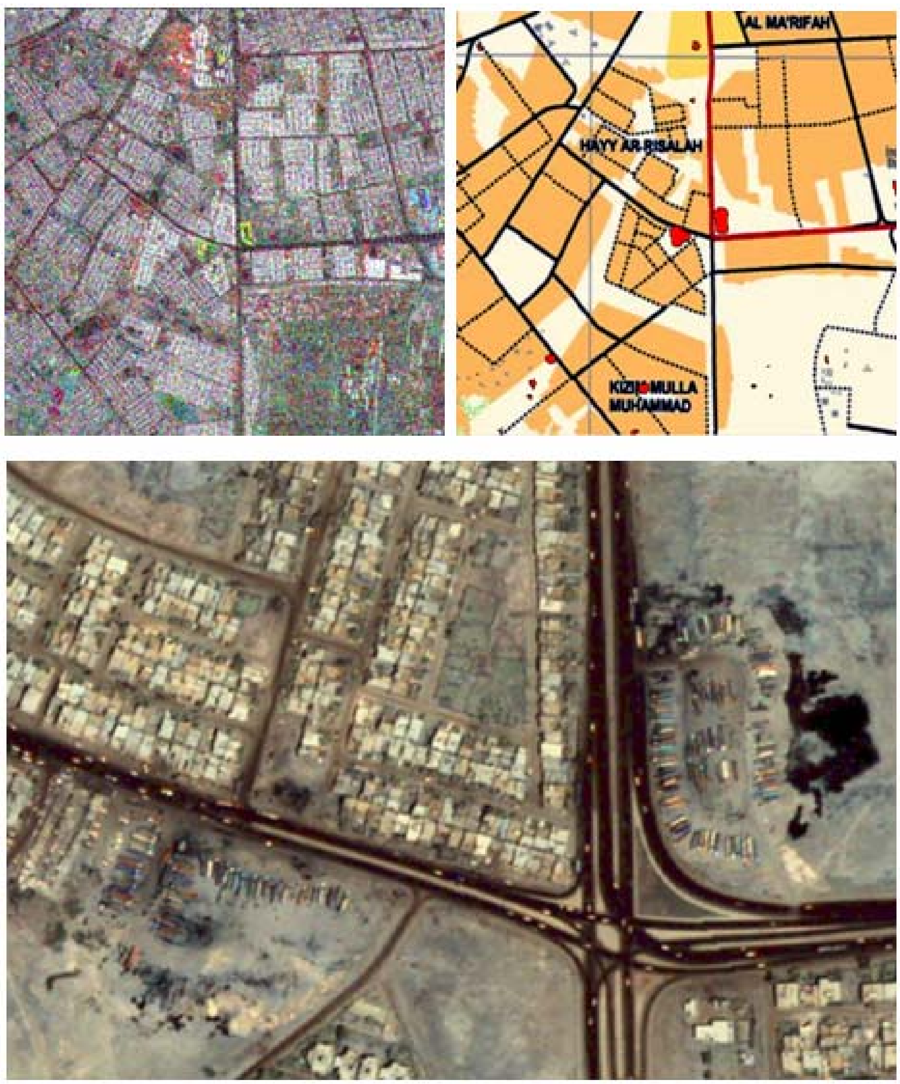

Figure 8. Top-left: Radarsat colour composite. Top-right: corresponding map with changes (red) in overlay. Bottom: Ikonos image showing the assembly points in 2000.

4. CASE STUDY: FUTURE RADAR SATELLITES

We present here a study of pipeline monitoring with high-resolution SAR imagery. Pipelines are often characterized as critical infrastructure, which has to be monitored regularly in order to avoid damages due to human activity (so-called third party interference). High-pressure gas pipelines have to be monitored every two weeks or so in order to control unwanted digging activities near these pipelines. A clue for finding such activity is the presence of excavators near the pipeline. The ability to detect objects typically depends on the resolution of the SAR sensor with respect to the size of the object. In order to detect devices such as excavators high-resolution SAR data are needed. In a study by van den Broek et al. [2] it was shown that the resolution should be at least 2 meters and preferably 1 meter or less (see figure 9). Current civil space borne SAR sensors have resolutions in the order of 10 meters and are not suitable for this kind of monitoring. In the near future, however, space borne radar systems like TerraSAR-X and Cosmo-Skymed have resolutions down to one meter, while for military space borne SAR sensors (SarLupe) submeter resolutions can be expected.

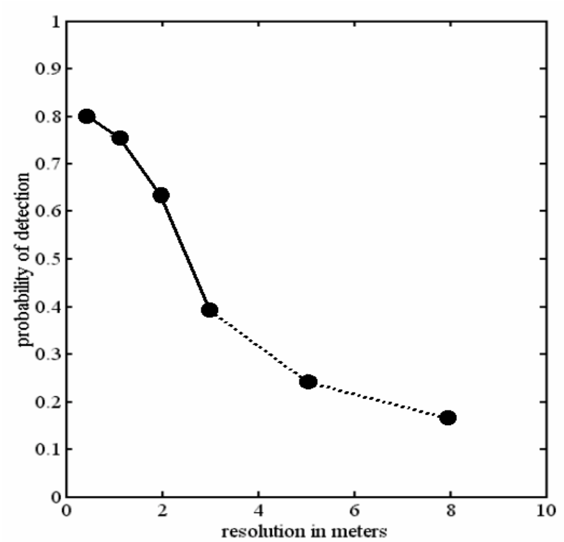

Figure 9. Probability of detection (POD) for objects such as excavators as a function of SAR resolution. Dotted line indicates less reliable results.

Within the framework of the EU PRESENSE (Pipeline REmote SENsing for Safety and the Environment, www.presense.net) project SAR monitoring techniques have been studied to prevent damage of high pressure gas pipelines due to uncontrolled digging activities [4]. To support the study an extensive airborne campaign has been conducted and high resolution SAR data have been collected with Intermap's AC-2 radar sensor for various test sites in the Netherlands, Germany and France. These data (X-band) have a resolution of 0.5 meters (3 looks) resembling the highest resolutions which possibly can be obtained with space borne SAR sensors. During the campaign two data takes took place with a time interval of a few hours. In between several excavators and other equipment were moved so that changes could be detected. In figure 10 we show the test site in the Netherlands (Borculo) in which an excavator was moved (see encircled area). Using the threshold method changes have been detected where the cyan colour indicates the presence of the excavator during the first data take and the red colour during the second data take in figure 10.

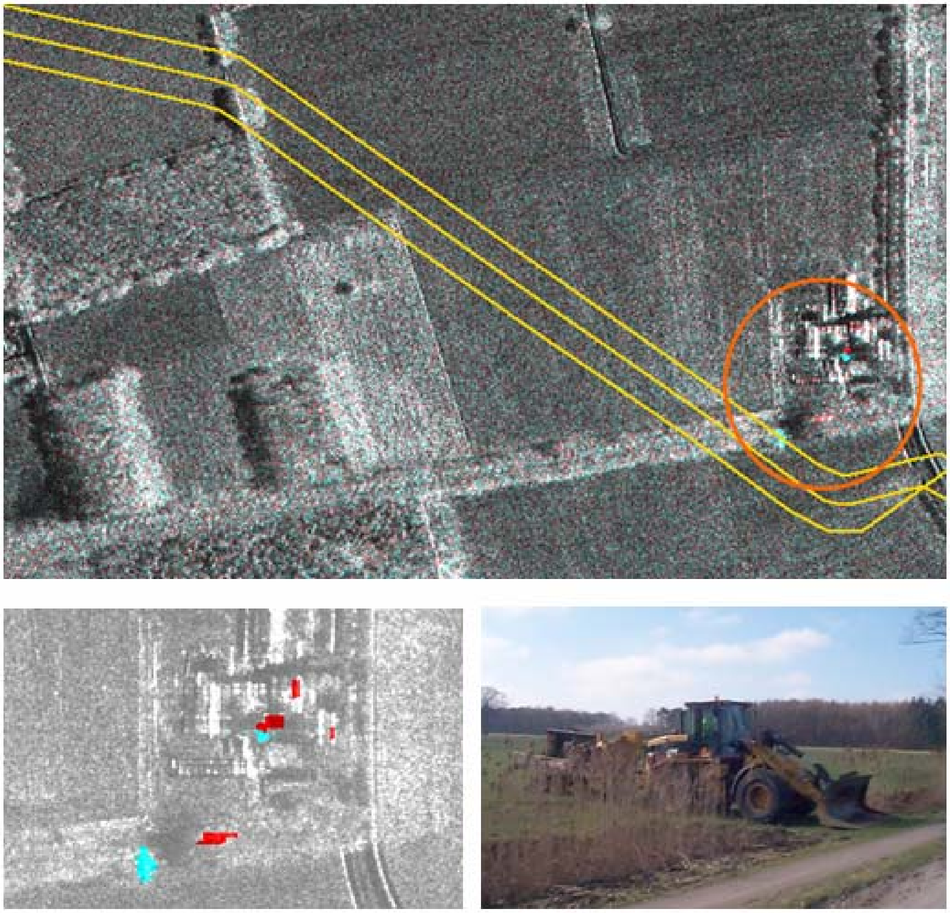

Figure 10. Top: colour composite of high resolution SAR data for test site Borculo. In an overlay the pipelines are shown. Lower-left: detected changes from the encircled region. Lower-right: excavator corresponding to the large cyan spot.

Note that also changes are detected in the farming complex. The next step is of course to characterize the detected changes in order to select the excavator from the changes in the farming complex. This can easily be done here by comparing the locations of the changes with the location of the pipeline and the farming complex.

In the following example using data from the test site in Germany (Dorsten) we focus on the characterization of detected changes in these high resolution data. The Dorsten test site of about 500 by 500 meters comprises the Ruhrgas premises, in which several targets were deployed. The target types varied from digging machines, vans and trucks to cable drums, an excavated hole and a water basin. The SAR data were collected in two data takes with a time interval of a few hours. In between targets were relocated, a hole of a few square meters was dug and the water basin was emptied.

Using the threshold method several changes were detected. The number of detections has been reduced using features extracted for the detected clumps of pixels. For example *sensor* related changes belonging to the strong side lobes visible in the images (see figure 11) were discarded on basis of dimension and backscatter level. Next, changes were selected by applying appropriate criteria to the extracted features for *objects* like excavators. The remaining changes were classified in categories like top-soil work (yellow), large machine off-road (green) and large machine on-road (purple) using scene data, which have been updated and refined with high resolution optical data (see figure 11, lower-left). A further selection was made on basis of the *contex*t to select changes, which can be related with activities that can endanger the pipeline integrity. The *context* consist here of two corridors along the pipeline; a wide corridor of 200 meters and a narrow corridor of 20 meters. Objects detected within the wide corridor are of interest to the pipeline operator and objects within the narrow corridor need immediate attention. On basis of historical records from *time series* data and on choices from the pipeline operator (*user)* a final selection can be made for changes which are considered as threatening.

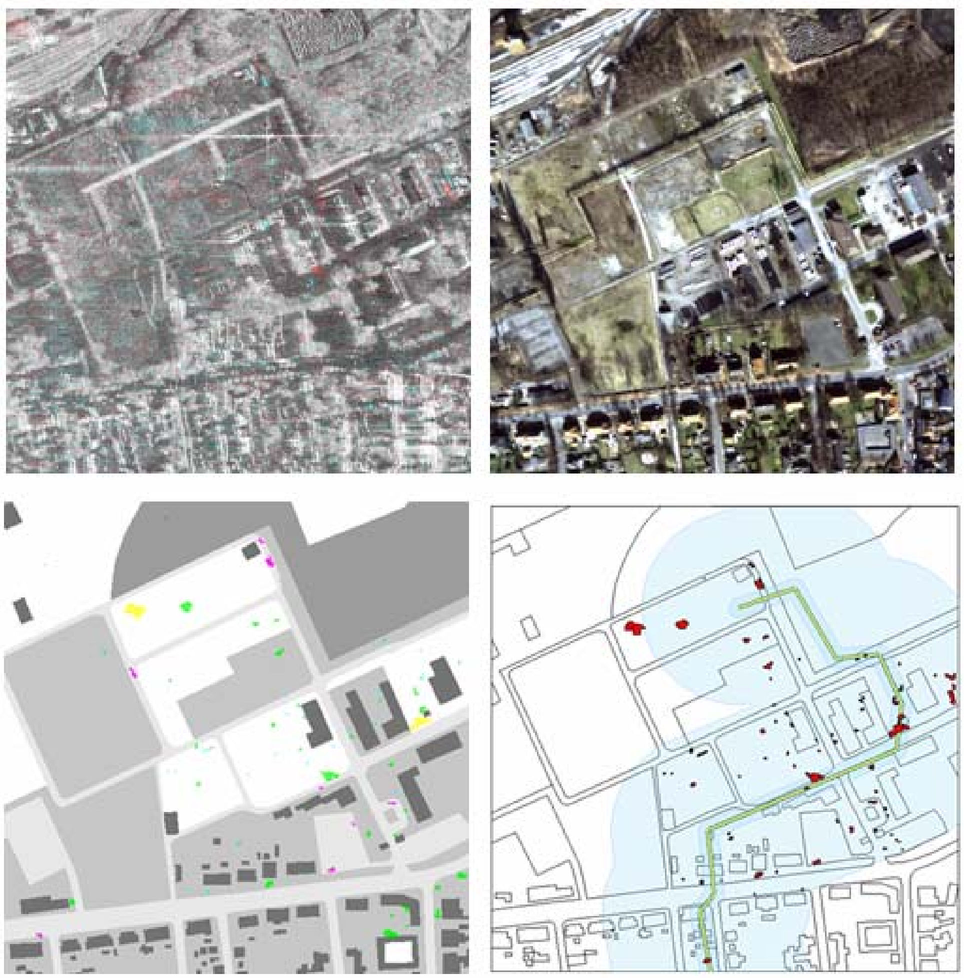

Figure 11. Top-left: colour composite of high resolution SAR data for test site Dorsten analogously to figure 10. Top-right: high resolution optical data for generating and updating scene data. Lower-left: classified changes (see text) in overlay on a map. Lower-right: context map (pipeline corridors) with changes in overlay.

5. Summary

We have proposed a workflow for regular monitoring and surveillance with SAR in combination with high resolution optical imagery and other information such as geographical information. SAR data is well suited for change detection, but does not give sufficient information to classify these changes. We have proposed 2 steps to handle the detected changes. Step 1 involves reduction of irrelevant changes, so-called false alarms. Step 2 comprises selection of the remaining changes by an interpreter. In these steps information about the *object, sensor, scene, time series, user and context* are important. We have discussed two case studies using these workflows, one with present-day satellite radar data and one with high-resolution air borne SAR data resembling data from future high-resolution radar satellites.

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