MONITORING THE URBANISATION OF DAR ES SALAAM USING ERS SAR DATA

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ABSTRACT

Information on human development and database building are crucial for providing the basic needs and infrastructure in fast growing urban areas, as in developing countries. To obtain this information for the area of Dar es Salaam in Tanzania, the application of ERS Synthetic Aperture Radar (SAR) remote sensing data was investigated. The objectives of this study were (1) the detection of new human settlements on the outskirts of the city, (2) the segmentation and classification of land use, and (3) the generation of a Digital Elevation Model (DEM) for storm water flow studies, using interferometry. Change detection was done by subtracting two images of 1996 and 1998, and reduce the speckle with a special filter. The result shows a high correlation with the ground truth. The fact that most houses contain corrugated-iron roofs contributes to this. The segmentation of land use was done on an image pair of 1997, using the intensity and textural information. The result is accurate enough for larger scale interpretation. A DEM was also generated from the 1997 image pair. Unfortunately its accuracy was insufficient for the application of storm water flow studies, due to decorrelation effects. A coherence image was generated from this data set to examine its application for land use classification in this area. The overall conclusion of this study is that ERS SAR imagery, in combination with the techniques presented, has a large potential for the monitoring of urban growth in developing countries.

1 INTRODUCTION

In developing countries a number of urban areas is growing fast and mainly unplanned. A problem related to this, is that basic needs and infrastructure (health care, water, sewerage, drainage, etc.) are often poor or not available at all. Another problem are land use conflicts. An example of an area where the authorities are dealing with such problems is Dar es Salaam in Tanzania. Information on human development and database building are crucial in solving the problems, but are often a major obstacle (Sliuzas 1997). The most important remote sensing information sources until now were SPOT satellite imagery and aerial photography, both optical. To investigate the potential of satellite microwave Synthetic Aperture Radar (SAR) imagery for this purpose, ERS SAR data was studied.

A SAR is an active instrument, and is therefore independent on sunlight and the time of day or night. Because it operates in the microwave region, it is also independent on atmospheric circumstances like cloud cover and rain. This can be very useful in tropical regions. It is a side-looking instrument resulting in slant (oblique) imagery. Radar backscatter has two quantities, an amplitude or intensity, and a phase. A SAR image normally shows the intensity. The phase is related to the distance between the illuminated object and the radar. In normal radar imagery it is of less importance, but in interferometry it is the key quantity.

A disadvantage of SAR is that it contains speckle noise, a consequence of the coherent nature of SAR signals. Speckle-noise can hamper the interpretation and information extraction, but various filter methods have been developed to reduce this problem. One of them is multi looking by averaging adjacent samples. A measure for the quantity of speckle is the number of looks. The larger the number of looks, the less the amount of speckle. Another speckle reduction method is adaptive filtering. Radar backscatter from urban areas can be strongly dependent on the view angle and the nature of the illuminated objects and surfaces (Henderson 1995).

The objectives of this study were (1) the detection of new human settlements on the outskirts of the city, (2) the segmentation and classification of land use, and (3) the generation of a Digital Elevation Model (DEM) for storm water flow studies. A DEM can be generated by interferometry. In the next section the ERS SAR and data set are discussed. Section 3, 4, and 5 are subsequently on change detection, segmentation and classification, and interferometry. In section 6 conclusions and recommendations are given.

2 URBAN MONITORING WITH SYNTHETIC APERTURE RADAR AND ERS DATA SET

The status of urban monitoring with SAR, at the beginning of this study, was clearly reviewed by Henderson and Xia (1997). They stated that, beside the view angle and the nature of the illuminated objects, the visibility and detectability of human settlements are also dependent on:
(1) the wavelength and polarisation of the sensor
(2) the surrounding land cover, which can facilitate or confuse the visibility of settlements
(3) the covering area, smaller settlements and medium cities are easier to detect and delimit than large ones
(4) the experience and knowledge of the interpreter (note that this also applies to detection algorithms)
Their conclusions with respect to the sensor were that it seems preferable to use an incidence angle greater than 35°, a shorter wavelength (i.e. X, C and L band) and cross-polarised imagery (i.e. HV or VH).

Chosen was for ERS SAR data because it is relatively cheap, easy to obtain and operating on a short wavelength, see table 1. Unfortunately it is a VV polarised system with a rather steep incidence angle, but in this paper will be shown that this is also a very useful combination with respect to urban monitoring in developing countries. It is even more preferable to use fully polarimetric imagery (i.e. HH, HV and VV, Hussin 1995, Xia and Henderson 1997, Forster et al. 1997), but this type of data is not available yet from satellites. It will become available in the future (e.g. ENVISAT).

ERS SAR imagery is available in all sorts of formats, from raw to fully terrain geocoded imagery. For interferometry only one product is suitable, and that is Single Look Complex (SLC) imagery. It is the only product that contains the phase information of the radar signal. Besides it has the advantage that it can be processed into imagery with a higher number of looks than the other products with a resolution better than 30 m. This was actually done by averaging 6 adjacent pixels, resulting in Multi Look (ML) images, for the purposes of change detection and classification. A disadvantage of SLC imagery is that geocoding still has to be performed. In terrain geocoded imagery (GTC), also suitable for change detection and classification, this has already been done. The DEM could have been used to geocode the image, but unfortunately it turned out to be not accurate enough, see section 5. Table 1 shows some general characteristics of the ERS SAR data. The data set and application can be found in table 2.

ERS SAR	
Average altitude	785 km
Average ground speed	7100 m/s
Wavelength	5.7 cm (C-band)
Polarisation	VV
Swath width	100 km
Range (slant, mid-swath)	840 km
Incidence angle (mid-swath)	21.5°
Ground range resolution (SLC)	30 m
Azimuth resolution (SLC-ML)	5 m-24 m
Number of looks (SLC-ML)	1-6

Table 1. Major parameters of the ERS SAR Single Look Complex (SLC) imagery and self generated Multi Look (ML) imagery.

Platform	Orbit	Frame	Date	Pass	DEM	CHD
ERS-1	32516	3738	03/10/1997	descending	•	
ERS-2	12843	3738	04/10/1997	descending	•	
ERS-2	04061	7049	29/01/1996	ascending		•
ERS-2	19091	7049	14/12/1998	ascending		•

Table 2. The ERS SAR data set and its application.

3 CHANGE DETECTION

To detect changes in SAR imagery different techniques are available. For the application of detecting new human settlement in developing countries two were studied. The first is a method that makes use of an edge (and point-target) preserving adaptive filter (Dekker 1998). This method already proved that it works properly on SAR difference imagery in The Netherlands. The second method that was studied, is called Order-Statistics Constant-False-Alarm-Rate (OS-CFAR) detection (Novak and Hesse 1991). It performs detection against the local background, which can mean that small changes in terms of intensity can possibly not be detected in predominantly-new areas. The method was studied because it performs well in military radar target detection. Both methods were applied on the difference of the logarithmically scaled image intensities. Logarithmic scaling has the advantage that it simplifies adaptive filtering and detection by transforming the distribution of the speckle noise into a symmetrical distribution. Another thing is that the intensity difference is now measured in dBs. Change detection is sensitive to a global intensity differences, which can be due to a difference in the radar system gain. In case of the method of Dekker (1998) a global difference has to be eliminated. The OS-CFAR detector is not sensitive to this phenomena because it detects against the local background. After thresholding, all change pixels connected to less than a certain number of adjacent pixels are rejected, to select the changes that fit at least one resolution cell.

Change detection was performed between the images of 29 January 1996 and 14 December 1998. For both algorithms the threshold was set to 3.719 times the standard deviation, corresponding to 9.73 dB and a false alarm rate of 0.01%. In case of the method of Dekker (1998) a global difference of 1.75 dB was subtracted. All change pixels connected to less than three adjacent pixels, were rejected. Figure 3 shows the result. The left image is a colour composite of both images in cyan and red, which results in unchanged objects having a grey tone and new objects being red. The right image shows the result of the method of Dekker (1998). The result of the OS-CFAR method is not shown. It performs well but the method of Dekker (1998) turned out to be more accurate. From figure 3 we see that a colour composite gives a good overview of the urban growth, but that the change detection algorithm gives a far more accurate picture. The result shows a high correlation with the ground truth: the most rapidly growing areas show most new objects. The fact that the incidence angle of the radar matches with the average tilt angle of the roofs, contributes to this. Another advantage of change detection maps is that they are very suitable as input for the estimation of the number of new houses, and the increase of the population index.

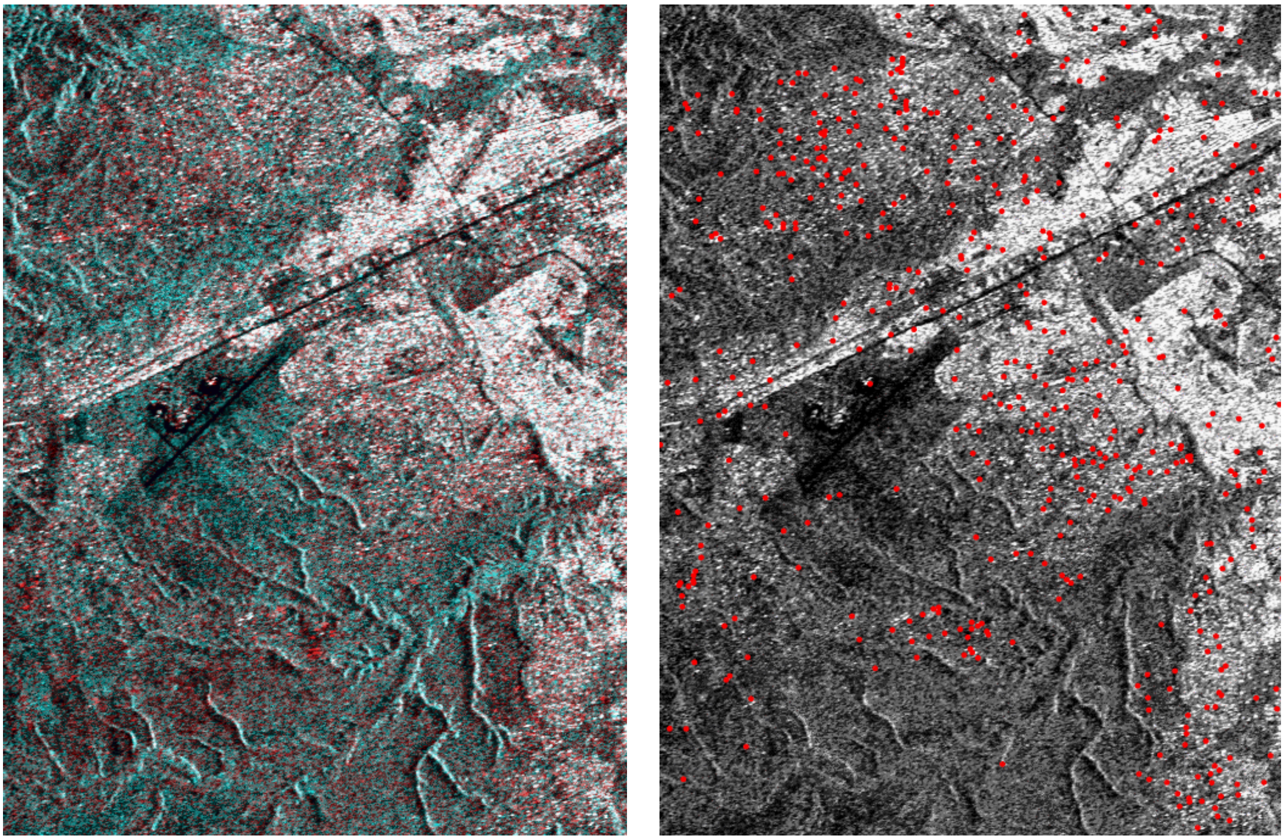

Figure 3. Colour composite of the images of 29 January 1996 (cyan) and 14 December 1998 (red), and the detected new objects projected on the image of 14 December 1998 (right). The less-dense expanding areas show most new objects.

4 SEGMENTATION AND CLASSIFICATION

Land use classification can be split up into segmentation and classification. In the first step an image is divided in segments or regions with a certain uniformity. In the second a land use class is assigned to every region by evaluating the features extracted from the region. In another study than the one described here, segmentation of SAR data using textural features was examined (Dekker 2000). Segmentation was done by optimised region growing. Among the textural features that were studied were the standard deviation, higher order moments, grey level co-occurrence matrix features, grey level difference vector features, wavelet based features, fractal based features and others. The lacunarity, a fractal based feature, turned out to be one of the more powerful features. It is computed from the content of the total number of specified windows within a region. When the size of this window is only one pixel, the lacunarity of a region is given by σ^2/μ^2+1, in which σ and μ stand for the standard deviation and mean intensity of the region (Dobson et al. 1997). Both the mean intensity and lacunarity were used for the segmentation of Dar es Salaam. To reduce the effects of speckle as much as possible, it was performed on the sum of the image pair of 3-4 October 1997. This way an image with a number of looks up to 12, for fully uncorrelated areas, is obtained. The result is given in figure 5. For the reason of comparison, the result of manual segmentation from vertical aerial photographs of 1992 (1:12,500 and 1:52,000, Sliuzas et al. 1999) is given in figure 4. Figure 5 is of course less accurate than figure 4, but is useful for larger scale interpretation. Note the difference with figure 3, with respect to the amount of speckle and the number of looks. Unfortunately no time was left to study the potential of texture for classification, but considering its capability of segmentation, it is recommended. The next section on interferometry comes up with another feature that can be used for segmentation and classification.

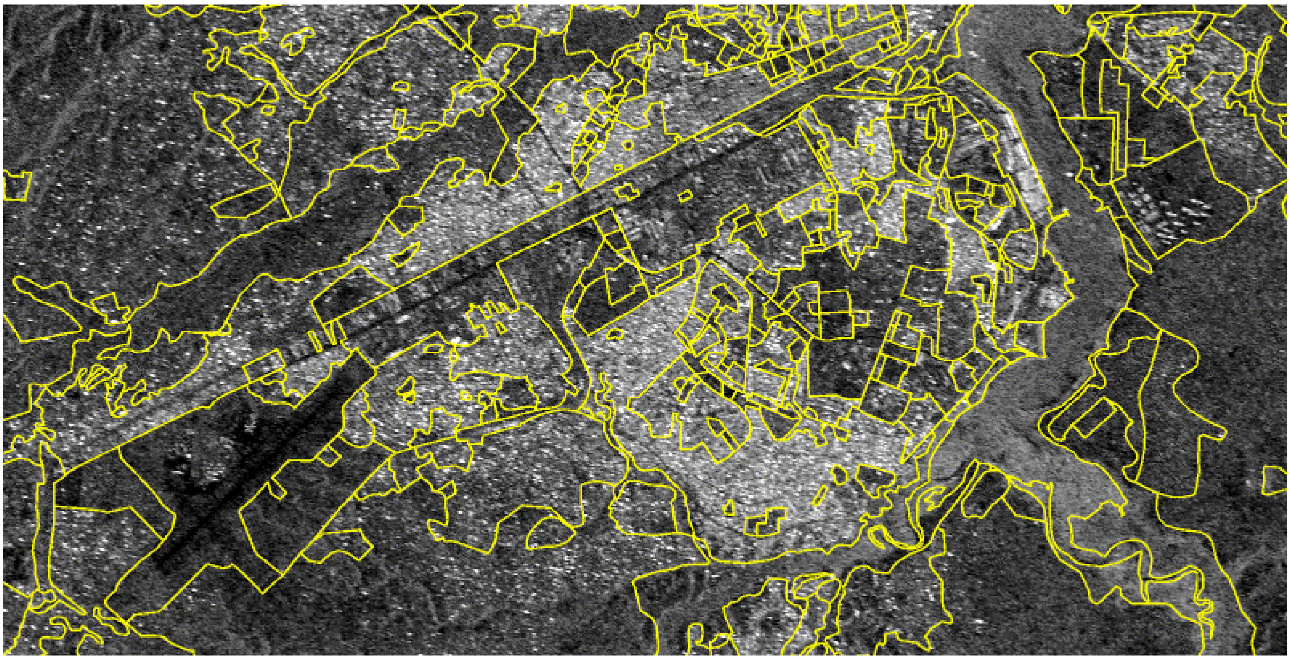

Figure 4. Manual segmentation of land use from vertical aerial photographs of 1992 (1:12,500 and 1:52,000), produced by ITC, The Netherlands, projected on the sum image of the tandem pair of 3-4 October 1997.

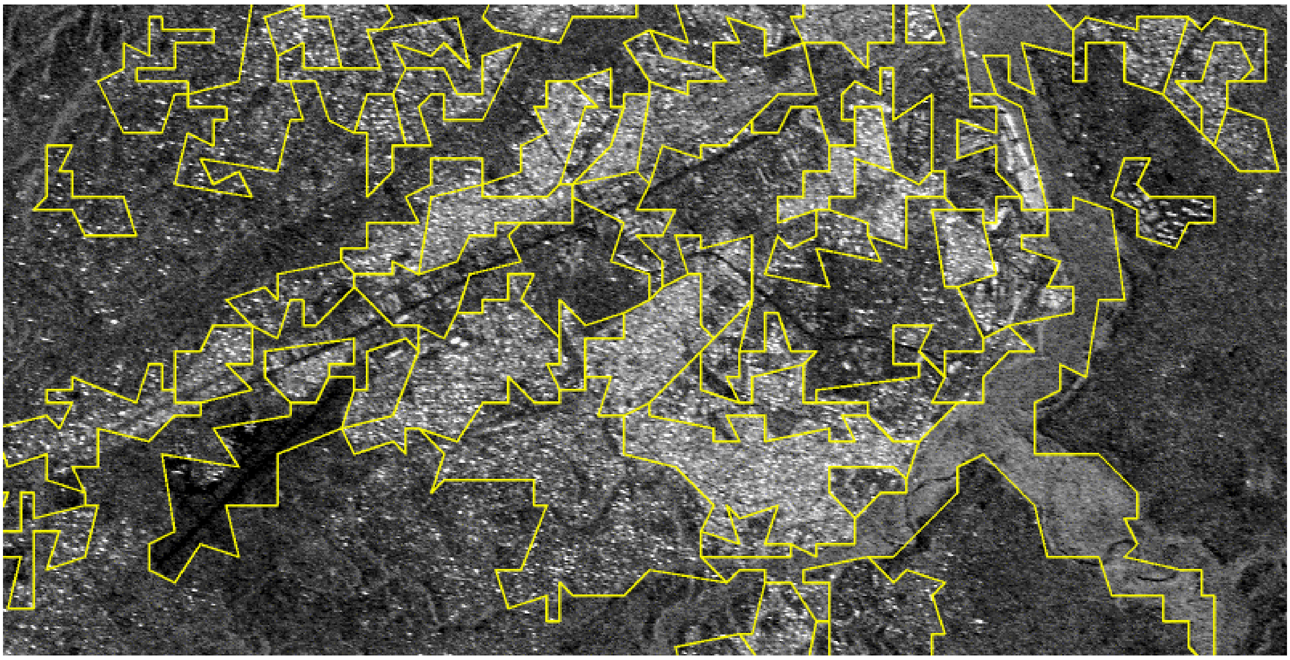

Figure 5. Automated segmentation of land use from the sum image of the tandem pair of 3-4 October 1997, projected on the sum image.

5 INTERFEROMETRY

SAR across-track interferometry (Li and Goldstein 1990) is a technique, like stereoscopy in optical imagery, that can provide a Digital Elevation Model (DEM). In the case of repeat-pass across-track interferometry, two single look complex images must be acquired. The terrain height information can be derived from their phase difference by:

$$h = \frac{\lambda r \sin\theta}{4\pi(B_z \sin\theta + B_y \cos\theta)} \Delta\varphi \quad (1)$$

Here h stands for the terrain height, r for the range (i.e. the distance between the illuminated object and the radar), λ for the radar wavelength, θ for the incidence angle and $\Delta\varphi$ for the phase difference between the images, corrected for the phase difference of the reference earth model that is applied. B_y and B_z are respectively the horizontal and vertical components of the baseline (i.e. the distance between the two flight paths of the platform). The main requirements of repeat-pass interferometry are (1) that the baseline perpendicular component must generally fit in between 150m and 300m (van Genderen and Gens 1996), and (2) that the time interval between the acquisitions must be as short as possible. The first requirement is associated with the spatial or baseline decorrelation between the images, defined by Zebker and Villasenor (1992):

$$\rho_{spatial} = 1 - \frac{2 B_y \delta_g \cos^2\theta}{\lambda r} \quad (2)$$

Here δ_g stands for the ground-range resolution. The spatial decorrelation (range 0 to 1) is an overall measure for the reliability of the phase difference, which directly relates to the reliability of the extracted terrain height in equation (1). The second requirement is associated with the temporal decorrelation, which is dependent on the stability of the illuminated surface. The temporal decorrelation is more a local measure for the reliability of the phase difference, because most images contain different surfaces with different natures. For example, urban and rock areas are generally more stable than surfaces like range land and wood. Water surfaces change very fast. The total correlation of a surface, including the spatial and temporal decorrelation, is also denominated as the coherence.

To generate a DEM the following procedure must be followed:
(1) co-registration
(2) calculation of the phase difference image, including correction for phase difference of the reference earth model
(3) phase unwrapping
(4) calculation of the local terrain height using equation (1)
(5) possible subtraction of an elevation trend or offset

Step 3 is an important step in interferometric processing. Because the range of the phase is 0 to 2π (meaning it is wrapped), the phase difference image has to be unwrapped. In practice, this is a difficult problem. Its success is dependent on the reliability of the phase (coherence) and the robustness of the algorithm. Therefore, most algorithms temporary stop unwrapping if the coherence is too low, and interpolate the missing parts. After unwrapping, the DEM can be calculated using equation (1). Sometimes it is necessary to subtract an overall trend or offset (step 5), due to errors in the reference phase. To calculate a possible trend or offset, the differences in elevation have to be small compared to the dimensions of the image. Another method is locating reference points in the image of which the height is known.

The tandem pair that was used was 32516-12843, acquired on 3-4 October 1997, see table 2. The baseline of this image pair is not ideal for interferometric processing, because it leads to a maximum coherence of 0.685, see table 6. This will have an effect on the phase unwrapping (step 3). Other suitable tandem pairs were unfortunately not available at the moment of this study. The procedure did not give any problems, except for step 3, as expected. An elevation trend was found so step 5 was performed. After processing, the DEM was compared with a photogrammetric DEM with a vertical accuracy better than 2 m (Sliuzas and Brussel 2000b). The analysis showed differences up to ±80m. The histogram of the differences in height between both DEMs, also showed three major Gaussian distributions at an in-between distance of 36 m. This indicates phase unwrapping errors because it corresponds to one phase cycle (2π). The RMS of the single Gaussian distributions measured about 16 m, which is not extreme for an interferometrically obtained DEM (Small and Nuesch 1996). But it is larger than that of the photogrammetric DEM. The main reason for this is the low coherence.

Atmospheric effects were not expected. To increase the accuracy of the ERS DEM, other and probably more image pairs are required, including another phase unwrapping algorithm.

Besides a phase image and its resulting elevation model, a coherence image was obtained from the co-registered image pair. This image gives us information on the stability and nature of the local illuminated surface. Classification schemes based on the coherence are given (Askne and Hagberg 1993, Wegmuller and Werner 1997). To investigate its potential for the case of Dar es Salaam, a colour composite was made of the coherence and the intensity sum of tandem pair 32516-12843, see figure 7. Unfortunately no time was left to include the coherence in a classification scheme. The coherence image of image pair 04061-19091 was also obtained. In this image only the city is visible because of the long time interval of 1050 days. Therefore this image was also much noisier.

Tandem pair	Interval	$B_{//}$	$B_{\perp}$	B_y	B_z	Spatial decorrelation
32516-12843	1 day	187.23 m	375.59 m	305.68 m	287.55 m	0.685
04061-19091	1050 days	347.96 m	966.75 m	661.12 m	786.51 m	0.319

Table 6. The baselines of the ERS tandem pairs (parallel, perpendicular, horizontal, and vertical components) and their spatial decorrelation.

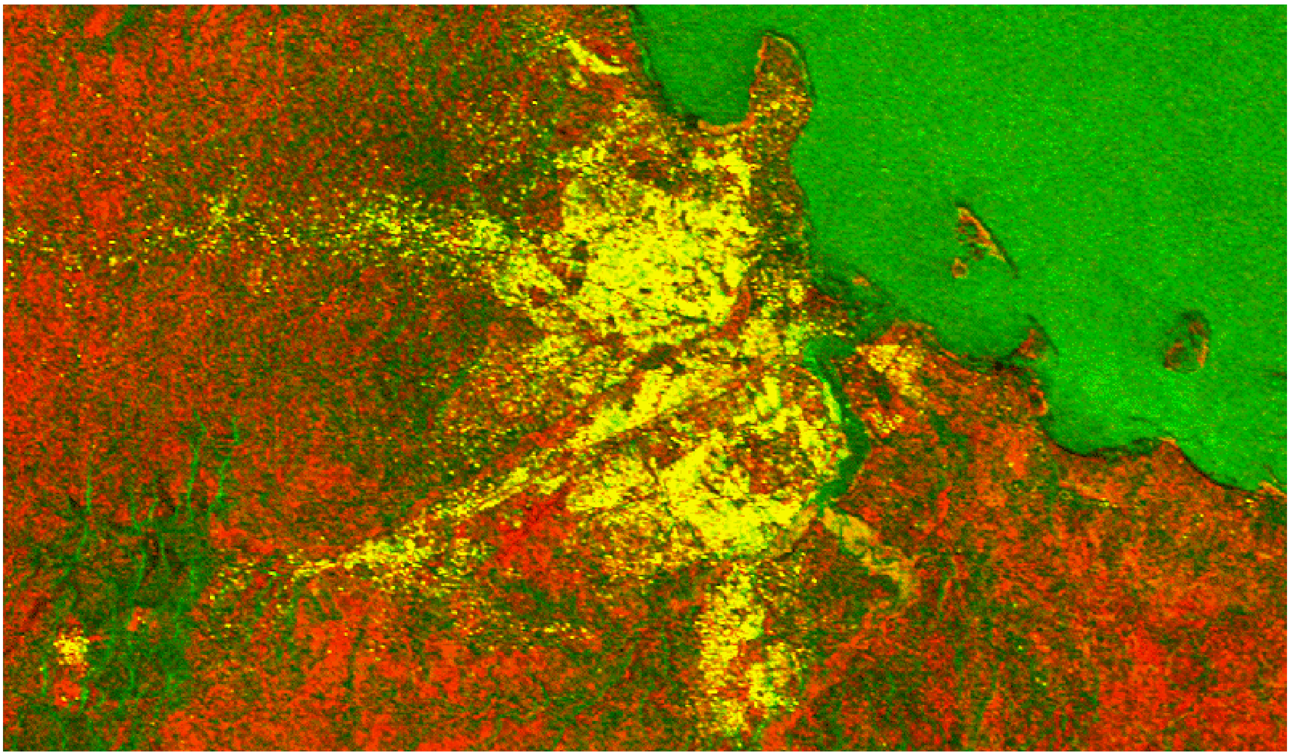

Figure 7. Colour composite of the coherence image (red) and the intensity sum image (green) of tandem pair 32516-12843. Urban objects have both a high intensity and coherence and will therefore be yellow. Forest has medium intensity and low coherence and will therefore be green (e.g. the Pugu Forest Reserve, bottom left).

6 CONCLUSIONS AND RECOMMENDATIONS

A change map, land use segments and a DEM are generated from four ERS SAR images.

The change map shows a high correlation with the ground truth. The method of Dekker (1998) proves to work properly in detecting new human settlement on the outskirts of Dar es Salaam. The fact that the incidence angle of the radar matches with the average tilt angle of the roofs contributes to this. The OS-CFAR method also works properly but proves to be less accurate than the last method. The change map is pre-eminently suited as input for the estimation of the number of new houses and the increase of the population index.

The result of land use segmentation, using the image intensity and texture, is accurate enough for larger scale interpretation. The high degree of speckle reduction of the imagery contributes to this. Classification of the ERS SAR image segments using texture was not performed, but is recommended regarding the results of segmentation. It is also recommended to study the application of coherence imagery in a classification scheme, as a measure for the changeability of a surface.

The DEM turned out to be not accurate enough compared to a photogrammetric DEM. Differences up to ±80m occurred. The major reasons for this are the large baseline of the data set, and the accuracy of the phase unwrapping algorithm. Other and more suitable data sets, and another phase unwrapping algorithm are recommended. The availability of other data sets must be studied. Other unwrap algorithms are available from literature.

The overall conclusion of this study is that ERS SAR imagery, in combination with change detection, segmentation, and interferometry, has a large potential for urban monitoring in developing countries. Despite Henderson and Xia (1997), ERS SAR imagery is suitable for change detection, land use classification, and population index estimation. However, research considering data of other radar satellites as JERS, RADARSAT, and especially future polarimetric satellites, is recommended.

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