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Radar Earth Observation Imagery for Urban Area Characterisation

Katrin Molch

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European Commission
Joint Research Centre
Institute for the Protection and Security of the Citizen

Contact information
Address: Via E. Fermi 2749, TP 267
E-mail: katrin.molch@jrc.it
Tel.: +39 0332 78 5777
Fax: +39 0332 78 5154

http://isferea.jrc.ec.europa.eu/
http://ses.jrc.it/
http://ipsc.jrc.ec.europa.eu/
http://www.jrc.ec.europa.eu/

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1 Abstract

This report introduces the use of medium to high resolution spaceborne radar (SAR - Synthetic Aperture Radar) Earth observation imagery for urban area mapping applications. Urban mapping can benefit from this type of satellite data since built-up structures induce strong backscatter and thus can be distinguished well on radar imagery. The objective is to raise awareness about the possibilities and some of the limitations associated with using SAR satellite imagery for characterizing the built-up area.

The delineation and thus knowledge on the distribution of urban agglomerations at a global or continental scale is of importance to a wide range of applications such as determining hot spots in the framework of disaster preparedness, or modeling the impact of a disease outbreak.

Population, however, is not distributed evenly throughout an urban area. For applications supporting e.g. humanitarian aid initiatives, the outline of the urban or built-up are, thus, might not be sufficient. These applications require reliable information on where the people are. At smaller scales, the density of built-up structures can serve as a first, coarse estimate of the population distribution within a city. Population density varies between different neighborhoods - and with time of day. Built-up density maps thus provide added value to binary built-up area delineations. Moreover, this density distribution changes over the years. It can be monitored by multi-temporal built-up density maps.

A critical parameter to measure at a regional scale is the built-up stock. Measuring built-up stock takes into account the type and distribution of buildings. This can aid in estimating the population of a given area, specifically in regions where administrative data of this type are not readily available. Population information is essential for assessing the number people potentially affected should a crisis, natural or man-made, occur, and will help determine the type and amount of aid required.

Most globally available land cover datasets, such as Global Land Cover (GLC) 2000, or Africover, merely provide urban area outlines. As a global population dataset, the Landscan data, updated every few years and available through the Oak Ridge National Laboratory, USA, depict population density in 1 km raster cells. This report addresses possibilities to use SAR data to improve these existing globally available datasets either with respect to spatial resolution or thematic information.

As a result of their reliability, weather independence, and relatively low cost, satellite SAR imagery at approximately 23 m spatial resolution (ERS-1 /-2, ENVISAT) constitute an attractive alternative to optical imagery for mapping purposes at scales of up to 1:100,000. Higher resolution satellite SAR data (RADARSAT-1/-2, TerraSAR-X) are useful for inner-city differentiation.

SAR data are different from optical data with respect to the surface parameters they measure and in the way the information is coded in the image. Moreover, the side-looking geometry introduces geometric effects. The sensor-specific image characteristics have to be taken into account during SAR data processing and information extraction.

After a brief introduction, the representation of urban areas on SAR images is illustrated. Specific issues and limitations are discussed. In the final chapter methodologies towards automating built-up area delineation and characterization from SAR data are introduced.

2 Introduction and Objective

For crisis management and related applications three main topics are of specific interest with respect to urban areas:

1. Delineation of the built-up area
2. Differentiation within the city
3. Detection and count of individual buildings in rural area

The delineation and thus knowledge on the distribution of urban agglomerations at a global or continental scale is of importance to a wide range of applications such as determining hot spots in the framework of disaster preparedness, or modeling the impact of a disease outbreak.

Population, however, is not distributed evenly throughout an urban area. For applications supporting e.g. humanitarian aid initiatives, the outline of the urban or built-up are, thus, might not be sufficient. These applications require reliable information on where the people are located. At smaller scales, the density of built-up structures can serve as a first, coarse estimate of the population distribution within a city. Population density varies between different neighborhoods - and with time of day. Built-up density maps thus provide added value to binary built-up area delineations. Moreover, this density distribution changes over the years. It can be monitored by multi-temporal built-up density maps.

A critical parameter to measure at a regional scale is the built-up stock (Ehrlich, 2008). Measuring built-up stock takes into account the type and distribution of buildings. This information can aid in estimating the population of a given area, specifically in regions where administrative data are not readily available. Population information is essential for assessing the number people potentially affected should a crisis - natural or man-made - occur, and will help determine the type and amount of aid required.

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As a result of their reliability, weather independence, and relatively low cost, satellite SAR imagery at approximately 23 m spatial resolution (ERS-1 /-2, ENVISAT) are an attractive alternative to optical imagery for mapping purposes at scales of up to 1:100,000. Higher resolution satellite SAR data (RADARSAT-1/-2, TerraSAR-X) are useful for inner-city differentiation and larger scale mapping of building aggregates and individual built-up structures (Esch, 2006: 5-7).

The use of spaceborne SAR data for civilian urban applications is not new. SAR backscatter, texture, interferometric, and fusion techniques for urban area analysis have been explored by various researchers (Dong, 1997; Molch, 1997; Quartulli, 2003; Trianni, 2004). More recently Esch (2006) has investigated automated urban area classification possibilities. In addition to area-based analyses, research also addresses SAR data exploitation at the level of building aggregates and individual built-up structures (Gamba, 2000; Bolter, 2001). Recently launched SAR sensors provide higher resolution data (RADARSAT-2) and, additionally, a different system frequency (TerraSAR-X, CosmoSkymed) which both affect urban area representation and offer new exploitation possibilities.

SAR data are different from optical data with respect to the parameters they measure and in the way the information is coded in the image. Moreover, the side-looking geometry introduces geometric effects. The sensor-specific image characteristics have to be taken into account during SAR data processing and information extraction.

The objective of this report is to raise awareness about possibilities and some of the limitations associated with using SAR satellite imagery for urban area mapping. While addressing effects related to individual buildings and aggregates the focus is on area-based approaches.

3 SAR Sensors and Characteristics

A series of medium and high-resolution SAR satellites are available to provide data of use for civilian urban applications. Table 1 lists currently available sensors, including the spatial resolution of the highest resolution acquisition mode of each sensor. Lower resolution modes are generally also available, however, these are less suitable for larger scale urban area mapping.

Data archives, background mission, and data continuity

For long-term monitoring purposes at scales of up to 1:100,000 the medium-resolution data of ERS-1, ERS-2, and ENVISAT are of particular interest. The data are available at relatively low cost. Via background missions, conducted by ESA, these sensors provide multiple global coverages and data continuity, with similar sensor parameters and acquisition geometries, back to 1991.

Data characteristics general

Radar or SAR (Synthetic Aperture Radar) data should be particularly suited for the purpose of extracting built-up areas in a variety of geographic locations. They constitute a reliable data source in all climatic regions, specifically also in tropical areas, where frequent cloud cover limits the acquisition of optical data. The calibrated SAR data provide consistent image quality, less affected by seasonal variations.

However, the SAR's side-looking geometry induces geometric effects, such as relief distortions, in the form of foreshortening and layover effects, which are particularly annoying in densely and tall built-up urban areas. Additionally, the local incidence angle and associated spatial resolution varies across range. A SAR sensor measures surface parameters which are different from the spectral characteristics measured by an optical system. It reacts predominatly to surface geometry and dielectric material properties. Additionally, the raw signal passes through an image formation process based on signal focusing. Antenna characteristics, backscattering mechanism, and the image formation procedure induce specific pixel patters in the resulting SAR image. For these reasons, the features present in the radar image are not comparable with the information contained in an optical image. Extraction and classification methods used for optical data, such as those based on radiometric similarity thus tend to fail.

This report looks in particular at data from medium to high resolution spaceborne SAR sensors, considering in particular ENVISAT and RADARSAT-1 data, and their application to built-up area delineation and built-up density mapping. Table 2 and Table 3 list the datasets which were available for study. Only selected datasets, however, are presented in this report.

Table 1. Spaceborne SAR sensors available for civilian urban area applications

Satellite	Maximum spatial resolution* [m]	Wavelength [cm] (band)	Polarization	Orbit repeat cycle [days]**	Country	Year launched
CosmoSkymed	1	3 (X-band)	HH, VV, HV, VH	16	Italy	2007
TerraSAR-X	1	3 (X-band)	HH, VV, HV, VH	11	Germany	2007
RADARSAT-2	3	5.6 (C-band)	HH, VV, HV, VH	24	Canada	2007
ALOS	10	23.5 (L-band)	HH, VV, HV, VH	46	Japan	2006
ENVISAT	23	5.6 (C-band)	HH, VV, HV, VH	35	Europe	2002
RADARSAT-1	8	5.6 (C-band)	HH	24	Canada	1995
ERS-2	23	5.6 (C-band)	VV	35	Europe	1995
ERS-1	23	5.6 (C-band)	VV	35	Europe	1991

*) Lower resolution acquisition modes are generally also available
**) Site revisit times at varying incidence angles and for multi-satellite missions are shorter

Table 2. ENVISAT data available to the project

Acquisition date	Orbit	Beam	Incidence angle*	Polarization	Absolute orbit	Track / Frame
13-Sep-03	Ascending	IS-1	18°	VV	8040	471 / 7167
06-Dec-06	Descending	IS-2	22°	HH	24924	321 / 3631
10-Jan-07	Descending	IS-2	22°	HH	25425	321 / 3631
14-Feb-07	Descending	IS-2	22°	HH	25926	321 / 3631
21-Mar-07	Descending	IS-2	22°	HH	26427	321 / 3631
04-Jan-07	Descending	IS-6	40°	HH	25339	235 / 3645
08-Feb-07	Descending	IS-6	40°	HH	25840	235 / 3645
15-Mar-07	Descending	IS-6	40°	HH	26341	235 / 3645
19-Apr-07	Descending	IS-6	40°	HH	26842	235 / 3645

* Approximate value at scene center

Table 3. RADARSAT data available to the project

Acquisition date	Orbit	Beam	Incidence angle*	Polarization	Absolute orbit	Cycle / relative orbit
09-Nov-06	Descending	F2	40.7°	HH	57489	167 / 124.50477
03-Dec-06	Descending	F2	40.7°	HH	57832	168 / 124.50477
03-Aug-07	Ascending	F4	44.7°	HH	61312	178 / 174.99329
16-Nov-06	Descending	F5	46.4°	HH	57589	167 / 224.50491

* Approximate value at scene center

4 Urban Area Representation on SAR Images

Three sets of parameters influence urban area representation on a SAR image, under the assumption of standard processing or image formation:

- Sensor parameters including wavelength and polarization
- Acquisition geometry including orbit direction, local incidence angle, and aspect of the target with respect to sensor position
- Target and surrounding area properties including roughness and material of building and surrounding area, spacing of individual targets

Buildings generally generate a strong response in SAR imagery. Exceptions are occasional omissions associated with unfavorable viewing geometry (specular reflections away from the receiving sensor, interference-related signal cancellations), non-reflective building material (wood, plastic), or vegetation-related signal attenuation and depolarization effects.

The SAR specific response of an urban area cannot be compared with that of an optical sensor. In contrast to optical sensors, SAR does not react to spectral reflectivity, i.e. to surface ‘color’, but primarily to surface geometry (roughness, specular and corner reflections, volume scattering), coupled with material properties such as moisture and penetrability. The individual response depends highly on the local incidence angle, with the side-looking geometry inducing additional effects. Tall buildings, for instance, are seemingly imaged lying down which is easily visible on VHR SAR imagery.

The signals are processed into SAR signatures, which include side lobe effects and overlapping responses from dominant scatterers. Information extraction methods applied to optical data therefore tend to fail since parameters measured and the way they are represented in the SAR image are different. Precise size measurements e.g. are challenging, since a strong target, much smaller than the system’s spatial resolution, can saturate an entire resolution cell or pixel. SAR information relevant for urban area characterization at the spatial resolutions discussed here, which are between 8 m and 30 m, is contained in image textures, local statistics, and in bright target responses.

4.1 Representation of different urban land uses in SAR imagery

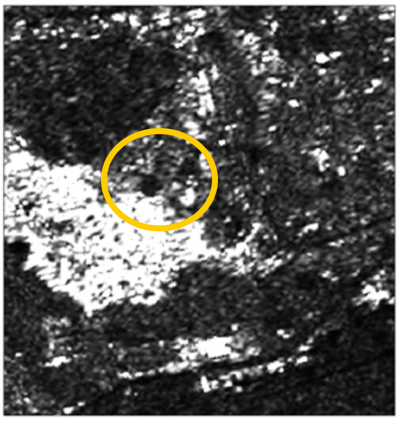
The following illustrations (Fig. 1) compare, at a small scale, the representation of various urban land uses on a high-resolution optical image with RADARSAT Fine Mode data at 8 m spatial resolution and ENVISAT data at approximately 23 m ground range spatial resolution. This comparison illustrates well the different representations in optical and SAR imagery and demonstrates the effects of different spatial resolutions, incidence angles, and polarizations.

Consistently higher responses can be observed in all five images for the densely built up areas, such as the Kibera slum (left, center) compared to the varying textures of medium gray levels with individual bright responses for more vegetated built-up areas. Areas which combine vegetation and built-up, respond in varying textures of medium gray with individual buildings and building aggregates leading to individual higher responses. Areas covered by taller vegetation (bushes, trees) respond as stronger textures in medium grays; short vegetation (grass) as a result of largely specular reflection appears dark.

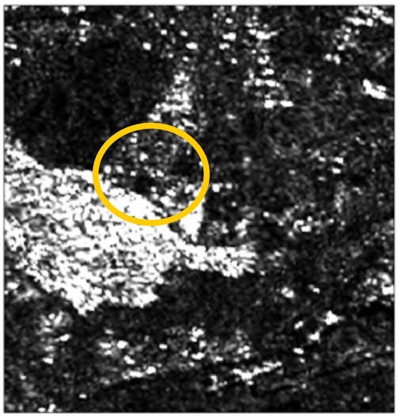
(a)
Quickbird, 11-Feb-02

(b)
RADARSAT-1 F2 (θ_i = 41°), descending, HH, 09-Nov-06

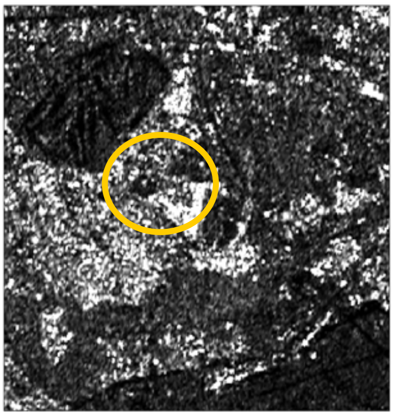
(c)
RADARSAT-1 F5 (θ_i = 46°), descending, HH, 16-Nov-06



(d)
ENVISAT IS-1 (θ_i = 18°), ascending, VV, 13-Sep-03



(e)
ENVISAT IS-2 (θ_i = 22°), descending, HH, 06-Dec-06



(f)
ENVISAT IS-6 (θ_i = 40°), descending, HH, 04-Jan-07

Fig. 1. A variety of different urban land uses on very high-resolution optical imagery (a), on RADARSAT-1 8 m resolution (b,c) and on ENVISAT 30 m resolution images (d,e,f) . On these three images the influence of the incidence angles (**θ_i**) on the urban area representation can clearly be seen. In these 'ground range,' geocoded images the ENVISAT IS-6 at 40° incidence angle (f) has a better spatial resolution than the IS-1 at 18° (d). As a combined effect of orbit, aspect, incidence angle, spatial resolution, and signal polarization, the same areas on the ground are represented in a different way in each image (yellow circle).

Resolution

The RADARSAT-1 Fine mode imagery at 8 m spatial resolution (b,c) provides better discrimination, in terms of textural variations, within individual areas of urban land use. The ENVISAT imagery at approximately 23 m spatial resolution, averages much of the smaller textural variation into larger, more uniform areas of high, medium, or low response.

Incidence angle

As a SAR specific effect, spatial resolution at ground range is also influenced by the incidence angle at which the image is acquired. The ENVISAT IS-6 image acquired at a larger incidence angle of 40° (f) has a higher spatial resolution, leading to better differentiation within urban land uses, than the IS-2 image acquired at the small, i.e. steep incidence angle of 22° (e).

Moreover, a higher target-to-clutter ratio at larger incidence angles adds to the improved differentiation of target vs. vegetation in the IS-6 image. However, larger incidence angles result in longer shadows, that can obscure ground features behind e.g. taller building aggregates. The circle shows a loss of response associated with viewing geometry, i.e. with the building aspect with respect to the SAR look direction, here associated with orbit direction. This effect will be described in detail below.

Polarization

HH polarization is generally preferred for better discrimination in urban areas. Here the combined effects of different orbit direction, incidence angle and polarization of the three ENVISAT images (d,e,f,) makes it difficult to isolate the specific effect of the polarization on the resulting image. In general, SAR data at ~20 m resolution, acquired in VV polarization over urban areas, are characterized by a reduced differentiation of land uses, specifically between built-up and vegetation.

4.2 Effect of data processing, filtering, and enhancement

In addition to data calibration, in general sigma nought (backscatter) or beta nought (brightness) in units of power, amplitude, or dB, the processing level and processing applied to the SAR data will greatly affect the radiometry of the SAR image product. Working with either single-look or multi-look imagery, a trade-off between maintaining spatial resolution vs. improved speckle reduction, the application of filter operations and resampling procedures, decisions on and during modification of the dynamic range of the data (float, integer, byte), and 'enhancements' in the form of look-up tables will result in radiometrically and texturally different images. Thus, the (pre-) processing is a critical factor, in particular when preparing the data prior to applying sensitive, automated numeric analysis techniques which are based on gray levels or derived values (gradient, textures, etc.). For these reasons, an operational workflow involving SAR imagery should include a standardized, reproducible pre-processing sequence, in order to ensure that data of the same radiometric and geometric qualities are used in the visual or automated analysis process.

The pre-processing steps performed should always take into account the analysis method to be subsequently used. For ease of visual interpretation, or for larger area based pattern or coarser texture analysis, data manageability and speckle reduction will likely dominate. Operations might include multi-looking, speckle filtering, orthorecification, byte scaling, or data stretching via look-up-tables. While rendering the image easier to interpret visually, these operations destroy the calibrated numeric value of the SAR image pixel.

For finer, building level analysis a loss of detailed, calibrated radiometric information might not be acceptable, since subtle discerning information picked up by specific analysis algorithms may be destroyed. To take advantage of this information, the analysis should be done on data which have been least modified, i.e. on single-look, slant range, not georeferenced, unfiltered data.

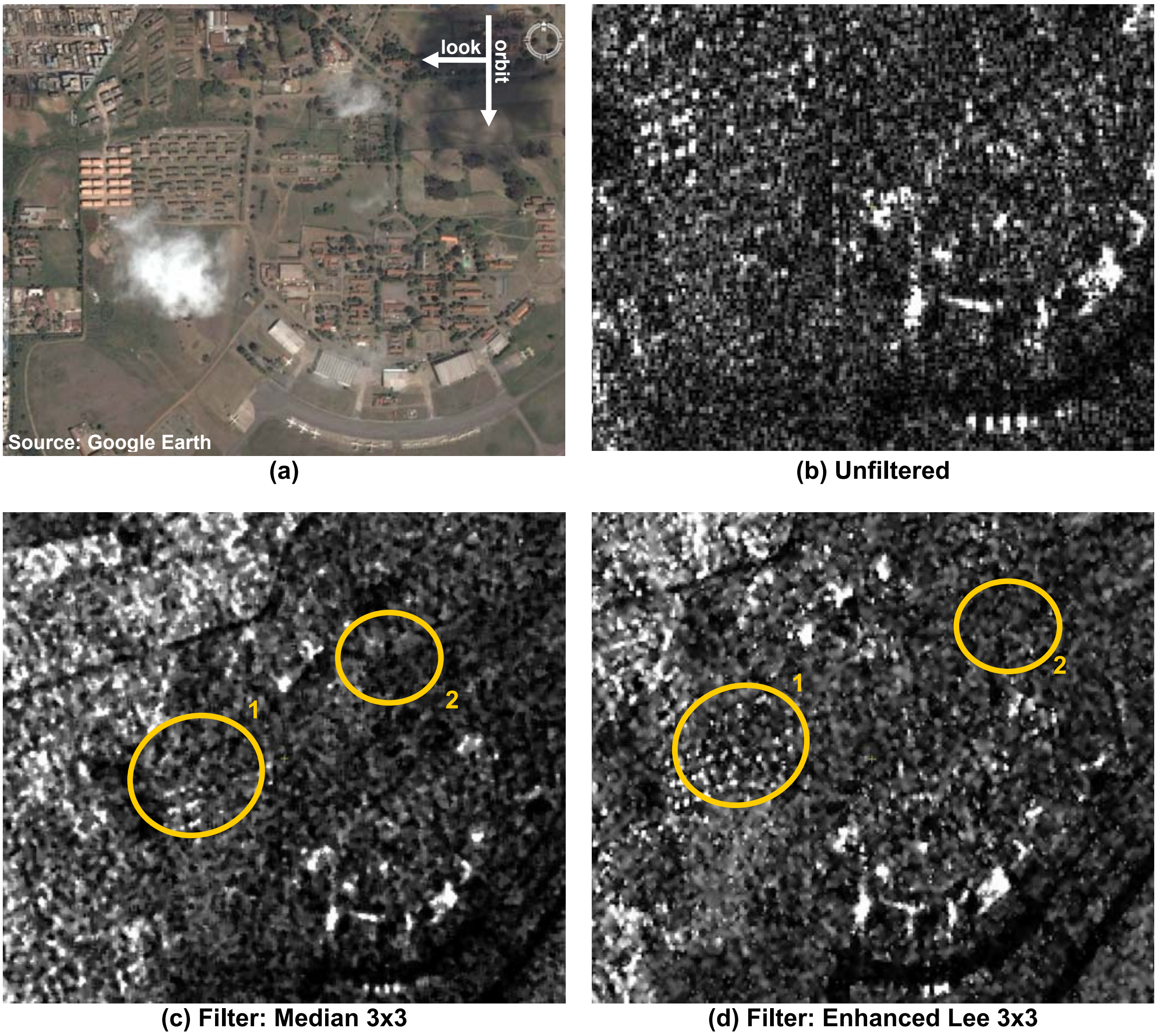
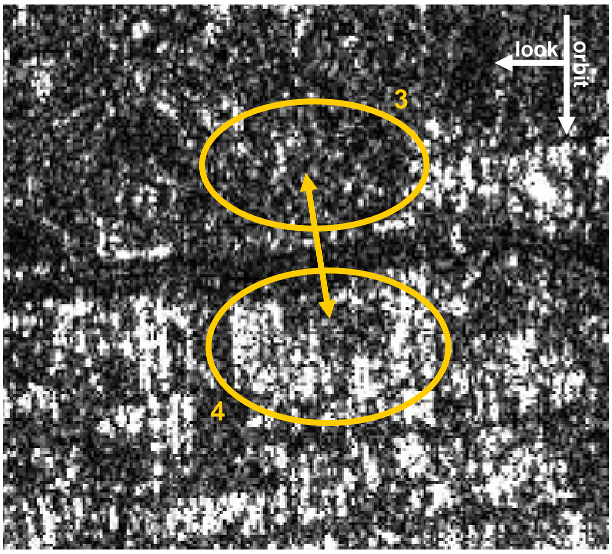


Fig. 2. The Quickbird image (a), acquired in December 2004, is compared to filtered and unfiltered, ungeoreferenced, single look RADARSAT-1 Fine mode (Beam 2, descending, 09-Nov-06) images (b-d).

In Fig. 2. a Quickbird image (a) of December 2004 is compared to filtered and unfiltered, ungeoreferenced, single-look RADARSAT-1 Fine Mode images (b-d) of November 2006. The time difference between the acquisitions with respect to construction activities has to be taken into account when comparing the imagery. The unfiltered image in (b) displays more speckle 'noise' but also enhanced radiometric detail. In (c) and (d) the effect which different 'speckle' filters have on the representation of buildings can be observed. Both reduce speckle but finer image detail is also lost. While the median filter is a generic filter, the Enhanced Lee filter belongs to a family of adaptive filters specifically designed for speckle reduction in SAR data. High-frequency image detail is maintained better by the Enhanced Lee filter (1). However, it produces high frequency image artifacts visible as single bright pixels (2).

4.3 Effect of vegetation on built-up area representation

Vegetation has a strong influence on the representation of urban areas. The incoming and reflected radar signal is affected by volume scattering and signal attenuation to a degree where even hard target echoes, such as from buildings in-between vegetation, do not return to the sensor. Thus, some buildings, clearly visible among the vegetation in the optical image are not depicted on the SAR image (Fig. 3).



(a) Quickbird 11-Feb-02 **(b) RADARSAT-1 F2d 09-Nov-06**

Fig. 3. Comparison of the representation of residential areas with different degrees of vegetation on a Quickbird (a) and a RADARSAT-1 Fine Mode image (right). The RADARSAT-1 image is an unfiltered, single-look power image in slant range. The residential area north of the main road is more vegetated (1) than south of the road (2) and is represented by lower backscatter on the RADARSAT Fine mode image (3) than the less vegetated area south of the road (4).

Fig. 3 shows the representation of different residential areas on Quickbird and RADARSAT-1 Fine Mode data at 8 m spatial resolution. The residential area north of the main road is more vegetated (1) than south of the road (2), which is clearly visible on the Quickbird image. The highly vegetated residential neighborhood is represented by considerably lower backscatter on the RADARSAT Fine mode image (3) than the less vegetated neighborhood south of the road (4). Additionally, the buildings in both areas are generally oriented at different angles with respect to the sensor, which can also induce a loss of signal. This effect is discussed in chapter 4.4

This vegetation effect is dependent on the wavelength (λ) of the SAR system and varies with local incidence angle. RADARSAT-1 (Fig. 3 (b)) operates in C-Band (λ=5.6 cm). The effect will be more pronounced at shorter wavelengths, e.g. in TerraSAR-X and CosmoSkymed data (X-band, λ=3 cm) and less obvious at longer wavelengths, such as in ALOS data (L-band, λ=23 cm).

Larger incidence angles generally provide better discrimination of hard targets vs. (lower) vegetation. The RADARSAT image in Fig. 3 was acquired with an incidence angle of 41° at the scene center.

4.4 Effect of viewing geometry on built-up area representation

In addition to the combination of target and surrounding surface material properties and vegetation related signal attenuation, the viewing geometry, i.e. a combination of orbit direction, (local) incidence angle, and aspect angles of the target with respect to the sensor look direction in azimuth and elevation, has a crucial effect on the way a target, e.g. a built-up neighborhood, is represented in the SAR image.

As an active sensor, SAR imagery can be acquired both during ascending (south-north) and descending (north-south) orbits, one of which usually occurs at night. The SAR sensors of RADARSAT-1 and ENVISAT look right at an angle of 90° with respect to orbit azimuth. Other sensors, such as RADARSAT-2, TerraSAR-X and CosmoSkymed, or airborne sensors can be programmed to acquire imagery either right-looking or left-looking. The downward looking angle is determined by the beam mode selected for the acquisition.

Occasionally, individual buildings or even entire neighborhoods, are not represented in the SAR image. In addition to vegetation attenuation as discussed above, these omissions can be explained by factors related to viewing geometry.

A regular spacing of main reflectors of a building (corner reflection, roof line) at integer multiples of the wavelength (λ) in slant range, shifted by ½ λ can lead to destructive interference of the reflected sine-shaped

SAR signals. The buildings will not be depicted in the SAR image. Similar destructive interference effects have been shown for vegetation with respect to leaf spacing, and can also cause dark speckle pixels.

The aspect of a building with respect to the look direction of the radar beam has a crucial effect on the way and whether at all a building or neighborhood is represented in the processed SAR image. Smooth building walls can be seen as specular reflectors. If the building is oriented at an angle other than perpendicular to the look direction, the incident radar beam can be reflected away from the sensor. With no portion of the reflected signal returning to the antenna, the building will not be depicted in the SAR image. A minimal shift in aspect angle can induce this effect.

Fig. 4 shows an example of how the 3-dimensional viewing geometry - incidence angle differences and variations in the aspect angle of the buildings with respect to the radar beam - influences the representation of built-up areas on SAR images. Three different ENVISAT images have been integrated into a multi-temporal, multi-aspect, and multi-incidence angle color composite. The red, green, and blue color channel assignments are as specified in Table 4.

The illustration (Fig. 4) shows an area in northeastern Nairobi. Neighboring buildings are generally oriented in the same direction, however, the direction changes along the road cutting across the neighborhood north to south. The buildings along the road (1) are depicted only in the IS-2, descending orbit SAR image (green channel), they respond little to none in the IS-1, ascending and in the IS-6 descending image. In contrast, the buildings, present in area (2) show up only on the IS-1, ascending image (red channel); they are not represented in the two images acquired from the opposite orbit.

Some parts of the industrial buildings in the bottom part of the image (3a) show up in the IS-6 image acquired at an incidence angle of 40° (blue); there is no response in the images acquired at the steeper incidence angles. In area (3b) the buildings are constructed at a slightly different angle. At this angle the same type of industrial buildings as in (3a) is not represented in any of the three images.

As a result of the azimuth angles of both axes of the buildings (90°/0° in 3a, 36°/126° in 3b), coupled with the smooth, angular roofs reflect the signal of both passes away from the sensor. Only the signal from the larger incidence angle of the IS-6 (40°) receives some reflection from the sides and between the buildings, visible in the blue channel in Fig. 4(a), area 3a and depicted in yellow in Fig. 5.

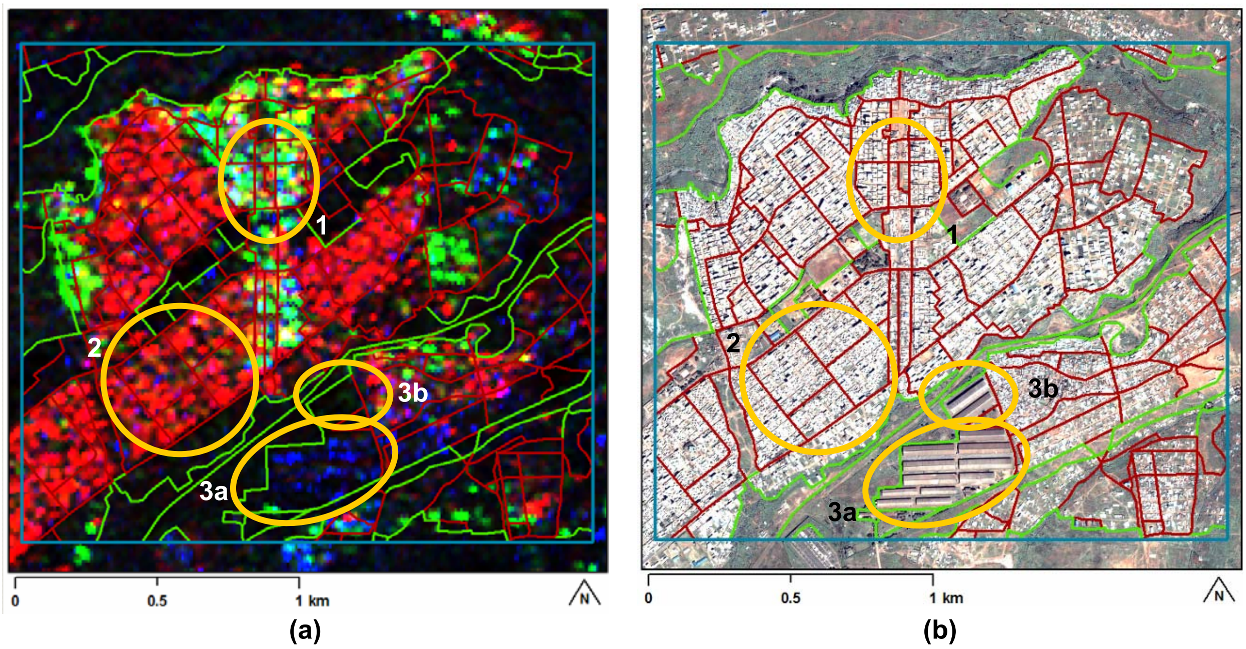


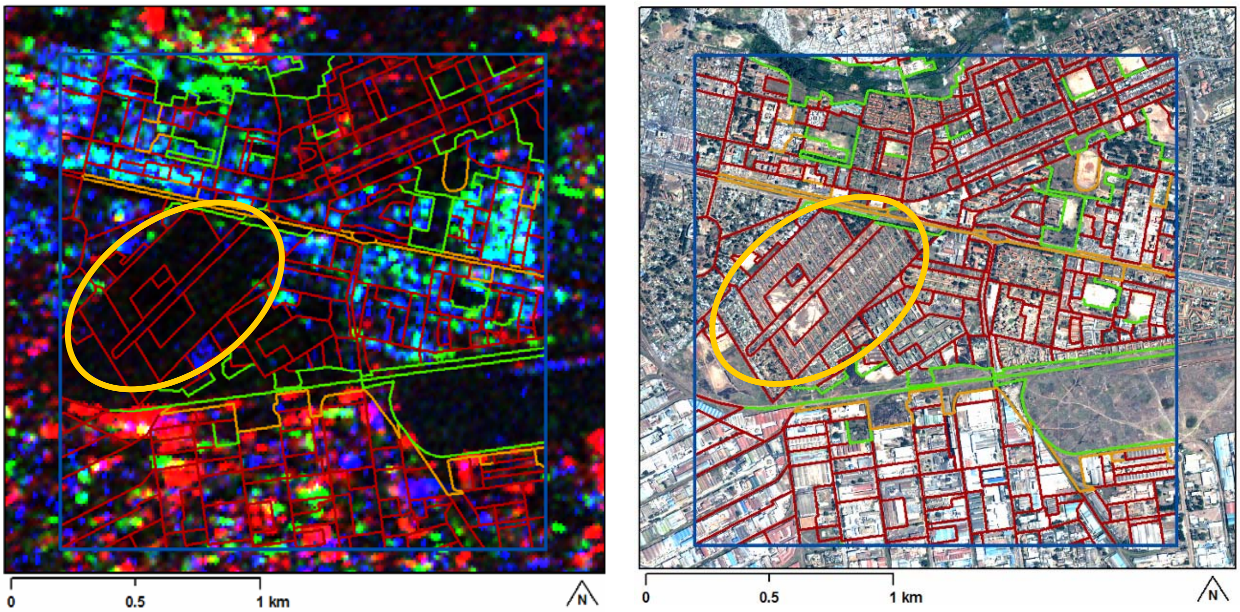
Fig. 4. An area in northeastern Nairobi on an ENVISAT multiple-incidence angle color composite (a) and on a pansharpened Quickbird image (b). Depending on the local incidence angle in combination with the aspect angle of the buildings with respect to the SAR look direction, certain built-up areas can show up only in one (1), (2), (3a) or even none of the incidence angles (3b). The polygons delineate the visually interpreted classes urban built-up (red), urban non-built-up (orange), and non-urban non-built-up (green).

Table 4. ENVISAT input data for multi-aspect / multi-incidence angle color composite presented in Fig. 4 and Fig. 6.

Color in color composite	Acquisition date	Beam	Incidence angle at scene center	Orbit (azimuth)	Look direction (azimuth)
Red	13-Sep-03	IS-1a	18°	Ascending (344°)	Right (74°)
Green	06-Dec-06	IS-2d	22°	Descending (196°)	Right (286°)
Blue	04-Jan-07	IS-6d	40°	Descending (196°)	Right (286°)

(a) (b)

Fig. 5. Industrial buildings in northeastern Nairobi on Quickbird (a). The strong responses from the ENVISAT IS-6 image are overlaid in yellow (b). It can be seen that the responses mainly originate from reflections in-between the buildings along the longitudinal axes.



(a) (b)

Fig. 6. An area in central Nairobi on an ENVISAT multiple-incidence angle color composite (a) and on a pansharpened Quickbird image (b). The circled residential neighborhood does not show up in any of the three images, irrespective of orbit and incidence angle The polygons delineate the visually interpreted classes urban built-up (red), urban non-built-up (orange), and non-urban non-built-up (green).

Fig. 6. shows an even more extreme case where a complete residential neighborhood is not represented in any of the three images, irrespective of orbit or incidence angle. The circled area in (a) is dark, i.e. it is not visible on any of the three images. As can be seen on the Quickbird image in (b) the apartment buildings are regularly spaced and constructed at an azimuth angle of 150° (long axis). This axis is hit by the radar beam at only 14° off perpendicular for ascending orbit, at 18° incidence angle, and 46° off perpendicular in the descending case, at incidence angles of 22° and 40°.

Due to the side-looking nature of active SAR systems, the three-dimensional incident beam angle (azimuth, elevation), coupled with smooth building and ground surfaces, can lead to signal reflections away from the sensor resulting in individual buildings or even entire neighborhoods not being represented on the SAR image. As seen above, this effect can be moderated to a certain degree by using multiple datasets acquired at incidence angles and form the opposite orbit. Both of which can add some, but not all, of the information which is missing in an individual dataset. This practice will, however, also induce a multi-temporal component to the dataset.

5 Towards Automating Built-up Area Characterizations

Where extensive areas are to be covered, at the scale of entire countries or even continents, manual interpretation of built-up area, from any type of Earth observation data, becomes impractical. For monitoring purposes, the interpretation might even have to be repeated frequently. In addition to the amount of time involved, oftentimes the subjectivity introduced by a human interpreter is not acceptable. It is therefore of importance to investigate possibilities for automatic built-up area extraction. Recent research has investigated and assessed possibilities in detail, and contributed to novel methodologies (Esch, 2006).

Several methods can be applied - separately or in combination - to extract built-up area from SAR data. Simple backscatter-based methodologies are complemented by texture-based and morphological approaches. For the application envisaged here, the method has to be:

- operational
- accurate
- efficient
- robust

The omissions discussed above will be present and affect the classification, but SAR data of spatial resolutions as considered herein (8-25 m), should be suitable for mapping urban area at scales of up to 1:100,000.

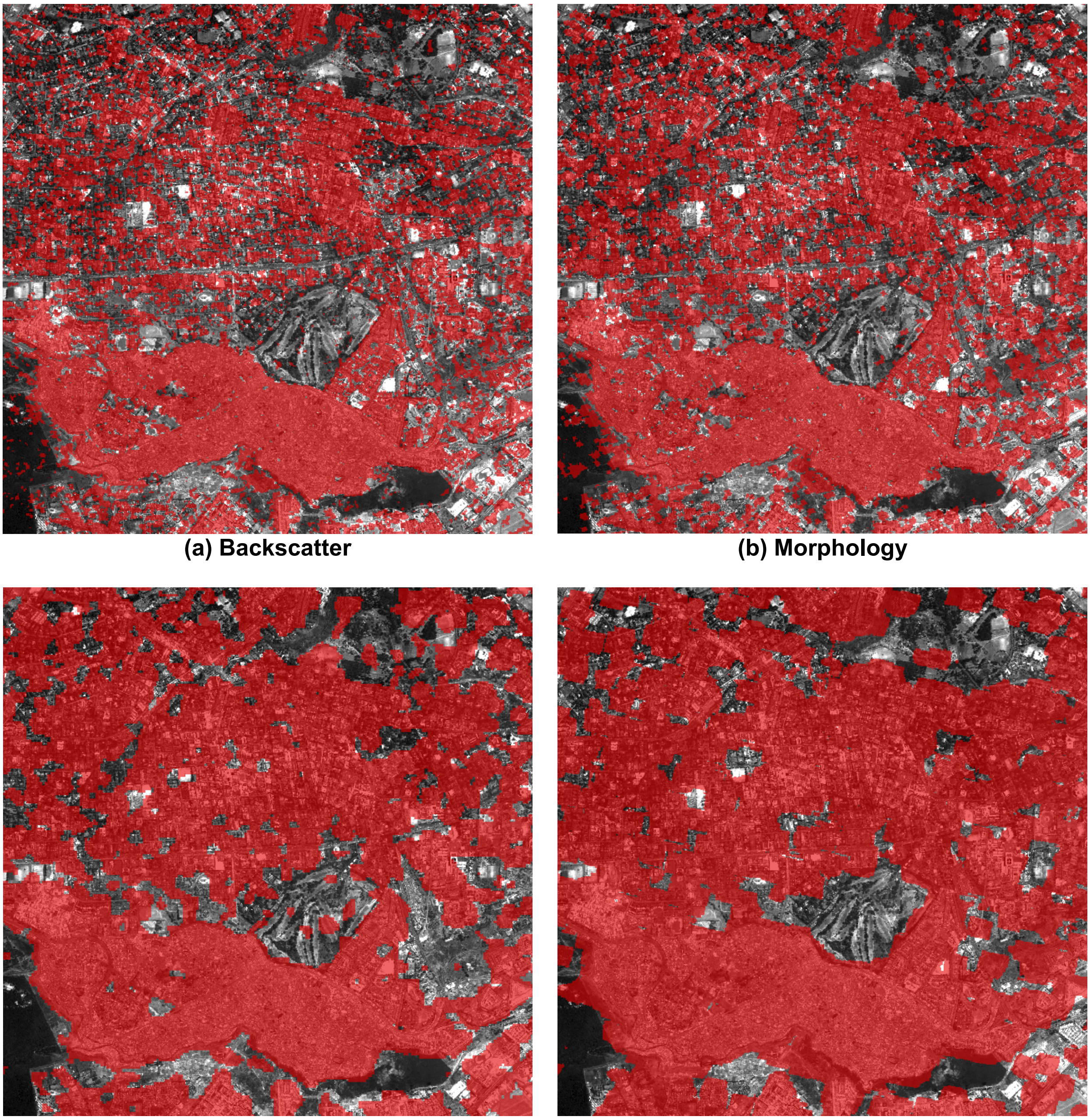
Three different approaches to built-up area mapping have been investigated. All three are geared towards making available a simple, robust methodology, with a view to global applicability. The attempt was to provide a balance between computational efficiency and classification accuracy.

While binary built-up area classifications from SAR data, discussed in 5.1 , discriminate between built-up and non-built up areas, the texture based 'anisotropic, rotation-invariant' built-up area index in 5.2 can also be used as a probabilistic or fuzzy classification with pixel values indicating differences in membership to the class 'built-up.' Binary urban area-classifications generated by any method can be aggregated into built-up density maps, which are discussed in 5.3 5.3 .

As introduced earlier, the objective is to assess the capabilities of medium to high resolution spaceborne SAR data for generating urban area layers which provide an added value, in spatial or thematic resolution, over existing global urban area and population datasets such as GLC 2000, Africover, or Landscan.

5.1 Binary built-up area delineations

Within the limitations discussed above, built-up structures induce high backscatter values in a radar image. They thus can be derived from SAR data via simple density slicing. Errors may occur where other image features e.g. cliffs or steep slopes result in equally high backscatter, or where an unfavorable viewing geometry or vegetation prevents the representation of the built-up structures in the resulting SAR image. These errors can possibly be overcome by combining different information layers extracted from various features of the SAR data, such as coherence, texture, or morphological parameters. Multiple aspect data, as discussed above, are another option to overcome these constraints.



(a) Backscatter **(b) Morphology**

(c) Coherence **(d) Texture**

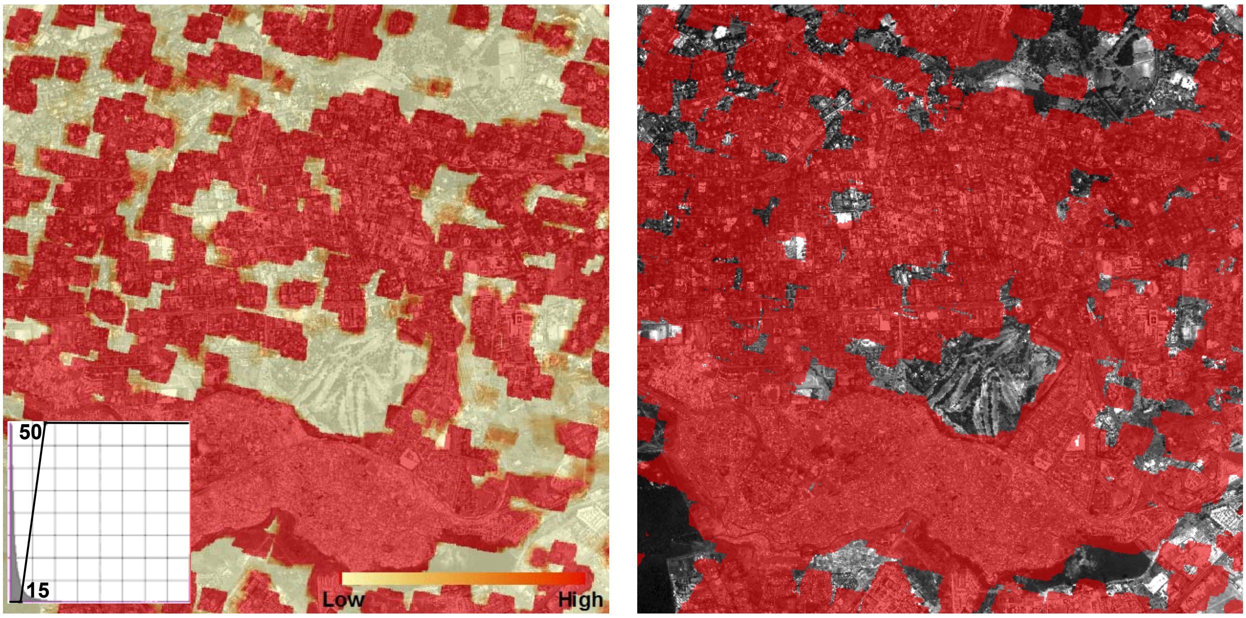
Fig. 7 Binary built-up area classifications based on SAR backscatter (a) or morphological approaches (b) outline the location of individual built-up structures and dense aggregates. The calculation of interferometric coherence involves an averaging which also leads to a delineation of larger contiguous built-up areas instead of individual structures (c).The anisotropic texture-based methodology developed at JRC also delineates contiguous built-up areas (d). The chosen cut-off value for generation of these binary classifications from the continuous coherence or built-up index products influences the delineated built-up area and has to be adjusted carefully, ideally based on reliable reference data.

Fig. 7 shows examples of binary built-up area delineations from ENVISAT data using classifications based on different SAR image features. Both the backscatter-based (a) and the morphology-based (b) classifications respond to the presence of individual built-up structures and building aggregates. Only very densely built-up parts of the city, such as the Kibera slum in the lower part of the image, are depicted as a contiguously built-up area. Interferometric coherence, with the drawback of requiring two identical SAR images, can also serve as input to a binary built-up area classification (c). Coherence responds to the presence of hard targets, to a certain degree also if these are within vegetation. Specialized software is required to process SAR data interferometrically. Making use of specific textural characteristics of a built-up area in the radar image, the classification in (c) was achieved. The built-up area index was converted to a binary map. The chosen cut-off influences the delineated built-up area and has to be adjusted carefully. This texture-based approach is discussed in detail in 5.2 Both, the averaging involved in the generation of the coherence image as well as the texture extraction result in the delineation of contiguous built-up areas as opposed to individual structures as in the backscatter and morphology-based approaches.

5.2 Texture-based built-up area index

Texture parameters, such as those extracted via gray level co-occurrence matrices (GLCM) as introduced by Haralick (1973), have been used for many years for the purpose of classifying area targets from SAR data. They are being employed successfully, e.g., for discriminating between different types of crops or tree species (Brisco, 1985; Simard, 2000).

The so-called 'anisotropic, rotation-invariant built-up area index,' introduced by Pesaresi (2007, 2008) also uses texture features extracted via a co-occurrence matrix. It has been developed at the JRC and is commonly used by the Isferea team of the JRC's Institute for Protection and Security of the Citizen for built-up area extraction from panchromatic optical satellite data. Its advantage over commonly used implementations of GLCM-based classifications is its independence from the directional components of texture and the fact that it results in a 256-level numeric index representing built-up presence. The general applicability of the algorithm to SAR data has recently been tested successfully by the JRC in cooperation with the University of Pavia (Gamba *et al*., 2008, Dell'Acqua *et al*., 2009). For this report the algorithm is employed to delineate and characterize the built-up area based on ENVISAT IS-2 and RADARSAT-1 F5d SAR data.



(a) Built-up area index **(b) Binary built-up area map**

Fig. 8 Results of applying the anisotropic, rotation-invariant built-up area index calculation to an ENVISAT IS-2 power image, acquired 06 December 2006. Lower and upper bounds of the membership function for the fuzzy classification (a) have been selected. The chosen cut-off value for the binary built-up area delineation, generated from the texture-based built-up area index (b), influences the delineated area and has to be adjusted carefully, ideally using reliable reference data.

The initial outcome of the anisotropic texture-based methodology is a gray-level built-up presence index, in which higher values indicate increasing membership of the pixel to the class ‘built-up.’ The index can be used as a fuzzy classification by applying a membership function and adjusting the lower and upper bounds for ‘not built-up’ and ‘built-up’ respectively. By defining a distinct cut-off value, a binary urban area map can be generated from the texture-based index, delineating contiguous built-up vs. non built-up areas. The chosen cut-off value or threshold influences the delineation of the built-up area and has to be adjusted carefully ideally employing reference data. In addition to interactively determining the threshold based on reference data, a statistical method, minimizing omission and commission errors, can be used (Pesaresi, 2008). The built-up presence index, as well as a binary built-up area classification, derived from ENVISAT IS-2 data, are displayed in Fig. 8.

In addition to ENVISAT data, the anisotropic, rotation-invariant built-up presence index has also been evaluated at the JRC for use with higher resolution RADARSAT-1 Fine mode data. Details of the investigations conducted can be found in Gamba *et al*., 2009 and Dell’Acqua *et al*., 2009.

SAR data are originally acquired in ‘slant range’ geometry, which distorts the image in range, i.e. in east-west direction in case of date acquired by a common, polar orbiting satellite. The amount of ‘distortion’ is larger for smaller incidence angles, i.e. a steeper viewing geometry. The conversion to a ‘ground range’ representation is usually done during georeferencing. The resampling involved, however, reduces the strong localized radar signal induced by small, individual buildings. In order to capture all relevant building signals, it is therefore advisable to apply the algorithm to the original, slant range data, and to then geocode the resulting index image. This is discussed in detail in several joint publications of the JRC and the University of Pavia, e.g. in Gamba *et al*., 2009 and Dell’Acqua *et al*., 2009. The effect is illustrated in Fig. 9. The window sizes and the set of displacement vectors used for index calculation are slightly adapted for the slant-range implementation of the algorithm. Using the slant-range implementation, omission errors have been reduced to 7% from 16% which were measured in the ground-range implementation (Dell’Acqua *et al*., 2009).

Fig. 10 (a) shows a built-up area map calculated from RADARSAT-1 Fine mode data. A comparison with a visual interpretation of the urban built-up area, derived from Quickbird VHR optical imagery, is shown in (b). While a considerable amount of time and manual labor was required for generating the map in (b), the RADARSAT-based built-up delineation map in (a) was derived automatically within approximately an hour. Errors of omission, i.e. residential areas not indicated as such by the automatically generated RADARSAT-based map (green), occur predominantly in strongly vegetated, low-density residential areas, e.g. at the top left. Errors of commission, where the RADARSAT-based map erroneously indicates built-up areas (red), are present along roads and in vegetated areas. In general, however, the RADARSAT-based and the manually derived map coincide well (orange) with an overall accuracy of 79% in this urban setting.

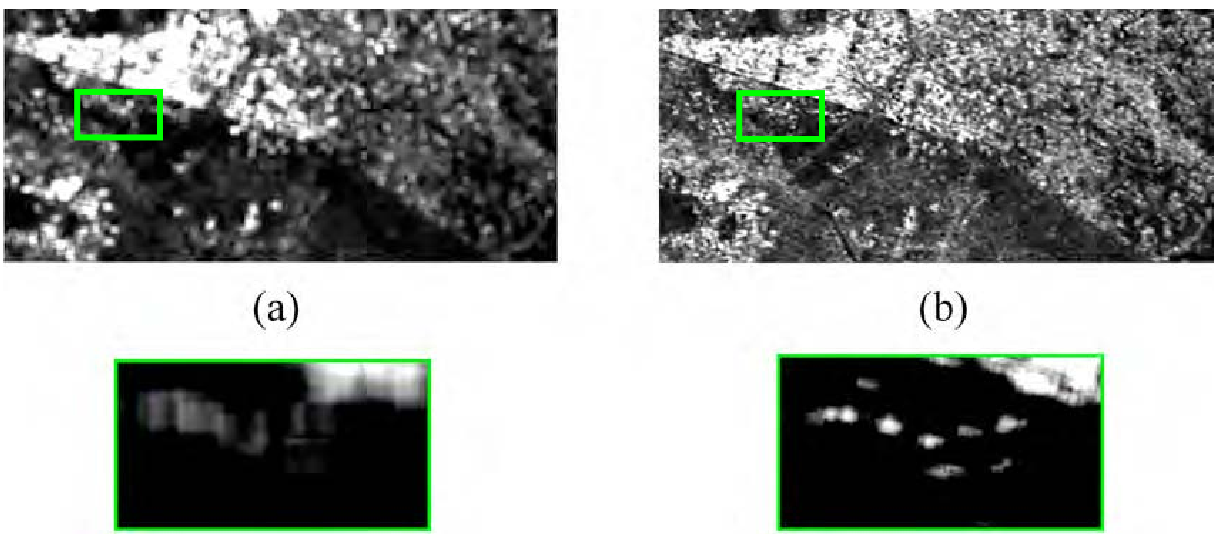


Fig. 9 Results of applying the anisotropic, rotation-invariant built-up area index to a RADARSAT-1 F5d image, acquired 16 November 2006. In (a) the algorithm has been applied to the georeferenced, ground-range image, while (b) shows the result of applying it to the original slant-range data. The individual buildings are detected well in (b), while the algorithm is not able to discriminate the individual structures in (a). This figure has been adapted from Dell’Acqua *et al*., 2009.

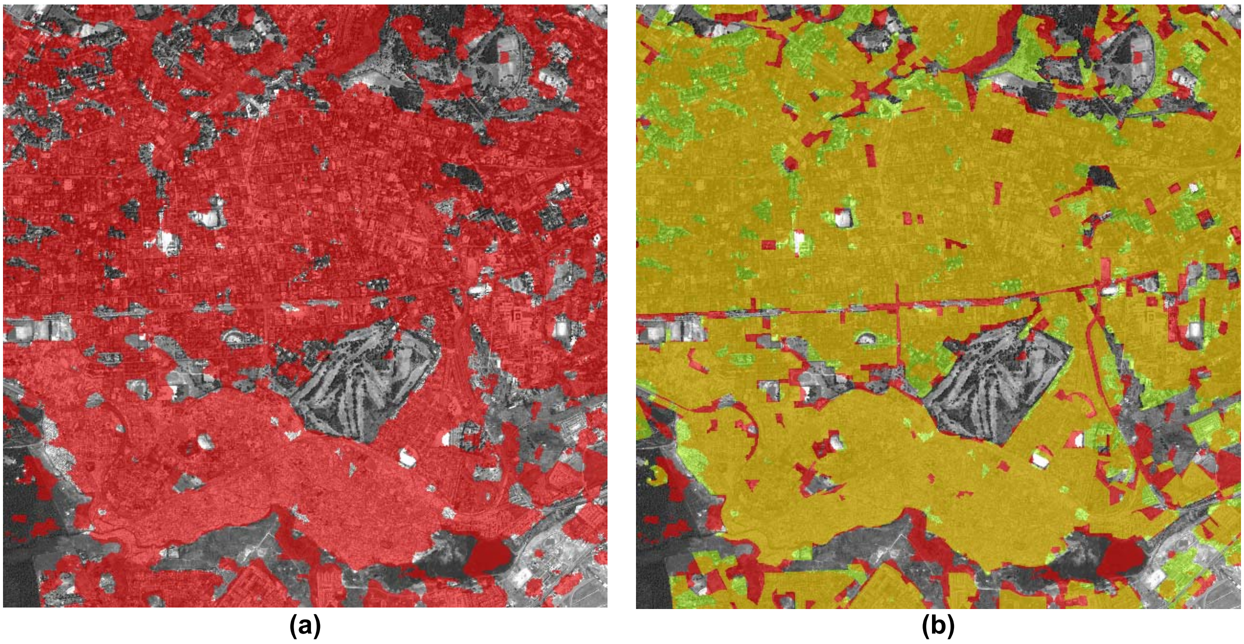


Fig. 10. The delineation of the built-up area, based on the anisotropic, rotation-invariant built-up presence index calculated from a slant-range RADARSAT-1 F5d image, acquired 16 November 2006 is shown in (a). The threshold has been selected interactively. A comparison with a visual interpretation of the urban built-up area, derived from Quickbird VHR optical imagery, is shown in (b). Errors of omission (green) and commission (red) are minimal and limited to areas dominated by vegetation. In general the RADARSAT-based and the manually derived map coincide well (orange) in this urban setting.

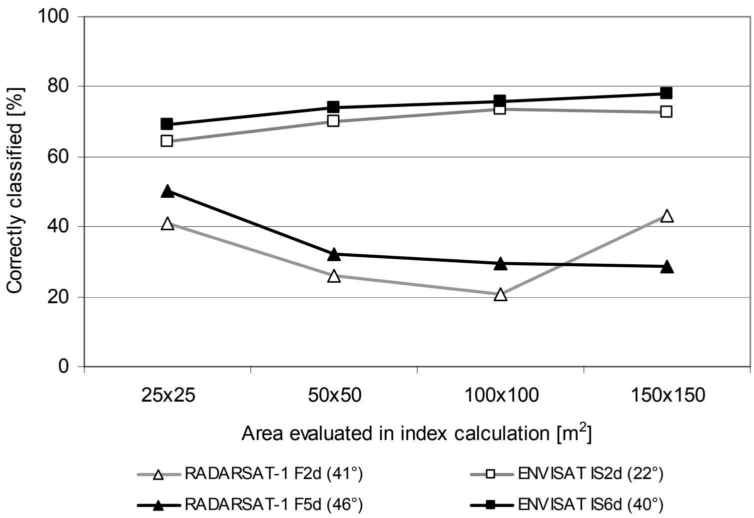
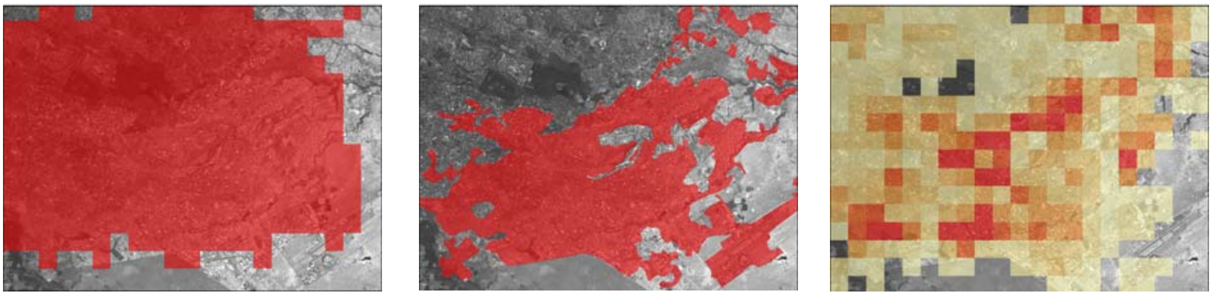


Fig. 11. Classification accuracies achievd applying the anisotropic rotation-invariant built-up area index to ENVISAT ASAR and RADARSAT-1 Fine Mode data. With close to 80%, ENVISAT data generally achieve higher classification accuracies than the RADARSAT data. A slight improvement of the classification accuracy with increasing area evaluated is visible for the ENVISAT data. This trend is not reproduced in the RADARSAT results. For the individual sensors, larger incidence angles (in parentheses) in general yield better results than smaller ones.

Ongoing research is systematically evaluating the built-up area presence algorithm for use with spaceborne SAR data. A variety of data and parameters are included in the investigations, which extends beyond the city limits itself into the surrounding rural areas. Initial results are presented in Fig. 11. These are based on delineating the built-up area form the index according to the statistical method introduced in Pesaresi (2008). With a maximum of close to 80%, ENVISAT data generally achieve higher classification accuracies than the higher resolution RADARSAT data. A slight improvement of the classification accuracy with increasing area evaluated can be observed for the ENVISAT data. This trend is not reproduced in the RADARSAT data. Larger incidence angles tend to yield better results than smaller ones.

5.3 Structure of the built-up area - qualitative built-up density measures



(a) GLC 2000 'Cities' **(b) Africover 'Urban areas'** **(c) Built-up density index (ENVISAT)**

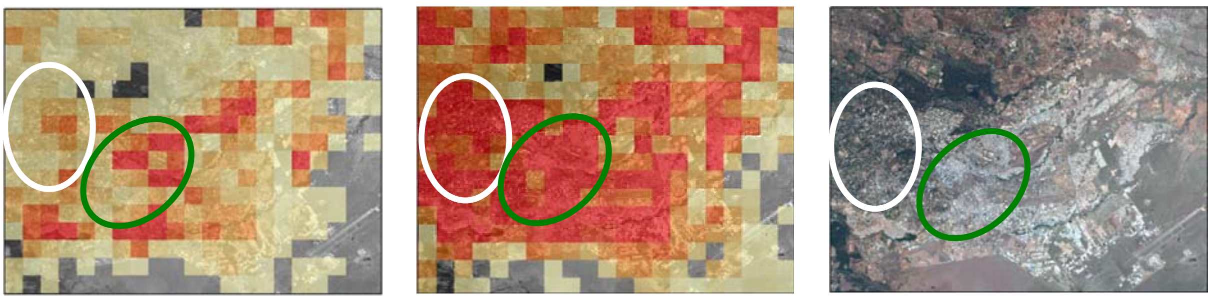
Fig. 12. The categories 'cities' on the Global Land Cover (GLC) 2000 dataset (a) and the 'urban areas' on Africover (b) outline the city of Nairobi differently. For the built-up density maps (c) a binary classification, based on ENVISAT backscatter, has been aggregated to a built-up density map at 1 km pixel size. High built-up densities are displayed in red.

Binary maps of built-up structure or built-up area, extracted as described above, can be aggregated into maps of built-up density. Built-up density provides added value over common binary urban area classifications. The outline of a city does not indicate where people and buildings are located. Mapping the density of the built-up structures allows for an initial estimate of the distribution of the population within the urban area. This information is valuable for applications in disaster preparedness and monitoring urban development. Fig. 12 shows two binary urban area delineations taken from different global databases (a,b) in comparison to a qualitative built-up density map derived automatically from radar satellite data (c). The ENVISAT-based built-up density index (c), derived from the binary map in Fig. 7(a), shows the density of individual built-up structures, aggregated to 1 km, which matches the spatial resolution of the GLC dataset (a).

Density of built-up structures vs. density built-up area

A density measure depends on the quality of and on the parameter measured in the underlying binary classification. There is a difference between measuring the density of built-up structures vs. the density of built-up areas. SAR backscatter and derived classifications, as discussed above, react to individual built-up structures; the derived density map thus represents - qualitatively - the density of built-up structures. A suburban, strongly vegetated neighborhood will have a different density value than the densely built-up downtown core Fig. 13(a).

The texture-based built-up area index, however, delineates built-up areas. It does not differentiate between densely and loosely built-up areas. Thus it measures a different parameter than a delineation of built-up structures. The derived density map represents a built-up area density map, with more similar densities for suburban neighborhoods and for the densely built-up downtown core - provided both are contiguous. This effect is depicted in Fig. 13(b). Remaining density differences are associated with vegetation induced data loss.

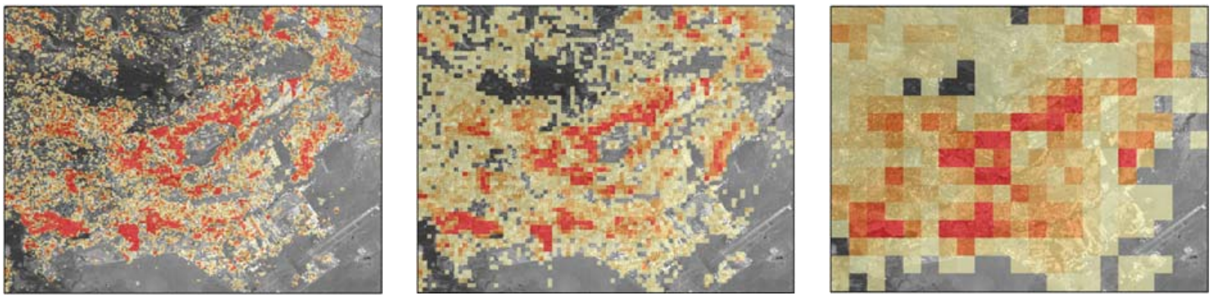


(a) ENVISAT backscatter **(b) ENVISAT texture** **(c) Quickbird**

Fig. 13. In the ENVISAT backscatter-based built-up density map (a), which measures the density of built-up structures, lower-density residential neighborhoods (white ellipse) receive lower density values than the densely built-up downtown core (green ellipse). In the density map, derived from the texture-based classification (b), both neighborhoods receive high density values. Differences remaining are associated with vegetation induced data loss. The two areas differ in the density of built-up structures, while the density of the contiguously built-up area, aggregated to a 1 km raster, is similar.

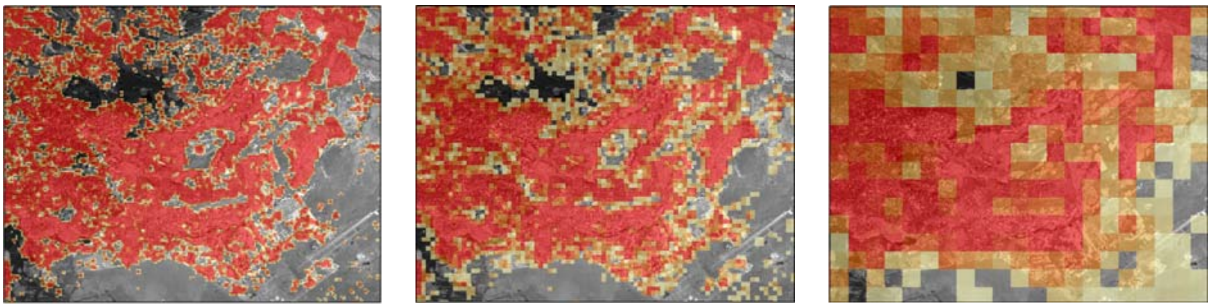
Built-up density mapping at various resolutions

ENVISAT data have a spatial resolution of approximately 23 m. A binary built-up structure classification derived from these can be aggregated to a density map at any required spatial resolution that is larger than the original pixel size. Fig. 14 and Fig. 15 show built-up density maps aggregated to 100 m, 250 m, and 1 km. The underlying binary map has been derived from ENVISAT backscatter (Fig. 14) and texture measures (Fig. 15) using the methods discussed above.



100 m **250 m** **1 km**

Fig. 14. The binary built-up structure maps derived from 30 m resolution ENVISAT (IS-2, descending) backscatter data have been aggregated to built-up structure density maps at various spatial resolutions. The aggregation to 100 m shows in detail the distribution of high-density agglomerations (red) vs. areas with little (yellow) or no (clear) built-up structures.



100 m **250 m** **1 km**

Fig. 15 Built-up density maps at various spatial resolutions derived from binarized texture-based built-up area index maps using the same ENVISAT data as in Fig. 11. Since the built-up index measures contiguous built-up area as opposed to individual built-up structures, high density areas are more extensive than in Fig. 14. The general location and distribution of high and low density areas remains the same as in the built-up structure density maps above.

6 Conclusions

This report introduced the use of medium to high resolution spaceborne SAR data for urban area mapping at scales of up to approximately 1:100,000. Specific SAR image characteristics and a number of urban area information extraction approaches have been presented and discussed. As a result of their reliability and the relatively low cost of some data, spaceborne SAR Earth observation data are a good alternative data source, replacing or complementing optical data where environmental conditions render their acquisition difficult.

Urban area mapping applications, such as for disaster preparedness or monitoring urban sprawl, benefit from the increasing availability of spaceborne SAR Earth observation data. A broad selection of frequencies, spatial resolutions, and acquisition parameters allow for obtaining specific surface information, targeted to the mapping requirements at hand.

Using SAR Earth observation data effectively for urban area mapping, as for any other application, requires an in-depth understanding of the technology involved. The examples presented in this report, which introduce and highlight some effects, stress the importance of a sound understanding of system and processes. It is important to take into consideration the influence which system and acquisition parameters, the image formation process, and pre-processing of the data, prior to the actual information extraction, have on the resulting image. Optimum parameters can then be selected for data acquisition, during processing, and analysis.

In confirmation of results of recent research (Esch, 2006), it has been documented that automatic urban area information extraction from spaceborne SAR data, depending on requirements with respect to spatial and thematic detail and accuracy, is generally possible.

Information derived from SAR backscatter or interferometric products constitutes viable input data on which automated urban area classifications can be based. In developing exploitation methods, again, the specific characteristics of SAR image data have to be known and taken into account. A standardized pre-processing sequence, specifically designed for the chosen analysis method, can ensure reproducible results.

The anisotropic, rotation-invariant built-up presence index algorithm, originally developed for use with high-resolution optical data, can be employed for indicating built-up presence also on radar Earth observation imagery and subsequently for delineating built-up area. In a further step built-up density maps can be derived from binary built-up area delineations. The information can be aggregated at a variety of different spatial resolutions as required by the application. Built-up density maps can provide valuable additional information for assessing population distribution within the urban area.

Empirical results, presented herein for ENVISAT and RADARSAT-1 Fine Mode data, are promising. With some further refinement the methods introduced can be applied in operational scenarios.

Further research into SAR data use for urban applications aims at verifying and operationalizing the methods introduced. Additionally it will explore the use of higher resolution SAR data for more detailed urban area analyses, moving from the scale of the entire urban area via neighborhood-based exploitation, towards the analysis of building aggregates and individual built-up structures.

While optical Earth observation data still constitute the main data source for deriving urban area information at various scales and for a variety of applications, the increasing availability of spaceborne radar data warrants increased research efforts into operational exploitation of this reliable but challenging data source.

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Abstract

This report introduces the use of medium to high resolution spaceborne radar (SAR - Synthetic Aperture Radar) Earth observation imagery for urban area mapping applications. Urban mapping can benefit from this type of satellite data since built-up structures induce strong backscatter and thus can be distinguished well on radar imagery. The objective is to raise awareness about the possibilities and some of the limitations associated with using SAR satellite imagery for characterizing the built-up area.

The delineation and thus knowledge on the distribution of urban agglomerations at a global or continental scale is of importance to a wide range of applications such as determining hot spots in the framework of disaster preparedness, or modeling the impact of a disease outbreak.

Population, however, is not distributed evenly throughout an urban area. For applications supporting e.g. humanitarian aid initiatives, the outline of the urban or built-up are, thus, might not be sufficient. These applications require reliable information on where the people are. At smaller scales, the density of built-up structures can serve as a first, coarse estimate of the population distribution within a city. Population density varies between different neighborhoods - and with time of day. Built-up density maps thus provide added value to binary built-up area delineations. Moreover, this density distribution changes over the years. It can be monitored by multi-temporal built-up density maps.

A critical parameter to measure at a regional scale is the built-up stock. Measuring built-up stock takes into account the type and distribution of buildings. This can aid in estimating the population of a given area, specifically in regions where administrative data of this type are not readily available. Population information is essential for assessing the number people potentially affected should a crisis, natural or man-made, occur, and will help determine the type and amount of aid required.

Most globally available land cover datasets, such as Global Land Cover (GLC) 2000, or Africover, merely provide urban area outlines. As a global population dataset, the Landscan data, updated every few years and available through the Oak Ridge National Laboratory, USA, depict population density in 1 km raster cells. This report addresses possibilities to use SAR data to improve these existing globally available datasets either with respect to spatial resolution or thematic information.

As a result of their reliability, weather independence, and relatively low cost, satellite SAR imagery at approximately 23 m spatial resolution (ERS-1 /-2, ENVISAT) constitute an attractive alternative to optical imagery for mapping purposes at scales of up to 1:100,000. Higher resolution satellite SAR data (RADARSAT-1/-2, TerraSAR-X) are useful for inner-city differentiation.

SAR data are different from optical data with respect to the surface parameters they measure and in the way the information is coded in the image. Moreover, the side-looking geometry introduces geometric effects. The sensor-specific image characteristics have to be taken into account during SAR data processing and information extraction.

After a brief introduction, the representation of urban areas on SAR images is illustrated. Specific issues and limitations are discussed. In the final chapter methodologies towards automating built-up area delineation and characterization from SAR data are introduced.

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