Mapping Urban Extent Using Satellite Radar Interferometry

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Abstract
Phase coherence between pairs of ERS SAR images is investigated as a method for mapping urban extent in South Wales, United Kingdom. Separability indices show that image pairs with time delays of greater than 2 months and baseline separations of less than 300 m can discriminate effectively between urban and non-urban land. Classification kappa coefficients greater than 90 percent are achieved, and there is evidence to suggest that a single coherence threshold is applicable for mapping urban extent in any similar landscape.

Introduction
Regular and up-to-date information on the extent of urban areas is primarily required for regional-scale planning purposes, such as mapping urban growth (Donnay, 1999; Weber, 2001; Bahr, 2001). Effective planning policy and appropriate resource management can only be accomplished through informed decisions, but even basic information on urban extent is often outdated, inaccurate, or simply does not exist (Barnsley et al., 2001). This is especially so within developing countries (Baudot, 2001).

Current approaches to urban monitoring generally involve ground surveys and interpretation of aerial photographs, but these are not cost-effective solutions and are very difficult to implement. Thus, more efficient methods that are capable of automatically mapping urban areas are desirable. To this end, satellite remote sensing can be used to provide an objective and consistent view of urban areas, and SAR (synthetic aperture radar) in particular has the required coverage and revisit reliability for this application (Henderson and Xia, 1997).

Urban areas are generally characterized by high SAR backscatter because of the predominance of single- and double-bounce scattering (Dong et al., 1997). However, it must be realized that the geometric relationship between azimuth angle and the orientation of the buildings strongly affects backscatter within towns and cities (Bryan, 1979; Hardaway et al., 1982). This may cause difficulties during the classification process because the same urban land covers can produce different backscatter intensities depending upon the azimuth angle of the sensor in relation to the built structures on the ground (Bryan, 1982).

Recently, satellite radar interferometry has received a great deal of interest within the urban remote sensing community. The phase stability of anthropogenic structures between SAR images has led several authors to propose long time-scale phase correlation, or coherence, as a good measure of urban extent, and thus an appropriate tool for mapping urban change (Stroazzi and Wegmuller, 1998; Usai and Klees, 1999; Stroazzi et al., 2000). It has also allowed the exploitation of multiple phase measurements of point scatterers for the precise measurement of ground subsidence in urban areas (Ferretti et al., 2001). Furthermore, digital elevation models derived by interferometry have been used to retrieve building height (Hepner et al., 1998; Gamba and Houssmand, 2000; Gamba et al., 2000).

The degree of coherence between a pair of SAR images determines the quality of topographic or displacement information that can be retrieved by interferometry (Li and Goldstein, 1990; Rodriguez and Martin, 1992; Bamler and Hartl, 1998). It has also been shown to be of value in classifying properties of the land surface, for instance, in forest assessment as well as in urban analysis (Wegmuller and Werner, 1997; Askne et al., 1997).

Coherence is influenced by a number of independent factors, including the time-delay between images, the difference in signals between images due to the different positions in space from which they were acquired, and other factors (Zebker and Villasenor, 1992). These other factors arise during data acquisition (e.g., thermal noise or differential atmospheric path delays) and processing (e.g., imperfect registration of the SAR images, causing mis-registration).

Within urban areas coherence remains high even between image pairs separated by several years. Thus, when considering only the urban landscape, baseline decorrelation is the dominant factor, and coherence is only reduced slightly by temporal and other factors which are independent of baseline. In contrast, naturally vegetated surfaces are significantly influenced by temporal decorrelation and lose coherence within a few days or weeks as a result of growth, movement of scatterers, and changing moisture conditions. Hence, small-baseline, long time-scale coherence images (months to years) can be used to discriminate between urban and non-urban areas, allowing basic information on urban extent to be retrieved (Stroazzi and Wegmuller, 1998). Moreover, a sequence of such observations can be used to automatically detect urban change.

As well as being able to clearly delimit extensive built-up areas within coherence images, it is also possible to identify many hamlets, farms, and other isolated buildings within rural areas as very distinctive points of high coherence.

Despite some studies illustrating the value of coherence in delimiting urban areas, there has been little attempt to quantify the accuracy of this technique. This paper provides a comprehensive analysis of the utility of ERS (European Remote Sensing) interferometric coherence data with a wide range of baselines and time-delays for distinguishing between urban and non-urban land covers over multiple cities within Wales and southwest England. Maps of urban extent derived from small-baseline, long time-scale coherence data and also backscatter data are validated.
Test Site and Datasets

SAR Data

The Cardiff to Bristol urban corridor (Figure 1) was chosen as the test site for its range of small cities and the availability of good quality mapping. SAR data from the ERS satellites were provided by the European Space Agency (ESA), and 20 images from a single descending-pass track and frame (137 and 2565, respectively) were chosen from the archive. These 20 images allow 59 pair combinations with a good range of baselines where repeat-pass delays are limited to a minimum of three and a maximum of 34 repeat-pass cycles (105 days and 31/4 years, respectively) (Figure 2).

Validation Data

The Land Cover Map (LCM) of Great Britain, produced by the Centre for Ecology and Hydrology Monkswood, United Kingdom (Fuller et al., 1994), was used as ground truth for training and testing the classified maps derived from the SAR data (Figure 3). The 25 LCM classes were aggregated into two classes: urban (which accounts for approximately 13 percent of the land surface within the study area) and non-urban. The LCM has a pixel spacing of 25 m.

One of the main difficulties within urban analysis is that there is no consensus as to what constitutes urban land, and definitions vary depending upon the specific application for which this information is required (Donnay, 1999; Weber, 2001). As a result, the LCM and the classified maps derived from the SAR data may not be consistent. In addition, the accuracy of the LCM is given as 80 to 85 percent, but this is not sufficiently accurate for selecting the training and testing sampling sites.

In order to ensure a high degree of confidence in the training and testing sites, high spatial-resolution (2-m) aerial photographs were also provided by aerial photographs in order to ensure a high degree of confidence in the sample sites. (a) Training polygons. (b) Testing polygons.

Figure 1. Geographic location of the study area (black rectangle) covering the Cardiff to Bristol urban corridor between South Wales and England.

Figure 2. Illustration of the 59 combinations of 20 ERS images used to generate coherence images along with their baselines and repeat-pass delays. The vertical length of the bars indicates the time delay for each pair. This varies from three ERS repeat cycles (105 days) to 34 cycles (31/4 years). Bar thickness gives an approximate indication of the perpendicular baseline for each pair.

Figure 3. The Land Cover Map (LCM) of the Cardiff and Bristol test area that was used for training and validating the classified maps derived from the SAR data. The testing sites and training polygons were acquired for regions where coverage was also provided by aerial photographs in order to ensure a high degree of confidence in the sample sites. (a) Training polygons. (b) Testing polygons.
photographs acquired for the cities of Cardiff and Bristol were also used for confirmation. The sampling sites within urban areas were purposefully selected for areas comprising built surfaces such as buildings and roads. Polygons were used to define several training regions for both the urban and non-urban classes (Figure 3). A second set of polygons were used as independent testing regions. Testing and training samples were selected to avoid (1) LCM polygon borders which are known to have high error (Fuller et al., 1994) and (2) areas of likely urban change between the LCM dataset and the SAR data.

Data Processing
The ERS data were provided by ESA as slant-range single-look complex scenes. The first image in the temporal sequence was chosen as a reference and the other 19 images were co-registered to this one to sub-pixel accuracy. Tie-points were found automatically by cross-correlation of intensity in small image patches and a polynomial transformation (second order in two dimensions) was applied, which typically leads to a co-registration accuracy of better than one-tenth of a pixel.

The 59 image pair combinations were interfered by the normal process using one by five multi-looking (to give suitable spatial resolution with acceptable noise reduction) and common-band filtering. Coherence was estimated using an adaptive window size (varying in size from 3 by 3 to 9 by 9) so as to maximize coherence while minimizing coherence bias (Monti Guarnieri and Prati, 1997; Touzi et al., 1999). Within high coherence areas, the spatial resolution is expected to be approximately 60 m by 60 m. The resulting coherence images were geocoded into the British National Grid Transverse Mercator map projection with the use of a coherence images were geocoded into the British National Geodetic Survey. The result of this data pre-processing was 59 coherence images, co-registered to sub-pixel accuracy, and presented in a map coordinate system on a 20- by 20-m grid. Baselines for these images range from 4 m to nearly 1000 m (Figure 2).

Results and Validation
Selecting Coherence Data

Temporal Decorrelation
To successfully discriminate between urban and non-urban surfaces, long time-scale coherence data are required. Tandem (1-day) interferometric pairs are not useful because coherence is also high in many non-urban land covers, particularly those characterized by short vegetation, such as pasture. Even within 35-day interval pairs, coherence may remain high in some agricultural areas, particularly for fallow land during the dry winter months. Once coherence has entirely diminished within non-urban areas (typically after about 2 months in temperate regions), urban areas may be clearly delineated from the surrounding countryside. Even after several (3 to 4) years, coherence in urban areas still remains high.

While long time-scale coherence images may be able to discriminate between urban and non-urban land cover in temperate regions, it must be noted that within semi-arid and arid regions coherence may remain high for very long time periods (months) in the surrounding natural environment, and discrimination may be problematic. Another difficulty is that within low-density suburban residential areas, where green spaces such as gardens and parks make up a considerable proportion of the land cover, coherence may be reduced (Strozzi and Wegmüller, 1998).

Spatial Decorrelation
The effect of spatial decorrelation on urban/non-urban discrimination was also investigated. The ability of each of the 59 coherence images to discriminate between urban and non-urban land cover was quantified using the Jeffries-Matusita (JM) separability index proposed by Swain and Davies (1978). The JM index measures the statistical separability between two classes on a scale of 0 to 2. Values close to 2 indicate a good separability, while values less than 0.5 shows that discrimination is poor. The urban and non-urban classes for the JM separability analysis were defined using the testing polygons presented in Figure 3b.

The JM values for coherence images with baselines smaller than 300 meters range from about 0.8 to about 1.4, indicating good urban/non-urban class separability (Figure 4b). For these small-baseline pairs, coherence within urban areas ranges from about 0.3 to about 0.6 (Figure 4a). This variation is mainly accounted for by decorrelation arising from thermal noise and atmospheric phase delay. At baselines larger than about 700 m, the JM values are close to zero because there is little difference in coherence between urban and non-urban areas.

Thus, to successfully discriminate between urban and non-urban land cover in temperate regions, coherence pairs with small baselines and a time interval of 2 months (i.e., two ERS 35-day cycles) are required.
Mapping Urban Extent in South Wales

Urban/non-urban classifications based on the backscatter and coherence were carried out because the information content of these datasets may be useful for urban analysis. While this paper is primarily concerned with the coherence data, analysis was also performed on the backscatter data to allow for comparison. This analysis was carried out despite the limitations of the utility of backscatter data within urban applications already mentioned.

Twenty-four of the 59 coherence images with baselines smaller than 300 meters were used in this subsequent classification analysis, because JM separability values of greater than 0.8 can be consistently attained. For each of these coherence images, the average backscatter image of the two corresponding SAR scenes was also calculated.

Single-channel coherence and backscatter classifications were achieved by selecting a threshold for urban and non-urban discrimination based on a posteriori optimization of the kappa coefficient using the selected testing regions. Two-channel classifications based on a combined dataset containing a coherence image and the corresponding average backscatter image were also performed using the maximum-likelihood classifier (MLC).

The percentage of correctly classified pixels, which is the conventional measure used in the majority of studies, was not used because it gives misleading results for asymmetrically distributed two-class problems. The kappa coefficient takes account of the chance agreement between pixels and as such is a more appropriate measure in this instance.

Validations of the classified maps were carried out using the whole LCM dataset and the test samples presented in Figure 3b. For classifications based on the coherence data, high kappa accuracies of 76 percent to 91 percent were calculated for the selected test polygons (Figure 5 and Table 1). A classified map derived from a single-channel coherence images is presented in Figure 6. Classified maps derived from coherence data are significantly more accurate than are classifications based on the backscatter data. The additional backscatter information contained within the MLC classifications does not significantly increase their accuracy.

Despite the high degree of confidence in the training and testing sample sites, misclassification may still arise due to differences in definitions as to what constitutes urban land cover. In addition, for the classified maps derived from the
coherence data, urban land may be incorrectly classified as non-urban due to gardens and parks, which reduce coherence.

For validations performed over the whole study area, lower kappa accuracies (40 to 50 percent) were achieved (Figure 5). This is to be expected because of (1) temporal differences between the acquisition of the LCM and SAR data; (2) mis-registration between the LCM and the SAR data, particularly within heterogeneous areas causing misclassification at class boundaries; and (3) differences in spatial resolution between the LCM and SAR datasets. As discussed earlier, these errors are minimized for the training and testing polygons.

The optimal threshold value applied to the 24 coherence images are relatively consistent, ranging between 0.20 and 0.27, which suggests that this approach is generalizable for a wide range of coherence data and to other regions with similar landscapes.

Conclusions
A comprehensive analysis of the utility of small-baseline, long time-scale interferometric coherence images for accurately and consistently discriminating between urban and non-urban land covers over very large areas was presented. Classifications that utilize single-channel coherence data can attain accuracies with kappa coefficients of greater than 90 percent. By applying a threshold value of 0.25 to long time-scale coherence data with baselines of less than 300 m, kappa accuracies of at least 75 percent can be attained in any similar landscape.

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References