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CHARACTERIZING HETEROGENEOUS ENVIRONMENTS: HYPERSPECTRAL VERSUS GEOMETRIC VERY HIGH RESOLUTION DATA FOR URBAN STUDIES

Patrick Hostert[1], Alexander Damm[1], Ellen Diermayer[1] and Sebastian Schiefer[1,2]

1. Humboldt-Universität zu Berlin, Institute of Geography, Geomatics Department, Berlin, Germany; [hostert, damm, diermayer, schiefer]@hurs.de
2. Center for Remote Sensing of Land Surfaces, Bonn, Germany

ABSTRACT

Surface imperviousness has proven to be a convenient and universal indicator to characterise environmental states and processes in the urban context. Geometric and spectral very high resolution data were hence employed in this study to quantify imperviousness for selected sites in the city of Berlin, Germany. HyMap data from 2003 and Quickbird data from 2002 were aquired for overlapping areas and compared with available information on imperviousness from the Urban Environmental Information System of Berlin.

Both datasets were parametrically geocoded, the HyMap data also atmospherically corrected to match reference endmembers from field and laboratory measurements. The HyMap data were enhanced through a stratified feature space optimisation based on minimum noise fraction transformation. The optimised dataset was then analysed by unsupervised clustering and linear spectral unmixing. The resulting classes were coded for their imperviousness. The Quickbird data were pan-sharpened and the resulting 0.7 m resolution multispectral data segmented. A hierarchical and object-based classification scheme led to the classes for imperviousness mapping.

A comparison revealed that hyperspectral imperviousness mapping correlates well with information from the information system, while geometric very high resolution data are not suited to properly map low imperviousness levels. Moreover, imperviousness levels over 80% appear to be underestimated in the Quickbird based analysis. It is concluded that a combination of the strengths of both data types may lead to the most useful results in the future.

INTRODUCTION

From a remote sensing point of view, urban areas are characterised by spatial and spectral heterogeneity alike. This setting finds its expression in equally heterogeneous environmental conditions and processes that are for example driving forces in urban climatology and hydrology or for characterising urban habitats. During the last decade, numerous indicators have been developed to describe environmental conditions or environmental change. While each approach may be valid and useful, it is an open question how a manageable framework may be elaborated to substitute or underpin a wealth of highly specific indicators with a more universal concept of meta-indicators.

One universal indicator, or “meta-indicator”, that has proven its usability is surface imperviousness. Imperviousness stands for direct or indirect impact on manifold urban environmental conditions and can hence serve as a target variable – among others – for urban and environmental planning. As such, maps and cadastres have been derived for numerous urban environmental databases. One of the earliest and most elaborated datasets characterising urban imperviousness is part of the Urban Environmental Information System (UEIS) of Berlin, Germany. First investigations were conducted in the 80ies and updated regularly. However, such databases are difficult and expensive to maintain; on one hand, regular revisions are needed and on the other hand, statistical extrapolation from test areas to large urban agglomerations bear diverse uncertainties.

Consequently, it would be a substantial step forward to extract reliable measures of imperviousness from remote sensing data in a (semi-) automated way. With the advent of geometric very high resolution (VHR) digital sensors and object-based image analysis tools, a wealth of new applications or new ways to approach problems in the urban context of remote sensing evolved, as for example demonstrated by De Kok et al. (i), Meinel et al. (ii), or Small (iii). Airborne scanners, e.g. the High Resolution Stereo Camera (HRSC) or the Leica Airborne Digital Sensor (ADS 40), but even more sensors on satellite platforms such as Ikonos or Quickbird have started to re-shape the focus in remote sensing based urban monitoring. Nevertheless, due to the complicated geometry of urban surfaces and the spectral limitations of VHR data there has not been a breakthrough in such concepts, even that major advances are obvious.

Hyperspectral airborne data offer an alternative in mapping urban imperviousness on the basis of spectrally driven analysis concepts. While sensor limitations will not allow for comparable geometric resolutions as with multispectral cameras, a high spectral and – relatively speaking – moderate geometric resolution offers different analysis concepts compared to geometric very high resolution data. Examples of successful applications of new methodological concepts include studies by Heiden et al. (iv), Herold et al. (v), or Segl et al. (vi).

However, to our knowledge there has been no research on comparing the concepts of geometric and spectral VHR data concerning their potential in mapping urban imperviousness. This research hence illuminates the differences in imperviousness estimates from spectral and geometric very high resolution data, exemplified on the basis of HyMap and Quickbird imagery. In this context, a focus was put on a straightforward analysis scheme that does not require a comprehensive endmember collection strategy and may hence be largely automated in the future.

METHODS

HyMap data were acquired during the HyEurope 2003 campaign over Berlin, Germany, with a geometric resolution of 3.9m. Two subsets representing densely built-up urban areas, open residential, areas, and industrial areas were extracted from a flight line covering central Berlin from SSW to NNE.

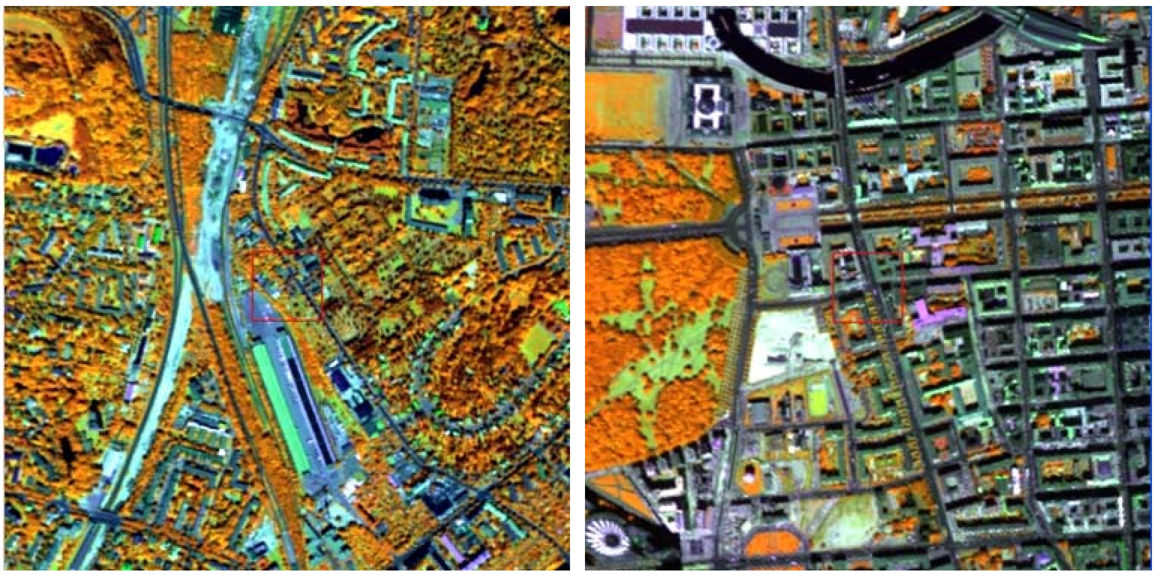


Figure 1: Test areas (Berlin-Schoeneberg, Central Berlin) in HyMap data (R-G-B 29-80-15).

Secondly, a multispectral and panchromatic Quickbird frame covering the SE-quarters of the city was employed to compare the analysis opportunities connected with geometric VHR data. Digital vector information from the UEIS served for comparison purposes.

HyMap analysis scheme

The pre-processing scheme for the hyperspectral data comprised a parametric geometric and radiometric correction. The HyMap data were distributed by the German National Aerospace Agency (DLR) as scaled radiance values along with auxiliary data from the onboard INS and DGPS systems. A set of 20 GCPs was extracted from digital orthophotos of Berlin and served, along with a DEM, to parametrically correct the imagery to UTM coordinates. The data set was corrected assuming a mid latitude summer atmosphere and rural aerosol. This appears reasonable for Berlin, as the city is virtually free of large industrial emission sources. Atmospheric water vapour was estimated via the 1130 nm absorption band to allow for a pixel-wise correction of the water vapour absorption.

Urban surface components are highly variable, but several problematic issues concerning the estimation of imperviousness will be generally relevant: Dark urban surfaces such as water, shaded areas or dark tar surfaces will be difficult to differentiate. Prominent absorption features are missing, while contrast is low and the signal to noise ratio decreases data quality. Moreover, bright impervious surfaces like concrete will appear similar to open soils, which are abundant in Berlin due to ongoing building activities and numerous brownfields. Consequently, a three-step analysis strategy is proposed:

- separation and analysis of dark surface components
- linear spectral unmixing of the remaining image components
- further separation of surfaces that are not separable through spectral unmixing

Dark targets with few features are easily extracted from the imagery, but difficult to be separated from each other. For example, shaded surfaces appear spectrally similar and tend to be confused with water – one common error source when analysing geometric VHR data with a low spectral resolution. All pixels with average reflectance below 10% were masked and run through a stratified minimum noise fraction (MNF) transformation. This procedure transforms the low reflectance feature space regions into optimally separable dimensions of MNF space. The MNF components 1 to 12 were then chosen for an unsupervised iterative clustering of 15 classes. These classes can easily be divided into water, shaded vegetation, and shaded sealed surfaces.

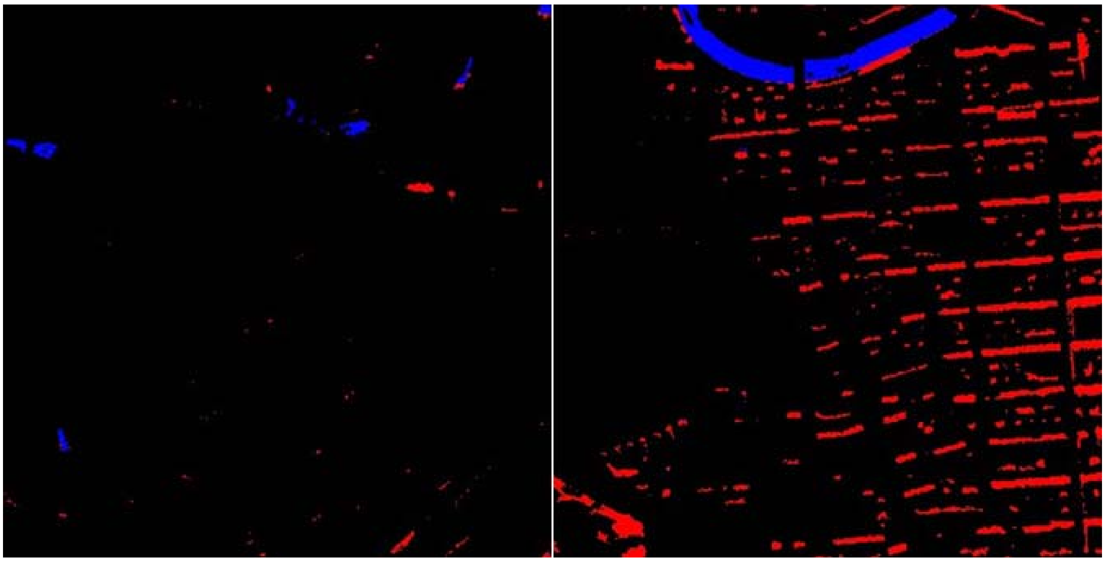


Figure 2: Separation of shaded areas (red) and water (blue)

The remaining image is free of shaded areas and can hence be analysed – for example – by linear spectral mixture analysis (SMA). An endmember combination slightly modified compared to the vegetation-impervious-soil model (vii) served as basis to separate photosynthetic active vegetation, soil, concrete, and asphalt. More complex models are possible, but would also infer more ambiguities in the analysis scheme. Reference endmembers were derived from a spectral data base of urban materials. The SMA performed generally well, but produced relatively high errors where the simple endmember model did not properly fit the rather complex spectral signatures in the urban environment. Moreover, the low dimension of endmember space lead to incorrectly analysed areas where soil is partially mixed with dry vegetation. These features could not be separated from some of the impervious surfaces. Areas dominated by vegetation or pure soil were contrarily characterised very well and could hence be masked with high accuracy.

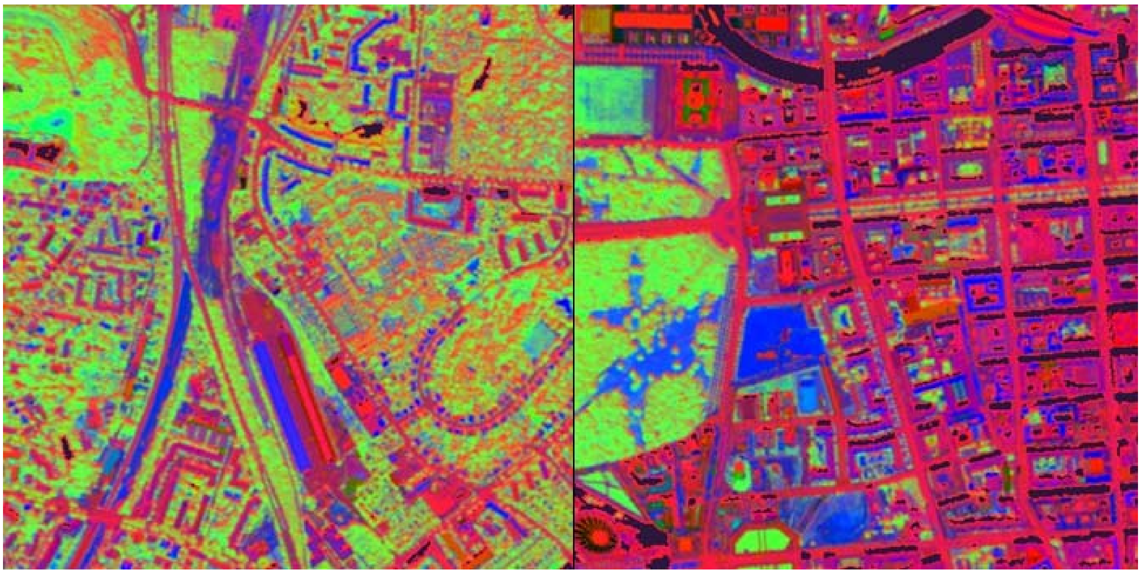


Figure 3: Spectral mixture analysis. R-G-B asphalt-vegetation- soil

The last step comprised an MNF transformation of the remaining image proportions – soils with residual or dry vegetation cover and most impervious urban surfaces – and an iterative unsupervised clustering in 30 classes. Those were afterwards labelled and the three analysis masks comprising dark surfaces, unmixed vegetation and soil, and the classified rest of the image were categorized in pervious and impervious surfaces.

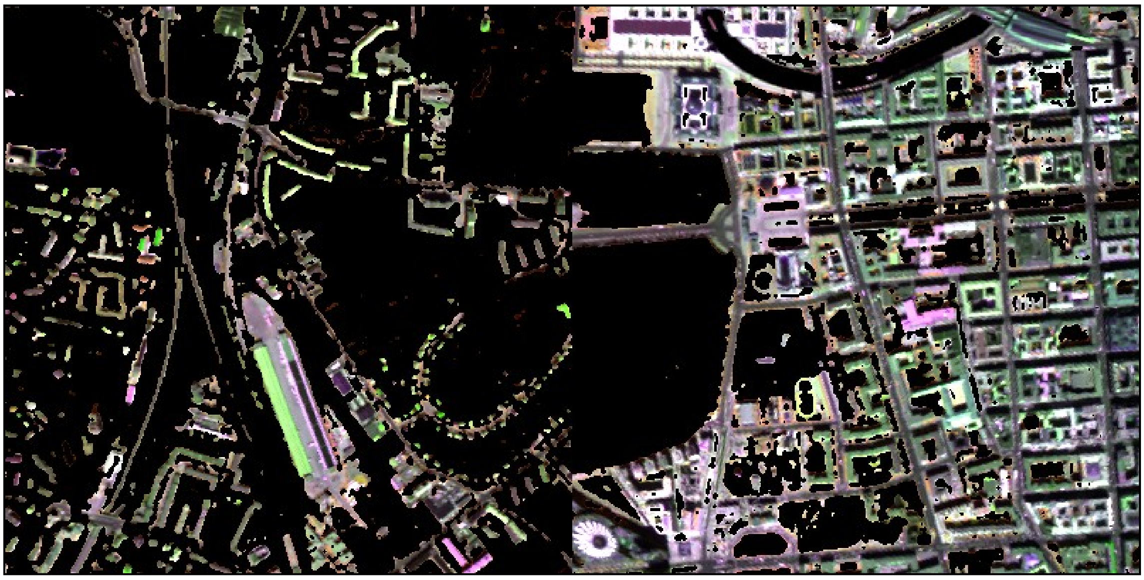


Figure 4: Mask of impervious surfaces

Quickbird analysis scheme

The geometric VHR satellite data were parametrically geocoded employing the available rationale polynomial coefficients, 20 GCPs from digital orthophotos, and a DEM. Even with a geometric resolution of 2.8 m, the multispectral data were too coarse to offer great advantages compared to the 3.9 m HyMap data. Consequently, the data were pan-sharpened with the 0.7 m panchromatic band using a principal component analysis. The resulting 0.7 m multispectral data served as input for a hierarchical and object-based supervised classification. 12 segmentation levels were calculated based on spectral properties only of which the coarsest level served as main input for the following classification. It was possible to derive 8 classes including water, roof materials, vegetation, and asphalt. Similar to the classes derived from HyMap data, those from the Quickbird analysis were coded into pervious and impervious features.

Figure 5: Subset of pan-sharpened Quickbird data (R-G-B 4-3-2, left); segmentation based classification results (right)

RESULTS

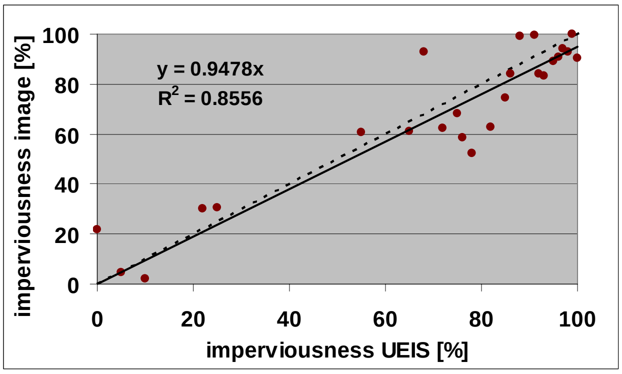
Imperviousness data from the UEIS Berlin was compared to the image derived imperviousness measures. This was done on the basis of blocks, i.e. larger units of homogeneously structured urban regions. The UEIS offers block-wise imperviousness information in 10% steps between 0 and 100% impervious surfaces per block. It is hence only possible to compare results in an integrated manner, whereas a spatially explicit localisation of potential errors in a block is not possible.

A first comparison of UEIS imperviousness and imperviousness derived from HyMap revealed a good correlation between both data sets with an r^2 value of 0.856 and a relationship close to the 1:1 line. However, it was obvious that a few blocks contributed to the deviations between both in a significant way. The deviating blocks were examined in detail to fully understand the reasons for the differences. While a definite clarification was usually not possible due to the above described aggregation of imperviousness per block, some logical reasoning was feasible: First of all, the analysis strategy did not perform perfectly for all surface types; partial imperviousness, as for example existing in the case of some cobblestone plastering, was not considered at this point. Moreover, roof gardens or tree crowns obscuring the view on underlying sealed surfaces are not easily separated from vegetation on open soils. Also, sub-surface sealing is generally not detectable and hence a source of error for all purely remote sensing based analyses.

Apart from these analysis dependent errors, some of the uncertainties obviously originated from errors in the UEIS dataset: These included geometric errors resulting in mismatching polygon information compared to the orthorectified image data. Furthermore, parks are often assumed to be sealed between 5 and 20 %, which appears to be slightly too high. It was also apparent that some of the backyards exhibited discrepancies between both datasets. However, it was not possible to evaluate the reasons for these differences in detail from the image and UEIS data alone.

Identifiable errors were then eliminated by excluding the respective block-wise information or by correcting errors in the geometry. Again, the rest of the imperviousness measures from the UEIS were compared to the image derived values. It turned out that the gain of the regression function did not change substantially, while the r^2 could be raised to 0.913.

The same analysis was performed for the imperviousness information derived from Quickbird data. Interestingly, while the imperviousness mask from Quickbird data appeared much more detailed compared to that from HyMap data when compared visually, it did not hold true that a higher level of geometric detail leads to a better correlation between UEIS and image based information. Quite contrarily, high imperviousness levels are generally underestimated in the image derived dataset, while low imperviousness levels cannot be estimated at all. An r^2 of -0.142 reveals the superiority of the HyMap based analysis.



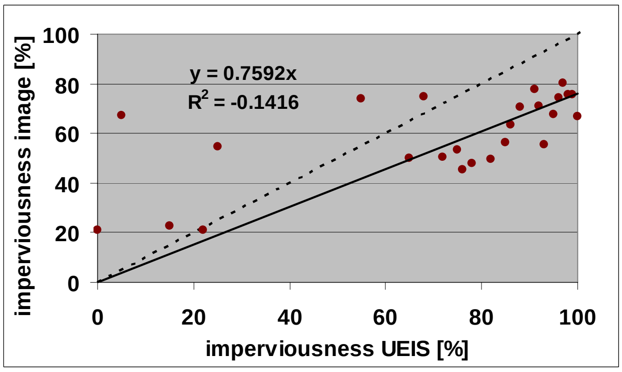


Figure 6: Comparison of imperviousness from UEIS with figures derived from analysis of HyMap data (left) and Quickbird data (right)

CONCLUSIONS AND OUTLOOK

It has to be kept in mind that the information from the UEIS Berlin cannot be regarded as an absolute reference data set. It rather contains different errors itself and was produced from heterogeneous sources (including aerial photographs) over several years itself. Hence, we must interpret the above described comparison carefully, as congruent errors in UEIS and remote sensing based imperviousness estimates can for example also produce a good congruence between different datasets. It is hence planned by the Berlin Senate Department of Environment to improve the imperviousness product of the UEIS in the near future based on a standardised analysis scheme including state-of-the-art remote sensing techniques and available digital geodatabases.

It is certainly possible to elaborate more complex analysis schemes, especially in the case of object-based hierarchical analysis of the geometric VHR data. However, such approaches are usually highly adapted to site or scene specific environments and therefore lack the transferability. Even changes in the same area leading to new structural types of surface features may result in inconsistent information in multitemporal analyses.

It has also to be evaluated, in how far such approaches are stable when transferred to larger subsets, e.g. whole administrative units of a city like Berlin. This refers to several aspects such as the universality of the analysis scheme. But there are also practical implications, as for example the computational performance connected to feature space optimisation by MNF or similar tools. Such transformations will either require high performance computing (e.g. cluster computing) or transformation statistics need be calculated on representative subsets.

While the comparison of geometric VHR and hyperspectral data for urban imperviousness mapping reveals the weaknesses of a low spectral resolution, it has not been tested here how a combination of both data types may enhance the performance of the approach. Different authors have meanwhile demonstrated that jointly analysing geometric and spectral VHR data offers new opportunities in urban mapping applications. The strength of hyperspectral data analysis certainly lies in the possibilities of optimising the feature space in a thematically driven way, while geometric VHR data may contribute with their strength concerning analysing image structures. It can hence be anticipated that future analysis concepts will focus on integrating both sensor types in the most useful way.

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