Fusion of Optical and Radar Images for the Enhancement of Different Surface Features

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***Abstract*—The aim of this study is to explore the performances of different data fusion techniques for the enhancement of urban features and evaluate the features obtained by the fusion techniques in terms of separation of different land cover classes. For the data fusion, multiplicative method, Brovey transform, principal component analysis (PCA), Gram-Schmidt fusion, wavelet-based fusion and Elhers fusion are used and the results are compared. Of these methods, the best result is obtained by the use of the wavelet-based fusion. Overall, the research indicates that multisource data sets can significantly improve the interpretation and analysis of land cover types.**

I. INTRODUCTION

Image fusion is used for many purposes. Very often it is used to produce improved spatial resolution. The most common situation is represented by a pair of images where the first acquired by a multispectral sensor has a pixel size greater than the pixel size of the second image acquired by a panchromatic sensor. Combining these images, fusion produces a new multispectral image with a spatial resolution equal to the panchromatic one. In addition, image fusion introduces important distortions on the pixel spectra which in turn improve the information content of RS images [27]. Over the years, different fusion methods have been developed for improving spatial and spectral resolutions of RS data sets. The techniques most encountered in the literature are the intensity-hue-saturation (IHS) transform, the Brovey transform, the principal components analysis (PCA) method, the Gram-Schmidt method, the local mean matching method, the local mean and variance matching method, the least square fusion method, the wavelet-based fusion method, the multiplicative and the Ehlers Fusion [11,15]. Most fusion applications use modified approaches or combinations of these methods.

In case of RS data sets, three different fusions such as fusion of optical data with optical data, fusion of microwave data with microwave data and fusion of optical and microwave data sets can be conducted. For several decades, fusion of multiresolution optical images has been successfully used for the improvement of information contents of images for visual interpretation as well as for the enhancement of land surface features. Many studies have been conducted on the improvement of spatial resolution of multispectral images by the use of the high frequencies of panchromatic images, while preserving the spectral information [7,9,16,23,27,28,]. A number of authors have attempted to successfully fuse the interferometric or multifrequency SAR images [6,8,26,30]. Unlike the fusion of optical images, most fusions of the SAR data sets have attempted to increase the spectral variety of the classes.

Over the years, the fusion of optical and SAR data sets has been widely used for different applications. It has been found that the images acquired at optical and microwave ranges of electro-magnetic spectrum provide unique information when they are integrated. Now image fusion based on the integration of multispectral optical and multifrequency microwave data sets is being efficiently used for interpretation, enhancement and analysis of different land surface features. As it is known, optical data contains information on the reflective and emissive characteristics of the Earth surface features, while the SAR data contains information on the surface roughness, texture and dielectric properties of natural and man-made objects. It is evident that a combined use of the optical and SAR images will have a number of advantages because a specific feature which is not seen on the passive sensor image might be seen on the microwave image and vice versa because of the complementary information provided by the two sources [3,4]. Many authors have proposed and applied different techniques to combine optical and SAR images in order to enhance various features and they all judged that the results from the fused images were better than the results obtained from the individual images [2,8,18,20,22,31].

The aim of this study is to investigate different data fusion techniques for the enhancement of spectral variations of different land surface features. For the data fusion, two different approaches such as fusion of SAR data with SAR data (ie, SAR/SAR approach) and fusion of optical data with SAR data (ie, optical/SAR approach) have been used. For the actual analysis, ASTER data of 2008, ALOS PALSAR data of 2006 and ERS-2 SAR data of 1997 of the urban area in Mongolia have been used. The analysis was carried out using PC-based ERDAS Imagine 9.1 and ENVI 4.3.

II. TEST SITE AND DATA SOURCES

As a test site, Ulaanbaatar, the capital city of Mongolia has been selected. The study area chosen for the present study covers mainly the central and western parts and is characterized by such classes as built-up area, ger (Mongolian national dwelling) area, green area, soil and water. Figure 1 shows ASTER image of the test site, and some examples of its land cover.

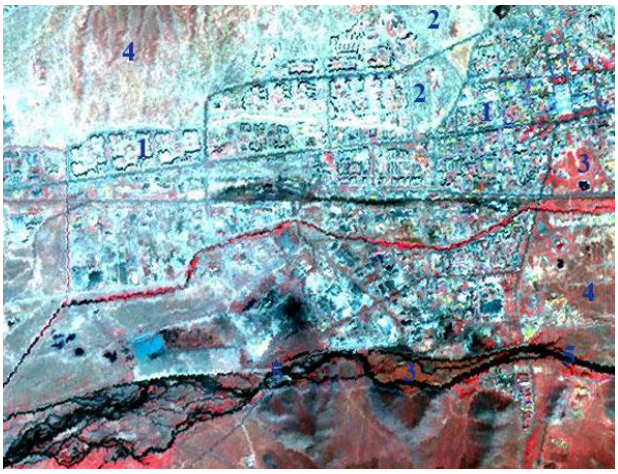

Figure 1. 2008 ASTER image of the selected part of Ulaanbaatar. 1-built-up area; 2-ger area; 3-green area; 4-soil; 5-water. The size of the displayed area is about 8.01kmx6.08km.

In the present study, for the enhancement of urban features, ASTER data of 23 September 2008, ERS-2 SAR data of 25 September 1997 and ALOS PALSAR data of 25 August 2006 have been used. Although ASTER has 14 multispectral bands acquired in visible, near infrared, middle infrared and thermal infrared ranges of electro-magnetic spectrum, in the current study, green (band 1), red (band 2) and near infrared (band 3) bands with a spatial resolution of 15m have been used. ERS-2 SAR is a European RS radar satellite which acquires VV polarized C-band data with a spatial resolution of 25m. ALOS PALSAR is a Japanese Earth observation satellite carrying a cloud-piercing L-band radar which is designed to acquire fully polarimtric images. In the present study, HH, VV and HV polarization images of ALOS PALSAR have been used.

III. CO-REGISTRATION OF MULTISOURCE IMAGES

There should be needed a high geometric accuracy and good geometric correlation between the images in order to perform successful data fusion. At the beginning, the ALOS PALSAR image was rectified to the coordinates of the ASTER image using 12 ground control points (GCPs) defined from a topograpic map of the study area. The GCPs have been selected on clearly delineated crossings of roads, streets and city building corners. For the transformation, a second-order transformation and nearest-neighbour resampling approach were applied and the related root mean square error (RMSE) was 1.18 pixel. Then, the ERS-2 SAR image was rectified and its coordinates were transformed to the coordinates of the rectified ALOS PALSAR image. In order to rectify the ERS-2 SAR image, 14 more regularly distributed GCPs were selected from different parts of the image. For the actual transformation, a second-order transformation was used. As a resampling technique, the nearest-neighbour resampling approach was applied and the related RMSE was 1.57 pixel. As the radar images have a side-looking effect, the errors of less than 1.6 pixel were considered as acceptable for further studies.

IV. SPECKLE SUPPRESSION OF THE ALOS PALSAR AND ERS-2 SAR IMAGES

As the microwave images have a granular appearance due to the speckle formed as a result of the coherent radiation used for radar systems; the reduction of the speckle is a very important step in further analysis. The analysis of the radar images must be based on the techniques that remove the speckle effects while considering the intrinsic texture of the image frame [2,25]. In this study, four different speckle suppression techniques such as local region, lee-sigma, frost and gammamap filters [13] of 3x3 and 5x5 sizes were compared in terms of delineation of urban features and texture information. After visual inspection of each image, it was found that the 3x3 gammamap filter created the best images in terms of delineation of different features as well as preserving content of texture information. In the output images, speckle noise was reduced with very low degradation of the textural information.

V. IMAGE FUSION

The concept of image fusion refers to a process, which integrates different images from different sources to obtain more information from a single and more complete image, considering a minimum loss or distortion of the original data. In other words, the image fusion is the integration of different digital images in order to create a new image and obtain more information than can be separately derived from any of them [5,20]. In the case of the present study, for the urban areas, the radar images provide structural information about buildings and street alignment due to the double bounce effect, while the optical images provide the information about the spectral variations and multitemporal changes of different urban features. Moreover, the SAR images provide some additional information about soil moisture condition due to dielectric properties of the soil. Over the years, different data fusion techniques have been developed and applied, individually and in combination, providing users and decision-makers with various levels of information. Generally, image fusion can be performed at pixel, feature and decision levels (Abidi and Gonzalez 1992, Pohl and Van Genderen 1998). In this study, data fusion has been performed at a pixel level and the following rather common and more complex techniques were compared: (a) multiplicative method, (b) Brovey transform, (c) principal component analysis (PCA), (d) Gram-Schmidt fusion, (e) Wavelet-based fusion, (f) Elhers fusion. Each of these techniques is briefly discussed below.

Multiplicative Method: This is the most simple image fusion technique. It takes two digital images, for example, high resolution panchromatic and low resolution multispectral data, and multiplies them pixel by pixel to get a new image [24].

Brovey transform: This is a simple numerical method used to merge different digital data sets. The algorithm based on a Brovey transform uses a formula that normalises multispectral bands used for a red, green, blue colour display and multiplies the result by high resolution data to add the intensity or brightness component of the image [29]. For the Brovey transform, the bands of Quickbird data were considered as the multispectral bands, while the HH-polarization of TerraSAR image was considered as the multiplying panchromatic band.

PCA: The most common understanding of the PCA is that it is a data compression technique used to reduce the dimensionality of the multidimensional datasets [21]. It is also helpful for image encoding, enhancement, change detection and multitemporal dimensionality. PCA is a statistical technique that transforms a multivariate data set of intercorrelated variables into a set of new uncorrelated linear combinations of the original variables, thus generating a new set of orthogonal axes.

Gram-Schmidt fusion method: Gram-Schmidt process is a procedure which takes a non-orthogonal set of linearly independent functions and constructs an orthogonal basis over an arbitrary interval with respect to an arbitrary weighting function. In other words, this method creates from the correlated components non- or less correlated components by applying orthogonalization process. Generally, orthogonalization is important in diverse applications in mathematics and other applied sciences because it can often simplifiy calculations or computations by making it possible, for instance, to do the calculation in a recursive manner [15].

Wavelet-based fusion: The wavelet transform decomposes the signal based on elementary functions, that is the wavelets. By using this, an image is decomposed into a set of multi-resolution images with wavelet coefficients. For each level, the coefficients contain spatial differences between two successive resolution levels. In general, a wavelet-based image fusion can be performed by either replacing some wavelet coefficients of the low-resolution image by the corresponding coefficients of the high-resolution image or by adding high resolution coefficients to the low-resolution data [19]. In this study, the first approach which is based on bi-orthogonal transforms has been applied.

Elhers fusion: This is a fusion technique used for the spectral characteristics preservation of multitemporal and multi-sensor data sets. The fusion is based on an IHS transformation combined with filtering in the Fourier domain and the IHS transform is used for optimal colour separation. As the spectral characteristics of the multispectral bands are preserved during the fusion process, there is no dependency on the selection or order of bands for the IHS transform [10,11].

A. Comparison of the Fusion Methods using SAR/SAR approach

Generally, interpretation of microwave data is based on the backscatter properties of the surface features and most SAR image analyses are based on them. Below the backscatter characteristics of the available five classes have been described. In case of two urban classes (ie, built-up and ger areas), at both L-band and C-band frequencies the backscatter would contain information about street alignment, building size, density, roofing material, its orientation, vegetation and soil, that is it would contain all kinds of scattering. Roads and buildings can reflect a larger component of radiation if they are aligned at right angles to the incident radiation. Here, the intersection of a road and a building tends to act as a corner reflector. The amount of backscatter is very sensitive to street alignment. The areas of streets and buildings aligned at right angles to the incident radiation will have a very bright appearance and non-aligned areas will have a more dark appearance in the resulting image. Volume and surface scattering will also play an important role in the response from urban areas. Therefore, these classes will have higher backscatter return resulting in bright appearances on the images. In the study site, green area consists of some forest and vegetated surface. In the case of forest, at L-band frequency the wavelength will penetrate to the forest canopy and will cause volume scattering to be derived from multiple-path reflections among twigs, branches, trunks and ground, while at C-band frequency only volume scattering from the top layer can be expected, because the wavelength is too short to penetrate to the forest layer. The vegetated surface will act as mixtures of small bush, grass and soil and the backscatter will depend on the volume of either of them. Also plant geometry, density and water content are the main factors influencing the backscatter coming from the vegetation cover. As a result, green areas will have brighter appearance on the image. The backscatter of soil depends on the surface roughness, texture, existing surface patterns, moisture content, as well as wavelength and incident angle. The presence of water strongly affects the microwave emissivity and reflectivity of a soil layer. At low moisture levels there is a low increase in the dielectric constant. Above a critical amount, the dielectric constant rises rapidly. This increase occurs when moisture begins to operate in a free space and the capacity of a soil to hold and retain moisture is directly related to the texture and structure of the soil. As can be seen, soil will have brighter appearance if it is wet and dark appearance if it is dry. Water should have the lowest backscatter values and dark appearance at both frequencies because of its specular reflection that causes less reflection towards the radar antenna.

As can be seen from figure 2, the images created by the multiplicative method, Brovey transform and Gram-Schmidt fusion have very similar appearances. On these images, the built-up and ger areas have either similar (figure 2b) or mixed appearances (figure 2a, d). The green area has similar appearance as the built-up area. This means that the backscatter from double bounce effect in the built-up area has similar power as the volume and diffuse scattering from the green area. Moreover, it is seen that on all images (except the PC image), soil and water classes have dark appearances because of their specular reflection (though in some areas wet soil has increased brightness). As the original bands have been transformed to the new principle components, it is not easy to recognize the available classes on the image created by the PCA. On the PC image, the two urban classes, some roads aligned at right angles to the radar antenna as well as some areas affected by radar layover have magenta-reddish appearances, while other classes form different mixed classes. On the image created by the wavelet-based fusion, it is not possible to distinguish much detail. On this image, the two urban classes and green area as well as soil and water classes have similar appearances. Furthermore, it is seen that the image created by the Elhers fusion looks similar to the image created by the Gram-Schmidt fusion, but has more light appearances. Overall, it is seen that the fused SAR images cannot properly distinguish the available spectral classes.

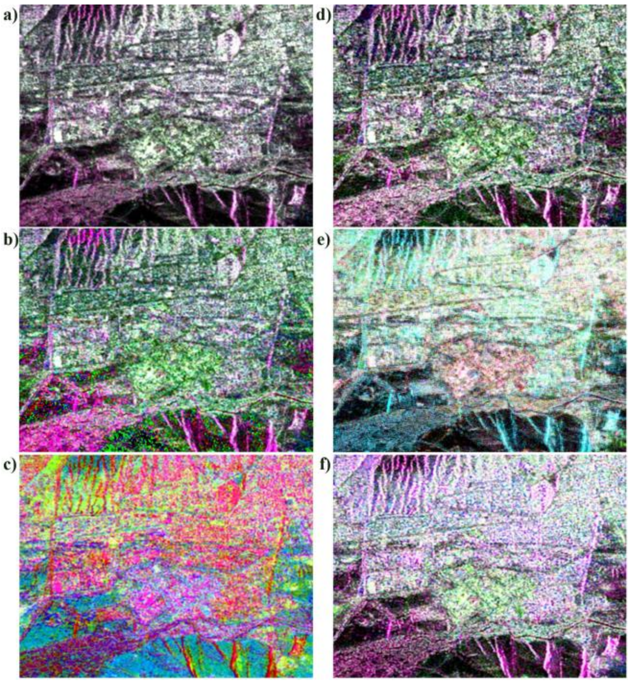

Figure 2. Comparison of the fused images of ALOS PALSAR and ERS-2 SAR: (a) the image obtained by multiplicative method; (b) Brovey transformed image; (c) PC image (red=PC1, green=PC2; blue=PC3); (d) the image obtained by Gram-Schmidt fusion; (e) the image obtained by wavelet-based fusion; (f) the image obtained by Elhers fusion.

B.Comparison of the Fusion Methods using Optical/SAR Approach

Initially, the above mentioned fusion methods have been applied to such combinations as ASTER and HH polarization of PALSAR, ASTER and HV polarization of PALSAR, ASTER and VV polarization of PALSAR, and ASTER and ERS-2 SAR. Then, in order to obtain good colour images that can illustrate spectral and spatial variations of the classes on the selected optical and SAR images, all the fused images have been visually inspected and compared. In the case of the multiplicative method, the fused image of ASTER and HH polarization of PALSAR demonstrated a better result compared to other combinations, while in the case of Brovey transform the combination of ASTER and ERS-2 SAR created a good image. On the image obtained by the multiplicative method, the built-up and ger areas have similar appearances, however, the green area, soil and water classes have total separations. Likewise, on the image obtained by the Brovey transform, the built-up and ger areas have similar appearances, whereas the green area and soil classes have total separations. Moreover, on this image, a part of the water class is mixed with other classes.

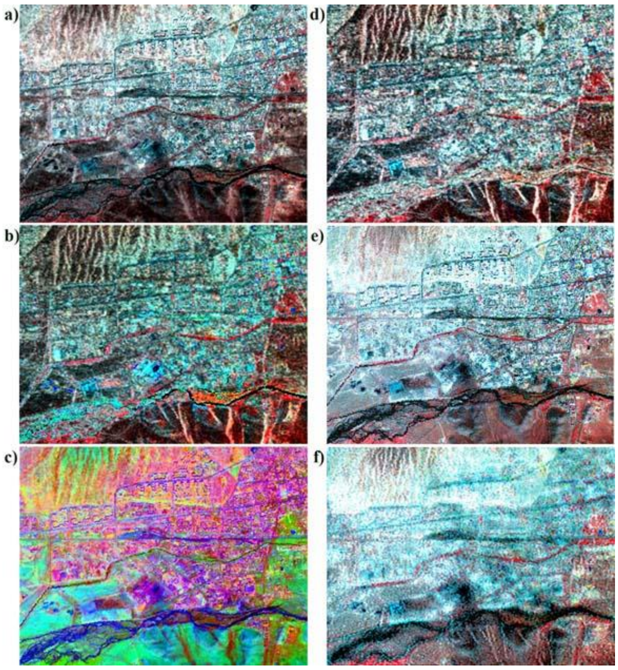

Figure 3. Comparison of the fused optical and SAR images: (a) the image obtained by multiplicative method; (b) Brovey transformed image; (c) PC image (red=PC1, green=PC2; blue=PC4); (d) the image obtained by Gram-Schmidt fusion; (e) the image obtained by wavelet-based fusion; (f) the image obtained by Elhers fusion.

Unlike the SAR/SAR approach, in this approach, PCA has been applied to such combinations as ASTER and ERS-2 SAR, ASTER and PALSAR, and ASTER, PALSAR and ERS-2 SAR. When the results of the PCA have been compared, the combination of ASTER, PALSAR and ERS-2 SAR demonstrated a better result than the other two combinations. The result of the final PCA is shown in table 1. As can be seen from table 1, HH polarisation of PALSAR and ERS-2 SAR have very high negative loadings in PC1 and PC2. In these PCs, visible bands of ASTER also have moderate to high loadings. This means that PC1 and PC2 contain the characteristics of both optical and SAR images. Although, PC3 contained 7.0% of the overall variance and had moderate to high loadings of ASTER band1, HH polarisation of PALSAR and ERS-2 SAR, visual inspection revealed that it contained less information related to the selected classes. However, visual inspection of PC4 that contained 5.6% of the overall variance, in which VV polarisation of PALSAR has a high loading, revealed that this feature contained very useful information related to the textural difference between the built-up and ger areas. The inspection of the last PCs indicated that they contained noise from the total data set. As can be seen from figure 3c, although the PC image could separate the two urban classes, in some parts of the image, it created a mixed class of green area and soil.

In the case of the Gram-Schmidt fusion, the combined image of ASTER and ERS-2 SAR demonstrated a better result compared to other combinations. Although, the image contained some layover effects available on the ERS-2 image, looked very similar to the image obtained by the multiplicative method. In the case of the wavelet-based fusion, the fused image of ASTER and ERS-2 SAR demonstrated a better result compared to other combinations, too. Also, this image looked better than any other images obtained by other fusion methods. On this image, all available five classes could be distinguished by their spectral properties. Moreover, it could be seen that some textural information has been added for differentiation between the classes: built-up area and ger area. In the case of the Elhers fusion, the combined image of ASTER and VV polarization of PALSAR demonstrated a better result compared to other combinations. Although, this image had a blurred appearance due to speckle noise, still could very well separate green area, soil and water classes. Figure 3 shows the comparison of the images obtained by different fusion methods.

TABLE 1. PRINCIPAL COMPONENT COEFFICIENTS FROM ASTER, PALSAR AND ERS-2 SAR IMAGES.

	PC1	PC2	PC3	PC4	PC5	PC6	PC7
ASTER band1	0.33	0.44	0.42	0.35	0.44	0.39	0.17
ASTER band2	0.50	0.37	0.34	-0.34	-0.38	-0.33	-0.32
ASTER band3	0.02	0.07	0.11	-0.09	-0.32	-0.19	0.91
PALSAR HH	-0.77	0.34	0.47	-0.14	0.06	-0.15	-0.08
PALSAR HV	0.14	-0.07	-0.06	-0.49	0.73	-0.40	0.13
PALSAR VV	0.02	-0.01	0.01	0.69	0.08	-0.71	-0.04
ERS-2 SAR	0.07	-0.73	0.67	0.01	-0.01	0.02	-0.01
Eigenvalues	8873.3	4896.7	1159.7	934.6	459.2	147.7	81.7
Variance (%)	53.6	29.6	7.0	5.6	2.8	0.89	0.51

V. CONCLUSIONS

The main aim of the research was to compare the performances of different data fusion techniques for the enhancement of different surface features and evaluate the features obtained by the fusion techniques in terms of separation of urban land cover classes. For the data fusion, multiplicative method, Brovey transform, PCA, Gram-Schmidt fusion, wavelet-based fusion and Elhers fusion were used. Although, fusion methods demonstrated different results, detailed analysis of each image revealed that the image obtained by the wavelet-based fusion gave a superior image in terms of the spatial and spectral separations among different urban features. Overall, the research indicated that the integrated optical and SAR images can significantly improve the interpretation and analysis of different land cover classes.

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