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Review article

Multisensor image fusion in remote sensing: concepts, methods and applications

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Abstract. With the availability of multisensor, multitemporal, multiresolution and multifrequency image data from operational Earth observation satellites the fusion of digital image data has become a valuable tool in remote sensing image evaluation. Digital image fusion is a relatively new research field at the leading edge of available technology. It forms a rapidly developing area of research in remote sensing. This review paper describes and explains mainly pixel based image fusion of Earth observation satellite data as a contribution to multisensor integration oriented data processing.

1. Introduction

Earth observation satellites provide data covering different portions of the electromagnetic spectrum at different spatial, temporal and spectral resolutions. For the full exploitation of increasingly sophisticated multisource data, advanced analytical or numerical data fusion techniques are being developed (Shen 1990). Fused images may provide increased interpretation capabilities and more reliable results since data with different characteristics are combined. The images vary in spectral, spatial and temporal resolution and therefore give a more complete view of the observed objects.

It is the aim of image fusion to integrate different data in order to obtain more information than can be derived from each of the single sensor data alone ('$1+1=3$'). A good example is the fusion of images acquired by sensors sensitive to visible/infrared (VIR) with data from active synthetic aperture radar (SAR). The information contained in VIR imagery depends on the multispectral reflectivity of the target illuminated by sun light. SAR image intensities depend on the characteristics of the illuminated surface target as well as on the signal itself. The fusion of these disparate data contribute to the understanding of the objects observed.

Image fusion has many aspects to be looked at. Before being able to implement and use an image fusion approach some of its questions that need to be answered by the user include:

— What is the objective/application of the user?
— Which types of data are the most useful for meeting these needs?

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- Which is the 'best' technique of fusing these data types for that particular application?
- What are the necessary pre-processing steps involved?
- Which combination of the data is the most successful?

These and other questions comprise a large number of parameters to be considered. The most important question to be answered first is: What is the application the data is needed for? Knowing that it is possible to define the necessary spectral and spatial resolution which again has an impact on the selection of the remote sensing data. The selection of the sensor depends on satellite and sensor characteristics such as

- orbit;
- platform;
- imaging geometry of optical and radar satellites;
- spectral, spatial and temporal resolution (Pohl and Genderen 1993).

The availability of specific data plays an important role too. It depends on the satellite coverage, operational aspects of the space agency running the satellite, atmospheric constraints such as cloud cover, financial issues, etc. (Pohl 1996).

The next step is the choice of a suitable fusion level. The pre-processing steps are depending on this. In case of pixel based image fusion the geocoding is of vital importance. Related to the geometric correction of the data, details such as the

- geometric model
- ground control points (number, distribution, accuracy)
- digital elevation model
- resampling method etc.

need further consideration.

The question of which technique to choose is very closely related to the definition of evaluation criteria. Both fields are rather difficult to define and depend very much on empirical results (further considerations on this topic are reviewed in § 4 and § 6.2).

The application also defines which season and weather conditions might be of relevance to the fused results. Naturally, the same is valid for the observed area. Especially the topography has a great influence on the fused remote sensing data besides the actual ground cover and land use. Another relevant issue in order to make full use of the benefits of image fusion is the selection of appropriate interpretation methods. Particularly when fusing very disparate data sets, e.g., VIR and SAR the resulting grey values might not refer to physical attributes. The data has to be carefully evaluated using ground truth for verification (Pohl 1996, Polidori and Mangolini 1996). Bearing in mind all these considerations further research is required to generalise and operationalize image fusion.

Image fusion requires well-defined techniques as well as a good understanding of the input data. This review is meant to contribute to the comprehension of image fusion including the definition of terms, the explanation of existing techniques and the assessment of achievements in image fusion. It is structured in five sections. Following this introduction a definition of image fusion provides the concepts involved. Then the paper explains why and in which cases image fusion might be useful. Thereafter, the existing techniques are reviewed including the necessary processing performances followed by an overview of the evaluation criteria for

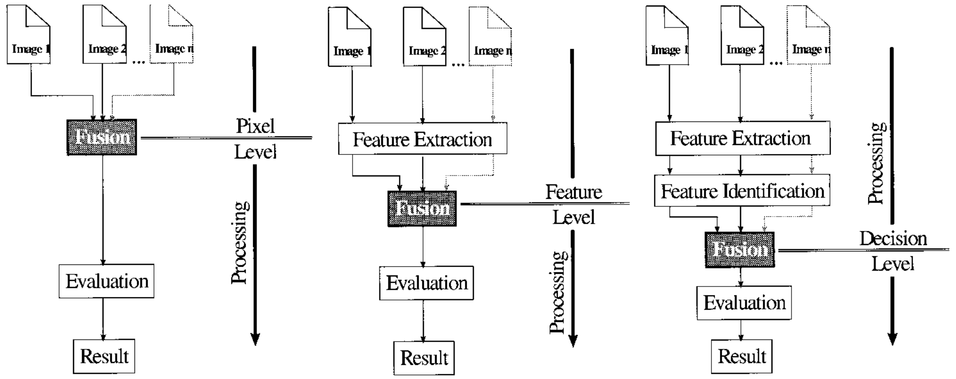

Figure 1. Processing levels of image fusion.

fused data. Finally, benefits and limitations of image fusion are summarized in the concluding section.

2. Concept of image fusion

Data fusion is a process dealing with data and information from multiple sources to achieve refined/improved information for decision making (Hall 1992). A general definition of *image fusion* is given as *'Image fusion is the combination of two or more different images to form a new image by using a certain algorithm'* (Genderen and Pohl 1994).

Image fusion is performed at three different processing levels according to the stage at which the fusion takes place:

1. Pixel
2. Feature
3. Decision level.

Image fusion at pixel level means fusion at the lowest processing level referring to the merging of measured physical parameters. An illustration of the concept of pixel based fusion is visualised in figure 1. It uses raster data that is at least co-registered but most commonly geocoded. The geocoding plays an essential role because misregistration causes artificial colours or features in multisensor data sets which falsify the interpretation later on. It includes the resampling of image data to a common pixel spacing and map projection, the latter only in the case of geocoding. A comparison of methods for the geometric and radiometric correction of remote sensing data is given in Cheng *et al.* (1995) and Toutin (1994).

Fusion at feature level requires the extraction of objects recognised in the various data sources, e.g., using segmentation procedures. Features correspond to characteristics extracted from the initial images which are depending on their environment such as extent, shape and neighbourhood (Mangolini 1994). These similar objects (e.g., regions) from multiple sources are assigned to each other and then fused for further assessment using statistical approaches or Artificial Neural Networks (ANN). Decision- or interpretation level fusion represents a method that uses value-added data where the input images are processed individually for information extraction. The obtained information is then combined applying decision rules to reinforce common interpretation and resolve differences and furnish a better understanding of the observed objects (Shen 1990).

This literature review mainly tackles pixel based image fusion. Techniques used to fuse data at pixel level are described in §4. In the literature a large number of terms can be found. Some terms define different approaches to image fusion, whilst others can be used equivalently. Keys *et al.* (1990) and Franklin and Blodgett (1993) describe the fusion as the computation of three new values for a pixel based on the known relation between the input data for the location in the image. The input images are different in terms of spatial, spectral or temporal characteristics. Other expressions accepted in this context are *image merging* (Carper *et al.* 1990), *image integration* (Welch and Ehlers 1988) and *multi-sensor data fusion* (Franklin and Blodgett 1993). A broader view of the term is presented by Mangolini (1994). He describes *data fusion* as group of methods and approaches using multisource data of different nature to increase the quality of information contained in the data. Often, in the case of data fusion, not only remote sensing images are fused but further ancillary data (e.g., topographic maps, GPS coordinates, geophysical information, etc.) contribute to the resulting image (Harris and Murray 1989). *Data integration* comprises algorithms for image fusion too (Nandhakumar 1990). This term is often used in the context of geographical information systems (GIS) (Ehlers 1993). Other scientists evaluate multisensor image data in the context of *combined* (Lichtenegger 1991), *coincident* (Crist 1984), *complementary* (Koopmans and Forero 1993), *composited* (Daily *et al.* 1979) or *co-registered* (Rebillard and Nguyen 1982) data analysis. In these cases not always an alteration of the digital numbers amongst the different image channels is involved. A simple overlay of multi-source data in a *Red-Green-Blue* (RGB) colour space integrates the data set. The replacement of one of the three channels or parts of it with an image from another data source is called *substitution* (Suits *et al.* 1988). Referring to a different level of image processing are the words *information fusion* (Shufelt and McKeown 1990). Here the images are already interpreted to reach the information or knowledge level before being fused. A very wide field of applications and approaches in image fusion are summarised by *synergy* (Genderen *et al.* 1994) or *synergism* (Harris and Graham 1976) of remote sensing data. It requires the input of data that provide complementary rather than redundant information.

Apart from the three levels at which fusion can be performed image fusion can be applied to various types of data sets:

- — single sensor—temporal (Weydahl 1993), e.g., SAR multitemporal for change detection
- — multi-sensor—temporal (Pohl and Genderen 1995), e.g., VIR/SAR image mapping
- — single sensor—spatial (Cliche *et al.* 1985), e.g., high/low resolution panchromatic/multi-spectral SPOT
- — multi-sensor—spatial (Chavez *et al.* 1991), e.g., high/low resolution SPOT/Landsat
- — single data—multi-sensor (Guyenne 1995), e.g., ERS-1/ERS-2
- — remote sensing data with ancillary data (Janssen *et al.* 1990), e.g., image with topographic maps, (the references given are not exhaustive but meant as example).

Having introduced the concept of image fusion, the following section outlines some goals of image fusion.

3. Objectives of image fusion

Image fusion is a tool to combine multisource imagery using advanced image processing techniques. It aims at the integration of disparate and complementary data to enhance the information apparent in the images as well as to increase the reliability of the interpretation. This leads to more accurate data (Keys *et al.* 1990) and increased utility (Rogers and Wood 1990). It is also stated that fused data provides for robust operational performance, i.e., increased confidence, reduced ambiguity, improved reliability and improved classification (Rogers and Wood 1990). Studying the literature, it appears that image fusion is applied to digital imagery in order to:

— sharpen images (Chaves *et al.* 1991);
— improve geometric corrections (Strobl *et al.* 1990)
— provide stereo-viewing capabilities for stereophotogrammetry (Bloom *et al.* 1988)
— enhance certain features not visible in either of the single data alone (Leckie 1990)
— complement data sets for improved classification (Schistad-Solberg *et al.* 1994)
— detect changes using multitemporal data (Duguay *et al.* 1994)
— substitute missing information (e.g., clouds-VIR, shadows-SAR) in one image with signals from another sensor image (Aschbacher and Lichtenegger 1990)
— replace defective data (Suits *et al.* 1988).

The following paragraphs describe the achievements of image fusion in more detail.

3.1. *Image sharpening*

Image fusion can be used as a tool to increase the spatial resolution. In that case high-resolution panchromatic imagery is fused with low-resolution often multispectral image data. A distinction has to be made between the pure visual enhancement (superimposition) and real interpolation of data to achieve higher resolution (wavelets) the latter being proposed amongst others by Mangolini (1994) and Ranchin *et al.* (1996). In this way the spectral resolution may be preserved while a higher spatial resolution is incorporated which represents the information content of the images in much more detail (Franklin and Blodgett 1993, Pellemans *et al.* 1993). Examples of fusing XS/PAN or TM/PAN for resolution enhancement were published, amongst others, by Simard (1982, simulated data) Cliche *et al.* (1985), Price (1987), Carper *et al.* (1990), Franklin and Blodgett (1993), Ranchin *et al.* (1996). A special case forms the fusion of channels from a single sensor for resolution enhancement, e.g., TM-data. The lower resolution thermal channel can be enhanced using the higher resolution spectral channels (Moran 1990). Other approaches increase the spatial resolution of the output channel using a windowing technique on the six multispectral bands of TM (Sharpe and Kerr 1991). The fusion of SAR/VIR does not only result in the combination of disparate data but may also be used to spatially enhance the imagery involved. Geometric accuracy and increase of scales using fusion techniques is of concern to mapping and map updating (Chiesa and Tyler 1990, Pohl 1996).

3.2. *Improvement of registration accuracy*

The multi-sensor image registration gains importance in areas with frequent cloud cover where VIR imagery is not continuously available. The drawbacks of conventional image to map registration are the differences in appearance of the features used as control or tie points. The positioning of points is facilitated if they are localised in similar 'views' (remote sensing data). Of advantage is an integrative rectification approach which iteratively improves the registration accuracy (Ehlers 1991). Multisensor stereo mapping requires accurately co-registered input data and shows improved results in comparison with image-to-map registration (Welch *et al.* 1985, 1990).

3.3. *Creation of stereo data sets*

It is proven that multisensor stereo data sets can help to overcome the lack of information, e.g., due to cloud cover. Combinations of VIR/VIR (different spatial resolution), SAR/SAR (multiple incidence angles) and VIR/SAR were successfully used. Some constraints exist depending on radiometric differences of the images used as stereo pair (Domik *et al.* 1986, Bloom *et al.* 1988, Welch *et al.* 1990, Buchroithner *et al.* 1992, Raggam *et al.* 1994, Toutin and Rivard 1995).

3.4. *Feature enhancement*

Taking advantage of the different physical nature of microwave and optical sensor systems the fusion of those data results in an enhancement of various features observed (Daily *et al.* 1979, Ehlers 1991, Franklin and Blodgett 1993, Yésou *et al.* 1993 b). The feature enhancement capability of image fusion is visually apparent in VIR/VIR combinations that often results in images that are superior to the original data (Keys *et al.* 1990). Multisensor image fusion enhances semantic capabilities of the images and yields information which is otherwise unavailable or hard to obtain from single sensor data (Mitiche and Aggarwal 1986). Conclusively, in order to maximise the amount of information extracted from satellite image data useful products can be found in fused images (Welch and Ehlers 1987).

3.5. *Improved classification*

The classification accuracy of remote sensing images is improved when multiple source image data are introduced to the processing. Images from microwave and optical sensors offer complementary information that helps in discriminating the different classes. Working with VIR data users rely on the spectral signature of the ground targets in the image. Some vegetation species can not be separated due to their similar spectral response. Therefore radar images can contribute different signals due to differences in surface roughness, shape and moisture content of the observed ground cover. The use of multisensor data in image classification becomes more and more popular with the increased availability of sophisticated software and hardware facilities to handle the increasing volumes of data. A new trend in this respect is the ANN approach since the conventional statistical techniques were found inappropriate for processing multisensor data from SAR and VIR.

3.6. *Temporal aspects for change detection*

Image fusion for change detection takes advantage of the different configurations of the platforms carrying the sensors. Based on the orbital characteristics the so called repeat-cycle of the satellite is defined and varies from system to system from daily (NOAA) up to tenths of days (Landsat, SPOT, ERS-1, etc.). This means that a certain area on the Earth is observed at different times of the day, month or year. The combination of these temporal images enhances information on changes that might have occurred in the area observed. *Temporal image fusion* is applicable to images from the same sensor as well as to multiple sensor data. It is nearly impossible to acquire multisensor data simultaneously so that fusion of data from different sensors mostly includes a temporal factor. An overview on image enhancement techniques for change detection from multisensor data including image differencing, ratioing and PCA is given in Mouat *et al.* (1993). The techniques are described in §4. There is a necessity of correcting the input imagery for radiometric distortions which occur especially in VIR data, i.e., atmospheric and illumination correction in order to create compatible data sets. The images to be fused should be acquired at similar seasons to account for seasonal changes which might influence the change detection capabilities of this approach.

Multitemporal SAR data provides good potential for change detection analysis because of its all-weather capability. The evaluation of single SAR imagery is difficult due to the ambiguities contained in SAR images (De Groof *et al.* 1992, Weydahl 1992, Kattenborn *et al.* 1993, Kohl *et al.* 1994).

3.7. *Overcoming gaps*

The images acquired by satellite remote sensing are influenced by a number of effects based on the carrier frequency of the electromagnetic waves. It is well known that VIR sensors are hindered by clouds to obtain information on the observed objects on Earth. Even the shadows of the clouds influence the interpretability of the imagery. SAR on the other hand suffers from severe terrain induced geometric distortions based on its side-looking geometry (layover, foreshortening, shadow). To overcome these influences it is possible to combine different images acquired by the same or a different instrument. Apart from creating simple or complex mosaics there are other techniques such as Optimal Resolution Approach (Haefner *et al.* 1993), IHS and others to fuse the data for the purpose of filling the gaps which are described in more detail in the following section.

4. Image fusion techniques

This section describes techniques to fuse remote sensing images. The evaluation of their usefulness and disadvantages is discussed later in §6. An overall processing flow for fusion optical and radar satellite data is given in figure 2.

After having corrected the remote sensing images for system errors, the data is further radiometrically processed. In the case of SAR, speckle reduction is an elementary operation in many applications. The speckle reduction can be performed at various stages of the processing; depending on the application, it is advisable to speckle filter before geocoding which implies an improved object identification for GCP measurements (Dallemand *et al.* 1992), others allow the filtering and resampling during the geocoding process in one step to reduce the number of times the data is resampled. Another aspect to be considered when dealing with SAR is the 16 to 8-bit data conversion. According to Knipp (1993) the 16 to 8-bit data conversion in SAR processing, in case that it is required, should be performed after speckle reduction in order to reduce the loss of information. Optical imagery is influenced by the atmosphere during data acquisition and therefore needs correction and/or other radiometric enhancements such as edge enhancement and others.

Following the radiometric processing the data are geometrically corrected. In some cases it is geocoded, in others only co-registered to coincide on a pixel by pixel basis depending on the height variations in the area contained in the data. Again it

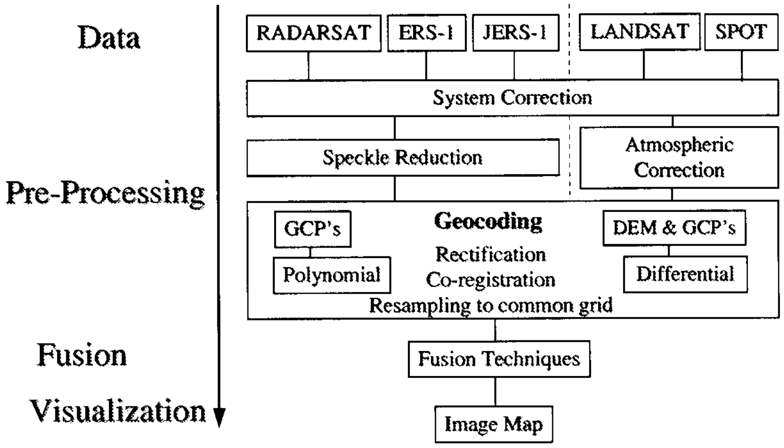

Figure 2. Processing flow chart for pixel based image fusion (Pohl 1996).

has to be pointed out that this is a major element of pixel level image fusion. These fusion techniques are very sensitive to misregistration.

Subsequently, the data can be fused using one of the fusion techniques described in this review. In some cases, especially if image data of very different spatial resolution is involved, the resampling of the low resolution data to the pixel size of the high resolution image might causes a blocky appearance of the data. Therefore a smoothing filter can be applied before actually fusing the images (Chavez 1987). The resulting image map can be further evaluated and interpreted related to the desired application.

In general, the techniques can be grouped into two classes: (1) Colour related techniques, and (2) Statistical/numerical methods. The first comprises the colour composition of three image channels in the RGB colour space as well as more sophisticated colour transformations, e.g., IHS and HSV. Statistical approaches are developed on the basis of channel statistics including correlation and filters. Techniques like PCA and regression belong to this group. The numerical methods follow arithmetic operations such as image differencing and ratios but also adding of a channel to other image bands. A sophisticated numerical approach uses wavelets in a multiresolution environment. The next sections describe these techniques in more detail.

4.1. *Band selection*

Some techniques only allow a limited number of input bands to be fused (e.g., RGB, IHS), whilst others can be performed with any number of selected input bands. One method that relies on statistics in order to select the data containing most of the variance. This is the selection method developed by Chavez *et al.* (1982) called *Optimum Index Factor* (OIF) mathematically described in equation (1).

$$\mathrm{OIF}=\frac{\sum_{i=1}^{3}\sigma_i}{\sum_{j=1}^{3}|cc_j|} \tag{1}$$

σ_i = standard deviation of digital numbers for band, cc_j = correlation coefficient between any two of three bands. Other considerations related to OIF can be found in Chavez *et al.* (1984), Keys *et al.* (1990) and Yésou *et al.* (1993 a).

Another approach is to select the bands which are the most suitable to a certain application. This requires *a priori* knowledge by the user (Sheffield 1985). Kaufmann and Buchroithner (1994) suggest to select the three bands with the highest variance. The principal component analysis is another solution to reduce the number of channels containing the majority of the variance for the purpose of image fusion (Yésou *et al.* 1993 a). Others provide a certain band combination based on an algorithm which takes into account the statistics of the scene including correlations between image channels (Sheffield 1985).

4.2. *Colour related techniques*

There are a variety of techniques to display image data in colour. In general, colours are mathematically described in two ways:

1. Tristimulus values,
2. Chromaticity

Each of these has several special cases. Tristimulus values are based on three different spectral curves. They can represent filters or emission spectra. A special representation of the spectral curves are the CIE tristimulus values obtained with the CIE tristimulus coefficients (see figure 3).

A chromaticity representation consists of the luminosity of an object and two quotients of the luminosity leading to intensity hue and saturation. A chromatic representation based on the CIE tristimulus values and using Cartesian coordinates is shown in figure 3. RGB refers to the tristimulus values associated with a colour monitor. Its advantages are its simplicity and the fact that other colour representations have to be transformed to RGB in order to be displayed on a colour monitor (Haydn *et al.* 1982, Russ 1995). It is one of the most common techniques to colour composite multi-sensor data and is mathematically described first in the following section.

4.2.1. *Colour composites (RGB)*

The so-called additive primary colours allow one to assign three different types of information (e.g., image channels) to the three primary colours red, green and

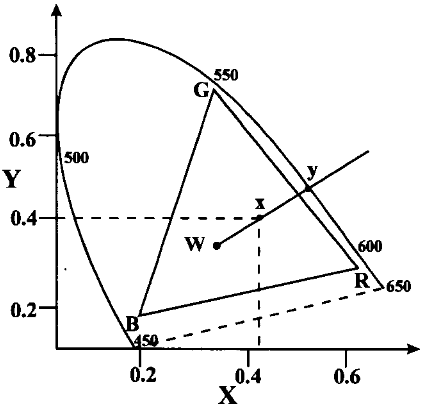

Figure 3. CIE chromaticity diagram (Haydn *et al.* 1982).

blue. Together they form a colour composite that can be displayed with conventional media, e.g., cathode ray tube (CRT). The colour composite facilitates the interpretation of multichannel image data due to the variations in colours based on the values in the single channels. The grey scale value, used to select a set of red, green, and blue brightness', is stored in a look up table (LUT) that are the voltages sent to the display tube. Operations on the LUT and the histogram of the image data can enhance the colour composite for visual interpretation (Russ 1995).

The possibilities of varying the composite are manifold. Depending on the selection of the input image channels the fused data will show different features. Very important for the colour composite is the distribution of the available 0–255 grey values to the range of the data. It might be of advantage to invert input channels before combining them in the RGB display with other data depending on the objects of interest to be highlighted (Pohl *et al.* 1994).

Examples of successfully used colour composites of optical and microwave data are described by Aschbacher and Lichtenegger (1990), Dallemand *et al.* (1992), Vornberger and Bindschadler (1992), Comhaire *et al.* (1994), Hinse and Coulombe (1994), Marek and Schmidt (1994), Oprescu *et al.* (1994), and Pohl *et al.* (1994). Reports about multi-sensor optical composites can be found in Welch *et al.* (1985), and Chavez (1987). Multisensor SAR fusion by RGB are reported by Marek and Schmidt (1994). Multitemporal ERS-1 SAR colour composites were used by Comhaire *et al.* (1994). On the basis of the complementary information from VIR (spectral reflectivity) and SAR (surface roughness) the features are enhanced in fused imagery. Work in the field of geology was published amongst others by Daily *et al.* (1979), Zobrist *et al.* (1979) and Yésou *et al.* (1993 b).

In many cases the RGB technique is applied in combination with another image fusion procedure, e.g., IHS, PCA, and others which are explained in the coming sections.

4.2.2. *Intensity-Hue-Saturation (IHS)*

The IHS colour transformation effectively separates spatial (I) and spectral (H, S) information from a standard RGB image. It relates to the human colour perception parameters. The mathematical context is expressed by equation (2) (*a–c*). I relates to the intensity, while ‘v_1’ and ‘v_2’ represent intermediate variables which are needed in the transformation. H and S stand for Hue and Saturation, (Harrison and Jupp 1990).

$$\begin{pmatrix} I \\ v_1 \\ v_2 \end{pmatrix} = \begin{pmatrix} \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{3}} \\ \frac{1}{\sqrt{6}} & \frac{1}{\sqrt{6}} & -\frac{2}{\sqrt{6}} \\ \frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} & 0 \end{pmatrix} \begin{pmatrix} R \\ G \\ B \end{pmatrix} \quad (a) \qquad (2)$$

$$H = \tan^{-1}\left(\frac{v_2}{v_1}\right) \quad (b) \qquad S = \sqrt{v_1^2 + v_2^2} \quad (c)$$

There are two ways of applying the IHS technique in image fusion: direct and substitutional. The first refers to the transformation of three image channels assigned to *I*, *H* and *S* (Rast *et al.* 1991). The second transforms three channels of the data set representing RGB into the IHS colour space which separates the colour aspects in its average brightness (intensity). This corresponds to the surface roughness, its dominant wavelength contribution (hue) and its purity (saturation) (Gillespie *et al.* 1986, Carper *et al.* 1990). Both the hue and the saturation in this case are related to the surface reflectivity or composition (Grasso 1993). Then, one of the components is replaced by a fourth image channel which is to be integrated. In many published studies the channel that replaced one of the IHS components is contrast stretched to match the latter. A reverse transformation from IHS to RGB as presented in equation (3) converts the data into its original image space to obtain the fused image (Hinse and Proulx 1995 b).

The IHS technique has become a standard procedure in image analysis. It serves colour enhancement of highly correlated data (Gillespie *et al.* 1986), feature enhancement (Daily 1983), the improvement of spatial resolution (Welch and Ehlers 1987, Carper *et al.* 1990) and the fusion of disparate data sets (Harris *et al.* 1990, Ehlers 1991).

$$\begin{pmatrix} R \\ G \\ B \end{pmatrix} = \begin{pmatrix} \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{6}} & \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{6}} & -\frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{3}} & -\frac{2}{\sqrt{6}} & 0 \end{pmatrix} \begin{pmatrix} I \\ v_1 \\ v_2 \end{pmatrix} \tag{3}$$

The use of IHS technique in image fusion is manifold, but based on one principle: the replacement of one of the three components (*I*, *H* or *S*) of one data set with another image. Most commonly the intensity channel is substituted. Replacing the intensity—the sum of the bands—by a higher spatial resolution value and reversing the IHS tranformation leads to composite bands (Chavez *et al.* 1991). These are linear combinations of the original (resampled) multispectral bands and the higher resolution panchromatic band (Campbell 1993).

A variation of the IHS fusion method applies a stretch to the hue saturation components before they are combined and transformed back to RGB (Zobrist *et al.* 1979). This is called colour contrast stretching (Gillepsie *et al.* 1986). The IHS transformation can be performed either in one or in two steps. The two step approach includes the possibility of contrast stretching the individual *I*, *H* and *S* channels. It has the advantage of resulting in colour enhanced fused imagery (Ehlers 1991). More results using IHS image fusion are reported by Rast *et al.* (1991), Jutz and Chorowicz (1993), Koopmans and Richetti (1993), Oprescu *et al.* (1994), Smara *et al.* (1996), and Yildimi *et al.* (1996). A closely related colour system to IHS (sometimes also called HSI) is the HSV: hue, saturation and value (Russ 1995). An example of HSV image fusion was presented by Chiesa and Tyler (1990).

4.2.3. *Luminance-chrominance*

Another colour encoding system called YIQ has a straightforward transformation from RGB with no loss of information. *Y*, the *luminance*, is just the brightness of a panchromatic monochrome image. It combines the red, green, and blue signals in proportion to the human eye's sensitivity to them. The *I* and *Q* components of the colour are chosen for compatibility with the hardware used. The *I* is essentially red minus cyan, while Q is magenta minus green. The relation between YIQ and RGB is shown in equation (4 *a*, *b*):

$$
\begin{aligned}
&(a) \quad \begin{pmatrix} Y \\ I \\ Q \end{pmatrix} = \begin{pmatrix} 0{\cdot}299 & 0{\cdot}587 & 0{\cdot}114 \\ 0{\cdot}596 & -0{\cdot}274 & -0{\cdot}322 \\ 0{\cdot}211 & -0{\cdot}523 & 0{\cdot}312 \end{pmatrix} \begin{pmatrix} R \\ G \\ B \end{pmatrix} \\
&(b) \quad \begin{pmatrix} R \\ G \\ B \end{pmatrix} = \begin{pmatrix} 1{\cdot}000 & 0{\cdot}956 & 0{\cdot}621 \\ 1{\cdot}000 & -0{\cdot}272 & -0{\cdot}647 \\ 1{\cdot}000 & -1{\cdot}106 & -1{\cdot}703 \end{pmatrix} \begin{pmatrix} Y \\ I \\ Q \end{pmatrix}
\end{aligned}
\tag{4}
$$

Since the Y, I and Q components are less correlated than the RGB ones, this transformation offers better possibilities for enhancing an image. This was shown in an example by Guo and Pinliang (1989).

4.3. *Statistical/numerical methods*

In this section all operations are grouped together which deal with mathematical combinations of image channels. It comprises addition, subtraction, multiplication and division (ratio) as well as combinations of these operations.

4.3.1. *Arithmetic combinations*

Certain combinations of bands of images can lead to image sharpening, i.e., higher spatial resolution. Common combinations are SPOT PAN and SPOT XS or SPOT PAN and Landsat TM. But the integration of SAR can also improve the spatial structure of an image because it introduces the surface roughness to the image.

4.3.1.1. *Adding and multiplication*

To enhance the contrast, adding and multiplication of images are useful. An example is the multiplication process expressed by equation (5 *a*, *b*):

$$\mathrm{DN}_f = A(w_1\,\mathrm{DN}_a + w_2\,\mathrm{DN}_b) + B \tag{5a}$$

$$\mathrm{DN}_f = A\,\mathrm{DN}_a\,\mathrm{DN}_b + B \tag{5b}$$

A and B are scaling factors and w_1 and w_2 weighting parameters. DN_f, DN_a and DN_b refer to digital numbers of the final fused image and the input images a and b, respectively. This method was successfully applied to Landsat-TM and SPOT PAN data (Yésou *et al.* 1993 b).

There are a large number of publications containing suggestions on how to fuse high resolution panchromatic images with lower resolution multi-spectral data to obtain high resolution multi-spectral imagery. The possibilities of combining the data using multiplication or summation are manifold. The choice of weighting and scaling factors may improve the resulting images. Details can be found in Simard (1982), Cliche *et al.* (1985), Pradines (1986), Price (1987), Welch and Ehlers (1987), Carper *et al.* (1990), Ehlers (1991), Mangolini *et al.* (1993), Munechika *et al.* (1993) and Pellemans *et al.* (1993).

4.3.1.2. *Difference and ratio images*

Difference or ratio images are very suitable for change detection (Mouat *et al.* 1993). The ratio method is even more useful because of its capability to emphasise more on the slight signature variations (Zobrist *et al.* 1979, Singh 1989). In some cases the resulting difference image contains negative values. Therefore a constant has to be added to produce positive digital numbers. However, differences do not always refer to changes since other factors, like differences in illumination, atmospheric conditions, sensor calibration, ground moisture conditions and registration of the two images, can lead to differences in radiance values. In ratioing, two images from different dates are divided, band by band if the image data have more than one channel. If the intensity of the reflected energy is nearly the same in each image then the ratio image pixel is one, it indicates no change. The critical part of this method is selecting appropriate threshold values in the lower and upper tails of the distribution representing change pixel values. In this respect the normalisation of the data is of advantage as indicated in equation (6), (Griffiths 1988):

$$\frac{XS_3 - XS_2}{XS_3 + XS_2} - \frac{TM_4 - TM_3}{TM_4 + TM_3} + C \qquad (C = 128 \text{ for positive values}) \tag{6}$$

A ratio for spatial enhancement is summarised by equation (7). The aim of this method is to maintain the radiometric integrity of the data while increasing the spatial resolution.

$$DN_{HybridXS(j)} = DN_{PAN}\frac{DN_{XS(i)}}{DN_{SynPAN}} \tag{7}$$

where $DN_{HybridXS(i)}$ - ith band of the fused high resolution image, DN_{PAN} - corresponding pixel in high resolution input PAN image, $DN_{XS(i)}$ - super-pixel in ith band of input low resolution XS image, DN_{SynPAN} - corresponding pixel in low resolution synthetic PAN image, created from low resolution multispectral bands that overlap the spectral response of the input high resolution PAN, (Munechika *et al.* 1993).

That is also the aim of the Brovey Transform, named after its author. It is a formula that normalises multispectral bands used for a RGB display, and multiplies the result by any other desired data to add the intensity or brightness component to the image. The algorithm is shown in equation (8) where DN_{fused} means the DN of the resulting fused image produced from the input data in n multispectral bands multiplied by the high resolution image $DN_{highres}$.

$$DN_{fused} = \frac{DN_{b1}}{DN_{b1} + DN_{b2} + DN_{bn}} DN_{highres} \tag{8}$$

4.3.2. *Principal component analysis*

The PCA is useful for image encoding, image data compression, image enhancement, digital change detection, multitemporal dimensionality and image fusion. It is a statistical technique that transforms a multivariate data set of intercorrelated variables into a data set of new un-correlated linear combinations of the original variables. It generates a new set of axes which are orthogonal.

The approach for the computation of the principal components (PCs) comprises the calculation of:

1. Covariance (unstandardised PCA) or correlation (standardised PCA) matrix
2. Eigenvalues, -vectors
3. PCs

An inverse PCA transforms the combined data back to the original image space. The use of the correlation matrix implies a scaling of the axes so that the features receive a unit variance. It prevents certain features from dominating the image because of their large digital numbers. The signal-to-noise ratio (SNR) is significantly improved applying the standardised PCA (Singh and Harrison 1985, Shettigara 1992). Better results are obtained if the statistics are derived from the whole study area rather than from a subset area (Fung and LeDrew 1987). The PCA technique can also be found under the expression *Karhunen Loeve* approach (Zobrist *et al.* 1979).

Two types of PCA can be performed: selective or standard. The latter uses all available bands of the input image, e.g., TM 1–7, the selective PCA uses only a selection of bands which are chosen based on *a priori* knowledge or application purposes (Yésou *et al.* 1993 b). In case of TM the first three PCs contain 98–99 per cent of the variance and therefore are sufficient to represent the information.

PCA in image fusion has two approaches:

1. PCA of multichannel image—replacement of first principal component by different images (*Principal Component Substitution*—PCS) (Chavez *et al.* 1991) or
2. PCA of all multi-image data channels (Yésou *et al.* 1993 a).

The first version follows the idea of increasing the spatial resolution of a multichannel image by introducing an image with a higher resolution. The channel which will replace PC1 is stretched to the variance and average of PC1. The higher resolution image replaces PC1 since it contains the information which is common to all bands while the spectral information is unique for each band (Chavez *et al.* 1991); PC1 accounts for maximum variance which can maximise the effect of the high resolution data in the fused image (Shettigara 1992).

The second procedure integrates the disparate natures of multisensor imput data in one image. The image channels of the different sensor are combined into one image file and a PCA is calculated from all the channels. Some examples of image fusion applying the first and the second method of PCA are reported by Yésou *et al.* (1993 a) and Richards (1984), respectively.

A similar approach to the PCS is accomplished in the *C*-stretch (colour stretch) (Rothery and Francis 1987) and the *D*-stretch (de-correlation stretch) (Ehlers 1987, Campbell 1993, Jutz and Chorowicz 1993). The de-correlation stretch helps to overcome the perceived problem that the original data often occupy a relatively small portion of the overall data space (Campbell 1993). In *D*-stretching three channel multispectral data are transformed on to principal component axes, stretched to give the data a spherical distribution in feature space and then transformed back onto the original axes (Jutz and Chorowicz 1993). In *C*-stretching PC1 is discarded, or set to a uniform DN across the entire image, before applying the inverse transformation. This yields three colour stretched bands which, when composited, retain the colour relations of the original colour composite but albedo and topographically induced brightness variations are removed.

The PCA approach is sensitive to the choice of area to be analysed. The correlation coefficient reflects the tightness of a relation for a homogeneous sample. However, shifts in the band values due to markedly different cover types also influence the correlations and particularly the variances (Campbell 1993).

4.3.3. *High pass filtering*

Another approach to enhance the spatial resolution of multispectral data adds the spatial to the spectral information: high pass filtering (HPF) in combination with band addition. The high spatial resolution image is filtered with a small high-pass-filter resulting in the high frequency part of the data which is related to the spatial information. This is pixel wise added to the low resolution bands (Tauch and Kähler 1988, Shettigara 1992, Jutz and Chorowicz 1993). Nevertheless, the HPF method has limitations in passing on important textural information from the high resolution band to the low resolution data (Shettigara 1992).

4.3.4. *Regression variable substitution*

Multiple regression derives a variable, as a linear function of multi-variable data, that will have maximum correlation with unvariate data. In image fusion the regression procedure is used to determine a linear combination (replacement vector) of an image channel that can be replaced by another image channel. This method is called *regression variable substitution* (RVS).

To achieve the effect of fusion the replacement vector should account for a significant amount of variance or information in the original multi-variate data set. The method can be applied to spatially enhance data or for change detection with the assumption that pixels acquired at time one are a linear function of another set of pixels received at time two. Using the predicted value obtained from the least-square regression, the difference image is the regression value-pixel of time one (Singh 1989, Shettigara 1992).

4.3.5. *Canonical variate substitution*

The canonical variate analysis is a technique which produces new composite bands based on linear combinations of the original bands. It derives linear combinations of the bands which maximise the differences between training or reference classes, relative to the variation within the training classes. Successful implementation of this approach requires the definition of homogeneous areas or training classes for each of the information classes of interest (Campbell 1993).

4.3.6. *Component substitution*

Shettigara (1992) presented a slightly different view of categorising certain image fusion techniques. He suggests to look at it in a more general way and calls any technique that involves a forward transformation, the replacement of a variable and a backward transformation, a *COmponent Substitution* (COS) technique. The aim of this technique is to sharpen imagery. The most popular COS technique (already described above) is the IHS colour tranformation. Other methods which can be fitted into the COS model are *Regression Variable Substitution* (RVS), *Principal Component Substitution* (PCS) and *Standardised PC Substitution* (SPS), already discussed in the preceding sections (Shettigara 1992).

4.3.7. *Wavelets*

A mathematical tool developed originally in the field of signal processing can also be applied to fuse image data following the concept of the *multiresolution analysis* (MRA) (Mallat 1989). Another application is the automatic geometric registration of images, one of the pre-requisites to pixel based image fusion (Djamdji *et al.* 1993).

The wavelet transform creates a summation of elementary functions (=wavelets) from arbitrary functions of finite energy. The weights assigned to the wavelets are the wavelet coefficients which play an important role in the determination of structure characteristics at a certain scale in a certain location. The interpretation of structures or image details depend on the image scale which is hierarchically compiled in a pyramid produced during the MRA (Ranchin and Wald 1993).

The wavelet transform in the context of image fusion is used to describe differences between successive images provided by the MRA. Once the wavelet coefficients are determined for the two images of different spatial resolution, a transformation model can be derived to determine the missing wavelet coefficients of the lower resolution image. Using these it is possible to create a synthetic image from the lower resolution image at the higher spatial resolution. This image contains the preserved spectral information with the higher resolution, hence showing more spatial detail. This method is called ARSIS, an abbreviation of the French definition 'amélioration de la résolution spatial par injection de structures' (Ranchin *et al.* 1996).

4.4. *Combined approaches*

In some cases it might not be enough to follow one approach in order to achieve the required results. Therefore, the use of combined techniques plays an important role in image fusion. The most successful techniques for using images are developed from combinations of techniques, such as multiple band combinations, mosaic and other fusion techniques. Aspects such as:

(*a*) cloud cover problem not solved,
(*b*) blurred image,
(*c*) colour assignment not acceptable,
(*d*) data stretch insufficient,

are reasons for investigating other possibilities and the optimization of techniques. The following paragraphs provide a brief overview on the manifold possibilities of combining techniques in order to fuse remote sensing images. They serve only as examples of the combination of techniques used by various authors. Many other combinations are of course also possible.

4.4.1. *RGB/other techniques*

The display of remote sensing data in RGB can be found with many of the fusion techniques mentioned above. The combinations of IHS/RGB and PCA/RGB found recognition especially in geology (Haydn *et al.* 1982, Singh 1989, Koopmans and Richetti 1993, Yésou *et al.* 1993 a, 1993 b). The arithmetic combination of image channels in combination with RGB display facilitate the interpretation in many applications (Lichtenegger *et al.* 1991).

4.4.2. *IHS/other techniques*

The IHS transformation offers a large number of possibilities to fuse remote sensing data with e.g., ratios and PCA as input. It is widely used to integrate especially very disparate data such as VIR and SIR (Ehlers 1991, Chiuderi and Fini 1993, Grasso 1993, Loercher and Wever 1994). Arithmetic methods combined with IHS including weighting factors can enhance the remote sensing data for visual interpretation (Yésou *et al.* 1993 a).

4.4.3. *HPF/Band combinations*

It can be of advantage to use subtraction of pre-processed data (e.g., HPF filtered imagery) from the original data in order to enhance lines and edges. The resulting data can then be fused using multiplication with SAR imagery. This creates sharpened VIR/SAR image combinations. A further development of the method described is the introduction of multispectral information to the merge of high-resolution PAN with SAR. The results of the triple sensor image fusion combine VIR/SAR and high spatial resolution in one image (Pohl 1996).

4.4.4. *Mosaic/other techniques*

In order to solve the cloud cover problem effectively, the mosaic approach offers a wide variety of possibilities in connection with other fusion techniques. SAR data is introduced to areas of no information on the optical data, i.e., clouds and their shadows. Likewise, SAR data from different sensors or orbits can reduce the regions of foreshortening, layover and shadow. The idea to input optical data often fails because the mountainous areas which are causing these geometric distortions in the SAR are also the reason for cloud coverage. Therefore, the contribution of other SAR imagery represents the more operational solution. Once the cloud/shadow (VIR) and layover/foreshortening/shadow mask (SAR) has been produced, it is possible to introduce all types of data in the various elements of the mask (Pohl 1996).

5. Examples of image fusion

There is an increasing number of applications in which multisensor images are used to improve and enhance image interpretation. This section gives a couple of examples of multisensor image fusion comprising the combination of multiple images and ancillary data with remote sensing images:

- — topographic mapping and map updating,
- — land use, agriculture and forestry,
- — flood monitoring,
- — ice- and snow-monitoring and
- — geology.

Each section contains a list of references for further reading on these topics.

5.1. *Topographic mapping and map updating*

Image fusion as tool for topographic mapping and map updating has its importance in the provision of up-to-date information. Areas that are not covered by one sensor might be contained in another. In the field of topographic mapping or map updating often combinations of VIR and SAR are used. The optical data serves as reference whilst the SAR data that can be acquired at any time provides the most recent situation. In addition the two data sets complement each other in terms of information contained in the imagery. Work in this field has been published amongst others in (Essadiki 1987, Bloom *et al.* 1988, Tauch and Kähler 1988, Welch and Ehlers 1988, Tanaka *et al.* 1989, Rogers and Wood 1990, Dallemand *et al.* 1992, Perlant 1992, Albertz and Tauch 1994, Kaufmann and Buchroithner 1994, Matte 1994, Perlant *et al.* 1994, Hinse and Proulx 1995 a, Pohl 1995, 1996, Pohl and Genderen 1995).

5.2. *Land use, agriculture and forestry*

Regarding the classification of land use the combination of VIR with SAR data helps to discriminate classes which are not distinguishable in the optical data alone based on the complementary information provided by the two data sets (Toll 1985, Munechika *et al.* 1993, Franklin and Blodgett 1993, Hussin and Shaker 1996). Similarly, crop classification in agriculture applications is facilitated (Ahern *et al.* 1978, Ulaby *et al.* 1982, Brisco and Brown 1995). Concerning multisensor SAR image fusion the difference in incidence angles data may solve ambiguities in the classification results (Brisco *et al.* 1983). Multitemporal SAR is a valuable data source in countries with frequent cloud cover and successfully used in crop monitoring. Especially, for Developing Countries the fusion of SAR data with VIR is a cost effective approach which enables continuous monitoring (Nezry *et al.* 1993, Mangolini and Arino 1996 a, 1996 b). Optical and microwave image fusion is also well known for the purpose of identifying and mapping forest cover and other types. The combined optical and microwave data provide a unique combination that allows more accurate identification, as compared to the results obtained with the individual sensors (Leckie 1990, Lozano-Garcia and Hoffer 1993, Kachwalha 1993, Hinse and Coulombe 1994, Aschbacher *et al.* 1994, Wilkinson *et al.* 1995). With the implementation of fusion techniques using multisensor optical data the accuracy of urban area classification is improved mainly due to the integration of multispectral with high spatial resolution (Griffiths 1988, Haack and Slonecker 1991, Ranchin *et al.* 1996).

5.3. *Flood monitoring*

In the field of the management of natural hazards and flood monitoring using multisensor VIR/SAR images plays an important role. In general there are two advantages to introduce SAR data in the fusion process with optical imagery:

1. SAR is sensitive to the di-electric constant which is an indicator for the humidity of the soil. In addition, many SAR systems provide images in which water can be clearly distinguished from land.
2. SAR data is available at any time of the day or year independent from cloud cover or daylight. This makes it a valuable data source in the context of regular temporal data acquisition necessary for monitoring purposes.

For the representation of the pre-flood situation the optical data provides a good basis. The VIR image represents the land use and the water bodies before flooding. Then, SAR data acquisition at the time of the flood can be used to identify flood extent and damage. Examples of multisensor fusion for flood monitoring are described by Corves (1994), Yésou *et al.* (1994), Pohl *et al.* (1995), Wang *et al.* (1995) and Fellah and Tholey (1996). Others rely on multitemporal SAR image fusion to assess flood extents and damage (Matthews and Gaffney 1994, ESA 1995 a, 1995 b, Lichtenegger and Calabresi 1995, MacIntosh and Profeti 1995, Badji 1995, Desnos *et al.* 1996). Furthermore, multitemporal SAR or SAR/VIR combinations are used together with topographic maps (Bonansea 1995, Brakenridge 1995, Kannen *et al.* 1995, Otten and Persie 1995).

5.4. *Ice/snow monitoring*

The fusion of data in the field of ice monitoring provides results with higher reliability and more detail (Ramseier *et al.* 1993, Armour *et al.* 1994). Regarding the use of SAR from different orbits for snow monitoring the amount of distorted areas due to layover, shadow and foreshortening can be reduced significantly (Haefner *et al.* 1993).

5.5. *Geology*

Multisensor image fusion is well implemented in the field of geology and a widely applied technique for geological mapping. It is a well known fact that the use of multisensor data improves the interpretation capabilities of the images. Geological features which are not visible in the single data alone are detected from integrated imagery. In most cases VIR is combined with SAR based on the fact that the data sets complement each other. They introduce information on soil geochemistry, vegetation and land use (VIR) as well as soil moisture, topography and surface roughness (SAR) (Daily *et al.* 1979, Blom and Daily 1982, Rebillard and Nguyen 1982, Reimchen 1982, Haydn *et al.* 1982, Aarnisalo 1984, Evans 1988, Baker and Henderson 1988, Hopkins *et al.* 1988, Paradella *et al.* 1988 and Taranik 1988, Guo and Pinliang 1989, Harris and Murray 1989, Koopmans *et al.* 1989, Harris *et al.* 1990, Grasso 1993, Jutz and Chorowicz 1993, Koopmans and Forero 1993, Koopmans and Richetti 1993, Yésou *et al.* 1993 a, 1993 b, 1994, Ray *et al.* 1995).

6. Advantages and limitations

In order to summarise the review some issues related to advantages and disadvantages along with constraints of image fusion are discussed below.

6.1. *Selection of appropriate data set and techniques*

The decision on which technique is the most suitable is very much driven by the application. Therefore, it is very difficult to make general statements on the quality of a fusion technique. In addition the type of data available and statistical measurements, e.g., correlation matrix may support the choice.

The choice of a data set is application dependent as is the technique used to fuse the data (Pohl 1996). Other limiting factors in respect to the data selection are operational constraints of the sensors that are supposed to acquire the data, including receiving stations and data distributors (Pohl 1996, Polidori and Mangolini 1996).

The characteristics of fused image data depend very much on the applied pre-processing and the image fusion technique. The constraints are related to the disturbance of spectral content of the input data and a blurring effect when introducing images with a low SNR. Also, the temporal aspect should not be underestimated. Changes in the area between the acquisition dates of the imagery might introduce problems in the fused image. The user of multisensor data in the context of image fusion has to be aware of the physical characteristics of the input data in order to be able to select appropriate processing methods and to judge the resulting data (Pohl 1996).

6.1.1. *Pre-processing*

All sensor-specific corrections and enhancements of image data have to be applied prior to image fusion since the techniques refer to sensor-specific effects. After image fusion the contribution of each sensor cannot be distinguished or quantified in order to be treated accordingly. A general rule of thumb is to first produce the best single-sensor geometry and radiometry (geocoding, filter, line and edge detection, etc.) and then fuse the images. Any spatial enhancement performed prior to image fusion will benefit the resulting fused image. An advantage is the possibility of filtering and enhancing the data during the geocoding process to avoid multiple resampling. The data has to be resampled at the pixel spacing required for the desired image fusion (Pohl 1996).

The importance of geometric accuracy to avoid artefacts and misinterpretation in pixel based image fusion should not be underestimated. Pixels registered to each other should refer to the same object on the ground. This implies that the data should be geocoded with sub-pixel accuracy. The DEM therefore plays an important role in this process. The need for DEMs of high quality and appropriate grid spacing is evident.

6.1.2. *Techniques and image combinations*

Categorized by technique the following sections summarize observations relevant to the judgement of the usefulness of a certain fusion technique:

6.1.2.1. *RGB*

Digital numbers in single images influence the colours in the RGB composite. This implies that the following factors need consideration:

1. Histogram stretching of single channels influences the visibility of features in the final colour composite.
2. Inversion of image channels might be desirable to assign colour to features.
3. RGB channel assignment significantly influences the visibility of features and visual interpretation by a human interpreter (blue = water, green = land, etc.).

The technique is simple and does not require CPU time-intensive computations. RGB overlay protects the contribution from optical imagery from being greatly affected by speckle from SAR (Pohl 1996).

6.1.2.2. *Band combinations*

The use of linear combinations have the disadvantage that these band combinations lead to a high correlation of the resulting bands and that part of the spectral information is lost compared to the original multispectral image (Ehlers 1987, 1991). The fusion of SAR with VIR data improves the interpretation of the SAR data. Subsequently, it helps applications that benefit from the interpretation of up-to-date SAR data (urban growth, coastal zone monitoring, tidal activities, soil moisture studies, etc.). The resulting fused image depends very much on the appearance and content of the SAR data. As a result, the SAR data have to be selected according to the field of interest of the application. Influence of terrain on SAR backscatter reduces the suitability of the data for recognizing features such as roads, cities, rivers, etc. This type of technique does not solve the cloud-cover problem because the range of digital numbers corresponding to clouds is preserved and even enhanced if not excluded from the calculation (Pohl 1996).

6.1.2.3. *Brovey*

The spectral content of the VIR data is preserved while introducing the texture from SAR. The resulting image is not quite as sharp as the one produced from multiplication only. The water-land boundaries are well defined in the fused images; it allows colours to be assigned to the water currents (e.g., tidal inlets) (Pohl 1996).

6.1.2.4. *PCA*

Radiometric pre-processing plays an important role in relation to the spectral content of the fused image. The appearance of SAR significantly influences the feature visibility in the fused VIR/SAR image. As a consequence, features that are detectable on SAR data can be introduced to the VIR data by image fusion to complement the data (e.g., soil moisture, urban area, oceanographic objects) (Pohl 1996). The PCA technique enables the integration of more than three types of data (Zobrist *et al.* 1979).

Principal component SAR images show potential for topographic mapping. This is valid, in particular, for the three-dimensional impression of topography and change detection. The possibilities have not yet been fully explored, e.g., combination of principal components with optical data (Pohl 1996).

6.1.2.5. *IHS*

The IHS offers a controlled visual presentation of the data. The informative aspects are presented in IHS using readily identifiable and quantifiable colour attributes that can be distinctly perceived. Numerical variations can be uniformly represented in an easily perceived range of colours (Harris *et al.* 1990). Other techniques produce images which are difficult to interpret quantitatively and qualitatively because the statistical properties have been manipulated and the original integrity of the data is disturbed. Related to the IHS technique the hue has to be carefully controlled since it associates meaningful colour with well defined characteristics of the input. An advantage of the IHS versus the RGB is the ability of integrating four instead of three channels in the fused image (Rothery and Francis 1987). IHS fused imagery have the capability of allocating data from the SAR to cloud covered areas without having to identify the clouds at an earlier stage. The speckle is preserved from the SAR data in the fused image. It shows similarities with the Brovey transformation in terms of spectral content of the imagery. A disadvantage is the reduced spatial detail compared to original optical data (Pohl 1996).

6.1.2.6. *Mosaic*

The mosaic has an important position amongst the image fusion techniques as far as cloud removal from VIR and the replacement of radiometrically distorted SAR data is concerned. The result depends very much on the quality of the mask designed for the mosaic. This is a critical point for the optical imagery. The identification of foreshortening, layover and shadow areas in the SAR is based on DEM calculations and pure geometry. These products are often delivered with the SAR image itself. It is essential to match the histograms of the various input data to each other. It can be used in combination with any other image fusion technique (Pohl 1996).

6.2. *Assessment criteria*

Working in the field of multisensor image fusion, the evaluation of the achieved results becomes relatively complex because of the different sources of data that are involved. The different aspects of image acquisition of the various sensors have to be considered as well as the approach of the image fusion itself plays a role.

A numerical quality assessment of image fusion processes was recently introduced by Ranchin *et al.* (1996). They implemented mathematical conditions to judge the quality of merged imagery in respect to their improvement of spatial resolution while preserving the spectral content of the data. With the use of difference images a comparison was made with the original data introduced to the fusion process. In addition, image bias, variance and correlation of imagery were taken into account as indicators during the mathematical quality assessment (Ranchin *et al.* 1996).

Another possibility is to validate findings from fused data by testing the methods on simulated data (known parameters) followed by a comparison with actual data sets. It is necessary to have access to a variety of situations, relevant parameters and ground truth (Polidori and Mangolini 1996).

In this respect much more research is required to provide objective evaluation methods for fused imagery (Pohl 1996).

6.3. *Levels of image fusion*

Some considerations regarding the judgement of image fusion are necessary regarding the processing levels as mentioned above. A constraint of pixel based fusion is the necessity of accurate geocoding, including a resampling of the data. The geometric correction requires knowledge on the sensor viewing parameters along with software that takes into account the image acquisition geometry. In areas with considerable height variations a digital elevation model (DEM) is necessary. This is especially important for SAR data processing due to the side-looking geometry of the sensor. In addition, pixel based methods deal with very large data volumes and long computation times are involved. Frequently, the difficulty of comparing pixels from heterogeneous data is mentioned in the literature. Feature level image fusion uses corresponding structures which makes the geometry a less critical issue. The pixel based methods have the advantage against feature or information level fusion of using the most original data. It avoids a loss of information which occurs during a feature extraction process (Mangolini 1994).

6.4. *Operational image fusion*

The fusion of multisensor data is limited by several factors. Often, the lack of simultaneously acquired multisensor data hinders the successful implementation of image fusion. In the case of large differences in spatial resolution of the input data problems arise from the limited (spatial) compatibility of the data. Since there is no standard procedure of selecting the optimal data set, the user is often forced to work empirically to find the best result. The use of multisensor data requires more skills of the user in order to handle the data appropriately which also invokes the availability of software that is able to process the data. The validation of the fusion algorithm bares some insecurity (Polidori and Mangolini 1996). Furthermore, the lack of available ground truth (Lozano-Garcia and Hoffer 1993) forms another constraint, and of course of the use of more than one scene has an impact on the costs involved.

6.5. *Future improvements*

The development of powerful hardware along with more and more sophisticated software allow the implementation of algorithms and techniques that require large data volumes and time intensive computation such as the wavelet approach. An improvement and the development of new techniques is currently being developed, e.g., concerning ANN and the wavelet transform as already mentioned in the context of the ARSIS method (Ranchin and Wald 1993). A combination of wavelet transform and ANN classification was already presented by Melis and Lazzari (1994). Also, the involvement of expert systems in a GIS can support the integration and evaluation of fused image data.

A very important aspect in future research and development activities is to place emphasise on methods to estimate and assess the quality of fused imagery. A start is the mathematical approach along with a set of criteria to check the radiometric integrity of the fused imagery described by Mangolini *et al.* (1993) and Ranchin *et al.* (1996).

More flexible satellite sensors are expected to contribute to the optimisation of the input data set (e.g., Radarsat). The operation of ERS-1 and ERS-2 in the so-called 'Tandem-mode' provides a solution to problems that occur due to temporal changes of ground cover between the acquisition dates of SAR data. Future satellites with multiple sensors on board will provide the opportunity to simultaneously acquire a data set. An example is SPOT-4 with the VEGETATION program (1 km resolution) as well as multispectral HRV at 20 m resolution (Pohl 1996). Value-added products are to be provided by the data processing agencies along with special training of the data users (Polidori and Mangolini 1996).

With upcoming improved sensors, the importance of multisensor image fusion and interpretation will increase and open new possibilities in Earth observation for operational applications for the protection and development of the Earth's environment (Pohl 1996).

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Appendix A—Abbreviations and acronyms

ANN	Artificial Neural Network
ARSIS	amélioration de la résolution spatial par injection de structures
CAMS	Calibrated Airborne Multispectral Scanner (CAMS)
COS	COmponent Substitution
CRT	Cathode Ray Tube
DN	Digital Number
HPF	High Pass Filtering
HSV	Hue Saturation Value colour representation
IHS	Intensity Hue Saturation colour space
LUT	Look Up Table
MRA	MultiResolution Approach
OIF	Optimum Index Factor
PAN	PANchromatic band
PC1	First Principal Component
PCA	Principal Component Analysis
PCS	Principal Component Substitution
RGB	Red Green Blue colour space
RVS	Regression Variable Substitution
SAR	Synthetic Aperture Radar
SIR-B	Shuttle Imaging Radar Experiment B
SNR	Signal to Noise Ratio
SPOT	System d'Observation de la Terre
SPS	Standardised PC Substitution
TIMS	Thermal Infrared Multispectral Scanner (TIMS)
TM	Landsat Thematic Mapper
VIR	Visible and Infrared
XS	SPOT multispectral bands (3)
YIQ	Luminance Chrominance colour space

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