Abstract - Remotely sensed data provided information on Earth phenomena in different modalities, spectrally, spatially and temporally inhomogeneous. But all this set of data proposes different representations of the same physical environment. How to handle these different representations, how to extract the best of a combination of them? Data fusion is one of the answers to the best possible use of this set of remotely sensed data. In this paper, the general definition of Data fusion in the field of remote sensing as defined by a panel of European experts of the domain is reminded and some winning applications of Data fusion in Earth Observation domain are exposed. Different examples are proposed, mainly based on the fusion of satellite images from different modalities. The variety of examples proposed enhances the wild range of potential applications benefiting from data fusion in the Earth Observation domain. Benefits of using data fusion in this domain are stressed.

Keywords: Remote sensing, data fusion, merging, Earth Observation, satellite data.

1 Introduction

Since the beginning of the 1990's, the availability of Earth Observation satellites has dramatically increased. In the past, only a few spatial and spectral resolutions images or a few modalities of data were available. Nowadays, the spatial resolutions available are going from a meter or less to few kilometers and with finer and finer spectral resolutions. The Earth Observation data are provided by optical sensors, SAR, altimeters, scatterometers, lidar... This new situation opens new applications and new fields of research in Earth observation.

But this wealth of information is difficult to manage for the user. He can select the most representative data for his application and not taking advantage of this wealth. He can process all the available data separately. But the most interesting attitude will be to combine the available set of information in the most efficient way.

For example, a panchromatic image from any satellite such as SPOT, IRS or IKONOS is of interest for visualizing details and structures over an area. The structure and characteristic scales of a city, the buildings, the hierarchy of streets, the vehicles, even more details are detected, recognized or identified according to the high spatial resolution.

The exploitation of the multispectral set of images provided by the same satellite, but with coarser spatial resolution achieves spectral recognition and further vegetation monitoring, studies on marine or air pollution, thematic mapping, precision farming, ... will be achieved. The use of color composition for visualizing multispectral images also facilitates the interpretation of the area of interest.

Combining both sets of information will obviously bring much more added value to the user, opening much more applications with the best spatial resolution available.

Hence, data fusion is becoming of paramount importance, in Earth Observation. Data fusion is an approach oriented to information extraction adopted in several domains. It is based on the synergetic exploitation of data originating from different sources. It aims to produce a better result than the one obtained by a separate exploitation of the same sources. According to Wald [1]:

"The exploitation of satellite images and more generally of observations of the Earth and our environment is presently one of the most productive in data fusion. Observation of the Earth is performed by means of satellites, planes, ships, and ground-based instruments. It results into a great variety of measurements, partly redundant, partly complementary. These measurements may be punctual and time-integrated, bi-dimensional and instantaneous (images), vertical profiles with time-integration or not, three-dimensional information (oceanic / atmospheric profiler / sounder at ground level, or satellite-borne, or ship-borne). Adding the large amount of archives and numerical models representing the geophysical / biological processes, one should conclude that the quantity of information available to describe and model the Earth and our environment increases rapidly. Data fusion is a subject becoming increasingly relevant because it efficiently helps scientists to extract increasingly precise and relevant knowledge from the available information."

The operation of data fusion by itself is not new in environment. For example, meteorologists predict weather for
several tens of years. In remote sensing (i.e. Earth observation from spacecraft or aircraft), classification procedures are performed since long and are obviously relevant to data fusion. Data fusion allows formalizing the combination of these measurements, as well as to monitor the quality of information in the course of the fusion process.”

In Europe and thanks to the impulsion of the European Association of Remote Sensing Laboratories (EARSeL), a Special Interest Group "Data Fusion" was created in 1996. This group contributes to a better understanding and use of data fusion in the field of Earth Observation by organizing regular meetings of its members and tackling fundamentals of Data Fusion in remote sensing. A series of bi-annual international conference called "Fusion of Earth Data – merging point measurements, raster maps and remotely sensed images" was launched in 1996 with the aim of browsing this field of research and to help the scientific community to fully understand the benefits of data fusion in the Earth Observation domain [2, 3, 4].

From the work of this Special Interest Group a set of reference terms emerged [5]. The definition of data fusion in the field of remote sensing was adopted as:

"Data fusion is a formal framework in which are expressed means and tools for the alliance of data originating from different sources."

This definition aims to conduct scientists to a formal approach of data fusion and to the benefits of a global reflection on data fusion. Data fusion aims at obtaining information of greater quality; the exact definition of 'greater quality' will depend upon the application. In this case, quality is a generic word denoting that the user is better satisfied by the results obtained through a fusion process.

In this paper, data fusion is illustrated through specific applications, from the synthesis of images at the best spatial resolution available in the set of images processed to the use of combined modalities for settlement detection. Conclusions on the benefits in data fusion in the Earth observation domain are drawn.

2 Improvement of the spatial resolution: methods

This first example proposes low-level fusion methods. Several studies and publications have shown that merging broadband high spatial resolution images with low spatial resolution and high spectral resolution images proves to be of great benefit in many applications. Photo-interpretation, classification techniques with specific aims such as precision farming, land-use classification, spectral identification of objects..., the range of potential applications for high spatial and spectral resolution is wide. Even producers of satellite data, such as Space Imaging, or SPOT Image, propose fused products for sale.

Many methods have been developed in that purpose and produce multispectral images having the highest spatial resolution available within the data set. They apply on a data set comprising multispectral images $B_{ij}$ at a low spatial resolution $I$ and images $A_h$ at a higher spatial resolution $h$ but with a different spectral content. Examples of such a data set are the SPOT-XS (3 bands, 20 m) and SPOT-P (panchromatic, 10 m) images, or the SPOT-4 case, with 3 bands at 20 m (XS1, XS3, and MIR) and the band XS2 at 10 m, or IRS-1C with the LISS (3 bands) at 23.2 m and a PAN at 5.8 m, or IKONOS with 4 multispectral bands at 4 m and a PAN at 1 m.

The number of methods is fairly large. Of interest are only concerned those methods which claim to provide a synthetic image close to reality when enhancing the spatial resolution, and not those which only provide a better visual representation of the image [e.g., 6].

The latter are very useful for photo-interpretation. This is particularly true when the number of spectral bands is much larger than the usual three bands for describing colors: red, green, and blue. However, such methods have their limitations, especially with the new space-borne sensors and the most recent techniques, which allow the reconstruction of high spatial resolution landscapes with objects having their natural colors. Here, in this context, natural colors mean the colors that are perceived by the human eye.

These methods aim at constructing synthetic multispectral images $B^*_h$ having the highest spatial resolution available within the data set (e.g. the 3 XS bands at 10 m in the case of SPOT 1-3) which are close to reality by performing a high-quality transformation of the multispectral content when increasing the spatial resolution.

All the methods can be associated in three groups of techniques currently used:

- Projection of original data sets into another space, substitution of one vector by the high resolution image and inverse projection into the original space, such as the IHS (Intensity, Hue, and Saturation) method [6].

- Relative spectral contribution such as the Brovey transform [7] which can be applied to any set of image and the CNES P+XS method [8] dedicated to the SPOT case. It should be noted that the Brovey transform does not well represent this group because of its poor principles in construction. Nevertheless, it is often used.
Scale by scale description of the information content of both images and synthesis of the high-frequency information missing to transform the low spatial resolution images into high spatial resolution high spectral content images. This group of methods can be presented through the ARSIS concept [9].

An analysis of this wide range of solutions for the improvement of spatial resolution of images [see e.g. 9] has demonstrated the superiority of the solutions based on the ARSIS concept. The resulting images were useful for better classification, improved photo-interpretation, road detection...

### 3 Fusion of optical and SAR data

The second example of data fusion concerns the combination of information extracted from a SAR image with an optical contextual image. The main objective of such an application is the detection of information that is not extractable when considering only one of the modalities. This type of fusion is more a fusion at feature-level. Figure 1 presents an example of a SPOT and a SAR image of the airport of Marignane, in southern part of France.

![Figure 1](image1.png)

Figure 1. (a) Original SPOT image acquired in 1992 over the airport of Marignane. The spatial resolution is 10 m. Copyright CNES 1992. (b) Original ERS-1 image acquired in 1992 over the airport of Marignane. The original spatial resolution is 12.5 m. The geometrical correction of the image leads to the resampling of the image at 10 m spatial resolution. Copyright ESA 1992.

A multiresolution analysis combined with a wavelet transform was applied to Figure 1b. A simple thresholding applied to the first wavelet coefficient image selects the brightest points (for details on the algorithm see e.g. [10]). Because the two images are superimposable, these bright points have been introduced on the original SPOT image. Figure 2a presents an enlargement of the original SPOT image and Figure 2b the results of the merging of the original SPOT image and of the information extracted from Figure 1b.

The bright points introduced in Figure 2b have been verified by a ground-truth travel. This travel allows us to verify if the points we have detected are corresponding to sub-pixel features or to artifacts. The main part of these points where identified as man-made features. A 3 m x 3 m metal house, a car which is used for frightening birds in the airport, an antenna, ... were detected. The border of the concrete buildings were also underlined by the bright points. This application of data fusion is of interest for the detection of objects with a strong answer in SAR images. The detection of the bright dots was also used in the last example proposed in this paper.

![Figure 2](image2.png)

Figure 2. (a) Enlargement of Figure 1a. (b) Resulting image of the merging of SPOT and bright points extract from Figure 1b.

### 4 Fusion of optical images and features detected in SAR imagery for geological purposes

This third example is a more complex one presenting the use of visible images fused at a pixel-level and a second level of fusion, feature-level, combining objects extracted from different modalities of images and interpreted in a geological framework.
The Three Gorges Project (TGP) is the largest water conservancy project ever built in China, and so in the world. The reservoir is of a canyon and river-like reservoir with a total length of about 600km and average width of 1.1 km which is less than twice the width of natural alluvial channel, and which has the storage capacity of the reservoir of 39.3 billion with the normal pool level (NPL) at 175m. The TGP is a multi-purpose hydro-development project, producing comprehensive benefits mainly in flood control, power generation and navigation improvement. The preparation of the Three Gorges building site started in 1993. Due to the very large area to cover, remote sensing was selected as a mean for studying the upstream geological impact of this project. Despite the importance of its historical floodings, the Yangtze River is the major axis of circulation for goods and people in this region. In the summer of 1998, the floods in this region killed around 4,000 persons and affected around 230 millions inhabitants. Due to the importance of this river for the economy of central China, the detection of geological problems as faults, landslides and rockfalls, that can affect the riverbanks, is of tremendous importance for evaluating environmental and human impacts of the future reservoir. The geological survey has been entrusted to the Chengdu University.

The detection of geological hazards is usually achieved by a photo-interpretation of color composition of high spatial resolution satellite images. Skilful photo-interpreters are able to locate the active faults and the landslides for a given site. In order to help them, a fusion algorithm is applied to a set of data composed of SPOT panchromatic (P) and multispectral XS images. This fusion is defined as a fusion of measurements [11]. The algorithm based on the ARSIS concept [9], allows the computation of XS images with the spatial resolution of 10 m and performs a high-quality transformation of the multispectral content when increasing the spatial resolution. Then the interpretation is achieved on the resulting color composition allowing a detection of active faults and of landslides.

For improving the quality and the quantity of good detection, fusion is again used in a second step. A multiresolution analysis based on the wavelet transform [12, 13] is applied to an ERS SAR image. It provides approximations of the original images with coarser and coarser spatial resolution. A difference between two successive approximations allows the computation of the wavelet coefficients image representing the details between the two approximations. Features or attributes can be extracted by a statistical thresholding of the wavelet coefficients images at different characteristics scales. They are representative of some geological hazards. These features such as lineaments for the faults or drop-like areas that are characteristic of landslides, are enhanced by this multiresolution analysis. The features extracted from the SAR are different of those detectable on SPOT image because of the specific characteristics of the SAR sensor.

Finally a next level of fusion (fusion of features) is performed by the interpreter based on the combination of the its knowledge of geological phenomena and on the detection of features performed on ERS and SPOT images. A complete description of the use of data fusion in this application can be found in [14].

The fusion of the results obtained from the interpretation of the synthetic SPOT XS-HR images and of the features extraction realized on the ERS-SAR image leads to the geological space-map presented Figure 3. In the Xiangxi-Yichang district the geological and structural features were systematically interpreted. From these maps, geologists can see the development of magmata rocks and the distribution of the strata from Cretaceous to Sinian as well as the developmental characteristics of linear structures in this area. Features of several big faults are displayed in the western district.

5 Data fusion for settlements detection within an hydrological application

With its objective to develop an Integrated Water Resources Management System (IWRMS) [15], a project has been launched addressing contentious challenges for water resources management in Southern Africa. The prototype IWRMS has been developed and validated for selected mesoscale and semi-arid catchments in three Southern African countries. The final product of the project, the prototype IWRMS, is an innovative computer based toolkit designed as an assembly of tested, validated and well
documented procedures comprising techniques of database management, remote sensing, airborne photo-interpretation, GIS-analyses, process modeling, GIS-based decision support and implementation strategies. It will enable managers and decision makers to improve the regional strategic planning of catchment water resources with respect to optimizing the use of water to satisfy the demand of competing stakeholders and protecting water and land resources.

This section enhances the benefits of fusion procedures applied to remotely sensed data for water resources management. An important issue is the assessment of the anthropogenic effects on water resources management, including water quality. In this area, these effects originate from the rural settlements, and an accurate mapping of these settlements is requested. Depending of the geographical location, 50 to 80 % of the farms are covered by metal roofs and surrounded by bare soils (see Figure 4). Such farms cannot be detected either on a SAR image or on SPOT or Landsat image. However, an appropriate joint exploitation of SAR and visible imagery permits to map them.

An active sensor acquires SAR images. The sensor sends a signal that reaches the Earth. The different target points reflect this signal and the sensor receives the returned signal. Then a complex process is applied for the calculation of an image. The backscattering coefficient of the different targets depends principally on their composition, the angle between their surfaces and the incident angle of the signal. Hence, if in a pixel (12.5 m by 12.5 m in the case of ERS images in PRI format) a sub-pixel target has a very strong backscattering coefficient compared to its surrounding, the pixel will represent mainly this sub-pixel target. The rural settlements are most often constructed on the model displayed in Figure 4, and are such a sub-pixel target.

From SAR images can be extracted indications on the roughness and conductivity of the area. As the corrugated iron roofs are very conductive, the backscattering coefficient of this material is usually high. Then these settlements can be detected in SAR images as very high-energy points using the algorithm proposed for the example of section 3 [10].

The detection of settlements based only on the use of SAR images has some limitations that prevent the detection of some of the settlements. Firstly, only the settlements with metal roofs can be detected. As shown in Figure 4, the typical rural settlement has a metal roof, but a few have not. The second limitation is due to the influence of the angle between the metal roof and the SAR sensor. Depending on this angle, the return signal may not be backscattered to the radar. Hence, the pixel may not represent the information related to the settlements. Finally, the last limitation is due to the geometric aspects of the SAR sensor. The SAR is a side-looking sensor. Hence for the relief, which faces the sensor, a foreshortening effect may occur. This effect leads to a compression of the slope in front of the sensor leading to a possible mixing of the different backscattering coefficient in the slope. For the relief in opposite of the sensor, a shadowing effect occurs. In this case, the settlements built in the slope opposing the sensor are not detected.

Calling on additional fusion processes and other data can solve these drawbacks.

Optical images with a high spatial resolution (better than 3 m) will help solve the first drawback. However, this will represent an enormous additional cost and will require a high quantity of photo-interpretation or the development of new algorithms for the detection of settlements in these images. Ironically, this enhances the value of the combined processing of SAR and optical data, which is mostly automatic.

The second and the third drawbacks can be solved by a combination of ascending and descending acquisition of SAR images. Presently only descending SAR images were used.

There is a further need to refine the classification of the different settlement or groups of settlements detected. Three possible criteria were identified:

- the first one is based on the size of the detected settlements,
the second on the proximity with other settlements and on the organization of neighborhood,

♦ the third one is based on criteria of distance to the source of water (river, pump...). Even if one of the results of the IWRMS study is that the inhabitants of the settlements are not necessarily going to the closest source of water, the proximity to the water is important for them. Hence, it seems to be interesting to test the potential of such a criteria for classify the different settlements.

The perspectives of such a study are high. Three catchments were under concern. Each covers an area comprised between 4 000 and 12 000 km2. The largest catchment supplies water to about 3 million people. A detailed socio-economic analysis of the water demand and of its usage has been made for three samples, representative of each catchment. Such ground surveys are mandatory to better understand the use of water, and, consequently, for a better management. However they are very expensive and time consuming, since they are done by visiting every homestead. Furthermore, population may change rapidly during the time period of the survey and its analysis. Hence, they can only be made for a few samples. Their results can be extended to the whole catchment and to a whole region using remote sensing.

The methodology is as follows. Statistics are derived from the ground survey. The ground survey permits to assess the quality of the automatic retrieval of settlements and especially to assess the percentage of undetected settlements, for the portion of the catchment that has been surveyed. In turn, ground survey statistics may be improved by taking into account the classification of the settlements (see above). The ground survey statistics are then fused with the map of settlements using these results of quality for this portion. Finally, the relationship found in this fusion process is spread on the whole area using the map of settlements. This generalization process provides a map of statistics of water demand and use for a whole catchment.

A better classification of the physiography of the catchments may be performed by fusing multitemporal sets of data obtained by various optical sensors: SPOT, Landsat, AVHRR, MoDIS, MeRIS, etc., and radar imagery. This classification may serve to extend statistics on water demand and use obtained in a given area to other catchments offering the same physiography and same type of demand.

6 Conclusions

The aim of this paper was to enhance the benefits of data fusion in the field of Earth Observation. The general definition of data fusion proposed by the SIG Data fusion of the EARSeL association was recalled and examples proposed. The applications proposed, are mainly focused on the use of satellite images of different modalities within the objectives of improving the knowledge over an area and obtaining a better description of the objects and phenomena under study. The benefits of using data fusion was demonstrated through the use of high spatial and spectral resolution images for different purposes, the detection of sub-pixel targets, the improvement of geological interpretation, and the detection of informal settlements in the South of Africa for hydrological application. Different levels of fusion were involved in the different applications. Of course all of them can be linked to more general models of fusion such as the JDL Model. But, as fusion is nowadays of common use in remote sensing, the choice of presenting applications as support for illustration of the definition of data fusion proposed by the Special Interest Group of EARSeL was deliberated. All these examples are winning applications of data fusion in remote sensing that should encourage the community to continue its works and the diffusion of the knowledge in the domain.

Nevertheless, many other applications dealing with Earth Observation data exist. The series of conferences Fusion of Earth Data allow a more complete tour of specific applications in this very vivid domain [2, 3, 4]. The fourth edition of the conference will be held in the French Riviera in January 2002.

References


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[15] See the Web pages of the project http://www.iwrms.uni-jena.de/