Quantitatively Assessing Roads Extracted from High-Resolution Imagery

Renaud Péteri, Isabelle Couloigner, and Thierry Ranchin

Abstract

Urban mapping has become a challenge for scientists since the launch of high spatial resolution satellites. This paper focuses on the problem of quality when extracting roads from such data. The definition of a judicious reference enabling the establishment of quantitative criteria is proposed. A method is presented and two sets of criteria dedicated to the evaluation of road extraction algorithms are introduced. An example of an application is proposed enhancing the benefits of a rigorous approach of this problem.

Introduction

Many methods have been proposed for the extraction of road networks from high spatial resolution images. Whatever the results of these methods, they are mainly assessed by visual inspection. Such a visual analysis is not sufficient to determine the limits and properties of the resulting maps. Users need this information, especially to create, build, or to update the maps of cities at the appropriate scales. A quantitative evaluation is then necessary. Few research projects deal with quantitative evaluation (Heipke, *et al.*, 1997; Harvey, 1999; Couloigner and Ranchin, 1998) regarding automated road extraction process. Since result evaluation enables both the characterization and provision of a reliable measure of the result, the road network reference needs to be carefully specified. On that account, this paper introduces, in the first part, a discussion about the possible references for a road extraction process from remotely sensed images. Then, a method to extract reference objects is proposed for the cases where the images are the only information available.

In the second part of this paper, some criteria are proposed for a quantitative assessment of the quality of extracted urban road networks. These criteria were defined with the contribution of urban geographers and cartographers. Two types of criteria are presented: some pertaining to the geometric accuracy of the extracted networks, and some relevant to the spatial characteristics of the network, i.e., its completeness or its redundancy. In the third and last part of this paper, the method and criteria presented are applied to a high resolution Ikonos image using a semi-automatic algorithm presented in Péteri and Ranchin (2003). Finally, conclusions are drawn enhancing the benefits of such quantitative evaluation and reference extraction methods. Future prospects are also discussed.

The Need for a Reference

Introduction

In regard to road extraction from remotely sensed images, research projects on quantitative evaluation are rather recent (Heipke, *et al.*, 1997; Couloigner and Ranchin, 1999; Harvey, 1998). All define reference objects that are used for the comparison step. They are mostly manually acquired from the image. However, there are few discussions on the choice and the influence of these reference objects on the result evaluation. This section tackles this issue and discusses a proposed method for defining a comparison reference when the only data available is the remotely sensed image.

Goals

In order to extract reference objects, it can be useful to also have a georeferenced image and a topographic database with a precision adapted to the targeted objectives. However, up-to-date ground truth data are not always available, especially in the case of developing countries covering large areas. This is the case considered when the only information available is a remotely sensed image. We then aim at defining a "relative" comparison of the result quality, where we want to get similar performances compared to human interpretation.

The images used are high-resolution images (1 meter or better) where details such as vehicles or ground marking are visible.

Our own experience, strengthened by discussions with several geographers, cartographers, and interpreters has shown a great variability of interpretation when acquiring a reference map manually from the image. The problem is the reliability of such a reference. Its variability increases with the increase in details that are brought by new high-resolution images. If the algorithm enables a subpixel precision, the chosen reference must have this precision. Because of the role of subjectivity in an image-based reference, a tolerance zone related to this reference is defined.

In this section, we first review the different possible references for a road extraction process from remotely sensed images. We then define a method to extract a reference map of the roads network. Quantitative criteria for characterizing the performance of a method compared to a chosen reference are also described.

The Different Types of Reference

In this part we discuss the different types of references that can be acquired. Our choice for the evaluation of road extraction algorithm is discussed.

Renaud Péteri and Thierry Ranchin are with the Ecole des Mines de Paris, Groupe Télédétection & Modélisation, BP 207, 06904 Sophia Antipolis cedex, France.

Isabelle Couloigner is with the Department of Geomatics Engineering, Faculty of Engineering, 2500 University Drive N.W., T2N 1N4, Calgary, Alberta, Canada.

Renaud Péteri is also with Computer and Automation Research Institute (SZTAKI) of the Hungarian Academy of Sciences, 1111 Budapest, Kende u.13-17., Hungary.

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Reference Based on Ground Truth

Ground truth data (such as GPS measurements) are a direct estimation of the physical reality of the road, used to detect, and enable its location with a good accuracy in the real world. However, an *in situ* data acquisition campaign is a long and costly process, not easily feasible at a large scale. The use of this kind of data needs frequent updates, and is not applicable to archived images.

Ground truth data are in physical units (m or m^2) and are not directly comparable to extraction results in the image domain. An automatic matching method between the two types of data is then needed. This complex step induces its own errors.

Reference Based on Image Interpretation

By its capacity for using contextual information, the human interpreter is an efficient pattern recognition "system." The possibility to use human interpretation for the evaluation of image analysis algorithms has been the purpose of joint efforts between psychologists and people working in image analysis. In order to compare it with automatic methods, these studies focused on finding some quantitative criteria for characterizing the human interpretation: performance of edge detection filters (Fram & Deutsch, 1975) or similarity measurement for image indexation (Squire & Pun, 1997). These research studies have shown the ability of interpreters to identify an object with a low contrast compared to its environment, and also the importance of using experts such as human interpreters.

In the road extraction context, the image interpreter is able to take the image context into account and to overcome local occlusion problems (e.g., trees, vehicles, shadows). He integrates high-level information, even at a semantic level, integration that cannot be easily done by an algorithm based on low-level information.

- *A posteriori* evaluation by interpreter

The easiest and the most common way for evaluating the result of a pattern extraction process is visual inspection. The operator visually compares the extracted object with his own interpretation of the reference shape. This reference, that can be considered as *a posteriori*, has the drawback of being a variable for each process output. Moreover, this reference only enables the development of qualitative and not quantitative criteria.

- *A priori* evaluation by interpreter

Asking an expert to locate the objects of interest on the image in advance is a common practice in image analysis. In the case of road extraction, some authors (Boichis, 2000; Couloigner and Ranchin, 1998) establish a visual *a priori* reference. An interpreter defines in advance with a pixel precision the object to be extracted. For Bordes (1997) and Ruskoné (1996), the reference is the *BDTopo®* database of the Institut Géographique National (IGN) obtained by photo-interpretation. The reference is then fixed for every algorithm result.

Selected Reference

In our case, the availability and acquisition frequencies of *in situ* data represent obstacles for their use as a reference for an extraction algorithm. According to our goals, when the only information available is the image, we have chosen a reference map based on the image interpretation. The only data used as input is the image for both the interpreter and the algorithm. For using such a reference map, it is preferable to define it *a priori*, and then to have a fixed reference map for every algorithm result. This allows the comparison of the results. However, the object location by an interpreter is subjective and generates a variability of interpretations between different interpreters. Hence, this variability should be taken into account.

In order to minimize this variability, a method is presented in the next section for defining reference objects within a tolerance zone. The tolerance zone enables the definition of a reliability interval for the reference object as well as an area characterizing the result of an automatic extraction process.

Method for Extracting the Reference

From now on, it will be considered that the knowledge of the object location is acquired by image interpretation. The reference object's estimation is linked to the subjective evaluation of each image interpreter. In order to minimize this variability, our choice is to establish a reference based on statistical measures from several image interpretations. A panel of analysts familiar with remotely sensed images is chosen.

A vector mode acquisition is used, which enables an accurate location and a precise description of geometrical features. This choice is justified because context and *a priori* knowledge (for instance, the typology of the object to be extracted) give the image analyst a vision of the scene with a sub-pixel precision. In the field of photo-interpretation, from discussions with cartographers, geographers, and photo-interpreters, it is generally considered that the interpreter has a limit precision of 0.3 pixel.

The characteristics of the chosen reference are:

- An *a priori* reference (fixed compared to each algorithm output)
- The reference is a vector object in the analytic space
- The reference is evaluated from statistics over a team of several image interpreters

The analysis of the different acquisitions enables the extraction of a reference object within a tolerance zone, notions that are explained in the next sections.

Extracted Reference

We aim at defining a reference object, representative of the different interpretations. The acquisition by the interpreters is in vector mode. Figure 1 represents the method used for extracting the reference object from *N* acquisitions. For clarity, only two interpretations and the roadside to extract are represented.

The extraction of a reference polyline consists of three iterative steps. The process direction is defined on Figure 1 and has little influence on the final result:

- The starting point for the process is chosen as the first polyline vertex met last in the process direction (vertex S_i on Figure 1). At this point, the vector $\mathbf{V_0}$ is computed as the average of the *N*-1 slope vectors of segments located before the vertex S_i,
- The transect, To, orthogonal to the vector $\mathbf{V_0}$ is then considered. An average is computed between the points located at the intersection between To and the different polylines (rejecting external points). The point D_0 is obtained and will be a vertex for the reference polyline,
- The mean slope vector $\mathbf{V_1}$ is re-evaluated from the *N* polyline segments starting from the transect, T_0. The transect, T_1, orthogonal to $\mathbf{V_1}$ is obtained, and is "propagated" in the $\mathbf{V_1}$ direction to the first vertex met. Point D_1 is then recomputed and will be another vertex for the reference polyline,

This process is iterated until the final vertex of one of the polylines is met.

Compared to a polyline acquired by a human interpreter, the obtained reference line has a higher number of vertices, and its slope variations are smoother. The slope variation between each vertex of the reference polyline corresponds to the contribution of only one polyline. Due to the average and the increase of the vertices number, the extracted reference polyline has a smoother shape compared to the polylines acquired by the image interpreters. Criteria for using this reference will be described in the following section.

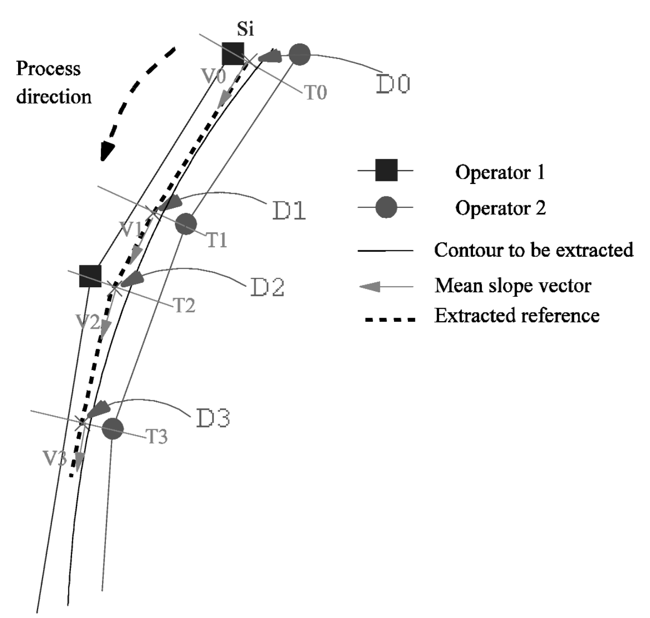

Figure 1. Extraction of a reference line from different interpretations.

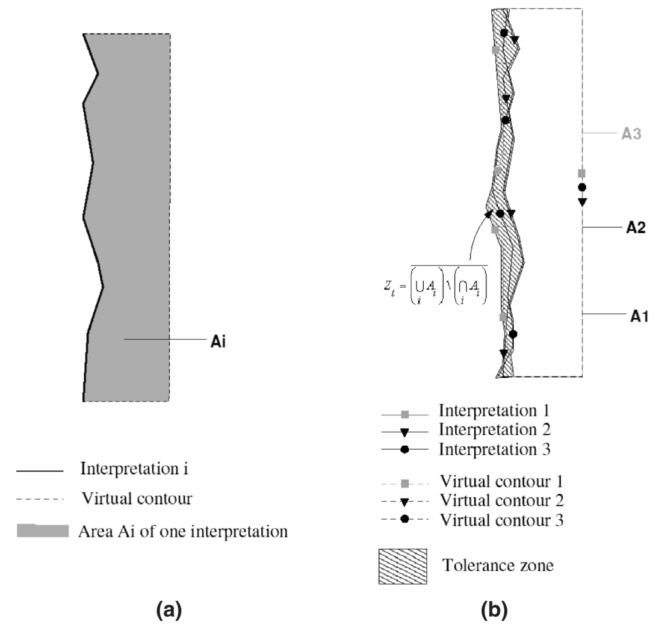

Figure 2. Tolerance zone: The virtual contours (dotted lines) aim at closing the border line of the road. (a) Surface defined by one interpretation and one virtual contour; (b) Tolerance zone from three interpretations.

Tolerance Zone

- Definition

The tolerance zone is representative of the interpretation discrepancies among the different interpreters. The use of such a zone is of double interest.

First, it enables the characterization of the uncertainty on the extracted reference line. A narrow tolerance zone reflects small variability in the interpretations and allows definition of a more reliable reference line.

Second, our purpose is also to allow an evaluation of the performances of road detection algorithms through a reference map acquired by photo-interpretation. Hence, the tolerance zone allows the evaluation of the quality of the extraction by automatic methods. This is done by establishing quantitative criteria.

In both cases, the use of human interpretation can generate a bias on the reference line determination and on the tolerance zone (possibility of a collective interpretation error, for example).

- Determination

Several image interpreters acquire the road contour in a vector representation using polylines. Consider the A_i area inside the object contour line acquired by the interpreter *i*. If the contour line is open, it will be closed by a virtual contour line (Figure 2a). The virtual contour is defined in order to provide an area for computation of the final border line and its tolerance zone. Virtual contours will disappear during the processing. The tolerance zone Z is then defined as:

$$Z = \overline{\left(\bigcup_i A_i\right)\setminus\left(\bigcap_i A_i\right)} \tag{1}$$

where A_i is the area of one interpretation i; ∪ the union of areas; ∩ the intersection of areas; and the bar above is the closure of the set.

Figure 2b exhibits a tolerance zone, representative of the interpretation variability between the different interpreters.

- Algorithmic implementation

The implementation of Equation 1 can be difficult because of the creation of new points when two polylines cross each other. The algorithmic solution is found by computing a *Delaunay triangulation* (Shewchuk, 1996), constrained by polylines and virtual contour lines (Figure 3). The boundary of the set is composed of segments belonging to only one triangle.

In the next section, criteria are established for characterizing both the planimetric accuracy of the extracted roads and the road network compared to the established reference map.

To conclude this paper, a real-case study will be presented. The quantitative criteria and the developed reference map will be illustrated through the assessment of the quality of a method that enables the extraction of road networks from very high spatial resolution imagery (Péteri and Ranchin, 2003).

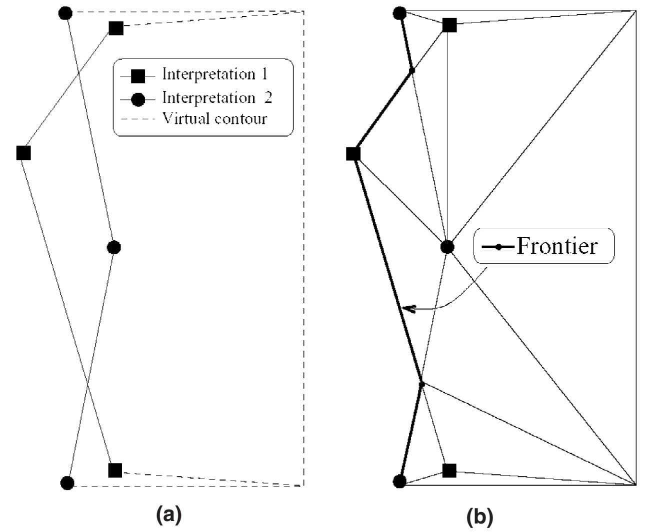

Figure 3. (a) Frontier obtained by constrained Delaunay triangulation.

Criteria to Quantitatively Assess Extracted Road Networks

To assess the quality of an extracted road network, two questions have to be answered:

1. What is the planimetric accuracy of the extracted roads relatively to the reference map?
2. What are the spatial characteristics of the extracted road network compared to the reference map?

To answer these questions, two sets of quantitative criteria have been developed.

Planimetric Accuracy of the Extracted Roads

For the evaluation of extracted roads, three sets of quantitative criteria have been defined: (a) The first defined criterion uses the tolerance zone previously defined in order to compare the extracted object with the reference object. The tolerance zone gives the boundaries where the extracted line should be located. The quantitative evaluation is done by calculating the percentage of the extracted object included in this tolerance zone; (b) The second defined criterion is based on the area included between both extracted sides of the roads under consideration. The error made on area is equal to the difference, in absolute value, between the reference and the estimated area of extracted roads. The difference is computed in square meters. This error is relative to the reference area. With this criterion, we can determine the extracted roads with the weakest accuracy. However, this is not sufficient. Two errors, such as a bad position of one side and a road that is not completely extracted for example, can offset each other; and (c) Then a third set of criteria has been defined. It is based on the position of the extracted roads compared with the position of their references. Sub-pixel errors might be detected. To determine the accuracy of the extracted roads, their characteristic polylines are compared with the reference polylines according to:

- The length of these polylines,
- The "distance" between the extracted and the reference polylines.

The measurement criterion chosen for the distance is the Hausdorff distance because it characterizes particularly well the similarity and the proximity of two vector objects (Abbas, 1994).

Given two polylines, $P_{ext} = \{p1_{ext}, \ldots, pm_{ext}\}$, the extracted polyline, and $P_{ref} = \{p1_{ref}, \ldots, pm_{ref}\}$, the reference polyline, the Hausdorff distance is defined as:

$$H(P_{ext,}, P_{ref}) = max(h(P_{ext}, P_{ref}), h(P_{ref}, P_{ext})) \tag{2}$$

$$\text{where} \quad h(A, B) = \max_{a \in A} \{\min_{b \in B} \{d(a, b)\}\}, \tag{3}$$

and where d (a, b) is the Euclidian distance.

The Hausdorff distance verifies the properties of identity, symmetry and inequality. It measures the degree of mismatch between two sets of data by indicating the maximum distance between any point of one polyline to the other polyline. This measure is better than the usual minimum distance which does not take into account the position and the whole shape of the objects.

Spatial Characteristics of Road Networks

Different spatial characteristics have been defined to specify a network (Musso and Vuchic, 1988; Béguin et Thomas, 1997) such as its size and form, indices of its topology, or indices to link its different components. To differentiate correctly two networks, a unique criterion does not exist, and even a set of criteria does not remove all ambiguity (Béguin et Thomas, 1997). To assess the extracted road network, a few criteria have been defined following the criteria described by Musso and Vuchic (1988). The list of these criteria is not exhaustive.

TABLE 1. ASSESSMENT CRITERIA FOR THE SIZE AND FORM OF A PARTICULAR ROAD

Name	Formula	Equation Number
Number Ir of squared intersections for a road r	$Ir = \sum_{i \in r} n_i$	(4)
Number Ar of arcs constituting a road r	$Ar = \sum_{i \in r} a_i = Ir - 1$	(5)
Length Lr of a road r	$Lr = \sum_{i \in r} l_i$	(6)

where n_i represents a node of the road r under consideration; a_i is one the segment composing the road; and l_i is the length (in meters) of one segment of the road.

TABLE 2. ASSESSMENT CRITERIA FOR A ROAD NETWORK

Description	Formulae	Equation Number
Number N_{cl_i} of roads r of class cl_i of the network R under consideration	$N_{cl_i} = \sum_{r \in R_{cl_i}} r, with \ldots i \in [1; k]$	(7)
Number N_R of roads constituting the network R	$N_R = \sum_{i=1}^{k} N_{cl_i} = \sum_{i=1}^{k} \sum_{\substack{r \in R \\ r \in cl_i}} r$	(8)
Number Iij of squared intersections between two roads r and r' of different classes constituting the network R	$Iij = \sum_{\substack{r,r' \in R \\ r \in cl_i \\ r' \in cl_j}} r \cap r'; j \neq i; i, j \in [1; k]$	(9)
Number $I_R^{\perp}$ of squared intersections for the network R	$I_R^{\perp} = \sum_{r \in R} Ir - \sum_{i=1}^{k} \sum_{j \neq 1}^{k} Iij$	(10)
Number I_R^{3+} of intersections of more than 2 roads in the network R	$I_R^{3+} = \sum_{r,r',r'' \in R} r \cap r' \cap r''$	(11)
Number of intersections in the network R	$I_R = I_R^{\perp} + I_R^{3+}$	(12)
Length L_{cl_i} of roads of class cl_i in the network R	$L_{cl_i} = \sum_{r \in R_{cl_i}} Lr; i \in [1; k]$	(13)
Length of the network R	$L_R = \sum_{i=1}^{k} L_{cl_i} = \sum_{r \in \mathrm{R}} Lr$	(14)

Size and Form Indices of the Road Network

The list of indices to define the size and the form of the road network is based both on graph theory (Marshall, 1971; Kuntzmann, 1972) and on specified defined indices for road network specification.

First, the size and form of an extracted road is assessed using the criteria presented in Table 1. If classes of road are defined (for instance a divided highway versus a simple road with two lanes), the size and components of the extracted road network can be defined using indices presented in Table 2.

Topology Indices

Different combinations between the previous indices can be used for defining quantitatively the topology of a road network. Three ratios have been chosen: we defined the first one, while the two others have been defined according to Musso and Vuchic (1988):

1. Overlapping index λ_{cl_i} of the class cl_i roads:

$$\lambda_{cl_i} = \frac{L_{cl_i}}{L_R}; i \in [1; k] \tag{15}$$

where L_{cl_i} is defined by Equation 13 and L_R is defined by Equation 14. This index gives an indication of the importance of each class in the road network under consideration.

(2) Index β of the network complexity:

$$\beta = \frac{\sum_{r \in R} Ar}{I_R} \tag{16}$$

where Ar is defined by Equation 5 and I_R by Equation 12. This index represents the complexity of the road network under consideration in terms of the number of segments relative to the number of nodes (intersections) composing the network. Its minimal value, 0.5, is reached for a road with two nodes (intersections) and one segment. As the number of segments and nodes constituting the road increases, β approaches 1 asymptotically.

(3) Index γ of the network connectivity:

$$\gamma = \frac{\sum_{r \in R} Ar}{3(I_R - 2)}, \; I_R > 2 \tag{17}$$

where Ar is defined by Equation 5 and I_R by Equation 12. This index represents the relationship between the number of segments composing the network under consideration and the maximum number of nodes possible in the network. The more numerous the segments, the greater the value γ ($0{,}33 \leq \gamma \leq 1$).

Case Study

In this section, a case study on the extraction of one road by a semi-automatic method is presented. The aim of this study is to give an example of both the extraction of a reference line and the use of the criteria related to the planimetric accuracy. The implementation of the network indices is in progress, and results will be available soon.

Extraction of the Reference and the Tolerance Zone

Protocol Carried Out

The image interpreter acquisitions were carried out on an image from the Ikonos satellite (courtesy of the firm Geographic Information Management). The image has a spatial resolution of 1 meter in the panchromatic band and is extracted from the area of Hasselt, Belgium (Figure 4). The scene represents a peri-urban area with a main road on which the method for extracting the reference polyline, and the tolerance zone will be applied.

Eleven interpreters were asked to determine in vector mode the location of the roadsides. The diversity of the different acquisitions will be considered as the variability of interpretations. The acquisition in vector mode was carried out with the software Arcview®, which enables the image interpreter to adjust contrast or to zoom into the region of interest.

Extraction of a Reference and of the Tolerance Zone

- Analysis

Plate 1 exhibits the superposition of the 11 acquisitions. Taken separately, each different acquisition seems to fit the roadsides. Nevertheless, variability between interpreters exists, reflected by the thickness of the road (Plate 1). For a more precise analysis of this variability, we have chosen to focus on a region including a part of the right roadside (red square on Plate 1). This region has a relatively high curvature and generates a big variability among the image interpreters.

Figure 5 represents the zoom area of 15 m · 20 m with the 11 acquisitions. Two polylines (6 and 10) have vertices represented in this area (S_6 and S_{10} on Figure 5). According to the method previously described, a vertex for the reference polyline will be computed at S_6 and S_{10} (in the process direction defined on Figure 5).

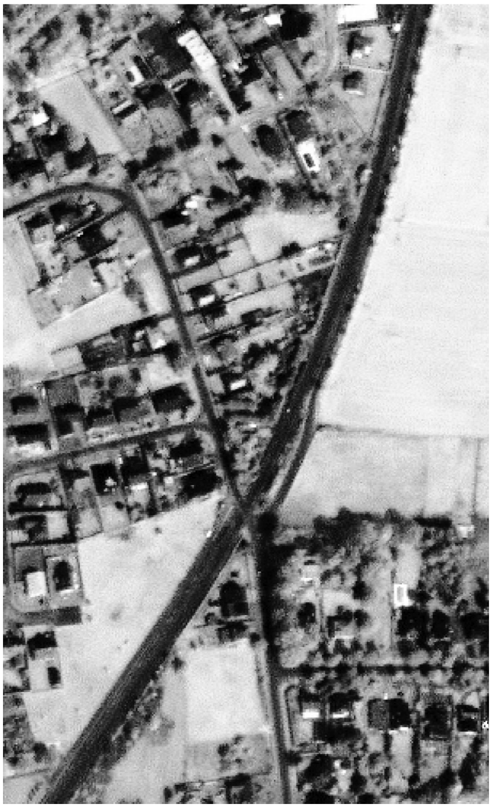

Figure 4. Original image with the road to acquire (Copyright 2000 Space Imaging Europe).

- Extraction of the reference polyline

The mean slope vector $\mathbf{V_6}$ is supposed to have been computed previously by averaging the slope vectors of the polylines located before the vertex S_6 (according to the process direction).

The transect T_6 at S_6 and orthogonal to $\mathbf{V_6}$ is then considered (Figure 6).

An average is computed between the points located at the intersection between T_6 and the different polylines (rejecting external points). The point D_6 is obtained and will become a vertex for the reference polyline (Figure 6).

On Figure 7, the radiometric profile of the transect T_6 is represented. The points corresponding to the different interpretations are reported on the graph. The x-axis presents the distances in meters from these points to S_6. The point D_6 corresponds to the average of those distances (rejecting the two extreme points). The standard deviation for the different interpretations at transect T_6 is 1.32 meters (i.e., 1.32 pixel for the 1 meter resolution Ikonos image).

The same process has been used to compute the transect T_{10}, giving a standard deviation of 1.65 meter. Even at the pixel precision, such a difference shows the variability of a reference polyline based on only one interpretation.

Compared to other polylines acquired by the interpreters, the obtained reference polyline has a smoother shape because of a higher number of vertices and of attenuated slope variations.

- Extraction of the tolerance zone

Figure 8 exhibits the tolerance zone computed according to the method defined with a constrained Delaunay triangulation.

The boundary of the zone is composed of the whole polyline 1 (left side) and of a part of polyline 10 and 11 (right side). The previously extracted reference polyline and the vertices D_6 and D_{10} are also drawn in this zone. The reference

Plate 1. Superposition of the eleven acquisitions. The color version is available at the ASPRS web site: www.asprs.org.

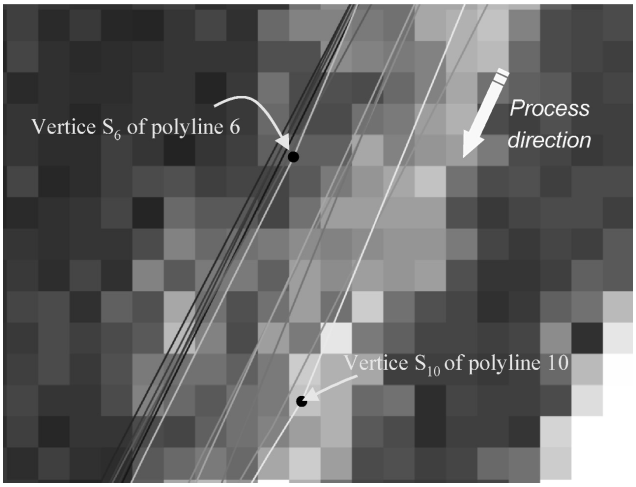

Figure 5. Superposition of the eleven acquisitions for the right roadside in the red rectangle of Plate 1.

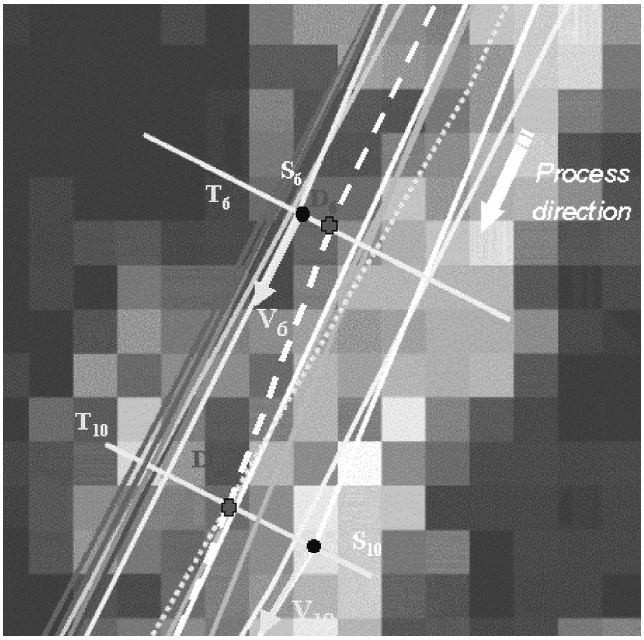

Figure 6. Extraction of the reference line (on the right side) *Dashed line*: extracted reference right roadside; *dotted Line*: automatically extracted right roadside.

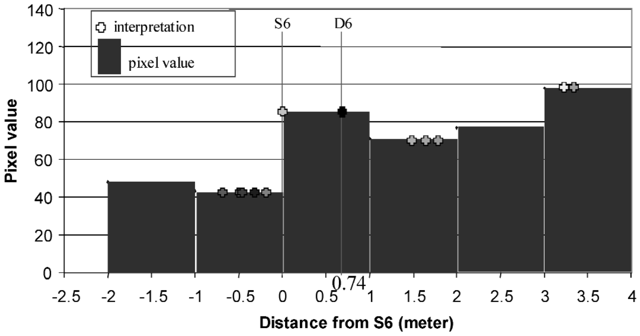

Figure 7. Radiometric profile of transect T_6. The dots are the eleven interpretations of Figure 6.

polyline is located in the tolerance zone and in this case, next to the zone axis.

In the following paragraph, a semi-automatic method is applied for extracting the road in order to illustrate the criteria related to the planimetric accuracy.

Method of Road Extraction

The quantitative evaluation is applied in the framework of an algorithm for road extraction defined by Péteri and Ranchin (2003). This algorithm is semi-automatic and is based on parallel active contours (snakes), using a multi-resolution analysis as introduced by Couloigner and Ranchin (2000). A model of the road at different resolutions is used. It is based on road properties such as parallelism of the two roadsides and width homogeneity along the road axis. It is a modular algorithm that aims to extract roads as areas from high-resolution images. The purpose here is not to evaluate the performance of this particular algorithm, but to illustrate the different quantitative criteria defined in this paper. For more details on the algorithm used one can refer to Péteri and Ranchin (2003) or Péteri (2003). The algorithm was applied to the same image as the one used for extracting the reference polyline and the tolerance zone; the resulting extraction is shown on Plate 2. The extracted shape fits the road quite well, except for the upper left roadside where a slight shift appears. That can be explained by the fact that the snake was defined to maintain the parallelism and the same distance between the two roadsides, whereas there is not a constant width along the road.

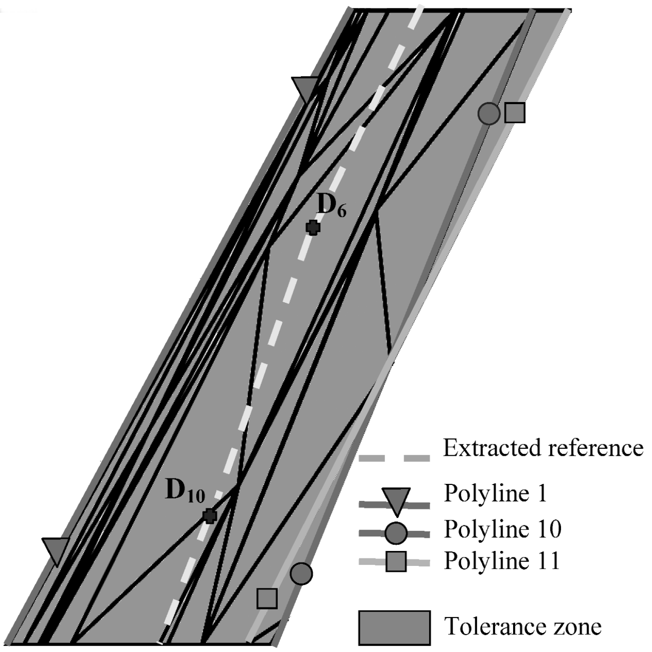

Figure 8. Tolerance zone computed from constrained Delaunay triangulation.

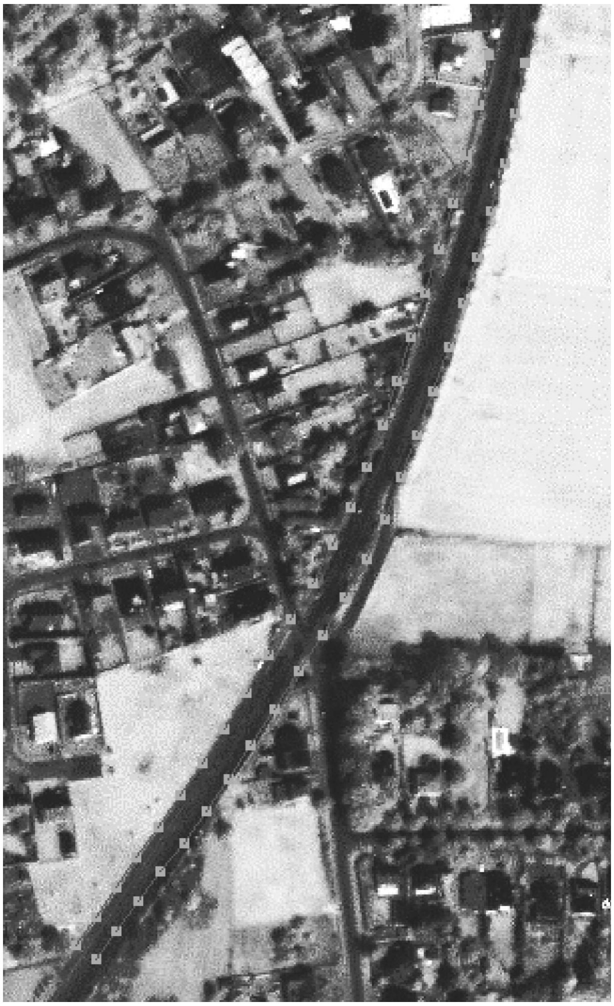

Plate 2. Result of the algorithm on the image used for interpretation. The color version is available at the ASPRS web site: www.asprs.org.

Table 3. Percentage of Both Sides of the Extracted Road and the Reference Included in the Tolerance Zone

Percentage of the Side in the Tolerance Zone	Extracted Road	Reference Road
Left side	7%	100%
Right side	61%	100%

Quantitative Criteria

In this section the previously described quantitative criteria for planimetric evaluation are applied to the extracted road compared to the extracted reference polyline.

For a more precise visual analysis, we still consider the region including a part of the right roadside (red square on Plate 1): the extracted side is located near the tolerance zone axis and next to the reference polyline. In Figure 6, the dashed line is the reference polyline, and the dotted line is the automatically extracted roadside.

If the visual inspection is important, a quantitative assessment is necessary. The following quantitative criteria have been evaluated on the whole image:

(a) The first criterion is the tolerance zone previously defined in order to compare the extracted roadside with the one achieved by human interpretation. The tolerance zone gives the boundaries where the extracted roadside should be located to have similar performances compared to the one achieved by human interpretation. The quantitative evaluation was done by calculating the percentage of the extracted line included in this tolerance zone for each side of the extracted road. By definition, the reference polyline extracted has 100 percent of its length in the zone. Table 3 gives the corresponding values for both sides of the extracted road and the reference road. As expected, the left side of the extracted road has a small percentage of its length included in the tolerance zone (7 percent), whereas the right side reaches 60 percent;

(b) The second defined criterion is based on the area included between both extracted sides of the roads under consideration. It is shown in Table 4. The 15 percent difference in area is mainly due to the left side of the extracted road where the automatic algorithm tried to maintain a constant width along the road; and

(c) Position of the extracted road compared with the position of the reference road:

- The length of the polylines, as well as the relative difference, are reported in Table 5.

One can observe that the error on the length for both sides is very weak. This criterion gives interesting information on the extracted shape but has to be completed by a distance criterion.

- The Hausdorff distance between the extracted contour line and the reference.

The value of the Hausdorff distance reflects the actual remoteness between the two objects. This distance was computed for the extraction of both the right and left side of the extracted road. Results are reported in Table 6. The Hausdorff distance for the right side is 6.94 meters, and for the left is 8.99 meters. These values, reflecting the mismatch of the extracted sides and the reference polylines, are relatively small. As expected, they correspond to the vertex located at the upper left side of the road of interest. The Hausdorff value could also be used for comparing the

TABLE 4. AREA CRITERION

	Extracted Road	Reference Road	|Difference|	Relative Difference
Area	8556 m^2	7455 m^2	1101 m^2	15%

TABLE 5. LENGTH CRITERION

Length	Extracted Road	Reference Road	|Difference|	Relative Difference
Left side	495 m	498 m	3 m	0.6%
Right side	501 m	502 m	1 m	0.1%

TABLE 6. HAUSDORFF DISTANCE

	Left Side	Right Side
Hausdorff distance	8.99 m	6.94 m

relative performance of several automatically extracted contour lines.

Conclusion

In this paper, a quantitative evaluation of roads extracted from high-resolution satellite images by means of automatic or semi-automatic methods has been presented. For this quantitative evaluation, the definition of reference objects is mandatory. The different ways of constructing a reference were described and the most appropriate solution for our purpose, an *a priori* reference map established by several image interpretations, was chosen. This choice was made according to the purpose of our work which is the evaluation of results from road extraction algorithms.

This *a priori* reference results from the computation of an "average" object from a set of interpretations. A tolerance zone representative of the variations in interpretation was defined. It allows the characterization of the uncertainty of the reference object, and the possibility of defining criteria for a quantitative evaluation. A selection of criteria for planimetric accuracy evaluation and spatial characterization of a road network was carried out according to Musso and Vuchic (1988).

In order to demonstrate the proposed approach for the definition and use of a reference object and its tolerance zone, a case-study was conduced on an Ikonos image. In this example, eleven photo-interpreters performed the extraction of one road. The reference road and its tolerance zone were defined. Then, to demonstrate the use of quantitative criteria, an algorithm of road extraction was applied and its results compared to the reference road.

The quantitative evaluation presented allows assessment of the algorithm and to analyze its behavior in a real case-study. From this analysis, it is possible to determine limits for this algorithm, and to determine in which cases it should be improved.

Quantitative evaluation of objects extraction algorithms is crucial for allowing operational use of high-resolution satellite images. The proposed method for determining a reference object and its tolerance zone is not restricted to roads and should be easily adapted to others objects, such as buildings or rivers. Once the reference object is defined, adapted quantitative criteria could be proposed and any means of object extraction evaluated in a rigorous framework.

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