SPOT and Landsat Stereo Fusion for Data Extraction over Mountainous Areas

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Abstract

In thematic and cartographic applications, planimetric features are extracted from multi-sensor images such as SPOT and Landsat in order to take advantage of their complimentarity features. When no precise elevation data are available to ortho-rectify these images, e.g., in mountainous areas, stereo digital photogrammetric workstations (stereo DPWS) are now available for the interactive stereo fusion and plotting of multi-sensor stereo pairs.

This paper presents a method and the quantitative results on the extraction of planimetric and altimetric features from a stereo pair generated with mixed sensor images (SPOT-P and Landsat TM) using the stereo DPWS, the DVP available at the Canada Centre for Remote Sensing.

Results from this mixed sensor stereo pair, which has a base-to-height ratio of 0.49 and was taken over a mountainous area of the Rocky Mountains (Canada), show a planimetric accuracy of 11 to 12 m for well identified cartographic features, and an altimetric accuracy of 37 m for the extracted elevation data.

Introduction

The increasing amount of image data in raster and vector format indicates a need for methods for their fusion, for their analysis, and for the extraction of geophysical information. Most of the development and the applications have focused on the co-registration of the different images using non-parametric rectification, based on tie points and polynomial transformations. When using and integrating already existing or extracted vector information into or from a map system, a precise geocoding process is then mandatory, especially in mountainous areas. A precise parametric relationship between the image reference system and the cartographic reference system is required. This parametric solution should take into account all the distortions generated during image formation, including terrain distortions. Consequently, to generate ortho-images in the cartographic reference system, a digital elevation model (DEM) is needed to correct the distortions related to the terrain elevation.

If the DEM does not exist or cannot be produced from the topographic map contour lines, different methods have been developed to extract DEM from remote sensing images. One of the methods, image matching, has made significant progress. As reported by Dowman *et al.* (1992), least-squares matching has been found to be the most accurate, and feature-based matching has not been very popular. More recently, global approaches which perform matching in object space have been studied. Furthermore, image pyramids, scale space algorithms, and consideration of breaklines are also used to achieve better and faster results. More consideration of image matching is outside the scope of this paper; Lemmens (1988) and Wrobel (1988) provide excellent surveys of image matching from the same sensors.

Few results have been published on image matching from multi-sensor data. Welch *et al.* (1990) and Raggam and Almer (1991) generated DEM from similar spectral bands of mixed SPOT multi-band and Landsat TM sensors. They reported a moderate success in the correlation step with a 50- to 100-m accuracy for the DEM.

This error will propagate through the geocoding process, ortho-image fusion, and planimetric feature extraction. Figure 1 shows the relationship between the DEM accuracy, the viewing angle of the image in the visible range, and the resulting error generated in the ortho-image (Toutin, 1995). As an example, a 50-m error for the elevation due to the DEM accuracy and the interpolation into the DEM generates during the rectification process 7-m and 15-m positioning errors for a Landsat TM image and a 15° viewing angle SPOT-HRV image, respectively. Consequently, the ortho-image fusion will be generated with an accuracy on the order of 17 m. These planimetric errors are not negligible for SPOT-HRV, nor for image fusion. Therefore, planimetric features (roads, power lines, rivers, etc.) cannot be extracted from Landsat TM and SPOT-HRV ortho-image fusion with an accuracy better than 20 to 25 m. Furthermore, resampling during the rectification process degrades the image geometry and radiometry (Gugan and Dowman, 1986).

When only two mixed sensor images are available or used on a study site, a complimentary approach to ortho-rectification and data fusion for planimetric feature extraction based on traditional photogrammetric techniques can be used: the stereoscopic fusion of multi-sensor images provides a virtual three-dimensional model of the terrain surface, and the interactive stereo plotting enables the extraction of cartographic features directly in the map reference system.

The brain can generate the perception of depth with images from different sensors, combining for example the spectral information from a Landsat TM image and the spatial information from a SPOT-P image for stereo plotting. Figure 2 is a sub-area (500 pixels by 600 lines) of the multi-sensor stereo pair used in this study: the SPOT-P image on the left and the Landsat TM1 image resampled at a 10-m pixel spacing on the right. It shows the feasability of stereo-viewing from multi-sensors, because they are similar in radiometry even if greater contrast exists in the Landsat TM image. Forested and cleared areas are well discriminated, and transportation networks (roads, railroads, power lines) are bright against the grey surroundings.

The advantages of stereo include improved visualization and interpretability of the Earth's surface, and improved ex-

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traction of information about the relationships between land shape and structure, slopes and water ways, surface material and vegetative growth, etc. It also enables a better location of ground control points (Welch *et al.*, 1990; Heipke, 1995). Furthermore, Benis *et al.* (1988) have shown that the interpretation of cartographic information can be facilitated by using three-dimensional (3D) or perspective representations, relative to flat 2D displays. Norman and Draper (1986) have also shown that the direct representation of objects (such as in stereo viewing) can better facilitate our understanding and interpretation than the manipulation of information related to these objects (such as DEM and ortho-image generation).

To achieve stereo fusion and restitution of cartographic features, digital photogrammetric stereo workstation are largely available (Dowman *et al.*, 1992; Heipke, 1995). Some of them have developed solutions to process stereo pairs from mixed sensors, such as the DVP available at the Canada Centre for Remote Sensing (CCRS). The system (Gagnon *et al.*, 1990; Toutin *et al.*, 1993) and the mathematical equations and modeling (Toutin, 1983; Toutin, 1995) similar to the photogrammetric equations (collinearity and coplanarity conditions), which drives the DVP, have been already described in detail. This paper will then expand on the feasibility and usefulness of stereo fusion and restitution from mixed sensor stereo pairs generated with SPOT-P and Landsat TM images. The main objectives of this paper is then to present a quantitative study of the type and quality of data which can be interactively extracted from the SPOT and Landsat mixed sensor stereo-pair, and to assess and discuss the accuracy of each extracted planimetric and altimetric feature (roads, railroads, power lines, spot elevations, DEM).

Study Site and Data Set

The study site located in British Columbia (Canada) overlaps two 1:250,000-scale maps: Hope (92H) and Penticton (82E). This area is characterized by rugged topography where the elevation ranges from 400 metres along Lake Okanagan to 2000 metres on Kathleen Mountain. The land cover consists

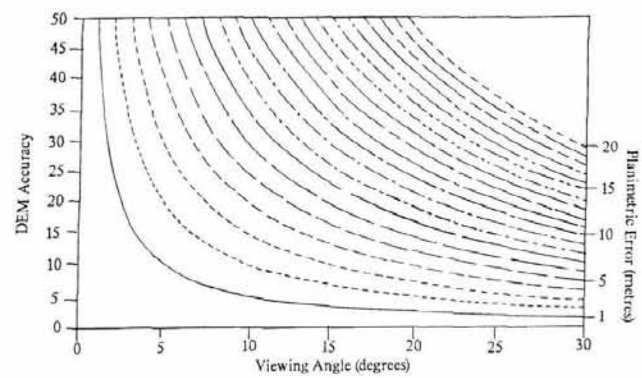

Figure 1. Relationship between the DEM accuracy, the viewing angle of the image acquired in the visible range, and the planimetric error on the ortho-image.

mainly of a mixture of coniferous and deciduous trees with patches of agricultural land and clearcut areas. The agricultural fields are found mostly along Lake Okanagan, while the clearcut areas, linked by new logging roads, are randomly located within the area. Roads are mainly loose or stabilized surface roads with two (2) lanes or less, but a few are hard surface roads with two (2) lanes or less. A few lakes and ponds are also found which are connected through a series of creeks flowing between steep cliffs.

The data set consists of remote sensing data (images, ephemeris, attitude) and topographic data. The SPOT-HRV image was acquired on 24 September 1989 with a viewing angle of +26.2°. It is a raw level-1 image with ephemeris and attitude data recorded in the panchromatic mode (10-m pixel size). The Landsat TM scene was acquired on 13 July 1990. It is a bulk level-4 quad-image with ephemeris data. The stereo

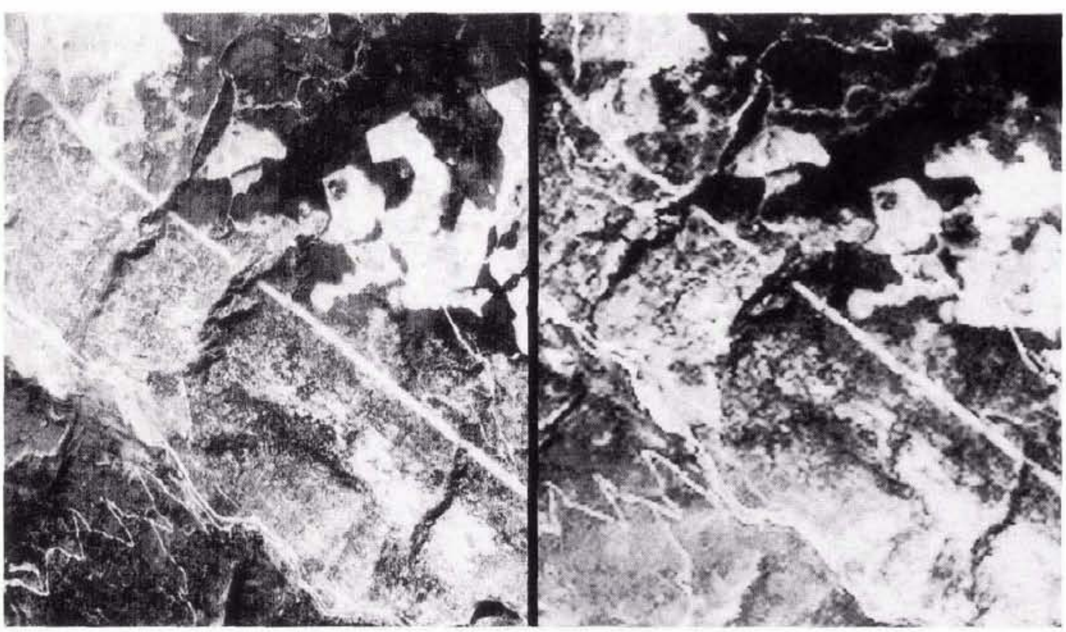

Figure 2. Sub-area of the stereo pair generated with SPOT-P (left) and Landsat TM1 (right) images (500 pixels by 600 lines). The Landsat TM1 has been resampled by cubic convolution with a 10-m pixel spacing.

TABLE 1. OMISSION AND COMMISSION RESULTS

Features	Omission			Commission		
	Length Topo (m)	Omitted Length (m)	Percent	Length DVP (m)	Committed Length (m)	Percent
Roads	263,241	45,826	17.4	238,664	40,518	17.0
Power Line	31,249	4,550	14.6	26,699	0	0
Railroad	19,473	55	0.3	19,418	0	0

pair generated with these two images has base-to-height ratio of 0.49, over an area of about 40 km by 50 km.

The topographic data were obtained from the Canada Centre for Topographic Information (CCTI) and cover an area of approximately 36 km by 28 km. The data were originally stereo-compiled from 1:50,000-scale aerial photographs taken in 1981, as observed on the surface of the Earth in cartographic *X*, *Y*, and *Z* coordinates and without movement of the elements due to a cartographic generalization.

The digital cartographic data, stored in an Intergraph Graphic Design System file (IGDS), were not cleaned, and did not possess topological structure. The IGDS file contained a set of planimetric entities stored in several layers. Most layers (roads, hydrography, land cover, etc.) have a horizontal accuracy of three (3) metres while the layer representing hypsography had a contour interval of ten (10) metres.

A 15- by 30-km area common to both the SPOT and Landsat stereo-model and the topographic data coverage was used for the evaluation of the photogrammetric stereo restitution. It is located in the vicinity of the city of Penctiton (Canada).

Processing

The processing steps deal with SPOT and Landsat data, ground control points, aerial photographs, and digital cartographic data. The main equipment used for the analysis are a traditional stereo plotter for the aerial photographs, a digital photogrammetric stereo workstation (on a PC computer) for the remote sensing raster data, and a geographic information system (GIS) for the vector data.

Digital Data Transfer to the DVP

The SPOT and Landsat data were read from magnetic tapes, radiometrically preprocessed (linearly stretched over 8 bits), and transferred to the DVP. Furthermore, the Landsat TM image was resampled by cubic convolution with a 10-m pixel size to generate the stereo pair with an equivalent pixel spacing. Ephemeris data and attitude data (for SPOT) were also read and pre-processed to initialize the geometric modeling. An example of the SPOT-P and Landsat TM stereo pair is given in Figure 2.

Stereo Model Set Up

Fourteen (14) ground points (mainly road intersections) were first identified and plotted in stereoscopic mode on the SPOT and Landsat TM stereo pair. The image coordinate accuracy is half a pixel (5 metres), achieved using an interpolated zoom. Then the ground coordinates (*XYZ*) were acquired on a traditional stereoplotter using the aerial photographs at CCTI. The cartographic coordinate accuracy is better than five (5) metres. Different types of control points can be used. Apart from full control points (*XYZ*), one can also employ altimetric points (*Z*) and homologous and tie points (no ground coordinates). These points are useful to reinforce the stereo geometry and fill in gaps where there are no ground control points (GCPs).

As few as six (6) GCPs, distributed around the perimeter of the SPOT-P and Landsat TM stereo model, are enough in general for the computation of the parameters and to set up the stereo model. Previous studies (Toutin and Carbonneau, 1989; Clavet *et al.*, 1993) have already discussed the number, the density, and the spatial distribution of the GCPs for the best results. Using GCP coordinates, attitude, and orbital parameters, the geometric modeling of the stereo pair is computed with photogrammetric techniques (colinearity and coplanarity conditions) and by an iterative least-squares adjustment (Toutin *et al.*, 1993). The resulting root-mean-square (RMS) residuals for fourteen (14) GCPs and seven (7) tie points were 11.7 m, 6.2 m, and 21.3 m in the *X*, *Y*, and *Z* directions, respectively. The maximum residuals were −19.9 m, 14.0 m, and −33.0 m. These residuals, which are on the same order of magnitude as the GCP accuracy and which represent an *a priori* stereo mapping error, are then a good indication of the final results. As a consequence, the SPOT-P and Landsat TM stereo model, without *y*-parallax (less than one pixel), is generated directly from the raw images.

Feature Extraction in the Stereo Model

Data extraction follows the stereo-model set up. For planimetry, an operator interactively digitizes in stereoscopy different features from the 10-m pixels: roads (small secondary), railroads, and power lines. Depending on the thematic application, other planimetric features could be extracted taking into account the radiometry of both sensors. For altimetry, height measurements are extracted on a ten-pixel regular grid in the left image. This generates an irregular grid of points when projected to the ground system. Unfortunately, no zoom was available in this feature extraction step.

The result of this feature extraction is files with *XYZ* ground coordinates in the map reference system. A descriptive code can also be attached to each feature.

Transfer to the GIS System

The *XYZ* files are transferred to the GIS using a bi-directional translator. The vector data (roads, railroads, power lines) are cleaned and edited using different GIS functions. The irregular grid DEM is directly transferred as a point file.

In the same way as for the topographic data, a translator is used to import the Intergraph files into the GIS environment. Only data common to both the topographic data and the SPOT and Landsat stereo model were retained. The vector data were also cleaned and edited. The contour lines are used to generate a triangular irregular network, which is then transformed into a 5-m grid file. This grid spacing avoids errors in the DEM comparison generated by any processing to transform the irregular DEM into a regular grid. The DEM are therefore compared directly point by point without any interpolation.

Results and Analysis

For each extracted feature, a first comparison is done between the topographic file and the DVP file to compute the omission and commission errors (Table 1). The commission error comes from overestimation and the omission error from underestimation. In a second step, buffered zones centered on the topographic file were generated at 3, 6, 9, 12, 15, 20, and 30 metres. These buffered zones act as corridors "parallel" to the topographic feature at different distances; they are used to quantify the cumulative distance of stereo-extracted features within each zone. The percentage for each zone and the cumulative percentage of linear distance can then be computed. For example, Table 2 gives the full results for roads and Table 3 gives the results summary for all features.

Roads Accuracy

The 17.4 percent omission error resulted mainly from forest regeneration on the old logging roads, but also from non-visi-

Table 2. Results of the Comparison for Roads Extracted from the SPOT-P and Landsat TM Stereo Pair with the Checked Topographic Data

Accuracy (metres)	Distance (metres)	Percentage	Cumulative Percentage
3	37,746	19.0	19.0
6	36,211	18.3	37.3
9	31,706	16.0	53.3
12	26,615	13.4	66.7
15	19,319	9.8	76.5
20	22,081	11.1	87.5
30	17,344	8.8	96.4
30+	7,125	3.6	100.0
Total	198,147	100.0	

Table 3. Results of the Comparison for all Planimetric Features Extracted from the SPOT-P and Landsat TM Stereo Pair with the Checked Topographic Data

Accuracy (metres)	Cumulative Percentage (%)		
	Roads	Railroads	Power Line
3	19.0	23.1	20.4
6	37.3	44.1	37.8
9	53.3	60.1	55.5
12	66.7	71.9	70.5
15	76.5	82.6	81.6
20	87.5	93.4	94.5
30	96.4	99.8	98.2
30+	100.0	100.0	100.0

bility of roads in the forest. The 17 percent commission error comes from the new logging roads visible on the stereo pair: the aerial photographs and the satellites data were taken 8 to 9 years apart, and the area has an intensive forestry activity. Table 2 shows a 12-m RMS accuracy (66 percent), and shows that there is no bias (larger than 3 m) because the percentage for each 3-m zone decreases from the "0 to 3" zone to the "over 30" zone, except for the "15 to 20" zone, which is not considered to change the bias. At the bottom of Table 2, one can note that 12.5 percent have errors greater than 20 m, and visually we have checked that few have errors larger than the tolerance (±3 times the RMS error). Each linear entity that had an error greater than 20 m was visually compared, by importing the topographic file into the DVP. The origins of most of these errors were due to the topographic data, to physical changes in position between 1981 and 1989-90, to the interpretation variation in locating curves and intersections, and to the definition of logging roads in their context.

Railroads Accuracy

The 0.3 percent omission error resulted from a 55-m service road, invisible on the images (few pixels). Table 3 shows an 11-m RMS accuracy, with no bias for the same reason previously mentioned, and there is almost no error (0.2 percent) larger than the tolerance. The 6.6 percent error greater than 20 m is related to the difficulty in identifying the railroad when it was located along a cliff (shaded area) or close to a road. The 30-m pixel resolution of the Landsat TM and the HRV sensor radiometry range does not provide enough details in this case.

Power Lines Accuracy

The 14.6 percent omission error resulted from underground gas pipelines. Table 3 shows an 11-m RMS accuracy, with no bias error for the same reasons previously mentioned. Only 5.5 percent have an error greater than 20 m, and few have been visually checked out of the tolerance. The origin of these errors is mainly due to the fact that power lines, which are not visible, are extracted as being the middle of the clear-cut, which is not always the physical reality.

Because Table 3 shows comparisons for the different features, the better results (5 to 6 percent difference) obtained with the railroads and power lines resulted from the definition of both these features: they are more consistent in size, shape, and direction with less changes and "small curves" than secondary or logging roads.

Elevation Accuracy

For the height measurements, a first evaluation was performed to quantify the altimetric pointing accuracy. Fifty points which span different features and cover types — such as wood, rock or clearcut area, roads, cliffs, etc. — were chosen. It should be noted that these are not necessarily identifiable features. By pointing at these features five times each, one gets a ±6.6-m altimetric pointing precision. Furthermore, 50 well identified check points with known ground coordinates (accuracy of 5 m) were plotted from the stereo model two times each to quantify the absolute altimetric error for spot elevation. An RMS elevation error of 29.4 m was obtained with a bias of −9.6 m. It is worth noting that the stereo images have a base-to-height ratio of 0.49 which gives an altimetric digitizing accuracy with a 10-m pixel size of 20 m, and that the original pixel spacing of Landsat TM is 30 m.

About 9100 points (irregular DEM), which cover an area of 12 km by 11 km, were extracted interactively from the stereo model, and directly compared to the DEM generated from the 10-m contour lines with the GIS functions. This avoids errors generated by any processing to transform this irregular DEM into a regular grid, because the objective was to assess the accuracy of the extracted data and not to generate a regular DEM. Table 4 gives the statistical results of this comparison. A bias of 4 m was found, and minimum and maximum errors were −173 m and +197 m, respectively.

Compared to the spot elevation accuracy computed previously (±29.4 m), the 37-m RMS error (66 percent) computed from Table 4 is consistent. The difference is due to the fact that DEM points are rarely well-identifiable points, unlike the points used to compute the spot elevation accuracy. But some of the errors from Table 4 are large (over 100 m). By selecting and displaying on the DVP these 100 points which had an error greater than the tolerance (±3 RMS bias error), it may be seen that they are spatially grouped rather than randomly distributed in the stereo model. These small errors are mainly human errors due to different reasons (operator fatigue, poor contrast, clouds and shadows, etc.), and replotting 50 percent of these points confirmed this, because the results improved.

Conclusions and Discussion

Due to the lack of a precise DEM, multi-source ortho-image generation and fusion sometimes cannot be realized with

Table 4. Altimetric Results of the Comparison for the Irregular DEM Extracted from the SPOT-P and Landsat TM Stereo Pair with the Topographic DEM

Errors (metres)	Occurrence	Cumulative Occurrence	Percentage	Cumulative Percentage
0-10	1805	1805	19.9	19.9
10-20	1726	3531	17.0	38.9
20-30	1576	5107	17.4	56.3
30-40	1300	6407	14.3	70.6
40-50	861	7268	9.5	80.1
50-60	618	7886	6.8	86.9
60-70	389	8275	4.3	91.1
70-80	267	8542	2.9	94.1
80-90	169	8711	1.9	95.9
90-100	109	8820	1.2	97.1

(sub-) pixel accuracy. This effect is most emphasized in mountainous areas, where large slopes can generate more errors during the interpolation process in the DEM coarse grid spacing. These errors then propagate through the extraction process of planimetric topographic features: it results in an accuracy which does not meet standards for mapping or a GIS. Therefore, this paper has demonstrated the feasibility of extracting information from two different sensors in the visible range with a digital photogrammetric stereo workstation: using a combination of mixed sensors SPOT-P and Landsat TM images to generate a stereo pair (base-to-height ratio of 0.49) and to extract planimetric and also altimetric features.

From the raw images, the cartographic information has been interactively stereo extracted, taking into account the complementary geometric and radiometric characteristics of the two sensors, and then transferred into a GIS environment. Comparisons have been made with digital topographic data, including planimetric and altimetric accuracies of roads, railroads, powerlines, spot elevations, and DEM.

In planimetry, statistical results of extensive stereo extracted data (239 km of roads, 27 km of powerlines, and 20 km of railroads) show an accuracy of 11 to 12 m, with no bias larger than 3 m. Few features (less than 1 percent) were out of tolerance. The origins of the larger errors were due to the topographic data, physical changes in the feature position between 1981 and 1989-90, and the limitation of the sensors in terms of geometry and radiometry. The use of zoom viewing in the extraction process should help to improve this accuracy because the planimetric digitizing error will be reduced by a factor of at least two (from ± 5 m to ± 2.5 m).

In altimetry, results over a set of 50 points show an accuracy of ± 6.6 m, and ± 29.4 m with a -9.6 m bias for the relative altimetric pointing and the absolute spot elevations accuracies, respectively. Furthermore, based on 9100 points, an accuracy of 37 m for an irregular DEM has been achieved. In this case, using zoom viewing would only reduce the spot elevation accuracy. Operator fatigue, poor contrast, variation between the two images, clouds, and shadows typical for visible images are the main problems in DEM extraction.

In comparison with the multi-source ortho-images generation and fusion approach, only an 11- to 12-m accuracy for planimetric feature could be obtained for this study site and data set with a 10-m accuracy DEM (Figure 1) on a 10-m grid spacing, because the SPOT-P was acquired with a 26.2° viewing angle and the test site has slopes on the order of 45°. On the other hand, the 38-m accuracy DEM generated from the SPOT-P and Landsat TM stereo pair will create errors of 25 m and 4 m on the SPOT-P and Landsat TM ortho-images, respectively. This would result, for the ortho-images integration, in (1) an error of about 25 m and (2) problems of mixed pixels. Therefore, planimetric feature extraction from these integrated ortho-images would not have been better than 30 m, a three-fold degradation relative to the results achieved directly with stereo restitution from the raw images.

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