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Generating DEM from Stereo Images with a Photogrammetric Approach: Examples with VIR and SAR Data[♥]

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ABSTRACT

This paper presents a fully digital photogrammetric method to generate DEMs from various types of stereo imagery (visible and SAR; spaceborne and airborne) using the same digital stereo workstation, the DVP. Based on personal computer, the DVP system enables the on-line three-dimensional reconstruction of a stereo-model, the capture in real time of elevation data from the raw images and the graphic overlay of vector data. The mathematical equations, which drive the DVP, are based on the collinearity and co-planarity conditions and integrate the platform, sensor, Earth and cartographic projection models into a single unified model. Elevation data is extracted visually by the operator, in real time in the stereomodel, using the DVP system, and then compared to digital topographic data. Four data sets over three different challenging study sites have been selected to test the limits of the method and the DVP system. Altimetric accuracies of 12.6 m, 38 m, 32.2 m and 23.9 m have been achieved with SPOT-P, SPOT-P/Landsat-TM, airborne SAR and ERS-SAR stereo-pairs, respectively. Better results should be achievable with less challenging study sites and data sets.

1. INTRODUCTION

Researchers have investigated various methods of generating a digital elevation model (DEM) using digital remote sensing data. One method is very similar to photogrammetry: to use two images at a time for the reconstruction of a three-dimensional stereo model in which the altimetric information can be extracted.

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Stereo imaging method provides a virtual three-dimensional model of a terrain surface permitting extraction of cartographic features. These models support map construction by allowing features to be collected through the use of two floating marks (one for each image of the stereo pair) which are fused visually to give the three dimensional cartographic coordinates.

This method requires a mathematical model relating the cartesian map coordinates of an object point to its image coordinates. Different mathematical models describing the acquisition geometry of visible-infrared (VIR) or synthetic aperture radar (SAR) images have been formulated and adapted to this photogrammetric method, and have been implemented on analytical stereoplotters (Masson d'Autumne, 1980; Vigneron et Denis, 1984; Dowman and Gugan, 1985; Mercer *et al.*, 1986; Kratky, 1987; Konecny *et al.*, 1987; Paderes *et al.*, 1989) or on digital stereoplotters (Lohmann *et al.*, 1988; Toutin *et al.*, 1991; Dowman, 1991; Leberl *et al.*, 1991; Ahac *et al.*, 1992; Toutin, 1994). Although some of these systems are operational and give good results, the model is limited to the use of a specific type of imagery. In addition different techniques for extracting elevation information from SAR imagery have been developed. These include shape-from shading (Guindon, 1990) and interferometry (Gray and Farris-Manning, 1993).

This paper will present a general approach using the same digital stereoplotter,(the DVP), to process different types of imagery. It enables the stereo restitution of digital images from different platforms (spaceborne and airborne) and from different sensors (VIR and SAR). This paper summarizes the main DVP characteristics, and presents the key processing steps and the accuracy evaluation of DEM (when compared with topographic derived DEM) derived from four different stereo-images: SPOT-P, SPOT-P/Landsat-TM, airborne SAR and ERS-SAR.

2. DVP SYSTEM

The DVP (Figure 1) has been developed through cooperation between the Canada Centre for Remote Sensing (CCRS) and the Département des sciences géodésiques et de télédétection de l'Université Laval.

Evolved as a by-product of educational tools developed at Laval University, the DVP is now a low-cost general-purpose digital stereo workstation. The objective for the first development was to create a system on common microcomputer hardware to solve standard photogrammetric problems in a user-friendly and efficient way (Gagnon *et al.*, 1990). Subsequently, the system has been adapted to process stereo remote sensing data: SPOT-HRV (Toutin *et al.*, 1991) and SAR data (Toutin, 1994, 1995). It appears to be the only stereo system that can process terrestrial and aerial photographs, SPOT and Landsat data, and airborne or satellite SAR images.

Figure 1: The DVP System based on a Personal Computer

The system enables the on-line three-dimensional reconstruction of a stereo model from various digital images, the capture in real time of planimetric and altimetric features, and the graphic overlay of vector data on the stereo model. The mathematical tools and the system have already been described (Toutin, 1983; Toutin *et al.*, 1991). The principal characteristics of the system are:

- the mathematical model fully integrates the platform model, the sensor model, the Earth model and the cartographic projection model;
- the geometric modelling is derived from the collinearity and coplanarity conditions and takes into account the position and the velocity of the platform and the parameters of the sensor, and of the Earth;
- as the system uses raw images, there is no need for resampling along the "epipolar curves" to cancel the y-parallax, which avoids radiometric transformation of the data;

- the feature extraction is done visually in real time on the different VIR or SAR stereo-model; and
- the hardware required is a 80386 PC computer with an ATI-VGA Wonder graphics card, and a mirror stereoscope.

The geometric modelling uses the former equations developed by Guichard (1983) and Toutin (1983) for SPOT data, and further transformed for SAR data (Toutin, 1994). As these equations reflect the physical reality of the viewing geometry (sensor, platform, Earth) and do not use polynomial transformations or look-up table corrections between two-dimension image space and three-dimension ground space, they are straightforward and easily adaptable to different transformations between the raw images and the stereo model. These transformations are the same for the different input data because the geometric modelling has been adapted to process indiscriminately airborne and spaceborne, VIR and SAR data.

Furthermore, this geometric modelling approach allows transformations from image space to ground cartographic space (and back) in a single computation sequence, without going through any geographic or geocentric system. The implementation on a low cost microcomputer is then greatly simplified. The main result is a computer-controlled real-time positioning of both images, which provides valuable continuity to the stereo model.

3. STUDY SITES AND DATA SET

To look at the capabilities and the limitations of the DVP system, challenging study sites were selected. For SPOT-P, Landsat-TM and airborne SAR, the study sites are characterized by high relief topography (1600 metres): the Rocky Mountains in Canada for the two VIR stereo pairs (SPOT-P and SPOT-P/Landsat-TM), and the Cordillera Centrale in Costa Rica for airborne SAR stereopair. For ERS-SAR, the study site is characterized by a rolling topography (300 metres) in the Sudbury Basin (Canada).

The Landsat-TM is a bulk image (level 4) with ephemeris data. Only the band 1 has been resampled by cubic convolution with a 10-m pixel size to generate a stereo pair with the 26° off-nadir SPOT-P. The base to height ratio is 0.49.

The two SPOT data are raw level-1 images in panchromatic mode with ephemeris and attitude data. The base to height ratio is 0.74.

The airborne SAR data (Figure 2) were acquired by the C-SAR of the Canada Centre for Remote Sensing (CCRS) from two same-side flight lines in nadir mode (the viewing angles go from 0º at near edge of the swath to about 84º at the far edge) during the SAREX-92 mission in Central and South America (Elizondo *et al.*, 1993). This mode gives the greatest challenge since it leads to much larger distortions along the range direction than other modes of the CCRS SAR system or other airborne SAR systems.

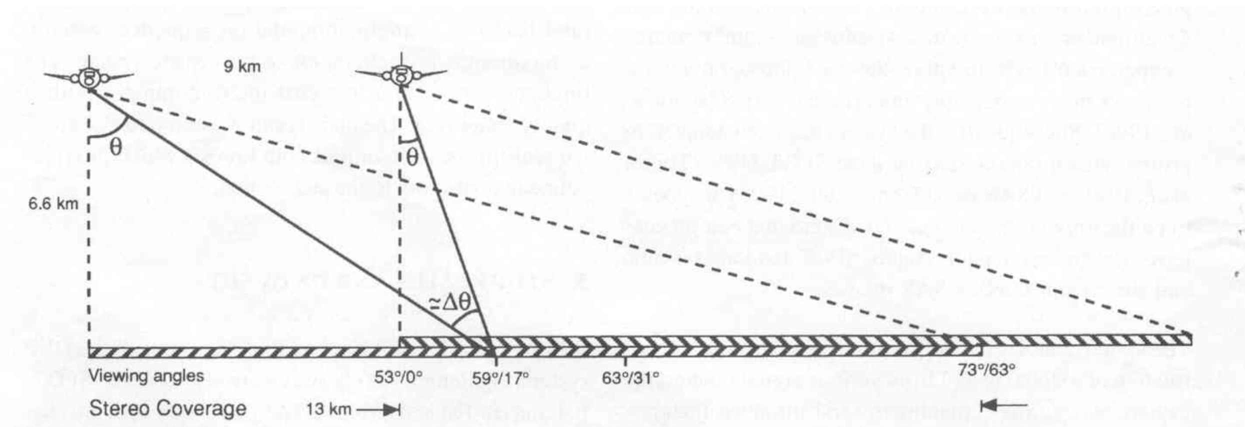

Figure 2: Airborne SAR Stereo Configuration (CCRS Nadir Mode) (θ: viewing angle; Δθ: intersection angle). Distances and angles are approximate due to the uncertainties in aircraft altitude and position, the relief and in the precise position of the nadir return.

The ERS-SAR data are opposite-side images from descending and ascending orbits. No ephemeris data were available. The images are in ground range presentation with 12.5-m pixel spacing.

The Rocky Mountains topographic data were obtained from the Canada Centre for Mapping. The accuracy of the ground control points (GCPs) cartographic coordinates is in the order of three metres and the DEM accuracy is five metres.

The Cordillera Centrale topographic data were obtained from the Instituto Geografico Nationale of Costa Rica. The accuracy of the GCPs cartographic coordinates is five metres and the DEM accuracy is 15 metres.

The Sudbury Basin topographic data were obtained from the University of New Brunswick (Canada). The accuracy of the GCPs cartographic coordinates is five metres and the DEM accuracy is ten metres.

Each "topo" DEM was generated with a fine grid spacing (5 m for the high relief study sites and 10 m for the rolling relief study site), to avoid any interpolation during the accuracy evaluation step.

Table 1 summarizes the topographic and image data for the different study sites of the four stereo pairs: SPOT-P, SPOT-P/Landsat-TM, airborne SAR and ERS-SAR.

Table 1: Topographic and Remote Sensing Data Description

STUDY SITE	Topographic Accuracy	Images	Dates	Presentation	Viewing Angles	Pixel Spacing	GCPs Image Accuracy
Rocky Mountains	GCP: 3 m DEM: 5 m	SPOT-P	1989/07/11 1990/08/24	Raw data Level 1	-10.4º +26.2	11x10 m 12x10 m	3 m
Rocky Mountains	GCP: 3 m DEM : 5 m	SPOT-P Landsat-TM	1990/08/24 1990/07/11	Raw Data Bulk Data	+26.2º 0º	12x10 m 10x10 m	5 m
Cordillera Centrale	GCP: 5 m DEM: 15 m	Airborne SAR	1992/04/27 1992/04/27	Slant Range	53º - 73º 0º - 63º	4.0x4.31 m 4.0x4.31 m	10-12 m
Sudbury Basin	GCP: 5 m DEM: 10 m	ERS-SAR	1992/08/27 1992/08/28	Ground Range	21º - 25º 21º - 25º	12.5x12.5 m 12.5 x12.5m	15 - 20 m

4. PROCESSING

As the geometric modelling and the DVP system has been adapted to process indiscriminately spaceborne or airborne, VIR and SAR data, the method and the different steps used for the orientation, the stereo model set-up, the real time stereo imaging and the interactive stereo measurements, are the same, no matter the VIR or SAR data. The main steps of the processing are summarized in Figure 3.

REMOTE SENSING DATA   **CARTOGRAPHIC DATA**

⇩

Introduce flight, sensor and image parameters

⇩

Acquire GCP in stereo mode ⟵ Introduce XYZ co-ordinates

⇩

Compute the model in stereo ⟷ Edition of GCPs co-ordinates

⇩

Set-up the stereo model

⇩

Acquisition of planimetric and/or altimetric features ⟵ XYZ-DVP files

⇩

Comparison with topographic data

Figure 3: Processing Steps

4.1 Digital Data Transfer to the DVP

The image data were read from magnetic tapes, radiometrically pre-processed and transferred to the DVP. For SPOT-P and Landsat-TM, ephemeris data and attitude (if exist) data are also read and pre-processed; for SAR data, parameters of the flight, of the radar and of the images are also introduced interactively.

4.2 Stereo-Model Set-up

GCPs are first identified and plotted in stereoscopic mode on the images using an interpolated zoom to a factor of two. The image coordinate accuracies for each image are given in Table 1. A minimum of four GCPs is needed for SPOT-P and Landsat-TM (Toutin, 1983), and seven for SAR (Toutin, 1994).

The geometric modelling of the stereo model is computed with photogrammetric techniques of least square adjustment, making use of the GCPs coordinates to refine the flight, sensor and image parameters. Different types of GCPs can be used:

- full control points with known XYZ coordinates;
- altimetric points with known Z coordinates; and
- tie points with unknown cartographic coordinates.

The two last types are useful to reinforce the stereo geometry and fill in gaps where there is no XYZ GCP. On the four stereo models, some tie points have been used to ensure a parallax free stereo model.

4.3 Data Extraction in the Stereo-Model

Once the stereo model has been set up upon completion of the least square adjustment, one has a parallax-free stereo model for data extraction. In this extraction step, no zoom was available. Two types of elevation data has been extracted:

- elevation (or spot) points using well defined feature like roads, railways, forest boundaries. These points were selected which were not in the neighbourhood of the GCPs used in the stereo model set up, and were representative of the full stereo model and of the terrain configurations;

- generic points on a ten pixel regular grid on the left image which generates an irregular grid of points when projected onto the ground system. Since the pixel size is different for each stereo pair, the size of these irregular grids varies. The goal of this research was not to generate DEM for operational purpose, but to evaluate elevation accuracy using a large number of points in different configuration, terrain locations, land cover, etc.

4.4 Comparison with the Topographic Data

The comparisons with the topographic data are done in the ARC/INFO environment. The elevation points have been manually compared to the "topo" DEM without any interpolation, because each "topo" DEM was generated with a fine grid spacing. In the same way, the irregular DEMs were directly compared point by point to the "topo" DEM without any interpolation. This avoids errors generated by any processing to transform these irregular DEMs into a regular grid, or by the interpolation of the "topo" DEM. The accuracies of the topographic data are summarized in Table 1.

5. ANALYSIS OF RESULTS

The first results are the root mean square (RMS) and maximum residuals of the stereo-model formation (Table 2). Former tests (Toutin 1983; Toutin, 1994) have already proved that the mathematical formulation properly describes the viewing geometry and that it does not induce any systematic trend. The residuals, which are in the same order of magnitude of the GCP accuracy and which represent the accuracy of the stereo-model, are then a good indication of the final results.

As the main factor contributing the modelling accuracy is the GCP image coordinate accuracy, the definition, quality and accuracies of these GCPs determine the quality and the accuracy of the stereo-model.

Table 2: Root Mean Square (RMS) and Maximum Residuals (metres)

Study Site	**RMS Residuals**			**Maximum Residuals**		
Stereo-Images (B/H)	**X**	**Y**	**Z**	**X**	**Y**	**Z**
Rocky Mountains SPOT-P (B/H=0.74)	5.1	4.4	3.4	11.6	6.7	6.0
Rocky Mountains SPOT-P/ Landsat-TM (B/H=0.49)	11.7	6.2	21.3	-19.8	14.0	-33.0
Cordillera Centrale Airborne SAR	13.8	13.7	22.7	-25.8	36.6	49.2

Sudbury Basin ERS - SAR	14.3	13.7	8.7	35.5	36.4	22.8

The second results are the RMS errors on the height measurements for elevation points and on the irregular DEM grid compared to topographic derived DEM. Table 3 gives the RMS errors for these elevation points and the DEM.

For the DEM accuracy derived from the SPOT stereo-model, 12,000 points have been used for the comparison. A RMS error of 12.6 metres has been achieved. This is a large error when compared to the elevation points error (3.4 metres) and it is noted that 5 percent of the DEM points have a very large error (50 metres or more). Displaying these points of very large error on the DVP, it may be seen that they are spatially and not randomly grouped in the stereo-model. These errors are mainly human errors (and not system errors) due to a variety of reasons (operator's fatigue, poor contrast,etc.). Replotting these points on the DVP confirms this statement, because the overall results improve to about ten metres for the RMS errors. It is worth noting that the stereo-images have a base-to-height ratio of 0.74, and the altimetric digitizing accuracy with a 10-m pixel size is ± 8 metres. The main problems with the SPOT stereo model were of course the clouds, but also the clouds' shadow, which appears on only one image of the stereo pair. In this situation the operator seems confident for the stereo plotting, but large errors (more than 3 times the RMS errors) can occur and the stereo plotting does not become reliable.

Table 3: RMS Errors (metres) on Elevation Points and DEM

Study Site	**Elevation Points**		**DEM**		
Stereo-Images (B/H)	**Number**	**Errors**	**Number**	**Coverage**	**Errors**
Rocky Mountains SPOT-P (B/H=0.74)	14	3.4	12 000	13x15 km	12.6
Rocky Mountains SPOT-P/Landsat-TM (B/H=0.49)	50	29.4	9200	12x11 km	38.0
Cordillera Centrale Airborne SAR	20	30.3	7600	5x5 km	32.2
Sudbury Basin ERS-SAR	50	14.1	6550	7x8 km	23.9

For the DEM accuracy derived from SPOT-P/Landsat-TM stereo model, 9200 points have been used for the comparison. A RMS error of 38 m has been achieved. When compared to the SPOT-P stereo pair, it is worth noting that the stereo images have a base-to-height ratio of 0.49, and the original pixel size of the Landsat-TM is 30 metres. With this stereo model, the same problems as with SPOT-P occur: operator's fatigue, clouds and shadows. The larger contrast variations between the two images due to different sensors and to the 10 m resampled pixel size of the Landsat-TM also decrease a little the stereo viewing and plotting quality. On the other hand, the variation in geometry was not a problem to keep the stereo viewing and plotting.

For the DEM accuracy derived from ERS-SAR stereo model, 6500 points have been used for the comparison. A RMS error of 23.9 metres has been achieved. This is consistent with the accuracy of elevation points (well-identifiable features) because it includes the accuracy of the points definition in the DEM extraction (about 1-2 pixels). Furthermore, only less than 0.5% of the points have an error greater than three times the RMS error. As in the SPOT test, these 0.5% points are spatially and not randomly grouped in the stereo model. Replotting these points reduces their error. The main difficulty with this data was to combine stereo viewing over a large area and precise stereo plotting on a specific point. The compromise in our study was to have a stronger stereo geometry with opposite-side stereo pair over a rolling topography making possible a better stereo plotting but a more difficult stereo viewing over a larger area.

For the DEM accuracy derived from airborne SAR stereo model, 7600 points have been used for the comparison. A RMS error of 32.2 metres has been achieved. It is also consistent with the accuracy of elevation points for the same reasons as the ERS-SAR test. The major problems occur at the near and far edges of the stereo pair for two completely different reasons. At the near edge, large distortions and their variation between the two images (the viewing angles are different 59° versus 17°, Figure 2) is due to the compression of planimetric scale at the nadir viewing in the right image. Therefore, the stereo viewing is limited locally around the floating marks where the y-parallax is automatically cancelled by the system. At the far edge, there is almost no variation between the two images (the viewing angles are almost the same 73° versus 63°; Figure 2), but the effect of shadowing in the backslope makes the precise plotting difficult and not reliable (as with cloud shadow for VIR data), even if the stereo viewing is possible. Without taking into account these two extreme limits (less than 1000 points) in the DEM elevation, the accuracy drops to a RMS error of 29.0 metres.

The large errors in the airborne SAR test come mainly from:

- the study site and the data set were more challenging; and

- the small intersection angle $\Delta\theta$ (Figure 2) and its variation in the range direction, for the nadir mode of the CCRS SAR system, lead to larger errors in altimetry with same-side flight lines than with opposite-side "flight lines" (SPOT and ERS tests) (Toutin, 1995).

Comparing these results between the visible imagery and the SAR imagery, one can see that the stereoscopic method does not work as well for SAR data and that it is not the best tool to extract altimetric information from SAR images. A combined and hierarchial approach of different methods (stereoscopy, shape-from-shading, and interferometry) which uses one result as input to the next method will likely provide better and more robust results, (Polidori, 1991; Toutin, 1994). Stereoscopy viewing could be used to resolve the low frequencies of the terrain elevation, shape-from shading the medium frequencies and interferometry the high frequencies.

6. CONCLUSION

This paper has presented results of DEM generation from different digital stereo images (SPOT-P, SPOT-P/Landsat-TM, airborne SAR, and ERS-SAR) on a PC based stereo workstation using a photogrammetric approach. The mathematical equations, which drive the DVP, are based on the collinearity and co-planarity conditions. They represent the physical reality of the full stereo viewing geometry: images-platform-sensor-Earth.

From the raw images, the elevation data are extracted and transferred to a GIS environment to be directly compared with a fine grid spacing DEM; this avoids errors from any interpolation. Compared to digital topographic data, altimetric accuracies of elevation points (well defined features) of 3.4, 29.4, 30.3, 14.1 metres have been achieved with SPOT-P, SPOT-P/Landsat-TM, airborne SAR and ERS-SAR stereo pairs, respectively. These points are very useful in topographic mapping to densify the altimetric network.

Furthermore, altimetric accuracies for DEM generation of 12.6, 38.0, 32.2 and 23.9 metres have been achieved with SPOT-P, SPOT-P/Landsat-TM, airborne SAR and ERS-SAR, stereo pairs, respectively. These results have been obtained with challenging data sets and study sites to test the limits of the system:

- for SPOT-P: B/H = 0.74 and high relief study site;
- for SPOT-P/Landsat-TM: B/H = 0.49, different sensors and pixel sizes, and high relief study site;
- for airborne SAR: CCRS nadir mode, same-side flight lines, large distortion variations in the range and high relief study site;

- for ERS-SAR: ascending and descending orbit images in which foreshortening and shadow are inverted.

Under these conditions, there are strong reasons to believe that the same methodology, if applied on less challenging images, viewing geometries, and study sites would be reliable to generate DEMs with 10m, 30m, 20m and 20m accuracies or better for SPOT-P, SPOT-P/Landsat-TM, airborne SAR and ERS-SAR, respectively. Furthermore, an interpolated zoom to a factor of two is now available for the capture of XYZ ground coordinates resulting in a better sub-pixel accuracy. This new zoom will then decrease the altimetric digitizing error by a factor of two: for example with SPOT-P from ± 8 m to ± 4 m.

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