

# Results of Automated Digital Elevation Model Generation from SPOT Satellite Data

Richard Swann, Space and Defence Systems Area Manager  
David Kauffman, Senior Research Analyst  
Bruce Sharpe, Senior Research Analyst  
MacDonald Dettwiler,  
3751 Shell Road, Richmond B.C.  
Canada V6X 2Z9  
Commission No.

## Abstract

Some recent results of a Digital Elevation Model (DEM) generation system for Landsat and SPOT stereo imagery are presented. A wide range of test imagery, including imagery affected by radiometric change due to multitemporal and atmospheric effects, as well as areas with a variety of topography were used to study the system's performance. Several reference DEMs of high accuracy and density were used to compare the derived DEMs at approximately 50,000 check points. Height accuracies better than 7 metres RMS were produced for a variety of the tested areas. Considerations given to the automatic processing of this data are presented as well as the use of spacecraft modelling which results in high DEM accuracy with very few ground control points.

## 1 Introduction

Since SPOT-1 was launched in January 1986, the process of extracting elevation data from off-nadir satellite imagery has moved from the laboratory to the production environment.

Stereo imagery from SPOT can exhibit a wide range of differences, for a variety of reasons.

1. The gain of the HRV sensors is such that a given scene may have a very narrow distribution of digital intensities, resulting in low contrast. When the imagery is radiometrically "stretched", quantization effects become clearly visible.
2. The ability to point the sensors in a particular direction means customers have an input into the programming schedule. The arbitration of these requests sometimes results in acquisition of stereo pairs days, weeks or months apart. The resulting *multitemporal* scenes can appear quite different due to agricultural, seasonal, and sun-angle changes.
3. Off-nadir viewing often results in a different brightness of the same ground areas between the two views. This occurs primarily when, in one view, the ground is

between the satellite and the sun, while in the other, both the satellite and the sun are on one side of the ground area. Off-nadir viewing can even have the effect of making areas that are light-colored in one image dark in the other. Furthermore, SPOT's sun-synchronous orbit is referenced to the nadir track of the satellite. With high off-nadir viewing, the satellite can be up to one-half a time zone away from the sun-time of the other pass.

## 2 System Overview

### 2.1 Background

Because of the difficulty anticipated in reliably matching features in the presence of the kind of complications mentioned in the previous section, MacDonald Dettwiler began work in 1983 on the use of computational vision techniques, then in use mainly by robotics research, to solve this problem in remote sensing. The computational vision approach was felt to have a higher likelihood of success in dealing with the wide range of imagery likely to be encountered by commercial satellite mapping systems than systems based on area correlation algorithms. At the time, SPOT was not yet launched, and the prototype work with LANDSAT-5 TM stereo pairs resulted in two significant developments:

1. The report of success of the prototype in extracting height information from a LANDSAT TM stereo pair to 60-70 metre RMS accuracy. The density of match points was approximately 139 points/km<sup>2</sup> from a base-to-height ratio (B/H) of 0.1. Landsat pixels are spaced at 30 metre intervals.
2. The use of this system to produce the Adam River mapsheet, a 1:50000 scale mapsheet derived totally from satellite data. This project involved precision image correction, classification, feature extraction, digital elevation model extraction, and orthoimage generation from the computed digital terrain model.

Since then, the Digital Elevation System has been generalized to handle both TM and SPOT imagery, tested on a variety of SPOT images, and was integrated with precision spacecraft modelling in order to achieve sub-pixel elevation accuracy. The system has been incorporated as a component of MacDonald Dettwiler's MERIDIAN Mapping System.

### 2.2 Precision Image Correction

The initial processing of a stereo pair begins with precision image correction. Image correction is performed using MacDonald Dettwiler's Geocoded Image Correction System (GICS). GICS constructs a spacecraft model, refined by ground control points, then resamples the raw imagery to a map projection. Geocoded images from GICS can be

directly overlaid on one another since each pixel represents an area defined by output map coordinates.

MacDonald Dettwiler's development of GICS began in 1981, with MOSAICS (Multi-Observational Satellite Image Correction System) for the Canadian Centre for Remote Sensing. Since then, GICS customers have included the European Space Agency, the Australian Centre for Remote Sensing, the India National Remote Sensing Agency, The National Research Council of Thailand, General Electric's Space Division and TRW Systems.

### **2.3 Image Preparation**

Once the imagery has been rectified, the MERIDIAN/GDEM operator examines the imagery for image quality. The operator then determines some initializing parameters for the system, including a coarse indication of area terrain displacements. The operator reduces the image parallax at a small number (10 to 20) of points throughout the scene to provide some initial constraints on the process. Subsequently, the GDEM system proceeds in a completely automatic mode.

### **2.4 Feature Identification and Matching**

The GDEM system operates on a feature-matching basis, extracting notable features from the image and using a systematic discrete matching technique to establish the optimal matching set of features. This work has been presented by Cooper, Friedmann and Wood (1985) and more recently by Kauffman & Wood (1987), so only a brief outline of the process is described here.

Based on computational vision work, primarily from David Marr and the MIT vision approach [Marr, 1980], MacDonald Dettwiler's system uses an edge-based approach to feature matching. The image is convolved with a series of Difference-of-Gaussian filters, which produce the second derivative of the smoothed image. The zero crossings of the resulting surface are then subjected to a validation pass, which removes edges introduced by image noise and undesired qualities of the filter itself. Adjacent zero crossings are linked together into "boundaries", linked lists of contiguous edges. These boundaries directly correspond to observable features in each image of the stereo pair. Boundary construction at several different widths of the Gaussian smoothing function allow a hierarchical, coarse-to-fine guided matching process.

At this stage of processing, the system has the image radiometry and the complete set of boundaries at each hierarchical level for each stereo pair. It is at this point that matching the stereo pairs begins. At very coarse levels, features can be matched readily, since many of the divergent effects mentioned previously are of lesser impact at this scale and there are a relatively small number of boundaries to match. Once the boundaries are matched at a coarse scale, the computed parallax is used to guide subsequent levels of matching, until finally the finest boundaries are matched. The result is a set of matched boundaries that identify matching features in each image to sub-pixel accuracy. The

output values of the matched boundaries are produced in the map coordinate system specified by the operator.

## 2.5 Imaging Geometry

Once the matching process has produced a set of matched boundaries, the geometry of the original feature can be reconstructed. This process involves the identification of the positions in space of the two satellites at the time each of the corresponding boundaries was imaged. The point-pairs consisting of each satellite position and its image boundary define two lines in 3-space, and their intersection represents the geocentric position and height of the matched feature. The reconstruction of the satellite imaging geometry is generated using the same GICS spacecraft model that was used to make the output products, so system accuracy is preserved.

## 2.6 Terrain Editing and Post-Processing

The match algorithm builds a simple terrain model through its operation. When this model is not sufficient, the erroneous matches are removed using both automatic and interactive methods. The automatic error removal builds a more complex model of the local terrain in order to identify outlying points. MERIDIAN/GDEM's operator interface then provides an interactive environment for identifying errors in more complex terrain. This involvement allows the operator to resolve final ambiguities and make sure the resulting digital terrain model corresponds to cartographic standards.

## 3 Case Studies

During 1987, a study comparing several methods of extracting height from SPOT stereo pairs was undertaken by the Mapping and Charting Establishment of Great Britain. MacDonald Dettwiler was one of the participants in this study.

A test area in Nottingham, U.K. was chosen for the test. The entire SPOT imagery was corrected using 9 ground control points acquired from 1:10000 scale maps. The resulting planimetric accuracy of the output products was better than 5 metres RMS in each of the  $x$  and  $y$  directions [Sharpe 1988]. While the east orbit view of the imagery was of good overall contrast, the west orbit image was marred by a great deal of mist. Not only did this cause a much lower standard deviation of image intensities in one image than the other, but in the hazy scene, several features were almost totally obscured. In this sense then, the test was an excellent test case of a feature-based approach.

Twenty test areas were chosen from the Nottingham mapsheet. Each region consisted of a 512 pixel square area. While most of the region was fairly level, there were regions of slopes, small hills and escarpments throughout the scene. In spite of the poor quality imagery, terrain height accuracy evaluated by the Mapping and Charting Establishment was better than 5 metres RMS.

A different site chosen for the GDEM system test was in sharp contrast to the Nottingham scene. The terrain in this area was extremely rugged, having parallax variation of over 500 metres over a single 10 km<sup>2</sup> area. In addition to the rugged terrain exhibited in this scene, the imagery was very low in radiometric variation. For example, one area had a range of only 34 digital values of intensity, and a standard deviation of 3.6 digital values. Again, in spite of the wide parallax range and the narrow radiometric values, digital elevation models were extracted that differed from elevation models extracted from airphotos by only 4.7 metres RMS. Match density is also a desired property of a feature-based matching algorithm, since it reduces the amount of interpolation required to produce regularly-spaced elevation points. Recent tests of the matcher have demonstrated an average of 1000 match points per km<sup>2</sup>.

## 4 System Performance

The GDEM system requires no special-purpose hardware. The system runs on a general-purpose computer system and the system throughput is dependent on the processing power of the host computer. Practical configurations to produce a few hundred to several thousand square kilometres per day are available.

Operator interaction with the system is required only in the initial stages, for ground control input and identification, and in the final stage for quality control. Intermediate status results can be obtained by the operator at any point if desired.

## 5 Conclusions

Automatically deriving grid Digital Elevation Models from stereo imagery, be it Landsat TM or SPOT MLA/PLA, is a difficult task. Solving it requires a number of cooperating technologies: accurate spacecraft modelling, robust computational vision techniques, and a productive interactive image analysis system for evaluation and editing. Drawing from our experience in Ground Station architecture, and the MERIDIAN image analysis system as well as combining research in computational vision, the MacDonald Dettwiler MERIDIAN/GDEM system has addressed these issues, and demonstrated that accurate DEMs can indeed be produced reliably in a highly automatic manner within an operational environment.

## Acknowledgements

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MacDonald Dettwiler is a SPOT RECOMMENDED<sup>TM</sup> systems supplier.

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Figure 1: Nottingham west chip.



Figure 2: Nottingham east chip.

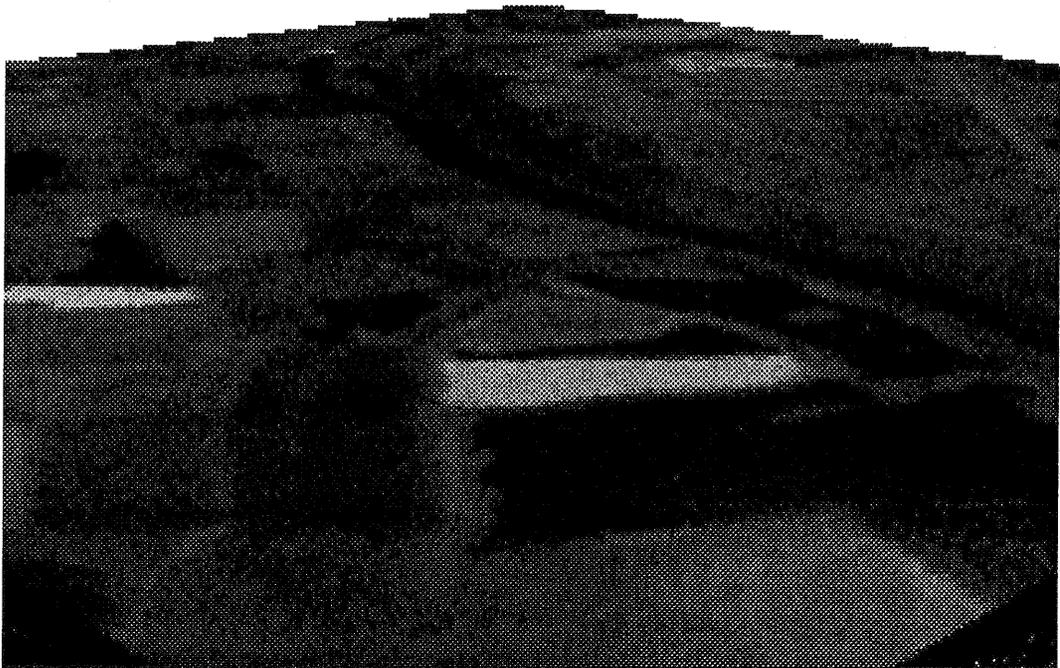


Figure 3: Perspective view.