ELEVATION EXTRACTION FROM SATELLITE DATA USING PCI SOFTWARE*

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ABSTRACT

Knowing "the lay of the land" has always been crucial to military success. High accuracy determination and visualization of topography of the Earth's surface is very important for defence applications such as Training and Simulation, Reconnaissance, and Tactical Planning. Most of defence applications using geo-referenced cartographic data require accurate DEMs (Digital Elevation Models). For example, siting of communication systems within a theater of operations requires calculations of Lines of Sight (LOS) and clutter map analysis for radio frequency propagation. This analysis requires DEM data, as well as ortho-rectified imagery. Also, DEM data can be used to determine routing of forces that should minimize chances of detection using terrain masking, based on the Line of Sight calculations.

In 1986, SPOT was the first satellite to provide stereoscopic images that allowed extraction of DEMs over large areas of the Earth's surface. For the first time, military organizations have been able to extract 3D data over areas of interest that were still inaccessible before SPOT launch. Since this time, various analogue or digital sensors in the visible spectrum have been flown providing users with spatial data for extracting and interpreting 3D information of the Earth's surface. Some of these sensors could be used for defence applications.

PCI Geomatics is a world leading developer of Geomatics software and solutions based on its remote sensing, digital photogrammetry, spatial analysis, and cartographic editing programs. PCI Geomatics developed an easy-to-use and complete software that addresses user needs for producing high-quality 2D and 3D geospatial information for GIS, CAD, and mapping applications. This paper will focus on PCI tools and techniques that have been developed for extraction of DEMs from satellite visible and infrared data. It will also present the results of elevation extraction tests performed with the help of PCI software.

1. INTRODUCTION

A digital elevation model (DEM) is a digital representation of the Earth's relief that consists in an ordered array of elevations relative to a datum, and referenced to a geographic coordinate system. The use of DEMs is now essential for many geoscientific applications, such as:

- production of 3D base maps for resource mapping and infrastructure planning
- optimum alignment (pipeline / rail / road /canal) surveys
- corridor route planning
- terrain studies analysis
- subsidence and erosion monitoring
- urban planning from terrain modeling
- water shed management
- slope map
- tower site location
- linear network extraction / updating (rivers / lakes, roads, railways, coast line, pipeline, drainage)

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Knowing "the lay of the land" has always been crucial to military success. High accuracy determination and visualization of topography of the Earth's surface is very important for defence applications:

- imagery intelligence
- mapping
- terrain analysis
- mission planning
- flight simulation

DEMs of usable details are still not available for much of the Earth, and when they are available they frequently lack sufficient accuracy. The digital format of a DEM has made it easier to derive additional information for various applications, so that elevation modelling has become an important part of the international research and development programs related to geospatial data. PCI Geomatics implemented operational software for DEM extraction from various satellite data, based on advanced algorithms and techniques for geometric modelling and elevation modeling developed by Toutin (1995) at Canada Center for Remote Sensing (CCRS).

This paper summarizes part of the review performed by Toutin (2001) corresponding to different techniques for DEM extraction from satellite visible and infrared (VIR) data. The most important technique (stereoscopy) has been implemented in PCI software. First, various existing high and medium resolution satellite sensors and data are reviewed. To better develop an understanding of PCI software tools that allow extracting DEMs from satellite images their methodology is presented. Finally results of different tests of DEM extraction using PCI software are presented.

2. High-Resolution and Medium-Resolution Satellite Stereo-Images

PCI software provides tools for extraction of DEMs from satellite VIR images of SPOT, IRS, ASTER, and IKONOS. In addition, the software supports DEM extraction from RADARSAT satellites. This section only summarizes part of the review performed by Toutin (IJRS, 2001) dedicated to the stereoscopic capabilities and techniques for DEM extraction from VIR satellite sensors.

To obtain stereoscopy with images from satellite scanners, two solutions are possible:

1. the along-track stereoscopy with images from the same orbit using fore and aft images; and
2. the across-track stereoscopy from two different orbits.

The second solution was the most used since 1980: first, with Landsat from two adjacent orbits, then with SPOT using across-track steering capabilities, and finally with IRS-1C/D by "rolling" the satellite. In the last few years, the first solution was used with the JERS-1 OPS, the German Modular Opto-Electronic Multi-Spectral Stereo Scanner (MOMS), the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER).

2.1 "Adjacent Orbit" Stereo

In the case of Landsat (MSS, TM, ETM^{+}), (Landsat-7 Web Site, 2001), the stereoscopic acquisition is only possible from two adjacent orbits as the satellite acquires nadir viewing images, and the tracking orbit ensures repeat path consistent within a few kilometers. In fact, as the mean B/H ratio with Landsat-MSS is around 0.1, a relief of about 4000 meters would generate a parallax of five Landsat-MSS pixels (80 meters resolution). The stereoscopic capabilities with Landsat data remain limited by the following factors:

- it can be applied for large areas only in latitude higher than 45° to 50° north and south;
- it generates a small B/H ratio leading to elevation errors of more than 50 meters; and
- only medium to high relief areas are suitable for generating sufficient vertical parallax.

2.2 "Across-Track" Stereo

The SPOT system with its across-track steering capabilities (±26°) can generate B/H ratios of 0.6 to 1.2 which represent a typical value to meet the requirements of topographic mapping. The perspective of the SPOT push-broom scanner is a conico-cylindrical perspective, as it is conical for imaging a line, and cylindrical for the displacement of the satellite. In conjunction with its 10 meters pixel size, a precise model should be used to transform the parallax extracted from the raw SPOT images into an elevation value.

The Indian Remote Sensing Satellites IRS-1C and IRS-1D also have across-track stereo capability. This is achieved by rolling the satellite rather than steering the instrument. However, it seems difficult to obtain stereo images outside of India. It is an operational digital space sensor usable for mapping with 5.8 meter ground resolution. Its 70 km swath (12 000 pixels) is imaged using three separate 4096 CCD push-broom optical sensor with 7 µm resolution. The three arrays are not well aligned generating translation and rotation between the array images. Due to misalignment and overlap the raw images are then useless without appropriate geometric correction and they require a precise geometric modelling.

2.3 "Along-Track" Stereo

IKONOS, the commercial satellite with the highest publicly available resolution, was successfully launched in September 1999. Since the satellite's sensor can generate 1-m panchromatic and 4-m multiband images with off-nadir viewing up-to-60degrees in any azimuth, stereo capabilities are then possible in across-track and along-track directions (http://www.spaceimaging.com).

ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) is an imaging instrument that is flying on Terra, a satellite launched in December 1999 as part of NASA's Earth Observing System (EOS). ASTER has along-track stereo-capability that allows acquisition of 15m data in near infrared bands 3N and 3B. The primary objective for the ASTER mission is to obtain high spatial resolution (local, regional, and global) images of the Earth in fourteen spectral bands. ASTER consists of three different subsystems: the Visible and Near Infrared (VNIR 15m), the Shortwave Infrared (SWIR 30m), and the Thermal Infrared (TIR 90m), (Yamaguchi, *et al.*,1998). The release of ASTER data has two significant impacts. First, the data can be downloaded free of charge from the web (http://asterweb.jpl.nasa.gov). Second, it provides a new alternative for mapping at medium-to-large scales and for generating DEM from the along-track stereo data. ASTER has the capability to provide both across-track and along-track stereo.

In fact, the same-date along-track stereo-data acquisition gives a strong advantage versus the multi-date across-track stereo-data acquisition. It reduces the radiometric image variations (refractive effects, sun illumination, temporal changes) and thus increases the correlation success rate in any image matching.

Table 1 - From Toutin (IJRS, 2001) integrated with results of tests with IKONOS, ASTER, and Landsat-7, Toutin (IGARSS, 2001): Summary of the results of the elevation extraction with the VIR scanners using the stereoscopic method. The values in brackets were obtained from simulated data.

Stereo-Pairs	Resolution	Across-track	Along-track
SPOT P	10 m	5-15 m	
SPOT/Landsat	10 m/30 m	35-50 m	
IRS 1C/D	6 m	10-30 m	
Landsat-7	15 m	50-90 m	
MOMS-2P	18 m		10-30 m
JERS-OPS	20 m		20-40 m
SPOT/ERS	10 m/30 m	20-30 m	
EOS-ASTER	15 m	(15 m)	15-25 m
IKONOS	1 m	(1.5-2 m)	2-4 m

3. PCI Software Methodology for Elevation Derivation

For generation of precise DEMs, PCI software uses geometric and stereoscopic models equivalent to the co-linearity and co-planarity equations in photogrammetry. PCI software employs the geometric modelling method, based on the co-linearity condition method, developed by Toutin (1995) at CCRS. This method reflects the physical reality of the complete viewing geometry and the following distortions that may occur during the image formation: (Details may be found at http://www.pcigeomatics.com)

- distortions due to the platform (position, velocity, orientation);
- distortions relative to the sensors (orientation angles, instantaneous field of view, detector signal integration time);
- distortions relative to the Earth (geoid-ellipsoid including relief); and

- deformations relative to the cartographic projection (ellipsoid – cartographic plane).

PCI software processing steps to produce DEMs from stereo-images is described in this section.

Ground Control Point (GCP) Collection

PCI software can read imagery and supplementary information such as ephemeris and attitude data (if exist) from SPOT, IRS, ASTER, and IKONOS using various types of media such as CD-ROM, magnetic tape, etc.

GCPs are collected to compute or refine the stereo-model geometry with a least square adjustment process in order to obtain a cartographic standard accuracy. With the parametric modelling method, based on the co-linearity condition method, developed by Toutin (1995) at CCRS, used in PCI software, few GCPs (3 to 6) are required. The number of GCPs depends on their accuracy. GCPs should be spread at the border of the stereo pair to avoid extrapolation in planimetry. It is also preferable to cover the full elevation range of the terrain. Different types of GCPs can be used:

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

PCI software allows extracting absolute and relative DEMs. To extract an absolute DEM, the user needs to collect GCPs and optionally tie points for each image. To extract a relative DEM, only tie points need to be collected.

Cartographic coordinates of GCPs can be obtained from global positioning system (GPS), air photo surveys, map digitizing, etc. PCI software allows GCPs collection from various sources using techniques as follows:

- enter GCPs coordinates manually;
- from geocoded image files;
- from geocoded vector files;
- from a Chip Database file, including correlation;
- collect GCPs from digitizing tablet; and
- import GCPs from text file.

3.1 Elevation Parallax Extraction

PCI software provides the capability of image matching technique, used to extract the elevation parallax. Once the GCPs are collected, and the geometric model is computed for each imagery of the stereo pair, the next step is to generate quasi-epipolar curve images from the stereo pair. An area based automated image matching procedure is then used to extract the elevation parallax, and produce the DEM through a comparison of the respective grey values on each of these images. This procedure utilizes a mean normalized cross-correlation matching method with a multi-scale strategy to match the image using the statistics collected in defined windows. Matching is performed by considering the neighborhood surrounding a given pixel in the left quasi-epipolar image (thus forming a template) and moving this template within a search area on the right epipolar image until a position is reached which gives the best match. The actual matching method employed with PCI software generates correlation coefficients between 0 and 1 for each match pixel, where 0 represents a total mismatch and 1 represents a perfect match. A second-order surface is then fitted around the maximum correlation coefficients to find the match position to sub-pixel accuracy. The difference in location between the center of the template and the best matched pixel position gives the disparity or parallax arising from the terrain relief, from which the absolute elevation value is then computed.

The advantage of using this procedure is that effectively the search for the matching pixels is limited to the epipolar line, thus significantly improving the algorithm's efficiency and accuracy. A further advantage arising from the matching method used is that it tolerates any spatially invariant, linear radiometric relationship between the two images.

PCI automatic DEM extraction software allows the user to:

- Specify the extent of the output DEM to be extracted.
  Choose full image or a subset window of the image.
- Specify approximate minimum and maximum elevation to aid in correlation.
- Select extraction option parameters governing the quality and resolution of the DEM extraction:
    - Pixel spacing
    - Level of DEM Detail
    - Filtering

- Score channel containing correlation score for each pixel
    - Set values to use for Background and Failed pixels.
- Creates a detailed report of the DEM extraction process.
- Schedule the DEM extraction process to run immediately or to start at a later time, within the next 24 hours.

3.3 DEM Post-processing

After computing the elevation parallax and producing the DEM, there is a need for post-processing the extracted elevation data: e.g., to remove blunders, to fill the mismatched areas, to correct for the vegetation cover and to smooth the DEM.

To fill the mismatched and the noisy areas, PCI software employs interpolation functions to replace the mismatched values interpolated from good elevation values of the edges of the failed areas.

PCI software provides manual DEM editing tools enabling the user to perform the following functions:

- create editing masks;
- interpolate elevations to cover areas with no elevation information;
- filter out ‘noisy’ elevation points;
- smooth out irregularities to create a more pleasing elevation model; and
- set areas (such as lakes) to constant values.

4. PCI Software Test Results for Elevation Extraction and Orthorectification

Results of testing PCI software for elevation extraction from satellite VIR stereo-images performed by various researchers are presented in this section, high and medium resolution sensors are evaluated.

Al-Rousan and Petrie (1998) evaluated PCI EASI/PACE, OrthoMAX, and DMS software, for the extraction of DEMs using 4 SPOT 1B images. The results obtained by PCI EASI/PACE system are consistently the best. The RMS error of the extracted DEMs at the control points and the check points for four scenes were between ±2.6m to ±6.2m, and the standard deviation compared to GPS profile values was about ±6m.

Using PCI software, Cheng, *et al.* (1999) generated a DEM from raw IRS-1C LISS stereo-images, with B/H = 0.52, over a mountainous area in Arizona, USA, with an elevation variation of 2100m. They reported an elevation accuracy of about 10m when compared both to ICPs and digital DEM of the United States Geological Survey (USGS). A DEM was also extracted on the same type of relief from SPOT stereo-images using PCI software. The extracted DEM was compared both to the input GCPs and ICPs elevation values. The RMS residual and maximum residual comparing to the input GCPs were both within 10m. The RMS error comparing to the ICPs was 6.6m.

Cheng and Toutin (2000) tested PCI software for producing IKONOS ortho-image. The experiment was performed using IKONOS Carterra Geo imagery covering an area in Richmond Hill, Canada, with an elevation range of 180 to 240 meters. 2 meter spacing DEM was used for the orthorectification, and 20cm orthophoto was used for extracting the GCPs, and the ICPs. The RMS residual and maximum residual comparing the generated IKONOS ortho-image with the existing 20cm ortho-photo were within 4m. IKONOS orthorectification accuracy obtained using PCI software is within the accuracy of Space Imaging IKONOS Precision product.

Toutin (IGARSS, 2001) presented results of testing PCI software for extraction of DEM from high-resolution (HR) IKONOS images, and medium-resolution (MR) ASTER and Landsat ETM^+ images. The study sites for HR and MR images are located in Canada in a semi-rural area in the North of Quebec City, and in the Canadian Rocky Mountains, respectively. The two sites have 500-m and more than 3000-m elevation difference, respectively. The checked DEMs were derived from digital 10-m contour lines from 1:20,000 and 1:50,000 maps with accuracies of 5 m and 10 m, respectively. The along-track IKONOS stereo-data was acquired on January 3rd, 2001 with a 54° stereo-intersection angle (B/H=1.0). The ASTER images are acquired on September 25th, 2000, with the backward (27.7°) and nadir images (15-m pixel spacing) generating along-track stereo with 0.6 B/H are used in DEM generation. The Landsat-7 ETM^+ data are two level 1G images (15-m pixel spacing), acquired August 24th and September 16th, 1999 from paths 44 and 45, respectively and row 24. With 40% overlap, they generate an adjacent-track stereo-pair (75 km by 180 km) with 0.15 B/H ratio. Accuracy of 4.9 m with high-resolution IKONOS images, and 33 m and 101 m with medium-resolution ASTER and Landsat-7 ETM^+ images respectively are obtained.

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