ELEVATION MODELLING FROM SATELLITE VISIBLE AND INFRARED (VIR) DATA: A REVIEW©

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ABSTRACT

Since the early emergence of Earth observation satellites, researchers have investigated different methods of extracting three-dimensional information using satellite data. Apart from a few early stereo-images by hand-held photographs acquired during the Gemini and Apollo missions, the first experiments to extract three-dimensional data using stereo viewing from space began with the Earth Terrain Camera flown onboard SkyLab in 1973/74.

Since this time, various analogue or digital sensors in the visible spectrum have flown to provide researchers and geoscientists with spatial data to extract and interpret three-dimensional information of the Earth's surface. Although clinometry techniques can be applied with the optical sensor images, stereo-viewing of images was and still is the most common method used by the mapping, photogrammetry and remote sensing communities for elevation modelling.

The paper will review clinometry and stereoscopy and their applicability to the different satellite sensors (space photographs and scanners). Their performances to extract absolute or relative elevation from various research and commercial organizations are addressed. The respective advantages, difficulties and constraints of the sensors are discussed, as well as the methods and the technologies used for extracting elevation data in an operational context.

1. INTRODUCTION

Not so long ago, a hill top view was the largest vista from which to observe nature's workings. Discoveries in optics, photography and flight have allowed us to see the Earth as never before. Advanced methods in computing and signal processing technologies, and so on, have enabled us to increase our ability to extract, visualize and perceive the Earth's surface information. Today Earth observation satellites orbit our planet collecting data to produce images, which allow us to monitor, understand and plan the use of our world's resources. Remote sensing has evolved into an important supplement to ground observations and aerial photographs in the study of terrain elevation features.

Why is it important that the third dimensions be conveyed? Because humans are naturally able to see in three dimensions. The "naturalness" of a three-dimensional (3D) representation of reality enhances our ability to interpret two-dimensional imagery. Cartographers, engineers, geologists, hydrologists, and other geo-scientists, use different three-dimensional viewing

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methods for perceiving the ground elevation in order to better understand the Earth's surface. For example, representation of the third dimension supplies important information about the relationship between land shape and structure, slopes and waterways, surface material and vegetative growth.

A digital elevation model (DEM), which is a digital representation of the Earth's relief, is now one of the most important data structures used for geo-spatial analysis. Unfortunately, DEMs of usable details are still not available for much of the Earth, and when available not always with a sufficient accuracy. Since the digital format of a DEM enables easily to derive subsequent information for various applications, elevation modelling then becomes an important part of international research and development (R&D) programmes related to geo-spatial data.

Due to high spatial resolution of recent satellite sensors in the visible spectrum (Landsat–TM, SPOT-HRV, IRS-LISS and others) a large number of researchers around the world have investigated the extraction of elevation and/or the production of DEMs. General books (Bonneval, 1972; Wolf, 1974; Manual of Photogrammetry, 1980) or review articles (Day and Muller, 1988; Lemmens, 1988; Buchroithner, 1989; Petrie *et al.*, 1997) and others have addressed different, but not all aspects of elevation modelling from aerial and/or satellite data. A comprehensive and update review is not available at this time.

Furthermore, the recent research in computer vision to model human vision has led to the advent of new alternative image processing approaches using satellite imagery. Consequently to expand on the previous works, this paper presents the two main methods (clinometry, stereoscopy) developed to extract elevation with their processing steps, and their applicability of the different data in the visible and infra-red spectrum (VIR) with a performance analysis. Finally some concluding remarks on these methods and prospects for the future with the next generation of satellites are presented.

2. CLINOMETRY

Shade and shadows are familiar phenomenon, which can help to judge size and shape of objects by providing with profile representation. It is particularly helpful if the objects are very small or lack tonal contrast with their surroundings. Shading is sometimes confused with shadowing. Shading is the variation of brightness exhibited in the image. It arises primarily because some parts of a surface are oriented so as to reflect more of the incident illumination towards the sensor (Horn and Brooks, 1989). Since shading provides cues all over the surface not just along special contours, this principle is used with the shape-form-shading technique to derive terrain slope and elevation. Shadow on a surface results when another surface intercepts the illumination from the source. It only provides localized cues (along special contours) to shape, although the shadow of a curved surface cast on another curved surface is very difficult to interpret. This principle is used to derive elevation of specific man-made or natural targets, such as buildings, bridges, towers and trees.

2.1 Shadowing

Cast shadow and occluded areas can be used to extract relative heights (Cheng and Thiel, 1995) or to determine ground control points (Brivio *et al.*, 1992). The shadow areas occur when the ground surface is not illuminated by the source ("backslope" related to the illumination source), and the occluded areas occur when the ground surface is not visible from the sensor ("backslope" related to the sensor). The effects of these two concepts are different with VIR images since the illumination source, the sun, and the sensor are different. While occluded areas are completely without information, shadow areas in VIR images have some information because the terrain receives some diffuse sun illumination partially reflected by the terrain.

Satellite VIR images are acquired from the descending path of a sun-synchronous orbit, and the local solar time is generally before or around noon (e.g., for SPOT, the local solar time of the descending node is around 10:30 am). Consequently, west-looking images will have shadow and occluded areas in the "illumination source direction". Care must be taken to separate these two effects. Since the sun elevation angle, around noon will generate shadow with steep slopes, the shadow lengths can be consistently measured only from vertical structures such as buildings, trees or very rugged terrain. However with a low sun elevation angle (in wintertime) the relief perception of a rugged terrain is inverted (Saraf *et al.*, 1996). Occluded areas could be also used to extract elevation information only with off-nadir viewing images, but this has been never addressed.

This method using shadow length measurements was largely applied with aerial photos in which the pixel resolution is much better than the object height (Huertas and Nevatia, 1988). To our knowledge, no attempt has been made with space photographs. Knowing the sun and sensor geometry, the same method can be applied to VIR satellite images, even if the resolution is coarser. Using a simple trigonometric solution, Cheng and Thiel (1995) computed elevation with 3.7-m accuracy over a sample of 42 well-defined buildings from a panchromatic SPOT image. A correction for the known terrain slopes was also introduced. Since the shadow length is manually measured at the pixel unit (10 m for panchromatic SPOT image) these good results can account for the size of the building (up to 60 m with a mean of 30 m), and the large shadow cast (up to 18 pixels with a mean of 8 pixels). Hartl and Cheng (1995) computerized the method and applied it over a complete city. Only 30% of the 78 800 buildings were extracted, with calculated heights less than 20 m for 90% of them. Seventy-seven buildings were randomly selected to check their height error, and the root mean square error was about 6 m, with only 11 buildings having errors larger than 10 m (on SPOT resolution). The main factors leading to the larger error were the high building density and the overlapping of grey value.

Since shadow boundary is a key point in the process, different tools to determine the shadow boundaries more accurately have been developed. Meng and Davenport (1996) created an edge-image template using the point-spread function of the sensor. After a manual rough location of the edge, a correlation process between the template and the actual image determines the best location of the shadow edge within $1/100^{th}$ of a pixel. Unfortunately no ground truth data has been provided for checking the accuracy.

On the other hand, Shettigara and Sumerling (1998) developed a four-step process using the spatial information of a panchromatic SPOT image and the spectral information of the SPOT image infrared band. Firstly, an appropriate threshold to delimit shadows in the images is selected. Shadows cast by rows of trees are used to estimate mean heights of trees. Calibration curves are then constructed to relate the actual mean heights of trees to the estimated heights. Finally, heights of industrial buildings are computed using their shadow lengths and the calibration curves, without any correction for the terrain slopes. Accuracy of 3 m has been measured with only three 12-m tall buildings. Although the shadow determination is more sophisticated, the results are similar to the first method (Cheng and Thiel, 1995). The advantage of this method is that the shadow boundaries are located with sub-pixel accuracy using an optimum threshold, which enables smaller building heights to be estimated. The disadvantages are that two SPOT images are used, and some ground data for the trees-row heights are necessary to determine the calibration curves. Conversely, the first method does not use ground data for their height estimation. No attempt to verify the method over a complete city in a real environment has been done, such as for the first method (Hartl and Cheng, 1995).

2.2 Shape-from-shading

One of the first applications of shape-from-shading was realized in robot vision to detect the 3D shape of industrial objects with diffuse reflecting surface (Horn, 1975). Using the principle that an image of smooth object known to have a uniform surface will exhibit gradations of brightness, or shading, the shape can be determined to map the height of this surface. Because there are two degrees of freedom to surface orientation, the reflectivity does not uniquely determine the local normal but a set of possible normal directions. Consequently, local operation on the brightness alone cannot be used to determine the shape of the surface and its orientations. Additional constraint must therefore be added: generally the surface is assumed to be continuous and smooth, so that the surface orientations of neighbouring surface elements are not independent. If the reflectivity function and the position of the illumination source are known, the shape can thus be obtained from the shading.

At first, the principle appears simple, essentially the inversion of a mathematical expression of the VIR reflectance in terms of the albedo and the local incidence angle. A first radiometric ambiguity is thus related to the inversion of the model since it depends on two parameters. Consequently the application of this concept to remote sensing data is not evident due to the sensitivity of shading to reflective properties of Earth’s surface. The VIR reflectance of the surface is altered if the surface properties vary from place to place. Even if this reflectivity function for satellite sensors has been described with many experimentations since the 1970s (Suits, 1971; Teillet *et al.*, 1982), a general Lambertian model can be chosen for simplification when small range of incidence occurs (Smith *et al.*, 1980). In this case assuming uniform reflecting properties (constant albedo) will recover a shape (incidence angle) that is different from the actual one. This hypothesis of constant albedo is only acceptable for very homogeneous landcover.

A second geometric ambiguity, called conic ambiguity, is related to the definition of the incidence angle. Even accurately determined, it does not define uniquely the orientation of the surface but a set of possible orientations. Their normal directions describe a cone with the axis being the illumination direction. Since there are two degrees of freedom to surface orientation, it takes two numbers to specify the direction of a unit vector perpendicular to the surface (Horn, 1975). One brightness measurement at each picture cell only gives one equation for two unknowns at every cell. With additional constraint or assumption to resolve this conic ambiguity, the local slope is then computed from the pixel reflectivity value and transformed into relative elevation by integration pixel by pixel.

In other words, shape-from-shading makes uses of the sensitivity of micro-topography, but it cannot provide absolute location. Some reference elevation information is needed to derive the absolute elevation. In summary, intrinsic radiometric and geometric ambiguities limit the accuracy of this technique with remote sensing data:

1. The reflectivity is not only dependent on the local incidence angle, but also on the albedo related to land cover and use as a function of the sensor.

2. The determined incidence angle yields to a set of potential orientations whose normal directions describe a cone.

3. The method only determines slopes; reference elevations have to be known, and the accuracy is limited by the height error propagation.

However, shape-from-shading can be practically applied to VIR imagery since information concerning the terrain is contained in multi-scanner data. With homogeneous surfaces where variations in reflectance may only refer to topographic surface differences rather than to land cover effect, a simple reflectance model can be used to derive the topographic information. It then resolves the radiometric ambiguity. Lodwick and Paine (1985) used two Landsat-1/2 images (July and October) over an ice-cap on Baffin Island, Canada to obtain high and low sun angles and maximum difference in sun azimuth. They considered for the reflectivity either a simplified Lambertian model (Teillet *et al.*, 1982) or two empirical models to resolve the radiometric ambiguity. On the other hand, the slopes being in the sun-azimuth direction resolves the conic ambiguity. They first demonstrated with a training sample that the reflectance conditions of an ice-cap are non-Lambertian for a large range of incidence angles, such as Smith *et al.* (1980) for pine forest cover types. The first empirical model used a second order polynomial computed over training samples. Difficulties in obtaining representative training samples were the main source of errors even if high correlations were obtained. The second empirical model applied a simple linear model between typical maximum slopes in the "sunfacing and awayfacing" directions and the reflectance values at the one-percent level of the grey value histogram. It was the best solution to generate height differences, which agreed broadly with values observed on the map.

Finally a weighted third-order surface adjustment was carried out with nine control points to transform the 50-m posting slopes in the sun-azimuth direction into elevations. The results for the basic shape of the ice-cap surface compared well with the surface given by the base map. Some variations could be partly explained by the surges (melting and re-freezing) of the ice-cap surface. No quantitative accuracy results have been given due to the lack of precise and digital topographic information.

Unfortunately, no other results with different study site and data sets have been presented to confirm the potential of this method with VIR images. Shape-from-shading thus remains a marginal technique, which could be applied mainly in difficult situations such as ice-cap, tropical land cover, extra-terrestrial sites without ground truth. This is mainly due to the fact that the radiometric ambiguity between the terrain albedo, the VIR reflectance cross-section and the incidence angle is rarely solved; only approximations on homogeneous terrain surface with a Lambertian model can be achieved. However, a large part of the Earth without cartography consists of these homogeneous surfaces.

3. STEREOSCOPY

Binocular disparity and convergence are the two psychological cues when viewing imagery in stereoscopy. The binocular disparity (or parallax) is the "difference" between the images of an object projected onto each retina. The degree of disparity between the two projected images depends on the convergence angle. Convergence is the ability to focus the optical axes of the two eyes on to a single object. The sensing of the amount of muscular tension in the eyes resulting from different convergence angles provides a cue to the absolute distance to the viewed point. The binocular disparity is considered the most important perception cue over medium distance, and predominates with optical images because it reproduces the natural process of human binocular vision.

In modern photogrammetry, "*stereoscopy is the science and art that deals with the use of images to produce a three-dimensional visual model with characteristics analogous to that of actual features viewed using true binocular vision*" (La Prade *et al.*, 1966). The principle of the binocular disparity is applied in aerial and satellite photogrammetry to compute the terrain elevation from the measured parallaxes between the two images.

In the last 50 years, first optico-mechanical and later analytical and digital 3D photogrammetric systems capitalizing on the binocular parallax and convergence cues have been developed to meet the needs of aerial and satellite stereo photogrammetry. The main concepts of the analytical and digital systems were developed by U.V. Helava in 1957. Most of the stereo workstations have now been adapted to process stereo-images from the same satellite sensor (space photo or VIR), but occasionally from mixed sensor stereo-pairs. Photogrammetric principles for space photos (collinearity and coplanarity conditions) and their equivalent for remote sensing data mathematically solve the relationship between 2D image co-ordinates and 3D ground co-ordinates. The hardware and software used to derive information from the 2D digital stereo-images has thus allowed the mapping process to become more automated (Helava, 1988a), but not completely with occasional unmatched expectations (Grün, 1997).

Among all the new developments of the stereo workstations, DEM generation is an important R&D topic, since any satellite images can be used to generate a stereoscopic pair and simulate the natural depth perception, as soon as the terrain is imaged from two different viewpoints. However, two main categories of VIR sensors have to be considered due to their different geometry: the space cameras and the digital scanners. Combinations of mixed sensors for generating stereo-pairs are also addressed. Since the stereoscopic methods to extract elevation, based on the binocular disparity and parallax, are "more or less" the same for the different sensors, their respective stereoscopic capabilities and performance are first analyzed. The processing, the methods and the error propagation are then addressed in a separate Section.

3.1 Space Cameras

The space camera technology remained a long time in the military domain. Since the techniques and technologies of space photographs are derived from classical aerial photographs, photogrammetrists have considered that space cameras should be the next logical step for topographic mapping.

The first significant satellite photogrammetry experiment was done using imagery on the Apollo 15, 16 and 17 missions to the moon. A lunar control net with 30-m relative accuracy in the three co-ordinate axes were generated, and 1:25 000 scale topographic ortho-photo maps have been realized (Doyle, 1979). After a few early stereo hand-held photographs acquired during the Gemini and Apollo missions, the Earth's Terrain Camera (ETC) experiment onboard SkyLab-D in 1974 produced the first along-track stereo-viewing images from space. One of the first attempts to measure heights from space images was realized by Mott (1975). He reported a root mean square (RMS) error of 120 m for a strip of four SkyLab models and concluded that the minimum contour intervals to be plotted should be approximately 250 m.

The ETC was followed by the German Democratic Republic's MKF-6M multi-band non-metric camera flown on Soviet spacecrafts Soyuz 22 and Salyut in 1976. None of the cameras was able to produce acceptable accuracy, even with an image pixel size varying from 17 m to 30 m. Furthermore, wide gap spaces between ground tracks hinder large areas to be mapped (Kostka, 1986; Buchroithner, 1989).

In 1978, the USSR flew the KATE140 metric camera on Salyut acquiring panchromatic images with 60-m resolution. Later the USSR developed RESURS, a series of remote spacecraft based on the recoverable Vostok capsule. They carry different multi-band metric cameras (KATE200, KFA1000 and 3000, LK1000 and MK4) with retrievable film on missions lasting between two and four weeks. The ground resolution varies from less than 5 m to 30 m. Research studies were performed only for image content analysis and planimetric features mapping, but no results on DEM accuracy were given because these cameras either do not have stereo capabilities or they generate poor base-to-height (B/H) ratios (about 0.15). At the same time, the German Zeiss Metric Camera (MC) initiated by the European Space Agency (ESA) took panchromatic and near-infrared images during the Space Shuttle STS-9 mission between November 28 and December 7, 1983. Later on, the ITEK Large Format Camera (LFC) initiated by NASA was flown in the Space Shuttle STS-41-G on October 5-10, 1989. The LFC has a Forward Motions Compensation (FMC) system to produce a better image quality.

Since these different metric cameras have along-track stereo-capabilities, elevation can be derived. However, most of the research work has been on the estimation of the stereo acuity (Doyle, 1979, Kostka, 1986, Buchroithner, 1989), or on the evaluation of planimetric and altimetric accuracies over a limited number of points (Meneguette, 1985). Other results were reported by various authors at the Metric Camera Workshop held in Oberpfaffenhofen, Germany in February 1985, or at the ACSM-ASPRS annual meeting held in Washington, D.C., U.S.A. in March 1986. They mainly used analytical stereo-plotter for which Earth curvature correction has been added to the normal photogrammetric bundle adjustment, but not for varying atmospheric conditions (Jacobsen and Müller, 1988).

Different experiments generated contour lines on analytical stereo-plotters with MC data (Ducher, 1985; Jacobsen and Müller, 1988) and with LFC data (Murai, 1986), or generated DEM with MC data (Petrie *et al.*, 1997). In the first experiment (Ducher, 1985), 50-m contour lines were digitally plotted and compared with 1: 25 000 scale topographic maps. The results showed a standard error of about 30 m with larger errors in the steepest areas. Jacobsen and Müller (1988) developed off-line software to compute the Earth curvature corrections for space photographs because their analytical stereo-plotter did not handle them properly. An elevation accuracy of ±22 m for the corrected contour lines was then obtained in a terrain with a mean slope of 33°.

Later on, Petrie *et al.* (1997) extracted a DEM over arid and semi-arid areas in the Red Sea region from MC photographs using a Kern DSR analytical stereo-plotter. Compared with 1,300 independent check points (ICPs) interpolated from the contour lines of 1:100,000 scale topographic maps, they obtained RMS errors varying over the range of 16 m for flat areas to 47 m for different sub-areas depending on the slopes and complexity of the terrain.

In the last experiment (Murai, 1986), difficulty in extracting 20-m contour lines was reported. The height accuracy of the extracted contour lines was only computed from 30 points, and was 15 m in average for stereo-pairs with a B/H ratio of more than 0.6. Although less significant these LFC stereo-pair results are better, due to the FMC system. However, although the obtained accuracy was in the same order as the predicted accuracy for generating contour lines at 20-m to 30-m intervals with LFC data (Doyle, 1979), it does not completely meet the requirements of cartography, particularly in mountainous areas (Kostka, 1986). Table 1 summarises the results of elevation extraction for the space photographs with the stereoscopic method.

Table 1: Summary of the results for the elevation extraction with the space photographs using the stereoscopic method. The results for the STS-MC were evaluated as a function of the terrain relief.

Platform-Sensor	Elevation Accuracy
SkyLab-ETC	120 m
STS-MC	15-45 m
STS-LFC	15 m

The main reasons why these data have not been used for operational DEM production are (Ducher, 1985):

- the limited distribution of the data relative to the amount of acquired images;
- the experimental nature of the data and system, and the lack of decision to make it fully operational and repetitive; and

- the relatively poor quality of the data.

Consequently the stereo capabilities of the MC and LFC camera have been oriented as a source of planimetric feature content for mapping using traditional photogrammetric techniques with analytical stereo-plotter (Whittington, 1989).

3.2 Digital Scanners

To obtain stereoscopy with images from satellite scanners, two solutions are possible:
1. the along-track stereoscopy from the same orbit using fore and aft images; and
2. the across-track stereoscopy from two different orbits.

The latter solution was more used since 1980: firstly, 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 as applied to space frame cameras got renewed popularity with the JERS-1’s Optical Sensor (OPS), the German Modular Opto-Electronic Multi-Spectral Stereo Scanner (MOMS), the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), the IRS-P5, and most of the high-resolution satellites such as Orb-View1 and Quick-Bird. Only Ikonos have sensor-steering capability in both along- and across-track directions.

3.2.1. *“Adjacent orbit” stereo*

In the case of Landsat (MSS or TM), the stereoscopic acquisition is only possible from two adjacent orbits since the satellite acquires nadir viewing images, and the tracking orbit ensures repeat path consistent within a few kilometres. In fact the B/H ratio with Landsat-MSS is around 0.1, so that relief of about 4 000 m is needed to generate a parallax of five Landsat-MSS pixels (80-m resolution). Due to its quasi-polar orbit, the coverage overlap grows from about 10% at the Equator to about 85% at 80º latitude. From 50º north and south the coverage overlap (45%) enables quasi-operational experiments for elevation extraction. Welch and Lo (1977) extracted elevation of ten control points from different colour-photograph stereo-pairs acquired from Landsat-1. They designed a precise parallax-bar instrument with various viewing magnifications (10x to 30x), and obtained a RMS error for the elevation between 300-500 m. They noticed a large error coming from the parallax difference measurements on the analogue photographs. Digital processing should thus allow a better parallax measurement accuracy.

Simard (1983) and Simard and Slaney (1986) then used digital Landsat-MSS and -TM stereo-pairs, respectively over the mountains in British Columbia, Canada. Due to a larger B/H (0.18) and a finer image resolution Ehlers and Welch (1987) also applied the method with Landsat-TM data over a low relief (500-m elevation variation). For both experiments, the images are first corrected for the geometric error associated with the platform, sensor and look geometry, and then the residual misregistration (parallax) between stereo-pairs reflects the relief influence. Cooper *et al.* (1987) also suggested correcting for the Earth curvature, if it is not done. Since the east-west component accounts for almost 98% of the total parallax, a simplified one-dimensional model to compute the elevation from the measured parallax can be used (Simard, 1983):

$$dh(x, y) = dp(x, y) H/B \quad (1)$$

Where dh and dp are the relative height and parallax at each image point (x, y), respectively.

This equation can be modified for the different orientation of the scan lines, but the variation in B/H is less than 0.004 (Ehlers and Welch, 1987). These models are an approximation of the stereo geometry, which is only good because of the coarse satellite image resolution (30-80 m), the poor B/H (0.1-0.2) and the final expected accuracy (50-100 m). The parallax for each pixel is measured using a hierarchical cross-correlation technique with variable reference window size (Simard, 1983). The window size for the search window can also be adjusted according to image content and signal-to-noise ratio (Ehlers and Welch, 1987). More details on the method are given in Section 3.4.

Qualitative evaluation of the resulting DEM or the derived contour lines show generally good agreement when overlaid on the ortho-rectified Landsat-MSS imagery (Simard, 1983) or with the existing map contour lines (Ehlers and Welch, 1987). Quantitative evaluation gives a RMS error of about 45 m when compared with ICPs (Simard and Slaney, 1986; Ehlers and Welch, 1987), and of 60 m to 70 m with a low precision 1:250 000 map derived DEM (Cooper *et al.*, 1987). The resulting variations of this last study can be accounted for the low precision map DEM, and from the correlation process using edge matching instead of grey level matching. More details in the correlation results and performances are given in Section 3.4.

In anticipation of the planned across-track stereo IRS-1C data, Malleswara Rao *et al.* (1996) used the same "adjacent orbit" stereo technique with the linear imaging self-scanning sensor data (72-m resolution) of the Indian IRS-1A satellite, which does not have across-track stereo capability. Using the same method than previously described with Landsat (geo-referenced data, least square matching and approximated elevation modelling) they generated a DEM over three study sites with stereo images displaying various overlaps (16% to 27%) and B/H ratios (0.12 to 0.14). The DEMs were then checked with 30 ICPs, and showed an error with 90% confidence of about 35 m with a slight correlation between the error and the B/H.

The stereoscopic capabilities and applicabilities of "adjacent orbit" satellite data still remain limited because:

- it can be used for large area only in latitude higher than 45º to 50º north and south;
- it generates a small B/H ratio leading to elevation errors of more than 50 m; and
- only medium to high relief areas are suitable for generating enough vertical parallaxes.

3.2.2. *"Across-track" stereo*

To obtain good geometry for a better stereo plotting, the intersection angle should be large in order to increase the stereo exaggeration factor, or equivalently the observed parallax, which is used to determine the terrain elevation. According to Light *et al.* (1980), B/H ratios of 0.6 to 1.2 are typical values to meet the requirements of topographic mapping. The SPOT system with its across-track steering capabilities (±26º) can generate such B/H ratios. In conjunction with a finer pixel size (10 m for panchromatic image) a more precise model has to be used to transform the parallax extracted from the raw SPOT images into an elevation value. Since the perspective of the SPOT push-broom scanner is a conico-cylindrical perspective (conical for imaging a line and cylindrical for the displacement of the satellite), new geometric and stereoscopic models, equivalent to collinearity and coplanarity equations in photogrammetry, have to be developed for the generation of precise DEM. To transform image co-ordinates or parallax into map co-ordinates, the parametric model has to take into account:

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

Some of the first studies have been realized at the Institut Géographique National (IGN), France from raw-type simulated stereo SPOT data generated by the Centre National d'Études Spatiales (CNES), the French Space Agency (Guichard, 1983; Masson d'Autumne, 1984; Toutin, 1985). These three studies reported 3-m accuracy both in planimetry and altimetry with the simulated stereo-pair (B/H ratio of about 1.1). Furthermore, 20-m contour lines were generated using automatic correlation, and qualitatively compared to contour lines generated from aerial photographs with an analytical stereo-plotter (Masson d'Autumne, 1984). Quantitative results have also been presented using the Matra Traster analytical stereo-plotter with the same simulated SPOT stereo-pair (Vigneron et Denis, 1984), and showed an elevation error of 5 m with 80 % confidence.

Simulation works of georeferenced-type SPOT data were also realized in Canada (Simard, 1981). He generated a DEM with a RMS error of 5.7 m from geo-referenced stereo images corrected for systematic distortions (satellite, sensor, Earth curvature and rotation) with a B/H ratio of 0.5. Other studies with simulated SPOT images have been realized later around the world (US, UK, Australia, Sweden) using analytical stereo-plotter or automatic correlation methods (Vincent *et al.*, 1984; Cooper *et al.*, 1987).

After the launch of SPOT-1 in February 1986, CNES sponsored the SPOT preliminary Evaluation Program (PEPS) to assess SPOT capabilities for thematic and topographic mapping. In preparation of the launch and early PEPS data, considerable research has been carried out to develop robust and rigorous mathematical models describing the specific acquisition geometry of the SPOT-HRV sensors (Masson d'Autumne, 1979; Khizhnichenko, 1982; Guichard 1983; Toutin, 1983; Konecny *et al.*, 1986; Gugan, 1987; Kratky, 1987; Paderes *et al.*, 1989 and Westin, 1990) and others.

Most of these authors used the photogrammetric solution (collinearity conditions for the conic perspective of a single image line), and took into account the displacement of the satellite (cylindrical perspective) to link the equations between themselves. Since the parameters of neighbouring lines are highly correlated, and satellite positions and attitude can be computed from on-board recording systems, the mathematical equations can be reduced to a minimum of eight to ten unknowns depending on the mathematical development and implementation of the solution. However, only some of these solutions were adapted to process stereo-data using the coplanarity condition.

Most of the first results with real data were presented at the SPOT-1 Image Utilization, Assessment, Results Symposium held in Paris, France in November 1987 (CNES, 1987). Academic research results rather than operational systems or projects dominated the conference. In general, accuracy of 10 m or less for the planimetry and the elevation was achieved, but mainly in R&D and not in an operational context. Later on, evaluations of commercial systems based on different SPOT geometric modelling show differences in the elevation accuracy of 20% to 40% (Al-Roussan and Petrie, 1998; Petrie, 1999). The differences are mainly dependent on the accuracy of the different SPOT geometric modelling and its implementation in the workstation since good cartographic data were generally used. For DEM generation two main methods for the processing have been presented: using an analytical stereo-plotter or a digital image analysis system.

The first method uses a stereo analysis system with SPOT data on transparency photographs. Following the Traster System of Matra realized with IGN, France (Vigneron and Denis, 1984), different universities or mapping agencies around the world developed solutions in collaboration with photogrammetric instrument manufacturers: the Kern DSR-1 (Gugan and Dowman, 1988), the Zeis Planicomp (Priebbenow and Clerici, 1987; Konecny *et al.*, 1987), the Wild Aviolyt (Trinder *et al.*, 1988), the Canadian NRC Anaplot-1 (Kratky, 1989). Contour lines can be interactively stereo-plotted to further generate DEMs. Petrie (1992) give more details on the progress of analytical stereo workstations and their processing capabilities. Later on, Hottier and Albattah (1991) described a method by re-sampling raw SPOT stereo images to generate a pair of quasi-epipolar images, which is suitable for stereo plotting on an analogue stereo-plotter. The processed stereo-image pair was thus plotted on a Wild AG1 without either excessive y-parallax or significant loss of information.

When digital photogrammetric workstations become more available the different analytical solutions and software were ported into these fully digital systems. Some of them also took advantages of low-cost personal computers (Welch, 1989; Toutin *et al.*, 1993; Toutin and Beaudoin, 1995). Dowman *et al.* (1992), Heipke (1995) and Walker and Petrie (1996) give more details on the progress of digital stereo workstations and their processing capabilities.

The second method uses fully digital images and processing without any stereo-viewing capabilities most of the time. They automatically derived DEM from the digital SPOT images using correlation techniques and a geometric SPOT model (Gugan and Dowman, 1986; Denis, 1986; Guichard *et al.*, 1987; Renouard, 1987; Simard *et al.*, 1987; Vincent *et al.*, 1987, and others).

Since the advent of SPOT satellites, the Indian Remote Sensing satellites (IRS) 1C and 1D have been launched, also with across-track stereo capability achieved by “rolling” the satellite instead of steering the sensor. Investigation have been carried with three IRS-1C images (two off-nadir, B/H = 0.8 and one nadir) over a mountainous relief (Gopala Krishna *et al.*, 1996) or an undulating relief (Jacobsen, 1997). Compared to ICPs, different accuracy in planimetry and elevation has been achieved: 2 to 5 pixels depending on B/H ratios for the first research study, and 1 to 2 pixels depending on the numbers of parameters used in the bundle adjustment for the second research study. The relief can account for these differences. No DEM was extracted and evaluated in both studies. The results are worse than those generally obtained with SPOT (better than one pixel) or with other IRS-1C data because:

- Gopala Krishna *et al.* (1996) used low accuracy ground control points (GCPs) and ICPs;
- Jacobsen (1997) noticed some problems in the CCD calibration and stability;
- Jacobsen (1997) used a non-parametric solution instead of using a rigorous photogrammetric solution adapted to the specific geometry and characteristics of the LISS sensors (Toutin *et al.*, 1998; Cheng and Toutin, 1998); and
- the attitude data are not always consistent and accurate (Toutin *et al.*, 1998).

When compared to research studies with SPOT data, few results on DEM extraction have been published due to the limited availability of stereo IRS-LISS images. Cheng *et al.* (1999) generated a DEM (least square matching, rigorous photogrammetric modelling) from raw IRS-1C LISS stereo-images (B/H = 0.52) over a mountainous area in Arizona, U.S.A. (elevation variation of 2 100 m). They reported elevation accuracy of about 10 m when compared both to ICPs and to a DEM of the United States Geological Survey (USGS). It is still worse (1.7 corresponding pixels) than results on same type of relief with SPOT (about one corresponding pixel or better), due most likely to the inconsistent attitude data. Further work with IRS-1D could provide a better answer if stereo-data could be more available to researchers.

3.2.3. *"Along-track" stereo*

JERS, launched in 1992, had the capability to acquire along-track stereo-images by the use of forward and nadir linear array optical sensors, named OPS. The 15º forward-looking image and the nadir-looking image (18-m ground resolution) generate a stereo-pair with a B/H ratio of 0.3. The simultaneous along-track stereo-data acquisition gives a strong advantage in terms of radiometric variations versus the multi-date stereo-data acquisition with across-track stereo. This was confirmed by the very high correlation success rate (82.6%) (Raggam and Almer, 1996). The simultaneous along-track stereo-data acquisition can then compensate for the weaker stereo geometry.

Although JERS was launched in 1992, few results on DEM extraction (Raggam and Almer, 1996; Westin, 1996) have been presented after the first Japanese experiment (Maruyama *et al.*, 1994). All experiments have generated DEM's with the correlation method and photogrammetric solutions. Although the methods used are approximately the same, Westin (1996) obtained results (20 m) twice better than Maruyama *et al.* (1994) or Raggam and Almer (1996). This 20-m accuracy corresponds to one pixel spacing, which needed automatic parallax measurement accuracy of better than one-third of a pixel with the 0.3 B/H ratio. Even when the GCPs were extrapolated from over 200-km distance on the same image strip, the elevation error was not affected by the interpolated distance and the distribution of the control data.

The German MOMS is another push-broom scanner with along-track stereo capability. This development started with MOMS-1 in 1979 with the first experiment flown mainly as a technical verification of the instrument line. In a second step, experimental data (ground resolution of 13.5 m) of the MOMS-2 have been acquired during the German space lab mission in 1993 for testing the map generation potential. Since the system has fore-and-aft scanners (±21º) a B/H ratio of

0.8 can be obtained. Both methods with a digital correlation (Ackerman *et al.*, 1995) or with an analytical plotter (Dorrer *et al.*, 1995) have been used over an Australian test site to produce either DEM's or 10-m contour lines with 5-m intermediate contour lines, respectively. Checked only with few ICPs, an elevation error of 16 m with 35-m maximum errors for the DEM has been measured (Ackerman *et al.*, 1995). Qualitative evaluation of the contour lines has been only realized, and showed very good consistencies (even for the 5-m contour lines) with the ground truth. It enables scales up to 1:25 000 to be mapped. These better results are accounted for by the superiority of human depth perception when compared to automatic correlation techniques with this data set (Dorrer *et al.*, 1995). Due to the bad quality of the control data in the Australian data set, they both expected to consistently improve the height accuracy to 5 m with the third MOMS-2P/PRIRODA mission to be flown on the Russian space station MIR. However the first experiment with this third mission data (18-m resolution and 0.8 B/H ratio) showed a degradation on the DEM accuracy to 25-30 m (Raggam *et al.*, 1997) while a second experiment has achieved a 10-m accuracy (Kornus *et al.*, 1998). The large discrepancy between these two experiments can be accounted for by the different type of relief or by the different geometric modelling of the 3D-array scanner used. Future studies could confirm the potential accuracy of this VIR scanner on MIR if the data becomes available.

3.3 Mixed sensors

Due to the increasing amount of image data it is very common to have data from different sensors over the same terrain area. The traditional stereoscopic technique can be applied. By combining the different radiometry in the brain the stereoscopic fusion of mixed sensors can also provide a virtual three-dimensional model of the terrain surface. Few results have been published on the use of mixed stereo sensors to generate DEMs. Welch *et al.* (1990) used a 23° viewing angle SPOT image (band 3) and a Landsat image (band 4) with the automatic stereo correlation capability of the Desktop Mapping System (Welch, 1989). Comparison of profiles for the stereo extracted DEM with the existing 1:50 000 scale topographic maps indicated a RMS error of about ± 100 m. This large error is mainly due to the polynomial co-registration process instead of a rigorous parametric geometric model. In fact, Raggam and Almer (1991) generated a 50-m accurate DEM from a 23º viewing angle SPOT image (band 1) and a Landsat-TM image (band 2). A proper relative registration process was used to generate the epipolar images for the measurement of corresponding image points with an automatic stereo correlation process. They reported 65% success in the correlation step due to the radiometric difference between the two images and to homogeneous areas (snow fields, glacier or shadow). Human interaction is still required to reject blunders or to fill the mismatch areas in order to optimize the DEM results. This requires a digital stereo workstation not only with automatic matching, but also with full stereoscopic capabilities (GCP and tie points stereo-plotting, 3D elevation editing, 3D cartographic feature extraction) (Toutin, 1998).

In fact, the brain can generate the perception of depth combining, for example, the spatial information from a SPOT panchromatic image and the spectral information from a Landsat-TM image for stereo plotting when image matching fails. Toutin (1998) reported an altimetric accuracy of 37 m for the elevation data extracted from a raw 26°-viewing angle SPOT-P and Landsat-TM (band 1) stereo-pair. The 10-m resolution of the SPOT-P image, and the fact that elevation data are extracted directly from the raw image (no polynomial co-registration or epipolar image resampling) account for the better results. More difficulties have been reported by Akeno (1996) when trying to generate a DEM from a NOAA-AVHRR and Landsat-MSS stereo pair due to the large resolution difference (1 km versus 80 m). He registered the two images using image-to-image correlation and degraded the Landsat-MSS image to the AVHRR resolution. He reported 320-m accuracy over the good matched DEM points. The main difficulty was to obtain the sub-pixel accuracy in the correlation process, applied in the NOAA-AVHRR image rectification and the parallax measurement.

When two optical images are not available, a stereo-pair can be generated and viewed by combining optical and radar images. Moore (1969) has first addressed the principle theoretically. He used simultaneously acquired infrared line-scanner and radar images. In neither case was the visual stereo effect perfect except near 45° viewing angle. Various scaling factors were also applied to different areas of the stereo-pair to obtain the proper stereo effect for the height determination. No quantitative measurement has been realized due to the lack of an "adapted" stereo-plotter.

Further evaluation has been realized with SIR-B and Landsat-TM images (Bloom *et al.*, 1988). Moderate results (in the order of 100-200 m) over 27 extracted points have been reported, mainly due to pixel offset error in the registration of the images and the approximated angular values used in the simplified elevation computation equation. Using a better parametric solution, Renouard and Perlant (1993) identified 30 tie points in two stereo pairs generated from west and east-looking panchromatic SPOT images with a west-looking ERS-1 SAR images acquired from descending orbits. They then computed off-line the elevation and obtained a RMS error of 22 m and 31 m. The better results were obtained with the stereo pair with the west-looking SPOT and ERS images since they are on the same side and then generate an additive elevation parallax (away from nadir for VIR image and toward nadir for SAR image). However, they noticed that this 3D-reconstruction capability is limited by the difficulty of matching tie points for generating DEM over large areas.

Raggam *et al.* (1994) had worse difficulties when extracting a DEM from a multi-band SPOT and airborne SAR stereo-pair (image-orientation and pixel-size differences). Since no meaningful results can be obtained from automatic image correlation, they interactively measured 500 corresponding image points and computed the elevation off-line. Results of the comparison with a reference DEM showed a standard deviation of 60 m with a 42-m bias and minimum/maximum error of about ±250 m. More recently, Toutin (2000) further investigated the mapping feasibility of mixed sensor stereo-pairs with parametric geometric solutions ported into a fully digital stereo workstation adapted to process on-line VIR and SAR stereo-pairs. The elevation data (about 10 000 points) are interactively stereo extracted and computed from the raw images (no epipolar resampling), and then directly compared to an accurate DEM. An accuracy of 20 m with no bias and minimum/maximum errors of less than ±100 m has been achieved from two different SPOT-P and ERS-SAR stereo-pairs: one being an opposite-side stereo-pair and the other a same-side stereo-pair generating subtracting and additive elevation parallaxes, respectively. The full stereo capabilities in the GCPs plotting and elevation measurements account for the good results. Conversely to the previous study (Renouard and Perlant, 1993), no accuracy difference has been noticed between the two stereo pairs. A closer evaluation of the two stereo-pairs geometry and results showed that the elevation parallax, which contributes to the determination of the elevation, is mainly dominated by the SAR geometry with its high sensitivity to the terrain relief. Conversely, the radiometry of the SPOT-P images mainly contributes to the determination of the features with the quality of the image content.

Table 2 summarises the results of elevation extraction for the different VIR scanners and stereoscopic capabilities: adjacent orbit, across-track, along-track and mixed sensors.

Table 2: Summary of the results of the elevation extraction with the VIR scanners using the stereoscopic method. The variations in the results for each stereo configuration are due to the different research studies. The values in brackets were obtained from simulated data.

Stereo-Pairs	Resolution	Adjacent-track	Across-track	Along-track
Landsat MSS	80 m	100-300 m		
Landsat TM	30 m	45-70 m		
IRS 1A	72 m	35 m		
SPOT P	10 m		5-15 m	
SPOT/Landsat	10 m/30 m		35-50 m	
IRS 1C/D	6 m		10-30 m	
MOMS-2	13.5 m			5-15 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	33 m		(15 m)	(12.5 m)
Ikonos	1 m		(1.5-2 m)	

3.4 Processing, methods and errors

The different processing steps to produce DEMs using stereo images can be described in broad terms as follows:

1. to acquire the stereo image data with supplementary information such as ephemeris and attitude data if available;

2. to collect GCPs to compute or refine the stereo-model geometry;

3. to extract the elevation parallax;

4. to compute the 3D cartographic co-ordinates using 3D stereo-intersection; and

5. to create and post-process the DEM (filtering, 3D editing and smoothing).

The steps 2 and 4 involve mainly geometric issues, and the step 3 involves radiometric issues while the steps 1 and 5 involve both geometric and radiometric issues. Since the stereo-model geometry computed from the GCPs and the step 4 are related and dependent on the type of images they are addressed in the Step 1.

3.4.1 *Acquiring stereo-image data*

With VIR images two types of data can be used: the raw images with only detector normalization and calibration (e.g. level 1A for SPOT), or the geo-referenced images (e.g. level 1B for SPOT) corrected for the systematic distortions due to the sensor, the platform and the Earth rotation and curvature.

The raw 1A imagery is preferred by photogrammetrists for use in analytical or digital stereo-workstations. As mentioned previously, the geometric modelling solution employs the well-known collinearity and coplanarity equations. They have been adapted to suit the geometry of scanner imagery, but also have been benefiting from theoretical work in celestial mechanics to better determine the satellite osculatory orbit and parameters (Escobal, 1965; CNES, 1980). More details on the development of the solutions and their implementation in the workstations can be found in the different referenced papers.

Since they have been systematically georeferenced the "level 1B" images just retain the elevation parallax. To compute the cartographic 3D co-ordinates (Step 4) the 3D stereo-intersection modelling is then reduced with a simpler 2D polynomial-based solution for the planimetry, and separately with a simple parallax equation solution for the elevation (Eq. 1). This method was mainly applied in the first experiments with Landsat (Simard, 1983; Cooper *et al.*, 1987; Ehlers and Welch, 1987) since the approximation generated by the method is smaller than the final expected accuracy. However with SPOT stereo-images (better resolution and larger B/H ratio) the approximation is no longer valid and generates poorer results than with "raw" stereo images (Gugan and Dowman, 1988; Al-Roussan and Petrie, 1998). The solution to overcome this approximation when using 1B stereo-images is to convert back the 1B-images to 1A-images using the reverse transformation (Al-Roussan *et al.*, 1997), or to "re-shape and re-size" the 1B-images to the raw imagery format (Valadan Zoej and Petrie, 1998). This 1B-geometric modelling can be mathematically combined with the normal 1A geometric modelling to avoid multiple image re-sampling. Although this mathematical procedure used for 1B stereo images works better than the simple parallax approximation, it is still recommended to use raw stereo-images with the rigorous parametric solution (collinearity and coplanarity equations).

3.4.2 *Collecting GCPs*

Whatever the VIR geometric modelling used for the stereo model and 3D intersection, some GCPs have to be acquired to refine the stereo-model with a least square adjustment process in order to obtain a cartographic standard accuracy. Since the polynomial modelling does not reflect the geometry of viewing it requires many GCPs (20 and more) spread over the full stereo-pair. Each image modelling is computed separately, which does not set-up a relative orientation between the images. Furthermore the elevation is computed from an approximated solution. Consequently this modelling cannot be used to provide the high cartographic accuracy required with the last generation of satellite such as SPOT, IRS and MOMS.

With parametric modelling such as those defined previously few GCPs (3 to 6) are required. In an operational environment their number will vary as a function of their accuracy. They have preferably to 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 co-ordinates;
- altimetric points with known Z co-ordinate; and
- tie points with unknown cartographic co-ordinates.

The two last types are useful to reinforce the stereo geometry and fill in gaps where there is no XYZ GCP. Furthermore, GCPs displayed only on one image in or outside the stereo pair can also be acquired as complementary points to the "stereo" GCPs. Combined with tie points they can be also helpful to avoid extrapolation in planimetry in areas where there is no "stereo" GCP.

The final accuracy of the stereo geometry is mainly dependent on the GCP's cartographic and image co-ordinates. The first can be obtained from different sources with different accuracies, such as GPS, air photo surveys, paper or digital maps, previously ortho-rectified images, chip database. It is also possible to use the more precise viewing geometry of an ERS-1 SAR image to reduce the number of GCPs required for VIR images (Renouard and Perlant, 1993). Although paper maps are certainly the most common GCP source used around the world, the potential map uncertainty affects the stereo model reconstruction and the final results. For reducing its impact in the least square adjustment of the stereo model, it is thus recommended to increase the minimum required number of GCPs by a factor of 2 to 4 depending on the map error.

The image co-ordinates are plotted interactively on the plotter or the screen. Since some of workstations do not have full on-line stereoscopic capabilities, the image co-ordinates are then obtained simultaneously in "double monoscopy". This plotting will then create artificial X- and Y-parallaxes between the images, and the parallax errors will propagate through the stereo model (relative and absolute orientations), the stereo-intersection and finally the DEM. However the error propagation is not too severe (few metres) with VIR stereo-pair because the plotting accuracy is about 1/3 pixel and the B/H ratio is around one. With a smaller B/H ratio this error propagation increases. True stereoscopic plotting using the human depth perception enables a better relative correspondence of the GCP between the images and a better absolute positioning on the ground. It is also a requisite that the two images are not computed separately using only the collinearity condition, but together using the collinearity and coplanarity conditions for the common GCPs and tie points to obtain a relative orientation between the images.

3.4.3 *Extracting elevation parallax*

Two methods principally can be used to extract the elevation parallax using image matching: the computer assisted (visual) or the automatic methods. These two methods can be of course integrated to take into account the strength of each one.

The computer assisted visual matching is an extension of the traditional photogrammetric method to extract elevation data (contour lines) on a stereo-plotter. It then requires full stereoscopic capabilities to generate the on-line three-dimensional reconstruction of the stereo model and the capture in real time of 3D planimetric and elevation features. For elevation, spot elevations, contour lines or irregular grid DEM can be generated. The stereoscopic viewing is realized on the computer screen using a system of optics. The stereo images are separated spatially, radiometrically or temporarily. Spatial separation is achieved by the use of two monitors or a split screen and an optical system using mirror and/or convex lenses. Radiometric separation is achieved by anaglyphic or polarization techniques with coloured or polarized lens, respectively. Temporal separation is achieved by an alternate display of the two images and special synchronized lenses. Petrie (1992), Dowman *et al.* (1992), Audet et Lapierre (1993), Heipke (1995) and Walker and Petrie (1996) present the lastest developments in analytical and digital stereo workstations for the last twenty years. Furthermore, Makarovic (1990) gives a comprehensive comparison between analytical and digital techniques and systems.

To retain real 3D performance in a stereo-workstation, the images are re-sampled into an epipolar or quasi-epipolar geometry, in which only the X-parallax related to the elevation is retained (Masson d'Autumne, 1979; Baker and Binford, 1981). Another solution to control the image positioning from the raw imagery is to automatically follow the dynamic change by cancelling the Y-parallax using the previously computed stereo-model (Toutin *et al.*, 1993; Toutin, 1995). In the same way as with a conventional stereo-plotter, the operator cancels the X-parallax by fusing the two floating marks (one per image) on the ground. The system then measures the bi-dimensional parallax between the images for each point, and computes the XYZ cartographic co-ordinates using the 3D intersection. The visual matching then combines in the brain a geometric aspect (fusing the floating marks together) and a radiometric aspect (fusing the floating marks on the corresponding image point). Some automatic tasks (displacement of the image or cursor, prediction of the corresponding image point position) are added.

However, computer-assisted visual matching, principally used with paper-format images and analytical stereo-workstations, is a long and expensive process to derive DEM. When using digital images automated image matching can thus be used. Since image matching has been a lively research topic for the last twenty years, an enormous body of research work and literature exists on stereo matching of different VIR sensors.

Most of the research studies on satellite image matching are based on Marr's research at MIT, USA into the modelling of human vision (Marr, 1982). If a computer program can be realized to see things as a human would, then the algorithm must have some basis in human visual processing. The stereo disparity is based on "correct" assumptions about the real world (Marr and Poggio, 1977): (i) a point of the surface has a unique position in space at any one time, and (ii) matter is cohesive. The first generation of image matching based on these assumptions is the grey-level image matching. Grey level matching between the two images really implies that the radiometric intensity data from one image, representing a particular element of the real world, must be matched to intensity data from the second image, representing the same real-world element.

Although satellite images of the real world represented by grey levels is not like a random-dot stereogram (easily matchable), grey level matching has been widely studied and applied to remote sensing data. Most of the matching systems operate on reference and search windows. For each position in the search window, a match value is computed from grey level values in the reference window. The local maximum of all the match values computed in the search window is the good spatial position of the searched point. The match value can be computed with the normalized cross-correlation coefficient, the sum of mean normalized absolute difference, the stochastic sign change or the outer minimal number estimator. The first one is considered to be the most accurate (Leberl *et al.*, 1994) and is largely used with remote sensing images. They also noticed that matching errors were smaller with SPOT images and digitized aerial photographs than with SAR images. The last two match value computation methods have rarely or never been used by the remote sensing community.

Another solution to the problem of matching, introduced by Förstner (1982), is the least-squares approach minimizing the squares of the image-grey level differences in an iterative process. This method makes possible the use of well-known mathematical tools and the estimation of the error. Rosenholm (1986) found that the more complicated least squares method applied on simulated SPOT images did not give any significant improvement when compared to the cross-correlation coefficient. However, this least-square method seems to be more accurate with real SPOT data (Day and Muller, 1988).

The notion of least squares matching in the object domain (groundel) rather than in the image domain (pixel) has been later introduced by Helava (1988b). Predicted image densities, corresponding to each groundel, is mathematically computed with known geometric and radiometric image parameters, and matched to the original one. The uncertainty in the parameters of a particular groundel is resolved by least squares. An advantage of this approach is to use more than two images from the same or different sensors to make the least squares solution meaningful, and a disadvantage is the ability to correctly model the groundel attributes for each image. Due to these it is mainly used with air photos since more than two images overlap the same ground area and their geometry and radiometry are better controlled.

Since one of the Marr's assumptions was either missing or incorrectly implemented in grey level matching (mainly with images of the real world), Marr developed a second generation of image matching: the feature-based matching (Marr and Hildreth, 1980). The same element of the real world may look considerably different in remote sensing images acquired at different times and with different geometry between the sensor, the illumination and the terrain. Instead, edges in the images reflect the true structures (Cooper *et al.*, 1987). Feature-based matching has not been very popular in the remote sensing community with satellite data, but some applications have been realized with simulated SPOT and real Landsat-TM (Cooper *et al.*, 1987). The DEM results were not as good as those obtained by Simard and Slaney (1986) with Landsat-TM stereo-pair using grey level matching. Hähn and Förstner (1988) also found that least-square matching is more accurate than the feature-based matching, conversely to Marr's theoretical prediction. Later on, Schneider and Hahn (1995) tested the two methods to extract tie points on MOMS-2/D2 stereo-images. Their results in planimetry and elevation were twice more accurate with intensity based matching than with feature based matching.

Hybrid approachs can be thus realized to achieve better and faster results by combining the grey-level matching, the feature-based matching with a hierarchical multi-scale algorithm, but also with the computer-assisted visual matching. The feature-based approach may produce good results for identified features, but no elevation at intermediate points. They can then be used as seed points for the grey-level matching. Another hybrid approach is to generate gradient amplitude images in a first step with grey-level values derived from the original stereo-images instead of gradient images with only binary edge values. In a second step, any grey-level matching technique can be used on these pre-processed images (Paillou and Gelautz, 1999). The linear gradient operator can be designed to be optimal to remove noise (if any) and to enhance edges. No attempt has been realized with VIR images.

Although the computer-assisted visual matching is a long process, it has been proven to be more accurate with photos or different satellite VIR data (Leberl *et al.*, 1994; Raggam *et al.*, 1994; Dorrer *et al.*, 1995; Toutin, 1995, 2000). It thus can be used either to eliminate the blunders, to fill the mis-matched areas or in areas where the automated image matching gives errors larger than one pixel (about 10% for SPOT and 15% for digitized photographs, Leberl *et al.*, 1994). It can also be used to generate seed points for the automatic matching.

Other developments have been realized and tested principally for airborne or close-range stereo images, but rarely with satellite images, such as the global approach, scale space algorithms, relational matching, consideration of breaklines and multiple image primitives. Some other research studies using the recognition of corresponding structures (Della Ventura *et al.*, 1990) or of uniform regions (Petit-Frère, 1992; Abbassi-Dezfouli and Freeman, 1996), a moment-based approach with a fine-invariant features (Flusser and Suk, 1994), or a wavelet transform approach (Djamdji and Bijaoui, 1995) were developed. They were only used to extract well-defined GCPs for image registration between different spaceborne VIR images.

More development could be done to integrate these solutions for generating seed points to grey-level matching. Some apparent contradictions should also be the issue of future research studies, such as:

- the theoretical prediction of Marr (1982) that the feature-based matching is better than grey-level matching versus better experimental results with the grey-level matching than with the feature-based matching;
- the theoretical automated image matching error (much better than one pixel) versus the experimental results (one and more depending on the data); and
- the “so-called” superiority of computer matching over the visual matching versus the experimental results.

These overall comments confirm our first statement that the image matching has been a lively research topic for the past twenty years, but may be for the next twenty years...

3.4.4 *Post-processing the DEM*

Whatever the matching method and strategy adopted, there is always 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. Different methods can be used depending on the capability of the (stereo-) workstation: manual, automatic or interactive. A blunder removal function is needed to remove any artefacts or noise when an elevation value is drastically different from its neighbours. These functions generally use existing filters based on statistical computation (mean, standard deviation). Some functions tend to remove small noisy areas, but inversely some tend to increase failed areas on the rationale that the pixels surrounded by failed pixels tend to have a high probability of being noisy. These functions are well adapted to be performed automatically.

To fill the mismatched and the noisy areas previously detected, interpolation functions are used to replace the mismatched values interpolated from good elevation values of the edges of the failed areas. Standard interpolation functions (bi-linear, distance-weighted), which can be performed automatically are adequate for small areas (less than 200 pixels). For larger areas, an operator should interactively stereo-extract seed points to fill the mismatched areas of the raw DEM. Another solution is first to transform the DEM into a triangular irregular network (TIN) and to display it over the stereo pair in the stereo workstation. The operator can then edit the appropriate vertex of triangles to better fit the shape of the TIN with his 3D perception of the terrain relief. In addition, the operator can extract some specific geomorphologic features (mountain crests, thalwegs, lake shorelines), which can be integrated to generally reduce the largest errors at the lowest and highest elevations in the DEM. Using the human 3D perception to edit DEM is thus advantageous since it produces a more coherent and consistent terrain relief reconstruction.

Forested areas also have to be edited for the vegetation cover, depending on the relation between the expected DEM accuracy and the canopy height. An automatic classification or/and an interactive stereo extraction can delimit the different forested areas and measure their canopy height, respectively. This information is then used "to reduce" the elevations at the ground level. Finally, an appropriate method of filtering must also be applied to smooth the "pit and hummock" pattern of the DEM, while preserving the sharp breaks in slopes. Filtering improves the relative DEM accuracy or the relationship between neighbouring values, while the absolute DEM accuracy appears to be controlled by the generation method, system and software (Giles and Franklin, 1996). Unfortunately, few research studies and scientific results have been devoted and published on the post-processing step. Most of the times, stereo workstation manufacturers develop theirs own methods and tools to achieve this last, but not least step of the DEM generation.

4.0 CONCLUDING REMARKS

Elevation modelling from satellite data has been a vibrant R&D topic for the last thirty years with the appearance of the first civilian remote sensing satellite. Different data (space photographs, VIR scanner) in different formats (analogue, digital) can be processed by different methods (shadowing/shading, stereoscopy) taking advantage of the different sensor and image characteristics (geometric, radiometric) using different types of technology (analogue, analytical, digital) and processing (interactive, automatic). Most of the techniques were proposed and addressed in the early years. However, the limited availability of data and associated technologies in the 1970s has restricted their evolution in comparison with traditional photogrammetry.

Two main methods have been reviewed: the shadowing/shading and the stereoscopy. Since shadowing provides only localized cues along special contours it is principally used to derive relative elevation of a specific target. Using mainly panchromatic SPOT images, sub-pixel accuracy has been achieved in different research work. Despite these good results the method and its application remain limited to research organizations. No attempt has been made to integrate this height information with a DEM to generate a digital surface model (DSM) of a city. The next high-resolution satellites should be an interesting source of data with which to apply this method.

Conversely to shadowing shading provides cues all over the studied surface, but can be applied successfully only on homogeneous surface. In fact, only one experiment has been realized over a Canadian ice-cap surface, and the qualitative results should have generated interest at least in the scientific community to expand on this work. It seems that most of the research effort in the applicability of the method has been directed toward the radar data. Whatever the potential accuracy, the shape-from-shading technique remains a marginal technique due mainly to the empirical approaches to resolve the different geometric and radiometric ambiguities, and their limited application to specific homogeneous terrain.

On the other hand stereoscopy is the most preferred method in the mapping, photogrammetry and remote sensing communities, most likely due to the heritage of the well-developed stereo photogrammetry. The early experimental work with LFC and MC space photographs showed an interesting potential for elevation modelling (Table 1). However, the limited distribution of the data and the lack of decision to make them fully operational led to the decline of this source of data. These reasons were also combined with the accessibility (distribution and area) to new VIR scanners and the convenience of their digital format.

Consequently, the different stereo capabilities have been addressed around the world: adjacent-orbit stereo with Landsat and IRS-1A, across-track stereo with SPOT and IRS-1C or along-track stereo with JERS and MOMS (Table 2). The latest advance in computer vision to model human vision has led to the advent of new automatic image processing approaches applied to the satellite VIR images. It has thus allowed the mapping process to become more automated, but not completely with occasional unmatched expectations.

Since any sensor, system or method has its own advantages and disadvantages, future solution for operational DEM generation should use the complementarity between the different sensors, systems, methods and processing. Furthermore, it has been proven in most of the previous experiments that the user has to make judgements and decisions at different stages of the processing, regardless of the level of automatic processing to obtain the final DEM product. Non-exhaustive examples of complementarity are listed below:

1. to combine VIR and SAR stereoscopic images where the radiometric content of the VIR image is combined with the SAR high sensitivity to the terrain relief and its "all-weather" capability to obtain the second image of the stereo-pair;

2. to integrate the building or tree height extracted from shadowing method to reduce a DEM into a DSM, or inversely;
3. to integrate the micro-relief extracted with shape-from-shading method with a stereoscopic DEM;
4. to use the visual matching to seed points to the automatic matching or to post-process and edit raw DEMs (occlusion, shadow or mismatch areas);
5. to use stereo measurements of objects edges and other geomorphological features (thalweg and crest lines, break lines, lake boundary and elevation) to increase the consistency of the DEM;
6. to combine the "know-how" of the users with the computer capability.

In the past, high-quality DEMs have been generated with traditional photogrammetry in such a way that they were used for many purposes. Presently, DEMs are considered the most permanent and reusable geo-related data set over time. Due to the limited availability of data, it is obvious that attention over the next years will be focused on the use of the new high-resolution satellites (VIR but also SAR) and the development of their associated technologies. Already some research studies have looked at stereoscopic potential of the US high-resolution satellites (Ridley *et al.*, 1997; Kaufmann und Sulzer, 1997; Li, 1998) and of EOS-AM1/ASTER data (Tokunaga *et al.*, 1996; Welch *et al.*, 1998). Most of them concluded that elevation data to generate DEM or 3D urban models would be one of the most important derived products. Preliminary evaluation using aerial imagery scanned at 1-m spatial resolution showed the potential to obtain a RMS error in elevation in the range of 1.5 m to 2 m (Ridley *et al.*, 1997). Table 2 shows a comparison of these new sensors with the existing sensors for the DEM accuracy. However, it is not sure if the raw imagery needed for generating DEMs and derivative topographic products will be available to the end users since, at that time, the high-resolution data resellers want to only distribute value-added products (DEM, ortho-images, mosaics).

Although the needs, requirements and specifications of DEM and derivative products are difficult to determine due to their multiple uses by different community, global DEM generation is still envisaged in a near future. For example, the US/German Space Radar Laboratory embarking on a US shuttle mission (SRTM) was flown in February 2000 (Jordan *et al.*, 1995; Werner, 1997). The accuracy of the released DEM generated by the US C-band radar interferometry should be on the order of DTED level-1 accuracy. Will it fulfil the requirements of all DEM users? The other satellite data resellers hope not, because many new satellites with high-resolution VIR images with along- or across-track stereo capability are proposed to be launched at the same time (2000-2002) by US, European, Indian, Russian, Japanese, Israeli, private or governmental organizations.

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