THE INFLUENCE OF TERRAIN TYPE AND DENSITY OF DIGITAL ELEVATION MODEL ON THE GEOMETRIC QUALITY OF SATELLITE ORTHOIMAGES

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ABSTRACT

Orthoimages generated from SPOT satellite images can contribute significantly to image map production and to GIS applications. The quality of the extracted data from orthoimages depends mainly on the accuracy of the input data and the used mathematical modals.
The aim of this paper is to study some factors influencing the geometric accuracy of SPOT orthoimages. The emphasis is on the effect of terrain type and Digital Elevation Model (DEM) density (grid size), on the geometric accuracy of orthoimages applying anchorpoints and pixel by pixel techniques.
Real data is used in this study, where a SPOT-1 image with mirror looking angle equal to 25 degrees and the corresponding DEM data were used. The original DEM data has a regular grid of 100 by 100 m covering about 140 square kilometers of flat, moderate and rocky mountains areas. The study area is divided into smaller areas according to terrain roughness. In the first stage the orthoimage was generated using the original DEM data. In the second stage orthoimages were resampled using a courser DEMs (grid size varying from 200 by 200 m. to 1000 by 1000 m.), where some points were omitted from the original DEM data. The orthoimage generated in the first stage is considered as a reference, in order to examine the orthoimages obtained in the second stage, and the relative geometric accuracy is demonstrated for different terrain types with different grid sizes. Computer programs were written by the author in order to carry out the resampling algorithms of this study.
Although the results of this study discuss the relative geometric accuracy of orthoimages, these results declared the influence of terrain type and DEM grid size on the accuracy of the end product of an orthoimage system. In addition the results of this study give detailed comparison between the anchorpoints (which has some computational advantages) and the pixel by pixel techniques. This comparison is demonstrated for different terrain types and different DEM densities .

1. ORIENTATION ALGORITHM

A rigorous photogrammetric approach is applied to SPOT level 1A image in order to determine its time dependent orientation parameters. The working coordinate system; image coordinate system; and the mathematical model used for orienting SPOT images will be briefly described .

1.1 Coordinate Systems Used in the Algorithm

A SPOT scene covers a large area of the earth's surface. To avoid distortions caused by earth curvature and the map projection characteristics, the Geocentric Coordinate System (X Y Z) is used as the working coordinate system. Coordinates of ground control points given in geographical coordinate system (latitude, longitude and height) or Universal Transverse Mercator (UTM) coordinates will be transformed to the geocentric system.
The image coordinate system (x, y and z) is constructed with the positive z direction at the center of a particular scan-line, along the normal to the image and pointing away from the earth. The (+x) is the direction of satellite flight. The linear array itself passes through the principal point in the focal plane where the x coordinate is zero. The x coordinate of the (6000 line * 6000 pixel) image is the line number of this pixel ($-3000 \le x \le +3000$) and it is used as a measure of time at which a point was imaged. The (+y) is the direction that results in a right hand coordinate system

1.2 Mathematical Model

The principle of an extended bundle solution is applied to the ground control points and their corresponding points in the SPOT image. The photogrammetric standard bundle solution is based on the following space resection formula:

$$\begin{vmatrix} x \\ y \\ -c \end{vmatrix} = s * M(\kappa) * M(\varphi) * M(\omega) * \begin{vmatrix} X - XO \\ Y - YO \\ Z - ZO \end{vmatrix} \qquad (1)$$

where:

c is the effective focal length
s is a scale factor
x and y are the photo coordinates of a point
X, Y and Z are the ground coordinates of the same point
XO, YO and ZO are the perspective center coordinates
M(κ), M(φ) and M(ω) are orthogonal matrices as a function of rotation angles (kappa, phi and omega) between ground and photo coordinate systems.

A SPOT panchromatic image is built by combining 6000 linear strips recorded every 1.5 millisecond as the satellite moves in its orbit. An important feature of the SPOT dynamic image is that the spatial bundles of the reconstructed image rays are restricted to a plane (the CCD size for each pixel of panchromatic image is 13 by 13 μm), and the sensor's field of view is very narrow (Michele 1981). This results in a high correlation between the projection center displacement and the sensor's tilt in the same direction. Another important feature of the dynamic SPOT image is that although the orientation elements are continually changing, they are changing in a highly predictable way, because the satellite is moving along a well defined orbit path and is always pointing toward the center of the earth (Gugan 1987).

The photogrammetric space resection formula (Equation 1) is expanded in order to include the effect of time dependent parameters and for the purpose of deriving design matrices of the linearised solution, the dynamic space resection formula for SPOT 1A image can be written for any image point (p) as follows (Farrag 1991):

$$\begin{vmatrix} 0 \\ y(p) \\ -c \end{vmatrix} = s^* M_{QLO}{}^* \begin{vmatrix} X(P) - (XO + a_1{}^*x(p) + b_1{}^*(x(p))^2) \\ Y(P) - (YO + a_2{}^*x(p) + b_2{}^*(x(p))^2) \\ Z(P) - (ZO + a_3{}^*x(p) + b_3{}^*(x(p))^2) \end{vmatrix} \quad (2)$$

Where:

c is the effective focal length (the nominal focal length of SPOT HRV is 1082 mm).
s is a scale factor.
XO; YO; and ZO are the coordinates of the perspective center corresponding to the center of the SPOT scene.
x(p) is image coordinate of point (p) along track (line number).
y(p) is image coordinate of point (p) across track (it is a function of pixel number);
y(p)=(pixel number - (6000+1)/2) * 0.013mm.
X(P); Y(P); and Z(P) are the ground coordinates of the same image point (p).
M_{QLO} is a compound orientation matrix as follow:
M_{QLO} =M(Q)*M(L)*M(O); where:
M(O) is an orthogonal matrix as a function of reference rotation angles κ_o, φ_o and ω_o, between the working and the image coordinate systems, corresponding to the scene center.
M(L) is an orthogonal matrix as a function of linear rates of change (κ_1, φ_1 and ω_1) in the reference rotation angles and the image line number x(p).
M(Q) is an orthogonal matrix as a function of quadratic rates of change (κ_2, φ_2 and ω_2) in the reference rotation angles and the image line number x(p).
a1; a2; and a3 are linear rates of change in (XO), (YO) and (ZO) coordinates respectively.
b1; b2; and b3 are quadratic rates of change in (XO);(YO); and (ZO) coordinates respectively.

Accordingly the dynamic space resection formula of the SPOT image include the following unknown exterior orientation parameters:
i- The coordinates of the reference position of the perspective center XO; YO; and ZO (corresponding to the center of the SPOT scene), {three unknowns}.
ii- The attitude reference values κ_o; φ_o; and ω_o (i.e. the elements of matrix M(O) {three unknowns}.
iii- The linear rates of change (κ_1; φ_1; and ω_1) of the attitude elements, (i.e. the elements of matrix M(L)), {three unknowns}.
iv- The quadratic rates of change (κ_2; φ_2; and ω_2) of the attitude elements, (i.e. the elements of matrix M(Q)), {three unknowns}.
v- Although the values of the linear and quadratic rates of change in the coordinates (XO; YO; and ZO) of the reference position can be determined as a function of the well defined earth rotation and satellite tracking speed, further corrections are given to these parameters during the solution. This will take care of random changes in the satellite tracking speed {this leads to six additional unknowns}.

Then the total number of unknown exterior orientation parameters of a SPOT image is 18; accordingly the minimum number of the required control points is nine control points.

2. RESAMPLING ALGORITHM

Resampling algorithm of SPOT level 1A images for orthoimage production is carried out in two steps:
Step 1: Locating pixels of the output image (orthoimage) on the original image plane;
Step 2: Assign a gray value for these pixels.
Special computer programs were written by the author in order to carry out the resampling algorithms of this study.
The two steps of resampling SPOT images for orthoimage production will be briefly discussed.

2.1 Step 1

This step can be carried out applying anchorpoints technique or pixel by pixel technique.

2.1.1 Anchorpoints Technique

Anchorpoints technique involve the following tasks (Farrag 1991):
- Determination of the image coordinates (in the original image plane) corresponding to the DEM grid points (anchorpoints).
- Determination of the image coordinates (in the original image plane) corresponding to the pixels of the output image within the DEM grid.

Equation (2) cannot be used directly to determine the image coordinates of the DEM grid points because we do not know exactly which scan-line orientation parameters to be used. This can be overcome by applying an iterative approach as follows:
i- Determine approximate position of the DEM grid points on the original image plane, i.e. the pixel No. and the scan-line

No. which pass by each DEM grid point. This can be achieved by applying a second order two dimensional polynomial transformation based on the same control points which were used to determine the orientation parameters of SPOT image (Equation 2).
This step gives the approximate image points (i.e. scan-lines x_i, pixel position y_i) for each DEM grid point (i).

ii- Use the computed x_i in order to compute the orientation parameters corresponding to these image coordinates. These parameters are (Equation 2):
. Satellite instantaneous position.
. Elements of matrices M(L)& M(Q).
iii- Substitute the computed orientation parameters for the corresponding parameters in the collinearity formula (Equation 2) and compute new image coordinates (x_i and y_i).
Repeat steps (ii) using the new image coordinates and then repeat step (iii). This repetition can continue until the difference between the new and the old computed values of image coordinates becomes less than a specified threshold (0.25 pixel size is used as threshold in our test and the solution is always converses before 5 iterations).
As a result of applying the iterative approach given above, the image coordinates corresponding to each four DEM points forming a grid will be determined. The positions of the pixels of the output image (orthoimage) within each DEM grid, on the original image, can be determined by applying a two dimensional transformation, where the previously determined image coordinates of the four DEM grid points are used in order to compute the parameters of this transformation.
Two different transformations are used:
-Affine transformation, where six parameters are computed.
-Eight parameters transformation. This method needs more computations compared with the previous method.

2.1.2 Pixel by pixel Technique

In the pixel by pixel technique the determination of the image coordinates (in the original image plane) corresponding to the DEM grid points is carried out exactly according to the method explained in the anchorpoints technique. The positions of the pixels of the output image (orthoimage) within each DEM grid, on the original image plane, is determined applying a three dimensional approach, where the ground height of each of these pixels is first determined by interpolation based on the surrounding DEM data. Then the corresponding positions on the original image are determined applying the iterative approach given above. The following four different interpolation methods for height determination within the grid based on the four surrounding DEM points are tested in this study:
- Nearest neighbour; - Inverse distance; - Inverse square distance; and - Bilinear polynomial in the form:

$H = a_o + a_1x + a_2y + a_3xy$

More elaborate algorithms were not tested in this study.

2.2 Step 2

This step involve computing a gray value for every pixel after being located in the original image plane. A gray value can be computed by one of the following methods:

2.2.1 Nearest Neighbour

It copies the value (from the original image) of the closest element. This method has a radiometric advantage, as it keeps the characteristics of the original image. But it has the disadvantage, that it produces geometric artifact.

2.2.2 Bilinear Interpolation

It interpolates between the gray values of the four surrounding pixels in order to compute the gray value for the resampled image. Its advantage is that it does not give geometric artifacts, but it has a radiometric disadvantage (a kind of smoothing).

3. TERRAIN CLASSIFICATION BASIS

The roughness factor (RF) is used in order to classify the different test areas. RF is computed as follows (Balce 1986):

$$RF = (\Delta z_{ave} / \Delta d_{ave})*100 \qquad (3)$$

where:
Δz_{ave} is the average height difference between successive significant breakpoints
Δd_{ave} is the average distance between successive significant breakpoints

The significant breakpoints are determined using the following criteria:
i- Height difference between any successive points exceeds $\delta_{interpolation}$ (δ_{int}); and
ii- If a point is linearly interpolated between its two neighboring points, and its computed elevation is compared with its sampled elevation , the discrepancy exceeds δ_{int}.
The value of δ_{int} is a function of aerial triangulation; model setup; sampling process; and interpolation. Unfortunately these values are not available for the data used in this study. Therefore a value of 5 m is assumed for δ_{int} and the terrain is classified as follows:
The terrain with RF $\leq$ 10 is considered as flat terrain;
The terrain with RF > 10 and $\leq$ 20 is considered as moderate terrain;
The terrain with RF > 20 is considered as rough terrain.

4. EXPERIMENTAL RESULTS

SPOT-1 (level 1A) panchromatic image, with high oblique mirror looking angle equal to 25 degrees (maximum mirror looking angle of SPOT images is 27 degrees), is used in this study. The image was sampled on 12 December 1986 and cover a part of Nepal. A topographic map produced by photogrammetric technique with map scale 1:100,000 and with 100m contour interval was the source of the control points and DEM data. Twenty seven control points were identified in the image and digitized from the map. These points are distributed over an area of 40 by 50 km. The control points were used in order to compute the 18 orientation parameters of SPOT image (Equation 2). The lack of accurate control points cause a big residuals in the control points, which was 47.2 m as the Root Mean Square (RMS) of the ground vector displacement. Although these residuals are big, they still in the range of the accuracy of control points assuming that the map is produced according to the map standards. This will have a minor effect on the final results of this study ; because we are comparing different orthoimages produced by different DEM densities of the same data while the same orientation parameters are used.

The test was carried out on a part of the image limited by minimum pixel No. = 905 ; minimum line No. = 3789; maximum pixel No. = 2216 and maximum line No. = 5065. The corresponding DEM data is generated by digitizing the contour map and the DEM was produced with an original regular grid of 100 by 100 m; covering about 140 square kilometers of flat, moderate and rocky mountains areas. The study area is divided into smaller areas of 2 by 2 km and these areas are classified according to terrain roughness (Equation 3).

In the first stage the orthoimage is resampled using the original DEM data (of 100 by 100 m regular grid), as a result the position of each DEM point is determined on the original image. In the second stage orthoimages are resampled using a courser DEMs (grid size varying from 200 by 200 m. to 1000 by 1000 m.), were some points where omitted from the original DEM data. In order to be able to judge the relative geometric quality of the orthoimages which are resampled using the courser DEMs (second stage), the position on the original image of points forming regular ground grids of 100 by 100 m as given by these orthoimages is computed and compared with the position of the same points as given by the orthoimage generated in the first stage. Then the discrepancies in units of pixels of the original image between the position of these points is used to compute RMS and is compared for each terrain type with different grid size and different resampling algorithm. The following Figures (Figure 1 to Figure 6) show the plot of RMS of vector displacement (i.e. in line and pixel directions) against the grid size for different resampling method.

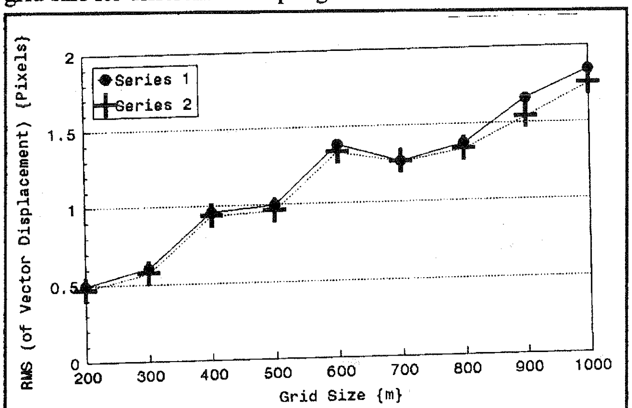

Figure 1 . Flat Terrain (Anchorpoints Technique)
Series 1= Affine tran.; 2= Eight parameters tran.

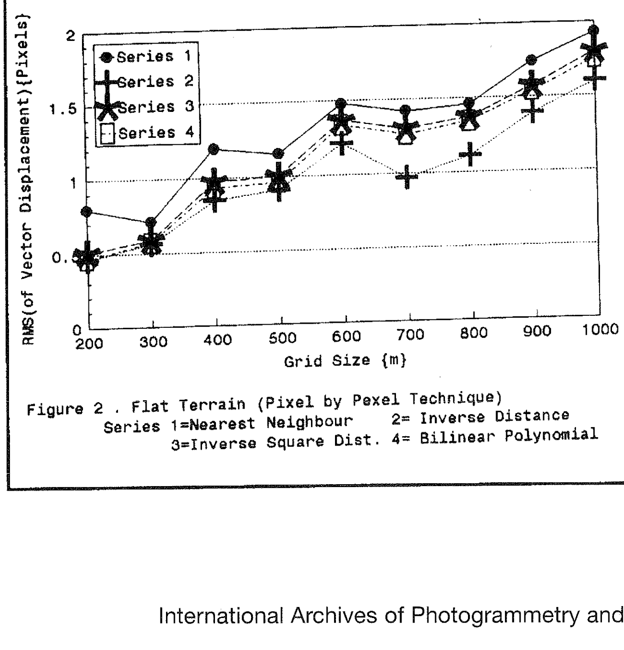

Figure 2 . Flat Terrain (Pixel by Pexel Technique)
Series 1=Nearest Neighbour 2= Inverse Distance
3=Inverse Square Dist. 4= Bilinear Polynomial

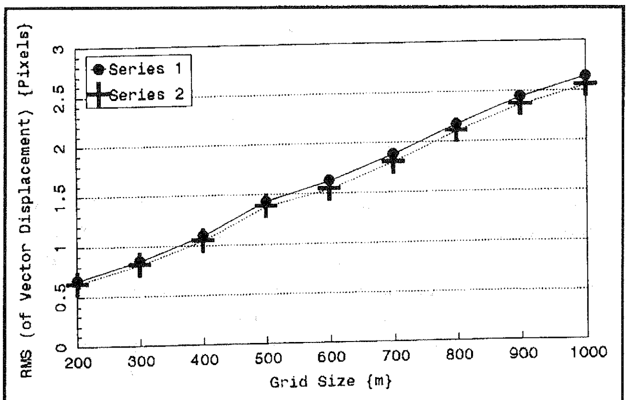

Figure 3 . Moderate Terrain (Anchorpoints Technique)
Series 1= Affine tran.; 2= Eight parameters tran.

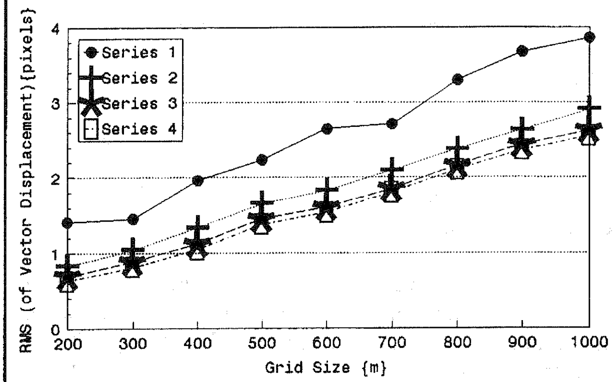

Figure 4 . Moderate Terrain (Pixel by Pexel Technique)
Series 1=Nearest Neighbour 2= Inverse Distance
3=Inverse Square Dist. 4= Bilinear Polynomial

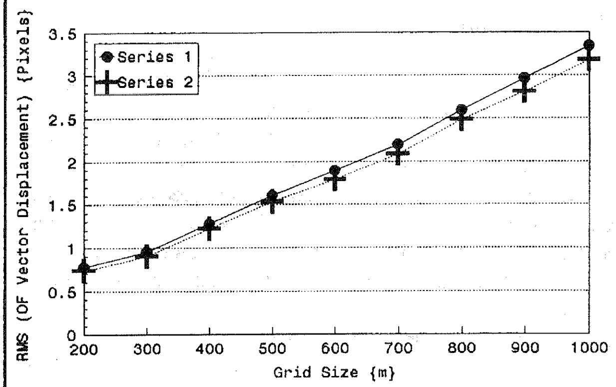

Figure 5. Rough Terrain (Anchorpoints Technique)
Series 1= Affine tran.; 2= Eight parameters tran.

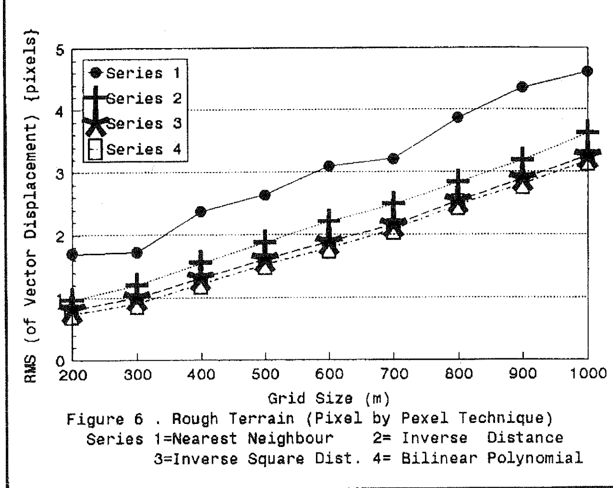

Figure 6 . Rough Terrain (Pixel by Pexel Technique)
Series 1=Nearest Neighbour 2= Inverse Distance
3=Inverse Square Dist. 4= Bilinear Polynomial

5. ANALYSIS OF RESULTS

The results of testing the anchorpoints technique are demonstrated for flat; moderate and rough terrain in Figures 1; 3; and 5 respectively. By examining these results one can conclude that, for all terrain types the eight parameters transformation within the DEM grid gives more accurate results compared with affine transformation. This is mainly because this method insures exact fit of the four DEM points forming a grid (because there is no redundancy as four points are used to determine the eight parameters).

The results of pixel by pixel technique are shown in Figures 2; 4; and 6 for flat; moderate and rough terrain respectively. These Figures show that:

- For flat terrain, the best results are obtained by interpolating height within the grid by inverse distance method..
- For moderate and rough terrain, the bilinear interpolation method give the best results.
- For all terrain types, the worst results are obtained by the nearest neighbour method.

Accordingly one can conclude that a simple formula such as inverse distance is able to represent flat terrain for orthoimage production, but more complex formulas are needed for representing moderate and rough terrain.

In order to be able to compare the anchorpoints and the pixel by pixel techniques, the method which give better results for each terrain type is selected to represent the technique. These methods are shown in Figures 7; 8; and 9 for flat; moderate and rough terrain respectively.

By examining Figures 7; 8; and 9 one can conclude the following:

- For flat terrain (Figure 7) it is clear that pixel by pixel technique gives better results at all grid sizes.
- For moderate and rough terrain (Figures 8 and 9) although it was expected that the pixel by pixel technique will give better results, the two techniques give almost the same results (only a very small improvements, not clear in the Figure because of its small scale, is obtained at bigger grid size using pixel by pixel technique). This could be due to that the used formulas for height interpolation could not represent such type of terrain accurately and more elaborate algorithms are needed for this purpose.

Figure (10) demonstrate the influence of DEM density (grid size) on the accuracy of orthoimages generated for different terrain types, where the pixel by pixel technique (which give the best results) is represented in this Figure.

As declared in Figure 10, in all terrain types, the accuracy of orthoimages decreases by increasing the DEM grid size but with different rates. The orthoimages of flat terrain are less affected by the increase in the DEM grid size compared with the orthoimages of moderate and rough terrain; and the orthoimages of rough terrain are most affected by the increase in the DEM grid size. The relationship between DEM grid size and the accuracy of orthoimages can be represented by straight lines for all terrain types

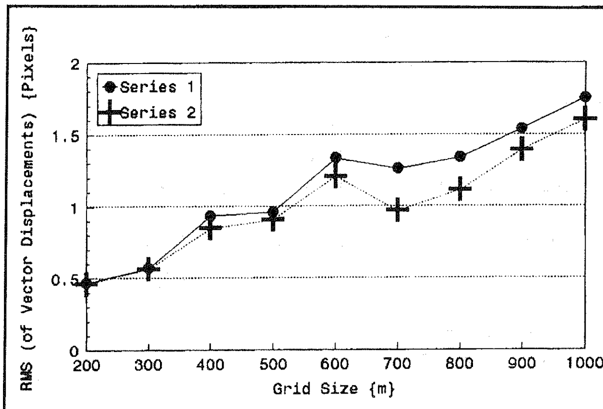

Figure 7. Flat Terrain (Anchorpoints and Pixel by Pixel Techniques)
Series 1= Anchorpoints 2= Pixel by Pixel

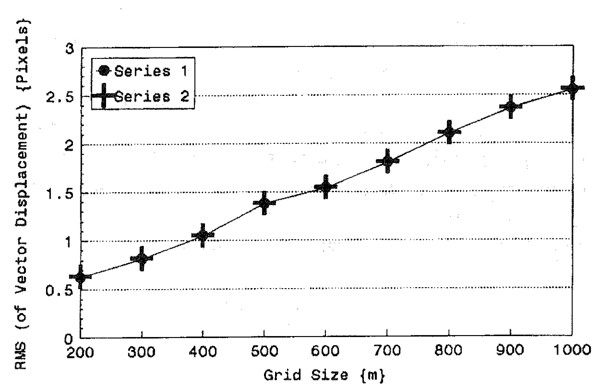

Figure 8. Moderate Terrain (Anchorpoints and Pixel by Pixel Techniques)
Series 1= Anchorpoints 2= Pixel by Pixel

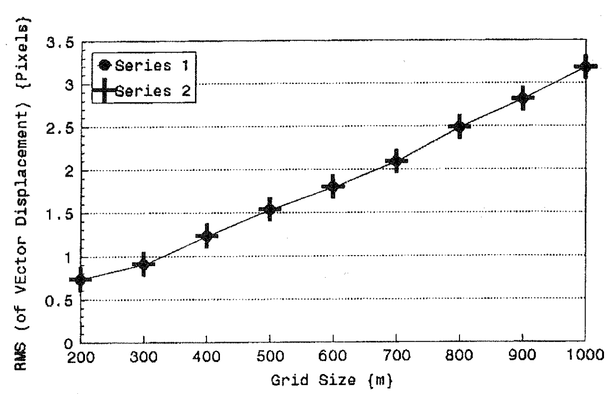

Figure 9. Rough Terrain (Anchorpoints and Pixel by Pixel Techniques)
Series 1= Anchorpoints 2= Pixel by Pixel

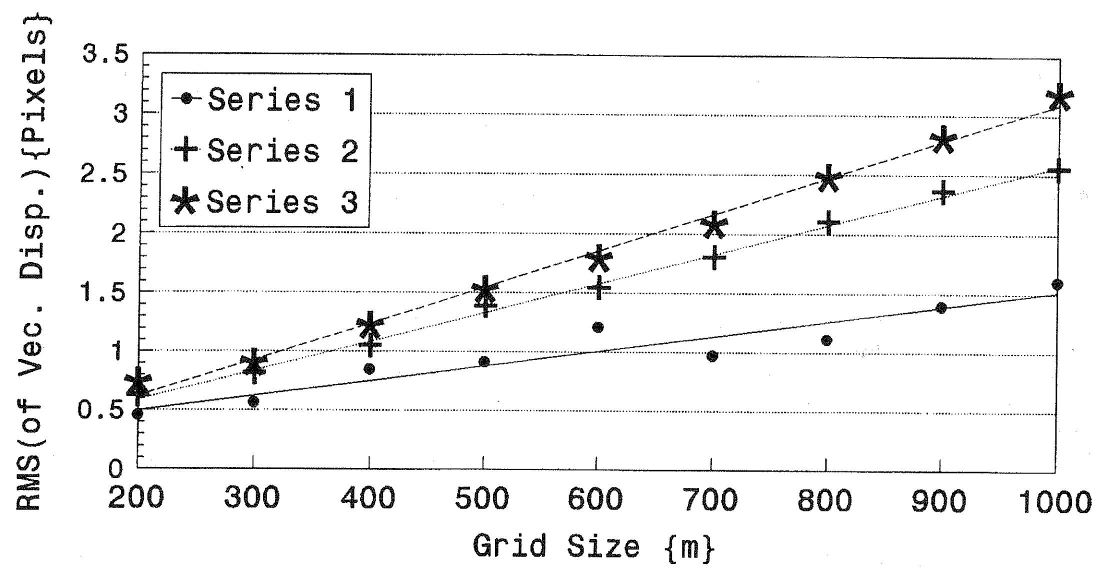

Figure 10 Comparison between Flat, Moderate and Rough Terrains.
Series: 1=Flat Terrain 2= Moderate Terrain 3= Rough Terrain

6. CONCLUSION

The influence of density of Digital Elevation Model (DEM) on the geometric quality of SPOT orthoimages is demonstrated. This influence is evaluated for different terrain types and using a high oblique SPOT image with 25 degrees mirror locking angle. Two different techniques for orthoimage production were examined, anchorpoints and pixel by pixel techniques. The demonstration of the influence of these factors was based on comparing the orthoimages produced using course DEMs with the orthoimage of the same area but produced using dense DEM.

i- As a result of examining orthoimages obtained by each of anchorpoints and point by point techniques, one can conclude the following:

-Concerning anchorpoints technique:

. For all terrain types, the eight parameters transformation within the DEM grid give more accurate results compared with affine transformation.

-Concerning pixel by pixel technique:

. For flat terrain, the best results is obtained by interpolating height within the grid by inverse distance method.

. For moderate and rough terrain, the bilinear interpolation method give the best results.

. Nearest neighbour method is not recommended for all terrain types because it gives the worst results.

ii- As a result of comparing orthoimages obtained by the anchorpoints and point by point techniques, one can conclude that:

- For flat terrain, pixel by pixel technique gives better results at all grid sizes.

. For moderate and rough terrain, although it was expected that the pixel by pixel technique will give better results, the two techniques give almost the same results. For such terrain types it is recommended to incorporate and test more elaborate algorithms for height interpolation such as patchwise or global methods.

iii- Concerning the influence of terrain type:

For all terrain types, the accuracy of orthoimages are decreased almost linearly by decreasing the density of the DEM. The orthoimages of flat terrain are less affected by the decrease of DEM density compared with moderate and rough terrain; and the orthoimages of rough terrain are most affected by the decrease of DEM density.

7. REFERENCES

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