

# TOPOGRAPHIC MAPPING AND TERRAIN MODELING FROM MULTI-SENSOR SATELLITE IMAGERY

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### ABSTRACT:

Digital satellite imagery provides substantial high quality data for mapping, inventorying, monitoring, and surveying. In the last decade, high-resolution satellite imagery from satellites such as IKONOS, SPOT5 and Quickbird has opened a new era of remote sensing and photogrammetry as their 1 m resolution imagery will display sufficient metric quality to support geopositioning with meter level accuracy and topographic mapping at scales of 1:10,000 and larger (Shi and Shaker, 2003). Recently, the use of high-resolution satellite imagery (HRSI) in digital mapping has been significantly increased and has become a reliable substitute for aerial photography in many applications. HRSI also offers the capability for rapid data acquisition in large areas. The objectives of the paper are to use images from different satellite sensors for topographic mapping and terrain modeling, study the potential accuracy of using empirical mathematical models for this process and evaluate the accuracy that results from the analysis of different datasets. The images are at different resolution and mono or stereo images.

## 1. INTRODUCTION

In the last decade, several mathematical models for satellite sensor orientation and 3D geo-positioning have been investigated. These models can be categorized into two groups: (a) Rigorous mathematical models which can present accurately the satellite sensor motion in space and the relationship between the satellite image space and the ground space. (b) Non-rigorous mathematical models (known as empirical models) that can approximate the relationship between the image and the object spaces with the aid of the control points. The empirical mathematical models do not need any information about the sensor motion in space or the satellite ephemeris data. They rely solely on the use of the control points to construct the relationship between the image and the object spaces. Generally, the rigorous mathematical models are more accurate than the empirical mathematical models. However, for the reasons of the restricted satellite sensor information for some of the new high-resolution satellites, the need to change the mathematical model for different satellite sensors and the need for the specialized software, the use of the empirical mathematical models has been increasing (Shaker, 2007). The great benefit of using the empirical mathematical models is that one set of equations can be used directly and can be applied to different images from different sensors (Shaker, 2007).

Recently, the 3D Affine model has gained a considerable interest due to its simplicity and accurate results. The model is linear in its unknowns; it does not require any further information about the satellite sensor (Shaker, 2007) and is a straightforward model that requires a minimum of 4 ground control points (GCPs) (Ono et al., 2000). The model was tested for IKONOS and Quickbird satellite images and the results revealed that the 3D Affine model is a practical model, which can be used for modeling high-resolution satellite sensors (Shaker and Shi, 2003).

In remote sensing, black and white or gray-scale imagery is called panchromatic and color imagery is called multispectral. Panchromatic satellite-imagery resolution varies from 60 cm for the Quickbird satellite, 1 m for the IKONOS satellite, 5 m for the Indian Remote Sensing series, 10 m for the French SPOT satellite series and 15 m for the Landsat 7 satellite.

## 2. METHODOLOGY

The 3D Affine model and different forms of the 3D Polynomial model were utilized to calculate the IKONOS/Quickbird, IKONOS/SPOT5, Quickbird/SPOT5 image transformation parameters and study the potential of the use of these models for topographic mapping. Several factors were examined, including the number and accuracy of the GCPs, the Base-to-Height (B/H) ratio for the stereo images, and the image viewing angles. The effects of the Earth curvature and the reference coordinate system used were assumed to be minimal, which is due to the small size of area covered by the stereo images and the use of the local (Hong Kong 1980) grid coordinate system (Shaker et al., 2007).

Since the 3D Affine model is a linear model, it may not fully represent the satellite instability and the unpredictable viewing angles. Therefore, additional terms such as  $X^2$ ,  $X^2+XY$ ,  $X^2+XZ+Z^2$ ,  $X^2+Y^2$ ,  $X^2+Z^2$ ,  $XY$ ,  $XY+Y^2$ ,  $XZ$ ,  $Y^2$ ,  $Y^2+YZ$ ,  $Y^2+YZ+Z^2$ ,  $Y^2+Z^2$ ,  $YZ+Z^2$  were added to the basic Affine model, to simulate these distortions (Shaker et al., 2007).

## 3. MATHEMATICAL MODELS

Polynomial models can also be used for the satellite sensor orientation, 2D-to-2D transformation (from the image space to the corresponding projected coordinate space), 3D-to-2D

transformation (the case of generating orthophotos) and 2D-to-3D generation by using the stereo models.

The use of the empirical mathematical models presented by the 3D Affine model and higher order Polynomials for satellite image orientation and terrain modeling have been studied for several satellite images such as SPOT 4, IRS/1D and IKONOS. These studies showed that the 3D Affine and Polynomial models may be successfully used for satellite sensor orientation, depending on adequacy of the ground reference coordinates system, the accuracy of the control information, and the size of the area covered by the images (Shaker et al., 2007).

The 3D Affine model consists of 8 coefficients to transform coordinates of the object space to the image space (Fraser and Yamakawa, 2004). These coefficients describe the rotations, scales, and translation parameters of the image. The model is written as follows:

$$x = A_1X + A_2Y + A_3Z + A_4 \quad (1)$$

$$y = A_5X + A_6Y + A_7Z + A_8 \quad (2)$$

where  $x, y$  = image coordinates  
 $X, Y, Z$  = ground coordinates  
 $A_n$  = image parameters

The image transformation parameters for each stereo are calculated, and then the intersection process is used to calculate the X, Y, and Z co-ordinates (El-manadili and Novak, 1996). The parameters of the 3D Affine model are calculated by the Least Squares Adjustment. In order to cope with some of the discrepancies which could exist due to the Earth curvature, terrain relief, image viewing angle, different higher order terms are added to the general form of the 3D Affine model performing the 3D Polynomial model. Then, the possibility of improving the accuracy of the results is investigated. The general Polynomial equation for the two variables can be defined as:

$$x = A_1X + A_2Y + A_3Z + A_4 + \text{additional higher order terms} \quad (3)$$

$$y = A_5X + A_6Y + A_7Z + A_8 + \text{additional higher order terms} \quad (4)$$

where  $x, y$  = image coordinates  
 $X, Y, Z$  = ground coordinates  
 $A_n$  = image parameters

The transformation process takes the following steps: the model coefficients are recovered by the substituting image and ground coordinates of the GCPs are included into the model. The minimum number of GCPs is based on the Polynomial order. The Least Squares Adjustment is used to calculate the model coefficients when increasing the minimum number of GCPs are required. Finally, in order to assess the transformed process, check points are used to determine the final product accuracy. To further control the quality of the transformed process, check points were used to determine the accuracy of the final results.

#### 4. EXPERIMENTAL DATA

The following steps were performed: The first step was to choose the study area and the number of GCPs. The data collection included the image coordinates, the study area and the GCPs that were collected using Global Positioning Systems (GPS). The mathematical models were programmed to build the relationship between the images and object space. Using the different images from the different satellite sensors, the image and the ground coordinates of the GCPs were used to calculate the image transformation parameters. The 3D Affine model was utilized to calculate the image transformation parameters. Different numbers of the well-distributed GCPs (from 4 to 16) over each image were used to calculate the coefficients of the 3D Affine model. Detailed experimental work was conducted using the mathematical model to calculate the ground coordinates of any points through the intersection process. Furthermore, results were obtained for Root Mean Square (RMS) for GCPs and check points. The ground coordinates of any points were calculated through the intersection process using the mathematical functions. Then, the 3D Affine model and the 3D Polynomial model were compared and analyzed.

Three different images from IKONOS, Quickbird and SPOT5 were used. Figure 1 shows an aerial image that extends 11.60 x 10.28 km over a part of Hong Kong Island and the Kowloon district (Shaker et al., 2005). The maximum ground height difference in the study area is about 450 m. The central part of this image is nearly flat, while the northern and southern parts are mountainous.

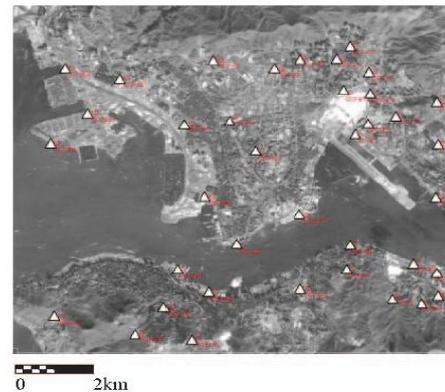


Figure 1. Hong Kong image - the stereo model area with GCPs. (Source: Shi and Shaker, 2003).

The collection azimuth and elevation angle were used to calculate the B/H ratios. The collection azimuth for Quickbird, SPOT5 and IKONOS were 105.40°, 13.9205° and 346.76°. The elevation angle for Quickbird, SPOT5 and IKONOS were 76.60°, 73.7849° and 70.9734°.

Table 1 displays the parameters of panchromatic stereo imagery which were used in the experiment. Table 2 illustrates the Base-to-Height ratios for IKONOS, Quickbird and SPOT5 combinations. The optimal result is a base-to-height ratio of 1. If it is much lower than 1, it will not be a good stereo model. When the combination is IKONOS-forward and Quickbird-backward, the B/H ratio is 0.65. The B/H ratio is 1.29 for the combination of Quickbird-backward and SPOT5-forward. For

the combination of IKONOS-forward and SPOT5-forward, the B/H ratio is 0.56. If the B/H ratio is a low value, the DEM

accuracy increases rapidly. In contrast, a higher B/H ratio value means that the DEM accuracy decreases. In essence, a B/H ratio between 0.5 and 1.0 is reasonable for DEM creation. Our results fell between these two ranges, indicating that the results were satisfactory.

	Quickbird – Backward	SPOT5 – Forward	IKONOS – Forward
Collection Azimuth	105.40	13.9205	346.76
Elevation Angle	76.60	73.7849	70.9734

Table 1. Parameters of panchromatic stereo imagery used in the experiment

	IKONOS – Forward Quickbird – Backward (IKQB)	Quickbird – Backward SPOT5 – Forward (QBSPOT5)	IKONOS – Forward SPOT5 – Forward (IKSPOT5)
Base-to-Height ratio (B/H)	0.65	1.29	0.56

Table 2. Base-to-Height ratios for IKONOS, Quickbird and SPOT5 combinations

Nominal collection azimuth and nominal elevation angles of IKONOS, Quickbird and SPOT5 satellites as viewed from the scene centers were provided by the vendors. Figures 2, 3 and 4 show the imaging geometries of the three different combinations of the satellite images. The angles in blue are the nominal azimuth and the angles in red are the elevations angles of IKONOS, Quickbird and SPOT5 satellites. With these parameters, the convergent angles can be calculated by an intersection of two lines: a line from the position of the first satellite to the center of the scene and the other line from the position of the second satellite to the center.

For this data set, 16 well-distributed GCPs and 9 check points for IKONOS-Quickbird, 16 well-distributed GCPs and 21 check points for IKONOS-SPOT5, and 16 well-distributed GCPs and 9 check points for Quickbird-SPOT5 were collected by GPS. Some of these points were pavement corners and others were road intersections or intersections between roads and canals. All GCPs and check points were chosen to be on the surface of the terrain and were situated not close to the residential areas. The accuracy of these points is estimated to be in the order of 5 cm in X and Y directions and 10 cm in Z direction.

The ground coordinates of the GCPs and the checkpoints were presented in the WGS84 reference frame and the UTM projection. GCPs were established by the differential GPS techniques with two Trimble 4000 SSI systems. The base lines did not exceed 5 km and the occupation time was about 20 minutes for each point. The measurements error of the image coordinates of both GCPs and checkpoints are within half a pixel.

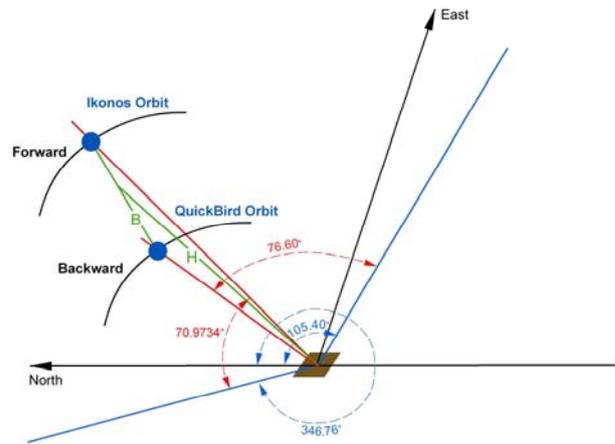


Figure 2. Imaging geometries of forward-IKONOS and backward-Quickbird combination

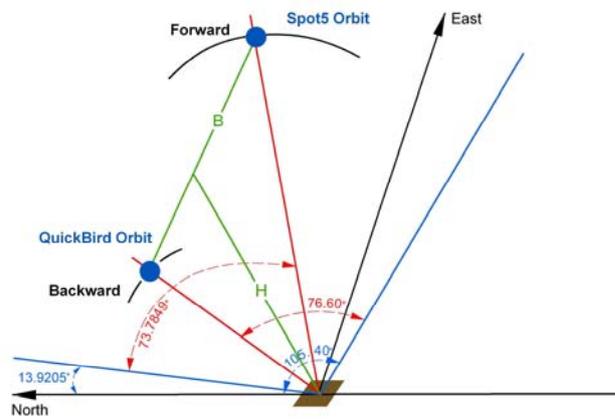


Figure 3. Imaging geometries of backward-Quickbird and forward-SPOT5 combination

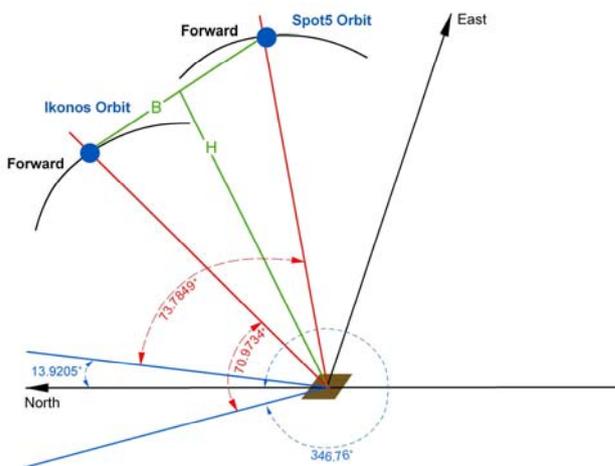


Figure 4. Imaging geometries of forward-IKONOS and forward-SPOT5 combination

### 5. RESULTS AND DISCUSSIONS

We aim to present the results and the accuracy that can be gained from using 3D Affine model and 3D Polynomial model.

The 3D Affine model was utilized to calculate the image transformation parameters. The effects from the number and the accuracy of the GCPs were examined. The study included two main steps: 1) the computation of the model coefficients (image transformation parameters) using the GCPs and the Least Square Adjustment for each image of the data set, and 2) identification and extraction of the ground coordinates of the checkpoints on each image of the data set. Different numbers of the well-distributed GCPs (from 4 to 16) over each image were used to calculate the coefficients of the 3D Affine model.

#### 5.1 Results of the 3D Affine Model

In general, it can be seen from Figure 5 that the RMS errors for IKQB, IKSPOT5 and QBSPOT5 in X direction decreases gradually with an increase in the number of GCPs, and that the error in QBSPOT5 is generally about twice the errors of IKQB and IKSPOT5. For the control configuration of 4 well-distributed GCPs, the 3D Affine model produced 1.85 m, 2.35 m and 4.31 m RMS errors for IKQB, IKSPOT5 and QBSPOT5 respectively in X direction, while the RMS error results improved significantly to 0.81 m, 1.23 m and 1.56 m when 16 GCPs were used. These results indicated that no significant improvements in the RMS errors were achieved when increasing the number of GCPs from 12 to 16. IKQB showed the best result because of the high resolution for the combination of IKONOS and Quickbird, and a satisfying B/H ratio of 0.65.

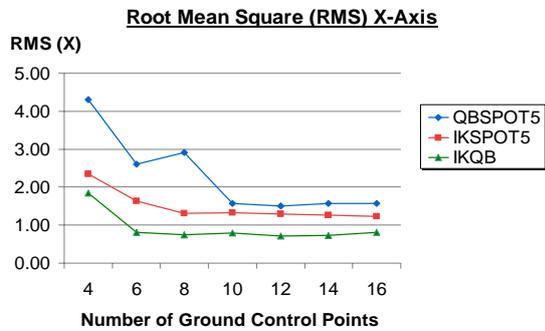


Figure 5. Results of the 3D Affine model in X direction

The graph in Figure 6 reveals that the RMS error for IKQB, IKSPOT5 and QBSPOT5 in Y direction decreases slightly with an increase in the number of GCPs. A significant finding is that the results for IKSPOT5 were more than double of QBSPOT5 and IKQB between 4 to 16 GCPs. Using 4 GCPs, the 3D Affine model produced 1.93 m, 6.09 m and 2.51 m RMS errors for IKQB, IKSPOT5 and QBSPOT5 respectively in the Y direction, while the RMS error results produced 0.92 m, 3.98 m and 1.09 m when 16 GCPs were used. These results indicated that no significant improvements in the RMS errors were achieved when increasing the number of the GCPs from 12 to 16. The result obtained for QBSPOT5 and IKQB remained really close together and this could be explained because of the high resolution of IKONOS and Quickbird, and the satisfactory

B/H ratio results of 0.65 for IKQB and 1.29 for QBSPOT5.

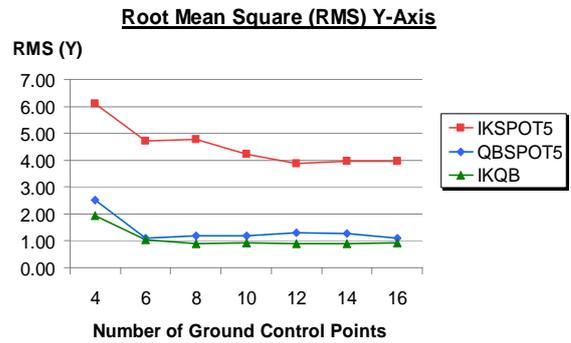


Figure 6. Results of the 3D Affine model in Y direction

Figure 7 displays that the RMS error for IKSPOT5 and QBSPOT5 in Z direction decreases progressively with an increased number of GCPs while the RMS errors for IKQB are almost the same using 6 to 16 GCPs and the line appears straight. The results for Z-axis were similar to X and Y-axis. The distance between the lines showing the RMS for IKSPOT5, QBSPOT5 and IKQB were almost equally spaced apart from each other. When there were 4 GCPs for IKSPOT5, it had the highest RMS error. After 10 GCPs, there was not much change in the RMS error. Using 4 GCPs, the 3D Affine model produced 5.29 m, 20.80 m and 18.58 m RMS errors for IKQB, IKSPOT5 and QBSPOT5 while the RMS error results showed 2.90 m, 12.03 m and 9.03 m when 16 GCPs were used. Although the number of ground control points was increased, it did not affect the accuracy. As observed, there was almost double the difference between IKQB and the other two combinations of stereo satellites (QBSPOT5 and IKSPOT5).

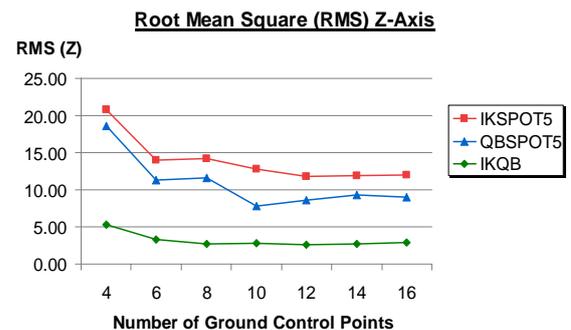


Figure 7. Results of the 3D Affine model in Z direction

#### 5.2 Results of the 3D Affine Model and Additional Terms

Table 3 presents the results from different forms of the 3D Polynomial model. It is noticeable that adding additional terms to the original form of the 3D Affine model does not improve the accuracy of the results. The accuracy of the same level or sometimes less satisfactory results could be achieved, indicating that IKONOS stereo images did not have additional distortions when compared to the images of SPOT5 and Quickbird. This could be because of the high stability of the IKONOS satellite in its altitude and trajectory comparing to the SPOT5 and Quickbird satellites. Therefore, using additional terms might

actually decrease the accuracy of the results due to over parameterization.

Table 3 was created to show the effect of adding the additional terms in X, Y and Z directions to the Affine model for IKQB, QBSPOT5 and IKSPOT5. In the legend, an *x* in black means that the accuracy that are too low while an *x* in red refers to the accuracy that are less than 20 m. An equal sign signifies that there is no change in accuracy. Improvements are presented by showing a checkmark and specifying the range for the number of ground control points with better accuracy compared to the 3D Affine model. Table 3 revealed that the accuracy of the results could be improved considerably (in terms of pixels), in some cases especially in the X direction by adding additional terms. However, not all of the additional terms could improve the accuracy of the results.

The results revealed that adding different additional terms to the 3D Affine model did not have that effect on the accuracy of the results in the Y and Z directions. The main effect from adding terms to the form of the Affine model was on the results of the X direction. In some other cases, adding terms to the Affine model had considerably improved the effect on the results as in case of adding the  $(YZ + Z^2)$ ,  $(X^2 + Z^2)$ ,  $(XZ)$  or  $(X^2 + XZ + Z^2)$  terms. This could be explained by the ability of the additional terms in the two directions (X-Z) to treat errors in both directions. In addition, these additional terms in the two directions were also able to consider some other errors related to the Earth curvature and any non-linearity from the sensor characteristics and the satellite motion. For other additional terms, no noticeable effect could be recorded.

The results showed that adding the  $(X^2)$  and  $(X^2 + XY, XY)$  terms had no influence on the accuracy of the results but adding other terms  $(X^2 + Y^2)$ ,  $(XY + Y^2)$ ,  $(Y^2)$ ,  $(Y^2 + Z^2)$ ,  $(Y^2 + YZ)$  and  $(Y^2 + YZ + Z^2)$  worsened the results and increased the errors to be more than 20 m. In addition, high errors were deleted to display errors that are less than 20 m. Charts were created to display the 3D Affine model plus additional terms that have errors less than 20 m

In general, the charts revealed that the results were not improved significantly by using more than 6 GCPs and the accuracy from applying the 3D Affine model was close to the accuracy of the results from using the different additional terms.

**5.2.1 Results of the IKONOS-Quickbird Data Set for IKQB:**

The results showed that adding the XZ term in X direction to the original 3D Affine model produced the lowest and the best results with an improvement of 0.25 m. Examining the results showed that adding another two terms,  $X^2Z^2$  and  $X^2XZZ^2$ , increased the accuracy of the results, while adding an  $X^2$  term did not improve the accuracy and generated almost the same results as the 3D Affine model. Furthermore, no effects were recorded by adding XY and  $X^2XY$  terms as the effect showed double the amount of errors than 3D Affine model.

Adding  $X^2, XZ, YZZ^2, X^2Z^2$  and  $X^2XZZ^2$  terms in Y direction did not improve the accuracy. Using 6 and 8 GCPs, there were very high errors shown but when the number of GCPs increased, the results were almost identical to the 3D Affine model. The results indicated that adding  $X^2XY$  and XY terms caused the effect of doubling the amount of errors than 3D Affine model.

Adding  $YZZ^2$  term in Z direction showed slightly improvement of 0.1 m to the 3D Affine model. Adding  $X^2, XZ, X^2Z^2$  and  $X^2XZZ^2$  terms had almost the same errors as 3D Affine model with errors less than 3 m. Furthermore, adding  $X^2XY$  and XY terms caused less accuracy in the results because they were over 10m .

**5.2.2 Results of the IKONOS-SPOT5 Data Set for IKSPOT5:**

The findings showed that adding the  $XZZ^2$  term in X direction to the original 3D Affine model had the same results and did not improve the accuracy. Adding the  $X^2XY$  term caused double the amount of errors than the 3D Affine model. However, adding all the other terms did not show any improvements.

Adding different additional terms to the original form of the 3D Affine model in Y direction did not show any improvements. Also, adding XY terms had almost the same results as 3D Affine model. When the GCPs were increased above 8, adding an  $X^2$  term showed that the error became less than 5 m. The

Model	IKQB			QBSPOT			IKSPOT5		
	X	Y	Z	X	Y	Z	X	Y	Z
Affine	√	√	√	√	√	x	√	√ / x	x
Affine + X2	=	(10 - 16) =	x	(10 - 16) =	(12 - 14) √	(10 - 16) √	(8 - 16) =	(8 - 16) =	x
Affine + X2XY	x	x	x	(10 - 16) =	(10 - 16) =	(12 - 14) =	(10 - 14) =	x	x
Affine + X2XZZ2	(10 - 14) √	(10 - 16) =	(10 - 14) =	(10 & 16) =	(10 - 16) =	x	(10 - 16) =	x	x
Affine + X2Y2	x	x	x	x	x	x	x	x	x
Affine + X2Z2	(10 - 14) √	(8 - 16) =	(10 - 14) =	(10 - 16) =	(10 - 16) =	x	(10 - 16) =	x	x
Affine + XY	x	x	x	(8 - 12 & 16) =	x	x	(8 - 16) =	(6 - 16) =	(8 - 10) =
Affine + XYY2	x	x	x	x	x	x	x	x	x
Affine + XZ	(8 - 14) √	(8 - 16) =	(8 - 16) =	(6 - 10 & 16) =	(8 - 16) =	x	(8 - 16) =	(8 - 10) =	x
Affine + Y2	x	x	x	x	x	x	x	x	x
Affine + Y2YZ	x	x	x	x	x	x	x	x	x
Affine + Y2YZZ2	x	x	x	x	x	x	x	x	x
Affine + Y2Z2	x	x	x	x	x	x	x	x	x
Affine + YZZ2	(10 - 14) √	(10 - 16) =	(10 - 14) √	(10 - 16) =	(8 - 16) =	(12 - 14) =	(10 - 16) =	(10 - 16) =	x

x	Accuracy that are too low
x	Accuracy that are less than 20 m
=	No Change in Accuracy
( — ) √	Improvement with Number of GCPs

Table 3. Analysis of 3D Affine model and Additional Terms.

results indicated that adding  $X^2XY$  term caused the highest error for all GCPs compared to the 3D Affine model with the majority of the errors that were fewer than 6 m. A study of the results showed that adding different terms in Z direction did not show any progress to the accuracy of the 3D Affine model.

**5.2.3 results of the Quickbird-SPOT5 Data Set for QBSPOT5:** The results revealed that adding an  $X^2$  term in X direction had no effects recorded and the errors were under 2 m. The results were similar to the 3D Affine model. The effect of adding the additional terms did not significantly improve the accuracy of the 3D Affine model.

The effect of adding  $X^2$ ,  $XZ$ ,  $YZZ^2$ ,  $X^2Z^2$  and  $X^2XZZ^2$  terms in Y direction did not improve the accuracy and had almost the same results as the 3D Affine model with errors less than 2 m. After adding  $XY$  and  $X^2XY$  terms, the errors increased as the number of GCPs increased from 4.46 m for 10 GCPs to 14.14 m for 14 GCPs. Adding an  $X^2$  term in Z direction increased the accuracy of the 3D Affine model for almost 1 m. After adding the additional terms, no significant improvements were observed.

## 6. CONCLUSIONS

The aim of this paper is to study the applicability of the 3D Affine model and its modifications for 3D Polynomial model for satellite sensor modeling. The assessment included identifying the most suitable 3D transformation model for image rectification and 3D modeling, by evaluating the factors that affected the accuracy of the rectification, such as variations in terrain elevation within the imaged area, sensor viewing angle, image resolution, and the number of GCPs. Three different satellite images from IKONOS, Quickbird and SPOT5 at different resolutions were used. The images and ground coordinates of the ground control points were used to calculate the image transformation parameters using the different images from the different satellite sensors. Using mathematical functions, the ground coordinates of any point were calculated through the intersection process. In addition, check points were used to determine the accuracy of the transformed process. The use of the empirical mathematical models presented by the 3D Affine model for satellite image orientation and terrain modelling was investigated for several combinations of stereo satellite images. The combination of IKONOS and Quickbird images showed the best results in all X, Y and Z directions because of the B/H ratio, the resolution and the image capturing techniques.

The results of this study showed that in some cases, adding terms to the Affine model had considerably improved the effect on the results as in case of adding the  $(YZ + Z^2)$ ,  $(X^2 + Z^2)$ ,  $(XZ)$ ,  $(YZ + Z^2)$  or the  $(X^2 + XZ + Z^2)$  terms. This could be explained by the ability of the additional terms in the two directions (X-Z) to treat the errors in both directions. These additional terms in the two directions were also able to consider some other errors related to the Earth curvature and any non-linearity from the sensor characteristics and the satellite motion. For other additional terms, no noticeable effect could be recorded. However, adding terms to the original form of the 3D Affine model should be done carefully to avoid over parameterization. In conclusion, the results obtained are encouraging for the future use of the Affine model with IKONOS and Quickbird imagery in 3D ground control points determination for different terrains.

The study also revealed that it may be feasible to use the 3D Affine model instead of the rigorous mathematical models in the topographic mapping and terrain modelling. Furthermore, the cost benefit of the study is that using the new remote sensing technique can save up to 60% of the cost by traditional land surveying techniques.

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