GEOMETRIC MODELS FOR THE ORIENTATION OF HIGH RESOLUTION OPTICAL SATELLITE SENSORS

K. Jacobsen*, G. Büyüksalih**, H. Topan**

*University of Hannover
*jacobsen@ipi.uni-hannover.de
** Zonguldak Karaelmas University
** gbuyuksalih@yahoo.com / htopan@karaelmas.edu.tr

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ABSTRACT:

Images taken by high resolution optical satellite sensors are available with different product levels, starting with the original images over close to original images, improved by the sensor calibration, to projections to a plane with constant object height and ortho-images based on very course digital elevation models (DEMs). All imaging satellites are equipped with satellite positioning systems like GPS and attitude control systems. Some very high resolution optical satellite systems do have precise attitude determination systems allowing a geo-reference sufficient for some purposes. The direct sensor orientation is available as satellite position together with attitudes or as rational polynomial coefficients (RPCs) describing the relation between object and image position by the relation of polynomials. An improvement of the orientation based on control points is necessary. The number and type of required unknowns is not the same for the different sensors.
Images projected to a plane with constant height or a course DEM do require a different mathematical model for the correct geo-referencing. For some of these image products no information about the sensor geometry is published, so a geometric reconstruction or a simplified mathematical model has to be used. In addition for some images additional parameters are required for reaching the highest possible accuracy.
The geometric models for handling original images are well known, but some have to be improved by special adapted parameters for an optimal solution. Not in any case orientation parameters are available with acceptable accuracy, so in some cases nearly the whole orientation is not known.
An overview about different solutions with advantages and disadvantages together with the achievable accuracy will be given.

1. INTRODUCTION

Modern satellites with high and very high resolution optical sensors are equipped with positioning systems like GPS and attitude control units with gyros and star sensors leading to good information about the sensor orientation. For reaching the possible object point accuracy the direct sensor information has to be improved based on control points. Different solutions are used, ranging from an improvement of the pre-orientation just by a shift in X and Y up to methods not taking advantages from the given sensor orientation.
The space images are available as different geometric products, ranging from original sensor images, just improved by inner orientation, originally named level 1A products, over projections to a plane with constant height, originally named level 1B products, up to rough ortho-images. Different mathematical models have to be used for their handling.

2. CONTROL POINTS

The highest level of accuracy only can be reached with control points and in addition the orientation process has to be confirmed by independent check points. Of course these points must have a sufficient object coordinate accuracy, but a precise definition in the images is as well as important. Very often corner points – building corners or corners of other objects are used. They are not optimal because their exact position is depending upon the grey value difference between the bright and the dark parts of the corner. In general bright parts tend to an enlargement caused by the human operator but also because of blooming effects.

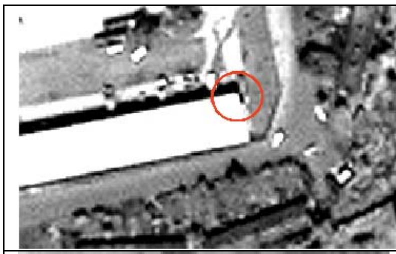	image contrast improved by contrast enhancement investigated corner encircled
	original image

Fig. 1: typical corner used as control point

The building corner shown in figure 1, upper part, has been influenced by a contrast enhancement – a typical process for space images. This shifted the corner against the position in the original image shown in the lower part of figure 1 by 1 pixel to right hand side and 1 pixel into the upper direction; that means from the bright part into the dark surrounding. A similar effect can be caused by the original image if the used element is very bright in relation to the neighbourhood.

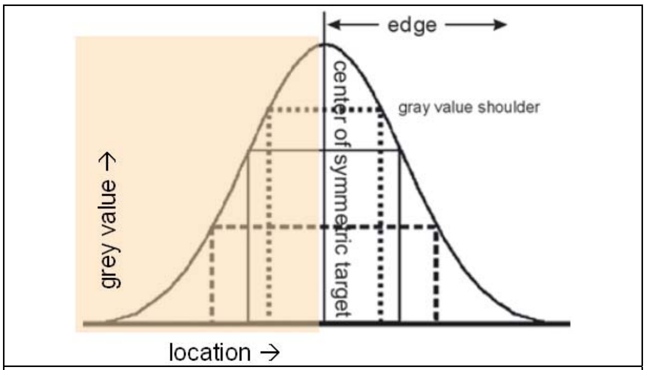

Figure 2: grey value profile of an edge (right hand side) and a symmetric target (whole figure)

As it can be seen in figure 2, the position of an edge is a function of the grey value shoulder used for the edge determination. The level of this shoulder is influenced by grey value manipulation e.g. by a contrast enhancement. Symmetric target do have a location independent upon the chosen grey value shoulder – the centre always will have the same location.

Fig. 3: left: not optimal corner position
right hand side: symmetric position

The position shown in figure 3 on right hand side shows a symmetric control point position, independent upon grey value manipulations. The corner position on the left hand side is simpler to be surveyed in the field, but its position is not optimal. With corner points usually no clear sub-pixel accuracy can be reached while this is possible with symmetric targets.

3. IMAGE GEOMETRY

The traditional CCD-line sensor satellites, like SPOT 1-4, ASTER, KOMPSAT-1, IRS-1C /1D and the HRS sensor of SPOT-5 do not change the view direction in relation to the orbit during imaging (figure 4a). SPOT 5 is using for the main imaging sensor HRG a yaw correction to compensate the effect of the earth rotation by a permanent change of the view direction across the orbit (figure 4b). The very high resolution and agile satellites like IKONOS, QuickBird, OrbView, EROS-A and TES are able to scan the earth surface in any direction by a permanent change of the satellite orientation. These satellites are equipped with high torque reaction wheels for all axes. If these reaction wheels are slowed down or accelerated, a moment will go to the satellite and it is rotating. No fuel is required for this, only electric energy coming from the solar paddles.

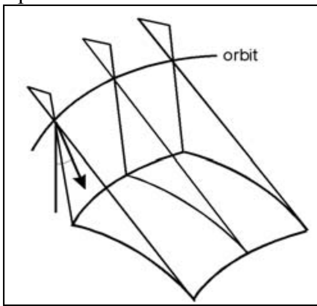

Fig. 4a: traditional image configuration – fixed orientation in relation to orbit

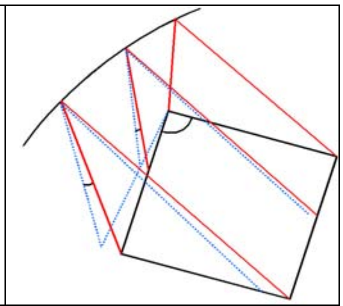

Fig. 4b: yaw control by SPOT 5 HRG - permanent change of view direction across orbit

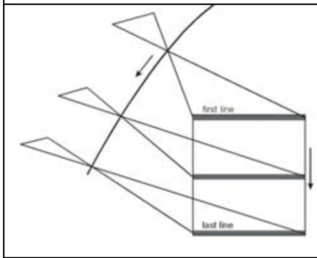

Fig. 4c: flexible view direction – also scan parallel to ground coordinate system

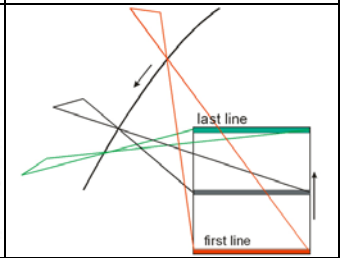

Fig. 4d: flexible view direction – scan against orbit possible

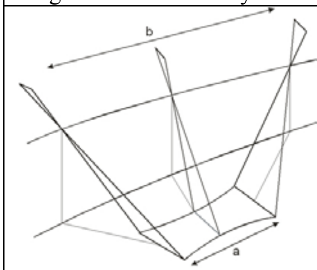

Fig. 4e: enlargement of integration time with factor b/a by continuous change of view direction

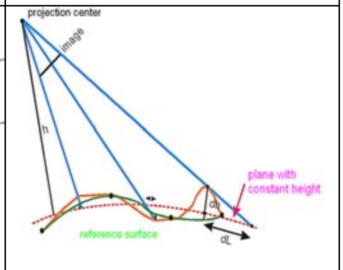

Fig. 4f: level 1B, IKONOS Geo, QuickBird OR Standard = projection to plane with constant height

The very high resolution systems EROS-A and TES are not equipped with TDI sensors which can sum up the energy falling on a CCD-element by shifting it to parallel arranged CCD-elements and continuing the energy collection. By this reason both sensors have to enlarge the integration time by a permanent rotation of the view direction during imaging (figure 4e). This is influencing the image geometry. Also QuickBird is using this effect for the compensation of the higher angular speed caused by the lower flying altitude of now 450km instead of the original planned 680km. With the reduced flying altitude the ground sampling distance (GSD) has been changed to 62cm instead of the original planned 94cm. But QuickBird is using a quite smaller relation of the orbit range to the ground range of approximately 1.5 instead of approximately 5 for EROS-A.
The images are distributed as original images (SPOT level 1A, IRS-1C level 1A, ASTER level 1A, QuickBird Basic, or KOMPSAT-1 or as images projected to a plane with constant height (SPOT level 1B, IRS-1C level 1B, ASTER level 1B, IKONOS Geo, QuickBird OR Standard). QuickBird is also available as a rough ortho-image using the GTOPO30 DEM with a point spacing of 30 arc sec corresponding to 925m at the equator (QuickBird Standard). The different geometry has to be respected by the used mathematical model.

4. MATHEMATICAL MODELS AND SOLUTIONS

The handling of original images (level 1A) and the projections to a plane with constant height (level 1B) is quite different. There are some solutions trying to reconstruct the original images from level 1B geometry – this is possibile, but not necessary. Rigorous mathematical models are in use like also approximations. In addition the available orientation information may be used completely, partially or even not.

4.1 Original Images

The available sensor orientation is not the same for the different sensors. In the optimal case for a sufficient number of lines the location of the projection centres and the attitude information with high precision is given, for some sensors no information will be distributed together with the images. The location accuracy for points projected to the ground may reach a standard deviation of 4m. Often more problems exist with the datum of the national net, which is not published in any case or even is not known. Approximate information about the local datum is available on the WEB-page of the NGA (former NIMA) (http://earth-info.nga.mil/GandG/datums/).

The solutions for handling original images are not new, at first they have been developed for SPOT images. In the Hannover program BLASPO, the image geometry is reconstructed based on the given view direction, the general satellite orbit and few control points. Based on control points the attitudes and the satellite height are improved. The X- and Y-locations are fixed because they are nearly mathematical dependent upon the view direction. In addition two additional parameters for image affinity and angular affinity are required. For these 6 unknowns 3 control points are necessary. More additional parameters can be introduced if geometric problems exist. Only for scenes with totally unknown orientation the full sensor orientation with 6 orientation elements will be adjusted together with necessary additional parameters. This requires a good vertical distribution of control points; for flat areas the full orientation cannot be computed. Other solutions do use the full given sensor orientation together with some required correction parameters. On the other hand sometimes no pre-information will be used with 3D-affine transformation, DLT and terrain dependent RPCs (see chapter 4.2). Like with the solution for level 1B-data more control points with a good three-dimensional distribution are required if the existing sensor orientation information will not be used.

4.2 Images projected to plane with constant height

The images projected to a plane with constant height are or can be geo-coded, but the position of the individual objects is influenced by the height difference of the object to the reference plane and the view direction (see figure 4f) in addition to the general orientation discrepancies which cannot be avoided. The geometric situation of these discrepancies has to be determined what is possible with different methods.

Rational Polynomial Coefficients (RPCs) from the satellite image vendors describe the location of image positions as a function of the object coordinates (longitude, latitude, height) by the ration of polynomials (Grodecki 2001) – see formula 1. These sensor related RPCs are based on the direct sensor orientation of the satellite together with information about the inner orientation and do have an accuracy depending upon the quality of the direct sensor information. Third order polynomials with 20 coefficients are used, so with 80 coefficients the relation of the image coordinates to the object coordinates can be described. The RPCs have to be improved by means of control points, named also bias corrected RPCs. IKONOS for example usually needs only an improvement by simple shift, for other sensors or old IKONOS images without the information of the reference height, a two-dimensional affinity transformation of the terrain relief corrected object coordinates to the control points is required. Under terrain relief correction we do understand the shift of the point position from the original geo-coded position by the height difference against the reference height multiplied with the tangent of the incidence angle in the direction of the azimuth.

$xij = \dfrac{Pi1(X,Y,Z)j}{Pi2(X,Y,Z)j}$	$yij = \dfrac{Pi3(X,Y,Z)j}{Pi4(X,Y,Z)j}$
$Pn(X,Y,Z)j = a_1 + a_2*Y + a_3*X + a_4*Z + a_5*Y*X + a_6*Y*Z + a_7*X*Z + a_8*Y^2 + a_9*X^2 + a_{10}*Z^2 + a_{11}*Y*X*Z + a_{12}*Y^3 + a_{13}*Y*X^2 + a_{14}*Y*Z^2 + a_{15}*Y^2*X + a_{16}*X^3 + a_{17}*X*Z^2 + a_{18}*Y^2*Z + a_{19}*X^2*Z + a_{20}*Z^3$	
Formula 1: rational polynomial coefficients xij, yij =scene coordinates X,Y = geographic object coordinates	

Reconstruction of imaging geometry: For the scene centre or the first line, the direction to the satellite is available in the image header data of the very high resolution sensors. This direction can be intersected with the orbit of the satellite published with its Keppler elements. For the location of a point in the image the time interval to the imaging of the scene centre can be computed, using also information of the header data. With this time interval the actual projection centre for each point can be computed and together with this the ground position also the actual view direction. This method requires the same number of control points like the sensor oriented RPC-solution, that means it can be used also without control points if the direct sensor orientation is accepted as accurate enough or it requires the same additional transformation of the computed object points to the control points like the sensor oriented RPCs.

The **three-dimensional affinity transformation** is not using available sensor orientation information. The 8 unknowns for the transformation of the object point coordinates to the image coordinates have to be computed based on control points located not in the same plane (see formula 2). At least 4 well distributed control points are required. The computed unknowns should be checked for high correlation values between the unknowns – large values are indicating numerical problems which cannot be seen at the residuals of the control points, but they may cause large geometric problems for extrapolations outside the three-dimensional area of the control points. Three dimensional means also the height, so problems with the location of a mountain top may be caused if the control points are only located in the valleys. A simple significance check of the parameters, e.g. by a Student test, is not sufficient. The 3D-affinity transformation is based on a parallel projection which is approximately given in the orbit direction but not in the direction of the CCD-line. The transformation can be improved by a correction term for the correct geometric relation of the satellite images having only a limited influence (Hanley et al 2002).

$$xij = a1 + a2*X + a3*Y + a4*Z$$
$$yij = a5 + a6*X + a7*Y + a8*Z$$

Formula 2: 3D-affinity transformation

Direct Linear Transformation (DLT): Like the 3D-affinity transformation the DLT is not using any pre-information. The 11 unknowns for the transformation of the object point coordinates to the image coordinates have to be determined with at least 6 control points. The small field of view for high resolution satellite images together with the limited object height distribution in relation to the satellite flying height is causing quite more numerical problems like for the 3D-affinity transformation. The DLT is based on a perspective image geometry which is available only in the direction of the CCD-line. There is no justification for the use of this method for the orientation of satellite images having more unknowns as required for the solution.

$$xij = \frac{L1*X + L2*Y + L3*Z + L4}{L9*X + L10*Y + L11*Z + 1}$$

$$yij = \frac{L5*X + L6*Y + L7*Z + L8}{L9*X + L10*Y + L11*Z + 1}$$

Formula 3: DLT transformation

Terrain dependent RPCs: The relation scene to object coordinates can be approximated by a limited number of the polynomial coefficients shown in formula 1 and can be computed based on control points. The number of chosen unknowns is quite depending upon the number and three-dimensional distribution of the control points. Just by the residuals of the control points the effect of this method cannot be controlled. Some commercial programs offering this method do not use any statistical checks for high correlations of the unknowns making the correct handling very dangerous. A selection of the unknowns may lead also to the three dimensional affinity transformation.

5. EXPERIENCE WITH ORIENTATION SOLUTIONS

The different mathematical models have been compared especially for IKONOS images in the Zonguldak test field in Turkey. In this area three dimensional distributed control points have been determined by GPS with a sufficient accuracy.

Figure 5 shows the result of the IKONOS orientation by means of the 3D-affinity transformation using 4 well distributed control points with quite different height values. Because of missing over-determination there are no discrepancies at the control points. Independent check points were leading to not acceptable root mean square differences of RMSX=1.91m and RMSY=18.53m. The geometric problem has been indicated by correlation coefficients listed with r=0.999, resulting in a warning by the Hannover program TRAN3D. Most other programs do not check the numerical problems which have been caused by the fact, that the 4 control points are located nearly on a tilted plane. Also more control points located in this tilted plane would not improve the results.

The orientation with a direct linear transformation resulted in similar problems which cannot be controlled just by the location and distribution of the control points. With 6 three-dimensionally well distributed control points the root mean square discrepancies at independent check points have been +/-2.4m - still too much for IKONOS (figure 6). With one additional control point, the discrepancies have not been better. The geometric problems are indicated again by high correlation coefficients which have reached r=0.999. Because of this a warning was given by the used Hannover program TRAN3D.

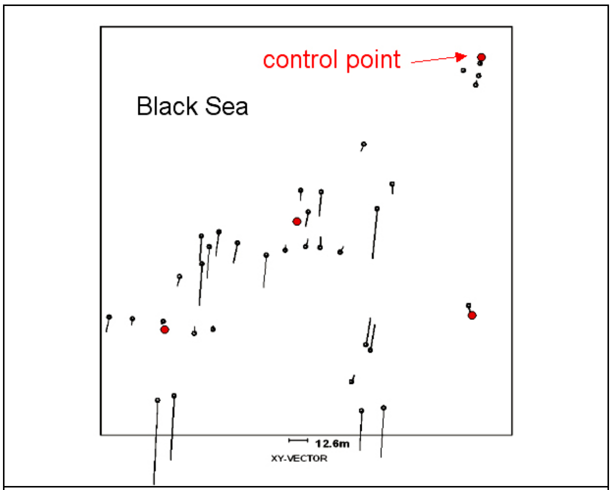

Fig. 5. IKONOS, Zonguldak
3D-affinity transformation based on 4 control points
discrepancies at independent check points:
RMSX=1.91m RMSY=18.53m

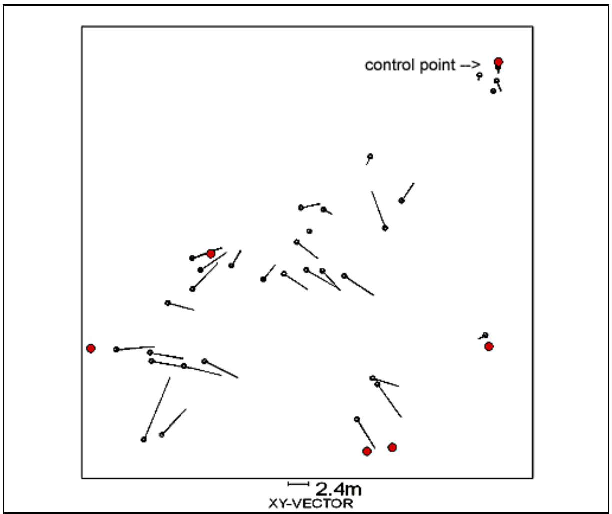

Fig. 6: IKONOS, Zonguldak
direct linear transformation based on 6 control points
discrepancies at independent check points:
RMSX/Y=2.4m

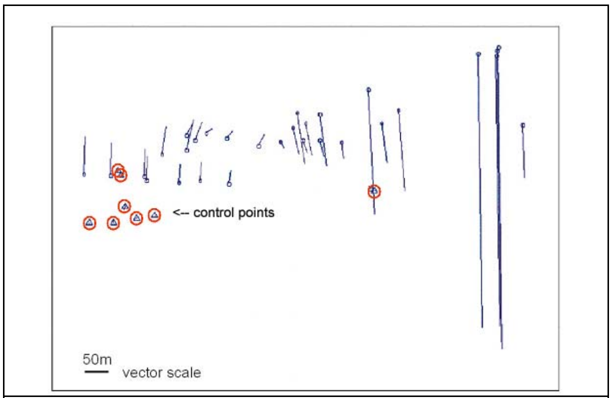

Fig. 7: IKONOS, Zonguldak
terrain dependent RCP-solution with 8 control points
discrepancies at independent check points

With the terrain dependent RPC-solution similar problems exist like with the two previously mentioned methods. The used commercial software did not indicate any problem for the case shown in figure 7 where 8 control points in a not optimal distribution have been used. The independent check points outside the range of the control points have had discrepancies up to 500m, but also in the area located within the range of the control points extreme errors up to 50m have been present.

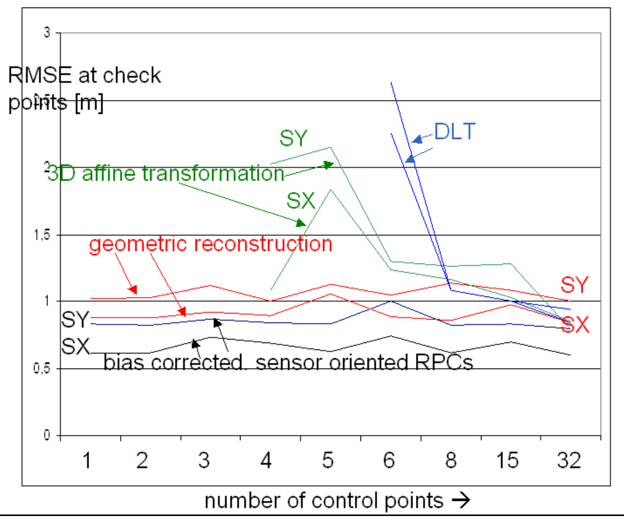

Fig. 8: IKONOS Zonguldak
Results at independent check points for the different orientation methods as a function of the number of control points - only the case of 32 reference points shows the residuals at control points

With the exception of the terrain dependent RPC-solution all other methods have been tested with a different number of control points (figure 8). Caused by the number of unknowns, the 3D-affinity transformation starts at 4 control points and the DLT at 6 control points. For the sensor oriented RPC-solution and the geometric reconstruction at least one control point has been used to determine the absolute positioning including also remaining datum problems. The geometric reconstruction and the sensor oriented RPCs do show very homogenous results, nearly independent upon the number of control points, while the 3D-affinity transformation and the DLT must have at least an over-determination of 2 control points before reaching acceptable results. Even with a higher number of control points these both methods do show larger root mean square discrepancies at independent check points. The sensor oriented RPCs are a little bellow the root mean square discrepancies of the geometric reconstruction, but both method are in the sub-pixel accuracy starting at just one control point. As a result it can be mentioned, that the direct linear transformation and the terrain dependent RPCs should not be used. The 3D-affinity transformation requires at least 3 more control points like the geometric reconstruction and the sensor oriented RPCs, in addition the unknowns of the 3D-affinity transformation have to be checked for strong correlations and the control points have to be distributed three-dimensional. So also the 3D-affinity transformation cannot be recommended. The sensor oriented RPCs and the geometric reconstruction can be used without problems with just a small number of not optimal distributed control points.

The geometric reconstruction and the sensor oriented RPCs do transform the scene coordinates to the ground coordinates using the height information and the view direction for the terrain relief correction. The terrain relief corrected ground coordinates are based on the accuracy level of the direct sensor orientation.

The relation to the control points can be determined by a simple shift of a two-dimensional transformation like a two-dimensional affinity transformation. In the Hannover programs RAPORI for the use of the RPCs and CORIKON for the geometric reconstruction, a two-dimensional affinity transformation can be used. The unknowns of the affinity transformation are checked for strong correlation and for significance by a Student test. The not justified unknowns can be removed. With this method the required type of transformation has been checked. For the IKONOS-data in the area of Zonguldak there was no justification of an affinity transformation. With just a shift in X and Y even a better accuracy has been reached. Only based on 15 or more control points there was a negligible advantage of the two-dimensional affinity transformation against a simple shift (see figure 9).

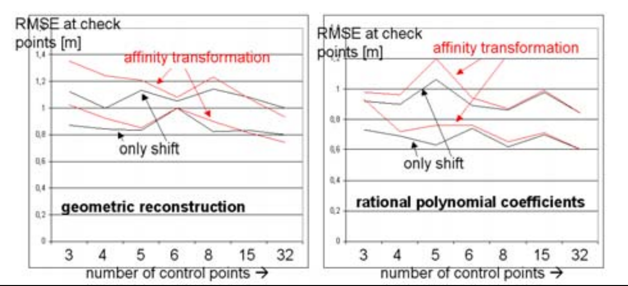

Fig. 9: influence of shift and affinity transformation after terrain relief correction IKONOS, Zonguldak

	RPCs		geometric reconstruction	
	RMSX	RMSY	RMSX	RMSY
shift	1.74m	0.72m	1.84m	0.89m
2D-affinity transformation	0.40m	0.59m	0.81m	0.66m
affinity + 2 additional parameters			0.48m	0.46m

Table 1: correction of QuickBird ORStandard after terrain relief correction – root mean square discrepancies at check points

A similar test has been made with a QuickBird image in the same area, partially using the same control points. The QuickBird image did not show the same inner accuracy like IKONOS and a two-dimensional affinity transformation to the control points was required (table 1). After affinity transformation the geometric reconstruction showed some not negligible systematic errors which could be removed with 2 special additional parameters. That means, sub-pixel accuracy is possible with QuickBird images, but at least an affinity transformation is required after the terrain relief correction based on at least 4 control points per scene.

In the Zonguldak test area and also other places TK350 and KVR1000 photos, ASTER, KOMPSAT-1, SPOT5 and IRS-1c images have been used in addition to the named IKONOS and QuickBird images. The achieved orientation accuracy is strongly depending upon the control point quality. With good control points and the correct data handling sub-pixel accuracy can be reached. In Zonguldak the same SPOT scene is available as level 1A and also as level 1B product. The accuracy reached with the programs BLASPO and CORIKON was nearly identical not indicating an advantage or disadvantage of one of the products.

6. CONCLUSION

The analysis of the different data sets and mathematical solutions showed very clear the advantage of a correct mathematical model for the handling of space images. All methods not using the scene orientation information do require more control points with a good three-dimensional distribution. The correlation of the used unknowns has to be checked to avoid uncontrolled problems outside the three-dimensional control point area. The direct linear transformation and the terrain dependent RPCs should not be used. Also the 3D-affinity transformation has some clear disadvantages, so the sensor oriented RPCs or the geometric reconstruction should be preferred for the handling of the level 1B-images – the projection of the images to a plane with constant height. No preference can be given for level 1A in relation to level 1B-images, the results have been equivalent. With the correct data handling and precise control points in general sub-pixel accuracy is possible.

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