

PRECISE GEOREFERENCING OF RECTIFIED HIGH RESOLUTION SPACE IMAGES

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WG I/5

KEY WORDS: high resolution space imagery, direct sensor orientation, geo-reference, RPC

ABSTRACT:

The high and very high resolution space images are often not available as original or near to original data but as geo-referenced rectified images. The geo-reference is based on the satellite position together with the known attitudes. In the case of IKONOS as lowest level product the CARTERRA Geo, a projection of the original image to a plane with constant height is distributed. For QuickBird the Basic Imagery which is just improved by the internal geometry, is available only as a full scene; less expensive sub-scenes are distributed as Standard Imagery rectified to the rough digital elevation model GTOPO30 or as Ortho Ready Standard Imagery rectified to a plane with constant height like CARTERRA Geo. Also SPOT images are sold as corresponding level 1B-product like also IRS-1C/1D, ASTER and KVR-1000 data.

With additional cost for some products the relation between such rectified images and the ground coordinate system is available as rational polynomial coefficients (RPC). The direct geo-reference for the RPCs is not accurate enough and has to be improved at least by a shift to control points. Other solutions are approximations and don't use the direct sensor orientation like the 3D-affine transformation. In some orientation programs the original images are reconstructed based on the rectified images like described by SPOT Image. For the precise geo-referencing the datum shift or higher degree transformation in addition to the terrain depending improvement based on the height differences of the individual points against the reference plane has to be determined. This requires the knowledge of the imaging ray from the actual projection centre to the point in the rectified and geo-referenced image. The view direction from the scene centres to the satellite orbit is available in all cases. Based on this, together with the general known satellite orbit, the individual view directions can be reconstructed without additional information. This strict solution requires the smallest number of control points like also the RPCs, but without additional financial effort.

In the area of Zonguldak, Turkey several very high and high resolution space images are available as rectified and geo-referenced products. The precise geo-referencing of these scenes has been made by GPS control points by means of the described method, reconstructing the direction of the imaging rays and requiring only a minimal number of control points.

1. INTRODUCTION

The use of the full geometric potential of high and very high resolution space images requires a correct mathematical model or a three dimensional interpolation function which is based on the sensor geometry and orientation. Also some three dimensional interpolation models based on control points are used, but they do need a higher number of well distributed control points. Today the very high resolution space sensors are equipped with positioning devices like GPS or DORIS and the attitudes can be determined with a combination of giros and star cameras allowing a standard deviation of the coordinates in the range of 12m or even better. In relation to the pixel size this is a limited accuracy, but together with the high relative accuracy within a scene it may be useful for some applications. For a higher geometric quality control points are required.

2. GEOMETRIC MODELS

2.1 Basic geometric relation

The high and very high resolution space sensors are equipped with CCD-lines. Most systems do have a combination of some shorter CCD-lines or small arrays. The relation between them belongs to the sensor calibration which will be done in advance by the data distributor. The user is getting only corrected data

sufficiently corresponding to an image taken with one homogenous CCD-line with perspective geometry. The combination of the CCD-lines in the orbit direction is depending upon the change of the sensor direction in relation to the orbit.

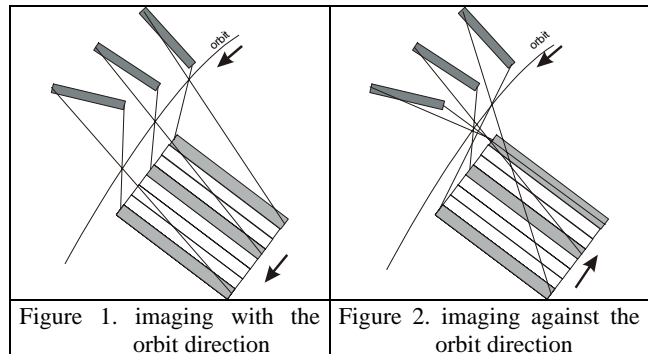


Figure 1. imaging with the orbit direction

Figure 2. imaging against the orbit direction

The very high resolution space sensors are equipped with fast rotating giros, the so called reaction wheels, allowing a fast and precise change of the view direction. The IKONOS satellite is able to take images also against the orbit direction (figure 2) without loss of accuracy. SPOT 5 is changing the mirror orientation continuously for the compensation of the effect of the earth rotation which is causing a deformation of the covered

area. This yaw correction is generating scenes with sides perpendicular to each other, but still rotated against the national net coordinate system. IKONOS and QuickBird even can generate images with sides parallel to the coordinate axis of the national coordinate system. Of course the rigorous geometric relation has to be respected by the mathematical model based on the correct imaging geometry.

2.2 Rational polynomial functions based on sensor orientation

Based on the sensor geometry and orientation, the relation between the image and the ground coordinates (geographic or national net coordinates) can be determined by a three dimensional interpolation in the object space with polynomials (Grodecki 2001).

$$x_{ij} = \frac{P_{i1}(X, Y, Z)_j}{P_{i2}(X, Y, Z)_j} \quad y_{ij} = \frac{P_{i3}(X, Y, Z)_j}{P_{i4}(X, Y, Z)_j}$$

$$P_{i1}(X, Y, Z)_j = a_1 + a_2 \cdot Y + a_3 \cdot X + a_4 \cdot Z + a_5 \cdot Y \cdot X + a_6 \cdot Y \cdot Z + a_7 \cdot X \cdot Z + a_8 \cdot Y^2 + a_9 \cdot X^2 + a_{10} \cdot Z^2 + a_{11} \cdot X \cdot Y \cdot Z + a_{12} \cdot Y^3 + a_{13} \cdot Y \cdot X^2 + a_{14} \cdot Y \cdot Z^2 + a_{15} \cdot Y^2 \cdot X + a_{16} \cdot X^3 + a_{17} \cdot X \cdot Z^2 + a_{18} \cdot Y^2 \cdot Z + a_{19} \cdot X^2 \cdot Z + a_{20} \cdot Z^3$$

Formula 1. rational polynomial functions

Usually the image coordinates are expressed with a third order polynomial of the national net coordinates X, Y, Z (formula 1), so 80 coefficients are required. Of course this is an approximation, but with the high number of coefficients the loss of accuracy against a rigorous model is negligible. The RPCs just based on the direct sensor orientation (sensor depending RPCs), have to be improved by a shift to at least one control point. As image coordinates also national net coordinates are used for geo-referenced scenes. The sensor depending RPCs optimally do use the available sensor information.

2.3 Rational polynomial functions based on control points

Not in any case the sensor based RPCs are available. With control points, the basic idea of a three dimensional interpolation can be used. Of course it is not possible to adjust 80 coefficients - this would require at least 40 three dimensional well distributed control points. So the number of unknowns has to be reduced. This also called terrain dependent solution is only able to determine the lowest order terms shown in formula 1. The number of unknowns is depending upon the number and distribution of control points.

This method is not using the available, but in some cases restricted sensor orientation information, by this reason more and well distributed control points are required. If all control points are located in the same height level, the position of points in a different elevation cannot be determined. So the control points are required three-dimensionally distributed around the area of mapping. In general an extrapolation out of the area of the control points has to be avoided. Even the low order polynomials can lead to extreme errors and random errors at the control points are enlarged outside the controlled area.

2.4 Three dimensional affinity transformation

The high resolution space sensors do have a small view angle, allowing the replacement of the perspective geometry in the CCD-line by a three dimensional affinity transformation (formula 2). This model can be improved by some corrections for a sufficient use of the perspective geometry in the CCD-line direction.

$$\begin{aligned} x &= A_1 + A_2X + A_3Y + A_4Z && \text{Formula 2: 3D-affinity} \\ y &= A_5 + A_6X + A_7Y + A_8Z && \text{transformation} \end{aligned}$$

Like the RPCs based on control points, the orientation information of the sensor is not used and the control points must be located three dimensional around the mapping area. This is often causing problems in mountainous areas because the control points are usually located in the valleys or lower areas and not on top the mountains, leading to geometric problems of the more elevated areas.

2.5 Reconstruction of the imaging geometry

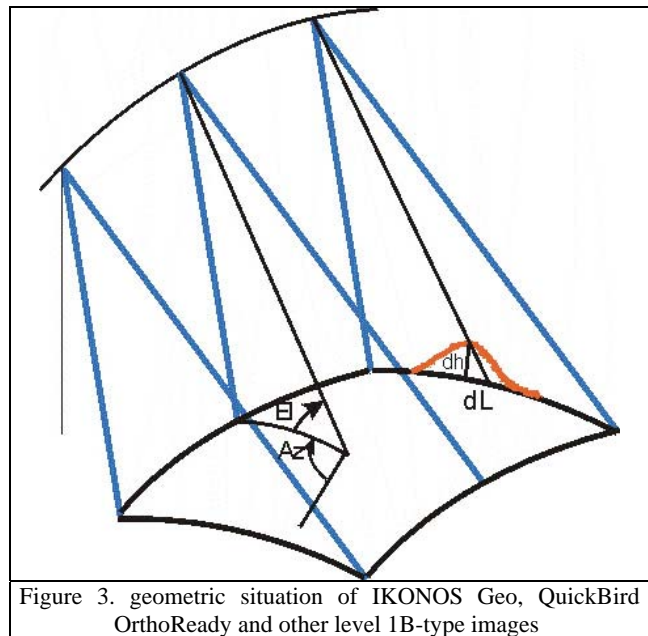


Figure 3. geometric situation of IKONOS Geo, QuickBird OrthoReady and other level 1B-type images

With the exception of the QuickBird Standard Imagery, the level 1B-type images like IKONOS (CARTERRA) Geo and QuickBird OrthoReady are projections to a plane with constant height. In all cases the azimuth and the incidence angle from the scene centre to the satellite are directly or indirectly available, allowing a reconstruction of the imaging geometry using also the published information about the sensor orbit. This has to respect also the change of the view direction in relation to the orbit during imaging with the extreme case of the imaging against the sensor movement (figure 2). The rectified images are usually available with the georeference. This may be given directly for any pixel like for IKONOS and QuickBird or the corner positions of the scenes are known and a transformation between ground and pixel positions is required for the georeference of any pixel. Depending upon the data set a similarity, an affinity or a perspective transformation is necessary.

Based on the reconstructed sensor geometry, the view direction for any scene position can be calculated and based on the height

difference between the ground point and the projection plane (Δh), the horizontal dislocation (ΔL) can be computed and respected (relief correction). In the case of the QuickBird Standard imagery the projection plane is not a plane with constant height level but the GTOPO30-DEM, so only the differences of both DEMs have to be used for the relief displacement.. Of course also a shift of the relief corrected scene to control points is required.

If the height level of the projection plane is known, by theory only a shift to at least one control point is sufficient. If it is not known, the image scale in the CCD-line direction is not determined and has to be computed based on control points.

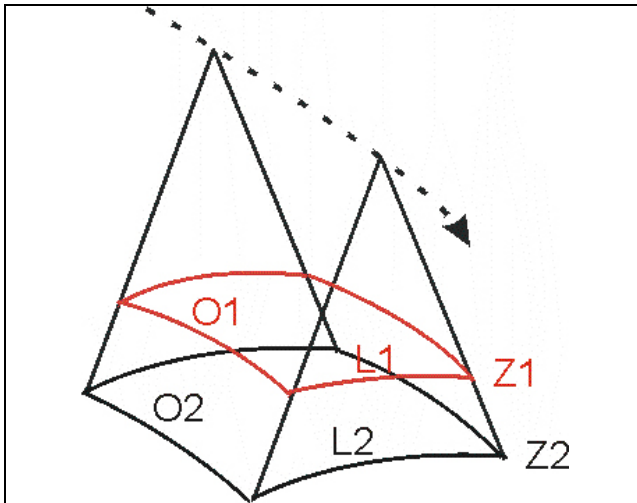


Figure 4. Influence of unknown height level of projection plane

As it can be seen in figure 4, the unknown height level of the projection plane is influencing the scale in the sensor line direction (distances L1 and L2) while the distances in the orbit direction are nearly not changed because of the constant incidence angle. With an affinity transformation of the relief corrected level 1B-images to the control points this effect can be controlled. Of course also the view direction, that means for IKONOS the nominal collection elevation and azimuth can be adjusted based on three dimensional distributed control points.

2.6 Other models

Also some other models like the direct linear transformation (DLT) and other not polynomial interpolations are used but do not play an important role. The DLT requires a higher number of well distributed control points and does not reach the same accuracy level.

3. EMPIRICAL RESULTS

3.1 IKONOS

In the area of Zonguldak, Turkey two IKONOS Geo scenes have been analysed with different methods. 39 control points determined by GPS, are located in an elevation between 217m and 652m above sea level. The mountainous area goes from the Black Sea up to 850m elevation.

For one scene also the rational polynomial coefficients (RPC) are available. This scene has been adjusted with the Hannover program CORIKON, reconstructing the imaging geometry, with

the Hannover program RAPORI, based on the RPC and with the PCI satellite modelling, which is also based on RPCs as input values. In the program CORIKON beside an affinity transformation (6 unknowns) also the view direction (2 unknowns) can be adjusted. The unknowns are individually checked for significance and correlation. Not significant unknowns are marked and can be taken out of the adjustment. If the view directions cannot be determined because of missing geometric information, automatically they will be taken out of the adjustment to avoid errors of extrapolation.

	RMSX	RMSY
RAPORI, RPC + 6 affine parameters	5.30 m	0.98 m
CORIKON, reconstruction of geometry + 6 affine parameters (6 unknowns)	5.33 m	0.86 m
PCI satellite modeling (RPC + 6 affine parameters)	5.85 m	0.82 m
CORIKON, 8 unknowns (affine + view direction)	1.01 m	0.80 m

Table 1. root mean square discrepancies at 39 control points of the IKONOS orientation in Zonguldak, Turkey

The first three results of the IKONOS scene orientation with different mathematical models listed in table 1 are very similar. Also the error vectors are going into the same direction. In relation to the pixel size of 1m it cannot be accepted. The root mean square difference between the first both solutions is just 0.38m for X and also for Y.

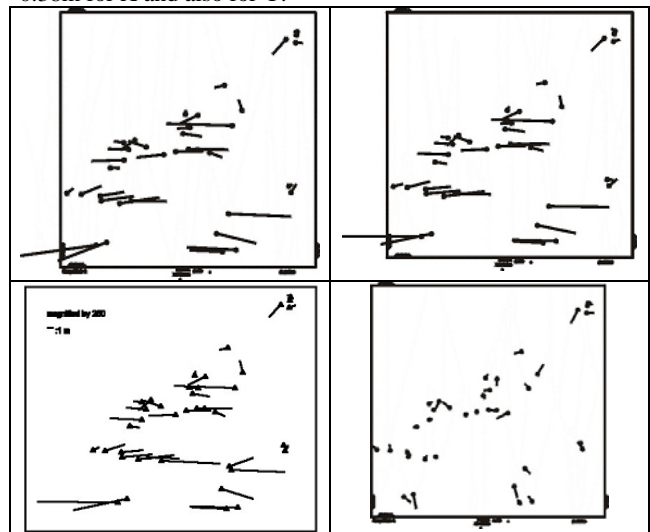


Figure 5. discrepancies at control points corresponding to IKONOS orientations listed in table 1

Upper left: RAPORI (RPCs), right: CORIKON 6 unknowns
Lower left: PCI satellite modelling, right CORIKON 8 unknowns

The orientation problems are obvious in this case, so with CORIKON also the nominal view direction and azimuth has been handled as unknown leading to a sub-pixel accuracy. The adjustment of the view direction resulted in a change of the nominal collection azimuth of 8.6° which is highly significant with a Student test value of 31. The nominal collection elevation has only changed 0.4° . This is also significant but only with a Student test value of 6.3. Only the affinity parameter 3 was not significant and could be taken out of the adjustment without any change at the discrepancies at the control points. A problem with the view direction has been seen also with a scene in Saudi Arabia, but not in other areas. In

the Saudi Arabia scene, based on 20 control points with differences in the elevation up to 338m, the azimuth has changed 2.0°, reducing the root mean square differences from 1.39m to 1.25m. In another area in Turkey the RMS-values of two scenes have not been improved with the nominal collection elevation and azimuth as unknown, but the 6 affinity parameters have been significant and required.

	RMSX	RMSY
CORIKON, 8 unknowns (affine + view direction)	1.45 m	0.97 m
CORIKON, 6 unknowns (affine)	1.51 m	1.00 m
CORIKON, 2 unknowns (shift X, Y)	1.61 m	1.09 m
CORIKON, only terrain correction	2.31 m	4.04 m

Table 2. root mean square discrepancies at 33 control points of IKONOS orientation, New Jersey pixel size 1m

In the case of the New Jersey data set the program CORIKON has removed the nominal collection elevation and azimuth as not required from the adjustment. This decision is based on a Student test and it takes also care about correlations of the unknowns. Also an affinity transformation of the terrain corrected IKONOS positions to the control points has had a limited influence, only a shift in X and Y was required. With just the terrain correction, the result is mainly depending upon the direct sensor orientation which is causing a shift in X of 1.7m and in Y 3.9m. In several countries the accuracy of the direct sensor orientation is quite better than the problems with the datum of the national coordinate system, requiring a fit to the actual used coordinate system at least by a shift in X and Y.

3.2 QuickBird

	RMSX	RMSZ
CORIKON 8 unknowns (affine + view direction)	0.58 m	1.27 m
CORIKON 3 unknowns (shift X, Y, nadir)	0.58 m	1.36 m
CORIKON 2 unknowns (shift X,Y)	0.58 m	1.36 m

Table 3. root mean square discrepancies at 45 control points of the QuickBird Standard image Saudi Arabia pixel size 0.61m

The geometric situation of QuickBird OrthoReady images is exactly the same like for IKONOS Geo. From QuickBird with the Basic Imagery also the original data only corrected by the internal calibration are available together with the full sensor information, but a full scene has to be bought. With QuickBird Basic images a standard deviation of 388 control points of SX=0.55m and SY=0.64m corresponding to approximately 1.0 pixel has been reached (Passini, Jacobsen 2004). This accuracy is usually limited by the identification and the ground coordinate accuracy of the control points. This accuracy of 1 pixel is an operational accuracy which can be reached with most of the space sensors. It is totally sufficient because the registration of object elements is in most cases limited by the object definition itself.

In an area in Saudi Arabia the control point definition in the images and the ground coordinate accuracy was not so good, so only an RMSX of 0.58m and an RMSY of 1.27m has been reached in the QuickBird Standard image. This is still sufficient for operational applications. The orientation with 8 unknowns (azimuth and elevation together with an affinity transformation

of the terrain corrected scene positions to control points) was not much better like an adjustment with just the 3 significant unknowns (shift in X and Y together with nadir). Without an improvement of the nadir direction the discrepancies have been the same, so in addition to the relief displacement just a shift in X and Y was required, that means by theory only one control point could be used. The shift values of 77.7m for X and 9.2m for Y do present more the datum problems of the national net than the accuracy of the direct sensor orientation. The rectification to the GTOPO30-DEM is reducing the height differences between the actual terrain surface and the reference plain. This has the negative effect of a poor convergence of an adjustment with the view direction, but it is still possible to improve the view direction. On the other hand an improvement of the view direction has only limited influence caused by the smaller differences in height between the actual DEM and the GTOPO30-DEM.

3.3 SPOT

	RMSX	RMSZ
CORIKON 8 unknowns (affine + view direction)	4.88 m 5.40 m	3.51 m 4.41 m
CORIKON 3 unknowns (shift X, Y, nadir)	6.27 m 6.72 m	4.05 m 4.38 m
CORIKON 2 unknowns (shift X,Y)	14.97 m 24.99 m	15.29 m 21.78 m

Table 4. root mean square discrepancies at 39 control points of 2 SPOT 5-scenes in Zonguldak pixel size 5m

SPOT scenes are available as original sensor images just improved by the internal calibration as level 1A and as rectified images, the level 1B. The level 1B-product is more close to the map geometry, but it has lost the original geometric relation.

The average of the root mean square discrepancies (RMS) at the control points of 2 level 1B-orientations in the area of Zonguldak is with 4.6m below the pixel size of 5m. Such an operational accuracy will be reached also with the level 1A-scenes. So the reconstruction of the imaging geometry with program CORIKON does not lead to a loss of accuracy in relation to level 1A-scenes like sometimes reported and it is also not necessary to reconstruct the original image geometry. With just the shift parameters and a correction of the nadir angle with 5.47m the average RMS values have been raised just from 0.9 to 1.1 pixels, but without an improvement of the nadir angle the result could not be accepted.

3.4 IRS-1C

	RMSX	RMSZ
CORIKON 8 unknowns (affine + view direction)	9.55 m	7.04 m
CORIKON 3 unknowns (shift X, Y, nadir)	9.40 m	7.17 m
CORIKON 2 unknowns (shift X,Y)	10.53 m	8.50 m

Table 5. root mean square discrepancies at 44 control points of an IRS-1C-scene in Zonguldak pixel size=5.8m

Like SPOT, also for IRS-1C the original (level 1A) and the rectified (level 1B) scenes are available. For nadir images IRS-1C has a pixel size of 5.8m on the ground. With just a nadir angle of 2° the available scene in the area of Zonguldak is close to this. The image quality was not optimal - this may be caused

also by the atmospheric conditions. An edge analysis was leading to a point spread function corresponding to a pixel size of 7.5m. In relation to this effective pixel size the orientation with 8 unknowns (affinity + view directions) but also with just 3 unknowns (shift in X and Y + nadir angle) is corresponding to 1.1 pixels. An adjustment with just the two shift parameters is leading to root mean square differences of 1.3 pixels.

3.5 KVR-1000

	RMSX	RMSZ
CORIKON 8 unknowns (affine + view direction)	10.26 m	11.49 m
CORIKON 6 unknowns (affine)	10.42 m	10.77 m
CORIKON 4 unknowns (shift X,Y, affine 3 and 6)	10.26 m	12.55 m
CORIKON 2 unknowns (shift X, Y)	14.81 m	17.10 m

Table 6. root mean square discrepancies at 44 control points from map 1 : 50 000 of KVR-1000 pixel size=1.6m

The panoramic KVR-1000-photos are distributed as original copies but also as digital images projected to the ground. For this scene only control points digitised from topographic maps have been available, so not the quality of the KVR-1000, but the control point quality has been checked. An improvement of the view direction was not necessary, but beside the shift in X and Y also a small rotation, covered by the affinity parameters 3 and 6 was available.

Like with the IRS-1C an edge analysis did not confirm the available pixel size of 1.6m. The image quality corresponds to a pixel size of 2.2m but nevertheless this is quite below the achieved accuracy reached with the control points digitised from the map.

4. CONCLUSION

It has been shown that a reconstruction of the imaging geometry, like used in the Hannover program CORIKON, is able to solve the orientation of satellite images rectified to a plane with constant height or a very coarse DEM. These images traditionally are named also as level 1B images, but for IKONOS it is named CARTERRA Geo and for QuickBird OrthoReady. In general an accuracy of 1 pixel or even better can be reached under operational conditions if the control point accuracy and definition is sufficient.

The orientation unknowns should be checked for significance and correlation to avoid problems with not optimal distributed control points. This is possible with a first adjustment using all 8 unknowns (6 affine parameters, nadir angle and azimuth of the view direction in relation to the scene centre) if at least 4 control points are available. Based on the result of the first adjustment, the not required unknowns should be taken out of the solution. For the view direction this should be done automatically by the program to avoid problems with an extrapolation out of the three dimensional area of control points. The final orientation can be made with only few unknowns; in some cases a shift in X and Y of the terrain corrected data is sufficient. The orientation of course is only the first step of the data handling, the determined orientation parameters have to be used in a corresponding orthoimage module and a module for the calculation of three dimensional ground coordinates of stereo scenes.

5. ACKNOWLEDGEMENTS

Parts of the presented results have been supported by TUBITAK, Turkey and the Jülich Research Centre, Germany. Thanks are going to Dr. R. Passini, BAE ADR, Pennsauken, NJ for the support with data and the data acquisition and also to Dr. K. Eren, Geotech Group, Riyadh for the data sets in Saudi Arabia.

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