Geometric Potential of IKONOS- and QuickBird-Images

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ABSTRACT

The very high resolution space images from IKONOS and QuickBird are today in a competition to aerial images. The resolution is sufficient for the generation of orthoimages at a scale of approximately 1 : 8000 up to 1 : 5000. Also the geometric potential is satisfying, but it is necessary to use a rigorous mathematical model. Rational polynomial functions for the ground coordinates in relation to image coordinates should not be determined directly based on control points, this will hide discrepancies at the control points and do not guarantee a sufficient geometric quality for areas with poor control point distribution. The geometric models used for CARTERRA Geo-images (IKONOS) and QuickBird Basic Imagery are explained together with the existing problems, especially some problems of the IKONOS images with the information about the view direction which is included also in the rational functions distributed by SpaceImaging. The mayor geometric limitation for the production of orthoimages is not the stable geometry of the space images; it is caused by the used existing digital elevation models (DEMs). DEMs also can be generated by automatic image matching of IKONOS and QuickBird Images. Stereo pairs taken from the same orbit do not cause any problem with the generation of DEM's; this is different for images taken with a larger time interval from different orbits. The change of the vegetation, but also the change of the length of shadows and other radiometric differences may lead to problems with the automatic image matching.

1. INTRODUCTION

The use of very high resolution space sensors for civilian mapping has opened a new field of applications and has created a competition to the use of small scale aerial images. For long time the high resolution space sensors have been limited for military use, but with the end of the cold war the situation changed. Now it is not any more possible for a country to restrict the use of high resolution information causing in some countries a curious situation of classified small scale aerial photos against free available very high resolution space images which sometimes do show more details. In areas without restricted use of aerial images it is only an economic decision for the use of one of the systems. With the growing number of space systems, the competition has yielded to reduced sales prices - this situation will continue.

As a rule of thumb, for mapping a pixel size of 0.05mm up to 0.1mm in the map scale is required. This takes care about the higher requirements of details in larger scale maps. Under this condition the 1m pixel size of IKONOS corresponds to a possible map scale of 1:10 000 and the 0.61m of QuickBird corresponds to a map scale 1:6 000 (Jacobsen 2002). For orthoimages 8 pixel/mm are required, leading to possible orthoimage scales of 1:8000 respectively 1:5000. Usually a coordinate accuracy of 0.25mm in the maps or orthoimages is requested corresponding to 2 pixels or 2m for IKONOS and 1.2m for QuickBird. For elevations which may be determined based on stereo configurations, no fixed accuracy rules do exist for map scales, the required height accuracy is more depending upon the area – if it is flat or mountainous. The situation is different for digital elevation models which shall be used for the generation of orthoimages; here we do have a clear dependency upon the nadir angle.

2. VERY HIGH RESOLUTION SPACE SENSORS

The number of very high resolution space sensors is growing; beside the established systems IKONOS and QuickBird the low cost version OrbView 3 has been launched at June 26^{th}, 2003 and others are announced.

	company	launch	mode	pixel size at nadir	swath [km]	pointing	height [km]
IKONOS 2	Space Imaging	1999	pan / 4ms	0.82 /3.28	11.3	free	680
EROS A	ImageSat Int.	2000	pan	1.8	12.6	free	600
QuickBird 2	DigitalGlobe	2001	pan / 4ms	0.61 / 2.44	16.4	free	450
TES	ISRO, India	2001	pan	1,0	12	free	565
SPOT 5	SPOT Image	2002	pan / 4ms	5 (2.5) /10	60	+/-27° across	830
OrbView 3	OrbImage	2003	pan / 4ms	1.0 / 4.0	8	free	470
Cartosat-1	ISRO, India	2003/4	pan	2.5	30	+26°, -5° in orbit	617
ALOS	NASDA, Japan	2004	pan	2.5	35 / 70	-24°, 0°, 24° in orbit	691
Cartosat-2	ISRO, India	2004/5	pan	1	10	free	630

Table 1: very high resolution civilian space sensors in space *and announced*

IKONOS and QuickBird are equipped with very similar Kodak Space Remote Sensing Cameras. The mayor difference between both systems are included in the width of the combined CCD-lines; IKONOS has finally 13800 pixels generating a swath width of 11.3km in the case of a nadir view while QuickBird has 27 552 pixels corresponding to 16.4km swath. Originally the pixel size on the ground should be the same for both systems with 82cm. At the time of the IKONOS launch, the US government allowed only a distribution of images with a pixel size of not smaller than 1m on the ground. This restriction does not any more exist why DigitalGlobe changed the orbit from originally planned 680km to now 450km, leading to 0.61m pixel size.

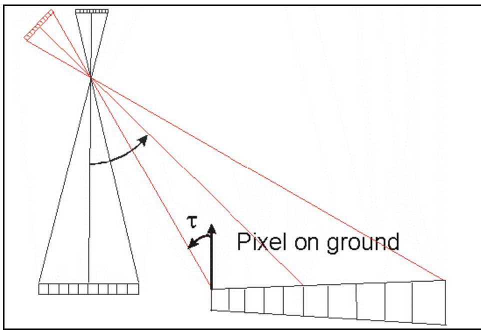


Figure 1: pixel size on ground depending upon local nadir angle τ

$pv = pn / \cos^2 \tau$ $\qquad$ $pc = pn / \cos \tau$

pn = pixel size on ground at nadir
pv = pixel size on ground in view direction
pc = pixel size on ground across view direction

nadir angle	0°	10°	20°	30°	40°	50°	
pan across view direction	0.82	0.83	0.87	0.95	1.07	1.28	IKONOS pan
pan in view direction	0.82	0.85	0.93	1.09	1.40	1.98	IKONOS pan
ms across view direction	3.28	3.32	3.48	3.80	4.28	5.10	IKONOS ms
ms in view direction	3.28	3.38	3.71	4.37	5.59	7.94	IKONOS ms

Table 1: original pixel size on ground [m] of IKONOS images depending upon view direction

SpaceImaging is not distributing the original images, only derived products. As it can be seen, in figure 1 and table 1, the pixel size on the ground is quite depending upon the local nadir angle. Nevertheless, SpaceImaging is distributing the derived products in any case with 1m pixel size. So the radiometric quality of an image taken with a nadir angle of 45° will not be so good like for a view up to 28°.

Most systems do have a combination of a panchromatic band and multi-spectral bands with a pixel size relation of 1 : 4. This corresponds to the sensitivity of the human eye, which is quite more sensitive for grey values like for colors. With a pan-sharpening, the lower resolution multi-spectral information can be joined together with the higher resolution panchromatic image to a higher resolution color image. This will not influence the accuracy; it will be the same like for the original panchromatic image. The expression panchromatic is not totally correct because it is not only the visible spectrum; it is extended to the near infrared for getting a better object contrast.

In addition to IKONOS and QuickBird also EROS A1 is taking high resolution images with a pixel size of 1.8m. The capacity of EROS A1 is limited against the other and the geometric accuracy is causing some problems. For OrbView 3, been launched at June 26, 2003, it will take approximately 5 month up start of operation. With SPOT 5 in the super mode 2.5m pixel size is available which can be used for medium scale mapping. Two additional systems also with 2.5m pixel size, but with a stereo combination in the orbit direction are announced with ALOS and Cartosat-1. Cartosat-2 will generate also a very high resolution pixel size of 1m and additional systems like SPOT Pleiades and the Russian ARKON will follow. There will be also a follow on program for IKONOS; IKONOS 3 and 4 with a pixel size below 0.5m are waiting for their launch approximately in 2005.

3. GEOMETRIC POTENTIAL OF IKONOS

As mentioned before, SpaceImaging is not distributing original images - the lowest level of an IKONOS image product is the CARTERRA Geo, a rectification of the image to a plane with constant height (figure 3). It is re-sampled to 1m pixel size independent upon the physical pixel size. Different high level products up to precise orthoimages are also available, but for this, the customer has to deliver also the control point information and the digital elevation model. The precise orthoimages for a scene are approximately 6000 US$ up to 14 000 US$ more expensive like the Geo-product. By this reason, usually only the Geo-images are ordered and the customers are producing the higher level products themselves.

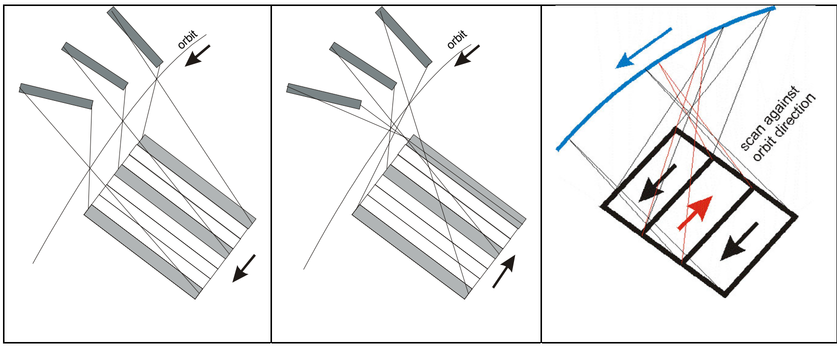


Figure 2: principle of IKONOS image generation - scan direction with orbit and scan direction against orbit

IKONOS is a highly agile satellite, it can change the view direction very fast into any direction, but usually the nadir angle is limited to in maximum 45°. If a larger area shall be covered from one orbit, the first strip will be imaged with the movement of the satellite like this will be done by standard line scanner sensors (figure 2, left hand side), after this, the view direction will be rotated to the side and the neighbored strip will be scanned against the satellite movement by continuously rotating the whole satellite (figure 2, centre). The next neighbored scene would be scanned again with the movement of the satellite (figure 2, right hand side). It is also possible to rotate the satellite and to scan across the orbit direction.

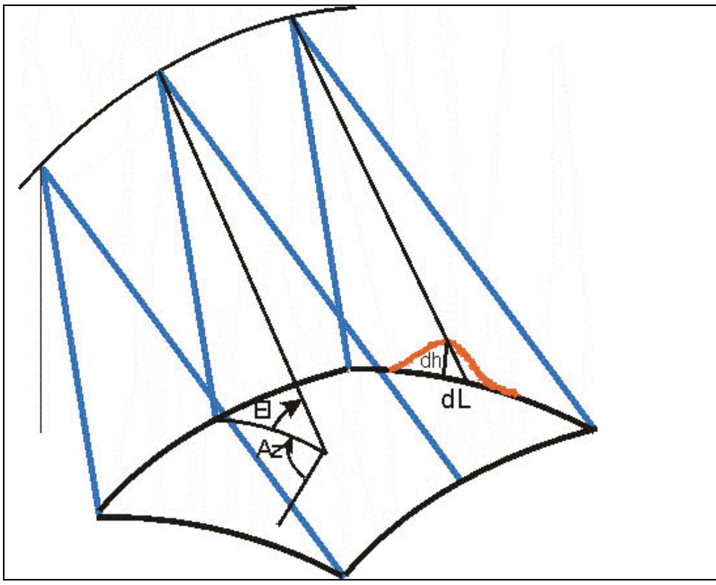


Figure 3: geometric condition of IKONOS Geo-images

dL = dh * tan (local nadir angle) .
Formula 1

The CARTERRA-Geo images are influenced by the local terrain elevation. A height difference dh against the height level of rectification is causing a dislocation dL. In addition the geo-reference of the Geo-scene has to be improved by means of control points. The geo-reference is based on the direct sensor orientation of the IKONOS satellite using GPS-positioning and a combination of an inertial measurement system together with star sensors. The absolute geo-reference without control points is claimed in the specifications with a standard deviation of 12m. Dial and Grodecki (2002) from SpaceImaging are reporting about a higher accuracy in the range of 4m, but it is not normal distributed. This range can be confirmed by own results, but under operational conditions it is often difficult to get information about the local datum of the national coordinate systems.
The sensor model for the IKONOS-images is not available, but SpaceImaging is distributing the relation of the Geo-Image to the national coordinate system in form of rational polynomial coefficients. They do describe the scene position as the relation of a polynomial as function of the three-dimensional ground coordinates divided by another (formulas 2 and 3).

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

Formula 2: rational polynomial functions

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

Formula 3: cubic polynomial

The horizontal ground coordinates are handled as geographic coordinates. Third order polynomials are used. So with 80 coefficients the relation between ground coordinates and the Geo-image can be described. SpaceImaging is adjusting the rational functions based on the not published sensor model. With such parameters a totally sufficient internal accuracy can be reached (Grodecki 2001).
The rational functions are a three-dimensional interpolation. They do have an advantage for the transfer of the image orientation to photogrammetric workstations. The workstations must not have the actual sensor geometry available.

Another possibility of the geometric handling of IKONOS Geo images is the reconstruction of the imaging geometry – this will be done by the Hannover program CORIKON. In the header data, belonging to the images, the view direction from the scene centre to the satellite is available as nominal collection azimuth and elevation (Az and El in figure 3). Based on this view direction the actual location of the satellite orbit can be reconstructed with the general information about the orbit which has been published. So the location of the individual projection centre for any image position can be calculated. This of course has to respect the imaging principle shown in figure 1. The required information is available as "scan azimuth" in the header data, where scan azimuth 180° means the scan with the satellite motion and scan azimuth 0° means the imaging against the satellite motion. The influence of the scan direction to the adjusted ground coordinates is limited. In the mountainous area of Zonguldak (see below), the root mean square difference of the adjusted ground control point coordinates handled once with the scan direction 180° and the next time with 0°, is limited to 0.17m with extreme values up to 0.61m.

Of course it is also possible to reconstruct the imaging geometry just based on control points without taking care about the available information. But for such a reconstruction the control points must be well distributed three-dimensional and a higher number of control points are required. This method will be used with the affine projection model (Hanley et al 2002) which is identical to the rational function shown in formula 2 and 3, but is limited to the linear coefficients (a1 up to a4). The affine projection model is not respecting the perspective geometry in the CCD-line. It is causing 1m error in the horizontal position for points with just 120m difference in height against the location of the control points for points at both ends of the CCD-line. In the case of the mountainous scene Zonguldak described later, positional errors up to 5m can be caused by this method. By this reason, the affine projective model is limited to flat terrain. The determination of a higher number of polynomial coefficients just based on control points requires a high number of control points and is not a save method.

In the area of Zonguldak, Turkey two IKONOS Geo scenes have been analyzed 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 modeling, which is also based on RPC as input values.

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

Table 2: root mean square discrepancies at 39 control points of the IKONOS orientation in Zonguldak, Turkey

Not only the results of all three solutions (first three lines in table 2), also the individual discrepancy vectors are similar. The slightly larger value for the PCI solution is based on an independent point measurement which cannot be compared directly with both other solutions. The large discrepancies in the X-direction are quite above the possible accuracy level. They are strongly correlated with the point elevation and are oriented perpendicular to the view direction (nominal collection azimuth). This obvious problem has been solved with the Hannover program CORIKON by adjusting also the view direction.

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 not on a so high level. Such a problem has been seen also with a scene in Saudi Arabia, but not in other areas. In the Saudi Arabia scene, based on 21 control points with differences in the elevation up to 338m, the azimuth has changed 4.3°, reducing the root mean square differences from 3.22m to 1.48m.
All unknowns in program CORIKON, 6 affine parameters and the horizontal and vertical view direction are checked for their significance and correlation. Not significant parameters are marked and can be taken out of the adjustment. Both unknown view directions are taken automatically out of the solution if they are highly correlated and / or not significant. This may happen if all control points are located in approximately the same height level. In the Zonguldak area the adjustment of the view direction has drastically improved the results even to values slightly below the pixel size of 1m.
A similar orientation quality like in the first Zonguldak scene has been reached also with a second scene in the same area. If all possible 8 unknowns are introduced into the adjustment, by theory 4 control points are required. An orientation with just 4 control points is leading to not save results. The accuracy tested at the not used control points, which are in this case independent check points, showed an accuracy quite depending upon the selected control points. With 5 control points or more, this problem was solved (figure 4). The accuracy will be only slightly improved by a higher number of control points. In areas without the special problem of the view direction, also with 4 control points satisfying results have been achieved. The dominating influence to the control point quality is the point identification. Without any problem an accuracy of 1 pixel can be reached. Larger discrepancies do appear if points are located at corners, especially at corners of roof tops – they can be identified very easily, but the exact identification is difficult, usually the position is shifted from the bright area to darker parts.

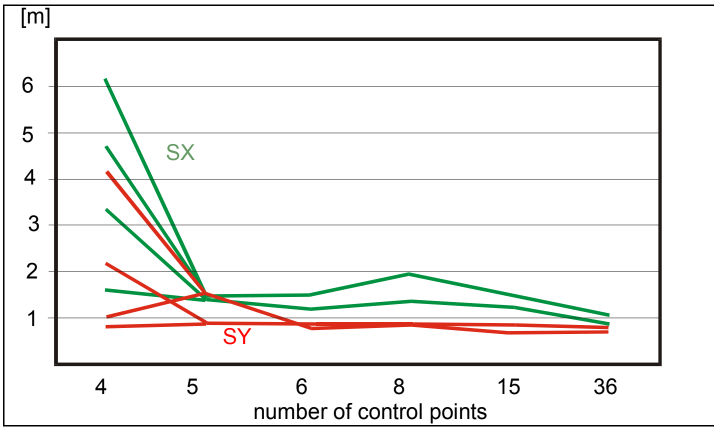


Figure 4: accuracy at independent check points depending upon number of control points,

data set: Zonguldak 1 and 2

By testing the unknowns in CORIKON for significance and against high correlations, save results have been reached. This is not the case with some commercial programs with solutions just based on control points and no test of the unknowns. With rational functions just determined by means of control points, discrepancies up to 200m outside the volume of the control points may appear. Such a solution should not be used. Also SpaceImaging is warning about the use of it.

With a stereo combination digital elevation models can be generated. But only few IKONOS stereo combinations taken from the same orbit are available in the archive.

An IKONOS stereo combination taken with just 12 seconds difference in time, corresponding to a height to base relation of 7.5 has been analyzed. The small angle of convergence leads to very similar images, an optimal condition for automatic image matching. So with a standard deviation of

0.2 pixel for the x-parallax excellent results have been reached, corresponding to a vertical accuracy of 1.7m (see figure 5). An automatic image matching of a combination of 2 IKONOS-scenes taken in September and November failed. Especially the change of the shadows in the mountainous area caused very strong radiometric differences enabling the matching only in some parts after low pass filtering.

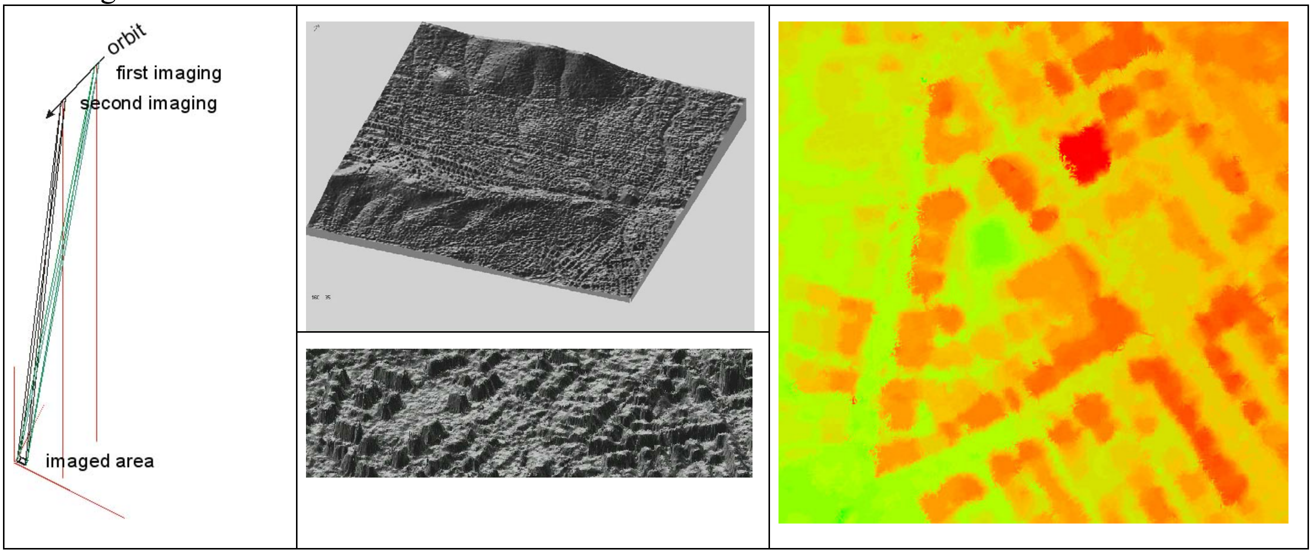


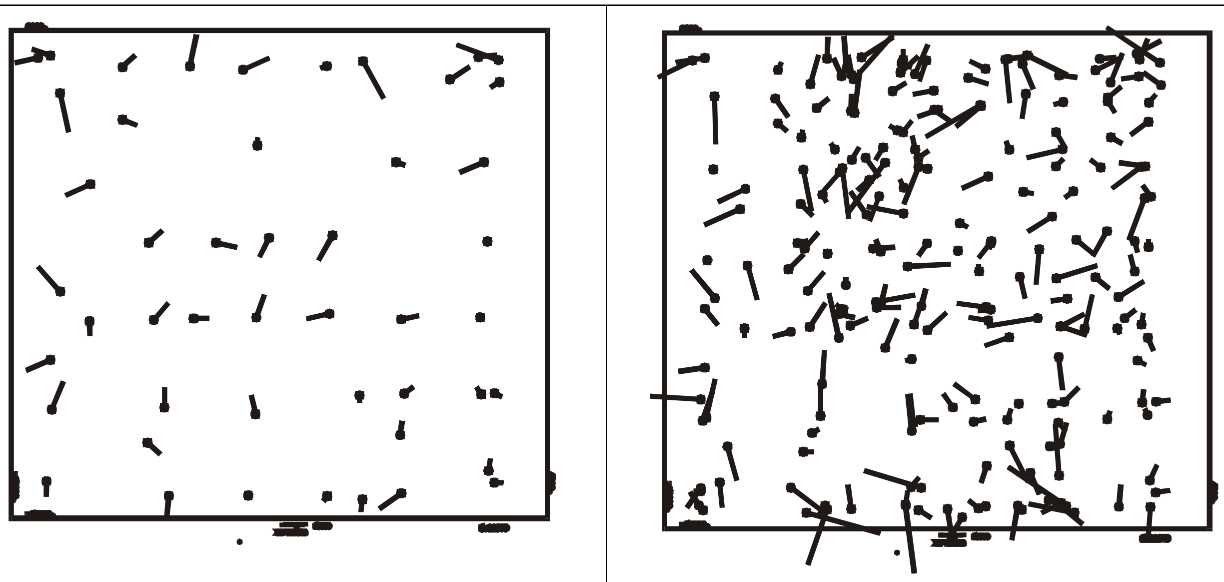
Figure 5: DEM generation with IKONOS stereo model, left: configuration, upper centre: generated DEM, lower centre + right: 3D-city model based on IKONOS-DEM

4. GEOMETRIC POTENTIAL OF QUICKBIRD

Opposite to IKONOS, for QuickBird the so called "Basic Imagery" is available which is close to the original sensor image. The Basic Imagery is a sensor corrected merged image of the individual CCD-lines. It corresponds to the geometry taken by a unique CCD-line with 27 552 elements without geometric distortion. The ephemeris are delivered together with the images. Also other products like the "Standard Imagery", having geometry similar to the CARTERRA Geo, are available.

In the area of Arizona for two Basic Imagery as control information, Digital Orthophoto Quarter Quads (DOQQ) of the USGS and the 7.5'-digital elevation model of the USGS have been available as reference. The Hannover Program BLASPO for the handling of satellite line scanner images has been upgraded for the QuickBird Basic Images. The ephemeris have not been used for the adjustment, only the required rough orbit information has been checked and improved by the ephemeris. BLASPO together with the pre-program SATRAC computes the actual orbit as inertial ellipse by means of the orbit inclination, semi-major axis and numerical eccentricity together with the view direction, focal length, scene positions and control points. The view direction in relation to the orbit, available as "in track view angle" and "cross track view angle", at first will not be changed and kept as the same for all scene lines. As unknowns in the adjustment the rotation of the whole scene and the semi-major will be changed. In addition to these 4 unknowns a scale factor in the orbit direction, and an angular affinity, corresponding to a change of the CCD-line orientation not perpendicular to the orbit has to be included. These 6 unknowns are sufficient for SPOT 1 - 4, ASTER, MOMS and IRS images. QuickBird is changing the horizontal angle of the CCD-line in relation to the orbit to cover an area on the ground oriented to the geographic coordinate system (yaw-control). This requires special additional parameters, if the ephemeris are not used.

The USGS orthoimages do have a pixel size of 1m - this is larger than the 0.64m of the used QuickBird scenes. So the DOQQs are not optimal for the control point generation. From the DOQQs only the horizontal coordinates can be achieved. The required height has been interpolated at the X-Y-position of the control points in the USGS 7.5'-DEM. Neighbored DOQQs are overlapping; in the overlapping area corresponding points have been measured resulting in a standard deviation of the outer parts of the DOQQs of +/-1.01m.



48 control points (symmetric objects)	207 control points (several points at corners)

Figure 6: QuickBird scene 12450 – discrepancies at control points

Figure 7: control point at a grey value corner

- intersection drive and road side

a shift from the bright drive to the dark road cannot be avoided

At first in the scene 12450 at symmetric objects 48 control points have been identified. An adjustment was leading to root mean square differences of SX=1.03m and SY=1.04m (figure 6, left hand). This is very close to the determined accuracy of the DOQQs, so the influence caused by the internal QuickBird accuracy is quite smaller. Of course the estimated accuracy of the DOQQs is pessimistic because only points at the border have been used for the investigation and they are not so accurate like the centre of an orthoimage. Later another person has measured 159 additional control points, but these control points are mainly at grey value corners like the intersection of drives and road sides (figure 7). Such corners in general are shifted from the bright side to the dark side. Corresponding to this, a common adjustment with all 207 control points resulted in SX=1.24m and SY=1.34m. Based on this common adjustment, the 48 symmetric points do have mean square differences of SX=1.08m and SY=1.22m. In spite of the not optimal point selection, in general this is a sufficient result for most applications based on QuickBird Basic images.

Of course such a high number of control points will not be used under operational conditions. By this reason different control point configurations have been analyzed (figure 8). The increase of the accuracy with a higher number of control points can be explained just by the influence of the individual control point accuracy. 9 control points are sufficient for the sensor orientation and do have enough redundancy for reliable results. Also because of the source of the control points not less than 9 control points should be used. If the data sets have been prepared for the image measurement, it does not matter if some more control points are measured.

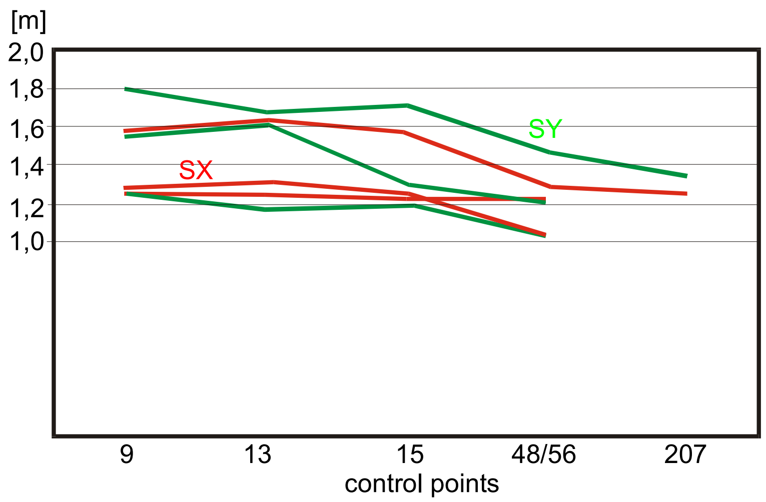


Figure 8: QuickBird, Basic Imagery:

accuracy at independent check points depending upon number of control points

scene 12450 and 12451

In the area of Atlantic City control points have been determined by automatic image matching of a QuickBird Basic Imagery and aerial images. As preliminary result with 381 control points an SX=1.75m and SY=1.02m has been achieved. Neighbored control points are highly correlated with a correlation coefficient of up to 0.75. The reason for this has not been identified up to now; it may be caused also by the ground reference. The relative coordinate accuracy for distances up to 1.2km is in the range of 0.58m. After least squares interpolation even a local accuracy of 0.44m for X and 0.32m for Y is available. This shows at least the local accuracy potential of QuickBird images.

From QuickBird two overlapping scenes taken with 10 days difference in time over suburbs of Phoenix, Arizona have been used for the generation of a DEM. The change of the sun elevation and the vegetation is negligible, so good conditions for the image matching do exist. The automatic image matching was excellent, leading to a vertical accuracy of 4.8m in relation to the USGS DEM, which is also not free of error. This corresponds to a standard deviation of the x-parallax of 0.8 pixels. The average correlation coefficient was in the range of 0.95 and the matching failed only in few limited areas with very low contrast like on roads, sandy areas and few roofs.

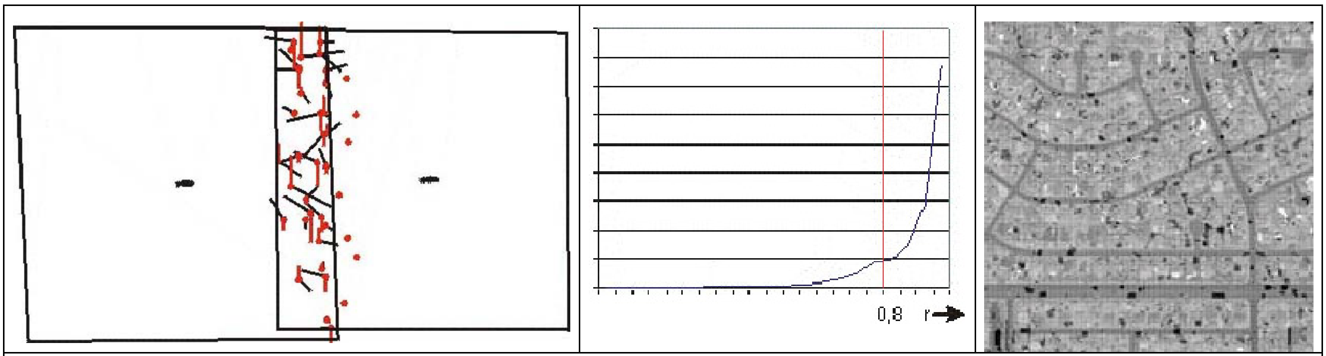


Figure 9: left: QuickBird model with control points, centre: frequency distribution of correlation coefficient, right: sub-image with overlaid matched points (dark = not matched)

5. CONCLUSIONS

With the very high resolution of IKONOS and QuickBird images and the possible geometric quality, a competition to aerial images exists and the use of the different products is only a question of economy. With a correct mathematical model and satisfying control points, orientation accuracy in the range of a pixel can be reached under operational conditions just with few control points. With stereo pairs taken from the same orbit or under very similar conditions, very detailed DEMs can be generated. If the radiometric changes caused by a longer time interval in taking both scenes of the model are too strong, the automatic image matching will fail.

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